Miniature Ion-trap Cavity System as Atom-Photon Interface

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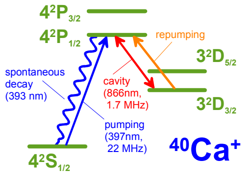
Introduction

A single Ca-ion, trapped in an r.f. quadrupole trap and placed between mirrors of a high finesse optical cavity, is an ideal system to deterministically control the interaction between an atom and a single mode of the radiation field. By confining the ion to a region smaller than its transition wavelength, a well-defined and stationary atom-field coupling strength is achieved. This system can be employed to generate single photons on demand, to map the quantum state between the ion and a photon and to entangle the ion and a photon. Two ions coupled to optical cavities have been proposed for quantum state transfer and entanglement of ions.



Using a high-finesse cavity on the 866 nm transition of the $^{40}Ca^+$ level-scheme provides ideal conditions for reaching the strong-coupling regime of cavity QED with a single ion.

Setup: linear Paul trap and cavity

Trap design:

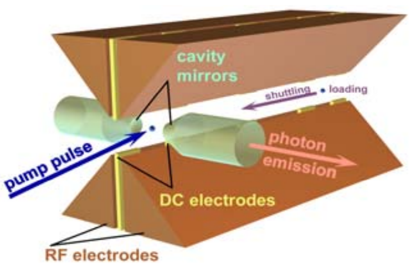
Linear r.f. trap with open electrode configuration

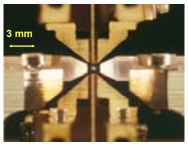
trap frequency	$\Omega = 2\pi \times 12.7$ MHz
radial confinement	$\omega_r = 2\pi \times 1.1$ MHz
axial confinement	$\omega_z = 2\pi \times 0.3$ MHz

Cavity design:

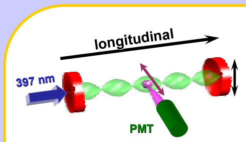
Fabry-Perot cavity with adjustable length

length:	L	= 0.8 ... 10 mm
waist:	w_0	= 23 ... 37 μm
damping:	$\kappa/2\pi$	= 1.0 … 0.2 MHz
coupling:	$g/2\pi$	= 4.6 … 0.8 MHz



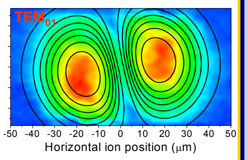


Single-ion mode mapping

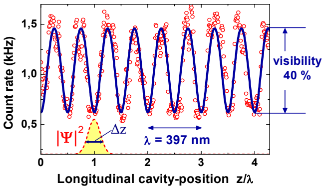


The cavity is locked to a specific mode at 397 nm. The position of either the ion or the cavity is scanned and the fluorescence is observed as a measure of the local field intensity.

Two-dimensional images of cavity modes obtained by scanning the ion horizontally and the cavity position vertically.



Longitudinal scan of cavity modes obtained by scanning the cavity along its axis with respect to the ion's position.



Visibility reduced by the spread of the ion's wave function Δz:

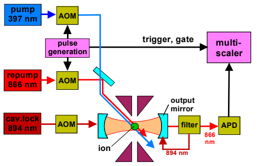
Δz = 42 nm → **2% variation of g**

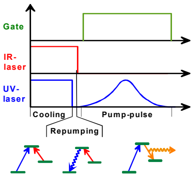
$(\lambda/10)$

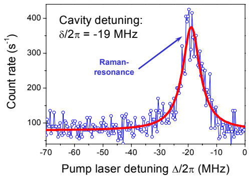
Deterministic ion-field coupling

Single-photon gun

Continuous generation of single photon pulses by applying a sequence of cooling, repumping and pump pulses to a single ion







Single photon peak observed by scanning the frequency of the pump laser.

Efficiency: 8%

Applications of a deterministic single-photon source:

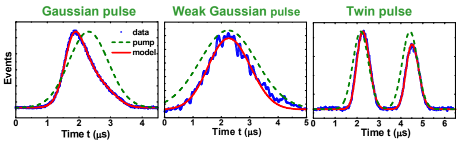
- quantum cryptography
- quantum communication
- quantum computation

J. McKeever, A. Boca, A. D. Boozer, R. Miller, J. R. Buck, A. Kuzmich, H. J. Kimble, Science **303**, 1992 (04)
M. Hennrich, T. Legero, A. Kuhn, G. Rempe, PRL **85**, 4872 (00)
J. Kim, O. Benson, H. Kan, Y. Yamamoto, Nature **397**, 500 (99)
C. K. Law, H. J. Kimble, J. Mod. Opt. **44**, 2067 (97)

Single-photon emission

Single-photon pulseshapes

Statistics of single photon detection times with respect to trigger (pump) → Temporal structure of single photon pulse

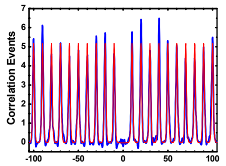


Arbitrary control over temoral structure of single photon pulse

Limitations:
- effective Rabi frequency
- cavity decay

Second-order correlations

Measure cross-correlations → $g^{(2)}$-function



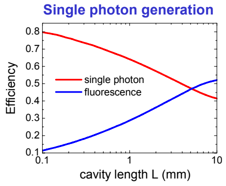
$g^{(2)}(0)=0$ ↕ single photon

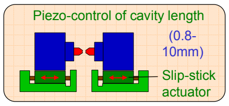
$$\frac{P_1^2}{2P_2} > 68$$

68 times better suppression of two photon events compared to a poissonian source

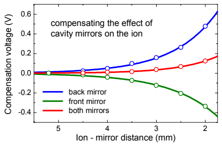
Influence of mirrors on trap potential

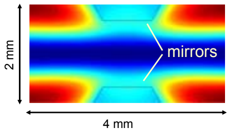
Increase efficiency and fidelity of quantum operations by decreasing the cavity length


Single photon generation


Piezo-control of cavity length

Measuring the influence of the mirrors on the trapping potential by observing the compensation voltage of the micromotion for different cavity lengths.


Measurement of the destortion

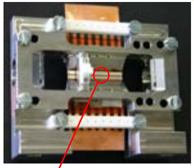

Simulation of the pseudo-potential

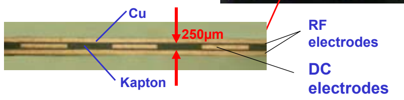
Strong influence of the mirrors on the trapping potential even for long cavities → Stabile trapping conditions: **Cavity length >4mm**

New trap design

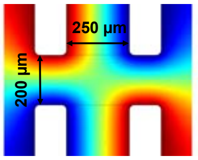
Small cavity which does not perturb the trapping field requires small trap structure

made from 125μm copper sheet, glued together with Kapton spacers

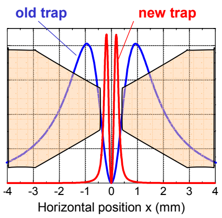




Radial RF field distribution:



Pseudo-potential (horizontal):

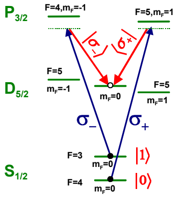


Less overlap of field and mirrors → 0.5mm cavity length feasible

Ion-photon coupling

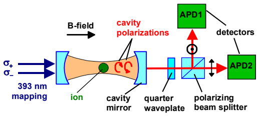
Mapping of quantum information

Make single photon emission dependent on quantum state



Ion state mapped to photons with different circular polarizations:

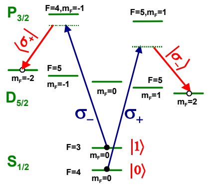
$$\alpha|0\rangle + \beta|1\rangle \Rightarrow \alpha|\sigma_+\rangle + \beta|\sigma_-\rangle$$



Selective coupling of cavity to one final state through Zeeman splitting

Ion-photon entanglement

Choose different final states for ion:



Ion state entangled with photon:

$$\alpha|0\rangle + \beta|1\rangle \Rightarrow \alpha|m_{-2}\rangle|\sigma_-\rangle + \beta|m_2\rangle|\sigma_+\rangle$$

Application:
Entanglement of ions in distant traps (entanglement distribution)