Investigation of Ion Interactions and Space Charge Effects in a Time of Flight Ion Trap Resonator

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Abstract

An ion trap resonator, typically used for mass spectrometry, as introduced by Zajfman et al. [1], uses a pair of opposite facing electrostatic mirrors and lenses to capture ions resonating between them (Figure 1). The electrostatic mirrors reflect the injected ions in the trap, while the lenses focus the ions and create a stable bunch with low ion particle diffusion. Another interesting phenomenon, that is observed in this resonator if certain criteria are met [2], is the existence of a synchronized state of the ions. This phenomenon leads to even lower diffusion rates in the trap, and makes very long measurements possible. In this study a smaller version of the trap is built in 2D axisymmetric geometry, and simulations are done using COMSOL Multiphysics software to optimize its performance.

Figure 1 shows half of the 2D model of the device and the different electrodes. Simulations are done using the AC/DC Electric Circuit "cir", Electrostatics "es", Charged Particle Tracing "cpt", and Electric Particle Field Interactions "epfi" interfaces.
The simulations start with the electrostatic voltage distribution in the trap. This is performed with "es" physics. Different voltages are applied to the mirror and lens electrodes. By these steps the voltage distribution in the resonator is defined, see Figure 2. Next, "cpt" simulations of the injected ions are performed. These simulations are used iteratively to optimize the lens and mirror voltages that in turn maximize the ion flight stability-criteria and also provide information on the focal point of the lenses.

Multi-physics "epfi" option is also used and space charge effects are simulated. The space charge induces voltages on the pickup electrodes, are connected to the ground via resistors. The resistors, not shown, are simulated using "cir" module. Simulations of space charges, as shown in Figure 3, demonstrate the induced voltages in the 2 pickup electrodes due to traversing ions. The inset of Figure 3 shows the result of an experiment where the ions passes through two pickup electrodes and are reflected back by the mirror. The differences in the pulse shapes of the experiments and the simulations are most probably due to the electronics of the experimental setup, which include amplification and additional stray capacitors. However, the time period of the induced voltage pulses on the electrodes of the simulation agrees well with the experimental results.

Ion synchronization due to Coulomb forces between the ions is simulated using the "particle-particle interaction" option. The results are shown in Figure 4 with and without this option activated. With the correct criteria defined by [2], the ion interactions in the Zajfman trap lead to less dispersion and diffusion.

In conclusion, these simulations are of high importance in the design of the trap since they provide insight on the optimum configuration of the electrodes and their effect on the stability of ion trajectories. These simulations also provide a good basis for the investigation of the ion interactions due to coulomb forces which help further in lowering the particle diffusion and increase the accuracy of the ion measurements.

Reference

[1] D. Zajfman et. al., “Electrostatic bottle for long-time storage of fast ion beams,” Phys. Rev. A, vol. 55, no. 3, pp. R1577–R1580, Mar. 1997.

[2] H. B. Pedersen et. al., “Diffusion and synchronization in an ion-trap resonator,” Phys. Rev. A, vol. 65, no. 4, p. 042704, Mar. 2002

Figures used in the abstract

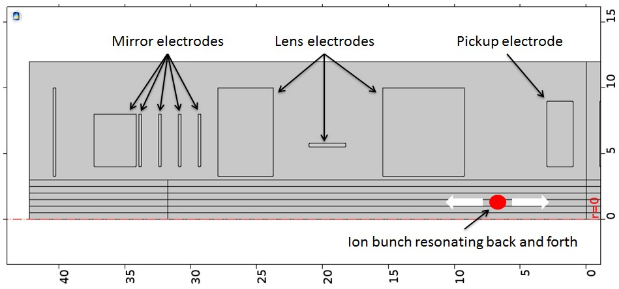

Figure 1: Half of the resonance chamber is shown with electrodes creating the electrostatic mirror, lens and pickup electrodes. The other half of the resonance chamber is the mirror of the shown part.

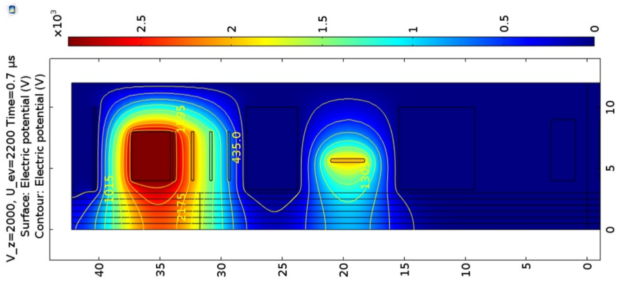

Figure 2: An example of resonance chamber electric field due to different applied voltages on the mirror and lens electrodes. Fine-tuning the voltages minimizes the diffusion of ions from the trap and increases the ion-bunch life time in the trap.

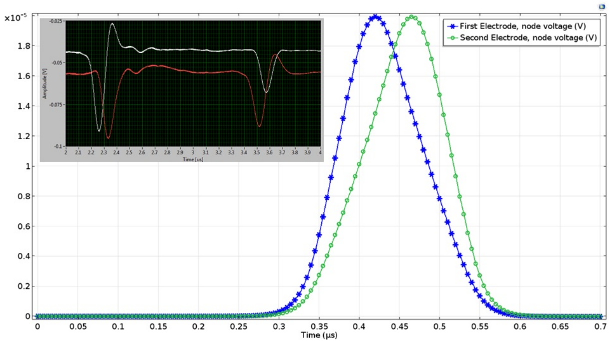

Figure 3: Simulation of induced voltage in 2 pickup electrode nodes, positioned one after the other. They are connected to the ground via two resistors. The inset shows the result of one experiment where the ions passed through two pickup electrodes and reflected back by the mirror. The difference in the pulse shape is most probably due to the electronics of the experimental setup. The time period of the induced voltage pulses on the electrodes agrees well with the experimental results.

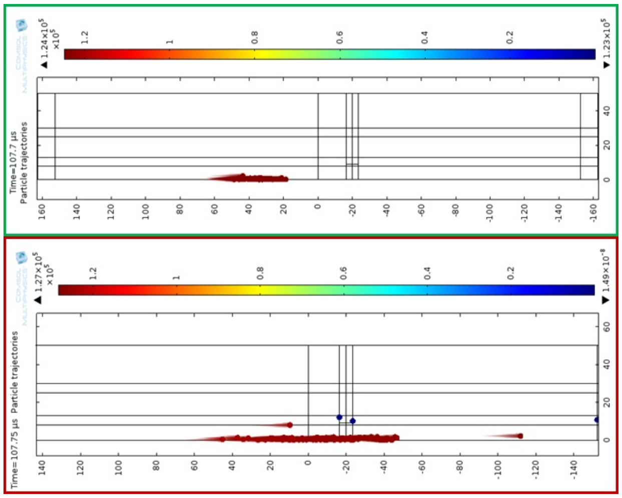

Figure 4: The results of simulations of ions with and without ion coulomb force interactions in the Zajfman trap [1]. The synchronization due to Coulomb forces (top) limits the spread of ions in time and makes longer measurement times possible.