The electric potential generated in surface-electrode ion traps: a comparison between an analytical model and finite-element methods.

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Introduction

Ultra-cold trapped matter offers a versatile toolbox for exploring the fundamental interactions of particles and serves as a valuable building block for quantum computing technologies [1]. Of particular interest is the confinement of charged particles in radiofrequency ion traps, in which the position of the particle is controlled by means of applying high-frequency voltages to a set of electrodes. Recently, this approach has resulted in the development of surface electrode ion traps, consisting of an array of planar electrodes to which the voltages are applied [1]. The functionality of these devices is highly sensitive to the shape of the electric fields produced by applying these voltages, and although analytical models are available, it remains important to confirm these results via performing numerical calculations of the resulting trapping potentials. Here, we present a comparison between the predictions of an analytical model [2] to the results obtained using the finite-element method package EMS as applied to the design of a surface electrode trap for the manipulation of calcium ions [3].

Theory

A charged particle in an electric field E experiences a force proportional to this field, F = q E. In theory, such a force can be used to confine particles in vacuum by ensuring that a point exists such that the particle is always accelerated towards that point. However, in free space, Maxwell's equations forbid the formation of such a point, as this would correspond to a region with non-zero divergence, and thus it is not possible for an electric field to form a static confining potential. Indeed, although a potential may be produced which is confining in two directions, it is necessarily deconfining in the third direction at any given point in time. This may be overcome by the use of a radiofrequency trap, in which the confining and deconfining potentials are rapidly switched, giving rise to dynamic confinement in a time-averaged pseudopotential.

Generating such a potential is achieved by applying voltages to a set of carefully designed electrodes. Traditionally, macroscopic three-dimensional traps have been employed. In recent years, however, there has been a trend towards the surface electrode architecture shown in Fig. 1), which enables a more precise control of the trapped particles [1].

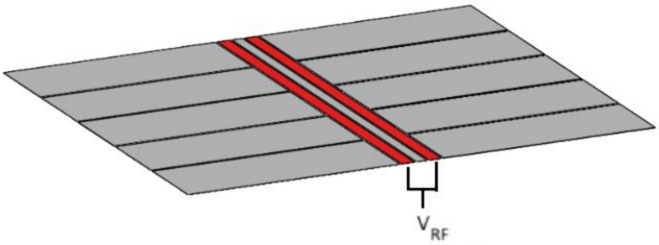

Figure 1) A schematic of a surface electrode ion trap. The red electrodes indicate those to which an RF voltage is applied to generate a trapping potential. Adapted from Ref. [3].

During the design of such a device, it is important to calculate the point at which the minimum of the time-averaged pseudopotential occurs, at this is the location at which the ions will be trapped. This may be achieved either through calculating the trapping field by means of numerical methods, e.g., finite element methods based on the trapping geometry, or through an approximate analytical method such as that described in Ref. [2]. In the latter case, it is necessary to confirm that the approximations used remain sufficiently accurate to avoid compromising the accuracy of the results. Consequently, for the electrode geometry shown in Fig. 1), we calculate the electric field generated by applying a test voltage of 1V to the electrodes marked in red to the field using the analytical model of Ref. [2]. To validate these results, the electric fields are also calculated using the finite-element solver EMS using the geometry of the trap designed in SolidWorks. For these calculations, the Electrostatic solver is used with boundary conditions set to be zero electric potential on the faces of the airbox. Both mesh size and the size of the airbox are varied to ensure convergence of the results.

Results

A contour plot of the pseudopotential is shown in Fig. 2), comparing the gap-corrected model proposed in Ref. [2] to the result of finite-element simulations. Qualitatively, the agreement can be seen to be good, highlighting the accuracy of the model for this geometry. In Fig. 2), the potential found along vectors perpendicular and parallel to the surface of the chip through the trapping region are shown, again finding a very good agreement between the analytical model and the numerical calculations. Thus, for the purposes of the design of this trap, it was concluded that the analytical model suffices to calculate the operating parameters of the chip for the work performed in Ref. [3].

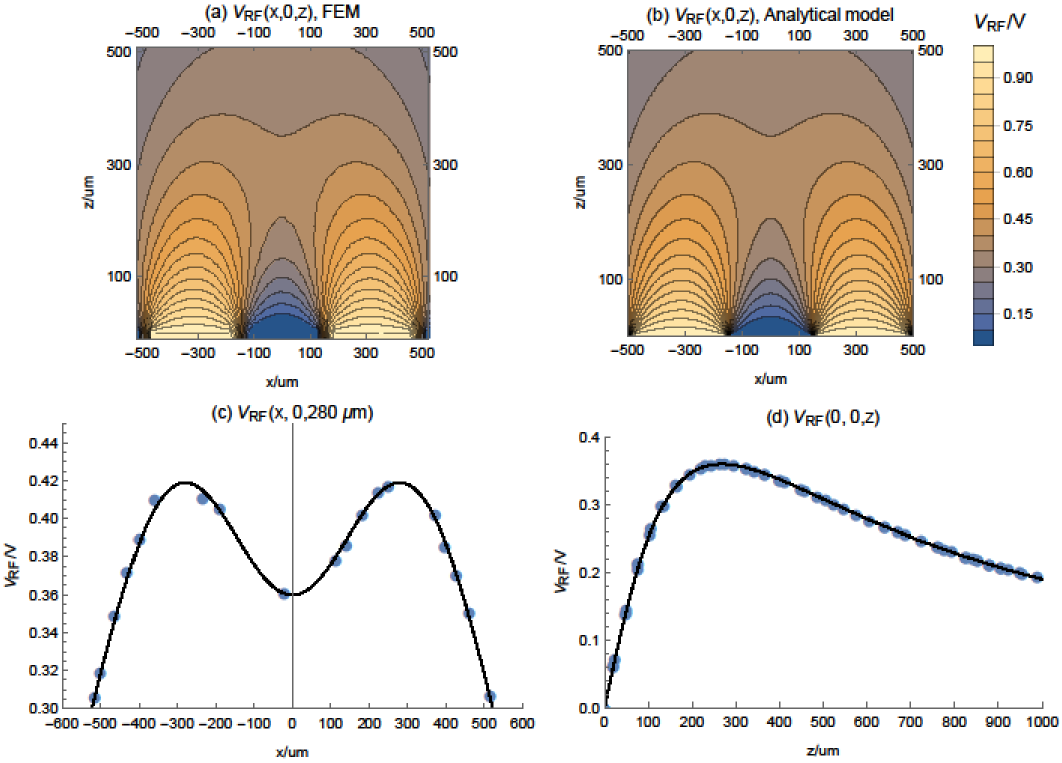

Figure 2) Contour plots of the time-averaged potential from the (a) finite-element method and (b) the analytical model. (c) and (d): A comparison of the numerical field (points) and the analytical model (line) through the centre of the trapping region. Figure reprinted from Ref. [3].

Conclusions

The analytical model of Ref. [2] was confirmed to be valid for the surface-electrode chip trap design of Ref. [3] by means of comparison to the results obtained from finite-element calculations using the EMS plugin for SolidWorks. The resulting trapping potentials are employed to investigate the properties of ions trapped in time-dependent potentials as discussed further in Ref. [3].

References

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