Nuclear Instruments and Methods in Physics Research B xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Universal main magnetic focus ion source for production of highly charged ions

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A R T I C L E I N F O

Article history:
Received 26 October 2016
Received in revised form 10 May 2017
Accepted 11 May 2017
Available online xxxx

Keywords:
Atomic ions
Ion source
Smooth and rippled electron beams

A B S T R A C T

A novel room-temperature compact ion source has been developed for the efficient production of atomic ions by means of an electron beam with energy E_e and current density j_e controllable within wide ranges ($100\ \text{eV} \lesssim E_e \lesssim 60\ \text{keV}$, $10\ \text{A/cm}^2 \lesssim j_e \lesssim 20\ \text{kA/cm}^2$). In the first experiments, the X-ray emission of Ir^{64+} ions has been measured. Based on a combination of two different techniques, the device can operate both as conventional Electron Beam Ion Source/Trap and novel Main Magnetic Focus Ion Source. The tunable electron-optical system allows for realizing laminar and turbulent electron flows in a single experimental setup. The device is intended primarily for fundamental and applied research at standard university laboratories.

1. Introduction

Nowadays there is a need to produce atomic ions of any elements of the periodic table in different charge states: from very low charged ions for modern lithography, fusion, astrophysics etc. to highly charged ions for atomic physics and accelerators. The electron beams required for such purposes should be characterized by current density j_e and energy E_e varying within wide ranges ($10\ \text{A/cm}^2 \lesssim j_e \lesssim 10\ \text{kA/cm}^2$, $100\ \text{eV} \lesssim E_e \lesssim 100\ \text{keV}$). Satisfying these requirements in a single device is a very complex task [1–3]. Most of Electron Beam Ion Traps (EBITs) developed around the world operate stably in rather limited energy regimes. As characteristic examples of such devices one can mention the CoBIT with incident electron energy from 100 eV to 2.5 keV [4], EBIT with electron energy of up to 30 keV [5] at the Lawrence Livermore National Laboratory (LLNL) and LLNL SuperEBIT with $E_e \sim 200$ keV [6].

2. Techniques for production of highly charged ions

At present, two methods for the production of highly charged ions by electron beams are known. The conventional technology is realized in the Electron Beam Ion Sources and Traps (EBIS/Ts) [5,7], where the working gas is ionized by the *smooth* electron beam propagating through a few (at least three) sections of the drift-tube assembly along the z axis (see Fig. 1(a)). Ions are radially confined by the space charge of the electron beam. In addition, the trapping potential well can be strengthened by means of the variable inner diameter of the drift-tube segments. Axial ion-trapping potentials are created by voltages applied to the outermost drift-tube electrodes. The extraction of ions from the trap is realized by decreasing the potential barrier in the direction of output. In the extraction regime, the EBIT is transformed into the EBIS. In the EBIT, the central section of drift tube is equipped with the slits for registration of the characteristic radiation of ions. In order to increase the current density, the electron beam is compressed by the axially symmetric magnetic field $B(z)$. In the EBIS, the characteristic length L_{trap} of ion trap ranges from 0.7 m to 1.5 m, while the electron current density falls between 100 and 500 A/cm^2. In the EBIT, the length of ion trap is reduced down to $L_{\text{trap}} \sim 2$–5 cm and the current density j_e is estimated to be at the level of about 2–10 kA/cm^2.

In the second method, highly charged ions are produced in the local ion traps formed by crossovers of the *rippled* electron beam. The up-to-date technology is realized in the Main Magnetic Focus Ion Source (MaMFIS), in which the crossover of the electron beam appears in the main focus of the thick magnetic lens [8,9] (see Fig. 1(b)). In order to extract the ions from the source, the rippled electron beam is transformed into the smooth flow by means of reducing potential of the focusing (Wehnelt) electrode. The depth of the axial potential well ΔU_{trap} is estimated as follows

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http://dx.doi.org/10.1016/j.nimb.2017.05.017
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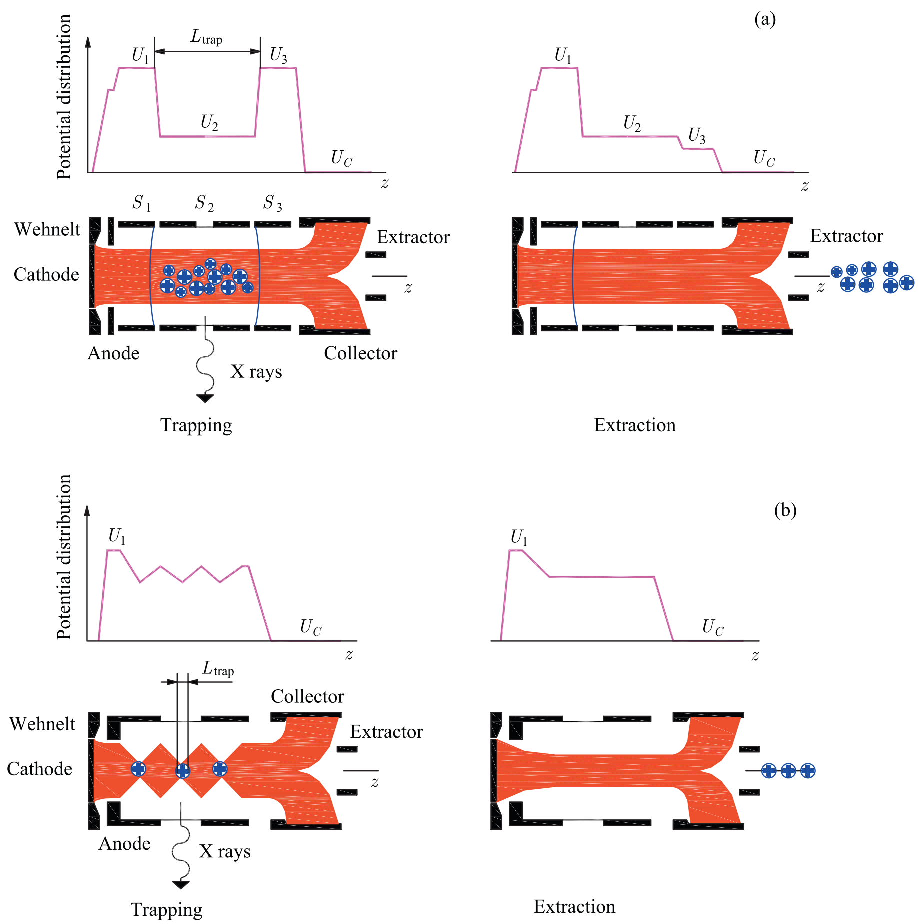

Fig. 1. Principle schemes of EBIS/T (a) and MaMFIS (b). The potentials U_1, U_2, and U_3 are applied, respectively, to the sections S_1, S_2, and S_3 of drift tube, U_C is the potential at electron collector. The z axis is directed along electron beam. Depth of the potential well ΔU_{trap} is equal to difference of the maximum and minimum potentials ($\Delta U_{trap} = U_1 - U_2$).

$$\Delta U_{trap} = \frac{PU_1}{2\pi\varepsilon_0\sqrt{2\eta}} \ln\frac{r_{max}}{r_{min}}. \quad (1)$$

Here r_{max} and r_{min} are, respectively, the maximum and minimum values of the electron-beam radius, ε_0 is the permittivity of free space, $\eta = e/m$ is the absolute value of the electron charge-to-mass ratio, U_1 is the accelerating potential of the first section of drift tube integrated with the anode relative to the potential of the cathode, $P = I_e/U_1^{3/2}$ is the perveance of the electron beam, and I_e is the electron current.

An advantage of the MaMFIS for the production of highly charged ions is extremely high value of the electron current density: the attained j_e exceeds 10 kA/cm^2 at length of ion trap of about 1 mm. A small size of L_{trap} is compensated by a miniature size of the ion source. It allows one to reduce the distance between ion trap and X-ray detector and accordingly to increase the geometric efficiency of the detector. In the first experimental tests of the device performed at the Institute for Atomic and Molecular Physics of the Justus-Liebig University Giessen, the X-ray emission of Ir^{64+} ions was successfully measured [8,10–12].

3. Basics of universal MaMFIS

Efficient ionization of light, moderate, and heavy ions is possible in a single apparatus by combination of the EBIS/T and MaMFIS techniques. It has been realized in the Universal MaMFIS (UniMaMFIS) with the cathode position adjustable in a focusing magnetic field [9]. The electron-optical system of the device allows one to change properties of the electron beam, namely, it can provide a rippled electron beam for high values of energy E_e and current density j_e as well as a smooth flow for low values of E_e and j_e. This is achieved by changing the magnetic field B_c on the cathode surface and geometry of the electron gun. For a number of cases, it is sufficient to change a position of the cathode relative to the anode of the electron gun and, respectively, relative to the magnetic field.

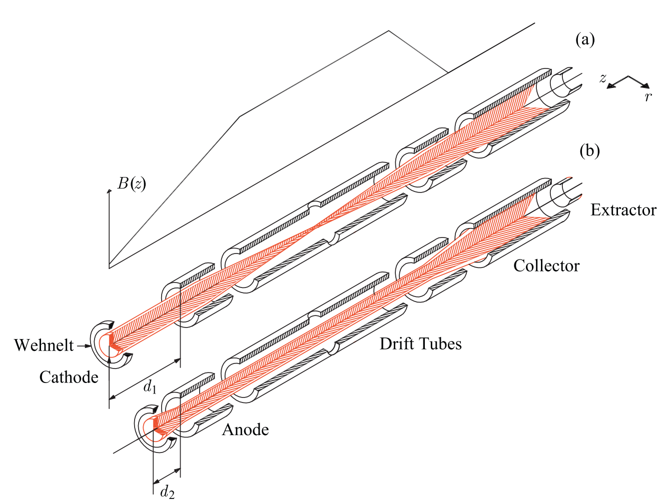

Fig. 2. MaMFIS running mode (a) and EBIS/T running mode (b). $B(z)$ is distribution of the focusing magnetic field along the z axis of electron beam.