Short time ion pulse extraction from the Dresden electron beam ion trap[a)]

U. Kentsch,[1] G. Zschornack,[2,b)] A. Schwan,[1] and F. Ullmann[1]
[1]*Dreebit GmbH, D-01109 Dresden, Germany*
[2]*Institute of Applied Physics, Dresden University of Technology, D-01062 Dresden, Germany*

(Presented 21 September 2009; received 18 September 2009; accepted 12 November 2009; published online 11 February 2010)

We present measurements of the extraction of short time pulses of highly charged ions (4 keV, Ar^{16+}) from the Dresden electron beam ion trap. Thereby the dependence of the extractable ionic charge on the extraction regime was investigated. The ion extraction time was varied between 20 ns and 1 μs. Furthermore the production of carbon ions and the influence of the extraction regime on the pulse widths was investigated to obtain information about the suitability of the Dresden EBIS-A in synchrotron based particle therapy facilities. © *2010 American Institute of Physics.*
[doi:10.1063/1.3271255]

I. INTRODUCTION

In the past the production of highly charged ions in electron beam ion traps (EBITs) has been demonstrated successfully for several applications.[1–4] The produced highly charged ions (HCI) were provided for experiments in atomic physics, materials research, astrophysics, and radiation biology. Additionally a number of proof-of-principle experiments have been done to demonstrate the application potential of HCI for technological developments, e.g., for surface analysis, nanostructuring, and medical applications.

For some applications the time structure of the extracted beams of HCI is of fundamental interest. As an example in surface analysis HCIs are of interest for applications in time of flight secondary ion mass spectroscopy (TOF-SIMS). Since the required pulses for the TOF-SIMS have to be very short preliminary measurements of the short time ion extraction of Argon as well as of Xenon ions were done. The number of ions extracted from the Dresden EBIT was measured depending on the extraction time as well as on the charge state. Furthermore the extraction regime (number of extracted pulses) was varied. The results give an information about the suitability of the Dresden EBIT/EBIS sources in a TOF spectrometer.

For applications in the medical particle therapy an adequate time structure of the ion pulses is of principal importance. For the application in synchrotron based medical accelerators for single-turn ion injection short pulses in the 2 μs range are required as well as pulses with a length of about 30 up to 40 μs in the multiturn injection regime.[5] Similar requirements result from applications of rapid cycling medical synchrotrons[6] and from CYCLINACs (Ref. 7) as novel medical accelerator structures.

[a)]Contributed paper, published as part of the Proceedings of the 13th International Conference on Ion Sources, Gatlinburg, Tennessee, September 2009.

[b)]Electronic mail: g.zschornack@fzd.de.

II. EXPERIMENTAL SETUP

The preliminary measurements for the integration of the Dresden EBIT in a TOF-SIMS were accomplished at a test beamline facility of the Dreebit GmbH at the Forschungszentrum Dresden-Rossendorf. The ions were produced with the Dresden EBIT.[8] In the Dresden EBIT the ion trap is realized by a threefold structured drift tube ensemble with an axial ion confinement via an electrostatic potential configuration between the first and third drift tubes. To generate ion pulses the ions were extracted by switching the third drift tube potential from U_{B1} to U_{B2}.

All measurements are realized at a test beamline as shown in Fig. 1. The extracted ion beam was guided into the beamline by various ion optical elements and charge state separated by an analyzing dipole magnet. Behind the magnet the ion beam current was measured by a Faraday cup. Since the available standard power supplies do not allow decreasing the ion extraction time below 1 ms the experiments were done with a computer controlled power supply of the IONTOF GmbH Münster.[9] It enables the extraction of N ion pulses with an extraction time t_{extr} and a pulse cycle time t_{cyc}. In this context the cycle time is the time between two pulses and was chosen to be in the order of 100 μs resulting in a pulse repetition rate of around 10 kHz similar to the pulse repetition of TOF spectrometers. According to the ionization time of the “normal” trap regime the Dresden EBIT was reloaded within the reload time t_{wait} after the extraction of N pulses. Then the ion extraction started again. Since the used fast pulsing power supply delivered a maximum voltage output of 4.0 kV the electrical potential of the drift tubes was limited to this value. A good operating regime of the Dresden EBIT was found at a cathode voltage of $U_{cat}=3.15$ kV resulting in a maximum electron energy of $E_e=7.15$ keV.

III. SHORT TIME EXTRACTION IN THE NANOSECOND RANGE

All measurements were performed with argon as working gas. To select a certain ion charge state q for the short time ion extraction experiments at first an ion extraction

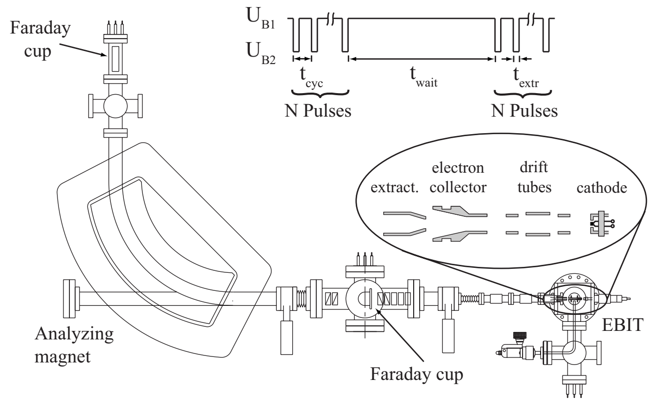

FIG. 1. Test beamline for studying short pulse ion extraction from the Dresden EBIT.

spectrum under "classical" extraction conditions with trap-open cycles of 10 ms was measured. The argon extraction spectrum is shown in Fig. 2. For the selected operation conditions the maximum of the charge state distribution is at Ar^{15+} and contributions from argon ions with $q<12$ do not appear. After adjusting the magnetic field of the dipole magnet for the transmission of Ar^{16+} the trap potential was switched to the fast voltage pulsing unit and the measurement of the extracted ion current was performed by a low noise current amplifier together with a 300 MHz oscilloscope. The applied amplification was 10^7 V/A. Because of the low signal level an average over 30 pulses was used to get statistically significant results.

The extracted ionic charge per pulse was measured depending on the extraction time t_{extr} (see Fig. 3). For extraction times longer than $t_{extr}>400$ ns the measured ion charges do not further increase. As shown in Fig. 3 for an ion extraction time $t_{extr}<150$ ns only a certain portion of the ionic charge stored in the trap can be extracted.

The dependency of the extracted charge on the number of extracted pulses N is shown in Fig. 4. Since the extraction time was chosen to be 50 ns at a cycle time of 100 μs only a small amount of the trapped ions was extracted during the time of one extraction pulse. For $N>8$ pulses the totally extracted charges per pulse do not significantly increase. Thus a further increase in the number of pulses does not lead to an increase in the totally extracted ionic charge. Furthermore we measured that the extracted charge Q is nearly constant over a wide range of t_{cyc} and especially for a cycle time between 50 and 150 μs, there is no decrease in the measurement signal.

Additionally the extracted charge in dependence on the reload time of the trap (t_{wait}) was measured and is shown in Fig. 5. The maximum of the ionic charge was obtained at $t_{wait}=1$ s. An increase in the reload time resulted in a slight decrease in the extracted charge for the Ar^{16+} component corresponding to a shift in the ion charge state distribution to higher charge states caused by the larger ionization time. We made computer simulations of the ionization dynamics in the Dresden EBIT at the specified parameters. The maximum of the Ar^{16+} component was obtained after about 1s of ionization time. At larger ionization times the charge state distribution is shifted gradually to Ar^{17+}.[10]

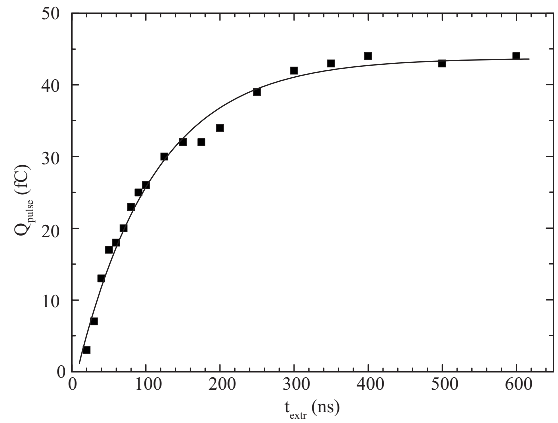

FIG. 3. Extracted ionic charges per Ar^{16+} pulse in dependence on the extraction time t_{extr} ($U_0=4.0$ kV, $I_e=24$ mA, $t_{cyc}=100$ μs, $t_{wait}=1$ s, $p=3.1\times10^{-9}$ mbar). The solid line is a guide to the eye.

IV. SHORT TIME EXTRACTION IN THE MICROSECOND RANGE

High energy Hadron radiation was proven to be effective in the treatment of cancerous tumors. Protons and light ions (carbon ions) deposit their energy at a depth determined by their initial energy, the so-called Bragg peak. Since the ions are accelerated, for example, in a synchrotron to reach their

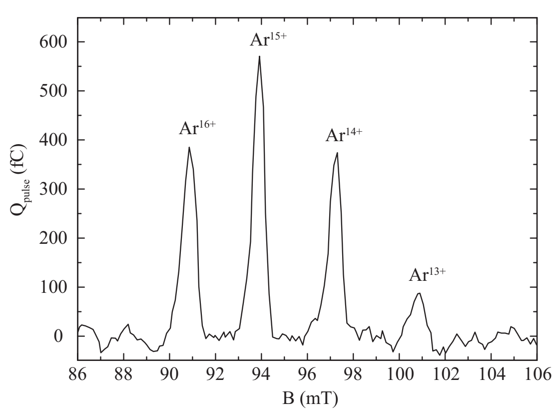

FIG. 2. Argon extraction spectrum obtained with classical ion extraction conditions at an open trap time of 10 ms.

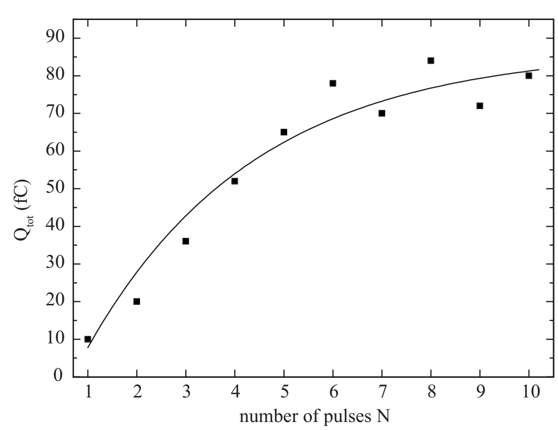

FIG. 4. Extracted ionic charge in dependence on the number of extracted ion pulses ($U_0=4.0$ kV, $I_e=29$ mA, $t_{extr}=50$ ns $t_{cyc}=100$ μs, $t_{wait}=1$ s, $p=3\times10^{-9}$ mbar). The solid line is a guide to the eye.

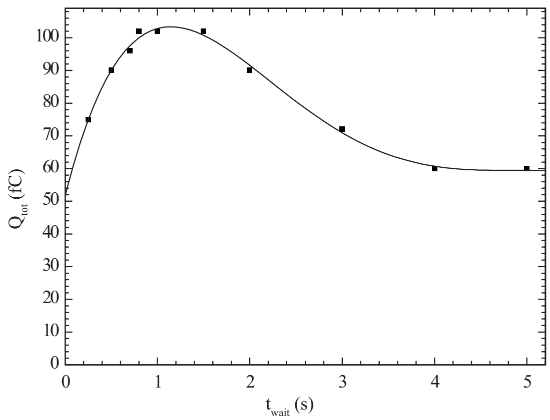

FIG. 5. Extracted ionic charge in dependence on the trap reload time t_{wait} (U_0=4.0 kV, t_{cyc}=100 μs, t_{extr}=50 ns, $p=3\times10^{-9}$ mbar, I_e=24 mA).

final energy, the ion beam has to fulfill high demands concerning its injection to the accelerator (beam purity, pulse to pulse stability, beam emittance, and time regime). Using EBIS sources at synchrotron based facilities the accelerator configuration can be simplified and high quality hadrons beams can be provided. For such therapy facilities the pulse widths of the injected ion beams have to be about 2 μs for single-turn injection and about 40 μs for multiturn injection, respectively. The repetition rate is in the order of 1 Hz. For alternative CYCLINAC solutions a pulse width of about 5 μs is required at a pulse repetition rate of up to 400 Hz.

We have investigated the pulse widths of carbon ion pulses extracted from the Dresden EBIS-A. The measurements were done at an ion energy of U_0=8.9 kV, an electron beam current of I_e=80 mA, a working gas pressure of $p=1\times10^{-8}$ mbar, an ionization time of t_{ion}=12 ms, and an extraction time of t_{extr}=1 ms corresponding to a pulse repetition rate of 77 Hz. The results are shown in Fig. 6. The pulse width strongly depends on the open trap potential (U_{B2}). The ion pulse width decreases from about 50 μs (U_{B2}=−90 V) to 8 μs (U_{B2}=−500 V) with decreasing U_{B2}. Furthermore the ion pulses are reproducible with a pulse to pulse stability of about 1%. With these experimental investigations of the time structure of the ion pulses, we have proven that the required pulse widths for synchrotron injection can be extracted from EBIS ion sources.

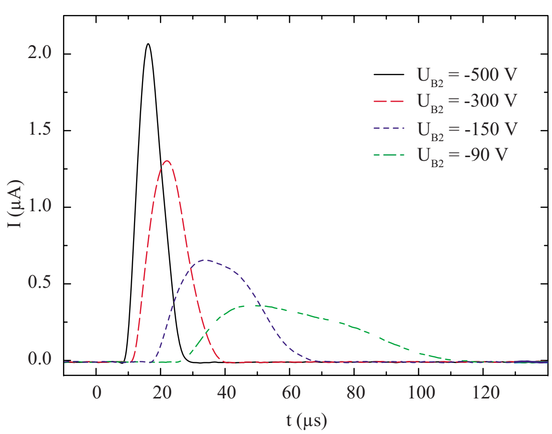

FIG. 6. (Color online) Extracted ion currents at several extraction regimes to achieve different pulse widths.

V. CONCLUSION

The present studies prove that a short pulsed ion extraction from the Dresden EBIT is possible. The extracted ion charges are in the range of some femtocoulombs. It is possible to extract several pulses until the trap has to be reloaded. The extracted ion charge significantly depends on the extraction time whereas the cycle time has a negligible influence. Due to their charge state HCIs have a large amount of stored potential energy. This energy is released during the ion surface interaction resulting in a larger yield of secondary charged particles, which can be important for TOF spectroscopy. The presented measurements have demonstrated that EBIT sources satisfy the required parameters for TOF-SIMS. Thus this kind of ion sources could be of fundamental interest for applications in surface analytics.

Furthermore we have demonstrated that the EBIS-A can provide ion beams meeting the demands of the time structure of ion beams for the injection into synchrotrons at medical particle therapy facilities. The width and the form of the extracted ion pulses depend on the time structure and the height of the trap potential supplied at the third drift tube of the EBIS-A.

ACKNOWLEDGMENTS

The work was supported by the EFRE fund of the EU and by the Freistaat Sachsen (Project Nos. 12321/2000 and 12184/2000, respectively).

[1] E. D. Donets, Nucl. Instrum. Methods Phys. Res. B **9**, 522 (1985).
[2] A. I. Pikin, C. A. Morgan, E. W. Bell, L. P. Ratliff, D. A. Church, and J. D. Gillaspy, Rev. Sci. Instrum. **67**, 2528 (1996).
[3] D. Schneider, D. DeWitt, M. W. Clark, R. Schuch, C. L. Cocke, R. Schmieder, K. J. Reed, M. H. Chen, R. E. Marrs, M. Levine, and R. Fortner, Phys. Rev. A **42**, 3889 (1990).
[4] U. Kentsch, G. Zschornack, F. Grossmann, V. P. Ovsyannikov, F. Ullmann, S. Fritzsche, and A. Surzhykov, Nucl. Instrum. Methods Phys. Res. B **187**, 238 (2002).
[5] T. Auberger and E. Griesmayer, *Das Projekt Medaustron—Designstudie* (Fotec GmbH, Wiener Neustadt, 2004).
[6] T. Satogata, E. Beebe, and S. Peggs, Collider-Accelerator Department, BNL Report No. C-A/AP/#226, May 2006.
[7] U. Amaldi, CYCLINACS: Novel fast-cycling accelerators for hadrontherapy, 18th Int. Conf. Cyclotrons and their Applications, 2007, see http://accelconf.web.cern.ch/AccelConf/c07/PAPERS/166.PDF.
[8] G. Zschornack, S. Landgraf, F. Großmann, U. Kentsch, V. P. Ovsyannikov, M. Schmidt, and F. Ullmann, Nucl. Instrum. Methods Phys. Res. B **249**, 921 (2006).
[9] See http://www.ion-tof.com for additional information on the company.
[10] I. V. Kalagin, D. Küchler, V. P. Ovsyannikov, and G. Zschornack, Plasma Sources Sci. Technol. **7**, 441 (1998).