Transportation of a Beam of Variously Charged Ions in Drift Tube

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Abstract – In this work, the transportation of an ion beam with a current higher than the limiting one though a plane equipotential drift tube has been studied theoretically and numerically. An analytical expression has bee obtained which relates the current and the charge state of the injected beam to the current and charge state of the beam passed through a virtual anode in the plane case. Numerical simulation (the PIC-code TRACKS (ES1D)) has shown the charge state of the beam passed though the virtual anode to depend strongly on the ion energy distribution.

1. Introduction

It is known that during the transportation of a beam of variously charged ions, the charge state of the beam changes at the output of the drift tube [1–3]. The change of the charge state of the beam in its transportation can be useful for generation of ion beams with a strictly determined charge state.

2. Theory

The solution of the problem on the transportation of a beam of like-sign charged particles in a plane equipotential gap is well known. If the current density of the injected beam is higher than the second critical value $j_{cr2} = 2j_{cr1}$, a virtual cathode (anode) is formed in the gap. This cathode reflects part of the charged particles, thereby limiting the current density of the beam passed through the gap [4]. The density of the current which can be passed through a plane equipotential gap j_{out} is related to the current density of the injected beam j_{in} as

$$\frac{1}{j_{out}^{1/2}} + \frac{1}{\left(2j_{in} - j_{out}\right)^{1/2}} = \frac{2}{j_{cr1}^{1/2}}, \tag{1}$$

$$j_{cr1} = \frac{1}{9\pi}\left(\frac{2eZ}{m}\right)^{1/2} \frac{U^{3/2}}{\left(L/2\right)^2}, \tag{2}$$

where j_{cr1} is the primary critical current (the Child-Langmuir current for half length of the gap), e is the charge of an electron, Z is the charge of a particle (whole number), m is the mass, L is the length of a plane equipotential gap, U is the voltage by which particles were accelerated.

Let us consider a one-dimensional problem on the injection of an ion beam into a plane gap for the case of different ion charges.

The Poisson equation which describes the potential distribution in the gap is written in the form

$$\frac{\partial^2\varphi}{\partial x^2} = -4\pi\rho = -4\pi\left(\sum_{Z=1}^{N}\frac{j^{(Z)}}{V^{(Z)}}\right). \tag{3}$$

Here $V^{(Z)}$ is the velocity of particles with a charge Z, $j^{(Z)}$ is the particle current densities of ions with a charge Z, N is the maximum charge of ions in the beam.

Because the ion energy is proportional to the ion charge, the relation of the a one-charged ion to the velocity of an ion with a charge Z is $1/\sqrt{Z}$. Let us define the effective charge of ions k as

$$\sqrt{k} = \frac{j}{\sum_{Z=1}^{N}\left(j^{(Z)}\frac{1}{\sqrt{Z}}\right)}, \tag{4}$$

where j is the total ion current in the system. Taking into account (4), the Poisson equation is rewritten in the form

$$\frac{\partial^2\varphi}{\partial x^2} = -4\pi\frac{j}{k^{1/2}}\frac{1}{V^{(1)}}. \tag{5}$$

The first critical current $j_{cr1}`$ can be written by analogy with expression (2)

$$j_{cr1}` = \frac{1}{9\pi}\left(\frac{2ek}{m}\right)^{1/2}\frac{U^{3/2}}{\left(L/2\right)^2}. \tag{6}$$

Solution (6) has bee obtained for the condition where particles move in one direction. In the region between the injection plane and the virtual anode (VA) the ion beam is partially reflected from the VA. It can readily be demonstrated that in this case the current density of the beam passed through the VA will be related to the injection current density as

$$\frac{1}{\left(\frac{j_{out}}{\sqrt{k_{out}}}\right)^{1/2}} + \frac{1}{\left(\frac{2j_{in} - j_{out}}{\sqrt{k}}\right)^{1/2}} = \frac{2}{\left(\frac{j_{cr1}`}{\sqrt{k_{in}}}\right)^{1/2}}, \tag{7}$$

where j_{in} and j_{out} are the current density of the injected beam and that of the beam which has passed through the VA, k is the effective charge of the beam between the injection plane and the VA, k_{out} is the effective charge of the beam passed through the AV.

It follows from formula (7) that the effective charge k_{out} may vary at specified values of the parameters of the injected beam and transportation system j_{in}, j_{cr1}, k_{in} due to transportation of the beam through the equipotential gap. Expression (7) describes the behavior of the current density and the effective charge of the beam in a stationary system where each type of ions of the injected beam has an energy multiple of its charge, i.e., it is assumed that before acceleration in the potential U the ions have a zero velocity. Surely, the part of variously charged ions which passes through the VA is determined by the initial ion energy distribution. The initial ion energy distribution will also affect the effective charge of the beam passed through the VA. The temperature energy distribution suffices to solve the problem.

3. Simulation

In this work the change of the charge state of an ion beam with a specified energy distribution which is passed through a VA is studied numerically.

The numerical simulation was performed using the one-dimensional PIC-code TRACKS(ES1D) [5]. In the simulation, a beam of one- and double-charged platinum ions of energy 200 eV was injected into an equipotential drift tube 1 mm long. The energy distribution was specified to be Gaussian and its FWHM $\Delta\varepsilon$ was varied from 12 eV to 30 eV. To consider quasistationary processes, the current rise time was taken to be much longer than the time it takes for the ions to fly through the gap and was ~0.3 ms (the time a one-charged platinum ion with an energy of 200 eV takes to travel through the gap was ~7 ns).

To determine the charge state of the beam passed through the virtual anode, we used the average charge K which was calculated by the fractions of the current density of one- and double-charged ions arrived at the collector.

$$K = \frac{j^{(1)} + 2j^{(2)}}{j^{(1)} + j^{(2)}}. \tag{8}$$

The average charge of the injected beam K_{in} varied form 1.1 to 1.9. The wide energy distribution of the ions is due to the fact that with narrower distributions the formed VA starts to oscillate with a natural frequency that strongly affects the current density and the average charge of the beam passed through the VA.

Calculations have shown that before the VA is formed the average charge of the beam leaving the system is equal to the average charge of the injected beam. However, once the VA is formed, the average charge of the beam passed through the VA is rapidly decreased. This is associated with more efficient reflection of double-charged low-energy ions by the VA. Increasing the current of the injected beam causes the average charge of the beam passed through the VA to decrease. There are modes where the beam passed through a VA consists only of one-charged ions that agrees qualitatively with experimental data [1, 2].

Figure 1 shows the average charge state of the beam passed through the VA versus the current of the injected beam for different energy distributions.

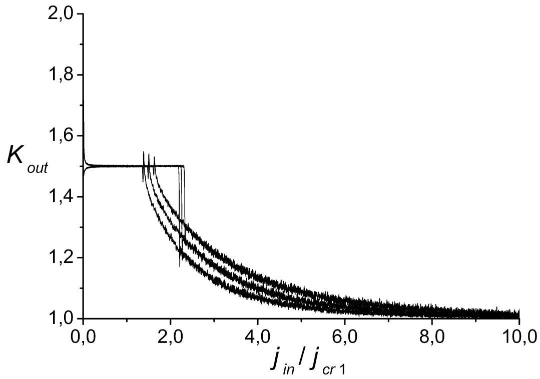

Fig. 1. The dependence of the average charge state K_{out} of the beam passed through the VA vs. the current of the injected beam for different energy distributions. The upper curve – $\Delta\varepsilon$ = 30 eV, middle – $\Delta\varepsilon$ = 20 eV, lower – $\Delta\varepsilon$ = 12 eV

It can be seen from this figure that the wider energy distribution the beam of one-charged ions leaving the system is attained at high densities of the injected current. This is explained by the fact that in such a beam there is a great number of double-charged high-energy ions which will pass through the VA.

Figure 2 shows the average charge of the beam leaving the system versus the injection current density of the injected beam for different charge states and invariant energy distribution. It is quite clear that at high injection current densities and high average charges of the ion beam only a flow of one-charged ions can reach the outlet of the system.

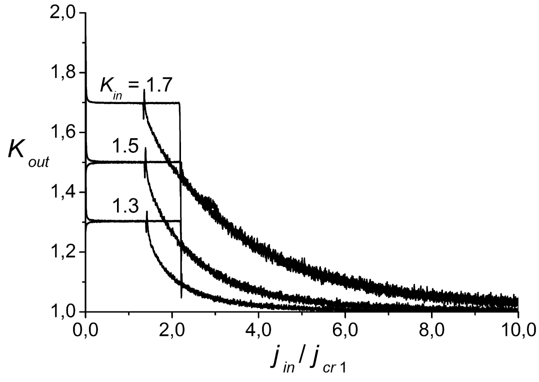

Fig. 2. The dependence of the average charge state K_{out} of the beam passed through the VA vs. the injection current density of the injected beam for different charge states and invariant energy distribution. The number under curve is average charge state of the injected beam

Let us introduce the parameter of the charge separation efficiency of the ion beam. In so doing, we assume these parameters to be equal to the ratio of the current density of the beam of one-charged ions passed through the VA to the current density of one-charged ions of the injected beam:

$$\alpha = \frac{j_{\text{out}}}{j_{\text{in}}^{(1)}}. \tag{9}$$

It follows from the definition that in the beast case where all one-charged ions are passed through the VA and all double-charged ions are reflected, the coefficient of charge separation efficacy will be equal to unity. The results of numerical simulation showed that the coefficient of charge separation efficacy independent of the average charge of the injected beam, and determinate by energy distributions of the injected beam.

4. Conclusion

Plasma ions always have a temperature energy distribution. Calculations have shown that during the transportation of such beams in an equipotential vacuum chamber the average charge of the beam at its outlet is invariably lower than the average charge of the injected beam. This is associated with more efficient reflection of doubly charged ions by the virtual anode. There are modes where the beam passed through the VA consists of one-charged ions. However, the efficiency of such a method of beam separation is too low.

References

[1] Humphries, Jr. et al., J. Appl. Phys. **59**, 1790 (1986).

[2] Humphries, Jr. and H. Rutkowsky, J. Appl. Phys. **67**, 3223 (1990).

[3] E. Oks, G. Yushkov, I. Litovko et al., Rev. Sci. Instrum. 73 (2), 702 (2002).

[4] R.B. Miller, *Introduction to the Physics of Intense Charged Particle Beams,* Plenum Press, New York, 1982; Mir, Moscow, 1984.

[5] V.A. Shklaev, S.Ya. Belomyttsev, V.V. Ryzhov et al., *in: Proceedings of the 6th International Conference on Modification of Materials with Particle Beams and Plasma Flows,* Tomsk, 2002, p. 631.