A compact source for bunches of singly charged atomic ions

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We have built, operated, and characterized a compact ion source for low-energy bunches of singly charged atomic ions in a vacuum beam line. It is based on atomic evaporation from an electrically heated oven and ionization by electron impact from a heated filament inside a grid-based ionization volume. An adjacent electrode arrangement is used for ion extraction and focusing by applying positive high-voltage pulses to the grid. The method is particularly suited for experimental environments which require low electromagnetic noise. It has proven simple yet reliable and has been used to produce μs-bunches of up to 10^6 Mg^+ ions at a repetition rate of 1 Hz. We present the concept, setup and characterizing measurements. The instrument has been operated in the framework of the SpecTrap experiment at the HITRAP facility at GSI/FAIR to provide Mg^+ ions for sympathetic cooling of highly charged ions by laser-cooled $^{24}Mg^+$. © *2016 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4944946]

I. INTRODUCTION

Most sources of atomic ions operate in two subsequent steps, first to produce a vapor from the material in question, and then to ionize it. For both steps, a multitude of techniques has been realized. With some techniques, ions can be produced from a bulk directly (e.g., in laser plasma sources). With others, atomic vapors are produced by methods such as thermal vaporization, sputtering or spraying, and subsequent ionization is achieved by electron impact, laser- or field ionization.[1–3] Methods can be classified by the charge states they offer. A usual distinction is made between sources of singly charged (cat)ions, anions, and highly charged ions. For the latter, electron impact ionization, usually of a gas, is the most common technique as realized in electron beam ion sources[4] and radio-frequency sources such as electron cyclotron resonance ion sources.[5] Singly charged ions can be produced using comparatively much simpler and smaller devices. When ion output currents need not be large, and the use of plasmas, radio frequency excitation, high alternating voltage, or pulsed lasers can be omitted, devices may be operated in a purely electric low-level direct-current mode and may be small in overall size. Such sources are favorable in experiments that are sensitive, e.g., to magnetic stray fields, electromagnetic pulses, or radio-frequency noise, like many ion trap experiments which employ electronic detection of the ion motion. In this article, we describe a simple and reliable compact source for singly charged ions, where the atomic vapor is produced thermally in a small electrically heated oven, while ionization is done by electron impact from a filament. We present the setup and operation of the device as installed at the SpecTrap setup,[6] where it is used to provide $^{24}Mg^+$ ions for a Penning trap in which they are laser-cooled down to crystalline temperatures of mK to sympathetically cool highly charged ions in a later step.

II. ION SOURCE

A. Setup

The atomic vapor source ("oven") is a tube made of a tantalum foil placed between two shielding steel plates and filled with small grains of bulk material, presently magnesium containing all stable isotopes in natural abundances. The temperature necessary for efficient evaporation is produced by a direct current of several tens of amperes through the oven tube, in the present experiments usually 25 A at a voltage of about 1 V. The oven setup is capable of efficiently vaporizing alkali metals and alkaline earth metals and may be operated well above 2000 K. From the measured pressure close to the oven of order 10^{-8} mbar and the vapor pressure curve[7] of Mg, we estimate an oven temperature of around 600 K which is still below the atmospheric melting point of Mg of about 900 K. Such a temperature is sufficient to produce enough vapor for the ion numbers in view, while not unnecessarily deploying the evaporating material. The source has been operated for several hundreds of hours with one filling of Mg material. Another tube is mounted coaxially onto the tantalum tube to direct the vapor of neutral magnesium atoms to the ionization volume and prevent contamination of the vacuum system. The atomic beam is directed perpendicular to the axis of ion extraction and stopped by a beam dump beyond the ionization region. Hence it does not enter the beam line together with the ions. Figure 1 shows a schematic of the ion source arrangement. The atom vapor is ionized by electron impact ionization in the interior of a cylindrical grid of 38 mm length and 16 mm diameter. The electron current of a few milli-ampere for ionization is provided by filaments made of thoriated tungsten (99% W and 0.9%ThO_2, temper annealed) with a diameter of 0.15 mm which are placed around the grid. The electric configuration of the ion source is schematically shown in Figure 2. For filament heating, a continuous current of typically 6 A is sent

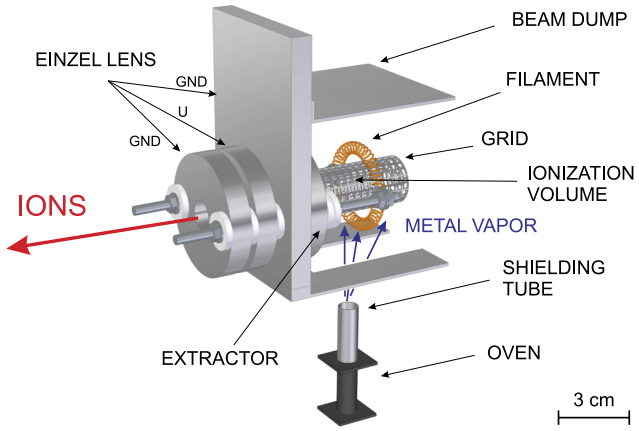

FIG. 1. Schematic of the ion source, true to scale. A current-heated oven produces neutral atomic vapor from small grains of Mg bulk material. A shielding tube directs the beam to the ionization volume inside a cylindrical grid, where the neutral atoms are ionized by electrons emitted from a heated filament. The atoms passing the grid without ionization are stopped by a beam dump to prevent the vacuum system from contamination. When the grid electrode is set to a 400 V potential for a μs duration, the ions created within the ionization volume are accelerated towards the extractor electrode and collimated by an Einzel lens for transport to the ion trap.

through the filament arrangement. A bias voltage applied to the filaments defines the kinetic energy of the electrons. For efficient ionization, the electron kinetic energy has to be about two to three times higher than the 7.65 eV ionization potential of magnesium.[8,9]

B. Ion extraction

Ion extraction from the creation region inside the grid is achieved by a high-voltage pulser which applies a pulse of several microseconds in duration to the grid. With pulse rise times below one microsecond, such pulses can be well suppressed from disturbing the ion trap by common low-pass filtering if necessary. The first ion optical element behind the grid is the extractor. When the grid potential is above the extractor potential, an electrostatic potential gradient is created which guides the ions from the interior of the grid towards the extractor. During the extraction pulse, the position-dependent potential energy of the ions' place of creation is partially or fully converted into kinetic energy. Only ions that are able to leave the grid volume during the short extraction pulse experience the full conversion of their potential energy. In many ion sources, the extractor electrode is set to a negative potential to enlarge the potential gradient and quicken the ion extraction. However, for this specific electrode configuration the effect was found to be different from this general behavior. The potential distribution inside the grid, as obtained by the particle trajectory simulator SIMION, is shown in Figure 3. The black (red) line shows the potential distribution with the extractor electrode at 0 V (−900 V) and U_{grid} = 400 V. In the first case (black dots in Fig. 3), only ions at a position $x \geq -16$ mm will be able to fully convert their potential into kinetic energy within the 3 μs pulse duration, while for a negative voltage of -900 V applied to the extractor, even ions that are farther inside the grid ($x \geq -21$ mm) are extracted (red dots). However, only ion bunches with a narrow energy distribution can be efficiently transported along the beam line and captured in a trap. Therefore, only ions created in a small area with a potential gradient just sufficient to leave the grid will contribute to the transportable ion bunch, i.e., -15 mm $\leq x \leq -10$ mm and -20 mm $\leq x \leq -15$ mm, respectively. As a consequence, the main effect of the extractor voltage is to shift the zone of extraction along the axis of the grid. This means that an optimum combination of the position of the filaments and the voltage of the extractor has to be found

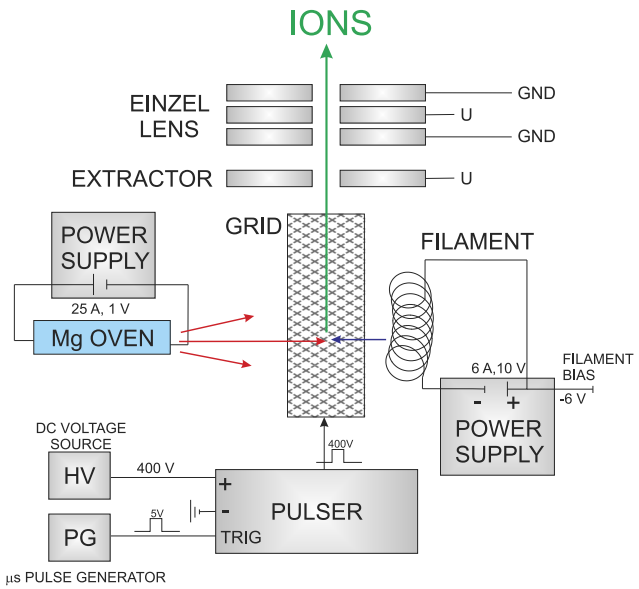

FIG. 2. Electric configuration of the ion source. The oven for neutral metal vapor production is heated by a 25 A low voltage current. The filaments made of thoriated tungsten are heated by a 6 A/10 V power supply to deliver several milli-ampere emission current. A bias voltage applied to the filaments determines the electrons' kinetic energy for impact ionization. A μs-pulse generator triggers the high-voltage pulser to apply a 400 V pulse to the grid electrode.

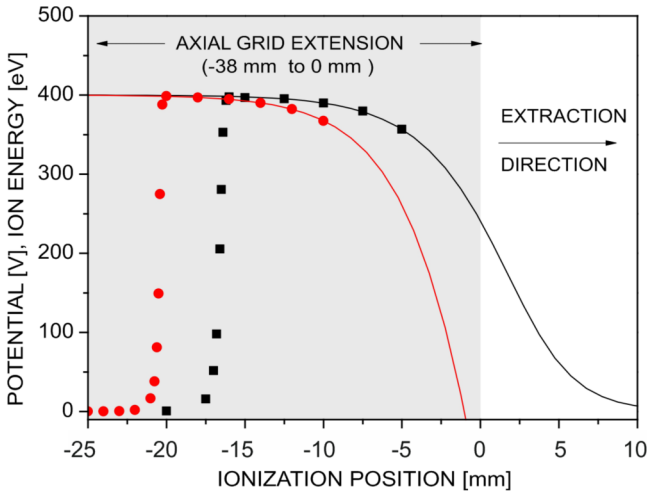

FIG. 3. Simulated electrostatic potentials (lines) and kinetic ion energies (data points) as a function of the position of ionization in the ionization volume for two different extractor voltages (black: 0 V, red: -900 V). The ions' kinetic energies (data points) are given after 3 μs of acceleration, i.e., at the end of the pulse applied to the grid electrode. Ions created too far from the grid exit do not fully convert their potential to kinetic energy within the pulse duration.

in order to maximize the ionization efficiency in the desired volume of the grid. In our case, the best results have been obtained with the extractor set to zero voltage and the Einzel lens operated at a voltage of -1000 V.

III. MEASUREMENTS

The following measurements have been performed with the ion source installed at the SpecTrap experiment,[6] where the ions created are guided along a UHV beamline towards the Penning trap housed in a superconducting magnet as shown schematically in Figure 4. For ion diagnostics, two different instruments have been used. One is a 2-layer Chevron-type multi-channel plate (MCP) with two amplification stages of 10^3 which is destructive and hence terminates the beam line. The other is a dedicated non-destructive charge detector (NID) which picks up the signal induced by the ions as they pass through a cylindrical electrode of the trap.[10] It serves both as an ion counter and for time-of-flight (TOF) information. The ion bunches are guided by electrostatic ion optical elements from the source through the trap and the NID to the MCP detector, as indicated in Figure 4. This beam path mainly features a quadrupole bender for 90° downward deflection ("Q") and re-focusing elements ("E" denoting Einzel lenses). The total distances to the trap/NID and the MCP are 2.5 m and 3.4 m, respectively. Figure 5 shows a signal from the MCP in a time-of-flight measurement with the bias voltage at the source grid

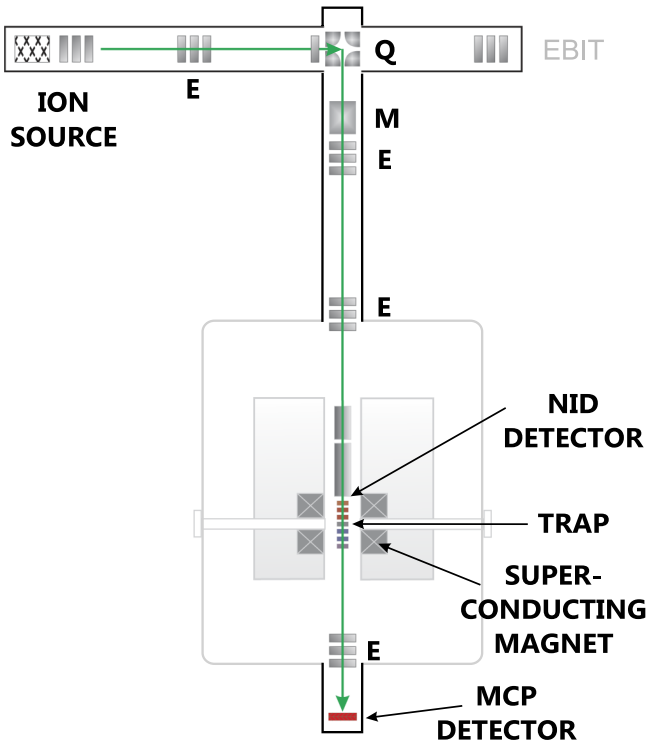

FIG. 4. Schematic of the ion trajectory in the present measurements with the source installed at the SpecTrap experiment. "E" names Einzel lenses for bunch re-focusing, "Q" quadrupole bender, and "M" multipole deflector. Two detectors for ion-bunch diagnostics are available, a non-destructive pick-up detector (NID) before and a destructive MCP detector after the Penning trap. The trap is placed inside the magnetic field of a super-conducting magnet.

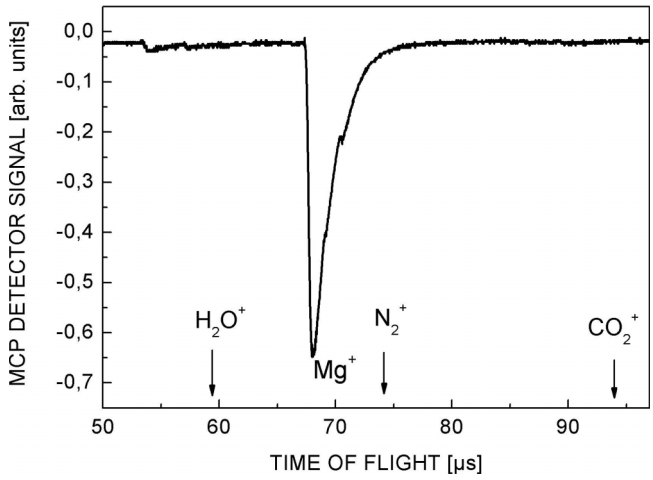

FIG. 5. Signal of the MCP ion detector for optimized Mg^+ production. The arrows indicate the positions where prominent contaminant ions would be expected.

optimized for production of Mg^+. Arrows indicate locations in the signal where prominent contaminant ions would be expected. None of these ions are detected. The kinetic energy of the electrons depends on the position at which they are emitted from the filament. The 6 V bias and the 10 V voltage drop across the filament (at presently 6 A filament heating current) result in electron emission with kinetic energies in the range of 6 –16 eV. In the present configuration, this choice leads to efficient Mg^+ production while avoiding energetically close contaminants. From the ion bunch containing all stable Mg isotopes, only ^{24}Mg is loaded into the trap by dynamically switching the trap's electrodes. The influence of the grid-pulse duration on the extracted pulse is depicted in Figure 6. The temporal ion bunch width is smaller than 1 μs and independent of the pulse duration. For extraction pulse lengths shorter than 3 μs, the amount of produced Mg^+ increases with the pulse duration. For even longer pulses, the main peak saturates and

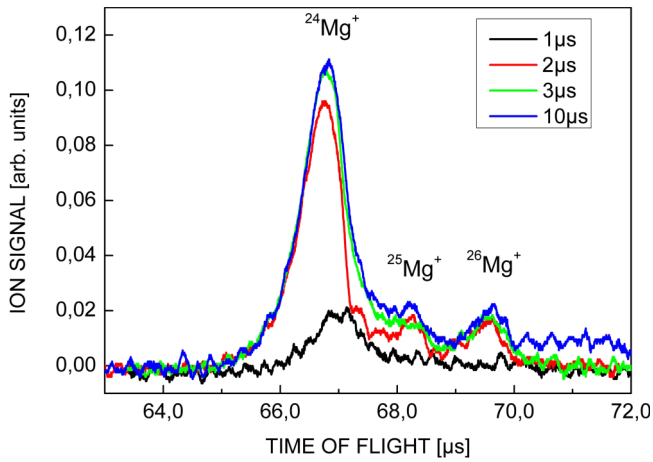

FIG. 6. Time-of-flight spectrum at the MCP for ions extracted with different grid-pulse lengths. Each ion bunch contains all stable magnesium isotopes in natural abundances, separated in the time-of-flight spectrum due to their different charge-to-mass ratio. The main peak has a duration of about 1 μs, independent of the grid-pulse duration. For pulse durations larger than 3 μs the number of extracted ions saturates and the signal develops a tail at longer flight times.

the signal develops a tail at longer times of flight. This behavior can be understood by the characteristics of the extraction process. As shown in Figure 6, a pulse duration of about 3 μs is sufficient to extract the ions from the main creation region. With increasing grid-pulse duration, ions created further inside the grid are extracted and follow the main bunch in the time-of-flight spectrum. Because of the small potential gradient in the grid interior, the extractable volume increases only slowly with grid-pulse duration and the signal declines at later times of flight. A SIMION simulation of the extraction process confirms this result. In Figure 7, the bunch structure after ion extraction and transport to the MCP is depicted. For simplicity, ion creation was assumed to take place only on the grid's axis of symmetry. The earliest arriving ions at t $\approx$ 55 μs form the main bunch, followed by a tail of ions with longer time of flight. Compared to Figure 6, the time of flight in Figure 7 is reduced by 2 μs. This small discrepancy can be explained by the decelerating effect of the ion optical elements, which has not been included in the simulation. Similar to the results shown in Figure 6, the TOF histograms resulting from simulations with grid-pulse durations of 3 μs and 10 μs, respectively, reveal the same main peak at early times of flight. Again, the tail of ions with longer times of flight is more pronounced for longer grid pulse length. This shows that the ions forming the main bunch stem from the volume close to the front end of the extraction region, where extraction with a short pulse duration is possible. This is again confirmed by the inset to Figure 7, where two histograms of the ions' kinetic energy are shown. The gray-filled histogram shows the energy distribution of the whole ion ensemble inside the grid volume, where the energy with the highest occurrence is given by the grid voltage U_{grid} = 400 V. The green-hatched histogram shows the energy distribution of the ions within the main peak, i.e., ions with times of flight less than 65 μs. The

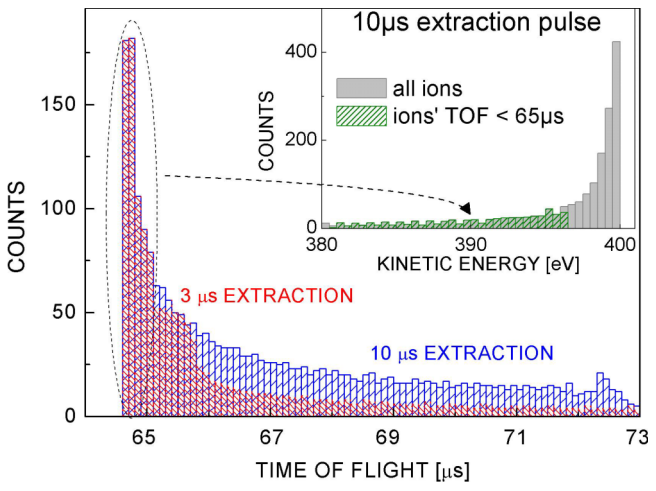

FIG. 7. SIMION simulation of the ions' time of flight to the MCP detector for grid-pulse durations of 3 μs and 10 μs. The potential applied to the extractor and grid electrode was 0 V and 400 V, respectively. For longer pulse durations, the distribution develops a tail to longer times of flight. Inset: corresponding distribution of ion kinetic energies for 10-μs grid-pulse duration (gray histogram). The kinetic energy of 400 eV with the highest probability is given by the potential applied to the grid electrode. The subset of ions arriving at times < 65 μs (green-hatched histogram) shows a kinetic energy distribution at lower energies.

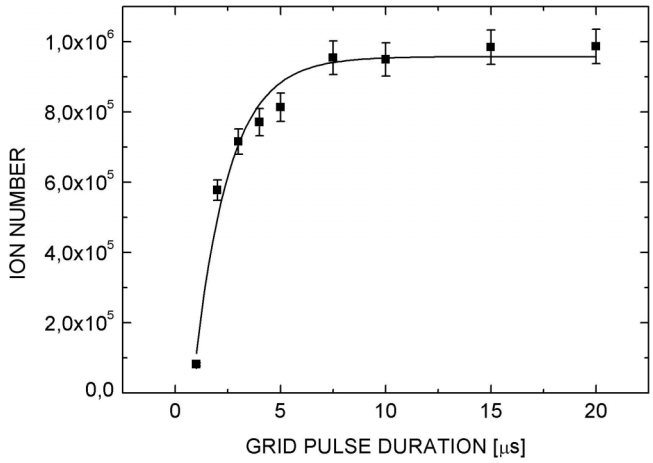

FIG. 8. Measured ion number per pulse detected with the NID as a function of the grid-pulse duration. An exponential saturation behavior has been fitted to the data.

kinetic energy of these ions is slightly reduced with regard to the voltage applied to the grid, as can be expected in the region close to the front end of the extraction region. Of course, the bunch structure evolves with time and is shown here only for that specific time of flight. Figure 8 shows the ion number per pulse detected with the NID as a function of the grid-pulse duration. An exponential saturation behavior has been fitted to the data, indicating that for the present conditions, pulse durations above roughly 7.5 μs do not change the ion number any more. Thus, a grid-pulse duration of 7.5 μs allows a reliable full extraction of ion bunches, but pulses as short as 3 μs extract 70% of the maximum ion number. For the given configuration, the expected space charge limit is about 10^6 ions.

Figure 9 shows the number of extracted ions per pulse (left hand scale) as a function of the electron emission current I_{em} for different oven currents. The ion yield increases significantly with increasing oven current. Currents above 26 A were not applied in order not to deplete the source unnecessarily

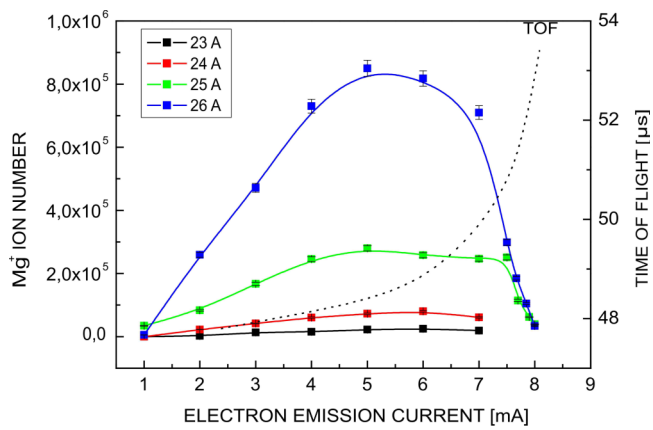

FIG. 9. Number of extracted ions per pulse as a function of the electron emission current I_{em} for different values of the oven current, measured with the NID. Grid pulse length was set to 3 μs and extraction voltage to 0 V. Lines have been drawn to guide the eye. With increasing electron emission current, the effective potential of the extraction pulse is reduced. As a consequence, for higher I_{em} the ions' time of flight (dotted curve) increases from 48 μs to 52 μs and the ion yield saturates or even decreases again.

fast. The ion yield increases with increasing electron emission current from the filaments, up to a point where the electron current to the grid reduces the voltage applied by the extraction pulse. This is visible in Figure 9, where the yield starts to saturate for I_{em} above 4.5 mA and even decreases again for higher I_{em}. To prove the influence on the pulse, the dotted curve (referring to the right hand scale) shows the corresponding time of flight of the ions which increases significantly in the regime of high electron emission currents.

IV. CONCLUSION

We have built and operated a source for bunches of singly charged atomic ions and have characterized it by a number of systematic measurements and by comparison with simulations. The source has been used to produce bunches of Mg^+ ions for dynamic capture into the SpecTrap Penning trap, where it has proven a simple and reliable device. As performance parameters for the present source configuration, we find ion numbers up to 10^6 ions per μs bunch after ion transport to SpecTrap over a distance of 2.5 m at kinetic energies between few tens of eV and few keV. For ion capture into the trap, the source has commonly been operated with grid voltages between 100 V and 600 V. We find the temporal ion bunch width to be smaller than 1 μs and basically independent of the grid-pulse duration. The possible extraction rate at these parameters is up to 1 Hz, above that the ion yield decreases until it becomes undetectable around roughly 100 Hz. The source has been operated for several hundreds of hours with one filling of Mg material. We expect the source to be of interest for other experiments, especially if short bunches are required.

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