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Design and construction of a linear Paul trap for the study of crystalline beams

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Abstract

We comment on the paper ‘‘Design and fabrication of a linear Paul trap for the study space-charge-dominated beams’’ by Takai et al. (Nucl. Instr. and Meth. 532 (2004) 508) and describe a preceding experimental setup which shows many similarities.

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1. Introduction

In the early 1950s alternating gradient (AG) focusing [1,2] revolutionized accelerator design [3]. This principle relies upon the fact that it is possible to obtain confinement in both transverse dimensions of a charged particle beam by combining two magnetic quadrupoles of opposite polarity into a doublet. Analogous to geometric optics focusing–-defocusing or defocusing–focusing lens pairs can give rise to net focusing if the inter-lens distance is chosen correctly. The concept of using alternating quadrupole fields for confinement was extended to the electric quadrupole mass filter [4] and electric quadrupole traps (commonly referred to as Paul traps) [5]. While typically a sinusoidally time-varying drive is applied in the electric quadrupole case the choice of waveform is quite arbitrary as long as a stable solution to Hill's equation [6] can be obtained. Experimentally, this was realized at least three decades ago for a rectangularly time-varying quadrupole drive [7]. More recently, a number of authors have discussed the possibility of exploiting the analogy in the dynamics of

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charged particles in the spatially varying magnetic quadrupole field of accelerators or storage rings to that of an electric quadrupole trap excited by square voltage pulses [8–10]. [1] While this analogy is obvious and a subject of standard textbooks on charged particle beams [13] an experimental realization could constitute an attractive tool for studying certain problems in beams physics. In a recent paper in the present journal [14], Takai et al. reported on the design and fabrication of a linear Paul trap for the study of space-charged-dominated beams. While these authors do not fail in stating, restating and citing their contribution to this ''new experimental method'', we believe they overlook the important fact that experiments on ions in a pulse-excited linear Paul trap have been reported on previous occasions [15–19]. Notably, Refs. [15,17] are concerned with emulations of beams in the ultra strongly coupled regime of Coulomb crystallization. As this omission may significantly mislead readers, we describe in more detail the experimental setup in which the results of Refs. [15–20] were obtained. We do not repeat here the results of these experiments that have already been reported elsewhere. This description along with our previous papers states our case.

2. Construction of a linear Paul trap

To realize the experiments reported in Refs. [15–20], a linear Paul trap setup was constructed following the ideas outlined in Refs. [10,16]. In the following, we describe this experimental setup in details.

2.1. Trap geometry

Fig. 1(a) shows a photo of our Paul trap and Fig. 1(b) shows the cross-section of one of the quadrupole rods. The electrodes are made of gold-coated stainless steel and sectioned in three parts separated by macor spacers as shown in the Fig. 1(b). Each quadrupole rod has a diameter of 8 mm and the distance between diagonally opposite rods is 7 mm. The ratio between these two quantities approximates 1.147 which ensures that the transverse electric field from the cylindrical rods is close to that of a perfect quadrupole when a voltage is applied [21]. The center electrode length is 5.4 mm. This choice was based on the desire to achieve a good approximation to a harmonic axial potential when a voltage is applied to the end piece electrodes with respect to the center electrodes. In this way our trap setup can emulate bunches which are harmonically confined, a situation typically achievable in accelerators. In Ref. [14], Takai et al. have constructed a trap with a flat axial potential with the aim of simulating axially infinitely long beams (referred to as ''two-dimensional beams'' in Ref. [14]) in the space-charge-dominated regime. However, with increasing space charge the plasma will change its shape from cylindrical to dumbbell-like, which is not equivalent with an infinitely long beam.

2.2. UHV chamber

The trap is installed in a UHV chamber, where the ultrahigh vacuum is maintained by a titanium sublimation pump and an ion getter pump. Fig. 2 shows an overview of the chamber indicating the purposes to which the various flanges are dedicated. The following parts have be installed:

- The trap. Electrode voltages supplied by copper wires via a feedthrough in a flange.
- Two ovens, each consisting of a hollow graphite cylinder heated by a tungsten (resistive) wire wound as coil around the cylinder. The ovens contain Mg and Ca, respectively, and when heated (the temperatures are monitored with thermo-sensors) they provide atomic beams effusing in direction of the trap from small holes in the ovens. The ovens are mounted in hollow ceramics cylinders (providing electric and thermal isolation) inside stainless-steel housings.
- Oven shutter for blocking the atomic beams. The shutter consists of a metal plate on an rod. By turning an external knob the atomic beams can be blocked individually or simultaneously.

[1] In what appears to be decoupled from this discussion, non-sinusoidal voltage excitation has recently attracted interest within the mass spectrometry community [11,12]

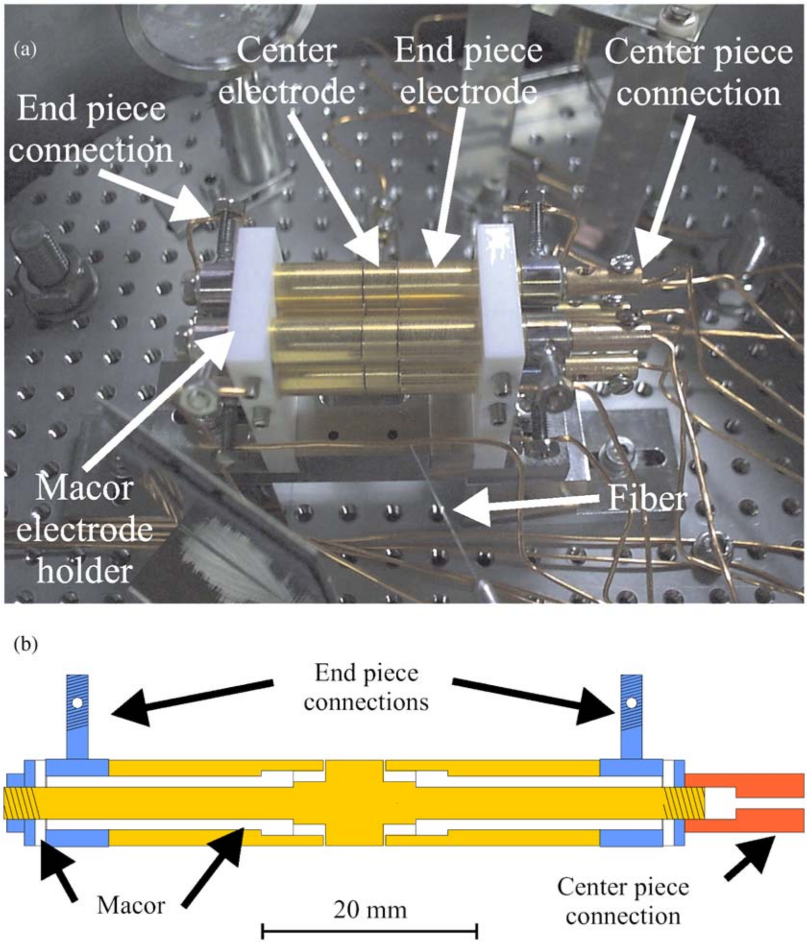

Fig. 1. (a) Close-up photo of the linear Paul trap installed in the UHV chamber. (b) Construction of a quadrupole rod (cross-section).

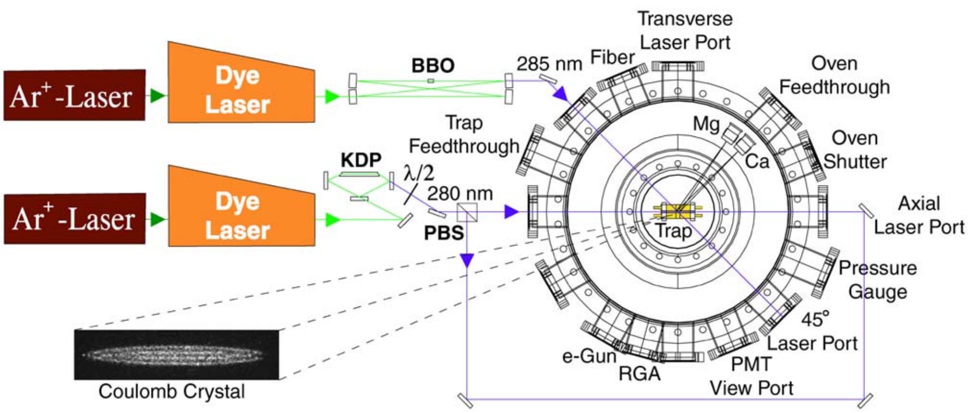

Fig. 2. Overview of the trap chamber and the laser systems employed for photo-ionization of ^{24}Mg and laser cooling of $^{24}Mg^+$.

- Skimmers for collimating the atomic beams. The skimmers are made of a thin stainless-steel plate with small holes.
- Fiber for calibration of camera magnification. The fiber ($\varnothing = 125\,\mu\text{m}$) is mounted on a stainless-steel arm and can be inserted to trap center by means of (xyz) translation stages.
- Laser ports (AR coated windows). The trap setup has bi-directional laser beam access to the trap center along the trap axis, perpendicular to the trap axis (radial direction), and at a 45° angle to the trap axis.
- Electron gun. A beam of electrons from an electron gun can be sent to the trap center to cause electron impact ionization of the atomic beams. Electron beam steering is achieved by a set of vertical and horizontal deflection plates. The electron beam position can be monitored on the surface of the skimmers (towards the trap) which has been coated with phosphor (i.e., impinging electrons give rise to phosphorescence).
- Rest gas analyzer (RGA).
- Pressure gauge.

Most of the parts listed above are identified in Fig. 3.

2.3. Trap voltage supply

Pulsed voltages may be applied (non-resonantly) to the quadrupole rods of the trap. The pulses are produced by a dual-channel pulse amplifier (constructed at the University of Aarhus) with inputs from two pulse generators (PHILIPS PM5715 1 Hz–50 MHz pulse generator) triggered at the desired repetition frequency by a function generator (Hewlett Packard 33120A 15 MHz function/arbitrary waveform generator). Each channel of our pulse amplifier is rated to a pulse amplitude of 200 V at $\omega_{\mathrm{RF}} = 2\pi \times 1\,\text{MHz}$ with a minimum pulse duration < 100 ns. Voltage pulses are applied alternately $\left(\begin{smallmatrix}\circledast & \odot \\ \odot & \circledast\end{smallmatrix} / \begin{smallmatrix}\odot & \circledast \\ \circledast & \odot\end{smallmatrix}\right)$ to the two pairs of diagonally opposite quadrupole rods. Fig. 4 shows examples of the resulting voltage difference between adjacent quadrupole rods.

DC offsets can be added to the trap electrodes via the interface shown in Fig. 5 (in total there are 12 of these—one for each trap electrode).

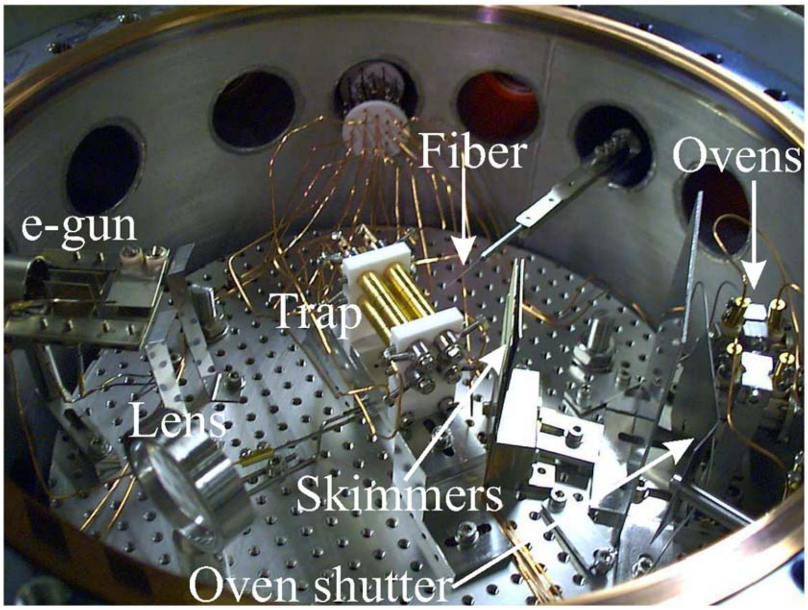

Fig. 3. Photo of the UHV chamber with the linear Paul trap installed and the top flange dismounted.

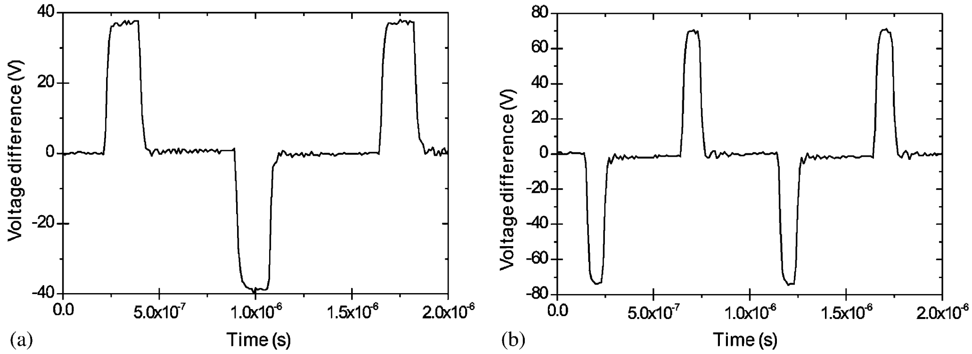

Fig. 4. Examples of measured time varying voltage differences between adjacent quadrupole rods when the dual channel pulse amplifier applies voltage pulses alternately to the two pairs of diagonally opposite quadrupole rods of Trap III. (a) $\omega_{RF} = 2\pi \times 700\,\mathrm{kHz}$ and pulse duration 200 ns. (b) $\omega_{RF} = 2\pi \times 1\,\mathrm{MHz}$ and pulse duration 100 ns.

2.4. Ion production, laser cooling, and detection

As shown in Figs. 2 and 3 our setup includes two ovens for production of atomic beams. The ovens contain solid Mg and Ca, respectively, and when heated neutral atoms effuse from the ovens in the direction of the trap. The beams are collimated by a pair of skimmers. At the trap center, the atoms can be ionized either by electrons from an electron gun or by ultraviolet laser light and the ions produced are captured by the trapping fields. Resonant photo-ionization works for both Mg and Ca [22] and is our preferred method since it offers isotope-selective loading of the trap.

During trapping the ions are laser cooled by two counter-propagating laser beams along the axis of the trap. Our beam emulation experiments [15,17] were conducted with $^{24}Mg^{+}$ ions for which light with a wavelength of 280 nm is needed to drive the $3s^2S_{1/2} \leftrightarrow 3s3p^2P_{3/2}$ cycling transition. The laser light for photo-ionization and cooling is produced by frequency doubling the output of tunable dye lasers using nonlinear crystals (BBO and KDP, respectively) inside optical resonators (see Fig. 2).

Due to the laser-induced fluorescence from the cooling process the ions can be imaged using an intensified digital camera. This provides a very powerful tool for investigating the trapping parameters for which stable Coulomb crystals can be achieved [15,17,18].

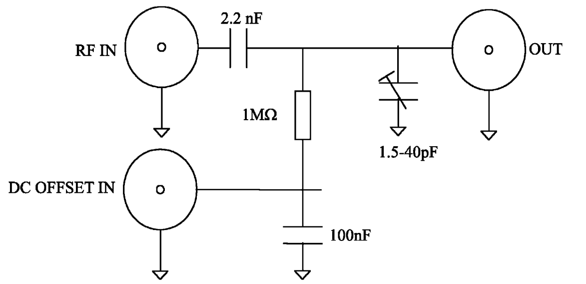

Fig. 5. Circuit diagram showing how a DC offset voltage (DC OFFSET IN) is added to a trap electrode connected to OUT.

3. Conclusion

We have described an experimental setup which has been employed to investigate the stability of Coulomb crystals in a trap with storage-ring-like transverse confinement. The setup shows many similarities to the one reported in Ref. [14] as a new experimental method.

Acknowledgements

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