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FUNDAMENTAL INVESTIGATION FOR HIGH INTENSITY ION SOURCES

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In this paper, we try to pigionhole and evaluate the main parameters which effect the characteristics of the ion source plasma and the extracted ion beam. By considering this evaluation, we also try to arrange the important methods for a high intensity ion beam production.

1. Quantity of Extracted Ion Beam Current

As to the extracted ion current from an ion source, the following equations are formed from both of the relation between the electric field and the ion space charge in an extractor and the capacity of the ion emission from a plasma source. The extractable current from an ion extraction hole is the space-charge limited current, which is given in the Eq.(1) for singly charged ions.

$$I_{si} = 4.3\times10^{-8}\left(\frac{2a}{d}\right)^2\left(\frac{1}{M}\right)^{1/2}V^{3/2}\gamma\ . \qquad (1)$$

The space-charge limited curret, I_{si}(A), given in the Eq.(1), is the current calculated assuming the one dimension model under the conditions of the extraction hole radius, a(cm), the extraction electrodes gap, d(cm), the extraction voltage, V(V), and the ion mass number, M. γ shows the space-charge compensation factor. When the space charge of ions in the extractor is compensated with the space charge of electrons, the space charge limitation is relaxed, and, then, γ value is more than 1.

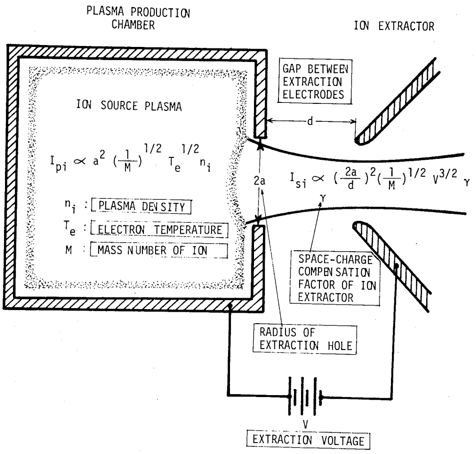

Fig.1 Ion source parameters related to the quantity of the extracted ion beam. The parameters are indicated in □ .

The extracted ion current from an ion source is determined not only by the Eq.(1), but also by the saturation current which has to be supplied from the plasma source (refer to the Fig.1). The saturation current, I_{pi}(A) is given in the Eq.(2).

$$I_{pi} = 3.0\times10^{-13}a^2\left(\frac{1}{M}\right)^{1/2}T_e^{1/2}n_i \qquad (2)$$

where T_e(eV) is the electron temperature of the plasma, and n_i the plasma density.

When it is conditioned between the extractor and the plasma that the two currents given in Eqs.(1) and (2) are the same, an ion beam can be formed. This condition is determined from the Eqs.(1) and (2).

$$\frac{d}{V^{3/4}\gamma^{1/2}}n_i^{1/2}T_e^{1/4} = 7.6\times10^2\ . \qquad (3)$$

As shown in the Eqs.(1) and (2) and the Fig.1, the plasma density, the electron temperature and the mass number of ion are counted as the parameters related to the quantity of the extracted ion current on the part of the ion source plasma. On the other hand, the radius of extraction hole, the gap between extraction electrodes, the extraction voltage, and the space-charge compensation factor are counted as the parameters on the part of the extractor. These parameters are not independent, except the mass number of ion and the radius of extraction hole. There is an important mutual relation among these parameters, as expressed in the Eq.(3).

As for the quantity of the ion current, the mass number of M appears in the Eqs.(1) and (2) in the same dependence of $M^{1/2}$, and does not appear in the Eq.(3) which indicates the mutual relation. If the other conditions except the mass number are the same, the heavier the mass of ion is, the lower the extracted ion current is. Therefore, in order to normalize the extracted ion current for the mass dependence, the ion current has to be multiplied by the square root of the mass number. This value shows the proton equivalent current.

In the case of no space-charge compensation, the extracted ion current increases with the square of the aspect ratio, 2a/d, as shown in the Eq.(1). It is desirable that the ion extractor with an aspect ratio which is as large as possible is designed keeping a good ion optics. But, the ion optics generally degrades with increase of the aspect ratio. The maximum value of an aspect ratio is estimated to be about 1. Therefore, the maximum ion current extractable from a single aperture depends only on the three-seconds power of the extraction voltage, regardless of the dimension of the extractor. If the radius of the ion extraction hole is multiplied L times, the gap between electrodes has to be also multiplied L times in order to keep the good ion optics of the extractor. Thus, the relation among the scaling factors of these variables is required to satisfy the scaling relation as shown in the Eq.(4).

$$\frac{V^3}{n_i{}^2T_e} = L^4 \quad . \qquad (4)$$

As for the magnetic field, the following relation is also required from the detailed analysis of scaling law, independently of the Eq.(4).1)

$$\frac{M\ V}{B^2} = L^2 \ . \qquad (5)$$

In order to increase the extracted ion current, the high extraction voltage is used within the dielectric breakdown voltage, and, at the same time, the plasma with high electron temperature and high plasma density which satisfy the relation of the Eq.(3), is produced. The plasma density and the electron temperature are considered to be the important parameters for a high intensity ion source. If the saturation current is larger than the space-charge limited current, the ion space-charge compensation with electrons can be used to relax the space-charge limitation, and so the high intensity ion current can be extracted from a single aperture with a good ion optics. The γ value of several tens can be easily obtained under the good space-charge compensation condition. The space-charge compensation factor is considered to be also the important parameter for a high intensity ion source.

2. Quality of Extracted Ion Beam

An emittance is used as an criterion of the quality of the extracted ion beam. If the acceptance of the ion beam transport system is clear, the percentage of the current which passes through the system can be easily estimated.

As shown in the Fig.2, the normalized emittance is related only to the radius of the extraction hole, the ion temperature of the plasma, and the mass number of ion.2)

$$\varepsilon_{2n} = 6.5\mathrm{x}10^{-7}a(\frac{T_i}{M})^{1/2} \qquad (6)$$

However, if the emittance is normalized for the energy, the normalized equation of the emittance can be written only in proportion to $a \cdot T_i{}^{1/2}$. On the other hand, the energy spread, E_s, can be written in the form of $E_s \cong T_i$. Therefore, three parameters related to the quality of the extracted ion beam are counted. The radius of the extraction hole and the mass number of

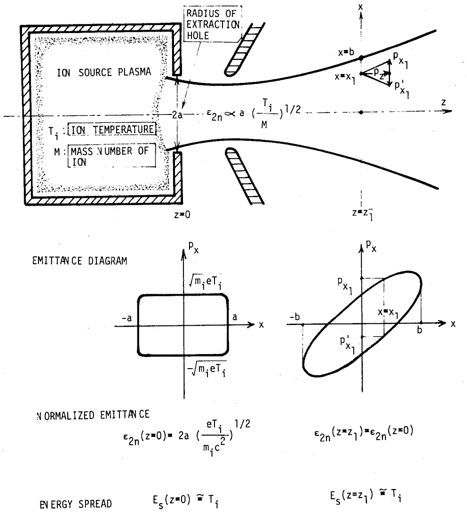

Fig.2 Ion source parameters related to the quality of the extracted ion beam. The parameters are indicated in ▭ .

ion are mentioned in section 1, and, thus, the ion temperature of the plasma is a new parameter.

In general, a low emittance can be obtained when the beam is extracted from the plasma with a low ion temperature through a small radius of the extraction hole. As the value of the emittance means by the random motion of the beam particles normal to the beam direction, the lower the value is, the better the beam quality is.

3. Transport of Ion Beam

The optics of the ion beam which is transported after extraction and acceleration is effected mainly by the ion space charge. The ion beam without space-charge neutralization can not transport in some cases. The condition to avoid this situation is given as $d > 2b$, where b is the radius of the ion beam. This condition is filled in the case of the single aperture extraction system, where the aspect ratio is lower than 1 in usual case. But, in the case of the multiaperture extraction system where the equivalent aspect ratio is much larger than 1, this condition can not be filled. In the latter case, the space-charge neutralization of ion beam in some degree is inevitably required.

The ion space-charge effect can be compared with the effect of the emittance by using the ion beam kinetic equation of the radial direction. The kinetic equation of the x direction in the cross section of the ion beam without the external force is given in the Eq.(7).

$$\frac{d^2\tilde{x}}{dz^2} = \frac{\tilde{\varepsilon}_{2n}{}^2}{\tilde{x}^3} + \frac{6.5\mathrm{x}10^5}{\tilde{x}} \cdot \frac{M^{1/2}\, I_i}{V^{3/2}} \qquad (7)$$

where the z axis is the beam direction. $\tilde{x}$ indicates the mean square root value. $\tilde{\varepsilon}_{2n}$(m.rad) shows the mean square emittance of the x direction. Figure 3 shows the relative contribution of emittance and perveance in determining the ion beam optics under the condition of $x=10^{-2}$m(beam radius b=1 cm)[3]. For example, when the energy and the current of H^+ beam are 10 keV and 10 mA, respectively, the perveance is calculated at 10^{-8} $A.V^{3/2}$. When the emittance is 10^{-4}m.rad, this beam condition is in the region where the perveance (space charge) dominates in the Fig.3. If the space charge is not neutralized, the beam is rapidly divergent. Therefore, in the case of utilizing the high intensity ion beam, the space-charge neutralization mechanism in the whole ion beam transport space is inevitably required.

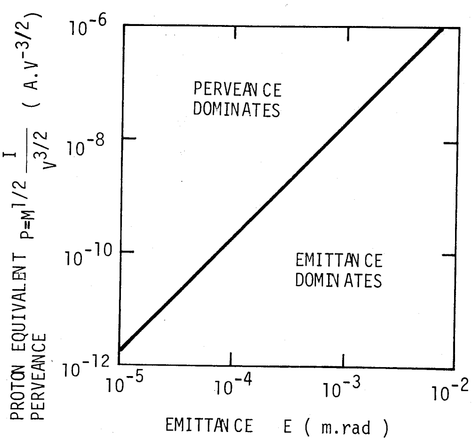

Fig.3 Relative contribution of emittance and perveance in determining the ion beam optics.

4. High Intensity Ion Source

In order to obtain a well focussed and high intensity ion beam current, it is necessary to investigate the improvements with regard to the parameters related to an ion source described in the prior sections. The improvements are put in order as following.

i) Ion source plasma.....High plasma density and high electron temperature ($I_i \propto n_i T_e{}^{1/2}$) are required to obtain a high intensity ion current. Low ion temperature ($\varepsilon_{2n} \propto T_i{}^{1/2}$) and uniform plasma density distribution on the ion emission surface are necessary for a good quality ion beam.

ii) Ion extraction system.....High extraction voltage ($I_i \propto V^{3/2}$), large aspect ratio ($I_i \propto (2a/d)^2$) are required for a high intensity ion beam extraction.

If the ion space charge in the ion extractor can be compensated with that of electrons, the space-charge compensation factor is desirable to be as large as possible ($I_i \propto \gamma$). The small radius of the extraction hole is necessary for a low emittance beam ($\varepsilon_{2n} \propto a$).

iii) Transport of ion beam.....The space-charge neutralization or compensation is required in the whole beam transport space for a low divergent ion beam.

a) Ion source plasma

The most effective method to obtain the plasma with high electron and low ion temperatures is, for example, the electron cyclotron resonance process, where a microwave with the electron cyclotron frequency is introduced into a magnetized plasma. If the plasma electrons are selectively heated by means of the electron cyclotron resonance process (ECR), only the electron temperature can be increased keeping the ion temperature low. Electron cyclotron frequency is expressed in the form of $f_{ce}(\mathrm{Hz})=2.8\times10^6\ B(\mathrm{gauss})$, and so in the plasma production chamber with the confinement magnetic field of a few thousands gauss, a microwave with the frequency of GHz order is required for ECR. As both of the ion cyclotron frequency ($f_{ci}(\mathrm{Hz})=1.5\times10^3\ B/M$) and the ion plasma frequency are much lower than the electron cyclotron frequency, the ions are not heated by this microwave.

Figure 4 shows the energy flow diagram for the ion source to investigate the effective plasma production. The effectivley utilized energy among the input power for ionization consumed in the plasma production chamber is about the ionization potential energy which is required for ionization at the time of stripping an electron from a neutral particle. The other power is consumed as loss into the wall surface of the plasma production chamber, such as the direct collisions of the electrons for ionization, the plasma electrons and ions to the wall. Therefore, to obtain the high intensity plasma, a high input power is effectively utilized for the ionization, and, at the same time, the loss of the charged particles is lowered as much as possible. When the ions are produced by the electron beam with the average energy, E_b, and the average velocity, v_b, the time dependence of the ion density is given in the Eq. (8).

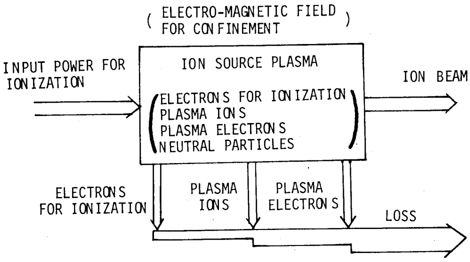

Fig.4 Energy flow diagram for the ion source.

$$\frac{dn_i}{dt} = n_o \cdot \sigma(E_b) \cdot v_b \cdot n_b - \frac{n_i}{\tau_{ci}} \tag{8}$$

where n_o is the neutral particle density and n_b is the density of the electrons for ionization. σ is the cross section for ionization, and τ_{ci} the ion confinement time. In the state of the perfect balance between the ion production and destruction, $dn_i/dt=0$ is satisfied, and so the ion density can be expressed in the Eq.(9).

$$n_i = \tau_{ci} \cdot n_b \cdot \sigma(E_b) \cdot v_b \cdot n_o \ . \tag{9}$$

As shown in Eq.(9), the importnat parameters related to the plasma production are the ion confinement time, the density of the electrons for ionization, the energy of the electrons for the ionization ($\sigma(E_b)v_b$), and the neutral particle density. It is desirable from the Eq.(9) that the ion confinement time is as long as possible. When the plasma potential is higher than the potential of the wall such as cathode or anode electrode, a large amount of ions in the plasma are destroied through the sheath on the plasma surface in contact with metal surface. The ion confinement time can be evaluated as the Eq. (10), assuming the simple model.

$$\tau_{ci} = 1.7\times10^{-6}\ \frac{V}{Sa}\ \left(\frac{M}{T_e}\right)^{1/2} \tag{10}$$

where V(cm^3) is the volume of the plasma production chamber and S_a(cm^2) is the metal surface area related to the ion destruction. If there is a high magnetic field to confine the plasma, the mobility of the normal direction to the magnetic field is very low for charged particles. Therefore, only the wall surface area normal to the magnetic field is evaluated as S_a, while the wall surface area parallel to the magnetic field is excluded from S_a. In the case of no or low magnetic field, S_a indicates the whole inside surface area of the plasma production chamber. From the Eq.(10), it is desirable that V/S_a is as large as possible. It is an effective plasma production method that the plasma is confined by use of a high magnetic field and the surface area normal to the magnetic field is utilized as the ion emission surface of the extraction hole with an end extraction. In the case of low magnetic field, it is desirable that the size of the plasma production chamber is larger, and the shape is spherical rather than long without unnecessary metal surface in the chamber.

Materials to be ionized are supplied into the plasma production chamber in the state of the vapour, i.e., the neutral particles. If the vapour is supplied to excess for the porpose of obtaining the high plasma density, a large amount of the neutral particles run away from the ion extraction hole, and so the gas efficiency is lowered. Moreover, the gas pressure of the whole vacuum chamber becomes high. The gas pressure P_o(Torr) necessary to obtain the gas efficiency, ζ, is given in the Eq.(11).

$$P_o = 1.57\text{x}10^{-19}\, n_i\, (\,T_oT_e\,)^{1/2}(\,\frac{1}{\zeta} - 1\,) \qquad (11)$$

where n_i(cm^{-3}) is the plasma density. T_o(K) and T_e(K) are the neutral particle and plasma electron temperatures, respectively. For example, in the case of the gas efficiency of 50% (ζ=0.5) and the electron temperature of 1.16x10^5 K (10 eV), the gas pressure to obtain the plasma density of 10^{12}cm^{-3} is calculated as follows.

$$\begin{aligned} P_o &= 9.3\text{x}10^{-4}\text{ Torr (at } T_o = 300\text{ K)} \\ &= 2.4\text{x}10^{-3}\text{ Torr (at } T_o = 2000\text{ K).} \end{aligned}$$

The gas pressure of the order of 10^{-2} - 10^{-3} Torr in the plasma production chamber is recommended.

When the electrons emitted from the cathode with the energy of 50-100 eV corresponding to the maximum cross section for ionization pass through the neutral particles with the gas pressure of 10^{-2} - 10^{-3} Torr, the number of times of ionization collision is 5x10^{-3} - 5x10^{-1} in the range of an electron passage of 5 cm. To increase the product of $\sigma(E_b)v_bn_b$ ($=J_b\sigma(E_b)/e$) as expressed in Eq.(9), the amount of electron beam has to be increased. However, if the electron beam current is simply increased, the input power is also increased with it, and so the power efficiency is not improved. The increase of "equivalent" amount of electron beam current is necessary. Threrefore, the electron beam motion is **effectively** controlled by means of the electric and/or magnetic fields which affect the motion of the charged particles. The methods to increase the effective passage of the electron beam are described as follows.

i) Utilization of electric field.....Electrons oscillate between the cathode and the anticathode.

ii) Utilization of electric and magnetic fields (crossed field).....Electron trocoid motion is effectively confined by the electro-magnetic crossed field.

iii) Utilization of ununiform field.....Electrons are reflected and confined by the mirror magnetic field.

b) Ion extraction system

In the case of the single aperture extraction system, extremely large aspect ratio with a good ion optics can not be expected as shown in the Eq.(1). In order to realize a high intensity ion beam extraction the two different methods can be adopted. The one method is that the equivalent aspect ratio is increased by use of the multiaperture extraction system and the other method is that the perveance is increased by means of the space-charge compensation of the ion extractor with that of electrons.

Figure 5 shows the fundamental transformation of the extraction electrodes by use of the multiaperture extraction system. One way to increase an extraction current is the increase of the extraction hole number (usual multiaperture extraction electrode system). Another way is the enlargement to one dimension (slit type extraction electrode system). To obtain a well focussed and high intensity ion beam by use of multiaperture extraction system, the size of the aperture is diminished and the dimension of the electrode including the whole apertures becomes as in the same order as the dimension of the original extraction single hole. It is important to notice that the multiaperture extraction system is equivalent in principle to the mesh electrode extraction system of a single hole.

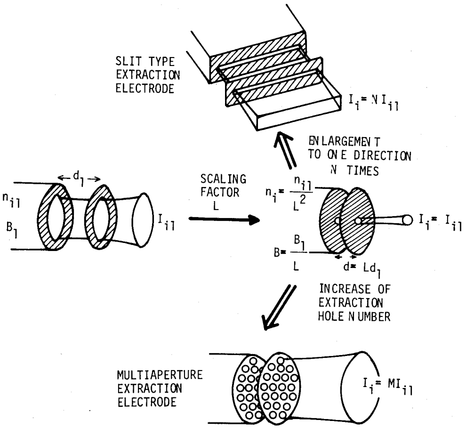

Fig.5 Fundamental transformation of the extraction electrode system by use of the multiaperture extraction system.

Ion space charge causes the limitation of the extractable current. Therefore, it is expected that the space charge limitation is considerably relaxed with the effective space-charge compensation in the whole region of the extractor. The amount of the ion space charge of the extractor is maximum on the ion emission surface of the extraction hole and decreases gradually toward the ion extraction electrode. In order to distribute the electron space charge in the similar shape of the ion space charge, dense plasma electrons with high electron temperature can be utilized, and, futhermore, the electron emitted from the ion extraction electrode can be also in use. If the energy and the density of the plasma electrons with high electron temperature are in optimum, the extractable ion current is large several times to several tens times as the current without the space-charge compensation.4)

c) Transport of ion beam

There are two methods to neutralize the space charge of the ion beam in the transport space. The one method is that the electrons are forcibly introduced into the ion beam from external. The other is that the secondary electrons generated by the collision between the ion beam and the residual neutral particles are effectively used.

In the last, the chemical interactions of the ionized particles and the fast neutral particles with the wall of the plasma production chamber are very important problem.5) However, this problem is omitted in this short paper.

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