

Compact electron beam ion sources/traps: Review and prospects (invited)^{a)}

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The Dresden electron beam ion trap (EBIT)/electron beam ion source (EBIS) family are very compact and economically working table-top ion sources. We report on the development of three generations of such ion sources, the so-called Dresden EBIT, Dresden EBIS, and Dresden EBIS-A, respectively. The ion sources are classified by different currents of extractable ions at different charge states and by the x-ray spectra emitted by the ions inside the electron beam. We present examples of x-ray measurements and measured ion currents extracted from the ion sources at certain individual operating conditions. Ion charge states of up to Xe^{48+} but also bare nuclei of lighter elements up to nickel have been extracted. The application potential of the ion sources is demonstrated via proof-of-concept applications employing an EBIT in a focused ion beam (FIB) column or using an EBIT for the production of nanostructures by single ion hits. Additionally we give first information about the next generation of the Dresden EBIS series. The so-called Dresden EBIS-SC is a compact and cryogen-free superconducting high- B -field EBIS for high-current operation. © 2008 American Institute of Physics. [DOI: [10.1063/1.2804901](https://doi.org/10.1063/1.2804901)]

I. INTRODUCTION

Beginning with the 1980s of the last century highly charged ions (HCIs) have become interesting in fields of research such as atomic physics, plasma physics, accelerator physics, and others. Hence there is a need producing HCI in laboratories independent of the existence of huge accelerator facilities. In this context the construction and successful operation of the first electron beam ion trap (EBIT) device¹ provided an economic access to HCI. The principle of operation of this device was similar to existing cryogenic electron beam ion source (EBIS) known from earlier works.²

Classical EBIT devices use liquid helium to ensure the necessary temperatures for superconducting coils forming the magnetic fields from 3 to 8 T. The axial magnetic field compresses the cathode-emitted electrons to a high-dense beam which acts as the ionization medium in the ion source. In this context the request for inexpensive compact devices arises at which liquid helium does not dominate the operating costs. A possible solution is the use of permanent rare-earth magnets instead of superconducting coils, i.e., the construction of a room-temperature EBIT. Basically the use of permanent magnets limits the maximum magnetic field strength resulting in lower electron current densities. In the present paper the development of the Dresden EBIT/EBIS family³ will be described answering the question which

ion charge states and ion beam currents can be produced with that technology. The presented work continues early attempts to develop room-temperature ion sources for highly charged ions.^{4–8}

II. ROOM-TEMPERATURE EBIS/T: THE DRESDEN ION SOURCE FAMILY

In 1999 a development program for room-temperature EBIT/EBIS was started as a cooperation project of the Dresden University of Technology and a medium enterprise active in the business segment of vacuum techniques. The goal was not to produce the highest ion charge states but to develop an ion source generation producing a wide spectrum of highly charged ions of almost all stable elements. The design of the ion sources was supposed to allow x-ray, UV, EUV, and visible light spectroscopies of radiation emitted by ions inside the trap. Furthermore, the produced ions should be provided for external ion irradiation experiments. The impor-

TABLE I. Basic parameters of cryogenic and room-temperature EBIT.

Parameter	Cryogenic EBIT/EBIS	Dresden EBIT/EBIS
Formation of the magnetic field	Cryogenic Helmholtz coils	Permanent magnet rings
Magnetic field strength	3–8 T	250–620 mT
Vacuum	10^{-10} mbar and better	$(1–100) \times 10^{-10}$ mbar
Electron energy	Up to 200 keV	Up to 32 keV
Electron beam density	Some 1000 A/cm ²	100–1000 A/cm ²

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TABLE II. Parameters of the Dresden EBIT/EBIS ion source family. B : magnetic induction on the axis; I_e : highest reached electron beam current (the used cathode diameter is given in parenthesis); j_e : highest measured electron current density; E_e : highest reached electron beam energy.

Parameter	Dresden EBIT	Dresden EBIS	Dresden EBIS-A
Trap length	2 cm	6 cm	6 cm
Magnets	SmCo	NdFeB	NdFeB
B (T)	0.25	0.40	0.62
I_e (mA)	70 (0.5 mm) 120 (1 mm)	250 (1 mm)	450 (1 mm)
j_e (A/cm ²)	150 (0.5 mm)	650 (0.5 mm)	
E_e (keV)	17	25	32

tant differences of the Dresden EBIT/EBIS ion source family in comparison to cryogenic ion sources are summarized in Table I.

The principle of construction and of operation of the ion source family is very similar to the well-known one of cryogenic sources, but it differs in the details of the realization of individual assemblies such as the electron gun, the drift tube design, the magnetic field formation, and the alignment of all functional units.^{9,10} In Table II parameters of the ion sources are listed. It should be emphasised that extreme values of j_e , E_e , and I_e do not necessarily lead to the highest ion currents and highest ionization stages. Experiments have shown that the set of optimal parameters of each source type is not associated with the maximum of reachable values.

Figure 1 shows the three ion source generations. It can be seen that the ion sources are characterized by very compact dimensions. They can easily be adjusted to assemblies such as focused ion beam (FIB) columns, time-of-flight secondary ion mass spectroscopy (TOF-SIMS) spectrometers, or existing beam lines. Ensuring work safety the ion sources are equipped with special electrical shieldings and connectors, as shown in Fig. 2.

III. EXPERIMENTS WITH THE DRESDEN EBIS/T

In 1999 the Dresden EBIT was primarily designed to provide x-ray spectroscopy on highly charged ions. How-

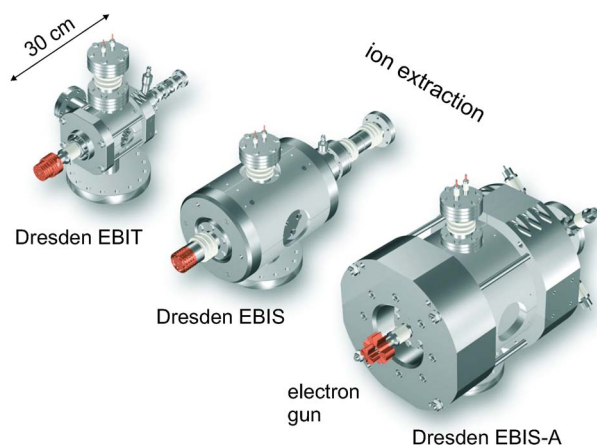


FIG. 1. (Color online) Design of the three ion source generations: Dresden EBIT, Dresden EBIS, and Dresden EBIS-A.

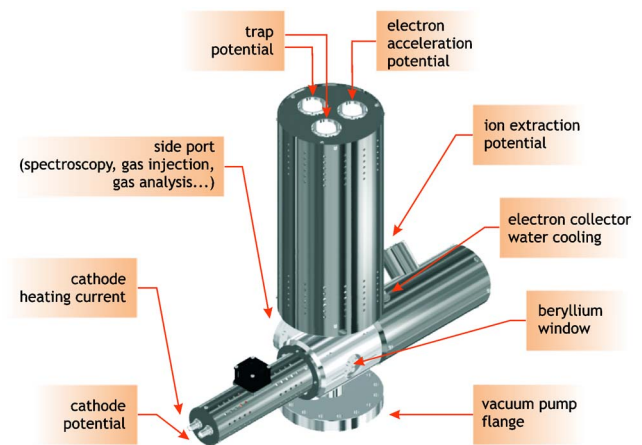


FIG. 2. (Color online) Scheme of the Dresden EBIT with electrical shielding.

ever, since that time the application spectrum of the EBIT/EBIS ion sources has increased significantly. Investigations on extracted beams of highly charged ions become more and more important. We will show exemplarily some results demonstrating the versatile applications of room-temperature EBIS/EBIT.

A. X-ray spectroscopy

X-ray spectroscopy on highly charged ions was done with energy-dispersive as well as with wavelength-dispersive spectrometers. It was shown that the spectral brightness of the source is sufficient performing spectroscopic investigations in a reasonable time frame. For example, the spectral brightness of the $4d(^3F_4) \rightarrow 5p(^3G_5)$ transitions in Xe^{10+} is approximately 2×10^4 photons/s mm² mrad²/0.1% $\Delta\omega/\omega$. The radiation power of many dipole lines is in the order of 10 nW. These properties are discussed in detail in Ref. 17. For light elements the x-ray output is measured from 10^7 to 10^9 photons in 4π sr s⁻¹.

X-ray spectroscopy on highly charged ions is concentrated on the spectroscopy of direct excitation processes (DE), radiative recombination, and dielectronic recombination, respectively.

In Table III we give an overview of the investigated

TABLE III. Ion production in the ion sources of the Dresden EBIT/EBIS family (selected milestones).

Year	Citation	Source	Ions
1999	9	EBIT	Xe^{44+} , Ir^{59+}
2000	11	EBIT	Ir^{63+}
2000	12	EBIT	Fe^{25+} , Ce^{48+} , Ge^{31+} , Sn^{44+} , Ir^{66+}
2000	13	EBIT	Ce^{48+} , Hg^{66+}
2001	14 and 15	EBIT	$\text{Xe}^{(45,46)+}$
2002	16	EBIT	Ar^{18+} , Mn^{25+} , Fe^{26+} , Ni^{28+}
2004	17	EBIT	Ti^{21+}
2004	18	EBIT	P^{15+}
2005	19	EBIS	Kr^{34+} , $\text{Xe}^{(45,46)+}$
2005	20	EBIT	Ge^{30+}
2007	21	EBIS-A	Ar^{18+} , Xe^{45+} , Ce^{49+}
2007		EBIS-A	H_2^+ , C^{6+} , Kr^{35+} , Xe^{48+}

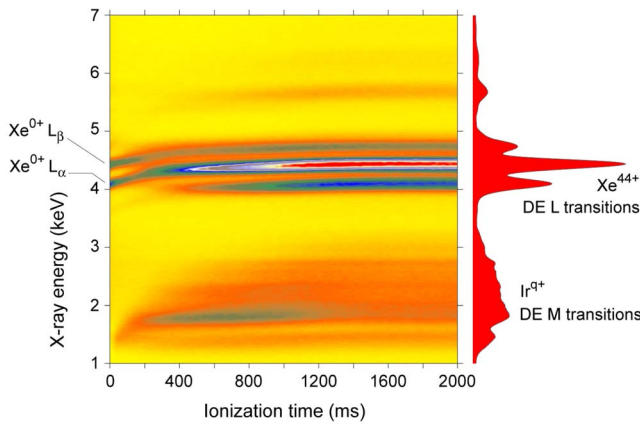


FIG. 3. (Color online) Scatter plot of the x rays from direct excitation processes of xenon.

ions produced in the Dresden EBIT/EBIS during the last years. Figure 3 shows a time-resolved xenon DE spectrum measured with a silicon semiconductor detector (energy resolution of 130 eV at 6 keV). The evolution of the charge states of the initially neutral xenon atoms can be seen in the scatter plot. Corresponding measurements can be used for ion source diagnostics yielding information of the ionization process.

B. Ion extraction

The ions are extracted in leaky (dc) mode or in pulsed mode from the ion sources. The ion sources of the Dresden EBIT/EBIS family differ in trap length, applied axial magnetic field, and maximum emitted electron beam current. Further on electron guns with cathodes of different diameters

TABLE IV. Number of ions produced in the ion sources of the Dresden EBIT/EBIS family (selected values).

Ion	Dresden EBIT leaky mode (ions/s)	Dresden EBIS-A leaky mode (ions /s)
H ⁺	1.5×10^8	2×10^{10}
Ar ¹²⁺	2.5×10^6	8×10^7
Ar ¹⁶⁺	4×10^5	2.5×10^6
Ar ¹⁷⁺	2×10^4	7×10^5
Ar ¹⁸⁺	...	5×10^4
Xe ³⁶⁺	...	1.2×10^6
Xe ⁴⁴⁺	...	2.4×10^5
Xe ⁴⁵⁺	...	8×10^4
Xe ⁴⁶⁺	...	3×10^4
	Pulsed mode ions/pulse	Pulsed mode (ions/pulse)
C ⁶⁺	2×10^6	8×10^7
Ar ¹²⁺	1×10^7	7.2×10^7
Ar ¹⁶⁺	9×10^5	8×10^6
Ar ¹⁷⁺	4×10^4	1.4×10^6
Ar ¹⁸⁺	6×10^3	9×10^4
Xe ⁴⁴⁺	1×10^4	7.4×10^5
Xe ⁴⁵⁺	2×10^3	5.6×10^5
Xe ⁴⁶⁺	6×10^2	1.1×10^5
Xe ⁴⁷⁺	...	5×10^4

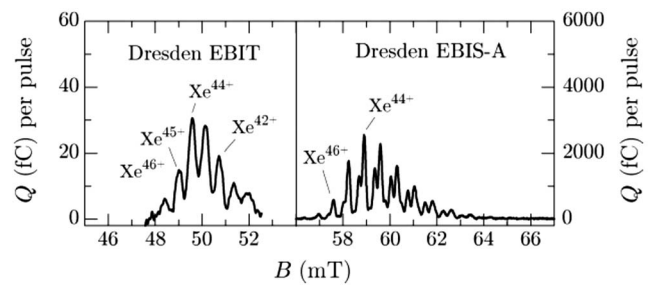


FIG. 4. Xenon ions extracted from the Dresden EBIT ($E_e=13$ keV, $I_e=34$ mA, $p=5 \times 10^{-10}$ mbar, gas: Xe-129) and the Dresden EBIS-A ($E_e=13$ keV, $I_e=80$ mA, $p=1 \times 10^{-9}$ mbar, gas: natural isotope mixture), respectively. The spectra are measured at different beamlines with different analyzing magnets.

(from 0.5 to 2 mm) can be employed due to the modular construction of all ion sources. Therefore different electron beam densities at various electron beam currents can be realized. Consequently cathodes with small diameters (i.e., small electron emission areas) lead to the highest ionization factors at the highest available magnetic fields. On the other hand intense currents of lower charged ions are produced in high electron beam currents emitted from cathodes of larger diameter (i.e., lower electron beam density).

In Table IV we give a comparison of the extracted ions measured at the Dresden EBIT and EBIS-A, respectively. The indicated ion numbers correspond to different operating parameters, i.e., the ion beam line optics was optimized for the production and the transport of individual ion charge states.

An example of extracted xenon ion charge state spectra measured at the different ion sources of the Dresden EBIT/EBIS type is shown in Fig. 4. The ion currents extracted from the Dresden EBIS-A are two orders of magnitude higher than those from the Dresden EBIT.

Usually the beam emittance is used to characterize the quality of the ion beam. It is defined as the product of the average of the ion trajectories and their slopes along the axis of motion. The emittance of an EBIT is determined by the virtual ion source size r_i , the ion temperature $k_b T_i$, and the ion beam potential U_{beam} ,

$$\varepsilon = \pi r_i \sqrt{k_b T_i / qe U_{\text{beam}}}, \quad (1)$$

$$\begin{aligned} \varepsilon_{\text{norm}} &= \varepsilon \beta \gamma = \varepsilon \beta (1 - \beta^2) = \varepsilon \frac{v}{c} \left(1 - \frac{v^2}{c^2}\right) \\ &= \varepsilon \frac{\sqrt{2qeU_{\text{beam}}/m}}{c} \left(1 - \frac{2qeU_{\text{beam}}/m}{c^2}\right), \end{aligned} \quad (2)$$

with the ion charge q , the ion velocity v , and the ion mass m . For typical source parameters (e.g., Ar¹⁶⁺ at 5 kV ion beam potential) we obtain an emittance ε of 5π mm mrad and a normalized emittance $\varepsilon_{\text{norm}}$ of $2 \times 10^{-3} \pi$ mm mrad, respectively. The emittance can be improved by decreasing the ion temperature (via evaporative self-cooling) and the ion source size (via higher magnetic fields).

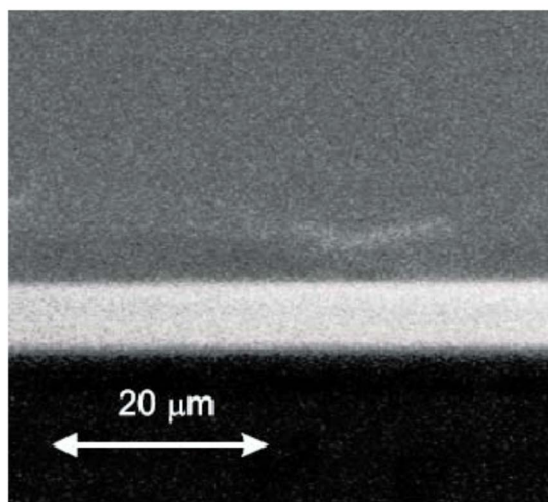


FIG. 5. (Color online) SEM image of an edge structure of a silicon sample by scanning the helium beam.

C. Experiments toward to applications of HCI

Ion sources of the Dresden EBIT/EBIS family have been successfully integrated in different experiments and irradiation facilities such as the MBF facility of the TU Dresden²² and the two-source facility of the Forschungszentrum Dresden-Rossendorf.²³

The small size of the ion sources allows integrating them in different production tools such as FIB columns or TOF-SIMS spectrometers. As an example we refer to the experiment of the production of helium beams in a focused ion beam column using a Dresden EBIT ion source²⁴ and producing helium beams of beam diameters less than 1 μm . These beams were used to obtain images from surface structures via secondary electron spectroscopy. An example of a scanning electron microscopy (SEM) image is shown in Fig. 5. In this experiment the EBIT was operated in dc mode with a helium beam current of about 1 nA at the entrance aperture of the FIB column and ion currents at the target of 1–2 pA. In additional experiments it was demonstrated that other noble gases such as neon, argon, and xenon can be used too.

In experiments at the two-source facility at the FZ Dresden-Rossendorf, it was demonstrated that highly charged ions can create surface structures on the nanometer scale. Thereby the dimensions of the structure depend on the ion charge state, the kinetic energy of the projectile, and the conducting properties of the surface. Figure 6 shows an example of a surface structure produced by xenon ion impact on HOPG. Currently there are worldwide activities investigating the influence of the ion charge state and associated parameters on the morphology of surfaces of different materials. In this context we demonstrated the use of the Dresden EBIT/EBIS ion sources for corresponding studies.

IV. THE NEXT STEP: THE DRESDEN EBIS-SC

An increase of ion beam current is necessary for some new areas of application, e.g., the deployment in medical irradiation facilities for cancer treatment.²⁵

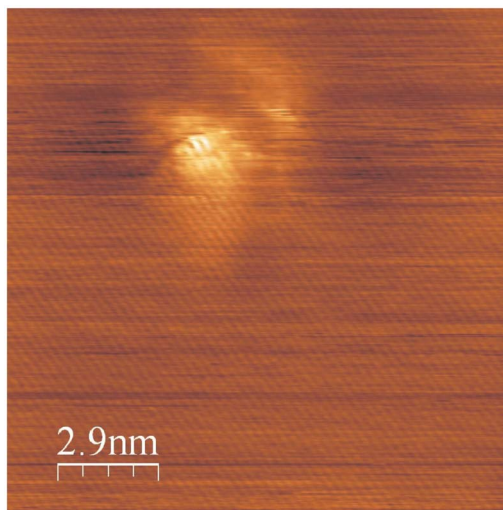


FIG. 6. (Color online) Transmission electron microscopy image of a HOPG sample irradiated with 4 keV Xe^{20+} ions.

The currently available room-temperature EBIT from the Dresden EBIT/EBIS family does not satisfy these requirements because the electrical trap capacity of an electron beam ion source is limited to

$$C_{\text{trap}} = 1.05 \times 10^{13} \frac{I_e(\text{A})L(\text{m})}{\sqrt{E_e(\text{eV})}}, \quad (3)$$

with the electron beam current I_e , the trap length L , and the electron energy E_e . A critical review leads to the conclusion that for a high-current EBIS the electron beam current and the trap length need to be increased. An unlimited lowering of the applied electron beam energy is not possible because the electron energy necessary for a certain ionization level has to be evidently higher than the corresponding ionization potential (up to three times of the ionization potential of the weakest bound electron in the system). For the operation with higher electron beam currents, a higher magnetic field compression is necessary to generate high electron current densities (ionization factor). This precondition can hardly be realized using permanent magnets. Hence a new ion source with significantly greater magnetic induction, the so-called Dresden EBIS-SC (SC. SuperConducting), is under construction.

The EBIS-SC will have an overall length of about 50 cm and a diameter based on DN 200CF. No liquid gases will be required due to a closed coolant cycle. Water with regular water pipe pressure will be used as coolant for the anode and the electron collector. The Dresden EBIS-SC is designed as a compact superconducting ion source based on the most modern principles of refrigeration technologies as well as electron beam technologies. Projected parameters of the new ion source generation are summarized in Table V.

V. CONCLUSION

Since 1999 three generations of high innovative EBIS/EBIT ion sources have been developed. The sources differ in the extractable currents of HCI and in the available output of electromagnetic radiation emitted by highly charged ions lo-

TABLE V. Projected parameters of the Dresden EBIS-SC.

Parameter	Value
Total length	Approx. 50 cm
Magnetic field	6 T
Electron energy	Up to 30 keV
Electron current	Up to 1 A
Effective electron current density	Up to 1000 A/cm ²
Trap length	20 cm
Trap capacity	eight drift tube segments Up to $5 \cdot 10^{10}e$

calized in the high-dense electron beam. It has been demonstrated that the ion sources can produce highly charged ions of almost all elements. The sources have a high application potential due to their compact design and simple system integration. They are used in several existing cooperations and will be deployed in further cooperations. Beside heavy HCI intense beams of light ions such as protons and C⁶⁺ ions are of special interest for applications in the medical particle therapy. Therefore a new generation, the Dresden EBIS-SC, is designed to satisfy the request for a higher ion current output. To keep the compact size and other advantages the design is based on modern superconducting and refrigerating technology. The beginning of operation of the Dresden EBIS-SC is scheduled for 2008.

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