Comparison of ion trap geometries with integrated optical cavities for effective ion-photon coupling

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The realisation of efficient ion-photon quantum interfaces is an essential step towards developing operational quantum information networks. Individual trapped ions have been shown as promising candidates for quantum information processing nodes, while effective ion manipulation and photonic links between nodes can be realised by deterministic coupling of ions to optical cavities. However, integrating optical cavities into ion traps remains a challenge as the trapping potential is affected by the presence of any dielectric or conductor.

Here we analyse advantages and disadvantaged of radio frequency ion traps of different geometries and study their stability with respect to an integrated optical cavity. We compare the distortion of the trapping potentials caused by dielectric mirrors in the case of different mirror orientations with respect to the trapping electrodes, as well as the trap stability to any mirror misalignment. Using the finite element method, five different ion trap geometries are modelled: two linear traps, two cylindrical traps and a planar surface trap. The linear traps consist of four either blade shaped or plane bar (wafer) electrodes. The cylindrical traps are the endcap trap (formed by a pair of two concentric hollow cylinders) and the stylus trap (formed by a single set of concentric hollow cylinders over an additional grounded plate). The planar trap consists of four parallel electrodes on a plane surface. All trap dimensions were scaled to have a characteristic distance of 1 mm between electrodes to allow for a fair comparison. In each of these cases, the optical resonator was modelled as two mirrors mounted on the facets of glass cylinders of 0.7 mm diameter, symmetrically aligned with respect to the trap centre, and with a distance between them varying from 1 to 5 mm.

We analyse the ion traps by comparing potential barrier heights and secular frequencies of a trapped calcium ion ($^{40}Ca^{+}$). We show that the linear traps create the deepest potential wells for trapped ions (potential barriers are 1.6 and 2.2 eV for the blade shaped and wafer electrodes at an rf-voltage amplitude of 400 V at 12.7 MHz). However, these traps are highly affected by the presence of the dielectric mirrors at a distance closer than 1.5 mm from the trap centre. Only the geometry with the mirrors aligned in the middle along the trapping axis shows little distortion to the trapping potential and appears to be the most stable with respect to any mirror misalignment. The surface trap is the most stable with respect to the presence of the dielectric mirrors, but exhibits a rather shallow trapping potential (the potential barrier is 0.14 eV in the direction perpendicular to the trap surface). No distortions are also observed for the cylindrical traps in the case where the cavity mirrors are aligned inside the cylindrical rf-electrode, and hence sheltered from the rf-field.

In conclusion, we find that while ion traps are known to be sensitive to nearby dielectrics it is possible to alleviate this problem by a proper choice of trap and cavity geometries.