Comment on "Ultracold plasma expansion in quadrupole magnetic field"

Matthew Schlitters, Matthew Miller, Ben Farley, and Scott D. Bergeson*
Department of Physics and Astronomy, Brigham Young University, Provo, Utah 84602, USA

(Received 29 February 2024; accepted 29 July 2024; published 21 August 2024)

Bronin *et al.* [Phys. Rev. E **108**, 045209 (2023)] recently reported molecular-dynamics simulations of ultracold neutral plasmas expanding in a quadrupole magnetic field. While the main results are in agreement with prior experimental measurements, we present data showing oscillations not captured in the simulations of Bronin *et al.* Plasmas formed using pulsed or continuous-wave ionization processes have similar confinement times.

DOI: 10.1103/PhysRevE.110.027201

Gorman *et al.* recently demonstrated magnetic confinement of an ultracold neutral plasma (UNP) [1]. The plasma, created by ionizing laser-cooled atoms in a magneto-optical trap (MOT), expanded in the presence of the quadrupole field used for the MOT. The plasma density fell rapidly at first as the plasma expanded to fill the trap volume. The electrons were confined by the magnetic cusp field, and the ions were trapped by the space charge of the electrons. After the initial fast decay, the plasma density fell slowly as electrons and ions "leaked" out of the magnetic mirror created by the MOT field.

The paper by Bronin *et al.* [2] used a molecular-dynamics simulation to gain deeper insight into the trapping dynamics. Their simulations reproduced the main results in Ref. [1]. They found that the trapping efficiency was not enhanced at larger field gradients and that the non-neutrality of the plasma increased at later times.

In this Comment we briefly report measurements of a confined Ca^+ UNP that confirm the results of Bronin *et al.* We also show that the UNPs in this configuration show dynamic oscillations not captured in their simulation.

The experiment has been described elsewhere in detail [3,4]. The Ca MOT operates at 423 nm, as shown in Fig. 1(a). We use pulsed lasers at 423 and 390 nm to ionize the Ca atoms just above the ionization threshold. An additional 424-nm laser eliminates a loss channel and increases the trap density [5]. The magnetic-field gradient along the symmetry axis of the MOT is 115 G/cm.

A 397-nm probe laser beam illuminates a 1-mm-wide slice through the center of the Ca^+ plasma. We use a slit to define the width of the probe laser beam and image that slit onto the plasma. The 397-nm laser is scanned ±300 MHz relative to the $4s\,^2S_{1/2}$–$4p\,^2P_{1/2}$ transition in 30-MHz steps. Optical pumping into the $3d\,^2D$ states is prevented using a repumper laser at 866 nm [Fig. 1(b)]. The probe laser propagates in the x direction, as shown in Fig. 2(a). The laser-induced fluorescence is collected in the $\pm y$ directions and measured using both an intensified CCD (ICCD) camera and a photomultiplier tube (PMT), as shown in Fig. 2(b). The probe laser beam is linearly polarized in the z direction.

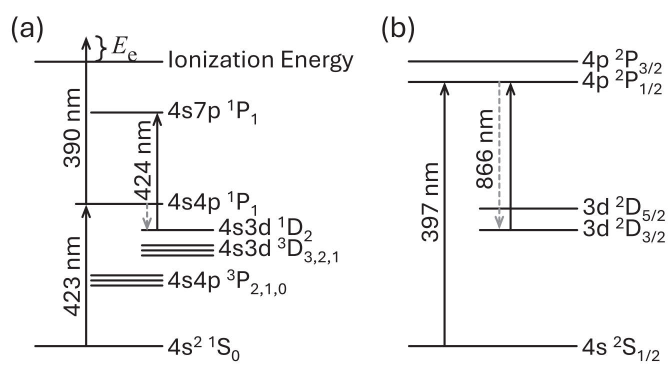

FIG. 1. Partial energy-level diagrams showing (a) the MOT (423 nm), repumping (424 nm), and ionization lasers (423 and 390 nm) for Ca. (b) Partial energy-level diagram for Ca^+. We probe the plasma ions at 397 nm and repump at 866 nm to close the optical system.

In our experiment we measure the number of ions illuminated by the laser beam as a function of time. The PMT data provide a laser-induced fluorescence profile for the ions

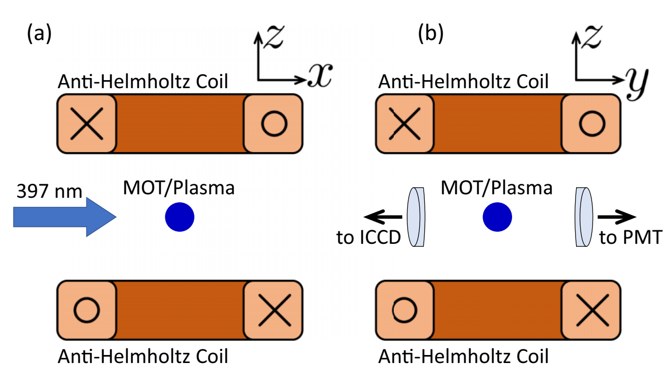

FIG. 2. Experimental setup showing (a) the 397-nm laser beam entering the chamber to illuminate the plasma and (b) the placement of the ICCD and PMT with their imaging systems relative to the plasma.

*Contact author: scott.bergeson@byu.edu

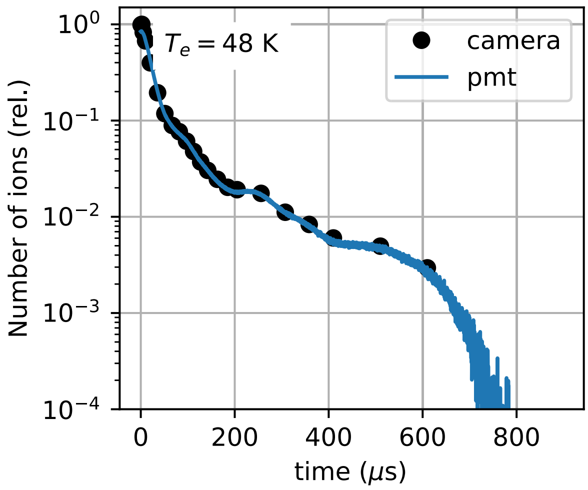

FIG. 3. Time evolution of the relative number of trapped ions as a function of time. The black circles show data from integrating the camera images over frequency at each time. The blue line shows data from analyzing the PMT data. These two methods agree well and provide complementary insights into the plasma dynamics. For these data, $\sigma_0 = 1$ mm and the peak central density $n_0 = 10^{15}$ m^{-3}.

for times up to 1 ms. The PMT signal is an integration over the illumination volume. At each time, we fit the fluorescence as a function of frequency to a Voigt profile. The underlying Gaussian distribution is then integrated to obtain the relative number of ions. On the other hand, the camera images are simply summed over frequency, providing detailed spatial information at a particular time after ionization. These two analysis methods for obtaining the relative number of ions in the illumination volume agree, as shown in Fig. 3.

The data in Fig. 4 show that the ion trapping time decreases as T_e increases. This was shown previously in Ref. [1] and is consistent with trapping lifetime being limited by electron dynamics. In the absence of a magnetic field, the asymptotic expansion velocity of the plasma increases as $v_{\mathrm{exp}} = (k_B T_e/m_i)^{1/2}$. Increasing expansion velocity corresponds to shorter trapping lifetimes. The data in Fig. 4(b) show the expansion time scaled by the field-free plasma expansion time $\tau_{\mathrm{exp}} = (m_i \sigma_0^2 / k_B T_e)^{1/2}$. The evolution of the relative number of ions with respect to t/τ_{exp} is independent of T_e. For each electron temperature, the relative number of ions drops off precipitously after $t/\tau_{\mathrm{exp}} \approx 40$. This is consistent with increasing non-neutrality at late times, as suggested by Bronin *et al.* The simulations in Ref. [2] suggest that at $t/\tau_{\mathrm{exp}} \approx 40$ the ion current changes sign. However, we see no evidence for that in this work.

The data in Fig. 4 show oscillations in the rate of ion loss during expansion. This is seen as a descending "staircase" structure in Fig. 4(a) and as oscillations around the characteristic slope in Fig. 4(b). The oscillation amplitude appears to increase as the electron temperature increases. This is consistent with the ions bouncing with greater energy in the magnetic mirror as the electron temperature increases.

To gain greater insight into the ion dynamics, we look at the gradient of the x component of the hydrodynamic velocity u_x at the center of the plasma. Data in Fig. 5(a) show how the field-free plasma expands. The x component of the hydrodynamic velocity

$$u_x = \frac{t/\tau_{\mathrm{exp}}^2}{1 + t^2/\tau_{\mathrm{exp}}^2} x \tag{1}$$

increases linearly with time at early times and falls as t^{-1} at late times. In contrast, when the cusp field is present as shown in Fig. 5(b), the plasma expands normally at first, but then is reflected by the mirror and demonstrates a breathing mode oscillation. As electrons escape the trap, these oscillations decrease in amplitude and frequency, similar to ion oscillations observed in a different experiment [3].

The results of Bronin *et al.* indicate that the magnetic trapping effect quickly saturates with the strength of the cusp field. Increasing the field strength did not improve the trap lifetime in their simulations. We verify that there is no change

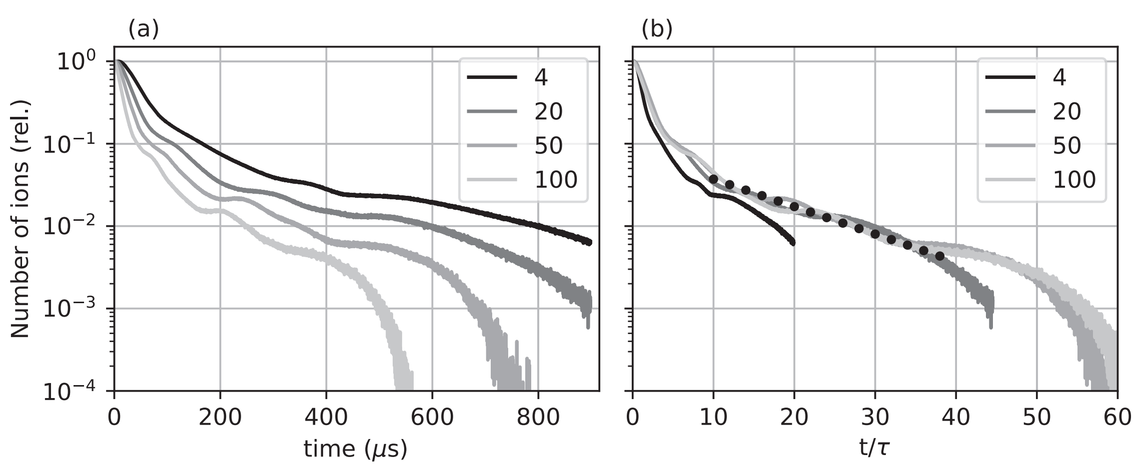

FIG. 4. Plot of the relative number of ions in the illumination volume as a function of (a) time and (b) scaled time t/τ_{exp} for different electron temperatures. The electron temperatures range from 4 to 100 K, as indicated in the legends. The black dotted line in (b) is an exponential fit to the data with a decay time of $13\tau_{\mathrm{exp}}$. Note that for an electron temperature of 4 K, the characteristic slope in (b) deviates slightly from the higher-temperature data. If the electron temperature is increased to 10 K, due to effects of the three-body combination, for example, the data all fall on the same line. For these data, $\sigma_0 = 1$ mm and the peak central density $n_0 = 10^{15}$ m^{-3}, settings identical to those in Fig. 3.

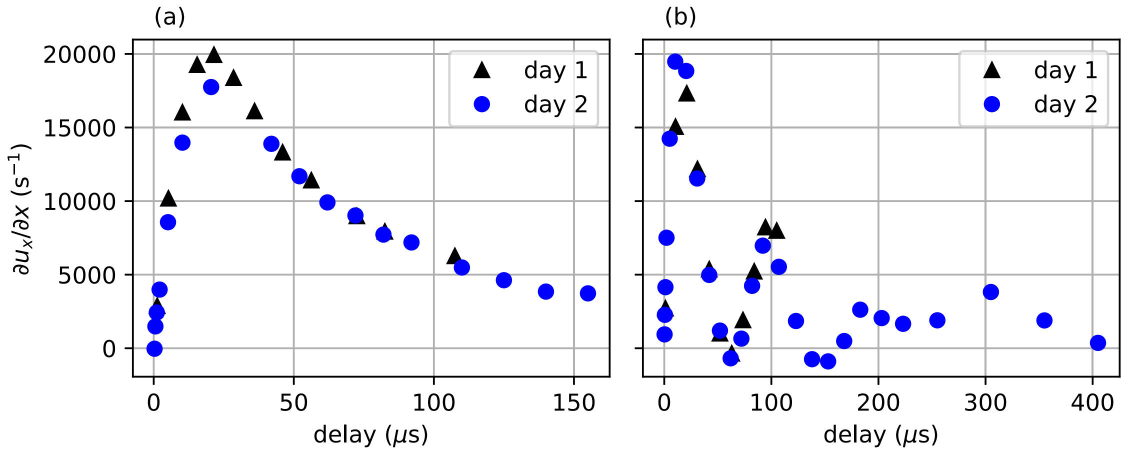

FIG. 5. Gradient in the x component of the hydrodynamic velocity with (a) no magnetic field and (b) the cusp field. Plasma oscillations are clearly evident, damping to a steady-state expansion and plasma loss from the trap. For these data, $T_e = 19$ K, $\sigma_0 = 1.22$ mm, and the peak central density $n_0 = 9 \times 10^{14}$ m^{-3}.

in trap lifetime in our experiment when we double the field gradient using an ancillary set of coils.

It was suggested in Ref. [1] that the cusp trap could be augmented with appropriate laser beams to cool trapped ions and perhaps to reduce the rate at which ions leak out of the cusp trap. Because the non-neutrality of the trap increases with time, it is unlikely that adding weak optical forces will extend the trap lifetime. In our work we have added intense retroreflected laser beams at different frequencies and polarizations and observe no change in the plasma confinement time.

In a previous paper by Bronin *et al.* [6] it was claimed that "[ultracold] plasma produced using a continuous wave (cw) laser is [steady state] with a lifetime of about [10 min]." To test this assertion, we used a cw laser at 390 nm to continuously ionize atoms in the MOT and measured the trap lifetime after turning off the ionization. We found no difference in the trapping time compared to our plasmas generated using pulsed ionization. These results are consistent with the trap lifetime data presented in Ref. [7], in which a cw plasma was in fact demonstrated when the trap loading rate exceeds the loss rate.

In summary, we have verified the basic observations of Bronin *et al.* using a Ca UNP experiment. We observe dynamic behavior of the plasma not captured in their simulations. Plasmas formed with either pulsed or cw ionization processes have similar lifetimes. For pulsed ionization cusp trap loading, confinement times scale as $T_e^{-1/2}$.

This work was supported in part by the National Science Foundation under Grant No. NSF-2009999.

[1] G. M. Gorman, M. K. Warrens, S. J. Bradshaw, and T. C. Killian, Magnetic confinement of an ultracold neutral plasma, Phys. Rev. Lett. **126**, 085002 (2021).

[2] S. Y. Bronin, E. V. Vikhrov, B. B. Zelener, and B. V. Zelener, Ultracold plasma expansion in quadrupole magnetic field, Phys. Rev. E **108**, 045209 (2023).

[3] C. Pak, V. Billings, M. Schlitters, S. D. Bergeson, and M. S. Murillo, Preliminary study of plasma modes and electron-ion collisions in partially magnetized strongly coupled plasmas, Phys. Rev. E **109**, 015201 (2024).

[4] R. T. Sprenkle, S. D. Bergeson, L. G. Silvestri, and M. S. Murillo, Ultracold neutral plasma expansion in a strong uniform magnetic field, Phys. Rev. E **105**, 045201 (2022).

[5] M. Mills, P. Puri, Y. Yu, A. Derevianko, C. Schneider, and E. R. Hudson, Efficient repumping of a Ca magneto-optical trap, Phys. Rev. A **96**, 033402 (2017).

[6] S. Y. Bronin, E. V. Vikhrov, B. B. Zelener, and B. V. Zelener, Magnetic field effect on the formation of ultracold plasma, JETP Lett. **117**, 116 (2023).

[7] B. B. Zelener, E. V. Vilshanskaya, N. V. Morozov, S. A. Saakyan, A. A. Bobrov, V. A. Sautenkov, and B. V. Zelener, Steady-state ultracold plasma created by continuous photoionization of laser cooled atoms, Phys. Rev. Lett. **132**, 115301 (2024).