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Main magnetic focus ion source: Basic principles, theoretical predictions and experimental confirmations

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ABSTRACT

It is proposed to produce highly charged ions in the local potential traps formed by the rippled electron beam in a focusing magnetic field. In this method, extremely high electron current densities can be attained on short length of the ion trap. The design of very compact ion sources of the new generation is presented. The computer simulations predict that for such ions as, for example, Ne^{8+} and Xe^{44+}, the intensities of about 10^9 and 10^6 ions per second, respectively, can be obtained. The experiments with pilot example of the ion source confirm efficiency of the suggested method. The X-ray emission from Ir^{59+}, Xe^{44+} and Ar^{16+} ions was detected. The control over depth of the local ion trap is shown to be feasible.

1. Introduction

The concept of using the ion trap for the production of *multiply charged ions* was presented by Donets in 1967 [1] following work by Redhead [2]. The Donets's invention was named the electron-beam method for the production of ions. In 1968, the first experimental device based on this method was demonstrated. The ions of gold with charges of up to +19 were successfully produced [3]. The ion source received the name EBIS (electron beam ion source). Afterwards, the ion sources have been widely used around the world for more than 40 years [4].

The specific applications of ion sources substantially affect their design (in particular, the length of ion trap L_{trap}) and the operation regimes. The first generation of devices was aimed at the extraction of multicharged ions for subsequent employment at accelerators. In this case, the length of ion traps was of the order of $L_{trap} \simeq 1$ m [5–8]. In 1988, the ion source with $L_{trap} \simeq 2$ cm in the trapping regime (without the ion extraction) received its own name EBIT (electron beam ion trap) was realized for the spectroscopical studies of the characteristic X-ray emission [9]. The small length of ion trap allowed one to suppress the problem of plasma instabilities. Further breakthrough was associated with development of the ion sources without cryogenics [10,11]. The peculiarity of ion sources of such type is to control the axial behavior of ions in the electron beam by using the *external* electrostatic fields due to variation of potentials applied to different sections of the drift tube. Accordingly, the drift tube should consist of at least three sections.

Although presently there is a variety of devices with different names, all the modifications employ the same method of multiple sequential ionization by the electron beam suggested originally by E.D. Donets. The argumentation of this method can be applied for the electron beam with constant radius only and, therefore, with the smooth bottom of the axial potential distribution. In the following sections, we shall consider the rippled electron beam, which creates its own local ion traps located in crossovers. If the period of undulation is significantly less than the length of the single drift tube, these local ion traps cannot be controlled by the external electric fields in accordance with the Donets's scheme.

2. Local ion traps in rippled electron beam

The rippled electron beam with the radius r_e varying periodically from the maximum r_{max} to the minimum r_{min} creates a sequence of the local ion traps. The explanation of physical base for this type of ion traps is shown in Fig. 1. The sag of the radial potential ΔU for the axially symmetric electron beam, which propagates along the drift tube with the radius R, is given by

$$\Delta U(r_e) = \frac{UP}{4\pi\varepsilon_0\sqrt{2\eta}}\left(1 + 2\ln\frac{R}{r_e}\right). \quad (1)$$

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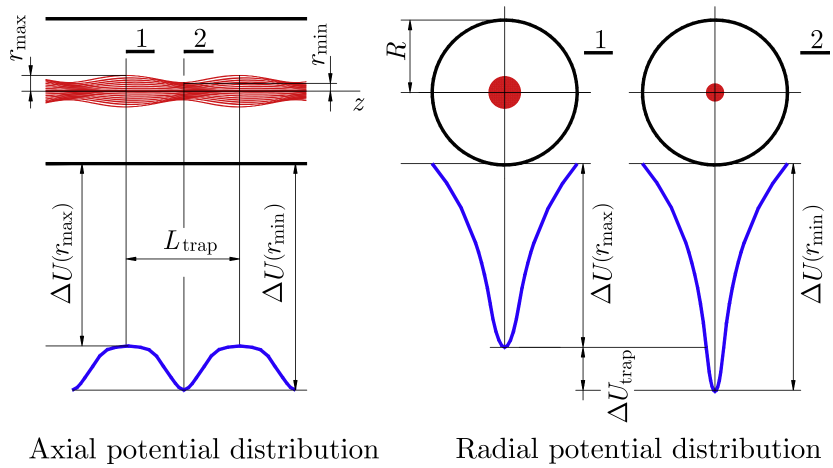

Fig. 1. Formation of local ion traps by the rippled electron beam, which propagates along the cylindrical drift tube. The electron beam is axially symmetric with respect to the z axis. The cuts are made at the places, where the radius r_e reaches either the maximum r_{max} or the minimum r_{min}.

Here ε_0 is the permittivity of free space, $\eta = e/m$ is the magnitude of the electron charge-to-mass ratio, U is the potential of the drift tube relative to the potential of the cathode, $P = I_e/U^{3/2}$ is the perveance of the electron beam and I_e is the electron current. Respectively, the depth of the axial potential well ΔU_{trap} is equal to the difference between $\Delta U(r_{min})$ and $\Delta U(r_{max})$:

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

As seen from Eq. (2), for the smooth electron beam ($r_{max} = r_{min}$), the local ion traps do not appear ($\Delta U_{trap} = 0$ V). By contrast, for the rippled electron beam characterized, for example, by the ratio of radii $r_{max}/r_{min} = 100$, the current I_e of 50 mA and the energy $E_e = eU$ of 10 keV, the depth of the local potential well is equal to $\Delta U_{trap} = 70$ V. Thus it is possible to create an effective local trap in the rippled electron beam without any external electric fields.

The length of the local ion trap L_{trap} along the z axis of the ion source is equal to half-length of the ripple wave. The value of L_{trap} depends on the acceleration voltage U, the distribution of the focusing magnetic field $B(z)$ and the magnetic field at the cathode B_c. The value $B_c = 0$ G corresponds to so-called the "Brillouin's focusing system". Theoretically, for given magnetic field and the energy of electron beam, the extended Brillouin's beam with constant radius acquires the highest current density [12]. This property of the Brillouin's focusing makes it very attractive for EBIS. However, the practical realization of such electron beam focusing is rather difficult [13]. Extremely careful shapes both for the magnetic field and for the electron trajectories in electron gun are necessary to obtain the nonrippled beam. There is only one combination of the shape of magnetic field and the electron gun geometry, for which the electron beam can have the constant Brillouin's radius. These are so-called the "Brillouin's conditions". In all other cases, the electron beam is rippled.

Generally, for arbitrary relationship between the magnetic field distribution and the electron trajectories, the thermal theory predicts formation of a sequence of images and crossovers [14]. In the crossovers, that is, in the local ion traps created by the rippled beam, the electron current density is many times higher than that in the case of the smooth Brillouin's flow. Therefore, new generation of the ion sources characterized by both small size and extremely high electron current density can be realized by using local ion traps in the rippled electron beam [15]. A low capacity of the ion trap due to very short length of the device can be compensated by running in the mode with high repetition rate.

3. Formation and control of local ion traps with extremely high electron current density

In general case, the focusing of the axial electron beam in the magnetic field of a solenoid is the focusing of charged particles by a thick magnetic lens. The electron beam from the cathode at zero magnetic field is transformed into a sequence of the focuses in the regular magnetic field. The most acute focus is called the *main* magnetic focus. In successive focuses, the diameter of electron beam increases under the influence of termal velocities, roughness of cathode surface, aberrations and nonlinear effects. A magnetically compressed electron beam was studied by Amboss [14]. The main conclusion of this work is that the electron beam damps out the undulations and looses the periodic structure within a relatively short distance. Therefore, in the following, we shall take into account the magnetic lens for three focuses only.

Taking into account the magnetic field distribution and the angular and energy spreads of emitted electrons, the computer simulations were performed for the project of pilot ion source with the electron-optical system presented in Fig. 2. The novel ion source is labeled as main magnetic focus ion source (MaMFIS), in accordance with definition of the most acute focus as the main one. For design purposes, we assume that the electron beam projected by cathode with the radius $r_c = 0.25$ mm is characterized by the current I_e of 50 mA and the energy E_e of 10 keV. The magnetic field $B(z)$ is distributed over the length of about 30 mm, while its strength reaches 4.2 kG at the maximum.

The electron trajectories in the focusing magnetic field for the trapping and extraction running modes are shown in Fig. 2(b) and (c), respectively. The corresponding potential distributions along the z axis, taking into account the potential of the electron collector, are shown in Fig. 3. The trapping mode takes place, if the potentials of cathode and Wehnelt's electrode are equal ($U_c = U_w = -3$ kV). The extraction mode is realized, when $U_c = -3$ kV and $U_w = -3.15$ kV. In this case, the rippled electron beam transforms into a relatively smooth flow.

The rippled electron beam in the trapping mode creates two local ion traps characterized by the depth of potential wells of about 30 V (see thick red curve in Fig. 3). The positions of ion traps correspond to the positions of the first and second focuses of the electron beam. For the particular potential distribution, the electric field of the electron collector penetrates into the drift tube and eliminates the local ion trap formed by the third focus. Reducing the potential of the focusing electrode by 150 V transforms the axial potential distribution. The local ion traps almost disappear