BEAM DYNAMICS

INVESTIGATION OF BEAM EXTRACTION AND FORMATION IN THE IONS INJECTOR

A.G. Belikov, L.A. Bondarenko, Ye.V. Gussev, O.V. Manuilenko, S.A. Vdovin
National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
E-mail: gussev@kipt.kharkov.ua

The results of analytical and numerical studies an ion beam extraction and formation from a plasma source are presented. The influence of ion optics parameters on the ion beam characteristics is studied. The studies were carried out using a package of three-dimensional computer simulation of ion beams optics with allowance for space charge – IBSimu. The results show that of extraction electrode shape has an important role in shaping of the ion beam characteristics.

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INTRODUCTION

The process of ion beams extraction and formation determines the possibility of their further use. Therefore in the beam forming device, carefully designed electrodes must be used to create an electric field configuration, both on the plasma surface of the ion source and along the beam propagation region, which provides the required ion beam characteristics. When using the device as an injector of an ion accelerator, as in ours case, they are beam energy, the radius of the beam envelope and the angular divergence in the injection plane into the accelerating structure or into beam transport device.

The development of the optics of plasma ionic injectors is based on the principles used in the formation of electron beams, proposed by E. Langmuir and K.B. Blodgett [1] and developed by J.R. Pierce [2, 3]. He considered a beam, which propagated between two plane electrodes and was not limited in transverse directions. Then a beam of the required dimensions (thickness/diameter) cut out from it, and remaining part of the beam had changed by electrodes of a special shape. The potential of the electrodes was chosen so that inside the cutout beam there was maintained the potential distribution the same as in the infinite beam in the transverse direction. In this case, a parallel electron beam is formed. Pierce also determined that the curvature of the cathode shape influences on the formation of the electron beam. This allows you to create beams converging/diverging in the radial direction.

However, the dependences found by them cannot be directly applied to the formation of beams from the plasma ion source. This is due to a number of constructive and physical features of ion beams extraction from the plasma. Not only the mechanical design and the device optical force, but also the potentials of the plasma and the electrode, as well as the heterogeneity of the current density in the aperture, are different. For instance, the current density decreases near the electrode. But the main difference is the mobility of the plasma boundary of the source.

Taking into account the peculiarities of ion extraction from the plasma, the result of ion optics analytical calculation should be checked and corrected by numerical simulation of the ion beam dynamics in the device, and in the future also by experimental studies.

Extraction devices, which are considered in the article, are represented by devices with one and two gaps (two- and three-electrode extraction devices). The influence of the shape and arrangement of the electrodes of ion optics (emitting or plasma and extraction electrodes) on both the diameter and emittance of the beam has been studied.

In the modeling process, the optimization parameters were an extraction gap dimension and a beam space charge, and in the case of a three electrode optics, an extraction voltage and gap between the extractor and the grounded electrode was additionally.

The purpose of the studies was to determine the conditions for obtaining the optimal ion flux at the output of the beam extraction and formation device.

Numerical studies were carried out using a package of three-dimensional computer simulation – Ion Beam Simulation (IBSimu). IBSimu is an ion optical code package made especially for the needs of ion source extraction design. Using the finite difference method (FDM), the code can simulate: systems of electrostatic and magnetic lenses, high space charge beams (low energy), positive and negative ion (and electron) plasma extraction in 1D, 2D, 3D and cylindrical symmetry. The code is created as a C++ library and is released freely under GNU Public License [4]. It is a highly versatile and customizable and can be used for batch processing and automatic tuning of parameters [5].

The code has been applied in the leading accelerator centers (CERN, SNS, etc.) to designing of several positive and negative ion source extraction systems. Simulation results are in good agreement with experimental data [6, 7].

ANALYTICAL AND NUMERICAL RESEARCH

The ion flux in the space between two infinite parallel planes can be described by solving the equation:

$$\frac{d^2V}{dx^2} = \frac{j}{\varepsilon_0\sqrt{2\frac{e}{m}V(x)}}, \qquad (1)$$

where j is the current density homogeneous over the entire surface $j(x)$=const, ε_0 is the dielectric constant, e and m are respectively the charge and mass of the ion, V is the electric potential distribution along the flow direction, and x is the longitudinal coordinate. Its solution is a function $V = Az^{4/3}$, where A depends on the current density and for protons $A = 6.959451 \cdot 10^3 \cdot j^{2/3}$.

In real conditions, the beam is injected from a finite-size area. This corresponds to the case when a part of the stream is removed in an infinite flow in the transverse direction. Because of the absence of charges outside the beam, the beam is expanded. To exclude the expansion of the flow, it is necessary to compensate for the effect of space charge. To do this, it is necessary to replace the space charge of the "missing" part of the stream by the electrostatic field of the electrodes so that the field of space charge on the beam surface is compensated by the field of the electrodes.

Compensation is achieved if, in the presence of an external field, the following two conditions are satisfied along the entire surface of the beam: the potential is continuous at the beam boundary and the component of the field strength normal to the beam surface is equal to zero.

Thus, it is necessary to consider two regions: the region occupied by the flow and the region free of charges. In the case of a plane-parallel flow in Cartesian coordinates (x, y), where the beam propagates along the x axis, $y < 0$ will correspond to the region occupied by the beam, and $y > 0$ to the charge-free region. On the boundary of the domain $y = 0$ the following conditions must be satisfied: $dV/dy = 0$. For $y < 0$, the potential is determined by the solution of equation (1). In a charge-free space (y>0), the potential must satisfy the solution of the Laplace equation:

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} = 0 . \qquad (2)$$

It is necessary to keep the conditions on the boundary and inside the beam the same as in the case of an unbounded flow, to ensure that the flow is not disturbed due to the absence of a charge outside the beam. Accordingly, equation (2) must be solved with boundary condition $dV/dy = 0$. The solution of equation (2) is find as an analytic continuation of the function $V = f(x)$, which describes the potential distribution in the region $y < 0$. It can be written in the form $V = [f(x+jy)+f(x-jy)]/2$ if we assume that for $y < 0 f \to f(x')$, where $x' = x+jy$ – complex variable, so that the condition $V = f(x')$ for $y = 0$ is satisfied. The potential chosen in this way satisfies the conditions on the boundary, and the lines of equal potential in the region outside the beam make it possible to choose the shape of the electrode.

The solution of the equation is a function that determines equipotential surfaces:

$$V = \mathrm{Re}\left(A(x+iy)^{4/3}\right) = A\left(x^2+y^2\right)^{2/3} \cos\left(\frac{4}{3} arctg \frac{y}{x}\right). \qquad (3)$$

From the condition that the potential at the emitting ions electrode is equal to zero, we find the electrode profile:

$$y = tg\frac{2\pi}{8}x = tg67.5^0 x.$$

The result of calculating the equipotential surfaces between the electrodes of ion optics for a proton beam was shown in Fig. 1. Here the beam envelope radius is 4 mm, the current is 0.15 A, the extraction voltage is 75 kV. As can be seen, the geometry of the extractor determined by the analytical method compensates for the effect of space charge forces and ensures the propagation of the beam without expansion.

Using the geometry of the electrodes shown in Fig. 1, numerical simulation of beam propagation in the extractor (IBSimu program) was carried out. The longitudinal section of the beam obtained as a result of the simulation is shown in Fig. 2. The behavior of the beam envelope differs from that shown in Fig. 1. This is due to the fact that in the first case (see Fig. 1) the emission surface of the beam is flat and fixed, and in the second case, since the emission is carried out from the plasma it is mobile, the surface curvature is determined by the ratio of the plasma density in the source and the electric field strength in the breaking gap.

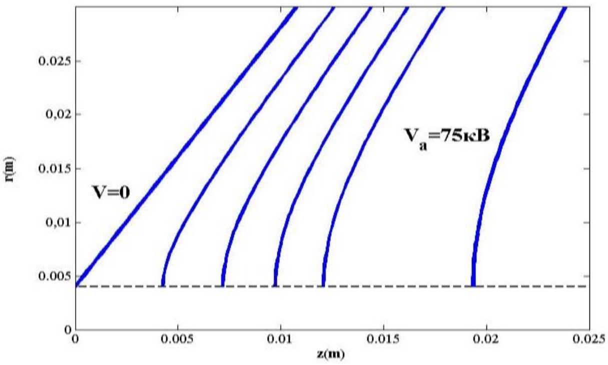

Fig. 1. The emitter and extractor electrodes shape (thick lines). Equipotential surfaces lines (thin lines) outside the beam region

An electric field perpendicular to the concave plasma boundary imparts the emitted particles of the beam an impulse directed to the axis of the system. Passing the extracting electrode, the beam begins to diverge, both under the action of space charge forces, and due to the action of the field at the output from the electrode. This is illustrated by the projections of the phase portrait of the beam on the (r,r') plane in Fig. 3.

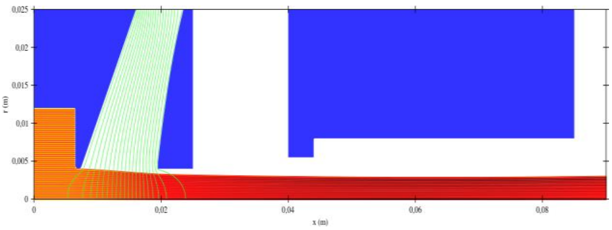

Fig. 2. The beam profile in the extractor. The electrodes of ion optics are shown in blue, the equipotential of the electric field is green, and the beam is the red one

The beam in Fig. 3,b was still remained converging, but the phase portrait angle have changed. Over 53.6 mm from the emission plane, it will have zero convergence and begin to diverge in the transverse direction. In Fig. 4 shows the projections of the phase portrait of the beam in the plane of zero divergence and at a distance of 78.5 mm from the emission plane at the entrance to the transport and matching device.

The beam radius at the point of zero divergence is 2.9 mm, then, as can be seen from Fig. 4,b it diverges and at its entrance to the transport device its radius exceeds 3.1 mm.

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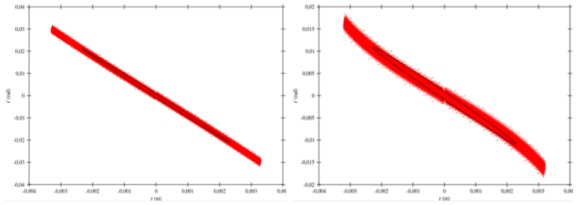
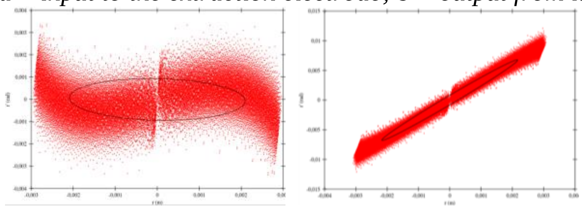


a *b*

Fig. 3. Radial profiles of the phase portrait of the beam: a – input to the extraction electrode; b – output from it



a *b*

Fig. 4. Radial profile of the phase portrait of the beam: a – in the plane of zero divergence; b – output to the matching device

We have considered the characteristics of beam extraction devices that differ in the shape of the emitter (plasma electrode) and the extractor (breaking electrode). The emitter was an electrode with Pierce geometry – a cone at an angle to the beam axis of 67.5°, shown in Fig. 1, and the spherical electrode whose prototype was the electrode described in [8, 9]. Extraction electrodes, in addition to the Pierce geometry, had a flat, conical and spherical shape.

The best result for two electrode extractors was obtained by using electrodes of a spherical shape similar to the shape of the electrodes given in [8, 9]. The results of modeling the extractor with spherical electrodes are shown in Figs. 5 and 6.

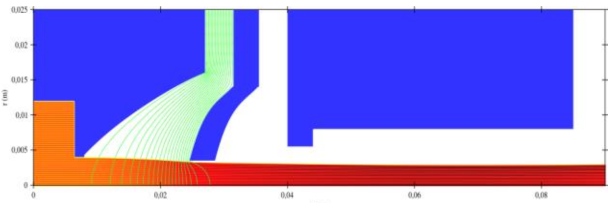
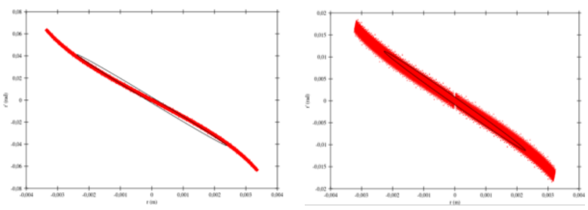


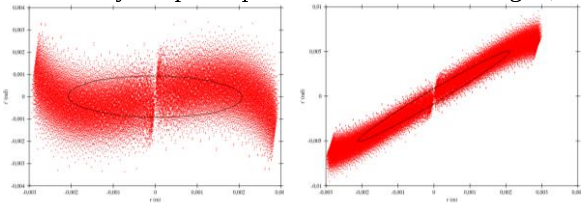
Fig. 5. The beam profile in the spherical extractor. Notations correspond to Fig. 2



a *b*

Fig. 6. Radial profile of the phase portrait of the beam: a – input to the spherical extraction electrode; b – output from it

The divergence at the exit from the extracting electrode became smaller (see Fig. 6,b). The distance to the point with zero divergence for a spherical system increased to 62 mm, the beam radius does not exceed 2.8 mm. Further, the beam diverges, but at the entrance to the matching device its radius increased by only 1 mm, i.e. the divergence became smaller, which is illustrated by the phase portrait of the beam in Fig. 7,b.



a *b*

Fig. 7. Radial profile of the phase portrait of the beam: a – in the plane of zero divergence; b – input to the matching device

To compensate for the divergence of the beam after the extraction electrode, two-gap extraction optics, so-called triode extractors, can be used. They allow you to influence beam parameters in a wide range while maintaining the beam energy at the output of the extraction device. The use of three electrode extractors makes it possible to increase the beam perveance in the first gap by rising the voltage of extraction. Varying of extraction voltage, it is possible to control both the radial and longitudinal characteristics of the beam. Beam energy at the output of the device remains unchanged when the voltage on the extraction electrode changes.

Determination of the correct arrangement and shape of the three electrodes providing compensation effect of the space charge forces is more difficult compared with the two-electrode device. In the presence of three electrodes. Pierce's problem for the extracting and focusing gaps should be resolved sequentially, given their mutual influence.

This problem was considered in [10]. The authors generalized Pierce's solution to the case of a multi-gap extraction system. They developed common approaches for determining the shape of the electrodes of an extraction device with two gaps. The paper notes that it is not always possible to obtain an exact solution, but it is possible to realize the system using a nonequipotential electrode between the gaps.

As it was shown in Fig. 8 the analytical solution of the distribution of equipotential lines (thin) and electrode surfaces (fatty) for a proton beam with an energy of 75 kV and a current of 0.15 A, which we obtained using the results of denoted work.

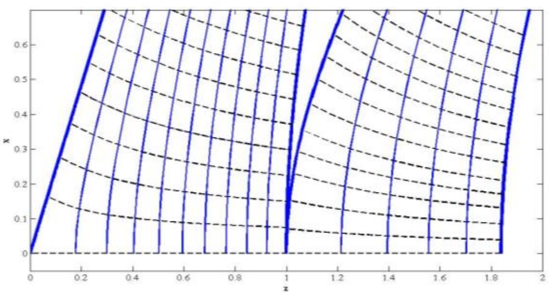


Fig. 8. Pierce electrodes in a three-electrode extraction system

Realize practically the distribution of the equipotential lines depicted in the figure is problematic due to the impossibility of producing an extracting electrode of form such as this. However, numerical simulation enable to create electrodes, the shape of which will make it possible to obtain geometrically close distributions.

Numerical methods were used to analyze the options for constructing a three-electrode extraction system. As a plasma electrode, a Pierce's electrode and spherical electrode was used [8, 9]. The extraction electrodes had a shape Pierce's electrode, and flat, conical and spherical shape.

Fig. 9 shows the variants of the three-electrode ion optics, which were used in the numerical study of the formative properties of extractors.

Numerical studies of three-electrode extractors were carried out for the following proton beam parameters: beam energy 75 keV, beam current 0.15 A, radius of emitting hole 4.4 mm, radius of aperture in extractors 4 mm. The potential on the extraction electrode varied from 0 to 40 kV.

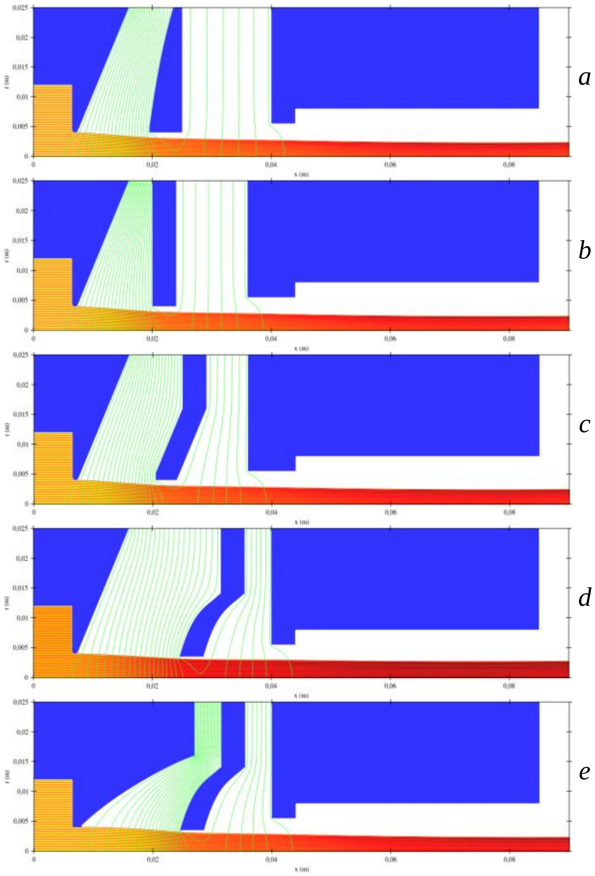


Fig. 9. Geometry of three-electrode optics.
Plasma electrode: a-d – Pierce; e – spherical; extraction electrode: a – Pierce; b – flat; c – conical; d and e – spherical

The criteria for comparing the simulation results were: the distance from the extraction hole to the point at which the beam has zero convergence/divergence, the beam envelope radius at the same point, as well as the envelope radius and the divergence angle in the point of entrance in the focusing field of the transport and reconciliation device.

As the results of the study showed, all of the devices presented in Fig. 9 with the beam parameters indicated provide extraction of the beam and its formation without loss of particles in the extracting device and can be used in the ion accelerator injector.

The best results were achieved when electrodes of spherical geometry was used in the extractor. The extractor of the quasi-pierce's geometry showed a somewhat worse picture.

In Fig. 10 presents the projections of the beam phase portraits at the point of zero divergence and at the entrance to the electrical field of the transportation and reconciliation device located at a distance of 78.5 mm from the emission plane of the beam at a voltage of -20 kV for the Pierce's and spherical extractor.

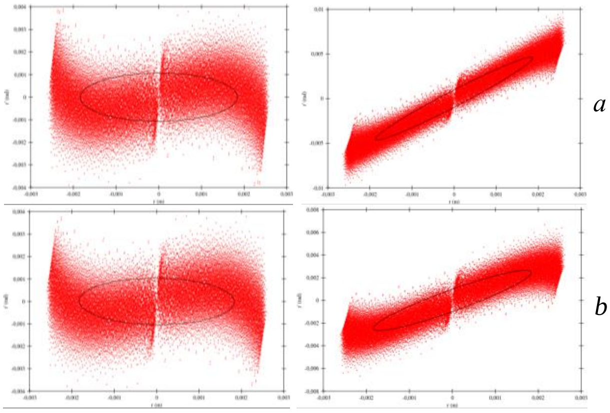


Fig. 10. Radial profile of the phase portrait of the beam: a – Peirce geometry; b – spherical

As can be seen from the comparison of portraits, the beam radius, both at the point of zero divergence and at the entry point into the field of the transportation device are approximately equal, but the beam divergence angle at the end point is almost 2 times smaller for spherical geometry. This difference increases with increasing voltage on the extractor.

At a voltage on the extractor -40 kV in the case of the Pierce's geometry, the beam from the point of zero divergence to the entrance to the transport device increases the beam radius by 0.1 mm, but remains divergent.

In the case of spherical geometry at a voltage on the extractor -40 kV, the zero divergence point coincides with the entry point into the electric field of the transport and reconciliation device.

For all simulated extractors, with increasing voltage on the extraction electrode, the point of zero divergence is shifted to the output from the device.

CONCLUSIONS

The carried out investigations showed that in the case of single-gap optics, the point of zero divergence is approximately 55 mm from the plasma electrode on average, and its beam radius is 3 mm on exit from the device and it diverges strongly.

Three-electrode extraction devices satisfy our purposes. Preferred are devices of spherical geometry. It also may be used quasi-pierce geometry, but to achieve the calculated parameters it is necessary to increase the voltage on the extraction electrode. In the case of using other configurations of the extractor optics, the design parameters of the beam can be obtained only at a tension in the extraction gap exceeding the breakdown strength of the gap.

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ИССЛЕДОВАНИЕ ЭКСТРАКЦИИ И ФОРМИРОВАНИЯ ИОННОГО ПУЧКА

А.Г. Беликов, Л.А. Бондаренко, Е.В. Гусев, О.В. Мануйленко, С.А. Вдовин

Представлены результаты аналитического и численного исследований процесса извлечения и формирования ионного пучка из плазменного источника. Изучено влияние параметров ионной оптики на характеристики пучка ионов. Исследования проводились с использованием пакета трехмерного компьютерного моделирования оптики ионных пучков с учетом пространственного заряда – IBSimu. Программный код базируется на библиотеках С++. Результаты показывают, что форма экстрагирующего электрода играет важную роль в формировании характеристик ионного пучка.

ДОСЛІДЖЕННЯ ЕКСТРАКЦІЇ І ФОРМУВАННЯ ІОННОГО ПУЧКА

А.Г. Бєліков, Л.О. Бондаренко, Є.В. Гусєв, О.В. Мануйленко, С.О. Вдовін

Представлені результати аналітичного та чисельного досліджень процесу вилучення та формування іонного пучка з плазмового джерела. Вивчено вплив параметрів іонної оптики на характеристики пучка іонів. Дослідження проводилися з використанням пакета тривимірного комп'ютерного моделювання оптики іонних пучків з урахуванням просторового заряду – IBSimu. Програмний код базується на бібліотеках С++. Результати показують, форма електрода, що екстрагує, грає важливу роль у формуванні характеристик іонного пучка.