# SHAPING OF ION PULSES FROM AN ELECTRON BEAM ION SOURCE FOR PARTICLE INJECTION INTO ACCELERATORS*

F. Ullmann, A. Schwan, DREEBIT GmbH, Dresden, Germany
G. Zschornack, TU Dresden, Department of Physics, Dresden, Germany
O. Heid, H. v. Jagwitz-Biegnitz, U. Hagen, SIEMENS AG, HTC, Erlangen, Germany

*Abstract*

Electron Beam Ion Sources (EBISs) provide highly charged ions (HCIs) for many applications, amongst others for particle injection into accelerators. Although EBISs are limited in ion output they feature a lot of advantages which qualify them for accelerator injection. The ion pulses extracted from the ion sources can be directly injected into an accelerator sequence which however requires ion pulses with distinct shape and length. The ions are produced by trapping in a high density electron beam for a certain time with electrostatic potentials providing for their axial trapping. Due to the ion energy distribution within the trapping region ion extraction can be controlled by controlling the trapping potential. A specific time dependent control mode of the trapping potential thus allow for the production of ion pulses with designated shape and length. Source parameters such as working gas pressure, electron beam current and energy influence the energy distribution of the ions which in turn influence the pulse shaping.

## INTRODUCTION

HCIs are used in various fields of basic and applied research, such as atomic and nuclear physics, astrophysics, plasma physics, materials science and nanotechnology. Another emerging field is their application in biotechnology and particle therapy [1,2].

Radiation therapy with charged particles, such as protons and carbon ions is an upcoming field with immense prospects and hopes. This is due to their energy distribution of the dose deposition, the so-called Bragg peak. On the other hand this poses technological challenges. Today, worldwide, more than about 25 hadron therapy medical centres are in operation, most of them are dedicated to proton therapy. Most are cyclotron-based, some are synchrotron-based. Since total costs for these facilities are very high other accelerator concepts are discussed for the development of medical accelerator technology, principally based on compact, high-frequency linear accelerators [3-5].

However, the requirement is an ion source providing sufficient numbers of charged particles with high beam quality, long-term stability and reproducibility.

Classical injection into accelerators is based on continuous beams which are chopped into pulses before injection.

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A new approach is the formation of adequate ion pulses from the ion source directly. Thus, EBIS systems come into consideration whose continuous ion output is orders of magnitude lower than from plasma ion sources such as electron cyclotron resonance ion sources but whose number of ions per pulse is comparable to chopped ion pulses. This allows to participate from advantages of EBISs such as their low transversal and longitudinal beam emittance as well as the absence of bothersome effects from plasma sources such as impurities or instabilities.

Typical pulse length of particle accelerator machines is in the range of 100 µs, which requires a pulse length from the ion injector in the same range. Moreover, an ideal pulse shape is a flat-top pulse, i.e. a pulse with a rise time as short as possible with a constant current apart from that and containing maximum charge.

In this paper, we present the formation of ion pulses from the Dresden EBIS-A machine [6,7], the influence of the ion source parameters onto the pulse shape, and a new method for influencing the pulse shape by changing the switch time of the electrostatic trap potential.

## ION PRODUCTION

The production of ions in an EBIS is based on electron impact ionization of neutral atoms or molecules in a high density electron beam. The ions are perpetually ionized while trapped, radially by the negative space charge potential of the electron beam and axially by additional electrostatic potentials as pictured in Fig. 1.

The control of the electrostatic axial trapping potentials allow for a definite production and extraction of the produced ions.

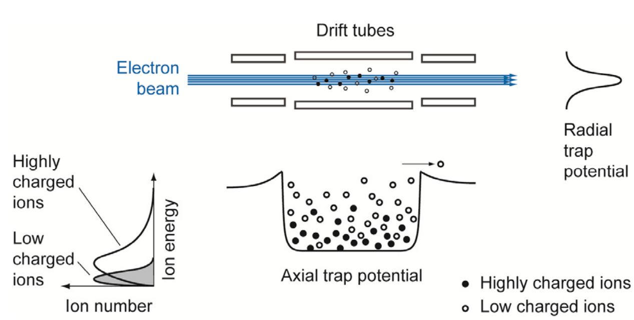


Figure 1: Schematic of ion trapping in the EBIS.

The radial source region is given by a narrow electron beam limiting the ion output but also resulting in a very low beam emittance. Axial trapping is realized by three drift tubes with the outer tubes on a higher positive potential of several tens of volts than the center tube.

Fig. 2 gives a schematic of the set-up and potential setting of the Dresden EBIS-A. The cathode is on negative potential $U_{Cath}$ of up to 3 kV. The drift tubes are on positive potential $U_0$ of up to 15 kV. The first drift tube section serves as anode. The ion trap is realized by a negative potential offset on the center drift tube $U_A$. Switching the third drift tube potential $U_B$ opens the trap after a preset ionization time. The extraction electrode allows for deflection of the electron beam into the electron collector and extraction of the positively charged ions.

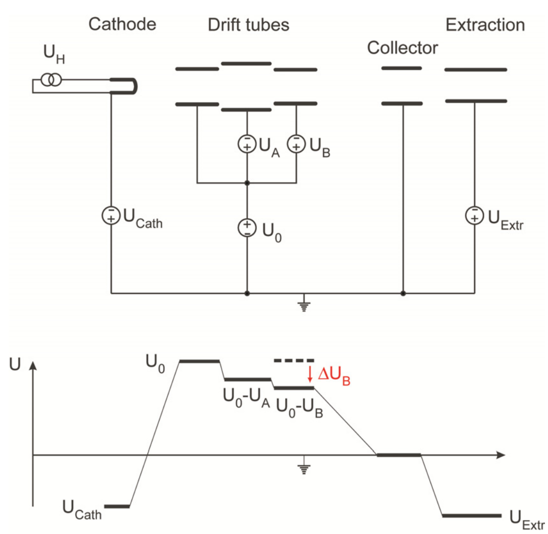


Figure 2: Potential scheme of the Dresden EBIS-A set-up.

The electron beam energy defining the ionization energy is given by $U_{Cath} + U_0 - U_A$. The start potential of the ions, i.e. their kinetic energy is given by $U_0 - U_A$.

The ions can be extracted in leaky mode, i.e. as continuous beam, or in pulsed mode. In leaky mode ions with sufficient thermal energy can leave the trap potential over a reduced but constant trap potential $U_B$. In pulse mode the ions leave the trap after and already while lowering the axial trap potential $U_B$.

In leaky mode the mean thermal energy spread of the extracted ions is principally given by the potential difference between the center and third drift tube. The energy spread of the ion pulses is primarily given by the ionization time. The ionization time not only determines the charge state distribution of the ions but also their energy distribution. In addition both the charge and the energy spread are influenced by the electron beam, i.e. its current density and beam energy, as well as by the neutral gas pressure having impact on atomic collisions within the trap. In summary, the kinetic distribution of the ions is influenced and thus controllable by a set of ion source parameters.

## PULSE EXTRACTION

The axial velocity of the ions in the trap results in a time the ions need to travel through the complete trap length of 6 cm that is in the microsecond range. Thus, after opening the trap all ions can leave the trap within typically less than 2 µs. If the switching time of $U_B$ is faster or equal to 1 µs the ion pulse represents the energy distribution within the trap. The fastest ions will leave the trap first and the slowest last, respectively. If the switching time of $U_B$ becomes slower the ions already start to leave the trap during lowering $U_B$. This enables to extend the original ion pulse by a slow-going potential switching of $U_B$. The length of the pulse is thus determined by the time until the trap is completely open. Fig. 3 shows an ion pulse after trap opening at three different switching times and slew rates respectively.

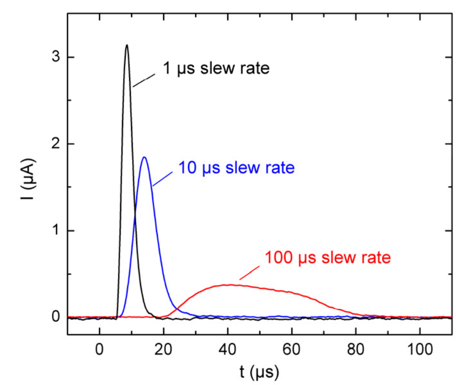


Figure 3: $C^{4+}$ pulse extracted from the Dresden EBIS-A, at switching times of $U_B$ of 1 µs, 10 µs and 100 µs.

The pulse after opening the trap with a slew rate of 1 µs represents the energy spread in the trap that is similar to a Gaussian distribution with FWHM of about 2 µs. This relates to an energy spread of about 10 eV. The trap is opened at t=0. The ions reach the Faraday cup after about 5 µs flight time. The pulse at 10 µs slew rate is clearly lengthened. At 100 µs slew rate ions start to leave the trap after about 15 µs when the first ions can overcome the slowly decreasing potential well.

Fig. 4 pictures proton pulses extracted after different ionization times. Maximum proton output is reached for about 20 µs. Before 20 µs the trap is not yet completely filled. With increasing ionization time the pulse is shifted towards shorter detection time resulting from faster ion velocities which is due to the accumulation of thermal energy via electron impact heating. At longer ionization time protons are getting hotter and start to escape from the trap potential well.

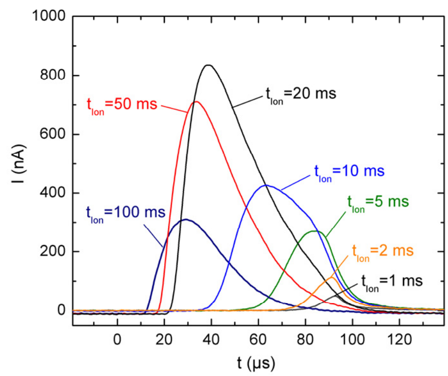


Figure 4: Proton pulses from the Dresden EBIS-A, extracted after different ionization times at a slew rate of 100 µs.

## PULSE SHAPING

The control of the voltage characteristic of $U_B$ allow for forming the shape of the extracted ion pulse.

For that purpose, a specially designed pulse shaping unit (PSU) has been connected to the third drift tube section. The PSU which is insulated to 20 kV produces a negative potential offset of maximum 400 V with a resolution of 10 bit resulting in a minimum voltage step of 0.4 V. The voltage characteristic is programmable in time steps of 100 ns and initiated by a trigger signal.

Fig. 5 shows a cascaded voltage curve of $U_B$ and the resulting ion pulse. Each voltage step produces its own pulse. The time between each voltage switch and the corresponding pulse is slightly increasing which is due to the decreasing thermal energy of the ions of the subsequent pulses.

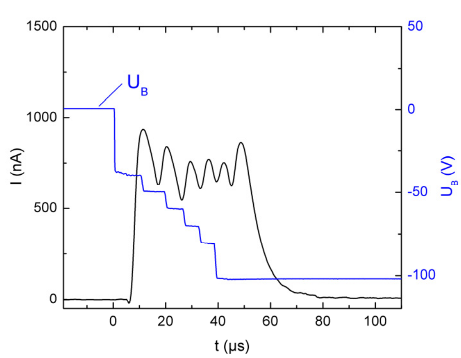


Figure 5: Cascaded voltage switching characteristic of $U_B$ and resulting $C^{4+}$ pulse.

Fig. 6 shows the same pulse at a smoothed voltage switching characteristic of $U_B$ resulting in a virtually flat-top pulse shape.

Finally Fig. 7 pictures a flat-top proton pulse with a length of more than 200 µs as it is required, for instance, for multi-turn injection into synchrotrons or into a DDA structure [5].

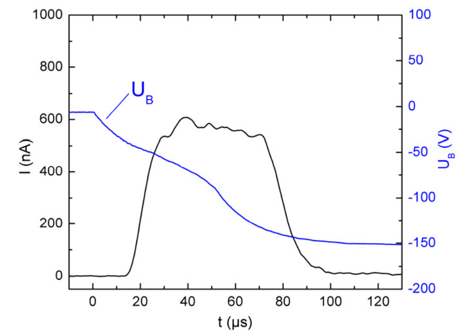


Figure 6: Smoothed voltage switching characteristic of $U_B$ and the resulting $C^{4+}$ pulse.

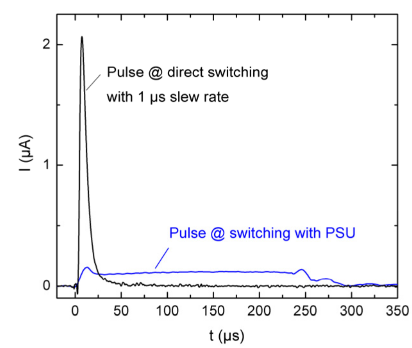


Figure 7: Proton pulses from the Dresden EBIS-A after direct trap opening and after switching with the PSU forming a flat-top pulse shape.

## CONCLUSION

The ion pulses extracted from an EBIS represent the energy spread within the ion trap. According to the slew rate of the axial trap potential a slow-going opening of the trap results in a corresponding pulse length extension. Controlling the voltage characteristic of the trap opening potential moreover allows to form the shape of the extracted ion pulse. By setting the ion source parameters basically any pulse length and shape can be provided.

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