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The use of high RFQ fields to manipulate ions

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Abstract

Recent tests of high dc and RF fields in helium at up to several tens of Pascals have shown that electric fields of tens of kilovolts can be used to manipulate ions under RFQ confinement in buffer gas. The theoretical and practical considerations of such confinement are considered and the results of a prototype linear RFQ ion trap designed for examining typical ion clouds under such confinement are presented. Operation at quadrupole field strengths of an order of magnitude greater than currently used is proven to be feasible. The ion temperature achieved is also of an order of magnitude greater than that in lower field devices but this higher temperature is believed to be due to distortions in the RF waveform from the purely simple harmonic rather than just due to the higher RF field.

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Keywords: RFQ confinement; High RF fields; Ion temperature

1. Introduction

Since its invention by Paul and Steinwedel in the early 1950s [1], ion confinement by radiofrequency quadrupole (RFQ) electric fields has become a widely used technique in the physical, biological and environmental sciences. The quadrupole electric field has two basic configurations; the azimuthally symmetric that provides confinement in all three-dimensions and the axiperiodic that provides only radial confinement leaving the axial motion unconstrained. These two fields are particular examples of the complete set that forms a solution to Laplace's equation, that set being

$$V = \sum_{l,m} a_{lm}\, \mathrm{e}^{im\phi} R^l P_l^m \cos\theta. \tag{1}$$

The azimuthally symmetric quadrupole field is the component with $l = 2$, $m = 0$, and is, ideally, produced by a ring electrode with two end electrodes that are infinite hyperboloids of revolution. In practice these are approximated by surfaces of finite extent that can be machined. The axiperiodic field is the component with $l = 2$, $m = 2$ and is, ideally, produced by infinitely long electrodes that are of infinite hyperbolic cross-section. In practice the electrodes are, of course, of finite length and the surface cross-sections approximate hyperbolas out to a finite radius.

The axiperiodic form is used as an ion guide, where ions drift along the axis. By operating the RFQ confinement in a mass-selective mode, this form becomes the familiar mass filter, most commonly used as a residual gas analyzer for vacuum systems but also widely used as a mass spectrometer in the chemical, biological and environmental sciences. The azimuthally symmetric form is used as a containment trap, now referred to as a "Paul trap" and is used in physics, as well as the other sciences. The basic principles of these devices, and their wide range of applications, can be found in many references, one of the best still being the 1976 textbook edited by Dawson [2].

Except for their use in metrology to confine single ions at very low temperature using side-band laser beam cooling, RFQ confinement is generally not done in a high vacuum. In fact in many applications a background gas of light molecular weight is deliberately introduced into the confinement region at typically 1–10 mPa to provide cooling of the ion motion. This is often necessary because of the coupling of the driven RF motion and the incoherent simple harmonic motions of the confined ions. This coupling results in heating of the incoherent motion, with subsequent expansion of the ion collection, a process usually

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referred to as “RF heating”.

A more recent development is the so-called “linear RFQ trap” which is essentially an ion guide with axial confinement in a dc axial potential well. This has become a very attractive means of collecting ions, particularly from an ion guide, because of the ease of extraction of the ions for delivery to other apparatus. An example of its use is the ISOLTRAP facility at ISOLDE at CERN [3]. Another example is as a collection device for delivery of ions to a time-of-flight mass spectrometer in biomolecular research [4].

To now, the electric fields used for RFQ confinement have been typically of the order of 10 V/mm^2, with radiofrequencies of the order of 1 MHz, resulting in typical ion containment at simple harmonic oscillation frequencies of the order of 100 kHz. Such fields can be easily engineered and have resulted in the wide variety of applications already mentioned. However, there would be many advantages from using much higher electric fields. These advantages are a result of the much tighter confinement provided by such fields, and hence the much higher ion density of the collection. This can be used to reduce the phase space volume of the collection, allowing more precise manipulation of the ions, or to increase the total number of collected ions within a given volume. In particular, it could be used in ion guides to produce cooled beams [5], where the emittance of the extracted beam and the intensity of the beam that can be cooled are very important considerations.

Recent results from our work have shown that high electric fields are indeed possible in small structures; up to 40 kV across electrode gaps of 0.15 mm [6]. Furthermore, these fields can be maintained in helium at pressures up to several 10s of Pascals. This paper gives the reasons for high RFQ confinement and presents recent results from a test of the use of high-field confinement in a small linear RFQ trap. It also presents some possible extrapolations of these results to working systems, with some of the considerations that must be taken into account in designing such systems.

2. The basic principles of RFQ confinement

The basic principle of RFQ confinement is given as a full mathematical development in Ref. [2]. What will be given here is a simple description of the motion under such confinement in practical devices such as ion traps and ion guides. Simple consideration of the dynamics of a driven oscillation shows that any oscillatory electric field that has a gradient will, over a full cycle of the oscillation, give a net impulse to a charged particle in the direction in which the field is weaker. This impulse is proportional to the amplitude of the electric field oscillation and if the electric field is a quadrupole the result will be an impulse on the ion that is toward the quadrupole center and that is proportional to the distance from that center. The result, providing the impulse is not too great, is simple harmonic motion (SHM) of the ion about the quadrupole center. An example of such SHM, with the superimposed RF motion that caused it, is shown in Fig. 1.

The simple harmonic frequency is related to the RF driving frequency through the dimensionless Mathieu parameter q commonly used to describe such parametric oscillations. For values of q up to 0.3 the angular frequency of the simple harmonic motion is related to the angular frequency of the driven oscillation, to within 1%, as

$$\omega_{\mathrm{SHM}} = \frac{q}{2\sqrt{2}}\omega_{\mathrm{RF}}, \tag{2}$$

where q is defined for an ion of charge e and mass m in a quadrupole field of strength $\partial E/\partial x$:

$$q = 2\frac{e}{m\omega_{\mathrm{RF}}^2}\frac{\partial E}{\partial x}. \tag{3}$$

The relative amplitude of the driven oscillation, at its peak, and the amplitude of the simple harmonic motion, again to within 1% for values of q up to 0.3, is

$$\frac{A_{\mathrm{RF}}}{A_{\mathrm{SHM}}} = \frac{q}{2}. \tag{4}$$

For the motion shown in Fig. 1, q is 0.3. Because of the increasing distortion of the simple harmonic motion by the RF motion at high q, the use of RFQ confinement for beam guides or simple ion containment in traps is usually restricted to q of this value or less, although, in principle, RFQ confinement is stable up to values of q of 0.91.

For a collection of ions, the motions under RFQ confinement are best displayed in displacement–momentum, i.e., “action”, diagrams for a particular coordinate of the motions. For collections of identical ions undergoing simple harmonic motion all in the same environment, and hence of the same frequency, these diagrams are particularly simple; right ellipses with the displacement extreme being simply the amplitude of the motion and the momentum extreme being that amplitude times the ion mass and angular velocity of the oscillation. The full diagram for the collection is then contained within the ellipse of the most energetic ion of the collection (Fig. 2).

At thermal equilibrium a collection of ions all undergoing simple harmonic motion at the same frequency in a particular degree of freedom will fill the action diagram of that degree of freedom in a Gaussian density distribution in both the displacement and the momentum coordinates. The standard deviation parameters for these coordinates will have the form:

$$\sigma_x = \frac{1}{\omega_{\mathrm{SHM}}}\sqrt{\frac{kT}{m}}; \qquad \sigma_{p_x} = \sqrt{mkT}. \tag{5}$$

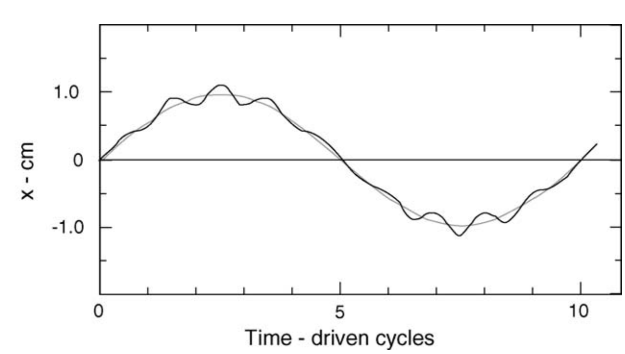

Fig. 1. Typical motion of an ion under RFQ confinement.

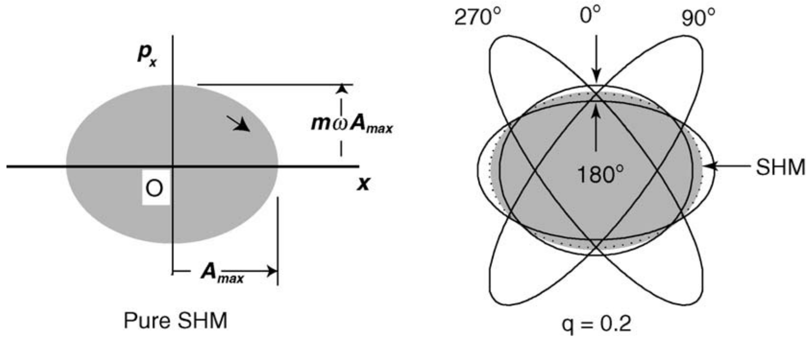

Fig. 2. Action diagrams for ions under RFQ confinement. The figure on the left is for a collection of ions undergoing pure simple harmonic motion, all at the same frequency but at random phases and amplitudes up to $A_{\max}$. The figure on the right shows the perimeters of the diagrams for the full motions, including the driven oscillations, at representative RF phases. (Zero phase is taken to be when the electric field is zero.)

For such a distribution about 95% of the collection will be within an ellipse that extends out to $\sqrt{6}\sigma$. This ellipse is therefore a useful measure of the action area of the collection in a particular degree of freedom. That action area is

$$S_x = 6\pi \frac{kT}{\omega_{\mathrm{SHM}}}. \tag{6}$$

For ions under RFQ confinement the cross-section of the beam and the effective action area will be considerably greater than that of pure SHM. This is because of the RF distortion of the action diagram, as shown in Fig. 2. This distortion, which follows the RF cycle, results in the cross-section of an ion beam at thermal equilibrium under RFQ confinement being expanded over that for pure transverse simple harmonic confinement by the factor $(1 + q/2)$.

Also, while the RF distortion preserves the area of the action ellipse, the rapid variation of the actual shape of the ellipse elongation increases the effective action area, at $q = 0.3$ by as much as a factor of 2.

Furthermore, before thermodynamic equilibrium is achieved, the ions will not fill the simple harmonic action diagram uniformly. Thus, there is an additional variation in beam cross-section due to the movement of the ions within the SHM ellipse. The result for an arbitrarily injected ion beam can then be quite a dramatic variation in the beam profile. A representative pattern for an RFQ parameter q of 0.32 is shown in Fig. 3.

The radial distance of the electrodes from the central axis of an axiperiodic confinement system will therefore have to be considerable greater than the amplitude of the SHM of the confinement.

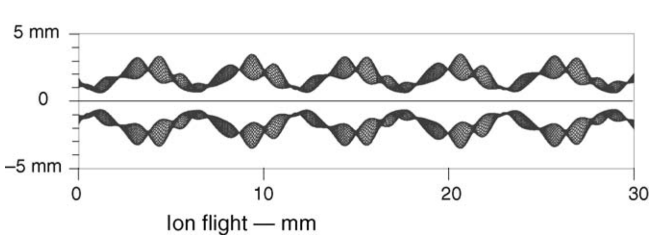

Fig. 3. A typical ion beam profile for axiperiodic RFQ confinement when the ions are not in thermal equilibrium. The parameter q for this confinement is 0.32.

3. The effects of high RFQ confinement

3.1. Emittance considerations

If an ion collection is rendered into a beam where the x coordinate is transverse to the beam, then the beam emittance is the action area of the collection divided by the particle momentum to which the beam is accelerated. For a given ion temperature and beam energy, the resulting emittance will then be inversely proportional to the angular frequency of the simple harmonic motion of the RFQ confinement.

Similarly, the longitudinal emittance of an extracted beam pulse, assuming distortion free extraction, will be simply the action area of the collection. The longitudinal emittance of a beam is important in many applications, such as collinear laser optical spectrometry and time-of-flight (TOF) mass spectrometry. In the case of TOF mass spectrometry it determines the resolution R that can be achieved through the relationship

$$R = s\left(\frac{2}{mE}\right)^{1/2} \frac{\Delta E}{S_z}, \tag{7}$$

where s is the length of the flight path of an ion of mass m at energy E in a collection with an energy spread of ΔE and longitudinal emittance S_z. In practical TOF mass spectrometry the energy spread is achieved by suddenly applying a high axial field to the ion collection to extract it into the flight tube. The energy spread is then this electric field multiplied by the axial extent of the collection. This energy spread is usually limited by the capabilities of the system to focus the ion collection onto the TOF detector and is typically about 100 eV.

Thus, increasing the angular frequency of the simple harmonic oscillation by increasing the strength of the electric field gradients results in smaller phase space of the ion collection and hence improved performance of any instrument analyzing the collection.

3.2. Space–charge considerations

The basic limitation on the number of ions that can be confined by an RFQ field is that of space–charge repulsion. In the manner first introduced by Dehmelt [7] for Paul traps, this effect can be approximated by assuming the ion collection to be of uniform density. (This is assuming that thermal motions are insignificant.) In the case of an ion guide for a beam such a collection would form a cylinder, the radial field at the surface of which would be

$$E_{\mathrm{r}} = \frac{1}{2\pi\epsilon_0}\frac{Q'}{r}, \tag{8}$$

where Q' is the charge per unit length of the cylinder, r the radius of the cylinder and ϵ_0 is the permittivity of free space. If the charge is confined to this radius by a field that is proportional to the distance from the axis:

$$E_{\text{confining}} = -kr, \tag{9}$$

and the linear charge density is

$$Q' = 2\pi\epsilon_0 k r^2. \tag{10}$$

The volume charge density Q is therefore uniform at

$$Q = 2\pi\epsilon_0 k, \tag{11}$$

verifying the a priori assumption that it was.

The RFQ confinement of a beam of charged particles of mass m and individual charge e is equivalent to a radial electric field of

$$E_{\text{RFQ confinement}} = -\frac{m}{e}\omega_{\text{SHM}}^2 r. \tag{12}$$

The density of the confined charge is then

$$Q = 2\epsilon_0\frac{m}{e}\omega_{\text{SHM}}^2. \tag{13}$$

This shows the extreme importance of the angular frequency of the simple harmonic motion of the RFQ confinement in achieving as high a density of confinement as possible.

3.3. Possible detrimental effects

One of the greatest concerns regarding high-field RFQ confinement is possible heating of the ion motion due to the high RF fields. To first order, in the ideal case there should be no more heating than for low fields. This is because, for a given energy of a confined ion the amplitude of its SHM will be inversely proportional to its oscillating frequency. For a given Mathieu parameter q this frequency will be proportional to the RF. According to (3), to keep q the same for strong field confinement the RF field must increase as the square of its frequency. Yet, since this field is proportional to the square of the distance of the ion from the quadrupole center, the maximum RF field experienced by the ion is the same for both high-field and low-field confinement.

In the real world of non-ideal geometries there will be electrode and potential asymmetries that will cause the quadrupole center to not be at the geometrical center of the structure. (There may be a dipole component to the field.) This is not of concern if the electric field is a quadrupole of one frequency since, like a mass hung by on a vertical spring, the ion would still find a region of zero field about which to oscillate. However, a harmonic of the RF that does not have the same symmetry on the electrodes as the fundamental, due to different harmonic components on different electrodes, would produce an oscillating dipole component at the center of particle oscillation in the fundamental quadrupole field. This would heat the ion motion. When it is considered that the RF potentials on the electrodes can be 10s of thousands times as great as the kinetic energy of the ion motions, eliminating such harmonics and asymmetries is seen to be a top priority in designing high-field RFQ confinement devices.

Another concern with high-field RFQ confinement in axiperiodic structures as beam manipulation devices is the fringing fields at the entrance and exit of the confinement. This field induces an axial energy change in the particle that depends on the distance of the ion from the axis and on its azimuth. Also, since the field is an RF field, that energy change depends on the phase of the RF as the ion passes through it. This can introduce a severe axial energy spread, and hence increase the longitudinal emittance of ions that have to pass through it.

An estimate of the magnitude of this effect can be obtained by considering the principal multipole of the field that is associated with it. Of the multipole set in (1) this is the multipole with $m = 2, l = 3$. Expanding the Legendre polynomial of this multipole gives

$$V_{32} = 15a_{32}\,\mathrm{e}^{2i\phi}zr^2. \tag{14}$$

Taking the maximum of this function (at $\phi = 0$) the coefficient a_{32} is given by

$$a_{32} = -\frac{1}{30}\left|\frac{\partial^2 E_{\mathrm{r}}}{\partial z\partial r}\right|_{r=0}; \qquad E_{\mathrm{r}} = -\left|\frac{\partial V_{32}}{\partial r}\right|_{r=0}, \tag{15}$$

whereupon the axial component of the multipole can be obtained from

$$E_z = -\frac{\partial V_{32}}{\partial z} = -15a_{32}r^2 = \frac{1}{2}r^2\left|\frac{\partial^2 E_{\mathrm{r}}}{\partial z\partial r}\right|_{r=0}. \tag{16}$$

To minimize the effect of this multipole the distance of the ion from the axis and the double derivative of the radial electric field must both be made as small as possible. At the entrance to a beam cooler this can be done by focusing the incoming beam so as to be as close to the axis as possible in this region. At the exit not much can be done in this regard but it is hoped that the beam will be small at the exit due to cooling. Also, the field derivative at the entrance and exit can be reduced by tapering the separation of the electrodes.

In any case, the effect has to be estimated by accurate numerical simulations before any particular design is approved.

4. Practical implications of high RFQ fields

4.1. General considerations

One of the most easily understood requirements for achieving high electric fields on the surfaces of electrodes is that the surfaces be smooth and highly polished of materials with high work-function. This is to inhibit the release of micro-protrusions that can lead to electrical breakdown. Stainless steel and copper are the preferred materials, where stainless steel has the advantage of structural rigidity. Electro-polishing is preferable but successive buffing with higher and higher grade abrasives, ending with optical rouge, can be used.

Care should also be taken in the design of insulating support structures. Although very high electric fields are possible in a vacuum, or even in a buffer gas such as helium at up to several tens of Pascals, electric insulators cannot stand electrical fields of more than about a 1000 V/mm along their surfaces, and even then only when they are very clean. This must be taken into account when designing insulating electrode support structures. Also, electric insulators should be of hard material devoid of any minute surface cracks that can produce local electric field discontinuities. Because of the difference in the electrical permittivity of an insulator and a vacuum, electric fields will tend to build up at such cracks and could lead to destruction of the insulator.

Finally, when designing for high RF fields attention must be given to shielding sensitive components of the apparatus from the fields. Also, the effects of inter-electrode capacitances should be considered when estimating the RF potentials that will appear on electrodes.

4.2. RF power requirements: resonant circuits

Except for systems with enormous RF power, high RF fields are only feasible using resonant circuits. For frequencies up to several tens of MHz air-cored inductors can be used in parallel with the inter-electrode capacitance of the quadrupole electrodes. Tuning of the resonant circuit to the desired frequency can then be achieved by paralleling the quadrupole electrodes with a high-voltage vacuum capacitor. This is the system used by Ghalambor Dezfuli et al. [8] to power a very large Paul trap to 10 kV amplitude on the ring electrode relative to the end electrodes at ground. The inductance of the resonant coil was 250 μH, which was resonated at 1 MHz with a vacuum capacitor of 20 pF in parallel with the inter-electrode capacitance of 80 pF. The quality factor Q of the resonant circuit was about 100.

For an axiperiodic quadrupole, such as that of the work of Gianfrancesco [6], the inductor is halved with each side powering adjacent electrodes in antiphase (Fig. 4). The individual inductors in that work were 60 μH and the tuning capacitors allowed resonance from 4 to 7 MHz. Again the quality factor was about 100.

For higher frequencies a coaxial quarter-wave resonator becomes feasible. This has the advantage of being a closed system that radiates no RF power and thereby having a much higher Q than an air-cored inductor. Such a resonator was developed by Jefferts et al., at NIST for a miniature trap for a single ion [9]. The resonant frequency was 250 MHz and the quality factor was of the order of 2000. For axiperiodic quadrupole confinement the resonating system would be a half-wave resonator with the RF power fed into the system at the voltage node.

4.3. Superposition of RF and dc on electrodes

When an axiperiodic RFQ field is used as an ion guide, or as a linear RFQ trap, it is necessary to superimpose relatively modest dc potentials onto the RF applied to the electrodes. With resonant circuits this can be done by feeding the dc potentials through insulated leads threaded through the interior of the conductor leading to the high end of the resonating circuit. In the case of the resonator based on an air-cored inductor, the coil would be made from a tube and the dc wires threaded through the tube. In the case of quarter or a half-wave coaxial resonator the wires would be the threaded through the inner conductor. In this scheme the dc wires are attached directly to the electrodes while the RF is shunted to the electrodes through series capacitors (Fig. 5).

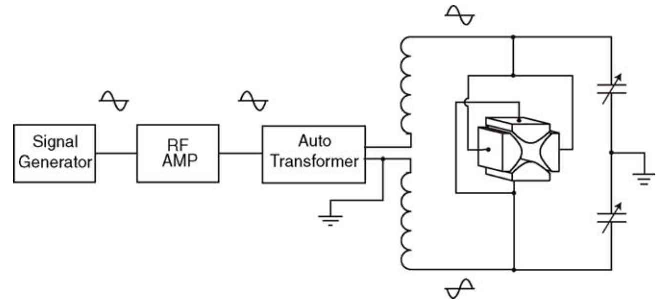

Fig. 4. A resonating system for powering an axiperiodic quadrupole confinement system using an air-cored inductor and a tuning capacitor. The autotransformer can be based on a ferrite ring. The amplitudes of the RF on adjacent electrodes are balanced and put into antiphase by adjusting the vacuum capacitors that parallel the electrodes to ground.

4.4. Injection decelerator requirements

As pointed out in Section 3.3, the decelerator delivering a beam to an RFQ beam cooler must be capable of accurate focusing of the beam onto the entrance region of the confinement. Also, it should do this with as few aberrations as possible, since these will increase the size of the beam at the focus.

The decelerating field with the least aberration is a static azimuthally symmetric quadrupole. Such a field can be produced by the electrode configuration shown in Fig. 6.

The radial electric field of this configuration is

$$E_{\mathrm{r}} = -\frac{\phi_0}{z_0^2} r. \tag{17}$$

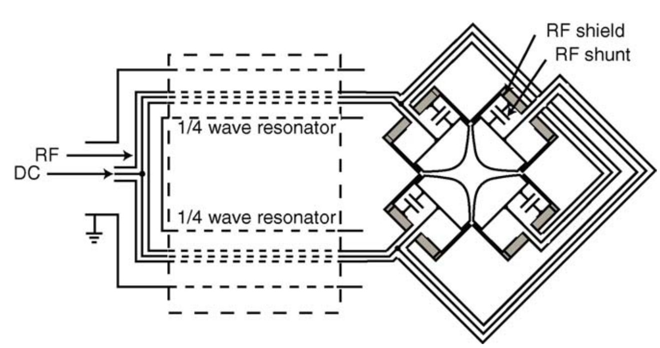

Fig. 5. Feeding the dc and the RF to an axiperiodic quadrupole electrode set. The capacitors should be several hundred times greater than the capacitance of the electrodes to ground. They then only have to withstand a small fraction of the full RF potential, the principle concern being that they withstand the dc potential.

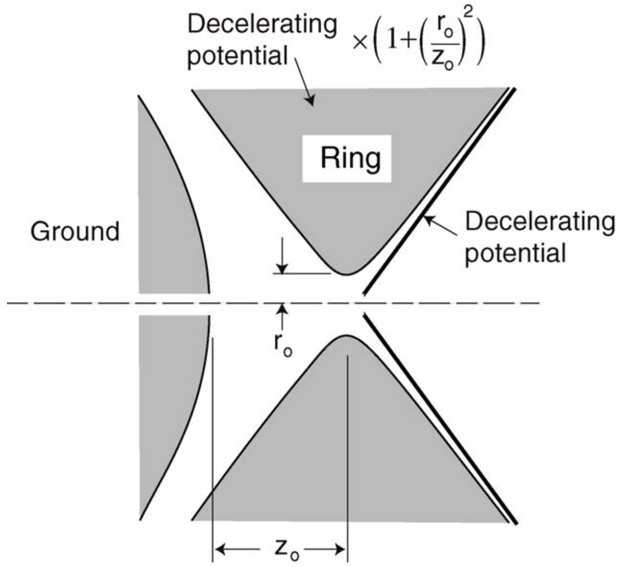

Fig. 6. The electrode geometry of an axially symmetric static quadrupole used as an ion decelerator. The ring electrode is the principle electrode creating the decelerating field. The far right electrode has a conical surface, with a hole just large enough to admit the ions into its interior.

Any ion in the beam therefore oscillates about the beam axis in SHM at angular frequency

$$\omega = \frac{1}{z_0}\sqrt{\frac{e\phi_0}{m}}. \tag{18}$$

If then all the ions in the beam fill an action ellipse of displacement semi-axis Δx and momentum semi-axis $m\,\omega\,\Delta x$ then this action ellipse will be preserved throughout the deceleration. The diameter of the beam will then be simply $2\,\Delta x$ throughout the deceleration. This situation can be achieved by focusing an incoming beam of emittance ξ to a diameter d at the decelerator entrance of

$$d = 2\sqrt{\frac{\xi p_0}{\pi m\omega}}. \tag{19}$$

Injection into the RFQ capture region should be most efficient when the action diagram of the decelerated beam is similar to that of the RFQ confinement. This means that the angular frequency of the SHM during the deceleration must be similar to that of the SHM of the RFQ confinement. This sets the parameter z_0 to

$$z_0 = \frac{1}{\omega_{\mathrm{SHM}_{\mathrm{Quad}}}}\sqrt{\frac{e\phi_0}{m}}. \tag{20}$$

For a representative case of the angular frequency of the RFQ confinement being 10 rad/μs and an incoming beam of ions of 100 amu at 60 keV, z_0 would be about 25 mm. To match the decelerator requirements a 60 keV beam of emittance 50π mm mrad would be focused to a diameter of about 3 mm at the decelerator entrance. The divergence (full width) of such a beam entering this focus would be about 35 mrad, which should be achievable with a small strong einzel lens at the final stage of the focusing process.

Of course, these parameters for the decelerator would be only the first to be tried in a series of successive approximations to a final design. Of particular concern would be the actual behavior of the ions as they enter the region of the extraction orifice leading to the RFQ confinement region, and how they subsequently behave as they enter the confinement region. Indeed, additional focusing electrodes may have to be placed just after the orifice in order to achieve satisfactory performance.

A prototype static quadrupole decelerator has been built and tested at McGill [10]. The z_0 of this decelerator is 50 mm and the geometry has been designed for decelerations from 60 keV. That is to say, the electrode structure was designed to withstand decelerating potentials up to 60 kV. However, the deceleration of a 60 keV ion beam could not be observed due to ions and free electrons produced in the background gas during the deceleration, even at background pressures as low as 0.1 mPa. (In operation with a beam cooler these charges are of no consequence since they are excluded from the RFQ confinement region.) The highest energy at which cesium ions could be decelerated without severe background currents was 12 keV. Such ions could be decelerated with 100% efficiency to about 20 eV. Assuming the linear approximation outlined above to be valid this would correspond to a deceleration from 60 keV down to about 100 eV.

The entrance and exit orifices of this decelerator cause deviations from a pure quadrupole field. The deviations at the entrance are of little consequence because of the high particle momentum in this region. The deviations at the exit are very weak electric fields that can be easily be corrected by separate annular electrodes following the extraction orifice. In any case, accurate simulations of the ion trajectories in this region must be carried out before a particular decelerator design is adopted.

5. Prototype test system

The major concern about high-field RFQ ion confinement is the temperature of the collection. In principle, the extent of an ion collection in thermal equilibrium will be inversely proportional to the quadrupole strength. Since, for a given quadrupole strength, the electric field on the ion is proportional to the square of its distance from the confinement center, and the velocity of its RF motion is proportional to this field, the energy of its RF motion will be independent of the quadrupole strength. Since it is the RF motion that heats the macromotion of the ion, the temperature of that motion should be independent of the quadrupole strength.

However, in a real system there will be imperfections, such as the axis along which the oscillating field is zero not being the geometrical center of the quadruple. Such a situation comes about, even for pure quadrupole geometry, when the potentials on adjacent electrodes are not balanced about zero. Even when the fundamental RF frequency is balanced, an oscillating electric field can occur if harmonics of that frequency are not. Indeed, with kilovolts of oscillating electric potentials only a few millimeters from an ion collection it would be surprising if ion collections reached sub-electron volt thermal energies.

We therefore undertook a research project to determine the equilibrium temperature of an ion collection under a typical RFQ confinement that involved several thousands of kV of RF. (For a full description of this work see Ref. [11]). The type of con-

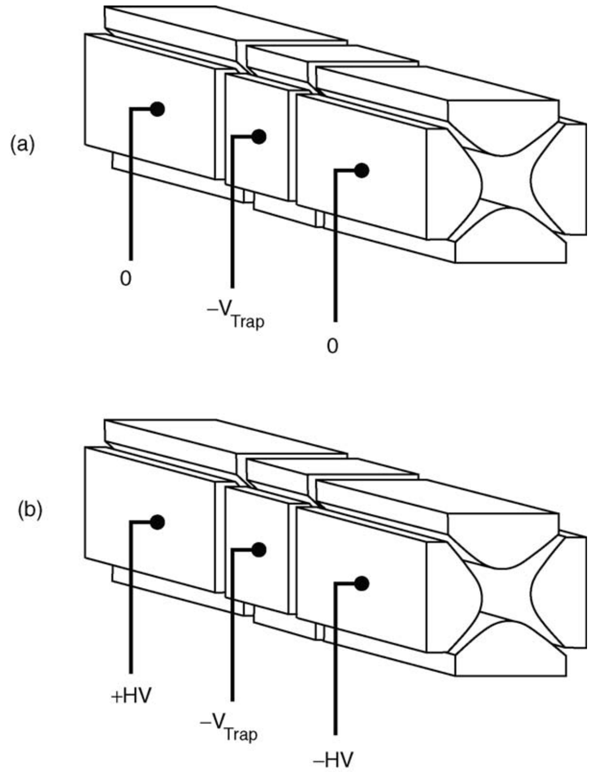

Fig. 7. The linear trap used to test high-field RFQ ion confinement. The RF is applied as shown in Fig. 5. The connections shown in the figures are for the dc and go to all four of the electrodes of each set. The dc potentials for ion collection are as shown in (a). The potentials for emptying the trap so as to observe the collection are shown in (b).

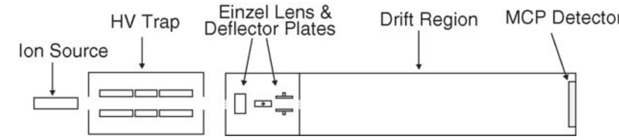

Fig. 8. The time-of-flight system used for studying the ion collection in a high-field linear RFQ trap.

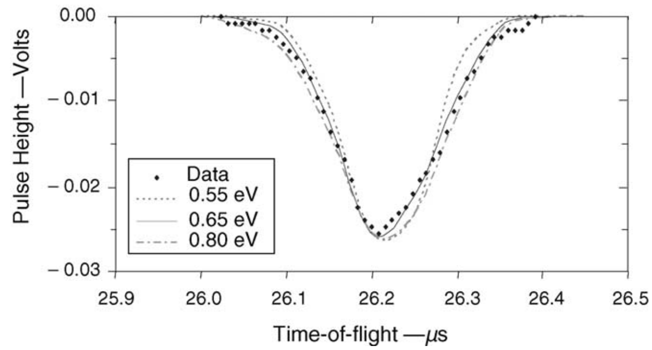

Fig. 9. A typical observed time-of-flight signal (data points) compared to that of simulations at three specific temperatures; 0.65 eV that provided the best fit, and 0.55 and 0.8 eV that bracketed that temperature.

finement chosen was a linear RFQ trap made of three segments. A sketch of this trap is shown in Fig. 7. The electrodes were of hyperbolic cross-section of $r_0 = 3.125$ mm (7.25 mm between opposite electrodes). The hyperbolas extended out to where their separation was 1 mm. The length of the center segment was 10 mm while the lengths of the end segments were 20 mm. The axial separation of the segments was 1 mm.

The ion selected for testing was cesium. Helium was used as a buffer gas, at a pressure of 1 mPa. The operating frequency was 7.5 MHz, at amplitudes between adjacent electrodes of 2000–4000 V. The resulting Mathieu parameter q therefore varied from 0.135 to 0.27. The applied axial trapping potential V_{Trap} varied from 10 to 100 V. The shielding of the end electrodes reduced this potential at the ion collection by about 5%.

The temperature of the ion collection was deduced by suddenly extracting it at a selected RF phase and directing it into a time-of-flight spectrometer. This follows the method pioneered by Lunney [12] for the study of ion collections in a Paul trap and further developed by Van Fong [13] to study ion collections in a low-field linear RFQ trap. The extraction potential HV used for this work, applied anti-symmetrically to the end segments, was 600 V.

The complete system used to obtain the time-of-flight spectrum is shown schematically in Fig. 8. The ions were loaded into the trap by simply placing a source on-axis at 3 mm from the entrance of the end electrode segment on the opposite side from the extraction. The time-of-flight system included deflection elements and an einzel lens for directing the ions onto a channel plate detector.

As in Ref. [13], the ion temperature was extracted from the observed time-of-flight spectrum by simulating the phase space distribution of the ions in the trap as a random distribution of a number of ions at a specific temperature and then numerically simulating the flight of the individual ions to the detector. Summing the signals gave a simulated signal for the collection. The temperature of the simulation was then adjusted until the simulated signal matched the observed. A typical result is shown in Fig. 9.

6. Results

Temperature measurements were taken for a wide range of trap operating parameters. The lowest temperature that could be obtained with the first power supply to be used was of the order of 1 eV. However, due to its unstable operation this was substituted by a more stable supply where, for small numbers of ions, temperatures as low as 0.5 eV could be achieved. The temperatures for increased ion loadings are shown in Fig. 10. The apparently linear relationship, with a base temperature for very low numbers, is in keeping with the work of Van Fong [13]. Because of difficulties in determining ion transport and detector efficiency the relationship between the ion count and the number of ions in the trap could not be accurately established but is believed to be between 5% and 15%.

The base temperature for low numbers of ions in the trap is about 10 times that observed for ions in the previous works at low RFQ fields [11–13]. Since the field for the data in Fig. 10 was of the order of 10 times that of the previous works, data was taken at higher RF fields, at the same frequency, in an attempt

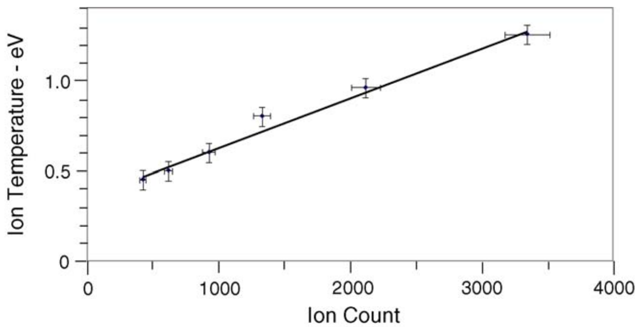

Fig. 10. The ion temperature at various trap loadings at 2400 V RF amplitude between adjacent electrodes. The ion count is believed to be from about 5% to 15% of the number of ions in the trap. The trend line is a linear fit to the data.

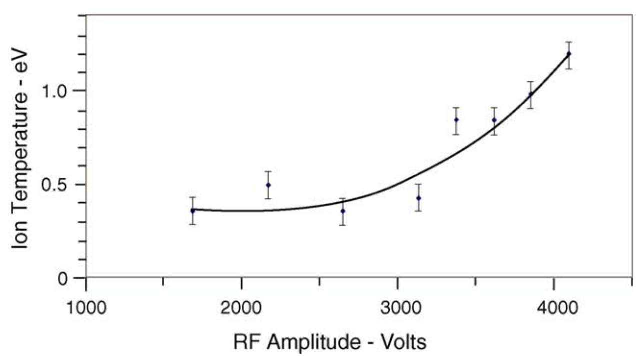

Fig. 11. The lowest ion temperatures that could be obtained at various values of the RF amplitude between adjacent trap electrodes. The trend line is a polynomial fit to the data.

to establish the relationship between temperature and RF field. The results are shown in Fig. 11.

The data shown in Fig. 11 indicate that the ion temperature is not directly related to the quadrupole field itself but to possible higher-order imperfections. Deliberately unbalancing the RF potentials of adjacent electrodes by several percent had no observable effect on the ion temperatures, so it appears unlikely that misalignment of the electric quadrupole center with its geometrical center was the cause of the high temperature. The higher-order rise in temperature with RF amplitude could therefore be possibly due to unbalanced harmonics of the radiofrequency. Using a frequency analyzer to probe the RF appearing on the electrodes showed that at RF amplitudes from 1200 to 3000 V there were harmonics up to the ninth that were of the order of 1% of the fundamental. Between 3000 and 4000 V these harmonics increased, on the average, to about 2%.

These results, combined with the observation of higher ion temperatures with the unstable supply, indicate that the primary source of the RF heating in the high-field trap could be distortion of the applied RF from a purely sinusoidal waveform at the driving quadrupole frequency.

7. Conclusions

Ion confinement in buffer gas is feasible at RFQ fields that are at least an order of magnitude higher than used in present systems. Also, by using resonant RF systems it is feasible to superimpose dc potentials of several kilovolts on the high RF potentials of the electrodes. For efficient operation, and for as low an ion temperature as possible, the resonant circuit should have a high quality factor and the RF supply should be as purely sinusoidal as possible.

By using such high electric fields, high densities of ion confinement would be possible without undue heating of the ion collection. This would enable the collection and cooling of much higher intensity beams than is possible with present devices.

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