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A compact electron beam ion source for highly charged ion experiments at large-scale user facilities

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Abstract

Probing and manipulating of 2D materials and their heterostructures using slow highly charged ions (HCIs) is currently a hot topic due to the ultimate surface sensitivity of electronic sputtering with profound implications for fundamental research and technological applications. To study surface modifications without the complications of sample transport from ion irradiation to complex microscopic or spectroscopic analysis tools, the development of compact and thus portable ion sources is essential. In this paper we present the first results of the electron beam ion source-Compact version 1 (EBIS-C1), a novel and highly compact source for highly charged ions manufactured by D.I.S Germany GmbH. The main focus of this paper is to demonstrate the suitability of the EBIS-C1 as an ideal source for ion scattering experiments at surfaces and at gas/liquid jet targets by presenting the first charge state spectra of extracted neon, argon and xenon ions. The results highlight the potential of this portable EBIS to become a versatile platform for the study of HCI-surface interactions, allowing investigations to be carried out at user terminals in different laboratory environments.

Keywords: highly charged ions, electron beam ion traps, compact ion source

1. Introduction

Electron beam ion traps (EBITs) and electron beam ion sources (EBISs) are sophisticated devices used in experimental physics and atomic research to trap, study, manipulate and extract ions in a high charge state [1–4]. They have become essential tools in many fields, including atomic and nuclear physics and even astrophysics [4–12].

The concept of the EBIT was first proposed in the late 1980 s [13] and since then EBITs have become indispensable tools for studying the properties of highly charged ions at low energies. An EBIS is a closely related device, first invented by Donets in 1968 [14, 15], which is primarily used to produce highly charged ions in the same way as an EBIT, but then extract them for various applications, including ion implantation, accelerator injection and collision experiments with slow highly charged ions. In the following, we will use 'EBIS' to describe all EBIT-like devices.

Both devices employ a magnetically compressed high energy electron beam, generated by a filament or electron gun, to ionize atoms and produce ions within its 'trapping' ionization chamber. Notably, the source enables 'charge breeding', the sequential ionization of ions, resulting in highly

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charged ions with exceptional efficiency. Extracted highly charged ions can be used for collision experiments with atoms, molecules, cluster and surfaces at low (100 eV-several 10 keV) energies [5, 8–10, 16] or further accelerated to high energies.

Highly charged ions have a wide range of applications in a variety of scientific fields. They are used in injectors for particle accelerators to boost the energy [17]. In semiconductor technology, heavy and sometimes highly charged ions are used for precise ion implantation to modify the properties of semiconductor materials for device fabrication [18]. In addition, highly charged ions allow fundamental physics to be studied, enabling precision experiments to test fundamental theories and calibrate detectors in high-energy physics applications [12, 19]. In addition, EBISs play a vital role in radioisotope production, providing highly charged ions of specific isotopes for medical applications and research, benefiting diagnostic imaging, radiotherapy and nuclear medicine procedures [20–22].

The interaction of slow highly charged ions (HCI) with surfaces has become a compelling area of research, offering insights into the fundamental physics governing atomic and molecular interactions at the nanoscale. Such investigations have numerous applications, ranging from nanofabrication to the characterization of material properties [23–26].

The electron beam ion source-Compact version 1 (EBIS-C1), developed and supplied by D.I.S. Germany GmbH [27], represents a significant advancement in EBIS technology. Its unique and innovative compact design endows it with portability, making it a versatile tool that can be readily transported and deployed at remote user end stations in various laboratory settings. This mobility opens up new possibilities for collaborations between different research facilities. While there already exist several other small EBISs (such as e.g. [1, 28–30]), the EBIS-C1 design is even more compact, enabling it to be mounted on surface science equipment not possible before. We believe that the miniaturisation of the EBIS beyond current designs and its commercial availability are the main advantages over custom-designed individual EBIS prototypes, as this makes the EBIS more accessible to a wider community, especially given the typically lower prices of smaller machines and devices produced in series. This is similar to the situation in surface science when the first commercially available small and lightweight singly charged ion sources became available for sample preparation and cleaning, for example, and could be easily mounted on any small flange of an experimental chamber.

In this paper, we present the commissioning of the first commercially available EBIS-C1 which is intended to be used in the study of HCI-surface interactions. Our primary objective is to showcase the potential of the EBIS-C1 as an ideal source for ion-surface experiments. Through the acquisition of first charge state spectra of neon, argon, and xenon ions under realistic laboratory conditions, we demonstrate the capabilities of the EBIS-C1 and its suitability for exploring diverse HCI phenomena.

2. Operational principles of the EBIS-C1

The D.I.S EBIS-C1 represents a new approach to EBIS technology, due to its ultra-compact design (see figures 1(a) and (b)) and cost-effectiveness. Despite its small dimensions, the EBIS-C1 exhibits the capability to generate beam currents of several hundred picoamperes of multi-charged ions from a variety of gaseous elements or even metallic ions when using volatile organic compounds (MIVOC). Notably, its modular and user-friendly design, integrated on a DN40CF flange, renders the EBIS-C1 suitable for a broad spectrum of applications, encompassing basic research across scientific disciplines and technological applications. The EBIS-C1 also incorporates a Wien filter module, offering precision in ion charge state and mass selection.

The EBIS-C1 generates multiply charged ions by electron impact ionization using a $\sim$10 mA electron beam. The electron beam is initially produced by a highly emissive cathode and magnetically compressed in the ionization zone. The ionization is enhanced by an electromagnetic ion trap, facilitating the required storage time of ions in the ionization zone. Subsequently, in the ion extraction zone, the electron beam is separated from the ion beam, enabling the extraction of positively charged ions.

The highly charged ions produced by stepwise electron impact ionization are radially confined by the strong negative space charge of the compressed electron beam, while axial confinement is achieved through electrostatic potentials generated by three colinear drift tubes. These tubes form an axial electrostatic trap, where ions are trapped and their charge state progressively increases over time. The mean charge state can be influenced by periodically opening and closing the ion trap, by lowering the third drift tube potential to leak ions with sufficient kinetic energy out of the trap, and by varying the electron beam energy.

The EBIS-C1 operates in three distinct modes:

- Permanently Opened Trap (Transmission Mode): high ion beam currents of the lowest charge states are achieved as the trap remains permanently open.
- Partially Closed Trap (Leaky Mode): operating with a low axial potential wall allows a continuous extraction (quasi-continuous-wave) of ions with intermediate charge states.
- Periodically Opened and Closed Trap (Pulsed Mode): by periodically switching the voltage between two values, ions of various charge states, including highly charged ions, can be extracted in a pulsed fashion.

It should be noted that the achievable charge states are solely given by the electron beam energy, the electron beam current density and the working gas pressure, whereas the difference in leaky and pulsed mode manifests mainly in intensity differences of individual charge states and extraction conditions (emissivity).

The key components of the EBIS-C1 are labelled in the technical drawing shown in figure 1(a). A corresponding

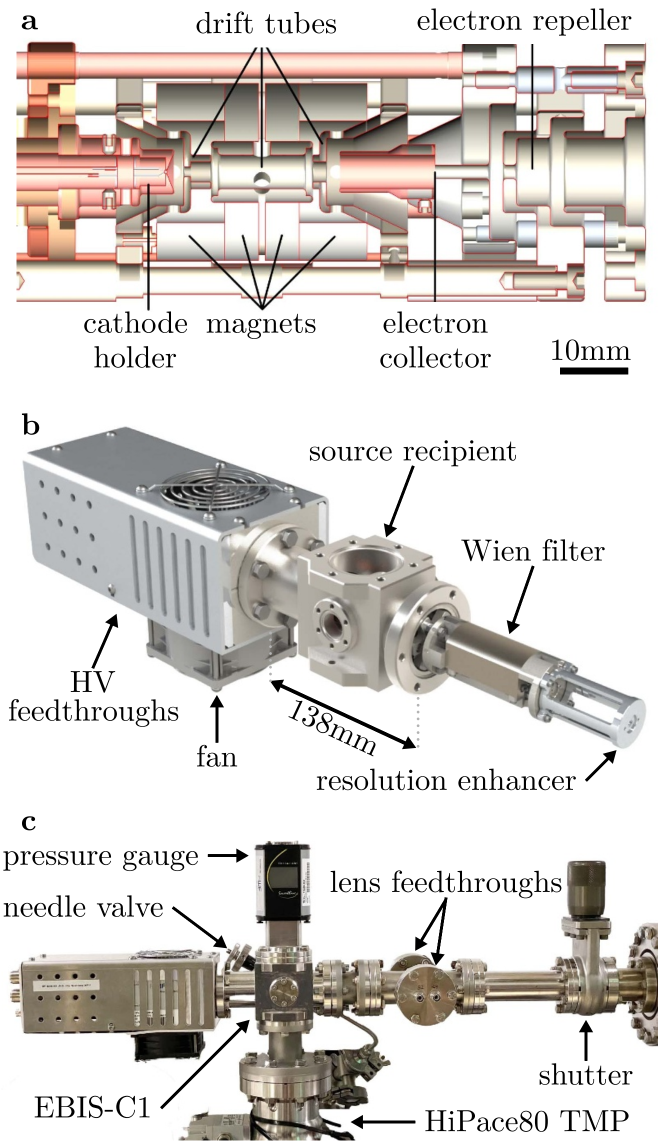

Figure 1. The EBIS-C1. (a) Technical drawing of the EBIS-C1. The important components are labelled in the figure. (b) Rendered image of the EBIS-C1. The source is housed in a DN40CF cube and two DN40CF tubes with a total length of 138 mm. A Wien filter and an additional aperture in a distance of ∼50 mm (resolution enhancer) are installed downstream of the ion source. The housing at the left side of the figure hosts a fan and HV feedthroughs for all source and Wien filter potentials. (c) Photograph of the EBIS-C1 setup at TU Wien. The target chamber where the extracted ion current is measured is located on the right behind the shutter. Dimensions of the EBIS-C1 with Wien filter: The housing of the HV feedthroughs and fan fits into a box measuring 243 mm in length, 105 mm in width, and 132 mm in height. Additionally, the distance from the ion source base flange to the end of the Wien filter is approximately 276 mm, and the source vessel itself is about 138 mm in length.

schematic representation is presented in figure 2(a), illustrating both operational modes. The associated potentials, as observed from the electron beam, are depicted in figure 2(b).

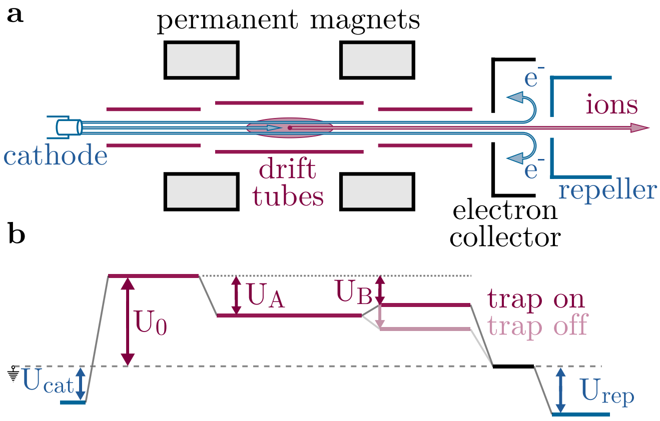

Figure 2. (a) Schematic of the source components: A cathode produces electrons, which are then accelerated towards a set of three drift tubes housed within permanent magnets, together serving as a trap for ions. The electrons are later repelled by an electrode and collected on an electron collector; the ions are extracted from the source. (b) The potential landscape of the source is shown: The three drift tubes are biased with potentials U_0, $U_0 - U_A$ and $U_0 - U_B$. Depending on the operation mode, U_B can be switched between two values to open and close the trap. The cathode and the electron repeller are biased to U_{cat} and U_{rep}, respectively.

3. Experimental setup and test chamber configuration

The experimental setup for the D.I.S EBIS-C1 prototype involved its installation at an ultra-high vacuum (UHV) chamber at TU Wien (cf figure 1(c)). Some support structure is necessary for proper mounting of the source; at TU Wien an Aluminium frame was designed for this purpose. A key feature of the EBIS-C1 is the compact design of NdFeB permanent magnets enclosing the drift tube column with an outer diameter of only ∼26 mm and a gap of 1 mm at the position of the second drift tube to allow also x-ray spectroscopy of trapped ions through a slit in the second drift tube utilizing a Be window DN16CF flange at the source vessel. NdFeB magnets are typically not UHV-suitable due to severe outgasing, but a special surface coating reduces the outgasing rate to maintain UHV conditions. To stay below the Curie temperature of the magnets (<150 °C) and to avoid damaging the ceramic components used, however, a maximum bakeout temperature of <120 °C has been specified for the EBIS-C1, which also needs to be carefully controlled. The magnet design achieves an axial magnetic field of ∼300 mT in the drift tubes. The electron cathode can be biased to ∼1.5 keV and the drift tubes to ∼5 kV (with 500 V offset for second and third drift tube to achieve the electrostatic trapping in axial direction). This results in an electron beam energy of ∼6.5 keV rendering charge states of Xe^{44+} or Ar^{18+} achievable, even though the cross section to produce these very high charge states is very small and their use is limited to single ion counting applications. If more intense HCI beams at pA or nA level are required, charge states of up to Xe^{30+} are available.

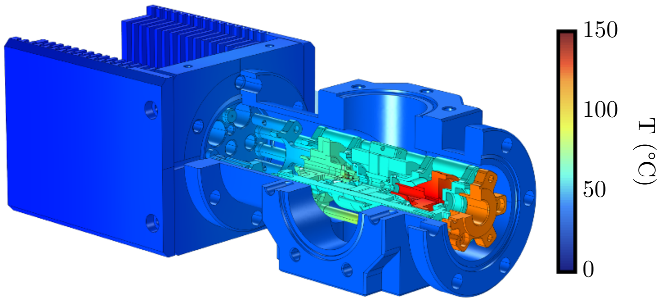

Figure 3. Temperature profile in the EBIS-C1 simulated with COMSOL Multiphysics 5.0 for continuous heat load of 30 W at the collector (red), 3 W at the cathode (1 Ω ohmic resistance and 1.5 A heating current) and 1 W at the second drift tube (150 μA blind current at 6.5 keV energy) considering a heat exchange to air at the passive cooling plates on the left (airside) with a heat transfer coefficient of 40 W $(m^2K)^{-1}$.

Table 1. Technical Data of EBIS-C1.

typical electron beam current	10 mA
required vacuum conditions	10^{-8} mbar or lower
maximum electron energy (at drift tubes)	11 keV
maximum ion acceleration potential	10 keV
ion trap length	15 mm
magnet system	bakeable NdFeB permanent magnets
cooling	air-cooling radiators
maximum bakeout temperature	120 °C
mounting flange	DN40CF, inner pipe diameter $\geqslant$39 mm
available space in the vacuum chamber	230 mm with Wien filter module

Another design feature of the EBIS-C1 is the passive cooling of the electron collector, omitting any water cooling system and complex vacuum equipment. The electron collector is made from a massive stainless steel part, which is connected to four ~5 mm thick Cu rods, which transport the heat to the base flange of the EBIS. On the airside the flange is connected to passive heatsinks and a standard fan-based air cooling suffices to remove the heat. The heat transport is designed for a continuous heat load of ~15 W at the collector, which corresponds to the product of 1.5 keV electron energy and 10 mA of electron current. This thermal load in addition to 3 W at the cathode and 1 W at the second drift tube with passive cooling to the airside where a heat exchange with 40 W $(m^2K)^{-1}$ is considered, was simulated with the Finite Element simulation package of COMSOL Multiphysics 5.0 neglecting any further convection to other metal UHV housing. Figure 3 shows that the collector (red) and assembly end cap (orange) heat the most. The drift tubes do not exceed 70 °C, keeping the magnets attached to the drift tubes well below the Curie temperature.

Note that for the EBIS-C1, larger fractions of 'blind currents', i.e. parasitic electron current on the drift tubes (and other electrodes) can be tolerated, as the total electron current (~10 mA) is relatively small compared to other EBISs. Hence, the heat load at and outgasing of electrode surfaces is not critical. A blind current is the result of unfavourable electron focus in the source due to a misaligned cathode or a non-optimal choice of voltages. In general, an EBIS operates at certain optimal working points (cathode potential, drift tubes, repeller voltage) characterised through minimal blind currents on the drift tubes, which in the case of the EBIS-C1 amounts to $\leqslant$50 μA. These working points, however, fix both the electron energy in the ionisation volume as well as usable acceleration potentials for the ions to distinct values. A larger tolerance window for blind currents up to 500 μA allows the operation of the EBIS-C1 with a wide range of electron energies and thus a tuning of the electron energy to certain ionization resonances or dielectronic recombination resonances. Versatile studies of atomic physics applications become therefore available. The key parameters of the EBIS-C1 are again summarised in table 1.

Operating an EBIS effectively requires the maintenance of ultra-high vacuum conditions. To achieve this, a Pfeiffer HiPace80 turbomolecular pump with a Pfeiffer HiCube80Eco pre-vacuum pump were installed, ensuring a base pressure of $\sim 1 \times 10^{-9}$ mbar. A needle valve is used to increase the pressure up to $\sim 1 \times 10^{-8}$ mbar by feeding the desired working gas into the system. The spectroscopy slit/holes in the magnet and DT2 further allow for good gas flow to the ionisation volume. Figure 1(c) shows the setup of our Small Ion Source for Surface Interaction experiments (SISSI) including the housing of the EBIS-C1 prototype on the left side, with two Thyracont VSH89DL pressure gauges employed for total pressure measurement. One gauge is positioned directly above the drift tube volume, while the other is mounted at the rear of the target chamber (not visible in the figure). Positioned beneath the target manipulator, a Gamma Vacuum TiTan ion pump, coupled with an attached titanium sublimation pump (TSP), further reduces pressure. A versatile 4-axis (xyzϕ) manipulator atop the chamber serves as a target holder for forthcoming irradiation experiments. The entire setup is controlled via LabVIEW software. Note that the target chamber and the corresponding pumping is used at TU Wien as a test setup to perform sample irradiations, to optimize ion source parameters, and is therefore not part of the actual ion source.

4. Results of commissioning experiments

For commissioning the D.I.S EBIS-C1 ion source, we analysed the ion current from leaky mode for various different parameters, such as electron beam current, electron beam energy, ionization time gas pressure and gas species. Regarding the latter, we present two Wien filter spectra for neon and argon working gas in figures 4(a) and (b), respectively. For neon, non-isotope-pure gas was used. Hence, all peaks appear in a double-peak structure consisting of a peak with small abundance followed by a peak with high abundance. These two peaks represent the natural mix of Ne, which consists of $\sim$10% ^{22}Ne and $\sim$90% ^{20}Ne. The isotope with smaller mass leads to higher velocities for the same acceleration potential and thus to a higher Wien filter voltage. Note that both spectra for Ne and Ar, respectively, were taken for parameter sets not tuned to highest charge states. The exact values for all electrode voltages, heating currents and gas pressures are given in the figure caption. To optimize the generation of ions in high charge states we varied the operation parameters in much detail, as shown as an example for xenon ions in figure 4(c). Charge states up to up to Xe^{33+} can be seen. Various electron repeller (suppressor electrode after the collector) voltages were used while all other parameters remained the same (given in the figure caption) and a dependence of the ion extraction on the repeller voltage was found: Low repeller voltages suppress low charge states. This result indicates that low and high charge states are produced at different sites inside the second drift tube and their emissivity is also different. Since the repeller electrode acts as an electrostatic lens on the ions, different areas in phase space will be imaged differently onto the entrance aperture of the Wien filter effectively suppressing or enhancing the usable ion current of certain charge states.

The currents shown in figure 4 are measured on a metal plate without electron suppressor and are therefore an overestimation of the actual ion current. From previous literature [31], we estimate the total secondary electron yield to be in the range of $2-3\times q$, when $q\gg 1$ is the charge state. Taking this factor into account, we estimate an usable ion rate of $\sim 10^6\,\mathrm{s}^{-1}$ for Xe^{30+}, which is for typical single ion (or secondary electron) counting based detectors already at the upper limit. For typical ion scattering or secondary particle spectroscopy, count rates as low as 1 kcps might be acceptable, rendering an EBIS-C1 suitable.

For beam shaping we used a self-built seven segment miniaturized einzel lens setup, similar to the one in [32]. The lens setup is designed to act as a deceleration lens if the EBIS-C1 would be negatively biased to produce very

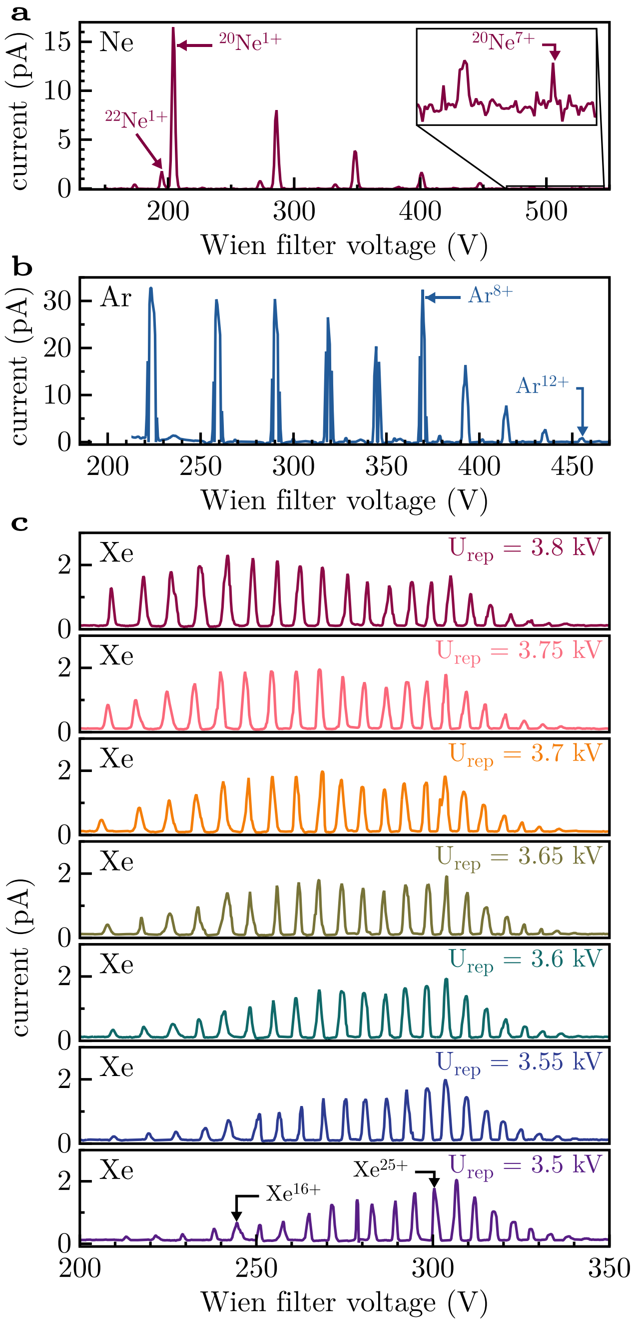

Figure 4. Charge state spectra of multiply charged ions extracted from an EBIS-C1 in leaky mode. (a) Neon spectrum up to Ne^{7+}. Note that the source was tuned for Ne^{5+}. Parameters used: cathode potential $U_{cat}=-786$ V and heating current $I_h=2.11$ A; electron emission current $I_e=3.37$ mA, drift tube potentials $U_0=4670$ V, $U_a=-110$ V, $U_b=-83.6$ V; repeller voltage $U_{rep}=1490$ V; working gas pressure $p=2.0\times 10^{-8}$ mbar. (b) Argon spectrum up to Ar^{12+}. Note that the source was tuned for Ar^{8+}. Parameters used: $U_{cat}=-771$ V, $I_h=2.14$ A, $I_e=7.36$ mA, $U_0=5000$ V, $U_a=-400$ V, $U_b=-358$ V, $U_{rep}=2200$ V, $p=2.2\times 10^{-8}$ mbar. (c) Xenon spectra for different repeller voltages. Low repeller voltages suppress low charge states. Parameters used: $U_{cat}=-945$ V, $I_h=2.17$ A, $I_e=8.4$ mA, $U_0=3300$ V, $U_a=-446$ V, $U_b=-415$ V, $p=9.3\times 10^{-9}$ mbar.

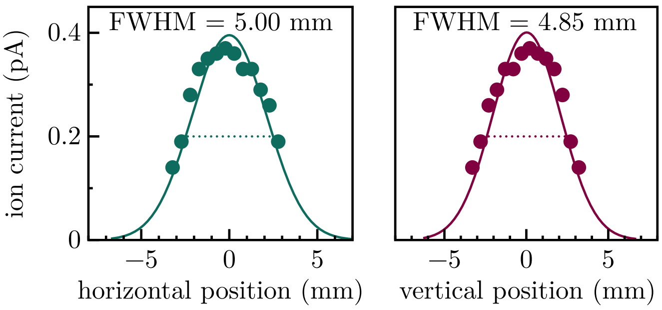

Figure 5. Horizontal and vertical beam profile of Xe^{30+} measured in a flat stainless steel plate ∼30 cm after the Wien filter without additional focusing. Measurement parameters used for the beam profile measurements: cathode potential $U_{cat} = -945$ V and heating current $I_h = 2.17$ A; electron emission current $I_e = 8.4$ mA, drift tube potentials $U_0 = 3300$ V, $U_a = -446$ V, $U_b = -415$ V; repeller voltage $U_{rep} = 3670$ V; Wien filter voltage $U_{WF} = 317$ V; working gas pressure $p = 9.3 \times 10^{-9}$ mbar.

slow highly charged ions with adjustable kinetic energy as described in [32], and it contains two sets of deflector plates to steer the ion beam. The HCI beam without any additional electrostatic focusing has a size of $\sim 5 \times 5$ mm^2 (see figure 5). At this spot size for a current of ∼500 fA Xe^{30+} ions (cf figure 5), we can therefore achieve a fluence rate of $\sim 10^5$ ions cm^{-2} s^{-1} also usable to produce about 10^{10} damage sites per cm^2 in a reasonable irradiation time of ∼24 h which is only somewhat longer than for established HCI irradiation facilities. Further focusing the beam utilising the electrostatic lens system would achieve much higher fluences or shorter irradiation times on a smaller spot.

5. Conclusion and outlook

The successful commissioning of the EBIS-C1 resulted in the generation of Ar, Ne, and Xe ions in sufficiently high charge states and quantities, demonstrating the importance of this compact EBIS for the study of the dynamics of HCI-surface interactions. Its compact design and simplified operation reduces the expertise and costs required, making it highly accessible for a broad range of experiments in atomic physics, astrophysics, surface science, and fundamental research. With its easy portability and adaptability, the EBIS-C1 opens up exciting new possibilities for carrying out experimental studies in large research infrastructures that were previously not possible with highly charged ions, or only possible after moving or shipping heavy equipment (ion source, pumps, power supplies, etc) and time-consuming installation of a complex assembly of many different parts. Attempts to miniaturize EBISs elsewhere [1] indicate a growing interest in this novel class of devices and aim to foster new applications of HCIs across diverse scientific domains.

For example, the compact nature of the EBIS-C1 allows it to be seamlessly integrated into almost any experimental setup, as easy as installing a commercial singly charged ion source, such as a sputter gun. In a surface analysis setup, which relies on the detection of charged particles emitted or reflected from a surface, such as a secondary ion mass spectroscopy (SIMS) or low-energy ion scattering (LEIS) apparatus, e.g. replacing the commercial ion source with a compact EBIS would allow to enhance the ratio of charged to neutral particles and thus boost the detection efficiency by orders of magnitudes [33]. This would make SIMS a quantitative technique without the use of calibration standards [34]. Installation in a scanning electron microscopy (SEM), transmission electron microscopy (TEM), scanning tunneling microscopy (STM) or atomic force microscopy (AFM) experiment would allow to employ novel methods of surface modifications [10, 25, 35]. When used in pulsed vapour deposition (PVD) equipment, highly charged ions could improve thin film deposition by depositing energy on the topmost growing surface layer enhancing atom diffusion and smooth layer growth.

The integration of a compact EBIS in the user end station of x-ray free electron lasers (XFELs) would provide an opportunity to perform laser spectroscopy on HCI in the x-ray region [36] and study the fundamental interaction of highly charged ions with light, in particular high-energy photons. A particular interesting possibility would be the production of highly polarized beams of highly charged ions by optical pumping when using polarized XFEL photon beams.

The ability to replace singly charged ions with highly charged ones offers the possibility of novel ion implantation techniques, manipulating and optimizing semiconductor properties for advanced device fabrication. Implantation of single nitrogen ions in diamond to create (regularly spaced) nitrogen-vacancy (NV) centers for quantum computing would benefit from the high electron emission yield of highly charged nitrogen ions ($>5\,e^-$/ion), which would make it possible to detect the impact of an ion and thus create an isolated NV centre with virtually 100% efficiency [37, 38]. Other examples are the beneficial effects of highly charged ions for the fabrication of Josephson junctions [39, 40].

EBIS's charge breeding capabilities offer the potential to improve particle acceleration for the development of more compact and efficient accelerators, which could be useful for radioisotope detection and mass measurements of short lived isotopes [41], medical imaging and therapy, and other accelerator-driven technologies.

Looking ahead, further advancements may include compact ion beam lithography applications, integration with quantum technologies, atomic clocks based on highly charged ions [42], enhanced portable medical applications, contributions to remote sensing in space exploration, and environmental analysis tools. All these applications would need major efforts to develop them, and the EBIS-C1 would contribute as a compact and easy-to-use supply of slow highly charged ions in lab-based design strategies.

Data availability statement

The data cannot be made publicly available upon publication because they contain commercially sensitive information. The data that support the findings of this study are available upon reasonable request from the authors.

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