E13-2006-146

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CALCULATION OF WORK PARAMETERS FOR PLASMA ION SOURCE

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Мончка Д. и др. E13-2006-146
Расчет рабочих параметров плазменного ионного источника

Дано описание конструкции плазменного ионного источника, используемого в электромагнитных сепараторах изотопов в Институте физики (Люблин, Польша) и в ОИЯИ (Дубна). Для данного типа источника рассчитаны ионный ток и эффективность. Также представлен ограниченный обзор характеристик ионного источника.

Работа выполнена в Лаборатории ядерных проблем им. В. П. Джелепова ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна, 2006

Maczka D. et al. E13-2006-146
Calculation of Work Parameters for Plasma Ion Source

Construction of plasma ion source used in the electromagnetic isotope separators at the Institute of Physics, Lublin, Poland and at JINR, Dubna is described. For this source calculations of ion currents and source efficiency are performed. A limited review of source characteristics is also given.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna, 2006

INTRODUCTION

In the last years one can observe increasing interest in the electromagnetic method of isotope separation. The exceptional purity of the samples obtained results in a wide application of this method in various fields of physics, particularly in nuclear spectroscopy investigations [1]. Many laboratories also work on the interaction of ions with matter, using a separator as an accelerator of the corresponding ions [2].

The application of the electromagnetic separators for the investigation of nuclides far from the stability line appears especially interesting. For this investigation separators directly connected with the accelerators are used, and therefore they are called on-line separators.

Special attention is paid to the investigation in microelectronics, where separated ion beams are used. The present work concerns such technological processes as production of thin layers on the surface of solids and introduction of impurities in semiconductors. The equipment used for these purposes is called the implanter, which is in fact a large mass separator adjusted to produce ion currents up to mA [3].

It is understood that such a wide application of separators causes, on the one hand, development of new constructions, and on the other hand, modification of existing equipment. The latter statement also concerns particular elements of the separator, especially ion sources, which are one of its more important parts [4–6].

The practice existing in this field indicates that the proper ion source should be characterized by large ion currents and high efficiency. These requirements are relatively well fulfilled by the plasma sources used in the separators in at the Institute of Physics, Lublin, Poland and at JINR, Dubna [7–9].

The main goals of our work is to estimate the influence of the source parameters, both plasma and geometrical ones, on the emitted ion currents and source efficiency. The performed measurements of the source characteristics allow one to compare the experimental results with theoretical predictions.

1. ION SOURCE

A design of the ion source under investigation is shown in Fig. 1. The basic part of the source is a discharge chamber with an extraction opening S. Inside the chamber there is a tungsten cathode K made in the form of a spiral (Fig. 2). In the discharge process the molybdenum tube A functions as an anode. This tube is

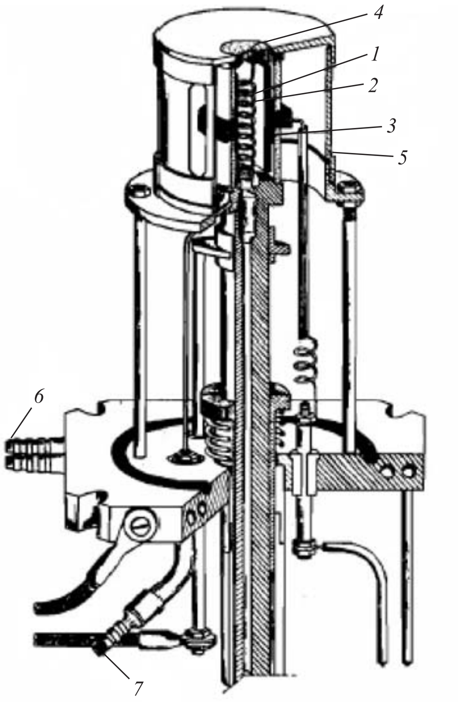

Fig. 1. Design of the ion source: *1* — ionization chamber, *2* — cathode, *3* — anode, *4* — extraction opening for ions, *5* — radiation shield, *6* — water cooling, *7* — gas inlet

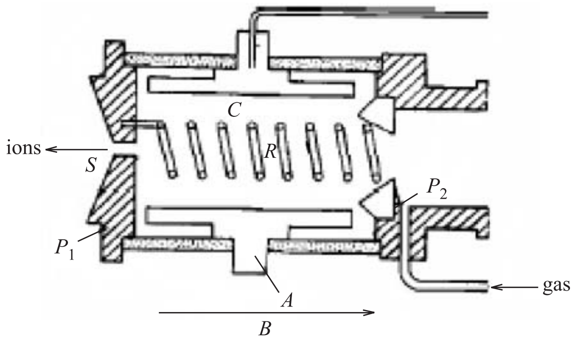

Fig. 2. Design of the ionization chamber: S — extraction opening for ions, A — anode, B — magnetic field lines, P_1, P_2 — plates on cathode potential, R — plasma column inside the spiral cathode

insulated from plates P_1 and P_2 (being on the cathode potential) by two insulators made of boron nitride. The source assembly is placed into the magnetic field, whose lines run parallel to the source axis. In order to burn the arc discharge in the chamber it is necessary to apply a voltage of a few tens of volts to the electrodes and to maintain gas pressure in the chamber about 10^{-3}–10^{-2} mm Hg. In these conditions plasma arises and, because of the diffusion effect, occupies the whole space of the chamber, including the space inside the spiral cathode.

The plasma is separated from the cathode by a double sheath of the space charge, in which almost all the voltage used is located. If there is no magnetic field in the source space R (the magnetic field created by the cathode current can be compensated for by the external field), part of primary electrons may oscillate inside the spiral cathode. Due to this, both the ionization probability of gas atoms and the plasma density increase. Since the extraction opening of the source is in the vicinity of this space, it is possible to obtain considerable ion currents.

2. ANALYSIS OF ATOM IONIZATION IN THE ION SOURCE

In order to estimate the concentration of positive ions in the discharge chamber and, in consequence, the ion current from the source, let us consider the plasma column inside the spiral cathode. This space plays an important role in the proper action of the source because the plasma created here is an emitter of ions.

The ionization probability of a neutral atom running through the plasma column can be expressed by

$$P = 1 - e^{-n_e \langle \upsilon_e \sigma \rangle t}, \tag{1}$$

where n_e is the electron concentration in plasma, σ is the cross section for atom ionization with electrons, υ_e is the electron velocity, t is the life-time of atoms inside the plasma column.

In Eq. (1) the term $\langle \upsilon_e \sigma \rangle$ denotes:

$$\int \upsilon_e f(\upsilon_e) \sigma(\upsilon_e) d\upsilon, \tag{2}$$

where $f(\upsilon_e)$ is the electron velocity distribution function. We assume that this distribution is Maxwellian

$$f(\upsilon_e) = \frac{2}{\sqrt{\pi}} (kT_e)^{-3/2} \sqrt{E} e^{-E/kT_e}, \tag{3}$$

where E is the electron energy, T_e is the electron temperature.

Let us calculate the number of atoms that enter the plasma column through *ds* per time unit. Considering Fig. 3, we can calculate this number as follows:

$$dN' = dn_{\upsilon_x \upsilon_y \upsilon_z} \upsilon_x ds, \tag{4}$$

where $dn_{\upsilon_x \upsilon_y \upsilon_z}$ is the number of atoms that exist in a volume unit and have the velocity components in limits: υ_x, $\upsilon_x + d\upsilon_x$; υ_y, $\upsilon_y + d\upsilon_y$; υ_z, $\upsilon_z + d\upsilon_z$.

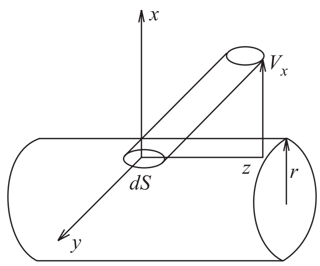

Fig. 3. Plasma column inside the spiral cathode

Assuming that the atom velocity distribution is Maxwellian too, we may write Eq. (4) as

$$dN' = n_a \left(\frac{m}{2\pi k T_a}\right)^{3/2} \exp\left\{-\frac{m\upsilon^2}{2kT_a}\right\} \upsilon_x ds d\upsilon_x d\upsilon_y d\upsilon_z, \tag{5}$$

where n_a is the atom concentration, T_a is the atom temperature, k is the Boltzmann constant, m is the mass of the gas atom.

Dividing the latter formula by ds and integrating with respect to $d\upsilon_x$, $d\upsilon_y$, $d\upsilon_z$ in limits $(0, \infty)$ $(-\infty, \infty)$ $(-\infty, \infty)$, respectively, we obtain the number of atoms dN that enter the plasma column per time and area units

$$dN = n_a \int_{-\infty}^{\infty} d\upsilon_y \int_{-\infty}^{\infty} d\upsilon_z \int_{0}^{\infty} \upsilon_x \left(\frac{m}{2\pi k T_a}\right)^{3/2} \exp\left\{-\frac{m\upsilon^2}{2kT_a}\right\} d\upsilon_x ds. \tag{6}$$

Equation (6) can be expressed in the system of polar coordinates (Fig. 4)

$$dN = n_a \int_{0}^{2\pi} d\varphi \int_{0}^{\frac{\pi}{2}} d\vartheta \int_{0}^{\infty} \upsilon^3 \cos\vartheta \left(\frac{m}{2\pi k T_a}\right)^{3/2} \exp\left\{-\frac{m\upsilon^2}{2kT_a}\right\} \sin\vartheta d\vartheta. \tag{7}$$

From *dN* atoms *dN*$^+$ ions will be formed in the plasma column:

$$dN^+ = dNP. \tag{8}$$

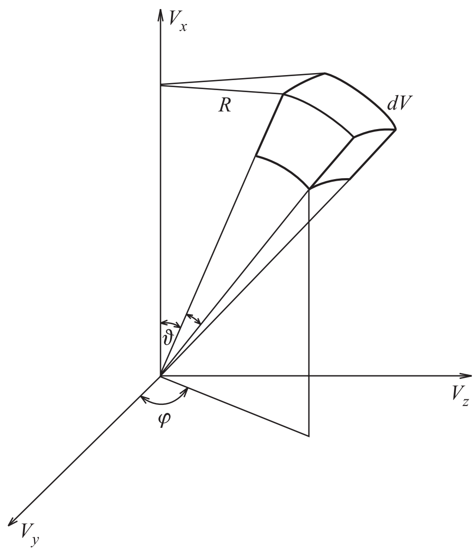

Fig. 4. Volume element in the system of polar coordinates

After partial integration and a few simplifications the solution of Eq. (8) has the form

$$dN^+ = \frac{n_a \bar{\upsilon}}{4} - n_a A(R), \tag{9}$$

where

$$A(R) = \left(\frac{2kT_a}{m}\right)^{1/2} \left(\frac{1}{\sqrt{\pi}}\right)^3 \int_0^{2\pi} \int_0^{\frac{\pi}{2}} \int_0^{\infty} x^3 e^{-x^2} \times \\ \times \exp\left\{-\frac{R}{x\cos\vartheta(1+\mathrm{tg}^2\vartheta\sin^2\varphi)}\right\} \cos\vartheta \sin\vartheta d\vartheta d\varphi dx, \tag{10}$$

$$R = 2rn_e \langle \upsilon_e \sigma \rangle \left(\frac{m}{2kT_a}\right)^{1/2}. \tag{11}$$

Analyzing Eq. (9) we notice that its second term has a simple physical meaning. It expresses the number of atoms from dN that do not become ions on diffusing through the plasma column. Note also the role that the parameter R plays in the atom ionization process in the plasma column. This parameter is non-dimensional and, as follows from Eq. (11), determines the number of ionized atoms in the plasma column. Due to this, the parameter R can be taken as an ionization coefficient of gas in plasma.

Let us estimate now the number of ions N^+ that are created in the whole plasma column in a time unit. For this purpose Eq. (9) must be multiplied by the external surface of the plasma column of the length b

$$N^+ = \left(n_a \frac{\bar{v}}{4} - n_a A(R)\right) 2\pi r b. \tag{12}$$

Formula (12) may be expressed in a more simple form

$$N^+ = N^{+'} \Omega, \tag{13}$$

where

$$N^{+'} = N^+_{R\to 0} = \frac{3}{2}\pi r b n_a \left(\frac{2kT_a}{m}\right)^{1/2} R \tag{14}$$

and

$$\Omega = \frac{4}{3}\sqrt{\frac{m}{2kT_a}}\left(\frac{0.25\bar{v} - A(R)}{R}\right). \tag{15}$$

It is easy to verify that Ω is non-dimensional and depends only on the ionization coefficient R. This dependence is given in Fig. 5. Let us calculate now the ion current emitted from the source. For this purpose we assume that plasma is in the thermodynamic equilibrium state, e. g., the losses of ions in plasma are equal to their production. The loss of the positive charge in the ion source can be attributed, first of all, to the diffusion and recombination processes in the plasma. There are two kinds of diffusions of ions from the plasma. One is diffusion to the spiral cathode and plates P_1, P_2 being on the cathode potential, the other is diffusion to space C through the holes between the coils of the cathode (Fig. 2).

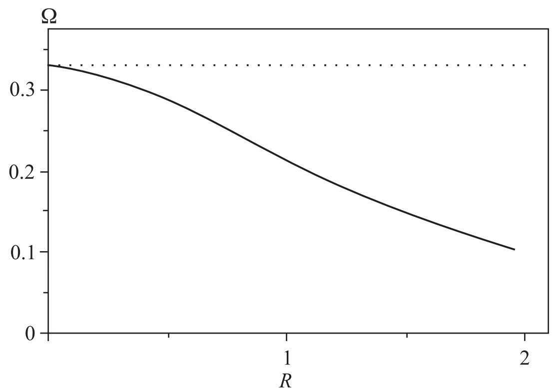

Fig. 5. Dependence of the factor Ω on the ionization coefficient R

The second process can be negligible because in the equilibrium state the ion current density from the plasma to space C and back is the same. Due to this and in view of Eq. (9), the equilibrium state of the plasma can be formulated as follows:

$$3\pi r^2 b n_a n_e \langle \upsilon_e \sigma \rangle \Omega = \frac{j^+}{e} 2\pi r(r + fb) + \alpha n_e n_+ \pi r^2 b, \qquad (16)$$

where α is the recombination coefficient of ions with plasma electrons, and n_+ denotes the ion concentration in the plasma, e — electron charge.

In Eq. (16) j_+ is the density of ion current diffusing through the sheath around the hot cathode. According to [10], this ion current density is equal to the density of the ion current emitted from the plasma through the extraction opening of the source

$$j^+ = \frac{I^+}{a}, \qquad (17)$$

where a is the surface of the plasma meniscus in the extraction opening of the source and I_+ is the total ion current from the source.

Assuming the neutrality of plasma ($n^+ \approx n_e$), we obtain from Eqs. (16) and (17) the formula for ion current extracted from the source

$$I^+ = \frac{rba}{2(r + fb)} e[3 n_a n_e \langle \upsilon_e \sigma \rangle \Omega - \alpha n_e^2] \qquad (18)$$

or assuming the molecular flow of gas from the source

$$I^+ = \frac{rba}{2(r + fb)} e \left[3A \left(\frac{m}{T_a^3} \right)^{1/2} n_e \langle \upsilon_e \sigma \rangle Q\Omega - \alpha n_e^2 \right], \qquad (19)$$

where Q denotes a stream of gas atoms introduced in the source and A is a constant.

From the latter equation one can obtain an important parameter characterizing the atom ionization in the ion source, i. e., the source efficiency η,

$$\eta = \frac{rba}{2(r + fb)} \left[3A \left(\frac{m}{T_a^3} \right)^{1/2} n_e \langle \upsilon_e \sigma \rangle \Omega - \alpha n_e^2 / Q \right]. \qquad (20)$$

3. EXPERIMENTAL RESULTS AND DISCUSSION

In order to verify the correctness of the performed analyses of processes taking place in the ionization chamber, some characteristics of the ion source have been measured. The measurements were performed with the electromagnetic isotope separator at the Institute of Physics of the UMCS (Lublin, Poland), which basic parameters are given in [3, 7]. Xe and Kr were used as testing gases.

Figure 6 shows typical dependence of Xe^+ ion current on the arc discharge current. The discharge current was changed by regulating the cathode temperature which determined the value of the electron current emitted by the cathode into the plasma column.

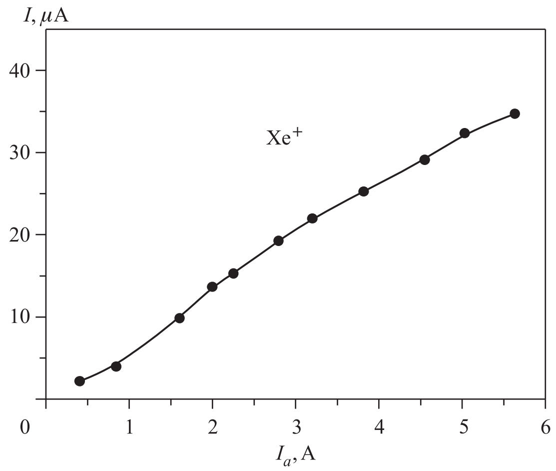

Fig. 6. Xe^+ ion current as a function of the discharge current I_a in the ion source

The resulting run of the curve can be explained using Eq. (19). For small discharge currents, e. g., for small plasma density, the ion recombination effect may be negligible.

In this case formula (19) is reduced to the first term, which is qualitatively in good agreement with experiment.

The deflection of the curve from the straight line for discharge currents larger than 5 A can be explained both by the recombination effect of ions with electrons and by a decrease in the factor Ω with increasing ionization coefficient R (Eq. (11)).

Figure 7 represents the Xe^+ ion current as a function of the voltage accelerating the electrons emitted by the cathode. In this figure dependence of the Xe ionization cross section on the electron energy is also shown (curve b). The comparison of these curves indicates that under our experimental conditions not only primary electrons are responsible for ion production. Displacement of the ion current maximum towards small electron energies should be attributed to ionization of the excited atoms, especially metastable atoms, which life-times in the discharge are of the order of 10^{-2}s , i. e., quite enough for their ionization.

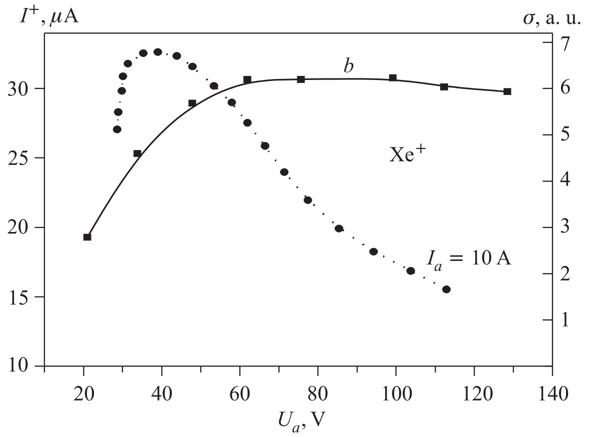

Fig. 7. Dependence of the Xe^+ ion current on the discharge voltage. Curve b is the ionization cross section with electrons as a function of the electron energy [11]

Due to this, Eq. (18) must be complemented to the form

$$I^+ = \frac{rba}{2(r+fb)} e \left[3n_e n_a \langle \upsilon_e \sigma_1 \rangle + 3n_a^* n_e \langle \upsilon_e \sigma_1 \rangle \Omega - \alpha n_e^2 \right], \tag{21}$$

where n_a* is the concentration of metastable atoms in the plasma and σ_1 is the cross section for metastable atom ionization with electrons.

Figure 8 represents dependence of ion current as a function of the gas flow introduced in the ion source. According to Eq. (19), this dependence should be a linear function of Q. The observed deflection of the curve from the straight line for a higher gas flow Q can be attributed, on the one hand, to an increase in

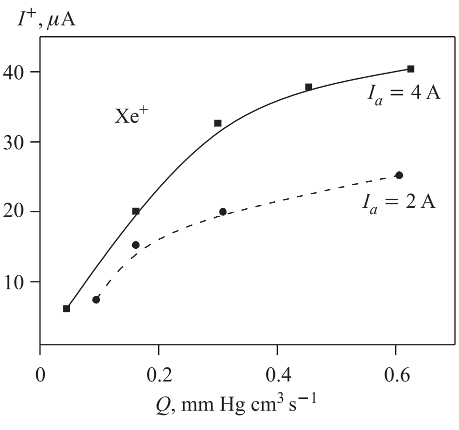

Fig. 8. Xe^+ ion current as a function of the Xe strem introduced in the ion sourse

ion recombination, and, on the other, to a decrease in electron temperature due to more frequent collisions of electrons with gas atoms.

In Fig. 9 dependence of the separation efficiency on the gas flow introduced in the ionization chamber of the source is shown. The difference between Eq. (20) and the run of the experimental curve can be explained by the same phenomena as in the case of the dependence of I^+ on Q.

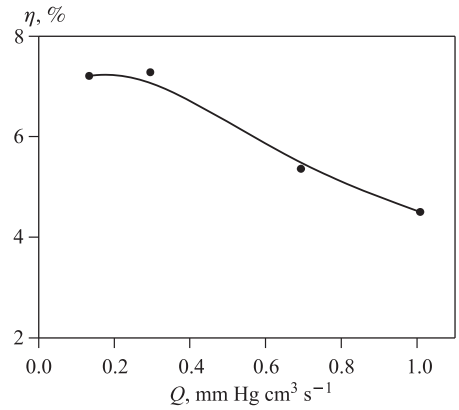

Fig. 9. Source efficiency as a function of the gas flow Q introduced in the ion source

The above comparison of the experimental results with theoretical predictions has only a qualitative character. An exact comparison is needed for obtaining many plasma parameters, for instance, electron and ion densities, electron and ion temperatures, electron velocity distribution in the plasma, etc. Measurements of this type will be the subject of further investigations.

This work was supported in part by the Russian Foundation for Basis Research (grant No. 5-02-17606).

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Received on October 27, 2006.

Корректор *Т. Е. Попеко*

Подписано в печать 07.12.2006.
Формат 60 × 90/16. Бумага офсетная. Печать офсетная.
Усл. печ. л. 0,69. Уч.-изд. л. 0,91. Тираж 310 экз. Заказ № 55578.

Издательский отдел Объединенного института ядерных исследований
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