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DESIGN OF A HIGH BRIGHTNESS ION SOURCE FOR THE BASIC TECHNOLOGY ACCELERATOR (BTA)

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Design of a High Brightness Ion Source for the Basic Technology Accelerator (BTA)

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An ion source has been designed and fabricated for a 10 MeV, 10 mA, CW proton accelerator called Basic Technology Accelerator (BTA). The ion source consists of a multicusp plasma generator and a two-stage extractor, and is expected to produce a 100 keV, 120 mA H^+ ion beam with a normalized emittance of as low as 0.5 πmm.mrad. Guiding principles of the design are presented together with calculations on magnetic configuration, proton yield, plasma production, beam optics, and gas efficiency of the ion source.

Keywords: Ion Source, Design, Linear Accelerator, High Brightness, High Intensity, Proton Ratio, Beam Optics, Multicusp, Basic Technology Accelerator, OMEGA Project

技術開発用加速器（ＢＴＡ）のための高輝度イオン源の設計

日本原子力研究所那珂研究所核融合工学部
奥村 義和・渡辺 和弘

（1992年１月31日受理）

技術開発用加速器（ＢＴＡ）と呼ばれる，10MeV，10mA，CW の陽子加速器のためのイオン源を設計し，製作した。このイオン源は多極磁場型プラズマ源と２段加速系から構成され，極めて高輝度の陽子ビーム（100keV，120mA エミッタンス0.5πmm.mrad）を生成する。このイオン源の基本設計方針と，ビーム光学やプラズマ生成部の磁場配位，プロトン比，ガス効率等に関する計算結果について述べる。

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1. INTRODUCTION

A 10 MeV linear accelerator called Basic Technology Accelerator (BTA) will be constructed at JAERI by 1996 [1,2]. The objective of the accelerator is to develop the basic technologies required for the construction of 1.5 GeV accelerator, which is being proposed for construction for use in the accelerator-driven nuclear transmutation system as one of the options of the OMEGA (Option Making Extra Gains from Actinides and Fission Products) project [3].

The target of the BTA is to accelerate 100 mA proton beams to an energy of 10 MeV with a duty cycle of 10 %. The average beam current is 10 mA, which is one or two order larger than that of the existing linear accelerators. Considering the beam losses in LEBT (Low Energy Beam Transport), RFQ (Radio Frequency Quadropole), and DTL (Drift Tube Linac), the ion source has to produce 120 mA proton beams at 100 keV for a pulse duration of 1 ms every 10 ms interval.

Table I shows the parameters required for the ion source. In order to obtain a high transmission efficiency in RFQ and DTL, the emittance of the beam should be very low; e.g. as low as 0.5 πmm.mrad in spite of the high beam current of 120 mA. In addition, the proton yield of the ion source is assumed to be more than 90 % and the impurity content is as low as 1 %, so that the momentum mass separator can be eliminated. The operating gas pressure is only 1-2 mTorr. These specifications are beyond the performances of the ion sources developed for the existing accelerators.

Fortunately, technologies producing an intense proton beams have been highly developed in these years for use in neutral beam injectors for heating the thermonuclear fusion plasmas [4,5]. For example, a high proton yield of 95 % and a low operating pressure of 1 mTorr were obtained in a multicusp ion source [6], and a good beam optics was observed in a multi-stage extraction system [7]. Some of the technologies are applicable to the design of the ion source for the BTA.

We have designed and fabricated a prototype ion source for the BTA by making use of the technologies developed for the fusion applications. In the present paper, the design of the prototype ion source is described together with the basic ideas and technologies used for the design. Calculations on beam optics, proton yield, plasma production, gas pressure, and magnetic configurations are also presented.

Table I Specifications of the Ion Source

Energy	**100 keV**
Current	**120 mA**
Duty Factor	**CW or 10 %**
Emittance	**0.5 πmm.mrad (100 % normalized)**
Proton Ratio	**> 90 %**
Impurity	**< 1 %**

2. DESIGN CONCEPT

2.1 Plasma Generator

Among several types of the ion sources used for accelerators the multicusp ion source is most preferable, because it offers a dense, uniform and quiescent plasma with a high gas and an electrical efficiency. The multicusp plasma generator has a strong magnetic field for plasma confinement and, at the same time, has a large field-free region for producing a uniform plasma. The advantages are;

1) From a view point of obtaining a low emittance beam, it is important to produce a quiescent plasma in which no oscillation occurs. In the multicusp source, there is no magnetic field in the extraction region so that there is no strong instabilities. A stable extraction sheath can be created and the electron temperature (hence the ion temperature) can be lower than that of the other sources.
2) Since there is no magnetic field in the extractor, the beam optics is not affected by the magnetic field.
3) A high proton yield is achievable, because the plasma confinement is so good that the hydrogen molecular ions (H_2^+ and H_3^+) are confined for enough time to dissociate to protons. (This will be discussed in more detail later.)
4) Operation of the plasma generator is reliable. The discharge is very stable over a wide range of plasma density of up to 10^{13} cm^{-3}. It is possible to change the plasma density (or the beam current) by regulating only one operating parameter; e.g. the arc voltage. This

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is preferable for programmed operation of the accelerator.

5) A better plasma confinement offers a lower operating gas pressure. By improving the plasma confinement, the multicusp plasma generator can be operated at a pressure of as low as 1 mTorr. Hence the gas flow rate can be reduced and high gas efficiency is expected. (This will be also discussed later.)

6) The structure of the multicusp plasma generator is simple. Effective water cooling is easy for high duty cycle or continuous operation.

The only one defect of the multicusp source is a short life time of the cathode. Since the cathode is immersed in a bulk plasma, it is easily damaged by ion bombardment resulting in a short life time at a continuous operation. The life time of the tungsten filament, which is widely utilized in the multicusp source, is an order of 300 hours. To overcome this problem, many studies have been done to improve the cathode life time by utilizing a LaB6 cathode, a hollow cathode, etc [8-10]. Plasma production by micro-waves or RF is more preferable, because it can eliminate the cathode from the source. Further study is necessary on this subject.

Although only a small area is required for ion extraction, the plasma generator should have an enough plasma volume for the good confinement and a stable operation at a low gas pressure. The smallest multicusp source we have developed has a dimension of 5 cm in diameter. However, the required gas pressure was high and the proton yield was poor. Therefore, in the present design, the size of the plasma generator is chosen to be a reasonable value. Although the required arc discharge power increases with the size of the plasma, the power is negligible in the total system of the high intensity accelerator.

2.2 Extractor

The extraction voltage is chosen to 100 kV, considering the optimum injection energy for RFQ and the present ion source technologies. For fusion applications, many ion sources are being operated at energies more than 100 keV; e.g. 40 A, 100 keV in JT-60 NBI [11], 3.5 A, 200 keV in JT-60 Active Beam Diagnostic System [7], and 50 mA, 300 keV in H^- ion source at NIAS [12]. Technologies obtained by these ion sources are useful in the present ion source.

There are two options to produce the required beam current of 120 mA. One is to extract a beam from a single aperture, and the other is to use multiple apertures and to focus these beamlets by beamlet steering technique [13]. The highest current extracted in a single aperture is determined by the space charge limit. In a rough estimation, the current I is given by;

$$I = \pi a^2 \frac{4}{9} \epsilon_o \left(\frac{2Z}{m_i}\right)^{1/2} \frac{V^{3/2}}{d^2}$$

$$= 4.3 \times 10^{-8} \cdot (2a/d)^2 \cdot (Z/M)^{1/2} \cdot V^{3/2} \qquad (1)$$

a: radius of aperture
d: gap distance
Z: ion charge number
m: mass of the ion
M: mass number of the ion
V: extraction voltage

The aspect ratio (2a/d) should be a small value to obtain a low beam emittance. Assuming (2a/d)=0.7 and (Z/M)=1, the upper limit of the beam current which can be extracted at 100 kV is 680 mA. The optimum current giving the lowest beam divergence is about 60 % of the current; 680 x 0.6 = 400 mA. In addition, a finite thickness of the electrode should be considered. Then the highest current achievable becomes 200-300 mA. On the other hand, there is a limitation of the extraction voltage determined by voltage holding capability. The highest field intensity is 12 kV/mm at 100 kV in the JT-60 Ion Source. Taking into account these limitations, we concluded that one aperture is enough to produce 120 mA H^+ ion beam. It should be noted that high proton yield is important in this respect; if the beam contains a lot of molecular ions, it becomes very difficult to obtain a H^+ ion beam current of more than 100 mA with a single aperture.

Although conventional ion sources are utilizing a single stage extractor consists of three electrodes, we chose a two-stage extractor in the present design in order to obtain a low beam emittance. The extractor consists of four electrodes, forming an extraction stage, an acceleration stage and a deceleration stage. By adjusting the voltage ratio applied to the extraction and the acceleration stages, it is possible to produce low emittance beams at a wide range of perveance.

Since the beam current is large and the pressure in the beam drift region is low, the produced ion beam is easily expand at the exit of the ion source because of the space charge effect. Figure A-1 shows an example of the space charge effect for both positive (H^+, He^+) and negative (H^-) ion beams, where the beam diameter and the current are almost same as the present ion source. The beam divergence becomes worse at lower pressures because of the space charge expansion. In case of the negative ion beam, the critical pressure at which the expansion occurs is about 5 x 10^{-3} Pa, while that of the positive ion beams is high; 10^{-1} Pa in case of H^{+} ion beam. Therefore, it is necessary to install a focusing element at the exit of the ion source. In the present design, the plasma generator is buried inside the insulator column, so that the focusing element can be installed close to the exit of the extraction electrodes.

3. SOURCE DESIGN

Figure 1 shows a cross sectional view of the prototype ion source for the BTA. The source has already fabricated and installed in a test facility for preliminary test on beam extraction. The source consists of a multicusp plasma chamber, a two-stage extraction system, and an insulator column. The dimensions of the plasma chamber are 20 cm in diameter and 17 cm in depth. The chamber is surrounded by 10 columns of strong SmCo magnets which form a longitudinal line-cusp configuration for primary electron and plasma confinement. These magnet columns are connected at a back plate by four rows of magnets. The open end of the chamber is enclosed by a plasma electrode, where additional 10 rows of magnets are installed except for the central extraction region. In the preliminary test, the plasma will be created by arc discharge between four tungsten filaments of 1.2 mm in diameter and the chamber wall. Plasma production by micro-wave or RF is being planned for long life operation. In this case, the micro-wave or an antenna will be introduced from the back plate. Preliminary test on the plasma production by 2.45 GHz micro-wave has already started in a different plasma chamber [14].

The extraction system is composed of four electrodes called plasma, gradient, suppression and exit electrodes. The ions are extracted by the potential difference between the plasma and the gradient electrodes and are accelerated to the full energy between the gradient and the exit electrodes. A negative potential of up to 5 kV is applied to the suppression electrode to repel backstream electrons from the beam plasma backstream. The shape of each electrodes is based on the extraction system of the JT-60 Ion Source, but is improved further to minimize the beam emittance by using a computer simulation code described later. The plasma chamber is made of aluminum alloy and the extraction electrodes are made of oxygen-free cooper. All elements including the plasma chamber and the electrodes are effectively water cooled for a continuous operation.

The insulator column is made of epoxy insulators and aluminum flanges.

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The dimensions of the insulators are 500 mm in outer diameter, and 50 mm (insulator A) and 120 mm (insulator B) in length. Voltage holding of up to 120 kV, DC was successfully demonstrated. Figure 2 shows a picture of the prototype source.

4. CALCULATIONS AND DISCUSSION

4.1 Magnetic Configuration

The magnetic field in the plasma generator was analyzed by using a computer code which calculates three dimensional magnetic configuration and can simulate primary electron orbits [15]. Figures 3 and 4 show a plain and a cross sectional view of the magnetic contour. Since the magnets are very strong (14 mm x 20 mm, BH_{max}= 27 MGOe), the magnetic field at the inner surface of the plasma generator is more than 2 kG. The magnetic field decreases to less than 30 Gauss within the central area of about 5 cm in diameter, where the plasma is expected to be uniform.

4.2 Proton Yield

The hydrogen ion beam contains not only H^+ ions (protons) but also molecular ion such as H_2^+ and H_3^+. Higher proton yield is desirable for the accelerator application. In the plasma generator, protons are produced by the following two main processes;

(a) Ionization of atom $\quad H_1^O + e \rightarrow H_1^+ + 2e$

(b) Dissociation of molecular ions $\quad H_2^+, H_3^+ + e \rightarrow H_1^+ + H_1^O, H_2, e$

In order to enhance the proton yield, there are two important factors. First of all, it is necessary to confine the molecular ions for enough time to allow dissociation. Hence, the loss area for the ions should be minimized or the plasma confinement should be good. At the same time, the confinement of atomic hydrogen is also important. Since the atomic hydrogen can not be confined by the magnetic field, large chamber volume or large volume-surface ratio is required. Secondary, the energetic electrons should be isolated from the region near the extractor to avoid generation and subsequent direct extraction of the molecular ions. For this purpose, the present source has a line cusps near the extraction area. By arranging the magnets, a transverse magnetic field or the magnetic filter can be created to repel the fast electrons.

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A rough scaling equation for the proton yield Γ was derived by Okumura et al.[16];

$$\Gamma = \frac{0.23\ V_p/S_L}{(\ 1 + 0.23\ V_p/S_L\ )} \qquad V_p:\mathrm{cm}^3,\ S_L:\mathrm{cm}^2 \qquad (2)$$

where V_p is the plasma volume and S_L is the total loss area for the ions. The parameter V_p/S_L is an index of the good confinement and is called "ion loss characteristic length". Figure 5 shows the dependence together with some experimental data obtained by the ion sources developed for fusion.

Now let's estimate the proton yield in a same manner as Ref.[16]. In the multicusp ion source, S_L can be written as;

$$S_L = S_A + S_F + (1/2)\beta S_p \qquad (3)$$

where S_A is the total cusp loss area, S_F is the area of the cathode, and S_p is the total area of the plasma electrode. The factor β indicates the fraction of the area that is actually illuminated by the plasma and the factor of 1/2 is multiplied to take into account the density gradient near the plasma electrode. The total cusp loss area may be approximated by total cusp length L_c times the diameter of the ion cyclotron motion,

$$S_A = 2L_c(M_i v_i/eB) \qquad (4)$$

where B is the magnetic field at the inner surface of the chamber. The velocity of ions escaping into the chamber wall v_i is assumed to be equal to the ion acoustic velocity C_s,

$$v_i = C_s = (kT_e/M_i)^{1/2} \qquad (5)$$

Substituting B=2.1 kG, L_c=250 cm and T_e= 4 eV, S_A becomes 48 cm^2. The total surface area of four filaments is about S_F= 30 cm^2. Since the plasma electrode are covered by the line cusps except for the central region, the loss area in the electrode is very small; βS_p= 40 cm^2. Hence the total ion loss area S_L is 98 cm^2.

The plasma volume V_p might be calculated by the expression;

$$V_p = \pi(r-\delta/2)^2(d-\delta/2) \qquad (6)$$

where r is the radius and d is the depth of the plasma generator. The parameter δ is the distance between the chamber wall and the uniform plasma area (B< 30 Gauss). As shown in Fig. 3, the distance δ is about 5 cm. Substituting r=10 cm and d=17 cm, V_p becomes 2560 cm^3. Hence the ion loss characteristic length V_p/S_L is 26 cm and the proton yield is estimated to be 86 %.

If the plasma could be produced by microwave, the cathode loss area could be eliminated. In this case, the V_p/S_L becomes 38 cm and the proton yield is estimated to be 90 %.

In addition, we can expect further enhancement due to the magnetic filter effect [17]. In fact, the proton yield was enhanced from 93 % to 95 % in our large semi-cylindrical plasma generator by introducing this magnetic filter effect [6]. Therefore, a proton yield more than 90 % is achievable in the present source.

4.3 Plasma Production

Plasma production in a multicusp plasma generator have been studied in many laboratories, for example, by Geode et al. at Culham laboratory [18] and by Arakawa et al. at JAERI [19]. In this section, we estimate the ion production rate and evaluate the arc discharge power required for the operation in a same manner as the Reference 19.

Ion production rate I_+ is given by;

$$I_+ = e n_p n_o \langle\sigma v\rangle_1 V_p + e n_e n_o \langle\sigma v\rangle_2 V_p \qquad (7)$$

I_+: plasma production rate
n_e: density of thermal electrons
n_p: density of primary electrons
n_o: density of neutral gas particle
$\langle\sigma v\rangle_1$: rate coefficient for ionization by primary electrons
$\langle\sigma v\rangle_2$: rate coefficient for ionization by thermal electrons

On the other hand, the loss of the ions is;

$$I_+ = 1/2 e n_e C_s S_L = 1/2 e n_e (kT_e/M_i)^{1/2} S_L \qquad (8)$$

where the velocity of ions escaping to the wall is assumed to be equal to the ion acoustic velocity.

The primary electron current is given by;

$$I_e = (en_p/\tau_e)V_p + en_p n_o\langle\sigma v\rangle_3 V_p \qquad (9)$$

τ_e: confinement time of primary electrons
$\langle\sigma v\rangle_3$: rate coefficient of deceleration of primary electrons

The confinement time τ_e is expressed by;

$$\tau_e = 4V/v_e A_a \qquad (10)$$

v_e: speed of primary electrons
A_a: effective anode area
V: chamber volume

Substituting (8) and (9) into (7), the ion production rate can be written as;

$$I_+ = f\cdot\frac{n_o\langle\sigma v\rangle_1}{1/\tau_e + n_o\langle\sigma v\rangle_3} I_e \qquad (11)$$

$$f = \frac{1}{1 - \dfrac{2V_p n_o\langle\sigma v\rangle_2}{(kT_e/M_i)^{1/2}\, S_L}} \qquad (12)$$

Now, let's substitute the parameters of the present source into these equations. Substituting v_e= 5x10^8 cm/s, A_a= 48 cm^2, V= 5300 cm^3 into (10), sthe confinement time of the primary electrons is 0.88 μs, where we assume the energy of primary electrons is 80 eV. Substituting V_p=2560 cm^3, n_o= 7x10^{13} cm^{-3}(2 mTorr), T_e= 4 eV, S_L= 98 cm^2, $\langle\sigma v\rangle_2$= 3x10^{-10} cm^3/s into (12), f becomes 2.2, which indicates that the rate of ionization by primary electrons is almost equal to the rate of ionization by the thermal electrons.

Then substituting these values and $\langle\sigma v\rangle_1$= 3x10^{-8} cm^3/s, $\langle\sigma v\rangle_3$= 3x10^{-8} cm^3/s into (12), we can obtain the ion production rate;

$$I_{+} = 1.43\ I_{e} \qquad (13)$$

In order to extract the ions with an extraction current density of 240 mA/cm^2, the ion saturation current density in a bulk plasma should be higher by more than a factor of five because of the existence of the magnetic filter. In this case, the total ion production rate should be;

$$I_{+} = 0.24\ (A/cm^2) \times 5 \times S_L\ (cm^2) = 118\ A$$

Hence the primary electron current I_e required is 83 A. The arc discharge current is a sum of the primary electron current and the current of ions impinging the cathode;

$$I_{arc} = I_e + I_i = I_e + \alpha(m_e/M_i)^{1/2}\ I_e \qquad (14)$$

where the coefficient α is a non-dimensional factor and is about 2.9 in the present case[19]. Therefore, the required arc discharge current is 89 A. Since the arc voltage is almost same as the primary electron energy (in fact, the arc voltage is lower than the electron energy by a few volt because of anode sheath), the required arc power becomes 80 V x 89 A = 7.1 kW.

4.4 Operating Gas Pressure

The operating gas pressure can be reduced as the plasma confinement is improved. Generally speaking, the lowest pressure at which the source can be operated scales inversely on the "ion loss characteristic length";

$$P_L \propto S_L/V_p \qquad (15)$$

In this section, we estimate the lowest limit of the operating pressure.

In order to create a stable arc discharge, the cathode sheath on the cathode surface has to satisfy the following Langumuir criteria;

$$J_i \geq \alpha(m_e/M_i)^{1/2}\ J_e \qquad (16)$$

J_i: ion current density
J_e: electron current density

J_i and J_e can be expressed by $J_i = I_+/S_L$, and $J_e = I_e/S_F$. Substituting these equations and the equation (11) into (16), the criteria for the neutral gas density is given by;

$$n_o \geq \frac{S_L \alpha (me/Mi)^{1/2}}{S_F f \ \tau_e \langle \sigma v \rangle_1} \frac{1}{(1-\alpha (m_e/M_i)^{1/2} \frac{S_L \langle \sigma v \rangle_3}{f S_F \langle \sigma v \rangle_1})} \qquad (17)$$

Although f is a function of n_o, $f \approx 1$ in the low pressures we are considering. Substituting the parameters of the present source,

$$n_o \geq 1.08 \times 10^{13} \text{ cm}^{-3}$$

Therefore, assuming a room temperature, we predict that the lowest limit of the operating pressure will be 0.3 mTorr.

4.5 Gas Flow Rate

The mean free path of the gas molecules is given by;

$$l = 1/\sqrt{2} \ \pi d^2 n_o$$

d: diameter of gas molecules
n_o: density of gas molecules

Substituting the diameter of hydrogen molecule (3×10^{-8} cm) and the typical operating gas pressure of 2 mTorr (7×10^{13} cm^{-3}), we obtain the mean free path of 3.6 cm. As the dimension of the aperture is 8-10 mm in diameter, the gas flow can be considered as molecular flow.

Using a conventional formula of the conductance for cylindrical aperture, the conductances of the plasma, the gradient, the suppression, and the exit electrodes are estimated to be 22 l/s, 32 l/s, 24 l/s, and 30 l/s, respectively. Considering the streaming effect of the gas flow [20], the whole conductance of the extractor becomes 7.8 l/s. Hence the neutral gas flow rate is 0.016 Torr.l/s (1.2 SCCM), when the pressure is 2 mTorr in the discharge chamber. The H^+ ion beam of 0.12 A corresponds to the neutral gas flow rate of 0.01 Torr.l/s. Hence the total gas flow rate injected into the source is 0.026 Torr.l/s (2 SCCM). The gas efficiency, defined by the ratio of the number of beam particles to that of input gas particles, is 38 % at 2 mTorr. If the source could be operated at 0.3 mTorr, the gas efficiency becomes 80 %.

In practice, higher gas flow rate will be required. This is because there is another gas flow channel through the periphery region of the electrode. It is necessary to have such a gas flow channel to keep the pressure constant during the beam extraction and to reduce the impurity content in the beam.

4.6 Impurity

The hydrogen ion beam produced by a conventional multicusp source contains 1-2 % low-Z impurities such as C, CH_n, O, H_nO and 0.1 % high-Z impurities such as Cu, Mo, W [21]. It was demonstrated that the low-Z impurity can be reduced to 0.3 % by conditioning or cleaning of the ion source by long period operation [22]. Careful selection of source materials and optimization of operating parameters will make it possible to reduce the impurity content to less than 1 %.

4.7 Beam Optics

The ion beam trajectory in the extractor was calculated by making use of the computer simulation code [23], which had been developed for the JT-60 Ion Source. Figure 6 shows an example of the trajectory, where the beam energy is 100 keV, beam current is 100 mA and the current density is 240 mA/cm^2. It should be noted that the electric field is stronger in the acceleration stage than that in the extraction stage, so that the beam is focused by the electrostatic lens formed at the exit of the gradient electrode. An emittance diagram is shown in Fig. 7 at the same condition. Almost all the points are distributed within the area of 3 mm x 0.6 deg, hence the normalized emittance is calculated to be 0.15πmm.mrad. This value is lower than the specification, although the thermal velocity of the produced ions is not taken into account in the present calculation.

The beam divergence defined at the grounded potential surface is plotted as a function of the current density in Fig. 8. There is an optimum current density which gives the lowest beam divergence or the lowest emittance. By regulating the voltage ratio Γ (Γ is the ratio of voltage applied to the gradient electrode to that applied to the plasma electrode), the optimum current density can be varied within a wide range.

5. CONCLUSION

We have designed a prototype ion source for the Basic Technology Accelerator. Calculations on beam optics, proton yield, plasma production, gas efficiency and magnetic configuration predicted that the required specifications are achievable in the prototype ion source. A preliminary test will be conducted in February 1992 in a 70 kV test facility (ITS-2M), which will be followed by a full scale test in a new 100 kV test facility by the end of 1992. Based on the data obtained in the prototype ion source, we are planning to design a production type ion source which is to be used in the test of RFQ and DTL in 1993.

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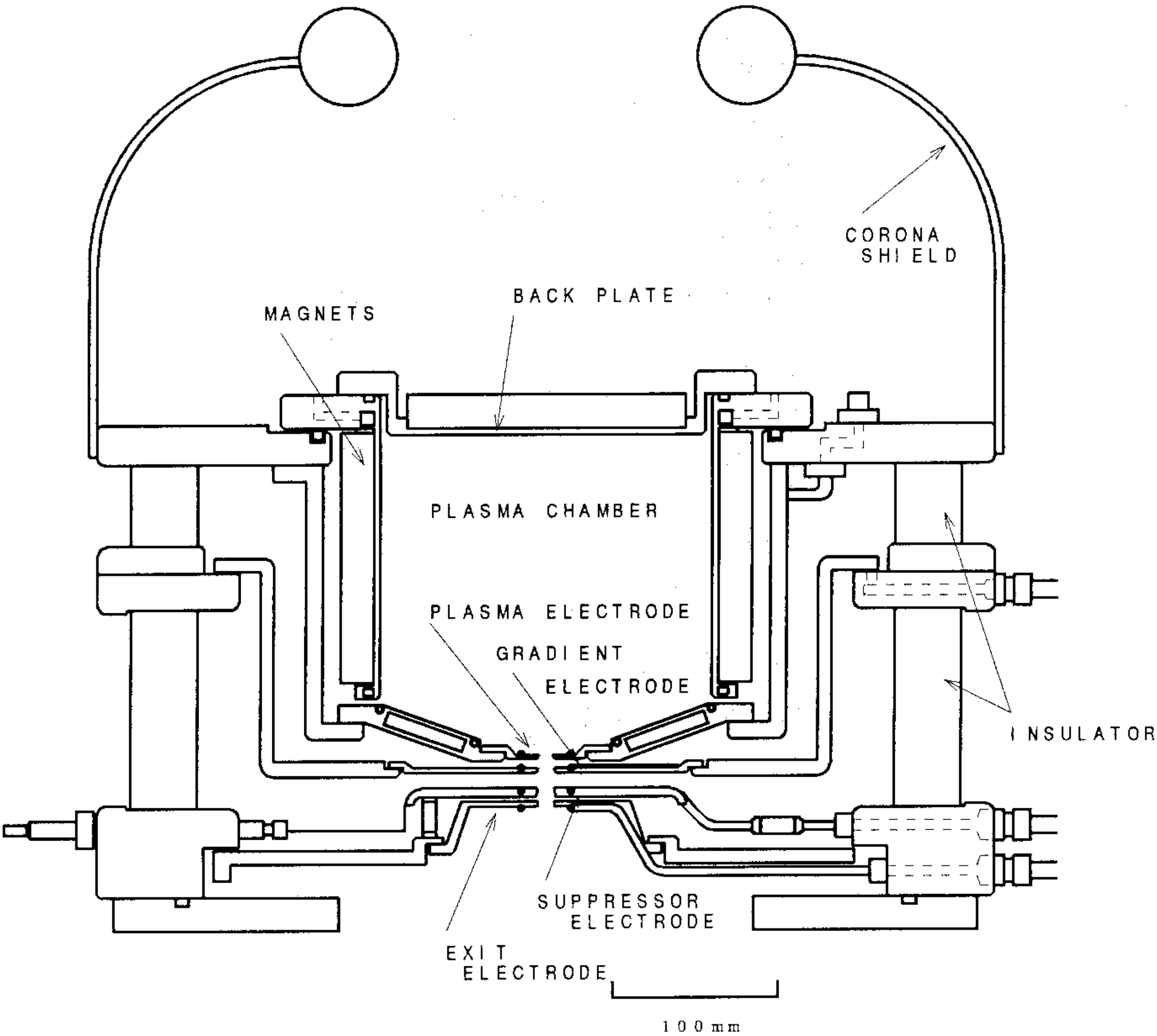

Fig. 1 Cross-sectional view of the prototype ion source for the Basic Technology Accelerator.

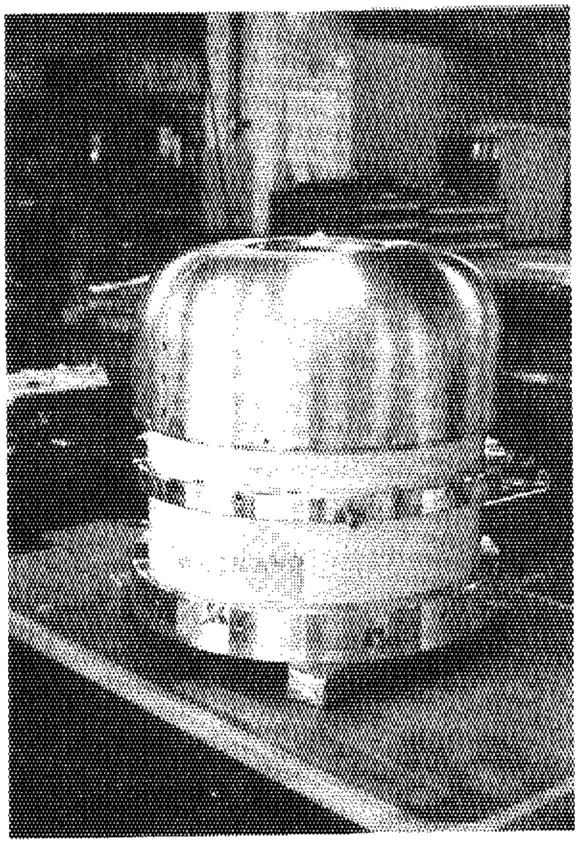

Fig. 2 Prototype ion source for the Basic Technology Accelerator

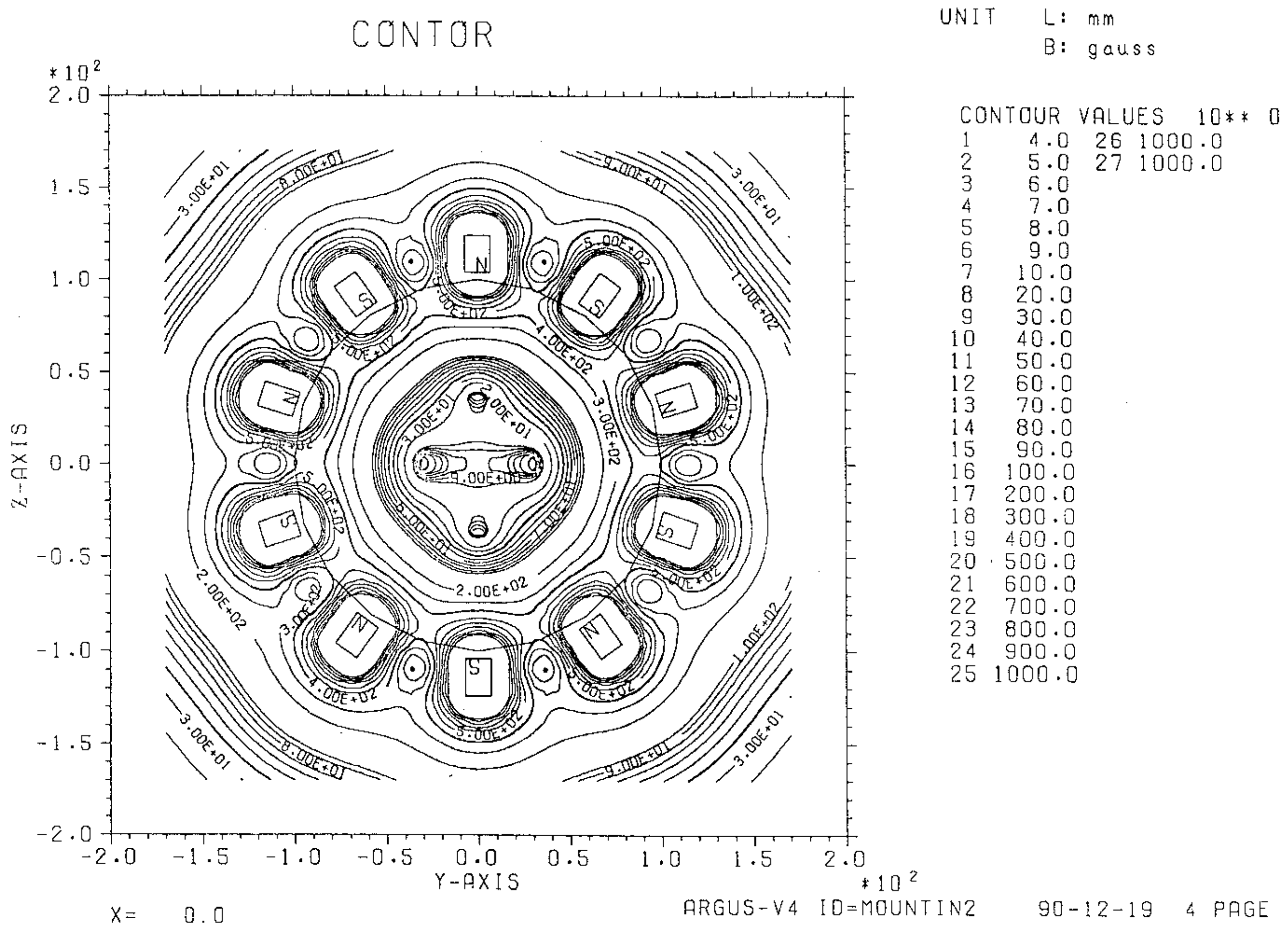

Fig. 3 Contour of the magnetic field in the plasma chamber (plain view)

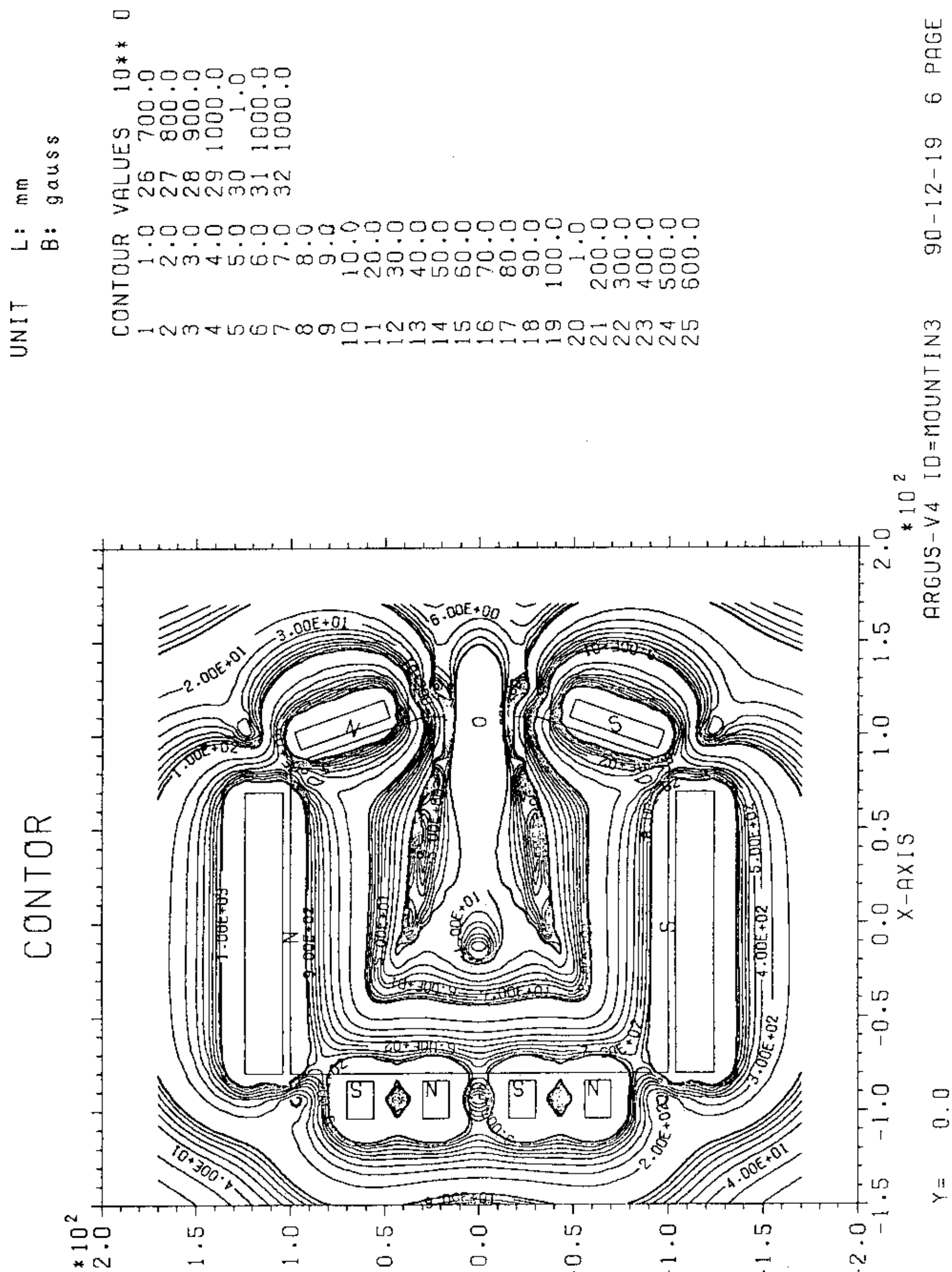

Fig. 4 Contour of the magnetic field in the plasma chamber (cross-sectional view)

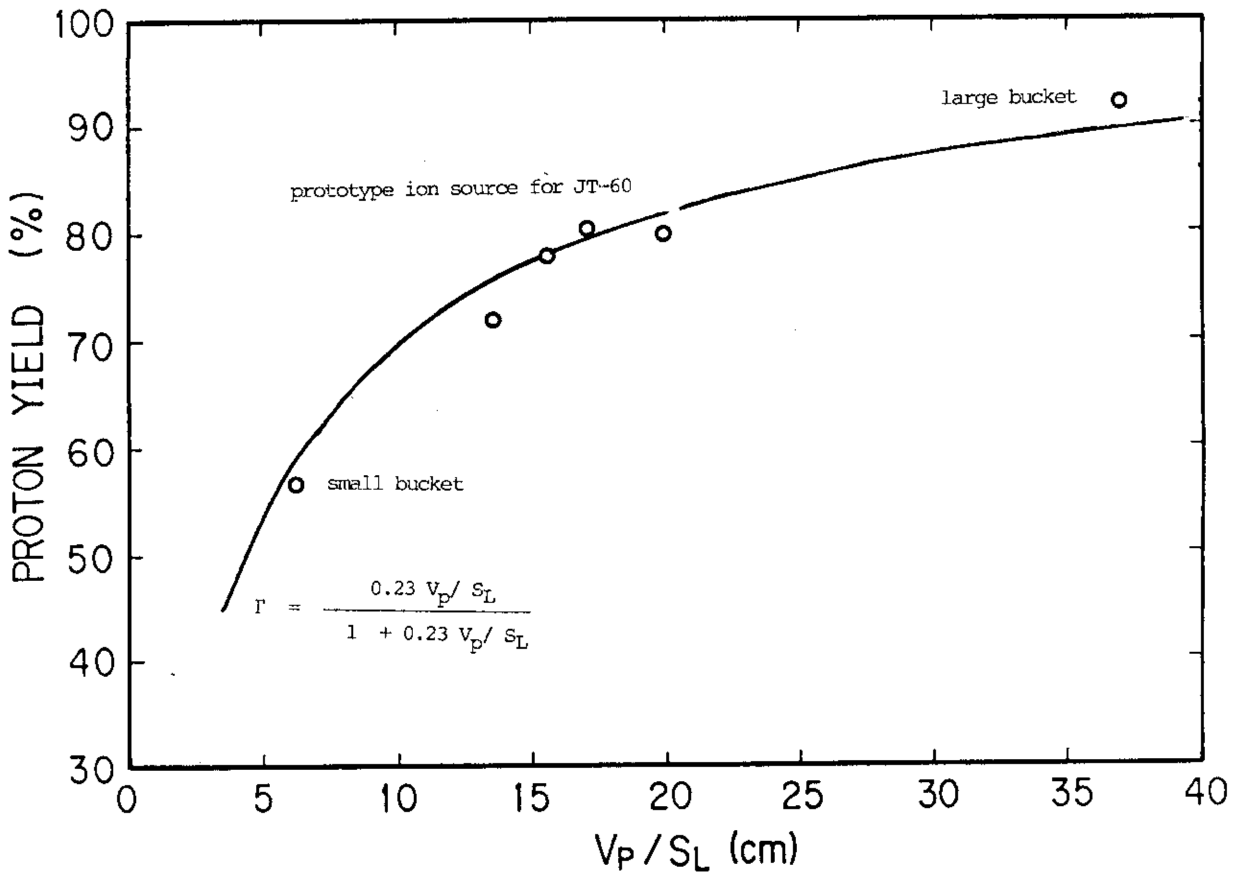

Fig. 5 Dependence of proton ratio **Γ** on the ion loss characteristic length V_p/S_L. The solid curve is calculated by the scaling Eq.(2). Ref.[16]

*KASOKUKI-YOU I.S. VACC=100KV GAM=0.7 H+ 240.0MA/CM2 (AA01)

CURRENT DENSITY = 2.4000E+02 (MA/CM2)
TOTAL CURRENT = 9.7886E-02 (A)
PERVEANCE = 3.0954E-09 (A/V**1.5)
MINIMUM POTENTIAL = -2.4557E+03 (V) AT Z = 3.0034E-02 (M)
DIVERGENCE (RMS) = 3.0405E-01 (DEG)
ELECTRON TEMPERATURE = 0.0 (EV)
ION TEMPERATURE = 0.0 (EV)

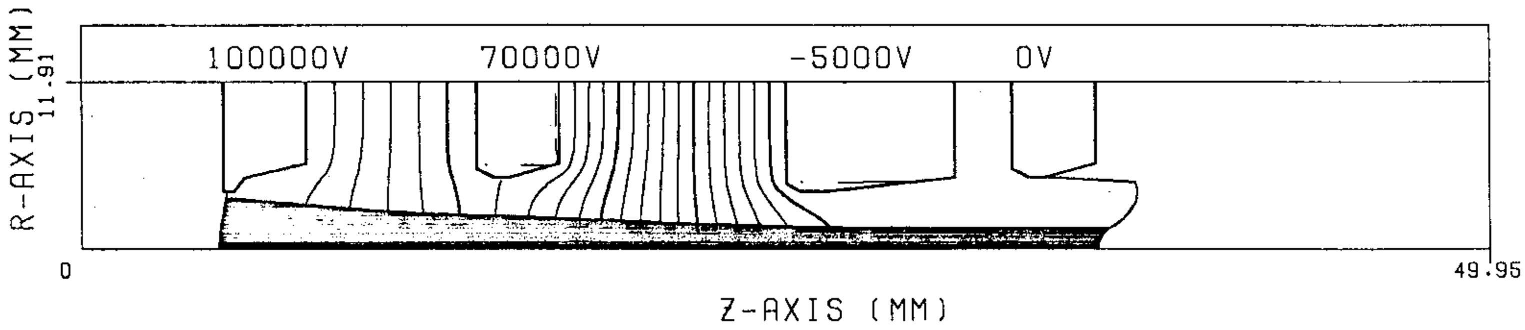

Fig. 6 An example of the ion trajectory in two-stage extraction system, where the beam energy is 100 keV and the current is 120 mA.

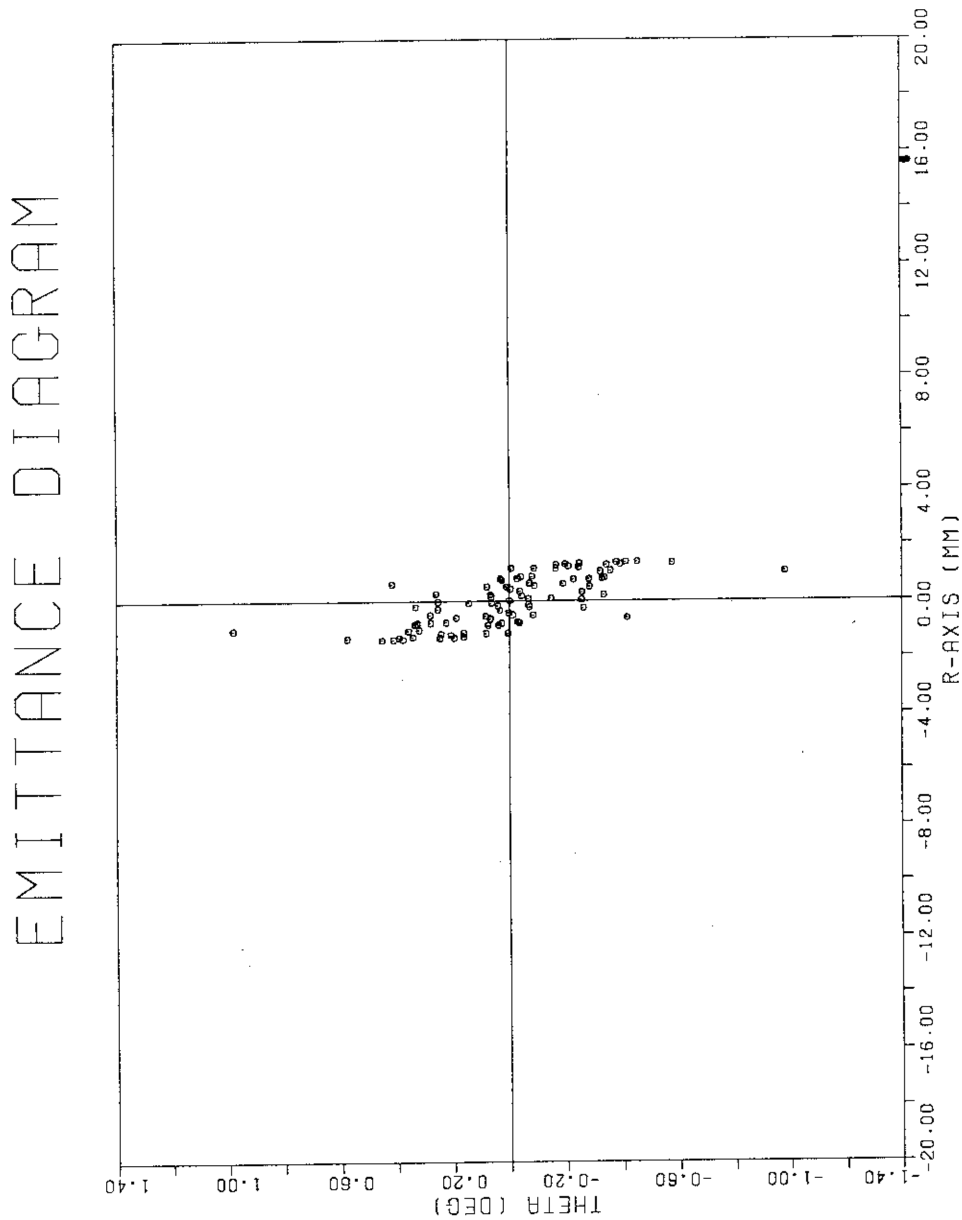

Fig. 7 Emittance diagram at the exit of the ion source.
The condition is same as in Fig. 6.

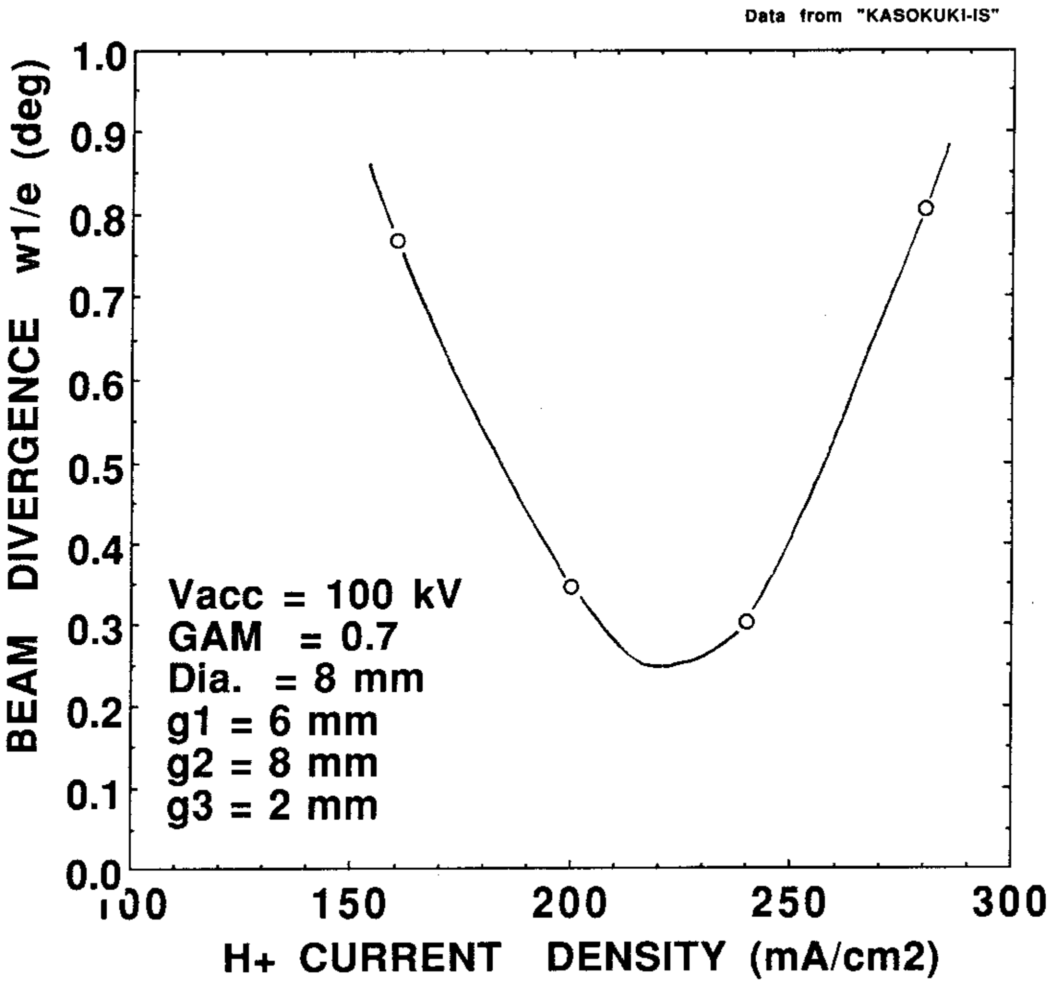

Fig. 8 Beam divergence as a function of current density.

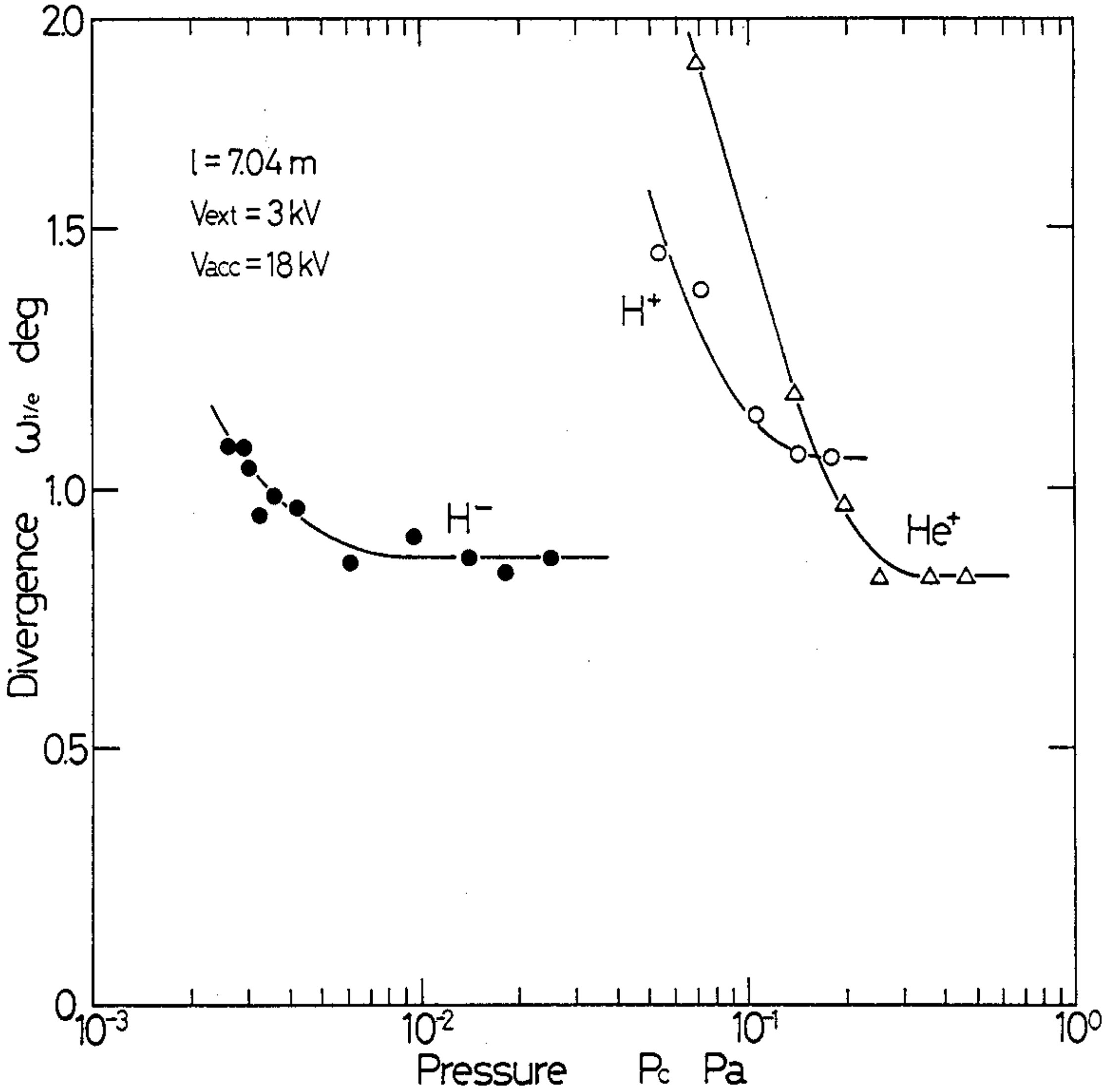

Fig. A-1 Divergence of positive and negative ion beams as a function of the pressure in beam drift region. The beam divergence becomes worse at lower pressures because of the space charge expansion. The beam conditions are 21keV/10 mA(H^-),30 keV/40 mA(H^+), and 30 keV/30 mA(He^+).