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Reply to “Comment on ‘Ultracold plasma expansion in quadrupole magnetic field’ ”

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In this Reply, we respond to the Comment by Schlitters *et al.* on our recent work [Phys. Rev. E **108**, 045209 (2023)], where we present simulation results of ultracold Sr plasma expansion in a quadrupole magnetic field using a molecular-dynamics method. In the Comment, Schlitters *et al.* present their experimental results, some of which, from their point of view, contradict our simulation results and others that confirm the experiments of Gorman *et al.* [Phys. Rev. Lett. **126**, 085002 (2021)] and our results. In addition, Schlitters *et al.* also provide results that were not described in our work. Here we show that there is not a contradiction but a misunderstanding of our results. This is due to the fact that simulations allow the use of processing methods that are difficult to obtain in experiment. We also present different simulation results related to expansion velocity variations that reflect the experimental results of Schlitters *et al.* and provide an explanation for the origin of these variations.

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The Comment by Schlitters *et al.* reports measurements of a confined ultracold neutral Ca plasma, which basically confirm our results and those of Gorman *et al.* Schlitters *et al.* also show that the ultracold neutral plasma in this configuration shows dynamic oscillations. In our recent work [1] we simulated the expansion of two-component ultracold Sr plasma with an initial cylindrical density distribution in a quadrupole magnetic field by means of molecular dynamics. Molecular dynamics provides additional possibilities to experimental methods for studying the physics of the phenomenon being studied. However, it is not yet able to consider systems with a large number of particles, which are obtained in the experiment (about 10^8), which should coincide with the experimental value. In [1,2] we proposed similarity parameters for plasma in the presence of a magnetic field, which allowed us to compare the results obtained for a small number of particles (approximately 10^4) with experiment.

The selected simulation parameters are close to those of the experiments of Gorman *et al.* [3]. An analysis of plasma evolution influenced by a magnetic field is carried out. The dynamics of both charge types is studied. An estimate of plasma confinement time and plasma density under various magnetic field strengths is given. Satisfactory agreement with experiment is obtained.

In the Comment by Schlitters *et al.* based on the experiments performed in ultracold Ca plasma, the results of Gorman *et al.* and the results of our simulations are confirmed. Also, the experiments of Schlitters *et al.* indicate a saturation effect with increasing magnetic induction gradient, which we established during simulations.

The Comment states that from the results of the experiment therein there is no evidence of ion return during the expansion process reported in our previous article [1]. This remark is primarily related to Fig. 3 of [1], which shows a time dependence of the ion flux through the lateral and base surfaces of the cylinder with $r < 5\sigma_0$ and $|x| = 2.5\sigma_0$ at $B' = 104$ G/cm.

The velocity along the axis becomes negative over time, although the velocity along the $x = 0$ plane remains positive. Experimental data from Schlitters *et al.* presented in Fig. 1, also demonstrate the possibility of reverse ion flow.

Figure 1 shows the results of calculations of the time dependence of the normalized radial velocity $u = \tau_{\exp} v_{ir}/r$ for $\beta = 0$ and 38. For the second case, results are presented for the velocity along the axis of symmetry x and along the plane $x = 0$. For comparison, the results of the experiment of Schlitters *et al.* are included.

The simulation results presented in Fig. 1 are in qualitative agreement with the experimental results. We see a coincidence in the behavior of the ion expansion velocity at short times and the appearance of velocity oscillations at long times, and the values of the maxima and minima of the oscillations are close to each other. The observed difference in the time dependence of the calculation and experimental results is most likely due to differences in plasma parameters.

Figure 2 shows the results of calculations of the normalized radial ion flux $q = n_i v_{ir} \tau_{\exp}/n_0\sigma_0$ at $\beta = 38$ and $r/\sigma_0 = 1.25$ for fluxes along the symmetry axis, along the $x = 0$ plane, and with the flux averaged over angular coordinates. It is clear that the flux averaged over angular coordinates can become negative. This indicates the possibility of reverse ion flows.

The Comment by Schlitters *et al.* reports measurements that show that as plasma expands, oscillations in the radial velocity of ions occur over time. We were able to obtain these oscillations when processing the simulation results and explain the reason for their occurrence. As an example, below we consider the results when simulating the expansion of Sr plasma with the initial data $N_i = 10\,000$, $n_0 = 10^6$ cm^{-3}, $T_{e0} = 20$ K, $\sigma_0 = 0.085$ cm, and characteristic expansion time $\tau_{\exp} = \sigma_0/\sqrt{k_b T_{e0}/m_i} = 20$ μs and for two similarity parameters $\beta = 0$ ($B = 0$) and $\beta = 38$ ($B' = 500$ G/cm, where $\beta = eB'\sigma_0^2/\sqrt{m_e k_b T_{e0}}$).

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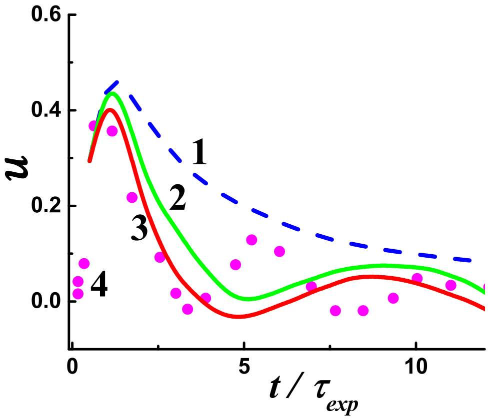

FIG. 1. Time dependence of the normalized radial velocity $u = \tau_{\exp} v_{ir}/r$. Calculation results $r/\sigma_0 = 1.25$ are shown for $\beta = 0$, curve 1; $\beta = 38$, curve 2, with velocity along the plane $x = 0$; $\beta = 38$, curve 3, with velocity along the axis of symmetry; and the experiment of Schlitters *et al.* curve 4.

It turns out that the influence of a magnetic field at certain parameter values during the expansion process can lead to the appearance of a potential well for ions localized near the center of the plasma. This occurs due to the formation of excess electrons in this part of the plasma. Figure 3 shows the dependence of the potential energy averaged over angular coordinates on the radius, which shows the time evolution of the potential well in the center of the plasma.

Figure 4 shows, for the similarity parameter $\beta = 38$, the dependence of the charge imbalance $\Delta N = N_i - N_e$, denoted by N_0 ($N_0 = 10\,000$), on the ratio of the radius to σ_0 at different expansion times $t/\tau_{\exp}$. The figure also shows this dependence in the absence of a magnetic field. It is clear from the graphs that in the absence of a field the charge imbalance ΔN for all r/σ_0 is greater than zero and in the presence of a field at average times in a certain region it becomes negative, i.e., the number of electrons in this region exceeds the number of ions. Moreover, the magnitude of the imbalance depends on the parameters of the plasma and magnetic field. A negative ΔN value results in the formation of a potential well for ions in front of the potential well for electrons. This should influence the nature of the movement of ions during the expansion process.

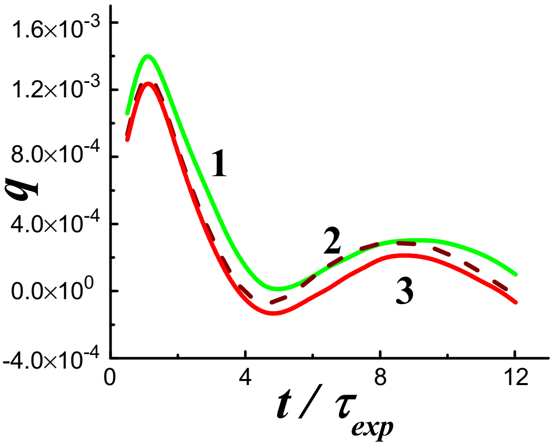

FIG. 2. Time dependence of normalized ion fluxes $q = n_i v_{ir} \tau_{\exp}/n_0\sigma_0$ at $\beta = 38$ and $r/\sigma_0 = 1.25$ for flux along the plane $x = 0$, curve 1; flux averaged over angular coordinates, curve 2; and flux along the axis of symmetry, curve 3.

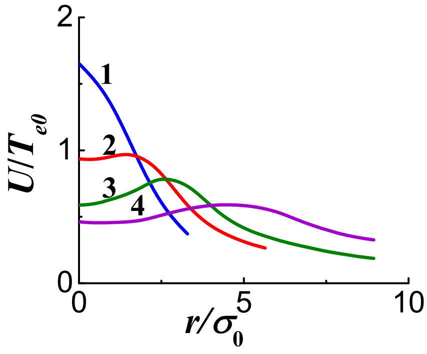

FIG. 3. Dependence of the ion potential energy U/T_{e0} on r/σ_0 for $N_0 = 10\,000$, $\beta = 38$, and $t/\tau_{\exp} = 0.5$, curve 1; $t/\tau_{\exp} = 1.5$, curve 2; $t/\tau_{\exp} = 2.5$, curve 3; and $t/\tau_{\exp} = 5$, curve 4.

The last remark regarding our work is related to our article in [4]. There is a misunderstanding here in our discussion of the behavior in a quadrupole magnetic field of a quasistationary ultracold Ca plasma, which was obtained in our laboratory [5] and can exist for a long time. In [4] we determined, using molecular dynamics, the dependence of particle density on the magnetic induction gradient. We agree that the phrase [4] "[ultracold] plasma produced using a continuous wave . . . laser is [steady state] with a lifetime of about [10 min]" is not quite right. The term "lifetime" is used here in the sense of an infinite time of existence of steady-state plasma concentration, when the trap loading rate equals the loss rate.

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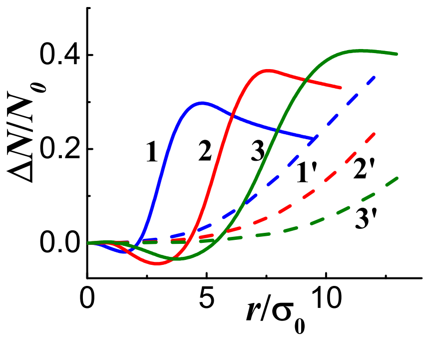

FIG. 4. Dependence of charge imbalance $\Delta N/N_0$ on r/σ_0 for $N_0 = 10\,000$, $\sigma_0 = 0.085$ cm, and, for $\beta = 38$ (solid lines), $t/\tau_{\exp} = 2.5$, curve 1; $t/\tau_{\exp} = 5$, curve 2; and $t/\tau_{\exp} = 7.5$, curve 3 and, for $\beta = 0$ (dashed lines), $t/\tau_{\exp} = 2.5$, curve 1′; $t/\tau_{\exp} = 5$, curve 2′; and $t/\tau_{\exp} = 7.5$, curve 3′.

[1] S. Ya. Bronin, E. V. Vikhrov, B. B. Zelener, and B. V. Zelener, Phys. Rev. E **108**, 045209 (2023).

[2] E. V. Vikhrov, S. Ya. Bronin, B. B. Zelener, and B. V. Zelener, Phys. Rev. E **104**, 015212 (2021).

[3] G. M. Gorman, M. K. Warrens, S. J. Bradshaw, and T. C. Killian, Phys. Rev. Lett. **126**, 085002 (2021).

[4] S. Ya. Bronin, E. V. Vikhrov, B. B. Zelener, and B. V. Zelener, JETP Lett. **117**, 116 (2023).

[5] B. B. Zelener, E. V. Vilshanskaya, N. V. Morozov, S. A. Saakyan, A. A. Bobrov, V. A. Sautenkov, and B. V. Zelener, Phys. Rev. Lett. **132**, 115301 (2024).