First investigations on the Dresden EBIS-A

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Abstract. We present first experimental investigations on the Dresden EBIS-A, an advanced design of the Dresden EBIT. The Dresden EBIS-A, an EBIT machine working at room-temperature is equipped with a NdFeB ring magnet system producing a magnetic field on axis of about 620 mT. The measurement of integral ion pulses from the ion source yield a number of extracted elementary charges in the order of \(10^9\) per ion pulse. It is shown that the width of the ion pulse can be changed from microseconds up to several tens of microseconds varying the potential of the third drift tube section. The measurement of separated charge states provides an indication of an increased ion output compared to that of the Dresden EBIT. X-ray spectra account for the production of ions such as Ar^{17+}, Xe^{44+} and Ce^{49+} in the electron beam of the ion source.

1. Introduction

In the past we reported on the development of two ion sources, the Dresden EBIT and the Dresden EBIS, producing highly charged ions at room-temperature using permanent magnets [1-3]. Their small sizes, simple installation and simple operation are advantages that come with a source design without superconducting magnets and liquid helium, in contrast to cryogenic EBIT devices [4-7]. It has been shown in a series of experiments and applications [8-10] that the ion output is limited to a certain extent. Many applications using ions, and particularly highly charged ions demand for an increased ion yield.

A further improvement of the Dresden EBIT comprises generally an increase of the electron beam current, which demands an increased magnetic field strength to keep the electron current density, that is necessary to obtain high ionization stages. This in turn causes an increase of the source dimensions. However, any improvement of the ion output will extend the range of applications of the ion source.

2. Ion source design

Since the trap capacity of an EBIS increases linearly with the electron beam current, the Dresden EBIS-A uses a cathode which is designed to emit an electron current of up to 500 mA. In addition the trap length is extended to 60 mm. The magnetic system is based on two NdFeB rings which are installed around the vacuum vessel of the source body. This allows for baking as well as modifications of any kind without concerning the magnetic infrastructure. The magnetic field strength which is available on the source axis is 620 mT. Altogether this results in an enlargement of the ion source set-up which is shown in figure 1.
Table 1. Parameters of the Dresden EBIT, Dresden EBIS, and Dresden EBIS-A.

| Parameter                  | Dresden EBIT | Dresden EBIS | Dresden EBIS-A |
|----------------------------|--------------|--------------|---------------|
| Trap length                | 20 mm        | 60 mm        | 60 mm         |
| Maximum electron current   | 50 mA        | 250 mA       | 500 mA        |
| Maximum electron energy    | 15 keV       | 30 keV       | 45 keV        |
| Magnetic induction on axis | 250 mT       | 400 mT       | 620 mT        |

Table 1 compares the parameters of the Dresden EBIS-A with its forerunner models. So far, the electron current has been set to a maximum value of 400 mA. The application of high voltage to the drift tubes has been tested to be stable up to 30 kV.

3. Ion extraction

The ions are trapped radially by the negative space charge of the electron beam, and axially by an electrostatic potential of some tens of volts realized by lowering the potential on the center drift tube section $U_2$ against the potential on the outer drift tube sections $U_1$ and $U_3$.

The ions can be extracted either in leaky mode, that is, in DC mode or in pulse mode. In DC mode the ions escape from the trap over a reduced constant axial trap potential $U_3$. However, the charge states that can be obtained are limited. In pulse mode the trap is opened after a definite ion breeding time, which is necessary to produce the designated charge state. To do so the potential on the third drift tube section $U_3$ is lowered beneath the potential on the second drift tube section $U_2$. The width of the ion pulse is determined by the potential on the third drift tube section $U_3$ while the trap is open.

The ion current is measured by means of the positive charges collected at a Faraday cup following the ion extraction lens system which is part of the ion source. The ion pulse signal is detected by an oscilloscope in addition with a current voltage converter that at the same time amplifies the signal. The amplification was set to $10^6$. Figure 2 shows the ion pulses obtained at different potential differences between the second and the third drift tube section $U_2 - U_3$. The broadening of the pulse width with decreasing amplitude of the potential difference is significant.
Figure 2. Ion pulses of xenon ions extracted after a confinement time of 100 ms assuming a mean charge state of about $\text{Xe}^{30+}$. The ions are detected for three potential differences $U_2 - U_3$. The time base is set to 10 $\mu$s per division, the vertical deflection is set to 2 V which corresponds to 2 $\mu$A per division.

Figure 3. Detection of argon ions extracted in DC mode from both, the Dresden EBIT (left part) at an electron current of 30 mA ($E_e = 7.7$ keV, $p = 3 \times 10^{-9}$ mbar) and from the Dresden EBIS-A (right part) at an electron current of 50 mA ($E_e = 15$ keV, $p = 3 \times 10^{-9}$ mbar).

Integration of the ion pulse gives the number of charges. Reading off the pulse width with 10 $\mu$s and the height with 10 $\mu$A at $U_2 - U_3 = 400$ V results in about $10^9$ elementary charges.

After passing an analyzing magnet the ions are separated according to their mass to charge ratio and collected in a Faraday cup. Figure 3 shows two extraction spectra of argon ions extracted in DC mode, one from the Dresden EBIT and the other from the Dresden EBIS-A. Although the maximum output in DC mode is reached for $\text{Ar}^{8+}$ higher charge states up to helium-like $\text{Ar}^{16+}$ ions can be detected in continuous output.

The ion output of the Dresden EBIS-A represented by the extracted ion currents in figure 3 is found to be about 5 times higher than that from the Dresden EBIT, which can be explained by the extension of the trap length (factor 3) and an increased electron current of 50 mA.

4. X-ray spectroscopy

The analysis of X-ray spectra taken from the trap region of the Dresden EBIS-A provides evidences of the production of highly charged ions. The left part in figure 4 shows an X-ray spectrum of highly charged argon ions detected by a solid state Si(Li) detector.

The $2p \rightarrow 1s$-transitions in argon at an X-ray energy of about 3.15 keV prove the existence of helium-like argon ions. The production of hydrogen-like argon ions can be read off by both its $2p \rightarrow 1s$-transition at 3.3 keV and the radiative recombination into the $1s$-shell at 17.8 keV. Evidence of the production of fully ionized argon ions is also provided by the radiative recombination into the $1s$-shell at 18.2 keV. In addition transitions in cerium and iridium ions which originate from the cathode surface are found. Since the atomic mass of argon is light
compared to that of cerium and iridium the argon ions act as coolants for them. Hence, iridium and cerium considerably contribute to the X-ray output. The observation of the radiative recombination into the 2p-shell of cerium accounts for the existence of fluorine-like Ce$^{49+}$.

The production of highly charged xenon ions is shown in the right part of figure 4. The applied electron beam energy of 11 keV is sufficient to excite L-shell electrons. The energetic position and structure of the following 3d→2p-transitions account for the production of neon-like xenon ions. The same is found analyzing the structure of the radiative recombination. Furthermore, the radiative recombination into the 2p-shell allows for the detection of Xe$^{45+}$.

5. Conclusion

An advanced design of the Dresden EBIT, the Dresden EBIS-A, has been put into operation successfully. The extraction of xenon ions with an integral number of $10^9$ elementary charges has been shown so far. The increase of the ion output of the Dresden EBIS-A, compared to that of the Dresden EBIT, is consistent with the extension of the trap length and the increase of the electron current. The analysis of X-ray spectra proves the production of high ionization stages, such as bare argon and fluorine-like xenon ions. In addition highly charged ions of the cathode materials cerium and iridium, such as Ce$^{49+}$ can be observed.

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