Analysis of an effective adiabaticity parameter to characterize ion temperatures in multipole radiofrequency ion traps

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Synopsis RF heating keeps buffer-gas-cooled ions in multipole RF traps warmer than the buffer gas, and predicting their temperature needs costly trajectory simulations. We define an effective adiabaticity parameter, η_{eff}, as the adiabaticity parameter averaged over the thermally accessible region of the effective potential. Across ideal and shifted 8-pole, 16-pole and 16-wire traps, it differs more than twofold at 4 K but converges at 300 K.

Radiofrequency (RF) multipole ion traps confine ions radially through the effective potential of an oscillating inhomogeneous electric field, $V^* = q^2E_0^2/4m\Omega^2$, while static endcap electrodes provide axial confinement [1]. Buffer-gas collisions cool the ions, but collisions in the RF field also transfer energy from the field to the ions. This RF heating keeps the ions warmer than the buffer gas, and predicting their temperature normally requires computationally demanding ion-trajectory simulations for every trap geometry and operating condition.

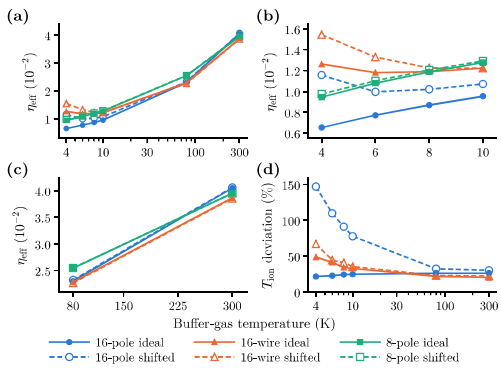

Figure 1. (a) η_{eff} versus temperature; (b, c) low and high ranges. (d) Ion-temperature deviation.

The effective-potential description holds when the RF field changes little over the full distance of the ion's oscillation compared with the field itself. Gerlich expresses this through the adiabaticity parameter $\eta = 2q|\nabla E_0|/m\Omega^2$ and gives $\eta < 0.3$ as the condition for safe operation [1]. This is most critical at the turning point of the ion, where the RF field is strongest and buffer-gas collisions cause RF heating. In real traps, displaced RF electrodes (shifted traps) distort the potential landscape and create minima away from the trap centre [2].

In this work, we introduce an effective adiabaticity parameter, η_{eff}, that accounts for the region occupied by the ions at a given temperature. The total effective potential, the sum of the RF effective potential and the static DC contribution of the endcaps (10 V), is calculated on a two-dimensional grid in the radial plane and referenced to its minimum. At a buffer-gas temperature T, each grid point is given a weight V^{-1} that falls linearly from unity at the minimum to zero where the potential equals the thermal energy $\frac{3}{2}k_{\mathrm{B}}T$. η_{eff} is the V^{-1}-weighted average of η over this grid.

Figure 1a shows η_{eff} from 4 to 300 K for ideal and shifted 8-pole, 16-pole and 16-wire traps. At 4 K it is largest in the shifted 16-wire trap and over a factor of two smaller in the ideal 16-pole trap, and shifting the electrodes raises it in every geometry (Fig. 1b). Up to 10 K, η_{eff} rises steadily in the 8-pole and ideal 16-pole traps but first falls in the other three, the same traps in which the ion temperature deviates most from the buffer-gas temperature (Fig. 1d). At high temperatures η_{eff} increases in all traps, the ideal and shifted curves merge, and all values agree within a few per cent at 300 K (Fig. 1c).

These results link η_{eff} to trap geometry and temperature, providing a route towards estimating the ion temperature directly from the effective potential, without full trajectory simulations.

References

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