Supplementary Information for "Levitated electromechanics: all-electrical cooling of charged nano- and micro-particles".

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Interaction with residual gas

In discussions of cooling ions or electrons, it is assumed that the background pressure is as low as possible, since gas collisions lead to trap loss. This is not necessarily true for much more massive nano- and micro-particles, where collisions with background gas lead to thermalization with the environmental temperature $T_{\rm gas}$. Indeed, in nano- and micro-particle trapping experiments, this dissipation process is necessary for loading conservative trapping potentials, with loading pressures ranging from 0.1 mbar [1], 3 mbar [2], 10 mbar [3], to atmospheric [4]. Furthermore, nano- and micro-particles in optical traps are observed to be unstable below pressures ranging from 10^{-5} mbar [5] to ≈ 1 mbar [3, 4, 6].

The damping rate on a sphere of radius $r_{\rm S}$ is [6, 7]:

$$\gamma_{\rm gas} = \frac{4\pi}{3}\frac{m n_{\rm gas} r_{\rm S}^2 \bar{v}_{\rm th}}{M}, \tag{S1}$$

where m is the mass of the gas molecules, $n_{\rm gas}$ is the number density of the gas, $\bar{v}_{\rm th}$ is the mean gas thermal velocity, and M is the mass of the sphere. As a sense of scale, for a $r_{\rm S} = 1\,\mu$m silica sphere, at a pressure of 100 mbar (N_2), $\gamma_{\rm gas} \sim 10^4$ Hz, and at 10^{-8} mbar, $\gamma_{\rm gas} \sim 10^{-6}$ Hz. This means that, when working at UHV, even modest cooling rates overcome heating due to gas collisions. Figure S1 shows simulations of the effect of residual gas on trapped particle dynamics.

Electrode surface noise

A major source of noise when considering atomic ions comes from both static and varying electric fields originating from electrode surfaces [8]. Following this reference and [9], we express the heating rate of the trapped particle due to electric field noise γ_E in terms of the spectral density $S_E(\omega)$ of the noise:

$$\gamma_E = \frac{q^2}{4M\hbar\omega_z} S_E(\omega). \tag{S2}$$

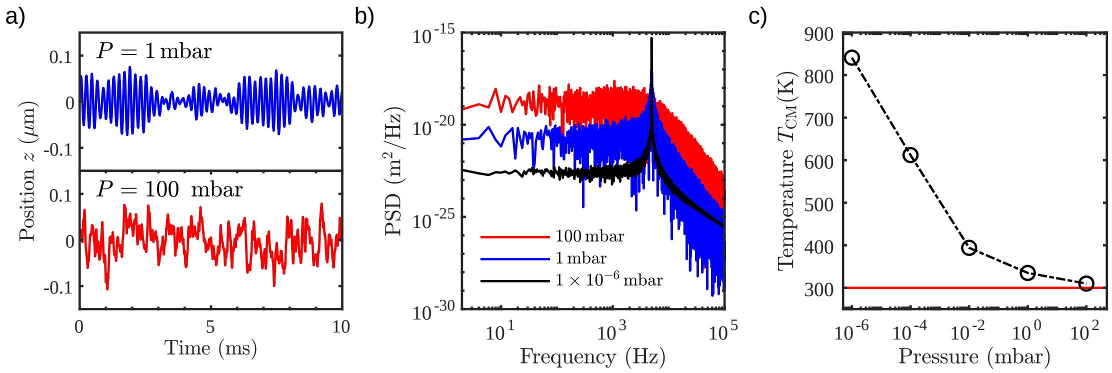

Figure S1. Background gas pressure: a) Simulated particle trajectories at two different gas pressures P. b) Simulated PSD of motion for different P. c) Variation in particle temperature $T_{\rm CM}$ after 500 ms with P, for an initial particle temperature $T_{\rm in} = 1000\,K$ and gas temperature $T_{\rm gas} = 300\,K$, showing that at higher pressures the particle rapidly thermalises with the gas (simulation: open circles, theory (300 K): solid line). Feedback gain $G = 0$ for these simulations, $q = 10^5\,e$, $R = 100\,\Omega$, $Q_{\rm f} = 100$, $T_R = 300\,$K.

Values of $S_E(\omega)$ can be estimated from the literature, however it is useful to understand the scaling of this noise with experimental parameters. It is typical [8] to treat the electric field noise as colored, with power spectral density

$$S_E = g_E \omega^{-\alpha} r_0^{\beta} T_E^{\chi}, \tag{S3}$$

where T_E is the temperature of the electrodes, which we set equal to T_R. For the purposes of this work, following the literature, we take $g_E = 10^{-12}, \alpha = 1, \chi = 2, \beta = 3$. The effect of electric field noise is shown in fig. S2. Figure S2 c) only shows significant heating for highly charged particles ($q = 10^6\,e$) at sub-100 μm particle-electrode distances. Previous work has noted that this is not a significant source of noise for a charged nanoparticle (as opposed to atomic ions), due to its large mass [9], and this work confirms this viewpoint.

Simulation parameters

In this manuscript, we always consider a quadrupole ion trap with $r_0 = 500\,\mu$m unless otherwise stated. Table S1 lists the ion trap operating parameters used in each figure. The pressure is always held at 10^{-10} mbar unless otherwise stated, though the dynamics are not effected at any pressure below 10^{-6} mbar, and the background gas is always considered to be at $300\,K$.

References

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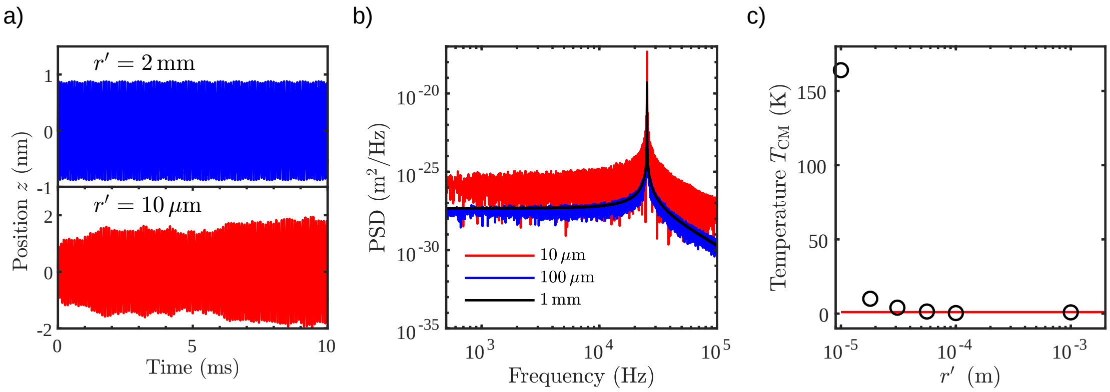

Figure S2. **Electrode noise:** The effect of electrode surface noise is explored through simulation by varying the trap-centre to endcap electrode spacing r'. a) Simulated particle trajectories for two different values of r'. b) Simulated PSD of particle motion for different r'. c) Simulated particle temperature as r' is varied, showing heating for small values of r'. The initial particle temperature is $T_{\text{in}} = 1\,\text{K}$ (red line in c)), $T_R = 300\,\text{K}$, $q = 10^6\,e$, $G = 0$. The resistance $R = 1\,\Omega$ and $Q_{\text{f}} = 100$ in these simulations, to remove resistive cooling. For all data presented in this paper, the electrode noise parameters as defined in eqn. S3 are $\alpha = 1, \chi = 2, \beta = 3, g_E = 10^{-12}$.

Figure	V_0 (V)	f_D (MHz)
2 a-b)	3000	100k
4 a-c)	3000	100k
S1 a)-c)	3000	200k
S2 a)-c)	1000	100k

Table S1. Quadrupole ion trap parameters used in the simulated data for the figures.

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