Real-time trajectory control on a deterministic ion source

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The major challenge to improve deterministic single ion sources is to control the position and momentum of each ion. Based on the extra information given by the electron created in a photoionization process, the trajectory of the correlated ion can be controlled using a fast real time feedback system. In this paper, we report on a proof-of-principle experiment that demonstrates the performances of this feedback control with individual cesium ions. The produced electron is detected with a time and position sensitive detector, whose information are used to quickly infer the position of the corresponding ion. Then the feedback system drives the ion trajectory through steering plates. Individual ion can thus be send to any dedicated location. This enables us to perform deterministic patterning and reach a factor 1000 improvement in spot area. The single ion feedback control is versatile and can be applied to different kind of ion sources. It provides a powerful tool to optimize the ion beam and offers new area for quantum systems and applications of materials science.

The preparation and handling of individual particles is crucial for new technology development. Deterministic and high precision placement of individual atoms and ions offers new and exciting perspective for the realization of quantum based devices at the nanoscale [1, 2]. Several mechanisms for the manipulation of individual atoms and ions have been demonstrated [3–5], but they are usually slow and non-deterministic. Recently new type of ion sources have emerged: either based on cold trapped ions [6, 7] or cold trapped atoms that are subsequently photoionized [8]. From trapped ions, deterministic source and implantation of ions with 6 nm resolution has been demonstrated but the repetition rate and the beam energy range have still to be improved [7]. From ionization of cold atoms, very high current and high brightness beam can be produced but with a non deterministic property [9, 10]. Progress toward deterministic production of single ions has been made by exploiting the correlation between an electron and associated ion following photoionization of cold trapped rubidium atoms [11] or an atomic beam [12]. The electron herald the creation of a corresponding ion. As stressed in ref. [11, 12], the next step would be to extend the scheme beyond time-correlated feedback to have a position- and momentum-correlated feedback in order to provide a total control over each single ion in a beam. This would provide general and powerful tools to optimize the ion beam and would offer a complete new portfolio for quantum optics and applications of materials science.

This position correlated feedback is exactly the step that we demonstrate in this paper. We exploit the correlation between an electron and the associated ion created by photoionization of an atom. We use fast real-time feedback to modify the ion trajectory based on information gained by direct detection of the electron. We demonstrate an active correction of the ion trajectory that allows to send it to any desired final location independently of its initial position. This allows a full control of the final spot pattern with an improved accuracy comparing to the non corrected one. For instance a three order of magnitude reduction in spot area is demonstrated in a one-by-one ion driving experiment. This trajectory correction improves the phase space density, the brightness and the emittance of the ion beam. In the following, we first present the apparatus. We then study the correlation between electrons and ions. And finally, we present the results of the feedback correction allowing us to realize arbitrary ion patterning.

The setup is based on a double time-of-flight (TOF) spectrometer ended by time and position sensitive detectors (TPSD). The acquisition system handles the information from the detectors and processes the data. The feedback system controls the ion trajectory by acting on the deflection plates with the appropriate voltages for each ion (presented here in 1D, see text for more details).

![FIG. 1: Scheme of the experimental setup.](image-url)
two holed electrodes (4 mm hole diameter) separated by 10 mm. By using narrowband lasers for the photoionization, Doppler selection can be performed to reduce drastically the effect of the effusive atomic beam velocity dispersion. Ionization of Cs atoms is performed with a three-photon transition process where the first transition uses an horizontal laser beam counter-propagating to the atomic beam. It is ensured by a 852 nm laser beam which excites atoms from the 6S\(_{1/2}\) F = 4 level to the 6P\(_{3/2}\) F = 5 one. For Doppler compensation, this laser is locked by saturated absorption on a vapour cell and detuned by an acoustic optical modulator. The second transition is performed by a perpendicular 1470 nm laser beam coupling the excited 6P\(_{3/2}\) state to the 7S\(_{1/2}\) one. This laser is locked thanks to a Cs cell excited by the 852 nm laser. The last transition is assured by a tunable Ti:Sa laser, in the same plane but tilted 45° from the previous lasers. It excites the atoms from the 7S\(_{1/2}\) state to a Rydberg state or the ionization continuum depending on the chosen wavelength (770-795 nm). This geometry enables us to control the ionization volume at the crossing of the laser beams. These lasers are focused, inside the extraction zone, with a typical size of \(\sim 500 \mu\text{m}\). For the results presented here, ionization occurs in a 2200 V/cm field and the (vacuum) Ti:Sa laser wavelength is tuned to 794.432 nm. Fine adjustments were made to the Ti:Sa laser wavelength to optimize the detected electron and ion signals. We choose this wavelength because it results in an efficient excitation towards a Rydberg state that autoionizes, and produces an efficient source of ion and electron pairs. Upon ionization, electron and ion are accelerated by the 2200 V/cm static electric field in opposite directions towards the TPSD located 355 mm (for electrons) and 285 mm (for ions) from the ionization region. Typical TOF values are about 20 ns for the electrons and 7 \(\mu\text{s}\) for the ions. Outside the ionization region, along the ion trajectory, a set of horizontal and vertical deflection plates are dedicated to the ion trajectory correction.

To reveal the correlation between electron and ion and use it to infer the ion position, we need to determine the position and TOF of both particles. For this, we use two TPSD monitored in coincidence mode by an acquisition system that works independently of the fast feedback system (see Fig. 1). The electron TPSD is composed by a set of imaging quality microchannel plates (MCP) and a delay line detector (DLD). The DLD is based on capacitive coupling between a resistive anode, that collects the electron cloud arising from the MCP, and an encoding surface through a ceramic plate [13]. This detector has a position resolution of about 50 \(\mu\text{m}\). The two pairs of analog signals coming from X (horizontal) and Y (vertical) delay lines pass through homemade fast amplifiers and peak-detection discriminators (PDD [23]) that deliver short \((\sim 15 \text{ ns})\) logical signals. These signals end in a multi-channel time-to-digital converter (TDC-V4 [24]) with a resolution of 60 ps (rms). The ion TPSD is composed by a set of imaging quality microchannel plates (MCP), a phosphor screen and a CMOS Camera. It is based on correlation between brightness of the spot on the phosphor screen and amplitude of the time signal on the MCP [14]. This detector has a position resolution of about 50 \(\mu\text{m}\). The two time signals for ion and electron generated by the MCP are digitized by PDD and recorded by the TDC-V4. This enables us to measure the relative TOF of the detected ion and electron. The time and position signals delivered by the two TPSD are handled by a C++ monitoring home-made program that controls acquisition and stores the data. For each detected event, the acquisition program determines the position and relative TOF of the ion and electron. If this TOF fits in a given range (\(\sim 200 \text{ ns}\)) around the expected value, the pair is considered coming from a unique ionization event and is labeled coincident in time. This is a mandatory condition to get a electron/ion correlation. A low counting rate is set for the experiment to drastically reduce the probability of getting false coincidences.

The acquisition system is used to characterize the correlation between the two particles issued from the ionization. Figure 2 shows typical correlation between individual ion and electron arising from all the validate coincident events. The images of all electrons and ions detected in coincidence are shown in Figure 2(a) and (b) respectively for several thousand acquisition events. For each coincident event, the X (resp. Y) coordinate of the electron is plotted with respect to the X (resp. Y) coordinate of the corresponding ion on the correlation maps seen in Figure 2(c) (resp. d). These maps show two narrow correlation patterns on each coordinate. Hence, for each detected electron, and from the measurement of its position, we can deduce the position of the coincident ion. The correlation pattern must be injective and its width limits the precision of the ion inferred position. This width is mainly affected by non-zero electron emission energy, ion velocity spread, extracting field inhomogeneity and a variety of other minor factors such as fluctuation of the fields affecting the trajectories, resolution of the electron detector, ... The main factors are overcome respectively by threshold ionization, Doppler selection and spatially resolved Rydberg state excitation inside the ionization zone.

The fast determination of the detected electron position allows us to perform an active feedback control in real time for each ion trajectory. The feedback system gets X and Y coordinates of the electron from the DLD and process them to apply the correction by sending appropriate voltages onto the four deflection plates. In more details, a copy of the logical signals arising from the DLD are sent to a field-programmable gate array (FPGA) [15] [16] that manages the feedback calculation. Inside this integrated circuit, four TDC calculate the arrival time of each signal. The TDC are tapped delay line
FIG. 2: (a) and (b): raw images from the position sensitive detectors of electrons (Xe,Ye) and ions (Xi,Yi) respectively; (c) and (d): correlation patterns between respectively the horizontal and vertical coordinates of the coincident events. The position scales are shown on (a) for (Xe,Ye) and (b) for (Xi,Yi) and are the same for all the images presented in this paper.

FIG. 3: Raw images from the ion detector after: (a) 1D correction along X coordinate on a selected zone; (b): 2D correction on a selected zone; (c): 2D correction with non-selected ions carried out of the target. (d) projection on the X-axis of the ion position distribution without (solid red) and with (dashed blue) the 2D correction, the FWHM is reduced by a factor of 30 on each direction.

Figure 3 (a) represents the image of the detected ions after applying a 1D-correction on the X-axis. As we can see, the corrected ions are aligned along the Y-direction. Here a simple linear transfer function $G(\Delta t)$ is set along the X component so that each ion is carried onto a vertical line when it reaches the target detector. The slight curvature seen on the resulted structure is due to the non-linearity of the correlation patterns. Figure 3 (b) shows the image of the detected ions after applying a 2D-correction on the X and Y axis. As we can see, the corrected ions are sent to a very small spot on the target detector. This corresponds to a remarkable increase of the brightness of the ion beam. Note that in these experiments we have selected a 1D zone (Fig. 3(a)) or a 2D zone (Fig. 3(b)) in which we apply the correction. If the validated electron coordinate X or Y is inside the zone of interest, the steering voltages are set to the appropriate values to correct the ion trajectory. If outside, these voltages are set to zero so that the ion passes through without deviation. An interesting alternative is to push out this non-selected ion. Figure 3(c) shows an experimental result of this configuration, where we can see at the center of the image the corrected ions spot, and at the edges of this image the pushed ones. Here we did not push out the non-selected ions very far from the zone of interest in order to see them, but we can easily drive them far away from the detector target. This corresponds to add
a virtual diaphragm to the correction process. Figure 3 (d) shows the profile of the ion spots with and without correction. It demonstrates a reduction by a factor of 30 of the spot width. The same result is obtained on the other axis, which gives a three order of magnitude reduction in the spot area of the ions after correction.

By numerically simulating the correction, using the raw data from the acquisition system without correction, we obtain the same result which means that this reduction factor is more limited by the width of the correlation pattern than by the feedback system accuracy. The virtual diaphragm functionality is thus very useful for instance when the width of the correlation pattern is not uniform, we can select a zone with the thinnest width in which we apply the correction and remove the non-selected ions. This leads to an improvement of the correction quality.

Our feedback system is versatile and allows us to realize more complex processes. Figure 4 (a) shows a sample of complex pattern that can be produced, where the selected ions are carried on to three different spots as a function of the position of their correlated electrons. Here the selected zone was separated into a 2 × a function of the position of their correlated electrons. The same result is obtained on the other axis, which gives a three order of magnitude reduction in the spot area of the ions after correction. This proves the quality of the correction system. A virtual mask implemented into the FPGA.

FIG. 4: Raw images from the ion detector after: (a) application of a 2D correction in which the ions are carried on to three different spots at the target; (b): application of a virtual mask implemented into the FPGA.

In conclusion, by using the correlation between ion and electron, produced by photoionization of an atomic beam, we developed a fast feedback system to control the ion trajectory. Compared to previous Rb photoionization experiment [11, 12] we have added, to the deterministic character of the ion delivery, the control of its trajectory and complex patterning such as multi-spots and virtual diaphragm/mask. This feedback system can correct more complex effects such as finite source size, electrostatic or magnetic lenses aberrations, stray fields... In principle such system can be used in reverse mode to control the electron instead of the ion. This only requires a dedicated (acceleration-deceleration) geometry to ensure to detect the ion before the electron. This proof-of-principle experiment was performed with a mm scale ion source that were downsized to µm scale on the target at ≃ 1 kHz repetition rate. Coupled to appropriate setup, this feedback system may produce 10 MHz rate (1 pA) beam by reducing the ion TOF inside the steering plates and increasing the capacity of the detector to handle high rate counts. Numerous methods such as discreet anodes detectors, coherent excitation process and Rydberg dipole blockade can probably be used to increase even further the rate [13, 14]. Such source can probably produce sub-nm spots even quite low beam energy, with deterministic and complex patterning property, making them very useful for focused ion beam studies such as for nano-structuring, microscopy and surface spectroscopy [20, 21]. This can be used in future semiconductor fabrication or in quantum technology development for instance by structuring devices at an unprecedented precision [22]. Hence, this feedback method offers new opportunities for ion beam techniques such as aberration correction, high resolution imaging or accurate implantation.

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