

# WORKSHOP ON ION TRAP TECHNOLOGY

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Book of Abstracts

**NIST**





*Invited talks*

# Status of Trapped-Ion Physics in Europe

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The status of trapped-ion physics in Europe is reviewed with particular emphasis on trap development and recent experiments in the field of quantum information processing and quantum simulation. First experiments implementing repetitive quantum error correction will be reported and quantum simulations of the Dirac equation as well as the Klein paradox were implemented. The coupling of quantum information between ions in separate trapping potentials [1] will be described. In this work, direct coupling between the motional dipoles of separately trapped ions is achieved over a distance of 54  $\mu\text{m}$ , using the dipole-dipole interaction as a quantum-mechanical transmission line [2]. This interaction is small between single trapped ions, but the coupling is amplified by using additional trapped ions as antennae.

[1] M. Harlander et al., arXiv:1011.3639, accepted for publication in Nature.

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# “TACK” ION TRAP FOR EFFICIENT PHOTON COLLECTION

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Detection of resonance fluorescence from trapped ions and atoms enables efficient measurement of the quantum state of these qubits. Thus, it is desirable to collect a large fraction of the (isotropically emitted) photons to make the detection faster and more reliable. Additionally, efficient fluorescence collection can improve the speed and fidelity of remote ion entanglement and quantum gates. Refractive and reflective optics, as well as optical cavities, and, more recently, bare multimode optical fibers have all been used to collect the trapped ion fluorescence with up to 10% efficiency. Here we show a novel ion trap design that incorporates a high numerical aperture metallic spherical mirror as the integral part of the trap itself (the RF electrode) which enables up to 35% solid angle collection of trapped ion fluorescence. The movable central needle-shaped electrode of this “tack” trap allows precise placement of the ion at the focus of the spherical mirror. We also study the properties of the images formed by the spherical mirror and comment on possible methods for the aberration correction. Owing to the simplicity of its design, this trap structure can be adapted for microfabrication and integration into more complex trap architectures.

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# CHALLENGES OF LASER COOLING MOLECULAR IONS\*

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Recent demonstration of the laser cooling of SrF opens the possibility of laser-cooling molecular ions [1]. The long trap lifetime of molecular ions allows for a wider array of cooling schemes, but also requires careful consideration of slow molecular processes. I will present results numerically examining the feasibility of laser-cooling AlH<sup>+</sup> and BH<sup>+</sup> [2]. I will describe a potential experiment using BH<sup>+</sup> sympathetically cooled by Ca<sup>+</sup> and explain how quantum logic spectroscopy [3] and sympathetic heating spectroscopy [4] can be used to measure the molecular ion spectra with sufficient resolution for laser cooling.

## References

- [1] E. S. Shuman, J.F. Barry, and D. DeMille, *Nature* **467**, 820 (2010).
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- [3] P. O. Schmidt, T. Rosenband, C. Langer, W. M. Itano, J. C. Bergquist, and D. J. Wineland, *Science* **309**, 749 (2005).
- [4] C.R. Clark, J.E. Goeters, Y.K. Dodia, C.R. Viteri, and K.R. Brown, *Phys. Rev. A* **81**, 043428 (2010)

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# FASTER QUANTUM OPERATIONS AND CONTROL FOR TRAPPED IONS

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If trapped ions are to become a truly viable technology for large-scale quantum information processing, things will have to speed up. This of course refers not only to the rate of advance of the field, but also to the speed of basic quantum operations. All demonstrated high-fidelity multi-ion gates have relied on trap-frequency-timescale operations; to reduce two-qubit gate times in this scheme, trap structures will need to be miniaturized. Reduction of measurement times will require enhanced light collection. Ion motional state initialization may also be made faster in more-tightly confining traps. The desire to go to small scales must however be balanced with the fidelity-reducing effects of anomalous heating and its scary scaling with trap size. Also, making large arrays of tight traps may lead to increased difficulty in controlling stray fields at ion locations.

A possible way out of this dilemma may be to skirt many of these problems through miniaturization and integration. I will describe an idea for straightforward integration of reflective optics with a surface-trap geometry to enhance fluorescence detection while maintaining the ability to have a small trap size and less dielectric surface area near the ion. This technique should be compatible with large-scale ion shuttling quantum computing architectures, static or semi-static arrays for quantum simulation, and individual traps for quantum communication applications. I will also describe a simple scaling argument for the suggestion that stray static fields in a large array of strongly confining traps will not be a terrible control problem, and I will briefly review a method for limiting the exposure of ions to noise on the rf trapping potential during movement by eliminating junctions in a scalable, reconfigurable, shuttling architecture.

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# TOWARDS HYBRID TRAPPED ION SYSTEMS: INTEGRATING SUPERCONDUCTORS, OPTICAL FIBERS, AND MIRRORS\*

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Exploration of hybrid quantum systems with trapped ions will require integration of ions with the materials and devices of other mechanical, electronic, and optical quantum systems, at previously unrealized degrees of intimacy. Here, we report on four experiments, characterizing single ions trapped above surface electrode geometries constructed with (1) superconductors made of Nb and NbN [1]; (2) a transparent conductor, indium tin-oxide; (3) an integrated optical fiber, centered in a point Paul trap, self-aligned to the ion [2]; and (4) gold electrodes patterned with a centered hole, on the surface of a high-reflectivity optical mirror [3]. Performance metrics include ion lifetimes and heating rates, light collection efficiencies, and delivered light intensities. These experiments, which are made possible by operating the traps cryogenically, at  $\sim 6$  Kelvin, enable the integration of superconducting devices near trapped ions [4], and the practical realization of ions coupled to very small mode-volume electromagnetic cavities.

## References

- [1] Shannon X. Wang, Yufei Ge, Jaroslaw Labaziewicz, Eric Dauler, Karl Berggren, and Isaac L. Chuang *Superconducting microfabricated ion traps*, Appl. Phys. Lett., vol. 97, 244102 (2010).
- [2] Tony Hyun Kim, Peter F. Herskind, Taehyun Kim, Jungsang Kim, and Isaac L. Chuang *Surface-electrode point Paul trap*, Phys. Rev. A, vol. 82, 043412 (2010).
- [3] Peter F. Herskind, Shannon X. Wang, Molu Shi, Yufei Ge, Marko Cetina, and Isaac L. Chuang, *Micro-fabricated surface trap for scalable ion-photon interfaces*, arXiv:1011.5259 (2011).
- [4] David I. Schuster, Lev S. Bishop, Isaac L. Chuang, David DeMille, and Robert J. Schoelkopf, *Cavity QED in a molecular ion trap*, Phys. Rev. A 83, 012311 (2011).

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# Ion traps for quantum information processing at NIST \*

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I will present recent experiments conducted in the NIST Ion Storage Group, with an emphasis on technical aspects. These experiments use either macroscopic traps, or microfabricated surface-electrode traps. Work since the last workshop has been devoted to (1) improving the performance of state manipulation for qubits that are transported and sympathetically cooled, (2) simplifying ion fluorescence detection, (3) demonstrating direct coupling of ions in separate traps, and (4) implementing qubit gates with microwave fields.

In the case of traps with small ion-electrode separation, anomalous heating of the ion can be a central issue, and its origin remains uncertain. To investigate the potential role of contaminants on the surface of the electrodes in anomalous heating, we have performed Auger electron spectroscopy on ion chips, and we are building an apparatus that will combine several types of surface preparation and analysis techniques with an ion trap used as a surface probe.

\* Supported by IARPA, NSA, ONR, DARPA, and the NIST Quantum Information Program

# QUANTUM GAS MICROSCOPE - SINGLE ATOM CONTROL FOR ULTRACOLD ATOMS

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The Quantum Gas Microscope<sup>1</sup> enables high fidelity detection of single atoms in a Hubbard-regime optical lattice, bringing ultracold atom research to a new, microscopic level. It bridges between macroscopic approaches in which ultracold atoms are studied on an ensemble level, and microscopic approaches such as in ion traps in which small quantum systems created, with full control over all quantum degrees of freedom. I will discuss how the quantum gas microscope is implemented and which new possibilities arise. I will give an outlook on recent experiments on observing the superfluid to Mott transition on a single particle level<sup>2</sup>, and on realizing magnetic models in the quantum gas microscope.

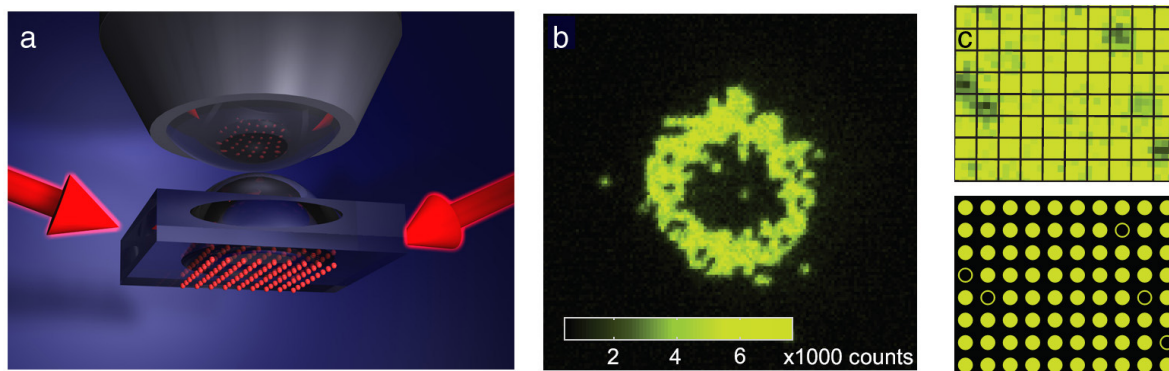


Figure: Mott insulator (MI) in a Quantum Gas Microscope. (a) Sketch of Quantum Gas Microscope, enabling high fidelity single lattice site imaging. (b) Mott insulator shell structure with  $n = 1$  MI (bright ring), surrounding a  $n = 2$  MI core (dark). (c) near perfect  $n=1$  Mott insulator.

## References

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# TRAPPED IONS MEET SOLID STATE PHYSICS

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Trapped ions provide an extremely clean system often under nearly perfect control of the experimenter. This situation is somewhat diametrical to what physicists encounter in solid state physics. In the first part of this talk, we will discuss how trapped ions can help to understand simple models of materials. Conversely, we will discuss in the second part how aspects of materials science can help to understand the so-called anomalous heating which seriously impedes progress in ion trap quantum computing.

The complexity of many-body quantum systems continues to challenge our understanding even of simple materials. We plan to implement model systems of materials with trapped ions to study how macroscopic phenomena emerge from quantum many-body physics. In our set-up, crystals of  $\sim 50$  Calcium ions are trapped in a conventional linear quadrupole trap. A cavity along the trap axis will allow us to generate a strong optical lattice thereby confining individual ions to micro traps. The resulting anharmonic quantum oscillators are weakly coupled to each other via the Coulomb interaction. We plan to employ this oscillator model to study quantum transport phenomena and thermalization. In particular, we are interested in understanding the friction of the ion crystal as a function of the lattice depth.

In the second part, we will connect insight surface scientists have obtained to the excessive heating observed in ion traps. In particular, we conjecture that impurity atoms adsorbed on metal surfaces and amorphous dielectrics cause part of this anomalous heating. To study this hypothesis, we incorporate surface analysis and cleaning tools into an ion trap apparatus. The surface will be cleaned via cycles of sputtering with Argon ions and annealing. Progress of the surface cleaning cycle will be monitored via Auger spectroscopy. Furthermore, the apparatus will be optimized for fast turn-around times enabling rapid trap testing at room temperature.

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# Scalable imaging of trapped ions for quantum information processing

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Trapped ions are a leading system for realizing quantum information processing (QIP). Most of the technologies required for implementing large-scale trapped-ion QIP have been demonstrated, with one key exception: a massively parallel ion-photon interconnect. Arrays of microfabricated phase Fresnel lenses (PFL) are a promising interconnect solution that is readily integrated with ion trap arrays for large-scale QIP [1]. We have demonstrated the first imaging of trapped ions with a microfabricated in-vacuum PFL, demonstrating performance suitable for scalable QIP [2]. A single ion fluorescence collection efficiency of  $4.2 \pm 1.5\%$  was observed, in agreement with our independent measurements of the PFL's optical performance. We have observed ion images of 440 nm FWHM, the highest-resolution images ever obtained with isolated atoms [3]. The spot size is only 20% larger than the transition wavelength of 369.5 nm and 50% larger than the ideal resolution limit given by the PFL numerical aperture. The near-diffraction-limited PFL imaging can greatly improve the coupling efficiency of ion photons into single-mode fiber, opening new prospects for scalable, high-speed quantum communication by ion-photon entanglement [4]. The excellent imaging resolution permits accurate thermometry of the ions through spatial measurements of thermal motion, allowing us to observe novel laser cooling phenomena [5].

## References

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- [2] E.W. Streed, B.G. Norton, A. Jechow, T.J. Weinhold, and D. Kielpinski, *Phys. Rev. Lett.* (2011).
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# ION TRAP NETWORKING WITH PHONONS AND PHOTONS\*

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Trapped ion spins can be entangled through a local deterministic coupling to phonons, and also through a nonlocal probabilistic coupling to photons. Each method has strengths and weaknesses, and each will rely upon future technological advances in trap fabrication and integrated photonics. These challenges will be discussed, as well as recent work at JQI/Maryland exploiting phonon interactions for scalable quantum simulations of magnetism, and combining both phonon and photon networks in a hierarchical quantum information architecture.

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## **A poor man's quantum computer? the experimental quantum simulator**

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First, I will provide an overview of the field of experimental quantum simulation with trapped ions in conventional radiofrequency traps. I will try to illuminate the work that has been done by the dedicated groups.

Experts in the field distinguish between experimental quantum simulations of two different classes. One class deals with problems that are efficiently solvable on classical computers. However, the quantum simulator provides an analogue that allows to experimentally address intriguing questions that are not directly trackable in the laboratory. The second class of simulations deals with objectives that are (probably fundamentally) not accessible via classical computation, for example, the complex quantum dynamics in solid state systems. However, the aim is not to simulate the effects including all disturbances and peculiarities. Experimental quantum simulations are predicted to allow for investigating "simple" Hamiltonians under very controllable conditions. This could allow to test whether simplifying the underlying physics (Hamiltonian) to its suspected basics is capable to reproduce and explain the observed complex behaviour. The obtained results might therefore provide deeper insight, for example, into quantum-phase transitions.

Furthermore, I will try to elucidate, how analogue quantum simulations differ from the alternative approach to calculate their results on a future universal quantum computer and will try to trigger a discussion about the related advantages and disadvantages.

The main challenge of the field remains to achieve scalability towards 50-100 ions and beyond. A simulated system of this size would outperform classical computation and already allow to address questions of interest. Some challenges for scaling will be discussed, for example, addressed in new, 2d-surface traps. I will also introduce an alternative approach, trying to combine the advantages of trapped ions and optical lattices.

# MICROFABRICATED SURFACE ION TRAPS WITH ARBITRARY LATERAL GEOMETRIES\*

Daniel Stick<sup>†</sup>, F. Benito, M.G. Blain, R. Cook, M. Descour, A.R. Ellis, K.M. Fortier, R.A. Haltli, C. Highstrete, S.A. Kemme, D.L. Moehring, B.P. Tabakov, C.P. Tigges

We will present the status of Sandia's efforts to engineer robust surface ion traps, specifically detailing the challenges we have overcome in order to render arbitrary surface geometries. These challenges include the precision placement of backside holes for loading from a neutral atom source, multi-level metalization which supports vertical interconnects and low electrical power loss in the substrate, and low profile wirebonds for surface laser access [1]. We have combined these capabilities to produce a successful and robust Y-junction trap which takes advantage of numerical simulations to tailor the RF pseudopotential field in the junction with precisely shaped electrodes. We will also present ongoing work at fabricating structures for quantum simulations in collaboration with NIST. In addition we will describe traps with an integrated high finesse optical cavity, junction traps capable of reordering strings of ions with multiple species, and ring shaped traps that we are fabricating for the IARPA sponsored MUSIQ program.

## References

[1] D. Stick, K.M. Fortier, R. Haltli, C. Highstrete, D.L. Moehring, C. Tigges, M.G. Blain, arXiv:1008.0990 (2010).

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# OPEN SYSTEM QUANTUM COHERENT CONTROL AND QUANTUM SIMULATION, AND IMPLEMENTATION

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While impressive progress has been reported in isolating the systems from the environment and coherently controlling their many body dynamics in both quantum computing and quantum simulation, we will focus here on the engineering the open system dynamics of many particles by a controlled coupling to an environment. We will discuss both the basic theoretical concepts as well as their physical implementation with neutral atoms, in particular cold Rydberg atoms, and trapped ions. Specific topics include non-equilibrium quantum phase transitions in many particle quantum systems, engineering of entangled states with dissipative processes, and dissipative quantum computing.

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# *Poster abstracts*

# THE OXFORD PLANAR ION TRAP PROJECT

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The Oxford Planar Ion Trap project currently involves three traps:

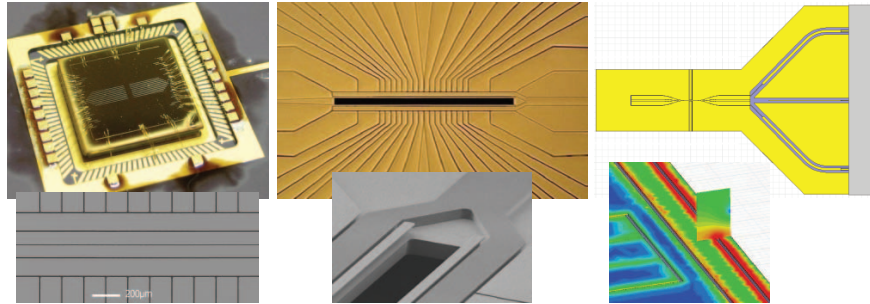


Figure 1: The Oxford fabrication (left) and detail of trapping region (inset). The Sandia fabrication (centre) and detail of electrode structure (inset). The microwave trap (right) and microwave field simulation (inset).

Trap 1: A gold-on-quartz surface trap with a  $150\mu\text{m}$  ion-surface separation, designed and fabricated at Oxford. This trap was used to develop the capability to design, fabricate and operate planar traps within the group. The trap incorporates a split centre dc electrode to allow the principal axes of radial motion to be rotated to optimize laser cooling. Improved methods for micromotion compensation and heating rate measurement were also developed using this trap [1].

Trap 2: Sandia National Laboratories have fabricated a monolithic silicon trap along the same lines as Trap 1 [2]. This fabrication method allows the removal of all dielectrics with line-of-sight to the ion and may reduce anomalous heating and trap charging effects. The trap incorporates a slot that in a future version will be able to accommodate a fiberized optics package for laser delivery and fluorescence collection. We are testing several of these traps and preliminary results will be presented.

Trap 3: This trap is currently being fabricated using the same process as Trap 1 and will be used to implement microwave-driven two-qubit gates [3]. For more detail on this experiment see the poster of T. Harty.

## References

- [1] D. Allcock et al. *New J. Phys.* 12, 053026 (2010)
- [2] D. Stick et al. *arXiv:1008.0990* (2010)
- [3] C. Ospelkaus et al. *Phys. Rev. Lett.* 101, 090502 (2008)

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# MASS ANALYSIS, DIRECTED ION TRANSFER, AND FIELD SHAPING IN LITHOGRAPHICALLY-PATTERNED PLANAR ION TRAPS

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Brett J. Hansen, Aaron R. Hawkins

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We have developed a series of radiofrequency ion traps using pairs of lithographically-patterned plates. Both 2-D and 3-D quadrupoles have been demonstrated, as well as an interesting arrangement in which both a 3-D quadrupole and a toroidal trapping field are created simultaneously and coaxially. In this coaxial ion trap, ions can be trapped in the toroidal region (which has a significantly larger storage capacity), transferred to and trapped in the 3-D quadrupole, and then mass analyzed. Although all of these devices rely on trapping fields that are primarily quadrupolar, the electrode patterns allow independent adjustment of higher-order components, e.g., hexapole, octopole, decapole, etc. We can also perform dipole resonant excitation resulting in either ion ejection or collision-induced dissociation. As mass analyzers these devices have demonstrated resolving power in excess of 1000 (m/dm). These devices have a very open structure, allowing easy access for lasers, incident particle beams, and optics.

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# Microfabricated Surface Electrode Ion Traps

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We report on the status of Sandia's ion trap micro-fabrication efforts, including the successful demonstrations of a linear surface trap and a Y-shaped surface trap. The Y trap design is based on numerical simulations yielding electrode shapes that optimize the RF pseudopotential at the junction. We also report on progress towards fabricating traps utilizing four metal layers, which further relaxes the trap geometry limitations and allows for leadless trap electrodes. These advances will be used in the devices we fabricate for the MUSIQC program, particularly a ring shaped trap, a junction trap for arbitrarily ordering ions, and a trap with integrated high-finesse optical cavities.

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### Quantum Information Processing using Scalable Techniques

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We have previously demonstrated the combination of the fundamental building blocks required for large-scale quantum information processing using trapped atomic ions [1, 2]. Qubits are stored in magnetic-field insensitive hyperfine-state superpositions in  $^9\text{Be}^+$ , and information transport is accomplished by moving the ions themselves with time-varying potentials applied to the electrodes of a multi-zone radiofrequency trap. We have characterized the repeatability of a multi-qubit operation involving a combination of one- and two-qubit gates with transport of trapped-ion qubits over macroscopic distances, demonstrating no loss of gate fidelity due to transport [1]. One limitation of our previous experiments was the two-qubit gate fidelity; a geometric phase gate [3] required a complicated pulse sequence to be compatible with our magnetic-field insensitive qubit manifold. We have switched to a two-qubit gate that works directly on the field-insensitive states [4] and have implemented it in a manner insensitive to drifts in optical phase [5]. Another limitation of our previous work was the large amount of sympathetic cooling of  $^{24}\text{Mg}^+$  ions required to combat the motional excitation acquired from imperfect ion transport. We have developed controls for our trap potentials that significantly reduce this excitation and have decreased transport times, dramatically increasing our operation speed.

This work is supported by NSA, IARPA, DARPA, Sandia, and the NIST Quantum Information Program.

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[5] P. J. Lee, et al., *J. Opt. B* **7**, S371 (2005)

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# HARMONIC OSCILLATORS COUPLED AT THE SINGLE QUANTUM LEVEL

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We have recently built a surface electrode ion trap for  ${}^9\text{Be}^+$  ions (ion-to-surface distance =  $40\ \mu\text{m}$ ) that incorporates electrodes cooled to 4.2 K. The small dimensions and low heating rate in this apparatus have enabled a first demonstration of quantized Coulomb interaction between ions held in separate trapping potentials [1]. This system demonstrates a building block for quantum information processing and quantum simulation, and is a natural precursor to experiments in hybrid quantum systems. The trap is housed within a cold copper enclosure that shields it from magnetic field fluctuations, and the small ion-to-surface distance makes possible radial trapping frequencies  $> 30$  MHz. We will present recent results and discuss potential applications that exploit these advantageous features.

This work is supported by IARPA, DARPA, ONR, and the NIST Quantum Information Program.

## References

[1] arXiv:1011.0473, accepted for publication in Nature

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# A COLLECTIVE ION-PHOTON INTERFACE FOR QIP

Marko Cetina<sup>†</sup>, Alexei Bylinskii, Andrew Grier, Dorian Gangloff, Kristin Beck, Leon Karpa, Matthias Sholz, Fedra Orucevic, Yufei Ge, Isaac Chuang, Vladan Vuletic

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We present a microfabricated linear array of RF ion traps integrated with a medium-finesse ( $\approx 4000$ ) optical resonator. We demonstrate coupling to the optical mode of up to 10 array sites containing Yb<sup>+</sup> ion crystals of 1-50 ions each. We show that the loading of array sites from an initially extended crystal is sub-Poissonian. With a calculated single-ion cooperativity of 2%, our system could operate as an ion-photon interface in the strong collective coupling regime while preserving single-ion addressability and resolution of motional modes, e.g. for doing quantum gates with ions.

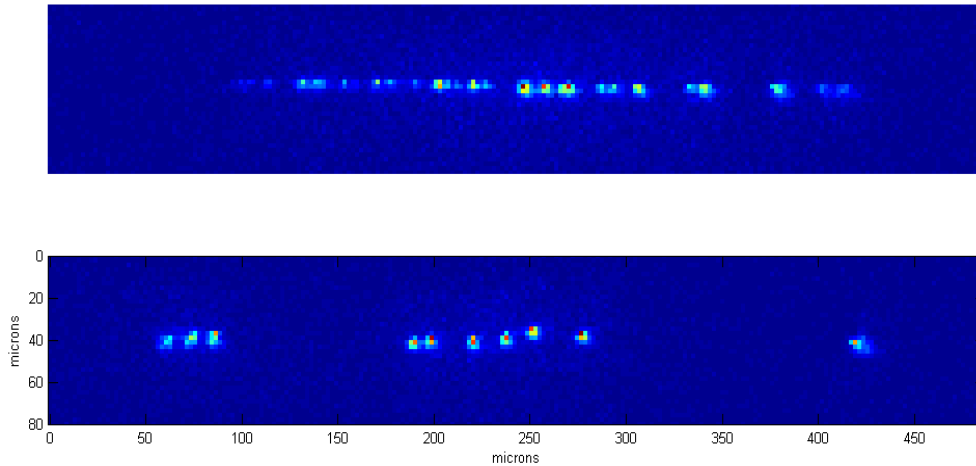


Figure 1: Top: linear ion chain illuminated by the cavity mode with the array potential off. Bottom: loading of single and few ions into array sites from the linear ion chain upon turning on the periodic potential.

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# ION-PHOTON NETWORKS FOR SCALABLE QUANTUM COMPUTING

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Trapped ions connected by photons are a promising avenue for large-scale quantum computing and quantum information transfer. Previous experiments with photonically connected, distant, trapped ions establish ion entanglement [1], teleportation [2], and generation of private random numbers [3]. Here, we report advances toward combining these photonic gates between distant ions with Coulombic gates between nearby ions in order to demonstrate a scalable quantum network [4]. We implement a novel protocol for the Coulomb two-ion and single-ion gate which shows increased robustness to errors from rf trap noise. Specifically, we use a composite pulse sequence, similar to spin echo, increasing the revival and coherence of the decoupled spin-motion state. We also present our results on individual optical addressing of single ions, allowing for photonic entanglement to be performed separately from the Coulomb gates. These improvements are important steps to the realization of a scalable ion-photon network.

This research was supported by IARPA through ARO contract, the ARO MURI program, the AQUITE program, the NSF PIF Program, the NSF Physics Frontier Center at JQI. Q.Q. received additional support from the IC postdoc administered by the NGA, currently an NRC postdoc with ARL.

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## Microfabrication and Microassembly for Ion Trap Technology

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Microfabricated components and microassembly are emerging as enabling technologies for ion trap system experiments. To date, these technologies have been utilized to realize various system components such as small-feature electrodes, microlenses, and compact ion ports. Future experiments and eventual applications utilizing trapped ions will undoubtedly require more sophisticated microfabricated components with higher levels of microassembly. Such components may include multi-layer electrodes, high-density/high-value RF passives, optical guiding, and active optics. These components, furthermore, may need to be assembled in a compact UHV package having both optical and electrical feedthroughs.

We present several microfabrication technologies with possible utility for ion trap experiments. Additionally, we present examples of the impact of advanced microfabrication/microassembly in two relevant areas: compact atomic clocks [1] and compact cold-atom systems.

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# MEASURING THE ELECTRON EDM USING TRAPPED MOLECULAR IONS

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Trapped molecular ions offer an ideal candidate platform for an electron electric dipole moment (EDM) search. The  $^3\Delta_1$  electronic state of  $\text{HfF}^+$  offers a large sensitivity enhancement to an EDM measurement. Additionally,  $\text{HfF}^+$  is easily trapped, allowing us to take advantage of a long coherence time to perform electron spin resonance. When performing our measurement we will use laser induced fluorescence to read out spin. We also require that electric fields be uniform to reduce uncertainty on the measurement. We present a design for a novel Paul trap optimised for fluorescence collection and field uniformity. We use large area ellipsoidal reflectors to achieve expected 50% fluorescence collection efficiency. The trap uses six electrodes shaped like parabolas. This distinctive electrode design will allow us to achieve better than 1% field uniformity over a 10mm diameter region.

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# TWO-QUBIT MICROWAVE GATES

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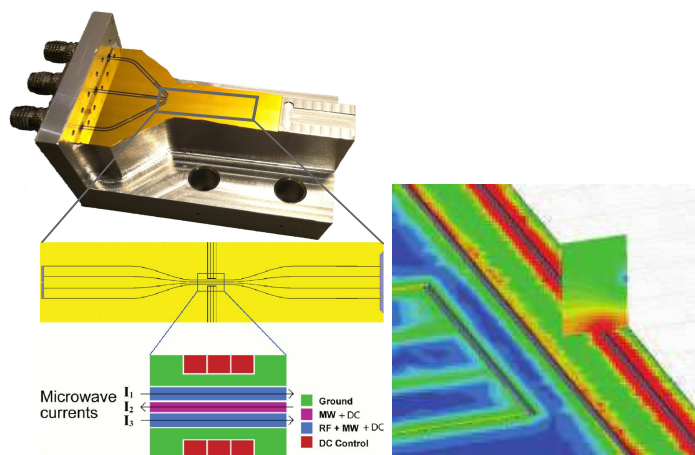


Figure 1: (a) Ion trap with three microfabricated waveguides. Microwave currents are inserted using SMA connectors and  $50\Omega$  transmission line (left of image). They are then coupled into low-Q half-wave cavities (shown magnified in the centre of the figure) using quarter-wave coupling sections. The cavities provide a build up of microwave power, with ions trapped at the centre (anti-node). (b) Simulated microwave currents and cross-section of the magnetic field (shown in the rectangular insert) around waveguides. Simulations were done using Ansoft HFSS<sup>TM</sup> software.

Ion trap quantum computers implement multi-qubit gates by entangling two or more ions via a shared motional mode. Traditionally this has been accomplished using lasers tuned to a motional sideband transition. However, this requires highly stable lasers and cooling to the ions' motional ground state, making it technically very demanding and difficult to scale to large numbers of qubits.

A recently proposed alternative is to use microwave frequency magnetic field gradients to create entangled states [1]. The required magnetic field gradients can be generated in the near-field region of a set of microfabricated waveguides (see figure). The use of microwaves instead of lasers and the compatibility of the waveguides with standard microfabrication techniques makes this approach much easier to scale to large numbers of qubits.

We present the design and construction, as well as initial electronic testing, of an ion trap (see image) and microwave electronics system to implement two-qubit gates. The trap is fabricated in house using a gold-on-sapphire process with a designed ion-surface distance of  $75\mu\text{m}$ . It features three low-Q cavities to produce build up of microwave power.

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# Efficient sympathetic cooling of an ion crystal in a double-well trap potential

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## Abstract

Efficient sympathetic cooling of two-ion system, in which one is laser-cooled and the other is sympathetically cooled, in a linear rf trap with a double-well potential is proposed. The double-well potential consists of two parabolic wells, and there is one ion in each well. By theoretical analysis, the normal modes of the small oscillations around the equilibrium are derived, and a measure of the sympathetic cooling rate is obtained. As a result, it is found that the sympathetic cooling is efficient when the resonant frequency of the small oscillation of the sympathetically cooled ion is close to that of the laser-cooled ion. In the double-well potential, therefore, the sympathetic cooling of the ion species whose mass is much heavier or lighter than that of the laser-cooled ion can be efficient. According to the estimation, the double-well potential may be made by the microfabricated electrode configuration or by the optical dipole force trap.

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# AN OPEN-SYSTEM QUANTUM SIMULATOR WITH TRAPPED IONS

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It was often thought that the creation and manipulation of entanglement require an isolated quantum system and the coherent control of its dynamics. However, decoherence in a quantum system can also serve as a useful resource for the preparation of a desired entangled state from an arbitrary initial state [1], for dissipative quantum computation [2], and for the simulation of arbitrary open-system dynamics [3]. While impressive progress has been achieved in controlling closed system dynamics, engineering the dynamics of many particles by a controlled coupling to an environment remains largely unexplored.

We report the first realization of a toolbox for simulating an open quantum system using up to five ion qubits [4]. The combination of multi-qubit gates with optical pumping implements coherent operations and dissipative processes. We illustrate this engineering by the dissipative preparation of entangled states, the simulation of coherent many-body spin interactions, and the quantum non-demolition measurement of multi-qubit observables. The combination of coherent operations with controlled dissipation offers novel prospects for open-system quantum simulation and computation.

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# QUANTUM INFORMATION USING MICROWAVE MANIPULATION OF LASER COOLED IONIC SPIN CHAINS

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We discuss – from a viewpoint of quantum information science and quantum simulations – laser cooled strings of trapped Yb ions exposed to an inhomogeneous magnetic field [1]. Such strings form a chain of interacting spins, whose coupling (mediated by the Coulomb repulsion) can be adjusted individually, when the individual ion positions can be controlled [1,2]. We use hyperfine levels of the electronic ground state of  $^{171}\text{Yb}^+$  which has a nuclear spin  $I = 1/2$  as our qubit and drive hyperfine transitions using microwave and rf radiation [3]. Addressability as well as the coupling between internal and motional state is provided by the magnetic gradient [4]. The longevity of hyperfine states and the ease and flexibility of implementation (when using microwave fields for coherent state manipulation) makes this an interesting system for simulating other quantum systems [5], as well as for quantum information [3] and can be viewed as combining the beneficial aspects of cold trapped ions and nuclear magnetic resonance experiments.

We present the status of an experiment with a segmented linear micro structured three-dimensional Paul trap that includes micro structured magnetic field gradient elements [6]. We discuss the status on measuring the coupling strength in spin chains and give an outlook on different approaches for protecting the qubit from decoherence. A possible solution is the transfer between magnetically insensitive storage states and magnetically sensitive processor states. Such systems can be found among Zeeman sublevels or by utilizing electron and nuclear spin separately in the Paschen-Back regime [7].

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# INTEGRATION OF MICRO-OPTICS WITH ION TRAPS TOWARDS EFFICIENT ENTANGLEMENT GENERATION BETWEEN REMOTE IONS

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Entanglement between remote quantum memories is a fundamental resource and has various applications from the loophole-free test of a Bell's inequality to many quantum information protocols such as quantum teleportation, quantum communication, and quantum computation. The entanglement established between two ions from remote ion chains can also be utilized to perform two-qubit quantum logic operations between these chains, and this mechanism could lead to scalable trapped ion quantum computing.

The heralded entanglement generation relies on the collection and interference of two photons from different ions [1]. In current experiments, the success probability of this protocol is very small and mainly limited by the photon collection probability. Increasing the probability of photon collection from a single ion is essential in making the remote entanglement needed for scalable quantum information processing.

Here, we present progress towards an experiment in which a single trapped Ytterbium ion will be coupled to the mode of a small high finesse cavity. The cavity will be formed by a fiber tip with highly reflective coating and a mirror with 5mm radius of curvature. A surface ion trap will be patterned on the tip of a fiber ferrule to trap an ion in the center of the tightly focused cavity mode. As a first experiment we fabricated the surface trap on a glass substrate and characterize the trap performance using an Ytterbium-174 ion.

To estimate the expected performance of the cavity, we theoretically analyze the photon extraction probability that is realizable with available dielectric coatings and compare it to the light collection and single-mode fiber coupling efficiency that can be achieved using a spherical micro mirror [2].

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# DEPHASING OF TRAPPED-ION QUBIT DUE TO STARK SHIFT DURING SHUTTTLING

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We investigate a speed limit for quantum processing for trapped ion quantum computers using the Kienpinski-Monroe-Wineland (KMW) [1] architecture. The limiting speed for single-ion shuttling between a storage trap and a logic trap is constrained by the need to avoid excessive ion heating, and excessive dephasing and decoherence due to Stark effect. We estimate the significance of these errors and find that dephasing is dominant. We minimize the error with respect to shuttling trajectory. The magnitude of dephasing is quadratic in the time of flight, and an inverse cubic in the operational time scale. From these dependence relations, a limit of operational speed of ion-trap quantum computer is deduced. Without subsequent phase correction, the maximum speed a qubit can be transferred across a 100 micron-long trap, without excessive error, is about 10 ns for calcium ion and 50 ps for beryllium ion.

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# PROGRESS ON MOLECULAR QUANTUM LOGIC SPECTROSCOPY WITH BARIUM

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We are currently constructing a trap to perform molecular quantum logic spectroscopy (m-QLS) to probe molecular transitions. A molecular ion of interest will be co-trapped with a barium ion in a linear Paul trap. The barium ion is laser-cooled and sympathetically cools the molecular ion; internal cooling on the molecular ion will be accomplished by optical pumping. Cooling and manipulating the barium ion involves lasers in the visible and IR regime, alleviating concerns of destroying co-trapped molecules which might arise when using different atomic ions with more blue cooling transitions. Also barium is one of the heavier coolable ions, allowing us to effectively cool relatively heavy molecular ion species. Spectroscopy of the molecular ion is mapped to the barium ion through their motional state by using Cirac-Zoller gate. We are particularly interested in probing rotational or vibrational transitions sensitive to a time-varying electron-to-proton mass ratio. m-QLS could potentially also be used to study parity violation in chiral molecules, in which the weak force causes a small energy difference between right- and left-handed molecules. Recently we have constructed the trap and will attempt to perform QLS using two different barium isotopes.

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# ENHANCED SPONTANEOUS EMISSION OF A TRAPPED ION IN A CAVITY QED SYSTEM

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A micro-scale ion trap is integrated with an optical cavity to enhance the spontaneous emission from a single trapped ytterbium ion. Exciting the atom from the side of the cavity with a near resonant laser beam, we monitor the scattered photon output from an undriven cavity mode. Operating in the intermediate regime of cavity QED, we find an enhancement of the spontaneous emission into the cavity mode by more than a factor of about 100 compared with the expected free-space emission into the same solid angle subtended by this mode. We investigate the spectrum of cavity photons as a function of the intensity of the excitation beam by varying the detuning between the atomic and cavity resonance. We also discuss the application of similar ion-cavity systems to enhance photon collection and thus improve the success probability of entangling remote ions [1,2].

This research was supported by IARPA through ARO contract, the ARO MURI program, the NSF PIF Program, the AQUITE program, and the NSF Physics Frontier Center at JQI.

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# SINGLE-ION HEISENBERG-LIMITED QUANTUM PHASE SENSORS

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We report on our efforts to construct a single-ion-qubit sensor capable of Heisenberg limited detection of external fields that can be efficiently coupled to the ion qubit. Based on a single-qubit iterative phase estimation algorithm (IPEA) [1], a quadratic enhancement in quantum phase estimation precision is achieved when compared to standard shot-noise limited measurement protocols without using any entanglement. This approach also has the advantage that it does not require an understanding of the quantum Fourier transform, and it is readily related to more conventional approaches for measuring phases. The bit-by-bit estimation of an unknown phase only requires standard quantum information processing (QIP) protocols in addition to the use of single-qubit rotations that are each of a relative phase that is conditioned on all previous classical outcomes in the measurement sequence. Successful implementation of the IPEA will demonstrate a working quantum circuit with relatively immediate and useful applications in basic science, remote sensing, and clock synchronization. We also describe the potential application of novel ion trap architectures previously put forth [2][3] to the problem of miniaturizing the IPEA experiment as well as other single- and multi-qubit quantum enhanced metrology experiments. While these architectures were initially conceived in the context of large-scale QIP and quantum simulation, we face similar technical challenges in developing deployable ion trap based quantum sensors. This provides further impetus for developing relevant enabling technologies with both long- and short-term applications.

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# INTEGRATED MICRO-SCALE OPTICS IN PLANAR ION TRAPS

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Efficient fluorescence collection of trapped atomic ions is required for rapid high-fidelity measurements in ion trap quantum information processing. For larger information processing experiments to become feasible, the required imaging systems must efficiently resolve many ions over a large field-of-view. We report the development and fabrication of planar traps with integrated microscale mirrors with an expected 14% collection efficiency. The design allows for multiple integrated mirrors in a single device, permitting fast, simultaneous measurement of many ions over a 10 mm object space [1].

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# ULTRAFAST CONTROL OF SPIN AND MOTION OF TRAPPED ATOMIC QUBITS

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We experimentally demonstrate ultrafast spin flips of a trapped ion, using individual picosecond pulses from a mode-locked laser to drive Raman transitions between hyperfine qubit levels.[1] The large bandwidth and intensity of each pulse allow an individual pulse to coherently transfer more than 50% population in a time on the order of 10 ps. Furthermore, the large intensity of each pulse allows us to be far detuned (33 THz) from resonance, which makes decoherence due to spontaneous emission and AC Stark shift negligible. Complete control over the quantum state can be accomplished by splitting the pulse into two halves and varying the relative delay, resulting in single qubit rotation times on the order of 50 ps. By setting the delay to zero and arranging the two pulse halves in a counterpropagating configuration, an optical standing wave is applied to the ion for 10 ps. Sequences of these optical standing waves, spaced appropriately, should combine to produce a fast spin-dependent momentum kick. We plan to use this to implement proposals for motional gates which can be performed much faster than the oscillation period of the trap.[2,3] This research was supported by IARPA through ARO contract, the DARPA OLE program under ARO contract, the ARO MURI program, the NSF PIF Program, the AQUITE program, and the NSF Physics Frontier Center at JQI.

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# A MINIATURE ION-TRAP FREQUENCY STANDARD

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We are developing a highly miniaturized atomic clock to probe the 12.6 GHz hyperfine transition in <sup>171</sup>Yb ions. Ultimately, we intend to produce a clock that is less than 5 cm<sup>3</sup> in size, consumes <50 mW of power, and has a long-term frequency stability of 10<sup>-14</sup> at one month. Our approach incorporates an integrated vacuum package using buffer-gas cooled trapped ions and microfabricated oscillator and light sources. We have designed and built several vacuum packages with different levels of integration for testing and characterization of their ion trapping and clock performance capabilities. We report on results from these packages and their contribution to our future plans for the project.

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## Simulation of non-adiabaticity in surface electrode traps

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Radio frequency (RF) surface electrode traps where all the RF and static control electrodes lie in a single plane are being developed for scaling ion trap quantum information processing to larger numbers of ions [1]. In such traps, ions are confined a small distance above the electrode surface. The RF ponderomotive potential is anharmonic, rising steeply for ion excursions towards the electrode surface but much more gradually for excursions away from the surface. Multipole RF traps can exhibit a significant reduction in the effective trapping depth from the calculated pseudo-potential well depth due to non-adiabatic ion motion in the anharmonic potential [2]. We simulate whether anharmonic contributions to surface electrode trap potentials can reduce the effective well depth of surface electrode traps. Specifically we simulate the motion of a charged particle in a 4-wire surface electrode trap. By starting the particle in the center of the trap with different energies we determine a safe or effective well depth as a function of the  $q$  parameter of the trap. We find significant reduction in the effective well depth for  $q > 0.3$ , resulting in a maximum well depth for  $q < 0.3$ .

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# A Microfabricated Surface Ion Trap on a High Finesse Optical Mirror

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A single trapped ion in a high finesse optical cavity offers a strong experimental platform in the pursuit of efficient light matter interfaces, which holds a great potential for large scale quantum information processing. Efforts towards realizing such interfaces are however, faced with three major challenges, currently impeding the advancement of the field: (i) the trapping potential can be perturbed in the presence of dielectric mirrors, which affect both the trap rf-fields and allows build-up of stray charges on the substrates via light-induced charging; (ii) when close to material surfaces, anomalous heating of ions may lead to rapid decoherence of their motional states; (iii) the need for scalable trap technology imposes severe design and fabrication constraints on the experiment.

Here we present a new approach to integrate an optical cavity into an ion trap, in which a linear surface electrode Paul trap is microfabricated directly on a high finesse mirror. A circular aperture located in the central trap electrode allows the ion to interact with the cavity mirror. Single to a few  $88\text{Sr}^+$  ions have been stably trapped for hours 170 microns above the surface of this trap, and the measured heating rate is only 0.1 quanta/ms. Furthermore, the additional optical loss introduced by the fabrication process has been evaluated using cavity ring-down spectroscopy, and found to be as low as 80ppm, without any post-fabrication cleaning. This validates the scalability of our fabrication procedure to integrate an ion trap with a high finesse mirror. Combining the system with a concave mirror (ROC = 1mm) with commercially available coatings for light at 408 nm (45ppm transmission + 25ppm loss), one can form a near-confocal cavity, with finesse of over 20,000. For the  $88\text{Sr}^+$   $5\text{S}_{1/2}$  to  $5\text{P}_{3/2}$  transition (408 nm) in particular, this implies a cooperativity of  $C = 9$ , which allows for the mapping of quantum states between ions and photons with high efficiency.



# ROBUST GENERATION OF ENTANGLEMENT AND GATE OPERATIONS WITH TRAPPED IONS USING ADIABATIC APPROACHES

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In most quantum information processing experiments using trapped ions, manipulation of quantum states are done with combinations of resonant laser pulses with time-independent (rectangular) envelopes, while adiabatic manipulation of quantum states with time-dependent frequency and envelopes enables operations that are robust against variation of experimental parameters and even preparation of large entangled states with relatively simple procedures, hence facilitates large scale operations.

We have generated a Dicke state  $|D_2^{(1)}\rangle = (1/\sqrt{2})(|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle)$  in optical qubits of two  $^{40}\text{Ca}^+$  ions, based on the proposal by Linington and Vitanov [1], by applying frequency chirped optical pulses with time-dependent envelopes to perform rapid adiabatic passage on sideband transitions [2]. Figure 1 shows parity signals after Dicke state generation followed by  $\pi/2$  pulses, from which fidelity  $F = 0.66 \pm 0.03$  is obtained. This method can also be extended to generation of larger Dicke states [1], *i.e.* with more particles and more excitations (number of ions in  $|\uparrow\rangle$ ). We have also verified robustness against variations of experimental parameters, which is one of the advantages of adiabatic approaches. Fidelity exceeding 0.5 has been observed over wide range of parameter values (Fig. 2) [3].

In addition, we are planning to perform gate operations using multiple dark states in a so-called tripod system [4], which consists of one upper state and three lower states connected by three lasers. It has two dark states and therefore can be used to implement non-commutable unitary operations by means of purely geometric phase factors. We have recently succeeded in performing  $\sigma_X$  and  $\sigma_Z$  rotation in a qubit of a single  $^{40}\text{Ca}^+$  ion. Details will be given in the session.

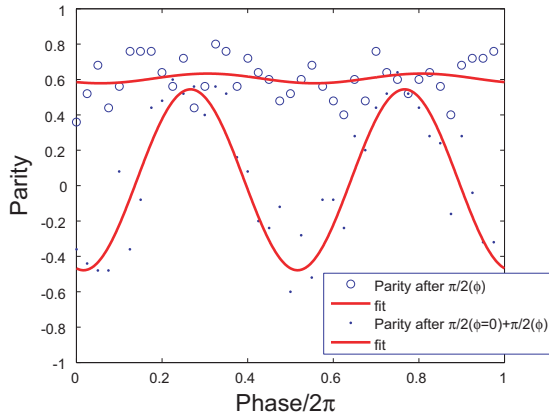


Figure 1: Parity after Dicke state generation

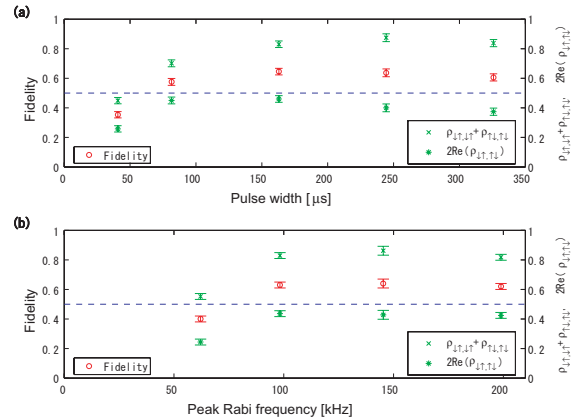


Figure 2: Robust generation of Dicke states

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## **Fabrication and testing of micro-cylindrical ion trap arrays for miniaturized mass spectrometer development**

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The ultimate goal of SRI International (SRI) mass spectrometer miniaturization efforts is to develop a method for very cost-effective fabrication of highly sensitive miniaturized mass spectrometers. Microelectromechanical systems (MEMS) fabrication technologies appear to offer the best opportunity for achieving this goal. Researchers at SRI have investigated the possibility of extreme miniaturization of cylindrical ion trap mass spectrometers (CIT MSs) by using MEMS fabrication methods, and have validated the MEMS approach for fabricating arrays of very small CITs (radii  $\approx 0.35$  mm) in silicon. Arrays of CITs operating in unison offer the possibility to recover the sensitivity losses encountered by miniaturizing individual CITs.

The approach in CIT array design has been to fabricate two identical arrays of half-CIT structures (each trap with a half-thickness ring electrode and an aperture endplate) which were then bonded back-to-back to form a full CIT array chip. Design and fabrication iterations optimized operation and performance. Experimental data from CIT arrays demonstrated the ability to increase mass spectral sensitivity by integrating signals from individual CITs in the array. Further optimization of the CIT geometry and fabrication process produced mass spectra with better than unit mass resolution.

Computer simulations to guide fabrication processes avoid excessive manufacturing iterations by predicting optimum CIT geometries, primarily with respect to the axial-to-radial dimension ratio ( $z_0/r_0$ ) and aperture size. These simulations predict optimum operating pressures for the micro-CITs that are several orders of magnitude higher than those for conventional size commercial ion trap mass spectrometers. Therefore, high vacuum pumps may not be required for mass spectrometer systems based on this technology. To realize truly handheld mass spectrometer technology, further miniaturization and integration of ion sources, detectors, and vacuum systems will be necessary.

# EFFICIENT SYMPATHETIC COOLING

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A challenge of performing ion trap quantum computation with chains of ions is the heating of the trap vibrational modes. Trap heating can result in unwanted occupation of vibrational modes and a reduced fidelity for two ion gates. To combat this, specific ions within the chain can be tasked with cooling the entire chain via sympathetic cooling. The strength of the interaction between the cooling laser and cooling ions may have a significant effect on how efficiently the chain is sympathetically cooled. This interaction can be controlled via the intensity and detuning of the cooling beam as well as the time the cooling ions spend interacting with the cooling laser versus thermalizing with the ion chain. By using separate isotopes of Ca<sup>+</sup>, we can construct a chain of cooling and information ions with each isotope interacting with its resonant cooling laser independently. By adjusting the aforementioned interaction parameters and measuring the sideband spectrum of the information ions, we will be able to find the most efficient sympathetic cooling parameters. We will describe the experimental results so far as well as future related investigations.

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# LASER-INDUCED CHARGING OF MICROFABRICATED ION TRAPS

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Microfabricated ion traps are promising candidates for realizing large-scale quantum computers, but small trap sizes leads to increased sensitivity of the trapped ions to surface effects, including localized charging of the trap electrodes. Prior work has studied laser-induced charging on glass substrate of gold traps [1] and on copper PCB traps [2]. In this work, we extend the study to aluminum traps and compare with gold and copper traps in the same experimental setup. Charging is studied by monitoring the ion micromotion over a period of up to 20 minutes that a laser is incident on the trap. The ion is trapped 100  $\mu\text{m}$  above the metal surface and the trap is operated at 6K. The lasers used are at 405, 460, and 674 nm, which are relevant atomic transitions in  $\text{Sr}^+$  ions, and the typical intensity at the trap is  $10^{35}$  photons/cm<sup>2</sup>s. A wavelength and material dependence of the charging behavior is observed: lasers at lower wavelengths cause more charging, and aluminum exhibits  $\sim 30$  times higher charging rate than copper or gold. We describe the charging dynamic based on a rate equation approach and find good qualitative agreement with the data and estimates of material properties.

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# MICROWAVE NEAR-FIELD QUANTUM CONTROL OF TRAPPED-ION QUBITS\*

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A major concern in the development of a future quantum processor is the scalability toward large numbers of qubits; it should enable arbitrary operations on the individual and entangling qubits. As for a classical processor, micro fabrication is a promising route to build a versatile ion-qubit quantum processor. Recent experiments with surface-electrode traps have demonstrated the key ingredients for scalable ion loading, transporting, and trapping architecture. Here, we present an approach to incorporate microwave ion-qubit manipulation into the surface-electrode structure which could enable its duplication along with the trap structure.

In ongoing experiments we investigate the building block for a microwave near-field quantum control based on the oscillating magnetic field generated by microwave currents in electrodes of a micro fabricated surface-electrode trap. The driving microwave frequency is tuned near resonant with a hyperfine transition in the Mg ion. The homogeneous field component is used to implement single-qubit gates, while the field gradient leads to a coupling of the ions internal and motional states. We are working toward performing a multi-qubit operation using this coupling.

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## **Quantum Interference and Superradiance from entangled Atoms**

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Recent years have seen the ability to create large varieties of entangled states among radiating particles. The question then arises how the optical properties of such entangled photon sources differ from a radiating source in a separable state. We investigate fundamental processes like emission and scattering of radiation from entangled systems. We show how entanglement can lead to enhancement of basic processes by explicitly taking into account the various quantum paths. We relate enhancement to quantum interference of multiple photon pathways. Our work also shows how Dicke super radiance from states with zero dipole moment can be understood as interference phenomena.

# Generation of all symmetric as well as all total angular momentum eigenstates in photonic or matter qubits

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We propose a method for the generation of a large variety of entangled states, encoded in the polarization degrees of freedom of  $N$  photons, within the same experimental setup. Starting with uncorrelated photons, emitted from  $N$  arbitrary single photon sources, and using linear optical tools only, we demonstrate the creation of all symmetric states, e.g., GHZ- and W-states, as well as all - symmetric and non-symmetric - total angular momentum eigenstates of the  $N$  qubit compound [1]. Modifying slightly the multiphoton detection technique and using  $\Lambda$ -level atoms as single photon sources, the same classes of states can also be generated among the long-lived ground state qubits of  $N$  massive particles [2-4]. Amongst others, the schemes enable to generate all canonical states representing all possible entanglement families of symmetric states inequivalent under SLOCC as recently defined in [5].

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