

Phase-space manipulation of stored ions using the δ -kick method

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We demonstrate compression of the velocity spread of a stored ion bunch in an electrostatic ion-beam trap, using the δ -kick method. An analytical formula for the optimum pulse is derived and is used in the laboratory. A 20% reduction in the asymptotic velocity spread is observed after application of a single cooling pulse to a bunch of 4.2-keV Ar^+ ions.

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I. INTRODUCTION

Over the past decade, various cooling techniques have been developed in order to manipulate the phase-space density of atoms or ions. Many interesting and new effects have been discovered and studied, and as a result of this a better understanding of the interaction of ions and atoms with external fields has been obtained.

Cooling of ions is different from atoms, in that ions are easier to manipulate and because, for high particle densities, the Coulomb interaction has to be taken into account. This has resulted in the formation of structures that have been observed in ion traps [1] and in both small- [2] and large-scale [3] storage rings. Cooling is most often achieved with lasers, although in the large-scale machines the cooling of the fast ion beams has also been achieved by electron cooling [3] or by stochastic cooling [4].

Recently, it has been demonstrated that it is possible to reduce the velocity distribution of a neutral molecular beam using the so-called δ -kick cooling [5]. This technique, which was proposed for atoms by Chu *et al.* [6] and by Summhammer *et al.* [7], was experimentally demonstrated by Marechal *et al.* and Myrskog *et al.* [8,9]. δ -kick cooling uses time-varying (Hamiltonian) magnetic or electric fields to achieve longitudinal focusing in velocity space. The method, to the best of our knowledge, has never been applied to charged particles. It is important to note that the single-particle phase-space density is left unchanged in this process, as it is well known [10] that conservative forces cannot increase phase-space density.

The basic requirement for δ -kick cooling is the existence of some known correlation between velocity and position of the particles. For fast (MeV) charged particle beams, where bunching and debunching are routinely used, it is common to manipulate both the spatial and the velocity distribution of the ion beam using time-dependent fields [11]. However, because of the high kinetic energy of the ion beams, sophisticated devices using rf fields are needed to obtain the desired effects. For (pulsed) beams produced at keV energies, the distance from the exit of the ion source to the target (or interaction region) is usually too short for the establishment of significant correlation between position and velocity in the ion pulse.

Recently, we have demonstrated that it is possible to store fast (keV) ions in an electrostatic ion-beam trap [12–14], much like photons in an optical resonator. The ions have

kinetic energies of a few keV in the central part of the trap, while inside the mirrors, near the turning points, their kinetic energies are reduced to a few meV. We have shown [15,16] that under specific conditions, it is possible to achieve either synchronization of the particle motion (self-bunching) in the trap, resulting in a bunch whose width is essentially constant in time, or enhanced diffusion of the bunch, in which the width of the bunch increases rapidly. Both self-bunching and enhanced diffusion were attributed to the Coulomb interaction between the ions in the bunch [17]. In particular, it was found that enhanced diffusion occurs when faster ions have shorter periods of oscillation than slower ions. Such a situation exists when the dispersion function of the ion trap, which is the derivative of the oscillation half period T with respect to the kinetic energy E , is negative: $dT/dE < 0$. Under this condition, faster ions are located at the front of the ion bunch and slower ions at the rear. The Coulomb interaction between the ions transfers momentum between the ions in the rear of the bunch and those located in the front, thereby increasing the velocities of the faster ions relative to the center of the bunch and decreasing the velocities of the slower ions. The net result is an increase in the velocity spread of the ions, producing a strong correlation between the ions' velocities and their positions within the bunch. After a large number of oscillations, the trap is filled with ions with a kinetic-energy distribution that is wider than upon injection. Such a large energy distribution might make specific experiments, such as high-resolution merged laser-ion-beam spectroscopy, difficult to carry out. Hence, it is important to try reducing this energy spread to the smallest possible value.

In this paper, we demonstrate δ -kick cooling for ion bunches stored in the enhanced diffusion mode of the electrostatic ion trap. Using simulation and an analytical one-dimensional model, we calculate the optimal shape of the cooling pulse. We present experimental results, compare them to the model, and discuss the effects of the Coulomb interaction, both in the buildup of the correlation needed for applying the δ -kick cooling method and in the reheating appearing shortly after the cooling.

II. EXPERIMENTAL SETUP

A schematic drawing of the ion trap is shown in Fig. 1. The mechanical design of the ion trap and its operation have been discussed previously [13,14]. The trap consists of two

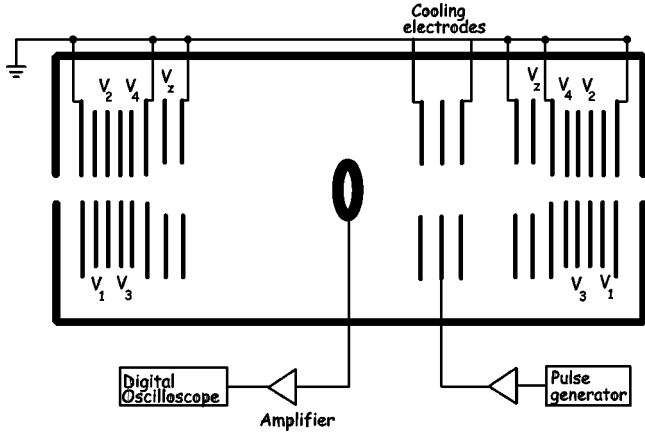


FIG. 1. Schematic view of the electrostatic ion trap and the cooling setup.

coaxial electrostatic mirrors, each of which is made of a stack of eight cylindrical electrodes. The configuration of the trap is defined by the potentials of five of these electrodes $\{V_1, V_2, V_3, V_4, V_z\}$, while the other three are grounded (see Fig. 1). The central region of the trap, between the two mirrors, is essentially field-free. The distance between neighboring mirror electrodes is 10 mm. The length of the field-free region of the trap is ~ 300 mm. When the field generated by the electrode potentials satisfy certain criteria [12,14], ions can be trapped, and will oscillate between the mirrors, with a lifetime which is mainly limited by the background pressure. The electrode configuration chosen for the present experiment, $\{V_1, V_2, V_3, V_4, V_z\} = \{6.5, 4.875, 3.25, 1.625, 3.2\}$ kV, is one of the configurations in which enhanced diffusion occurs, i.e., $dT/dE < 0$ [14].

A beam of Ar^+ is produced in an electron-impact source and accelerated to an energy of $E = 4.2$ keV. The beam is chopped after acceleration by an electrostatic chopper, producing a narrow bunch of ions for each injection. The ions are mass selected first by a 20° magnet and later by a 45° magnet. Faraday cups located along the beam line allow monitoring of ion-beam current. Typical dc beam currents (nonchopped) were of the order of 150 nA. Additional ion optics enable steering and focusing of the beam. The potentials on the entrance mirror electrodes are grounded in synchronization with the chopper to allow injection of the ion bunch into the trap. The potentials are rapidly raised before the bunch returns to the entrance mirror, thus confining the bunch between the two mirrors. The trap is pumped to a pressure below 3×10^{-10} Torr using cryopumps. The number of ions injected into the trap can be varied with the help of slits located upstream from the trap, and ranged between 8×10^4 and 7.5×10^6 ions.

The evolution of the ion bunch in the trap is monitored using a cylindrical pickup electrode (see Fig. 1) with length $l_p = 8$ mm and inner diameter of 18 mm located at the center of the trap. The total capacitance of the pickup was measured to be ~ 10 pF. The pickup electrode is connected to the gate of a junction field-effect transistor whose drain is fed to a charge-sensitive amplifier. The amplified signal is recorded with a digital oscilloscope at a maximum sampling rate of

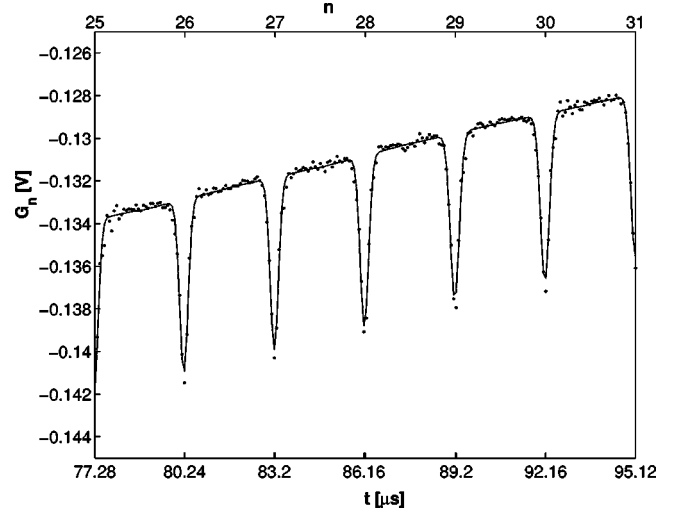


FIG. 2. Pickup signal averaged over 50 injections (dots) and Gaussian fits according to Eq. (1) (solid line) as a function of both time and half-oscillation number n .

50 MHz using 14-bit analog-to-digital conversion. A typical measured signal, averaged over several tens of injections, is shown in Fig. 2. For every passage of the bunch through the pickup electrode, a negative signal (due to the polarity of the preamplifier) is measured. Its area is proportional to the number of ions and its width is proportional to the length of the bunch (as long as the bunch is much longer than the electrode size). The signals usually sit on a slowly varying background which is due to the noisy electromagnetic environment of the laboratory.

The temporal evolution of the bunch was quantified by fitting the averaged signals [15,16] for each half oscillation n , with a negative Gaussian function on a linear background (see Fig. 2):

$$G_n(t) = -\frac{S_n}{\sqrt{2\pi}W_n} e^{-(t-t_n)^2/2W_n^2} + a_n t + b_n, \quad (1)$$

where S_n is the area under the peak, W_n is the bunch width, t_n is the time of arrival of the bunch at the center of the pickup, and a_n and b_n are the coefficients of the linear background. S_n , W_n , t_n , a_n , and b_n were free parameters for each peak. A similar parametrization technique was previously used and is discussed in Ref. [14].

An additional set of three electrodes located between the pickup and the exit mirror allowed introduction of a time-dependent potential (see Fig. 1). The potential on the central electrode was variable, while the other two electrodes were grounded. The inner diameter of these three electrodes is 10 mm, their thickness is 3 mm, and the distance between them is $L = 10$ mm. The region between the outer two electrodes will be referred to as the cooling region. The cooling pulse was created by a 40-MHz arbitrary wave form generator and amplified first by a preamplifier and then by an additional fast amplifier, so that a pulse of width $2T_p \sim 1 \mu\text{s}$ and of height of up to ~ -200 V could be achieved without distorting the shape of the pulse generated by the wave form

generator. This pulse was then applied to the central cooling electrode, and the trigger to the wave form generator was generated by a separate function generator with variable delay, allowing fine time steps of ~ 10 ns relative to the injection time.

III. ION MOTION IN THE TRAP

In order to apply the δ -kick cooling method to the trapped ions, a good understanding of their motion is needed. For this purpose, we simulated the ion trajectories in the electrostatic fields due to the potentials on the mirror electrodes given in Sec. II. We took advantage of the cylindrical symmetry of the system and solved the two-dimensional problem using the SIMION, Version 6 [18] program that numerically solves the Laplace equations for the potentials on the various electrodes. This program generates a grid of points where the potential is estimated, on which the motion of ions can be calculated. More details can be found in Ref. [14]. The particles were chosen to be Ar^+ with an average kinetic energy of 4.2 keV and an initial spread of 1.4 eV, a realistic value based on the ion source operation. In order to reduce the computation time, the bunch itself was represented by 20 interacting particles, each with charge of 25 000 $|e|$, so as to represent the typical overall number of ions (5×10^5) injected into the trap. The motion of the ions was integrated for ~ 100 oscillations, and the position and velocity of each ion were registered as a function of time. The half-oscillation time of the ions was found to be $T \sim 3 \mu\text{s}$.

For the present work, and to be able to apply the δ -kick cooling method, the quantity of interest is the correlation between the particles' positions relative to the center of the bunch ($x_i - \bar{x}$), where x_i is the position of particle i along the trap axis and \bar{x} is their average position, and their velocities relative to the mean bunch velocity ($v_i - \bar{v}$), where v_i is the velocity of particle i along the trap axis and \bar{v} is their average velocity. Snapshots of the (single-particle) phase space after increasing numbers of oscillations, when the center of the bunch is located at the center of the trap, are shown in Fig. 3 (left panels). It is clearly seen that the bunch widens as a function of time, and that the phase space of the particles changes, so that correlation between velocity and position is created.

Figure 3 (upper right panel, circles) shows the correlation function given by

$$C_{xv} = \frac{\langle (x - \bar{x})(v - \bar{v}) \rangle}{\sigma(x)\sigma(v)}, \quad (2)$$

where $\sigma(x)$ and $\sigma(v)$ are the standard deviations of the particles relative positions and velocities for $\bar{x} = 0$. The lower right panel in Fig. 3 shows the development of γ , the slope of the linear correlation as a function of time, as obtained from a fit of the simulated phase-space distribution with the linear function

$$(v_i - \bar{v}) = \gamma(x_i - \bar{x}). \quad (3)$$

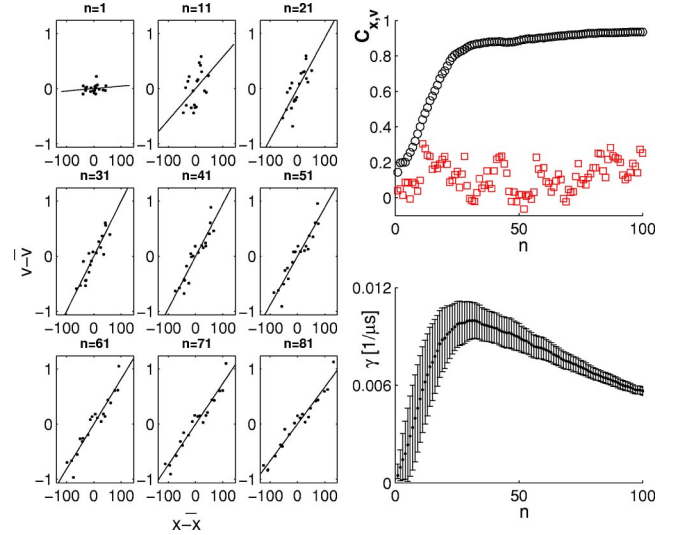


FIG. 3. Left panels: Snapshots of single-particle phase space as a function of oscillation number n . The line is a fit through the data points using a linear function. Right panel, upper: Correlation function as a function of n for particles with interaction (circles) and without interaction (squares). Right panel, lower: Slope γ resulting from the fit to the phase space as a function of half-oscillation number n . All panels are the result of a simulation, using 20 particles with a total charge of $5 \times 10^5 |e|$ divided equally among them.

After ~ 30 oscillations, the correlation C_{xv} reaches a value of ~ 0.85 , and is already approximately linear [see Fig. 3 (left panels)] with a slope approaching $\gamma = 0.01 \pm 0.0015 \mu\text{s}^{-1}$. It is remarkable that such a high correlation is obtained after such a short time (about $90 \mu\text{s}$) while the size of the bunch has increased by only $\sim 13\%$. Clearly, such a high degree of correlation does not usually occur in free space, where the ions are allowed to move without the influence of a trapping field. Both the high correlation and the small bunch size are important for the application of the δ -kick cooling method in the electrostatic ion trap, since the size of the bunch has to be smaller than the trap length (see Sec. IV).

The main reason for the fast correlation buildup is the Coulomb interaction between the particles. There are, in general, two reasons for the bunch to spread in the electrostatic trap: First, the particles move on different trajectories (due to the finite beam size of ~ 4 mm in diameter), which leads to a distribution of oscillation times. Second, the particles have some initial velocity spread. While the first contribution does not lead to any phase-space correlation (or rather destroys it), the second one does (for $dT/dE < 0$) [16]. For charged particles, the Coulomb interaction increases this velocity spread on a short time scale, depending on the density of ions, so that the correlation buildup is faster than it would be for noninteracting particles. The interaction between the ions is enhanced in the mirror region where the density is increased by about two orders of magnitude [16]. Simulations performed without the Coulomb interaction (squares in the upper right panel of Fig. 3) demonstrate that the buildup of the correlation is much slower, and would make the application of the δ -kick cooling method difficult. For the purpose of

δ -kick cooling the number of oscillations is limited by the finite dimension of the trap. The bunch must reach a reasonable level of correlation before it begins to overlap with itself inside the cooling region. Hence the presence of the enhanced Coulomb interaction between the ions is an essential ingredient to the fast buildup of correlation.

IV. THEORETICAL MODEL

In this section, we calculate the shape of the optimal pulse to be applied to the central cooling electrode (see Fig. 1). Consider a bunch of ions, assuming that the velocity spread of the ions is small ($\sigma(v) \ll \bar{v}$) and that the correlation between ion position and velocity relative to the center of the bunch is, to a good approximation, linear, as was shown in the preceding section. The velocity of each ion can thus be related by Eq. (3) to the time t_i at which it passes through the center of the cooling electrodes,

$$v_i \approx \bar{v}(1 - \gamma t_i). \quad (4)$$

When using the δ -kick method, a time-dependent force is applied to the ions so that the slope γ after application of the pulse is close to zero. To achieve this, the required energy change for an ion with velocity v_i is given by

$$\Delta E_i = \frac{m}{2}(\bar{v}^2 - v_i^2) \approx m\bar{v}(\bar{v} - v_i) \quad (5)$$

and can be related to t_i through Eq. (4),

$$\Delta E_i \approx 2E\gamma t_i. \quad (6)$$

In order to induce the required energy change ΔE_i , a time-dependent potential $U(t)$ is applied to the central cooling electrode of the cooling region (see Fig. 1). The potential on the trap axis at the central electrode position is given by $\beta U(t)$, where $\beta < 1$ and depends only on the geometry of the electrodes.

The potential $V(x', t)$ generated between the electrodes, close to the axis of the trap, is given, to a good approximation, by

$$V(x', t) = \begin{cases} 0, & |x'| > L \\ \beta U(t) \left(1 - \frac{|x'|}{L}\right), & |x'| \leq L, \end{cases} \quad (7)$$

where x' is the distance from the central electrode, and L is the distance between the central and grounded electrodes.

Consider now a single ion with charge Q approaching the cooling region from the left. The work done on this ion as it passes through the cooling region $|x'| \leq L$ is given by

$$\begin{aligned} \Delta E &= -Q \int_{-L}^L \frac{\partial V(x', t)}{\partial x'} dx' \\ &= -Q \int_{-L}^0 \frac{\beta U(t(x'))}{L} dx' + Q \int_0^L \frac{\beta U(t(x'))}{L} dx'. \end{aligned} \quad (8)$$

Assuming that the change in the ion velocity in the lab frame is small, namely, that $|v_i(t) - \bar{v}| \ll |\bar{v}|$ at all times t , we obtain

$$\Delta E \approx \frac{Q\beta}{\tau} \left[- \int_{t_i - \tau}^{t_i} U(t) dt + \int_{t_i}^{t_i + \tau} U(t) dt \right], \quad (9)$$

where t_i is defined as the time at which the ion passes through the central electrode ($x' = 0$) and $\tau = L/\bar{v}$ is approximately equal to half the time it takes for a particle to pass through the cooling electrodes. A general polynomial guess for $U(t)$ is given by

$$U(t) = U_0 [1 - (t/T_p)^j], \quad (10)$$

where T_p is half the width of the applied pulse and U_0 is the pulse height at $t = 0$. Given that the pulse is long enough, $T_p \geq \max(|t_i|) + \tau$, the following expression for ΔE as a function of t_i is obtained:

$$\Delta E(t_i) \approx \frac{-Q\beta U_0}{(j+1)} \frac{\tau^j}{T_p^j} \sum_{k=0}^j \binom{j+1}{k} (t_i/\tau)^k [1 - (-1)^{j-k}]. \quad (11)$$

To produce the linear ($k = 1$) energy correction, required in Eq. (6), the lowest contributing power is $j = 2$, leading to the time-dependent potential

$$U(t) = U_0 (1 - (t/T_p)^2), \quad (12)$$

where the optimal value for U_0 is determined from comparing Eqs. (6) and (11),

$$U_0 = - \frac{\gamma E T_p^2}{\beta \tau}. \quad (13)$$

V. EXPERIMENTAL RESULTS

The results obtained in Secs. III and IV provide the guidelines for using the δ -kick cooling method on a bunch of interacting particles in the electrostatic trap.

A bunch of 4.2 keV Ar^+ ions, with an initial temporal width of $\sim 0.12 \mu\text{s}$ (corresponding to a length of ~ 17 mm) was injected into the electrostatic trap. A parabolic δ -kick pulse with a variable U_0 [see Eqs. (12) and (13)] was applied, usually during oscillation number $n_c = 28$, chosen so that the correlation between position and velocity was near linear with a predicted slope of $\gamma = 0.01 \pm 0.0015 \mu\text{s}^{-1}$, while the bunch was still narrow enough as to avoid overlapping itself in the cooling region (see Fig. 3).

In order to assess the effect of the cooling pulse on the velocity spread, we observe the evolution of the bunch width W_n as a function of the number of half oscillations n , before and after application of the cooling pulse. As pointed out in Sec. III, the main contribution to the increase in the bunch width is the velocity spread of the trapped ions. Thus, the effect of the δ kick on the velocity spread can be quantified by the change in the growth rate of W_n . Simultaneous monitoring of the area of the bunch (S_n) allows one to verify that

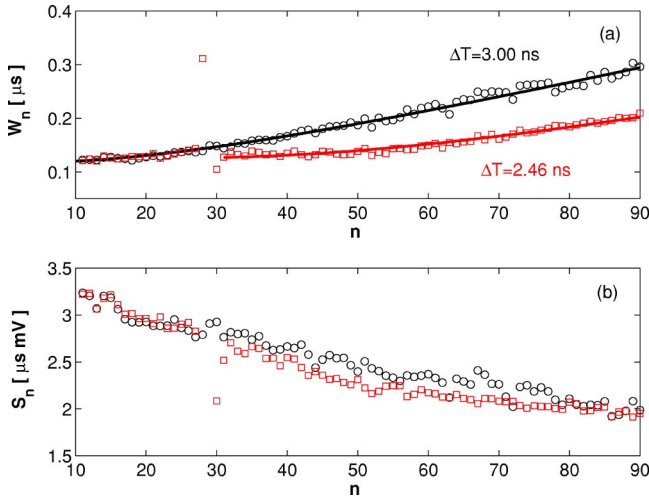


FIG. 4. (a) Measured bunch width W_n as a function of half-oscillation number n , with no cooling pulse (circles) and for $U_0 = -150$ V (squares). The sensitivity of the pickup to the cooling pulse leads to large errors for $n=28$ and the oscillations immediately after. Solid lines show fits of both sets of data using Eq. (14). (b) Measured bunch area as a function of half-oscillation number n , with no cooling pulse (circles) and for $U_0 = -150$ V (squares).

the changes in W_n are indeed due to a reduction in the velocity spread, rather than the loss of ions.

Figure 4(a) shows the dependence of W_n [obtained using Eq. (1)] on the number of half oscillations n , averaged over 50 injections. The data points obtained immediately after the cooling pulse, up to $n \sim 32$, are not reliable because of the electromagnetic interference induced on the pickup. Two different sets of data points are shown, identical for $n < 28$. The circles are the data obtained without applying a cooling pulse (i.e., $U_0 = 0$), and the bunch width is observed to increase steadily, in agreement with the results obtained by Pedersen *et al.* [16]. The squares in Fig. 4(a) show the results obtained when a cooling pulse of the shape given by Eq. (12), with $U_0 = -150$ V, is applied to the central cooling electrode. The bunch width, after application of the cooling pulse, is approximately independent of the number of oscillations for about 20 half oscillations, and then starts to grow, albeit at a slower rate than for the previous case, implying that a reduction in velocity spread was achieved. Figure 4(b) shows the corresponding time evolution of the bunch area, indicating that there was almost no ion loss due to the cooling pulse.

In order to quantify these results, we extract the local growth rate of W_n , $\Delta W/\Delta n$, in the interval from $n=33$ to $n=43$, for different values of U_0 . This slope is extracted from a linear fit to W_n versus n . The results are shown in Fig. 5, where $\Delta W/\Delta n$ is plotted as a function of U_0 . The local slope is seen to decrease as the applied (negative) pulse is increased, from 3 ns/oscillation when no pulse is applied ($U_0 = 0$) to almost 0 ns/oscillation when a $U_0 = -150$ V pulse is applied. For $U_0 < -150$ V (the largest value which could be generated was -200 V), the local slope is negative, indicating that the width of the bunch decreased during the first few oscillations following the application of the cooling pulse. This is an indication of negative correlation

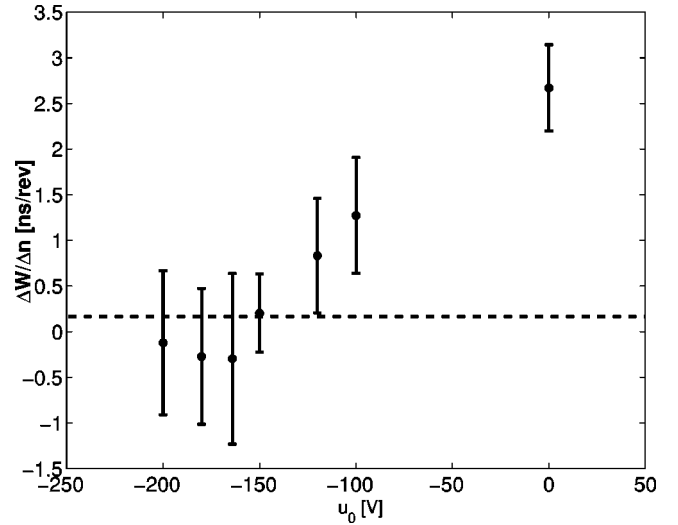


FIG. 5. Local slope $\Delta W/\Delta n$ of bunch width after applying the cooling pulse as a function of pulse height U_0 . The local slope change sign for $U_0 \approx -150$ V.

($\gamma < 0$) between velocity and position. As a result of the cooling pulse, the velocities of the faster ions, located in the front of the bunch, are reduced below the average bunch velocity, while the velocities of the slower ions are increased to values higher than the average bunch velocity. Since in the chosen trapping configuration the dispersion dT/dE is negative, the faster particles, now located at the tail of the bunch, have relatively shorter oscillation times, and therefore move forward towards the center of the bunch, while the slower particles, which are now positioned at the head of the bunch, move backwards towards the bunch center. Thus, the bunch width is reduced in the first several oscillations after the cooling pulse is applied, leading to $\Delta W/\Delta n < 0$ obtained for $U_0 < -150$ V. The negative correlation indicates that the cooling pulse is too strong, and that the phase space of the particles is “sheared” by more than the optimal value needed to flatten the velocity distribution. We conclude that the optimal value of U_0 is ~ -150 V, for which the local slope immediately after application of the cooling pulse is close to zero.

Even after the optimal pulse has been applied, the bunch eventually begins to spread [see Fig. 4(a)]. This is a result of the same factors mentioned in Sec. III: First, the ions follow different trajectories, which leads to a distribution of oscillation times. Second, the remaining Coulomb interaction between the particles results in a “renewed” velocity spread. Thus, even if the velocity spread has been reduced to a very small value by the cooling pulse, reheating and thus debunching still occur, and the narrow velocity distribution is kept only for a short time.

In order to quantify the effectiveness of the cooling pulse using the data shown in Fig. 4(a), we use the parametrization obtained by Pedersen *et al.* for the dependence of the bunch width W_n on the oscillation number n [15,16]:

$$W_n = \sqrt{W_0^2 + \Delta T^2 n^2}, \quad (14)$$

where W_0 is the initial width of the ion bunch and ΔT is the asymptotic slope of W_n as a function of n . Since Eq. (14) is correct under the assumption that there is no initial correlation between the ions' positions and velocities at $n=0$ (upon injection), it does not generally describe the dynamics of the bunch after the cooling pulse has been applied. However, at oscillation $n=n_c$ for which the local slope of W_n reaches zero (see Fig. 5), ion velocity and position are uncorrelated, and Eq. (14) is a correct description of the evolution of the bunch for $n>n_c$, when n is replaced by $(n-n_c)$. The solid lines in Fig. 4(a) show Eq. (14) fitted to both sets of data, with $W_0=0.117 \mu\text{s}$ and $\Delta T=3.00\pm 0.02$ ns as fitting parameters for the case in which there was no cooling (circles), and $W_0=0.137 \mu\text{s}$ and $\Delta T=2.44\pm 0.03$ ns when a pulse of height $U_0=-150$ V was applied (squares). Given ΔT , the longitudinal energy spread of the bunch can be evaluated using the relation

$$\Delta E = \left| \frac{dT}{dE} \right|^{-1} \Delta T, \quad (15)$$

where dT/dE depends on the trap configuration. Using the value of $dT/dE = -0.23$ ns/eV, calculated as described previously [16] using SIMION [18], we obtain that the longitudinal energy spreads (after long trapping times) are $\Delta E = 10.6\pm 0.1$ eV and $\Delta E = 13.3\pm 0.1$ eV with and without application of the cooling pulse, respectively. Thus, a decrease of $\sim 20\%$ in the *asymptotic* longitudinal energy spread is achieved when a single cooling pulse is applied (without particle loss).

An additional verification that the effect observed in Figs. 4 and 5 represents a real decrease in the width of the velocity distribution and not an overall change of the mean velocity can be achieved by measuring the local slope $\Delta W/\Delta n$ as well as the oscillation half period T as a function of the time delay Δt between the cooling pulse and the arrival of the bunch at the center of the cooling region. The delay Δt for which $\Delta W/\Delta n$ is minimum should correspond to an oscillation time T which is left unchanged. Only in such a case, the data presented in Figs. 4 and 5 correspond to a real narrowing of the velocity distribution. The results of such a measurement are presented in Fig. 6 (for $U_0 = -120$ V), where $\Delta W/\Delta n$ (upper panel) and T (lower panel) are plotted as a function of Δt . The shaded horizontal line denotes the value of $\Delta W/\Delta n$ with its estimated error in the case when cooling was not applied (upper panel) or the value of T with its estimated error when cooling was not applied, (lower panel). The four vertical lines indicate the points at which U reached U_0 exactly at the same time when the center of the ion bunch passed the center of the cooling region. Since the cooling region is not located at the center of the trap, these points are not equally spaced in time, despite the fact that they correspond to consecutive half-oscillation numbers. The data (upper panel) show clearly that there is a decrease in $\Delta W/\Delta n$ to ~ 2 ns whenever the passage of the bunch and the cooling pulse coincide. At the same time, the half period of oscillation T is unchanged (lower panel) indicating that there is no overall change in the velocity, but rather only a narrowing of its distribution. For delays Δt

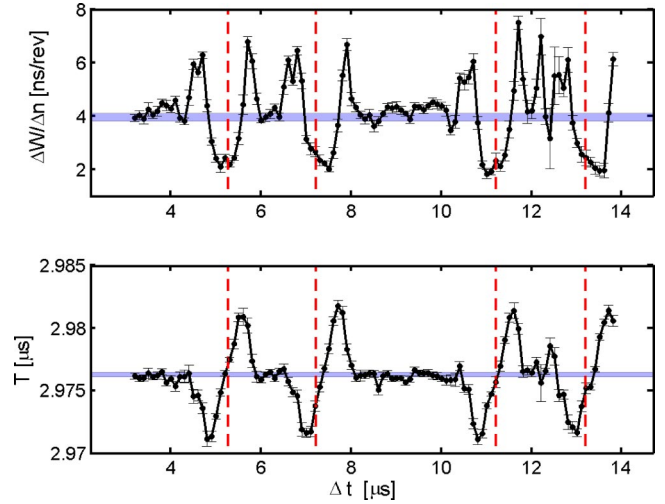


FIG. 6. Local slope $\Delta W/\Delta n$ of bunch width (upper panel) and the oscillation half period T (lower panel) as a function of the time delay Δt between the peak of the cooling pulse and the arrival of the center of the ion bunch at the center of the cooling region. The shaded regions correspond to the values of $\Delta W/\Delta n$ (upper panel) and T (lower panel) and their respective errors when the cooling pulse is not applied. The vertical lines correspond to the delays when the peak of the cooling pulse and the time at which the center of the bunch reaches the center of the cooling region coincide. Error bars show 68% confidence intervals.

which are shorter or longer, the oscillation time is seen to decrease or increase, respectively, indicating that the average velocity has been increased or decreased, respectively. The additional regions where T is left unchanged is when the bunch is completely outside the cooling electrodes when the cooling pulse is applied.

In order to compare directly the experimental results obtained in this section with the theoretical prediction developed in Sec. III [Eq. (13)], we assume the predicted value of $\gamma = 0.01\pm 0.0015 \mu\text{s}^{-1}$. The geometrical constant $\beta = 0.77$ is extracted by using SIMION [18] for the actual geometry of the cooling electrodes and fitting the numerical potential along the electrode axis using a linear function. The half-time it takes for a particle to pass through the cooling electrodes is calculated to be $\tau = 86$ ns. With these values, the predicted optimum value is $U_0 = -159\pm 25$ V, which is in very good agreement with the experimental value of -150 V (see Fig. 5).

Although the correlation slope at $n=28$ cannot be extracted directly from the data, its value for $n=90$ can be estimated and compared to the simulated value by using the asymptotic longitudinal energy spread, which is extracted from the data by fitting the noncooled data shown in Fig. 4 (as discussed above), which corresponds to a velocity width of $\sigma(v) = 0.022$ cm/ μs . Combined with the measured bunch size at $n=90$, $W_{90} = 0.3 \mu\text{s}$, we obtain

$$\gamma(n=90) \approx \frac{\sigma(v)}{\sigma(x)} \approx \frac{\sigma(v)}{\bar{v}W_{90}} = 0.0052 \mu\text{s}^{-1}, \quad (16)$$

a value which is slightly lower than the simulated value for

the correlation slope at half oscillation $n=90$, $\gamma \approx 0.006 \mu\text{s}^{-1}$ as shown in Fig. 3. The fact that the experimental and simulated correlation slopes are close to each other demonstrates that the dynamics of the ions in the trap is well understood, and can be faithfully represented by the numerical simulation including only 20 ions.

VI. CONCLUSIONS

In this work, we have demonstrated δ -kick cooling of ions trapped in the diffusion mode of the linear electrostatic trap. Both the shape and the height of the cooling pulse were chosen based on the results of the one-dimensional model presented. Although the correlation between ion velocity and position within the bunch was assumed to be near linear, the one-dimensional model can easily be extended to other types of correlation. The experimental results indicate that when the cooling pulse is timed correctly the diffusion of the ion bunch is reduced, while the average velocity and the number of ions in the bunch remain unchanged. These experimental facts taken together are a clear indication of the compression of the ions' velocity spread. We estimated that the cooling pulse reduces the asymptotic longitudinal energy spread of the ions by $\sim 20\%$ without ion loss, based on the rate at which the bunch spreads with and without application of the

cooling pulse. Although the resulting energy spread is still high (~ 10 eV), the reduction was achieved with a single pulse. Clearly, the energy spread just after the kick is much narrower, but since no measurement of the velocity spread could be performed at this particular time in the experiment, it is not known whether it is possible to achieve a velocity distribution narrower than the initial one (i.e., upon injection in the trap).

An important extension of this experiment is the development of a cooling cycle, based on multiple cooling pulses, which are applied successively to the bunch of ions. In such a case, a stronger reduction of the asymptotic energy distribution should be possible, allowing the storage of ions in the trap with a reduced energy spread. This might have important application in experiments such as merged laser-ion-beam spectroscopy in the trap, where the final spectral resolution is a function of the velocity spread of the ions.

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