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Simulation Study on Ion Extraction from ECR Ion Sources

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SIMULATION STUDY ON ION EXTRACTION FROM ECR ION SOURCES

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Abstract

In order to study beam optics of NIRS-ECR ion source used in HIMAC, EGUN code[1] has been modified to make it capable of modeling ion extraction from a plasma. Two versions of the modified code are worked out with two different methods in which 1-D and 2-D sheath theories are used respectively. Convergence problem of the strong nonlinear self-consistent equations is investigated. Simulations on NIRS-ECR ion source and HYPER-ECR ion source (in INS, Univ. of Tokyo) are presented in this paper, exhibiting an agreement with the experimental results. Some preliminary suggestions on the upgrading the extraction systems of these sources are also proposed.

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1. INTRODUCTION

HIMAC accelerator complex is dedicated for cancer treatment and related researches. It consists of two ion sources(PIG and ECR), an RFQ and an Alvarez linacs, and dual synchrotron rings[2]. Ion beam optics is initially determined in ion source and therefore a good optic property of a source beam can benefit a lot to the accelerator system. An intense current and a high brightness are, of course, the aims in the design of a source. The extraction system of an ion source is the critical part for a good beam quality, and hence it is necessary to pay a great attention to the study of the extractor.

ECR ion source makes use of the principle of the plasma electron cyclotron resonance with the input microwave in a mirror magnetic field to generate highly charged ions in high density plasma. Ion extraction from such a plasma source is different from the extraction from a source with a fixed emitting surface, such as electron gun or surface emission ion gun, in the aspects that the emitting surface of the plasma is changeable in its position and shape, responding to the variations in the extraction field and the plasma density, and that the space charge force is not so effective on the extracted current from a plasma source.

These differences bring a lot of complexity in the study of ion extraction. Even though some simple analytical descriptions have been proposed for ion extraction study[3–5], the assumptions on emitting surface and of linear optics in these work limit their applicability in real design of extraction system for their low accuracy, though they can provide physics insight about extraction mechanism. Code simulation is an effective way and usually used in the design study of many ion sources for different purposes, including neutral heating plasma for fusion and ion implantation, as well as accelerators. The mathematical model of the simulation is essentially based on the self-consistent solution of Poisson–Vlasov equations and plasma sheath theory. Now there exist many codes [6–13] with similarity in solving Poisson–Vlasov equations but differences in some aspects, such as in sheath description, in dimension, in inclusion of magnetic field, as well as in output.

EGUN is a widely used 2–D code for the simulation study of electron gun[1] for its almost complete functions generally required in gun design. In this code, five–point discrete differential equation of Poisson is solved to get the static–electric field with space charge force depended on the electron emittion from the cathode according to Child–Langmuir law. Then Vlasov equation is solved by ray trace in the field and meanwhile the space charge of the rays is deposited on the mesh nodes according to the continuity equation. And then Poisson equation is solved again with the space charge and so is the Vlasov equation. After several iterations, a convergent solution is reached and the code yields the output. Magnetic field and initial electron temperature can also be included in the simulation.

In the sense of strong space charge effect and strong magnetic field in our ECR ion source, EGUN is the most suitable code for the simulation study on the source. So under the permission of the code author Prof. W.B.Herrmannsfeldt, we made use of these advantages of the code and modified it to make it usable for ion extraction from a plasma. The modification is concentrated on the plasma sheath region which is described by the theory developed by Self and Chen [14,15]. In the following section we will review the theory and explain the modification methods with emphasis on the convergent problem of the non-linear equations. And then the modified code is applied to the simulation study of the ion extraction from NIRS-ECR and Hyper-ECR ion sources.

2. MODIFICATION OF EGUN

The main task of the modification is to implant the sheath theory into EGUN code as ion emission mechanism instead of the space charge limited emission used in EGUN. The ions emit from a plane surface at the plasma potential behind of the outlet electrode and then go through presheath region to acceleration area, as shown in Fig.1. Although adding the presheath to EGUN has no many difficulties, reaching a convergent result is not a easy task because of the strong nonlinear problem in the presheath. Many code makers used different techniques to tackle this trouble on the same basis of sheath theory. In this section we will first present a brief introduction to the simple sheath theory, and then illustrate two modification methods based on 1-D and 2-D sheath theory.

2.1. Review of 1-D sheath theory

In 1-D sheath theory, plasma is assumed to be collisionless and electric-neutral. There is no macro-electric field and the temperature of ion is zero in plasma. The plasma ions emerge from plasma with a drift velocity and then pass through presheath. Meanwhile, plasma electrons will also come out from plasma with their thermal velocity. Therefore the ion space charge is partially compensated by the electrons in the presheath region. But the most of electrons can not go far from the plasma with the thermal velocity because of the repellency of the applied field and hence the electron density will decline with the distance from the plasma. When the space charge compensation effect of electrons is weak enough, the ions go through the sheath surface and reach to the acceleration region, just as the ions were extracted from this imaginary emission surface with an analog to the case of an electron gun. In fact some codes [6,9,12] does not include the presheath and directly starts the ions from the sheath surface which is found according to 1-D sheath theory. But it is obvious that the simulation with the description of presheath is more accurate.

The ions start from plasma with mono-energy distribution:

$$f_i(z,v)=n_0\delta[(v^2+\frac{2q\Phi}{m_i})^{1/2}-v_0] \tag{1}$$

advantages of the code and modified it to make it usable for ion extraction from a plasma. The modification is concentrated on the plasma sheath region which is described by the theory developed by Self and Chen [14,15]. In the following section we will review the theory and explain the modification methods with emphasis on the convergent problem of the non-linear equations. And then the modified code is applied to the simulation study of the ion extraction from NIRS-ECR and Hyper-ECR ion sources.

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The ions start from plasma with mono-energy distribution:

$$f_i(z,v)=n_0\delta\left[\left(v^2+\frac{2q\Phi}{m_i}\right)^{1/2}-v_0\right] \tag{1}$$

and electrons have Maxwellian distribution:

$$f_e(z,v)=n_0(\frac{m_e}{2\pi kT_e})^{1/2}\exp[-m_e(v^2-\frac{2e\Phi}{m_e})/(2kT_e)] \tag{2}$$

In these equations, n_0 is magnitude of the charge density of electron and ion in the plasma, Φ the potential with respect to the plasma, which is always less than zero, v_0 the initial drift velocity of ion, k Boltzmann constant, T_e the plasma temperature. q and e stand for the charges of ion and electron, m_i and m_e the masses of ion and electron. From the distribution functions, the charge density distributions of the two species can be integrated:

$$n_i=n_0\sqrt{\frac{U_i}{U_i-\Phi}} \tag{3}$$

$$n_e=n_0\exp(\frac{\Phi}{U_e}) \tag{4}$$

with $U_i=\frac{m_i}{2q}v_0^2$ and $U_e=\frac{kT_e}{e}$. Then we have 1-D Poisson equation:

$$\Phi''=-\frac{n_0}{\varepsilon_0}\left(\sqrt{\frac{U_i}{U_i-\Phi}}-\exp(\frac{\Phi}{U_e})\right) \tag{5}$$

with the space charge term compensated by electrons. In the region close to the plasma $\Phi\rightarrow 0$ therefore space charge is completely compensated. Far from plasma Φ becomes a large negative value and hence the electron space charge term becomes zero. The first integration of Poisson equation yields:

$$\Phi'^2=\frac{4U_in_0}{\varepsilon_0}(\sqrt{1-\frac{\Phi}{U_i}}-1)+\frac{2U_en_0}{\varepsilon_0}(\exp(\frac{\Phi}{U_e})-1) \tag{6}$$

under the initial conditions: $\Phi'=\Phi''=0$ at z=0, which is consistent with our assumption that no macro-electric field exists in the plasma. The further analytical integration can only be conducted under an approximation $\frac{\Phi}{U_e} \ll 1$ and a quadratic expansion, resulting in:

$$\Phi \rightarrow -U_e \exp\left(z \sqrt{\frac{n_0}{\varepsilon_0 U_e}\left(1-\frac{U_e}{2U_i}\right)} \right) \tag{7}$$

In order to obtain a meaningful result it is required that $U_i > U_e/2$,which is called Bohm's criteria for small Φ/U_e.

Plasma potential must be found out because in above equations the potential Φ is referenced to it. In general outlet electrode is electrically insulated, so we should suppose that the current densities on the wall of the electrode contributed from ions and electrons are just completely offset. The electron current density on the wall depends on the potential deference between the plasma and the wall. This condition gives out the plasma potential in terms of the wall potential which is actually set by experiment. In plasma only those electrons whose thermal velocity is large enough to overcome the repellency of the wall potential can reach to the wall. So the electron current density on the wall is the sum of these electrons:

$$J_{ew} = n_0 \sqrt{\frac{m_e}{2\pi k T_e}} \int_{\sqrt{-2e\Phi_w/m_e}}^{\infty} \exp(-\frac{m_e v^2}{2kT_e}) v dv \tag{8}$$

Let $J_{ew} = J_{iw}$, with the constant of ion current density:

$$J_{iw} = n_0 v_0 = n_0 \sqrt{\frac{2qU_i}{m_i}}, \tag{9}$$

we get the plasma potential in term of the wall potential U_w:

$$U_p = U_w - \Phi_w = U_w + \frac{U_e}{2} \ln \frac{m_i U_e}{m_e U_i \pi}. \tag{10}$$

2.2 *An Approximate Solution of Meniscus Position*

Plasma meniscus is generally considered as the equivalent emitting surface of a plasma ion source. Different from electron gun, the position and shape of the emitting surface are variable. Space charge limit on extracted ion current is now no longer effective and the emission current is source limited. Current density is a constant for different extraction voltage, but the distance between the meniscus and the extractor changes, or more exactly speaking, the shape the meniscus varies, as shown in Fig.2, and hence the source emits ion beam with different optics property. The dependence of the meniscus position on applied extraction voltage and ion current density has been given out in Ref.[16]:

$$d_e=\sqrt{\frac{4\varepsilon_0}{9}\sqrt{\frac{2q}{m_i}}\frac{V_0^{3/2}}{j_i}}, \tag{11}$$

which is the same as Child–Langmuir law for space charge limited emission. In the induction of the formula, some assumptions ware made: plasma electron is cold; on the plasma side of meniscus, electrons provide complete cancellation of electric field; when ions acrose emitting surface with an initial velocity, they see no field; after the meniscus, the applied extraction electric field exerts on ions.

In fact, however, there is no such an emitting surface at which no electric field exists for ion extraction from a plasma. As we have discussed in last section, there is a pre-sheath region between plasma and meniscus in which electric field is not equal to zero, and therefore at the emitting surface there exists electric field. So a more exact meniscus solution should come from Eq.(6). But unfortunately, an analytical solution can not be worked out from that equation.

To overcome this difficulty, some simplifying assumptions need to be made. We can divide the problem into two regions: pre-sheath region and extraction region. In pre-sheath region, sheath theory of Eq.(6) is used to give the boundary condition of electric field at the emitting surface. Then in the following region, it is supposed that no electron exists, and consequently the second term of Eq.(6) is omitted. This assumption is reasonable because the space charge effect of electron will much more sharply drop down than that of ion in the extraction region, as shown in Fig.3.

Suppose the meniscus is at outlet electrode potential. So from Eq.(6), the field at meniscus can be found:

$$\Phi'^2_w=\frac{4j_i}{\varepsilon_0}\sqrt{\frac{m_i}{2q}}\left(\sqrt{U_i+U_p-U_w}-\sqrt{U_i}\right)+\frac{2j_iU_e}{\varepsilon_0\sqrt{U_i}}\sqrt{\frac{m_i}{2q}}\left(e^{-\frac{U_p-U_w}{U_e}}-1\right) \tag{12}$$

where $j_i=n_0v_0, U_p-U_w=-\Phi_w$. In the extraction region, there is no electron and hence the

Poisson equation of Eq.(5) is integrated:

$$\Phi'^2=\frac{4j_i}{\varepsilon_0}\sqrt{\frac{m_i}{2q}}\left(\sqrt{U_i-\Phi}-\sqrt{U_p+U_i-U_w}\right)+\Phi'^2_w \tag{13}$$

under boundary condition given by Eq.(12). Further integration from meniscus to extractor yields:

$$d_e=\frac{2}{3}\left(\frac{\varepsilon_0}{j_i}\sqrt{\frac{2q}{m_i}}\right)^{\frac{1}{2}}\left[\left(\sqrt{U_{p,i}}-\sqrt{U}\right)^{\frac{3}{2}}-\left(\sqrt{U_{p,i}-U_w}-\sqrt{U}\right)^{\frac{2}{3}}-3\sqrt{U}\sqrt{\sqrt{U_{p,i}-U_w}-\sqrt{U}}+3\sqrt{U}\sqrt{\sqrt{U_{p,i}}-\sqrt{U}}\right] \tag{14}$$

where $U_{p,i}=U_p+U_i$, and

$$\sqrt{U}=\sqrt{U_i}\left(1+\frac{U_e}{2U_i}\left(1-e^{-\frac{U_p-U_w}{U_e}}\right)\right). \tag{15}$$

When d_e equals d_w,i.e.,the distance between the anode and extractor, the emitting surface is a plane one, emitting ion beam with a parallel profile. If it is longer than the distance, a concave emitting surface is formed, resulting in a focused ion beam. If it is shorter than the distance, a divergent ion beam will be emitted from a convex meniscus. Of course, these conclusions are drawn out under some geometric assumptions, as made in the deduction of Child–Langmuir law, that the anode is infinite thin and the electrodes are infinite planes.

In Eq.(14), $\sqrt{U}$ is a value much smaller than $\sqrt{U_p+U_i}$. And $\sqrt{U_p+U_i-U_w}$ is also a small value. Therefore in Eq.(14), the first term is the dominate one, while the third term is negligible. Comparing the second with the fourth, the latter is the larger one because $\sqrt{U}$ is typically a number greater than unit. From the analysis, we find the distance from emitting surface to extractor for given current density and applied extraction voltage is longer than that calculated from Child–Langmuir law of Eq.(11). This result is attributable to the effect of the space charge compensation of electrons.

Figure 4 shows the dependence of the meniscus position on the extraction voltage, in which the solid line is calculated from Eq.(14) and the dash line from Child–Langmuir law. Although the difference between the two curves is not very large, it still has some effects on the extracted beam because the optics is very sensitive to the curvature of the emitting surface.

It should be pointed out that the result is calculated from 1–D model. It is found in simulation study the position or curvature of emitting surface is not so sensitive to the extraction potential applied on extractor as the figure shows for the reason of 2–D effect and the field shielding effect near anode hole.

2.3 Modification: Method I

In this modification, the analytic space charge expression for ions in Eq.(1) is used in the region with potential higher than wall potential. Out of this region ion space charge is found by ray trace. Electron space charge is always given by Eq.(2). The reason for such a scheme is to avoid the divergence triggered by the incorrect space charge accumulation on some mesh points in presheath from inaccurate ray trace in the beginning several iterations. And a further measurement must be taken to prevent the iteration from divergence: the potential in the space charge terms should also be consistent with the space charge expressions. To do so, the potential is found by numerical integration of Eq.6 from the place at wall potential to plasma surface:

$$z=z_w-\int_{U_w}^{\Phi}\left[\frac{4U_i n_0}{\varepsilon_0}\left(\sqrt{1-\frac{\phi}{U_i}}-1\right)+\frac{2U_e n_0}{\varepsilon_0}\left(\exp(\frac{\phi}{U_e})-1\right)\right]^{-\frac{1}{2}}d\phi \qquad \textbf{(16)}$$

This 1–D potential result is only suitable to the consistent space charge distribution, rather than to the ray trace of ions. The 2–D field seen by ions is still solved from Poisson equation with the source term given by above method.

In EGUN the space charge average with the previous cycle was weighted with a fixed factor in all iterations. It is found the convergence process can be speeded up by an accelerated under relaxation method:

$$\rho^{(n+1)}=\omega\rho^{(n+1)}+(1-\omega)\rho^{(n)} \qquad \textbf{(17)}$$

where the weight factor ω between the present result $\rho^{(n+1)}$ and previous one $\rho^{(n)}$ is unit in the first iteration, but is divided by 1.1 after each iteration. In this way, a stable space charge will be reached after a number of iterations. The flow chart of this scheme is shown in Fig.5.

To start the calculation, we need to input following initial data: the initial ion directed energy by U_i, which should satisfy Bohm's criteria, plasma temperature by U_e, mass of ion m_i and the current density of ion, and the other input data needed in EGUN. The potentials of all Dirichlet boundaries are set in input data file except that of plasma surface which is calculated after the code begins according to Eq.10. The boundaries of electrodes can be shifted horizontally and vertically by simply input the shifting distance data without renewing the old boundary data as required in EGUN. This feature helps one out of the troublesome and monotonous boundary input work when the extractors are relocated to search for better beam optics or to compare with experiment data. The relative shifting data of the boundaries is input following the boundary data, with zero boundary code in the last line of boundary shifting input section to end the boundary modification.

It is necessary to accurately stop the ray trace when ion strikes on any electrode or slit plate. EGUN can do this but not very accurately: some rays close to the inner edge of electrode can still pass through the electrode to continue their traces. These rays can sometimes contribute a large amount of current to the total extracted current and influence the movement of the remaining rays. In the modified code, this weakness has been eliminated.

It is found that this method can not always give a convergent result. In the case of intense current and existence of large field stagnation area, the iteration may never go to convergence: it oscillates between two results, but none of them is the correct one. The reason for this phenomenon is that the space charge is so strong that it dominates the field distribution in some area, such as in the hole of outlet electrode which screens the area from the applied field. As a result, many ions will be diverted in r direction and can't get out of the hole. Consequently, in the next iteration there almost is no space charge effect and all ions can pass through the hole. This results in an oscillation in the successive iterations. It seems that space charge limit can be reached in ion extraction from a plasma source. But this is not the real physical case. In fact, before the space charge limit is approached, electrons will instantly compensate ion space charge. However, simulation can do this only in the next iteration. Therefore it is necessary to avoid the diversion and to compel ions to go out, and then the correct space charge compensation can be expected in the next iteration, resulting in a convergent iteration. To achieve this goal, raising the ions initial velocity and plasma temperature, which is proportional to the potential difference between plasma and outlet electrode, is an effective way. This parametric cure for the divergence trouble was also used by other author[17]. It has been demonstrated that the convergent results have little dependence on these parameters. Therefore this cure is reliable.

It should be pointed out that this modification is based on 1–D sheath theory. Therefore when the form of sheath is too much curved, in the case that the current density is so high that the plasma expands out of outlet electrode, the results from this modification method may be dubious. So an alternative method is applied.

2.4 Modification: Method II

In this method, 1–D sheath solution is avoided to be used in the simulation by means of directly solving non–linear Poisson equation, just as done in AXCEL code[7,18,19]. Ion space charge is found by ray trace in all region and electron space charge is calculated consistently with potential in Poisson iteration, as shown in the flow chart of Fig.6. In method I, the source term of Poisson equation is determined in ray trace subroutine and then keeps a constant in Poisson solver subroutine. Now only ion space charge keeps constant in Poisson iteration, while electron space charge iterates with potential by successive under–relaxation:

$$n_e^{k+1} = \omega_e^k n_e + (1-\omega_e^k) n_e^k \tag{18}$$

in which $n_e = n_0 e^{\frac{\Phi}{U_e}}$ is calculated from the potential of present iteration, n_e^k is the result of the previous iteration, n_e^{k+1} is the new result, ω_e^k is the electron relaxation factor which is generated from previous value divided by a constant D larger than unit (typically 1.02) with the initial value $\omega_e^0 = 1$. The new result will be used for the next Poisson iteration to calculate the new potential. So this scheme simultaneously iterates electron space charge and potential until a convergent potential result is reached.

The Chebyshev relaxation is used in Poisson solver of EGUN. In this method, the relaxation factor varies from one to next iteration:

$$\omega_p^{k+1} = \frac{1}{1-\chi_m \omega_p^k} \tag{19}$$

with constant χ_m about 0.24 and $\omega_p^1 \approx 1.98$. However it is found that the iteration started with such a large over–relaxation factor will not approach convergence quickly in the case of the non–linear problem. It is better to increase the factor from a value slightly greater than unit to about two, in order to obtain a stable electron space charge.

The convergence speed has a strong dependence on the relaxation factor and plasma density. How to choose an optimum value of convergent factor is a matter of experience and no general rule has been figured out. As the plasma density gets higher, the factor should increase more slowly. The residual error is also used as a judgement of the increment of the factor. When the error is small, the increment can be large in order to speed up the convergent process.

A comparison of the two methods shows that they give out almost the same results for the problem in which the sheath surface is nearly plane, as indicated in Fig.7. But when the sheath surface is very much curved, as shown in Fig.8, the two methods result in an obvious difference in beam optics. This means that the 1–D sheath theory used in Method I is not accurate enough in this situation. In order to reach a convergent result for intense beam extraction, method I needs to raise the plasma temperature, while method II needs to low the value of relaxation factor. Of course, more than ten iterations will be needed to reach a convergence for both methods at high current intensity.

3. SIMULATION STUDY ON NIRS-ECR ION SOURCE

Beam extraction from NIRS-ECR ion source is studied by the modified code. The extraction system is composed of a Pierce type diode extractor and an einzel lens. After passing through a slit, the beam is analyzed by the analyzing magnet. Fig.9 is a sketch of the system with a movable extractor[20]. The dependence of the current downstream the magnet on the position of the extractor and the extraction voltage was tested. In these tests the voltage of the einzel lens was always adjusted at the optimum focusing strength.

3.1 The effect of the extraction voltage

The test results [21]of the source indicate that the current obtained after the analyzing magnet increases with the extraction voltage. It is reasonable to suppose the current is proportional to the total ion current. The simulation shows that the current dependence on extraction voltage does not mean the existence of the space charge limit in the extraction from the plasma source. It is found that the extracted currents at different voltages have no obvious variations, but the ion beam with higher energy suffers less space charge effect and hence has less losses in the transportation, especially on the slit plate before the analyzing magnet. Fig.10 presents the test and the simulation results of the normalized current by the current at 10 kV versus the extraction voltage.

3.2 The effect of the puller position

The dependence of the analyzed current upon the position of the puller was conveniently tested owing to the design of the moveable puller. The reason for the presence of optimum puller position in the test, as shown in Fig.11, is explained by means of simulation. It is found that the optimum position corresponds to the best match of the extracted beam with the transport line. When the puller is too close to the anode, the extracted beam spread greatly, even though the aberration is really small. As the beam pass through the einzel lens, however, it suffers a great amount of aberration from nonlinear field due to its large radius, and consequently, a lot of ions are lost on the slit plate, as shown in Fig.12. If the puller is positioned too far from the anode, the extracted beam gains a large aberration in the extraction gap and then in the einzel lens. Therefore, as we can see in Fig.13, many ions can not go through the slit. At the optimum position, the puller extracts a slightly convergent ion beam with a little aberration. The beam is suitable for a little spread by space charge effect to make a nearly parallel beam in the einzel lens, and hence accepts little aberration. The good quality of the beam assures almost all of the ions can pass through the slit, as indicated in Fig.14. The geometry of the anode and puller in Fig.12–14 is enlarged three times for a good accuracy in the sheath region and Ar^{+8} beam with an ion temperature of 1 eV is used. The einzel lens is set on the optimum voltage for maximum current after the slit in each case.

3.3 The transmission efficiency of the anode

When ions go through the anode, some of them will not get out of the extraction hole but streak on the anode. The transmission efficiency of an anode is defined as the radio of the extracted current to the current on the emitting surface of the area of the hole of the anode. The dependence of the efficiency on the thickness of the anode and the position of the puller is investigated for our ECR ion source. It is obvious that thick anode has more chance to be hit by the ion, and hence it decreases transmission efficiency, as shown in Fig.15. Therefore a thin anode is preferred for the reason not only of less aberration, but also of the high transmission efficiency. But, of course, there is a limit on the thickness of an anode set by the requirement to resist the high temperature of source plasma[22].

In the hole of a thick anode, the space charge can dominates the field due to the shielding function of the hole from the applied extraction field and therefore a strong space charge field in r–direction in the hole will push ions toward the bore of the anode. As the extractor is so close to the anode that the sheath surface locates near the inner wall of the anode with a concave form, the field in the hole has a focusing effect on ions and therefore almost all ions going through the hole can get out of the anode. As a result, it yields a large transmission efficiency. But unfortunately, the emittance of the extracted beam is also very large, as shown in Fig.16. When the extractor is far away from the anode, the sheath locates at the out surface of the anode with a convex form, including almost all anode hole region into the plasma. So ions can go through the hole without any strong force in r–direction, resulting in a high transmission efficiency but also a bad beam quality. Between the two extremes, there is an area for both low transmission efficiency and low emittance.

From the simulation study on NIRS–ECR ion source, it is found that a thin anode would be better for high transmission efficiency and good beam quality. High extraction voltage is preferred for low emittance growth in the long transportation.

3.4 The Effect of Ion Temperature

Ion random motion in transverse direction of the plasma, expressed as a finite ion temperature, is one of the sources of beam emittance. The extracted beam will obtain a finite emittance from ion temperature even though the extraction system has no any aberration. The effect of ion temperature is modeled in the code by starting ions with an angle with respect to the optical axis. At a position of the plasma surface, ions are grouped in either three or five, depending on user' choice, and then these three or five rays set out with different angles, transverse speed and current, which are calculated from Boltzmann distribution for a given ion temperature. It was found that in EGUN the inclusion of ion temperature will cut down the current assigned to the rays in a group. As a result, the total current on the emitting surface will greatly decrease comparing with the case of zero ion temperature. Therefore some modifications must be made in order to keep the total current on the emitting surface the same as that at zero ion temperature. The emittance dependence on ion temperature is then investigated for NIRS–ECR ion source, as shown in Fig.17. Of course, the emittance in the figure is due to not only to

finite ion temperature, but also to the aberration, which can not be avoided in our case.

4. MODELING OF HYPER-ECR ION SOURCE

This source is used in Institute for Nuclear Study, Tokyo University[23]. The extraction system of the source is somewhat similar to NIRS-ECRIS except for its large extraction hole, as shown in Fig.18. The simulation of the source was compared with the test data[24] for various extraction voltages. In the simulation current density of the source is determined by the way to make the extracted current the same as that of the test. In the experiment, the einzel lens was not used, therefore the extracted beam drifts directly to the slit. In Fig.19, the dependence of the current after the slit on the extraction voltage is compared with the test results for relatively low total extracted current. There is a good agreement at high voltage but some discrepancy at low voltage. In the higher current case, as shown in Fig.20, the test and simulation lines exhibit almost the same dependent relation of current with the voltage but with a gap between the two lines. The difference between the data of test and modeling is believed to be resulted from the simple simulation model, which does not include all physical phenomena actually happened in the machine, such as uneven current density distribution on the emission surface, Larmor rotation of electrons in sheath under strong magnetic field and secondary emission in the transport channel.

In the simulation study, it is found that the focusing bar of the outlet electrode shields the outlet hole from the extraction field too much, and therefore the sheath surface is very much curved. The low energy beam near the outlet hole is subjected to a strong nonlinear field (also due to the large radius of the hole) and has a heavy aberration. And then the extracted beam spread greatly, as shown in Fig.21(a). Cutting the bar shorter can ameliorate this case. Fig.21(b) exhibits a nearly plane sheath surface and less aberration near the outlet hole. And therefore the extracted beam has better quality.

5. CONCLUSIONS

In order to study ion extraction from a plasma ion source, EGUN code was modified by replacing space charge limited emission mechanism with plasma sheath theory. 1-D analytical sheath model is applied in the first version of the modified code to pursue a stable sheath surface. Generally it can give a satisfactory modeling. But when the sheath surface is much curved in the case of high current density and low extraction voltage, 2-D sheath model must be more precise. Therefore the second version of the modified code has been developed without 1-D assumption. In the second version, strong non-linear Poisson equation is solved simultaneously with electron space charge. To overcome any instability, a gentle successive over-relaxation method is adopted in Poisson solver and electron space charge is under relaxed.

The modified codes are then applied to the study on NIRS-ECR ion source and

finite ion temperature, but also to the aberration, which can not be avoided in our case.

4. MODELING OF HYPER-ECR ION SOURCE

This source is used in Institute for Nuclear Study, Tokyo University[23]. The extraction system of the source is somewhat similar to NIRS-ECRIS except for its large extraction hole, as shown in Fig.18. The simulation of the source was compared with the test data[24] for various extraction voltages. In the simulation current density of the source is determined by the way to make the extracted current the same as that of the test. In the experiment, the einzel lens was not used, therefore the extracted beam drifts directly to the slit. In Fig.19, the dependence of the current after the slit on the extraction voltage is compared with the test results for relatively low total extracted current. There is a good agreement at high voltage but some discrepancy at low voltage. In the higher current case, as shown in Fig.20, the test and simulation lines exhibit almost the same dependent relation of current with the voltage but with a gap between the two lines. The difference between the data of test and modeling is believed to be resulted from the simple simulation model, which does not include all physical phenomena actually happened in the machine, such as uneven current density distribution on the emission surface, Larmor rotation of electrons in sheath under strong magnetic field and secondary emission in the transport channel.

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The modified codes are then applied to the study on NIRS-ECR ion source and

HYPER–ECR ion source. Some test phenomena are explained by simulation and the codes are also checked with the experimental data. Modeling of NIRS–ECR ion source suggest that a thinner outlet electrode is better for both high transmission efficiency and good beam quality. For HYPER–ECR ion source, a shorter focusing bar on the outlet electrode is found to be better for suppressing the strong aberration near the outlet hole. The agreement and the discrepancy in the comparison with test results of HYPER–ECR ion source indicate the reliability of the codes and the incompleteness in the physics model used in the codes. A further work is expected to include Larmor motion of electron in sheath and space charge neutralization in transport channel by collision with residual gas.

In addition to the code modification and simulation work, a theoretical research is also carried out. 1–D meniscus equation,i.e. Child–Langmuir law for plasma, is modified to include non–zero electric field at meniscus.

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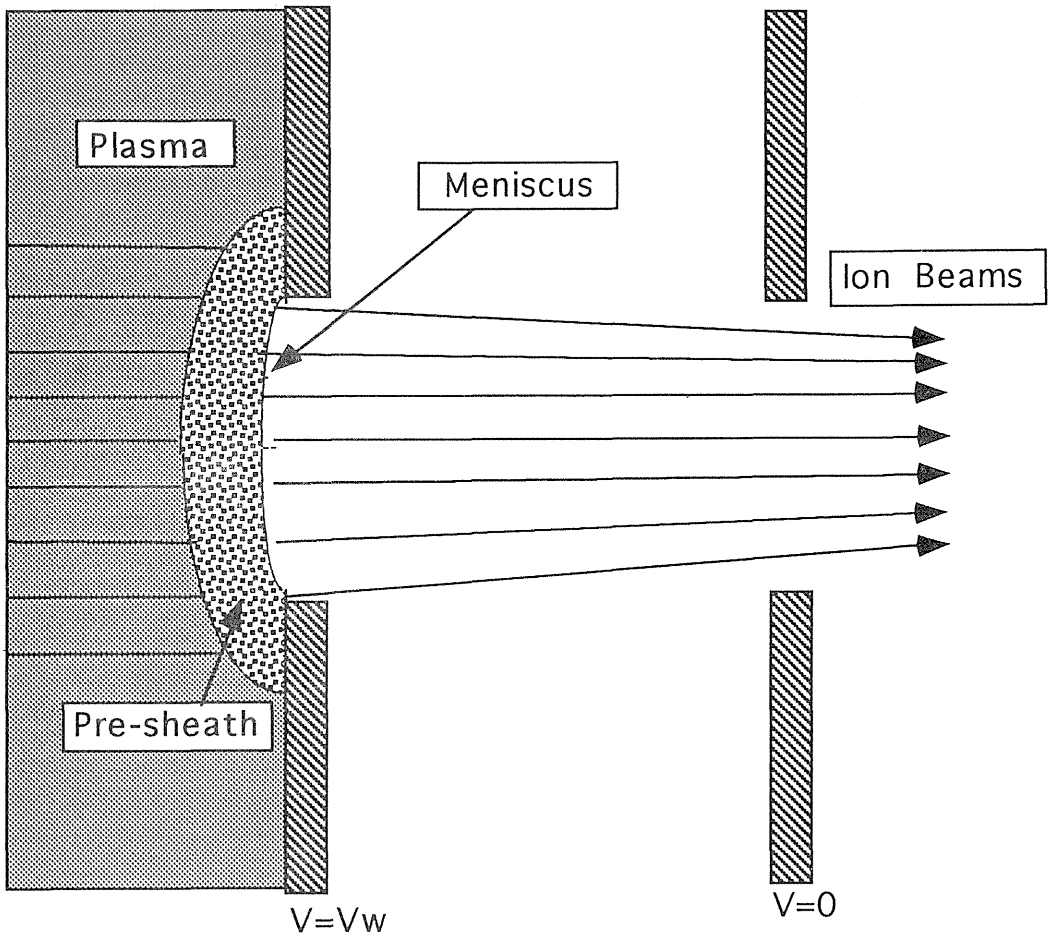


Figure 1. Ion Emission From A Plasma Source

It is assumed in the simulation that the ions emit from a plane surface at plasma potential behind the outlet electrode and then go through presheath into extraction gap.

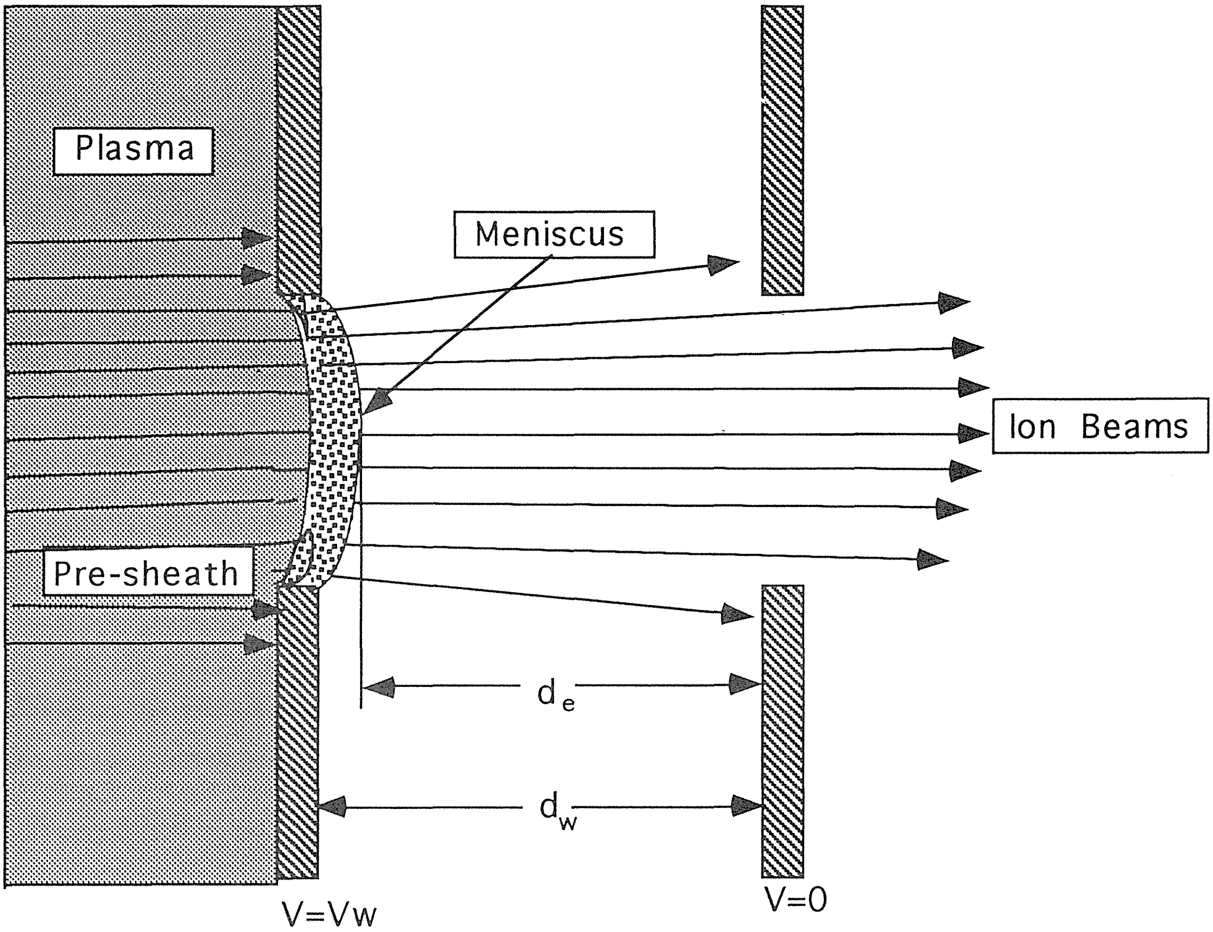


Figure 2. Dependence Of The Form Of Meniscus
On The Extraction Voltage

In this figure, plasma meniscus expands out of the outlet electrode because of the lower extraction voltage than in Fig.1 with the same plasma density. The distance between the meniscus and the extractor becomes shorter in the viewpoint of 1-D (on the axis). But actually, in 2-D, it results in the change in the meniscus' form, and then in different optics of the extracted beam.

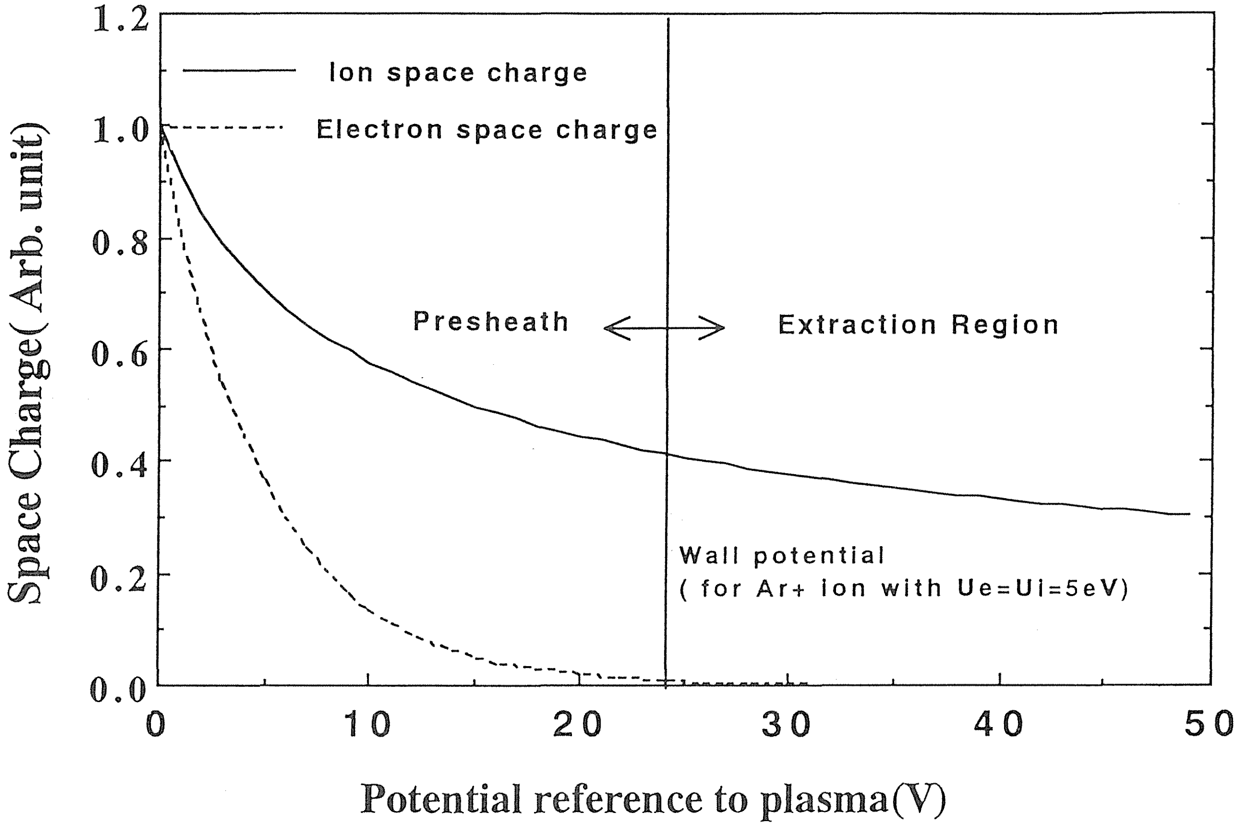


Figure 3. Space Charge of Ion and Electron in Presheath and Extraction Regions

In presheath region, the plasma electron partially compensate the space charge of ions. But in extraction region the electron space charge effect can be neglected.

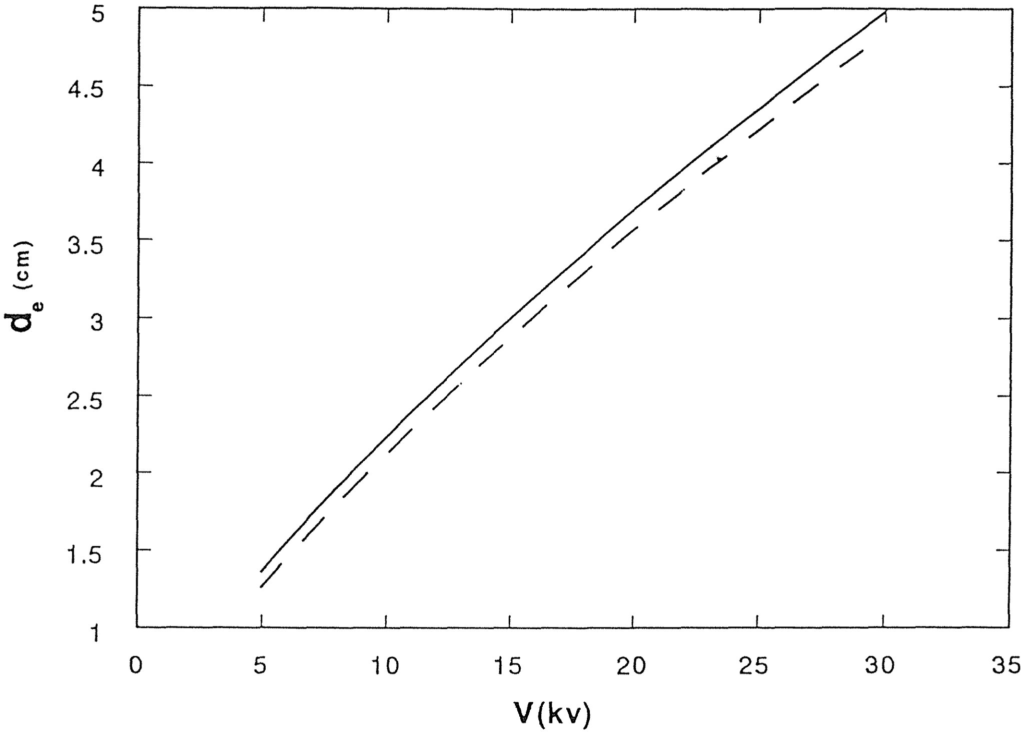


Figure 4. Position Dependence of Emmiting Surface on Extraction Voltage

(Solid line from Eq.(14), Dash line from C-L law)

(d_e is the distance between meniscus and extractor).

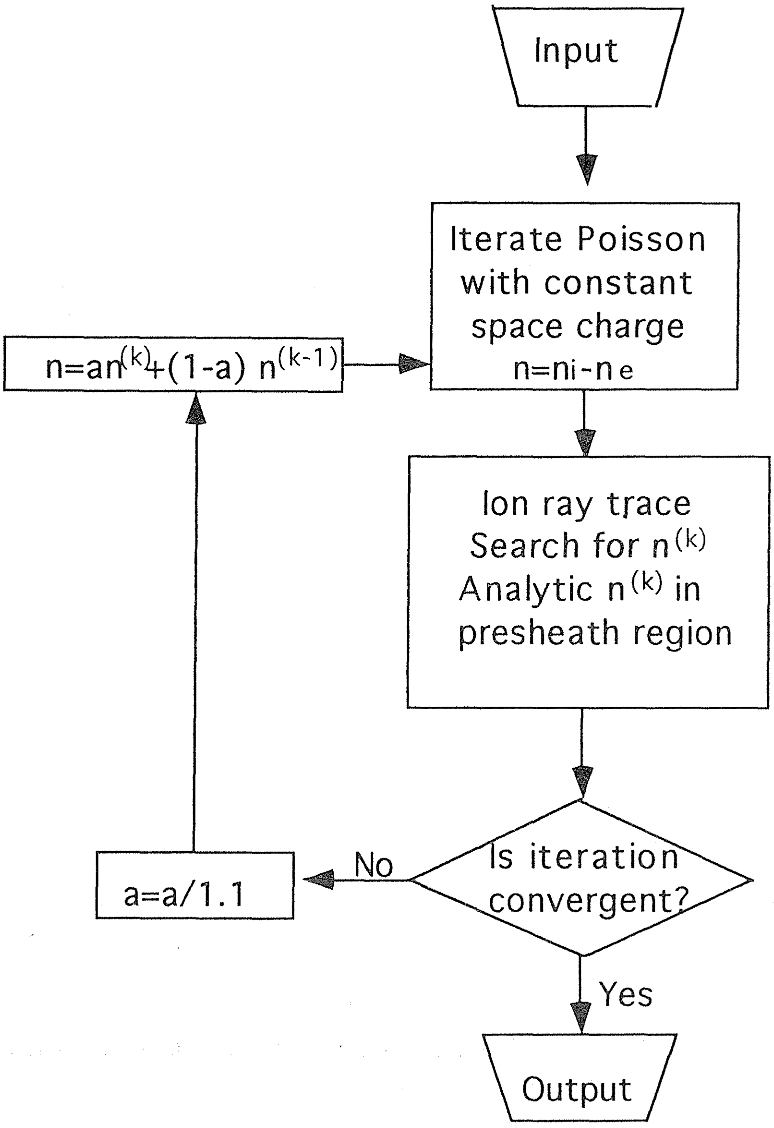


Figure 5. Flow Chart of Method I

1-D sheath theory is applied in this method. Space charge keeps a constant in Poisson solver but is under-relaxed in ray trace-Poisson iterations.

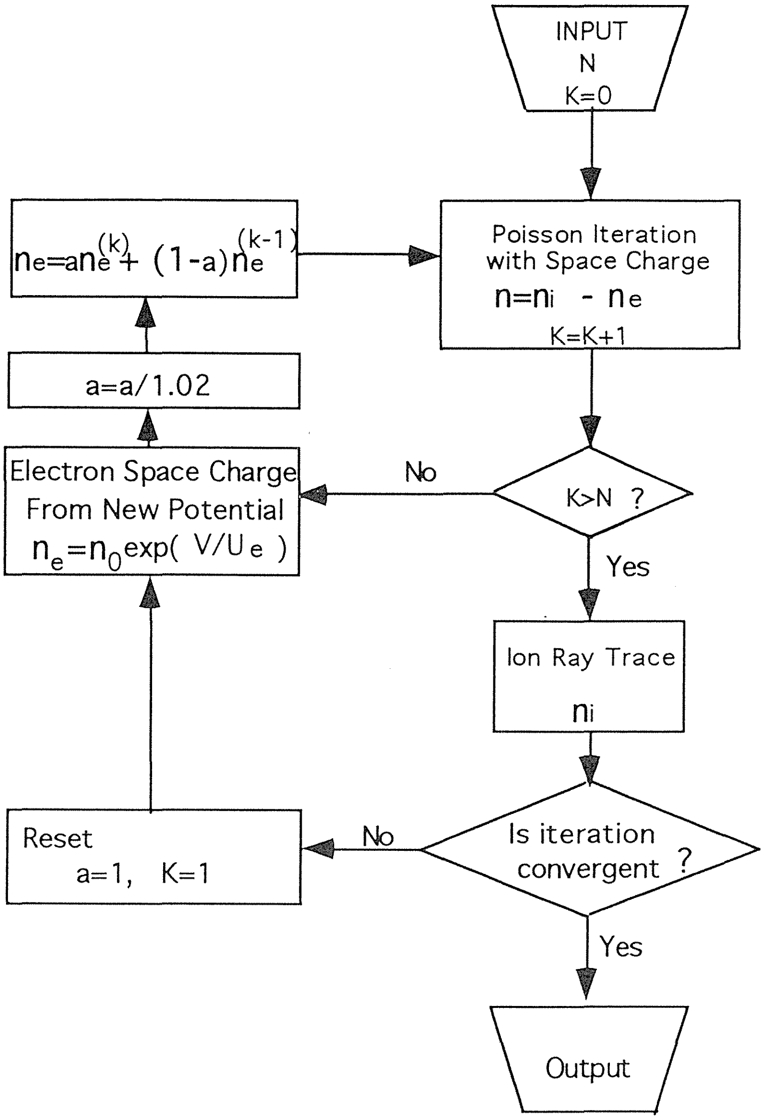


Figure 6. Flow Chart of Method II

Electron space charge is iterated simultaneously with potential in Poisson solver by an under-relaxation, while space charge of ions still remains a constant which is found in ray trace.

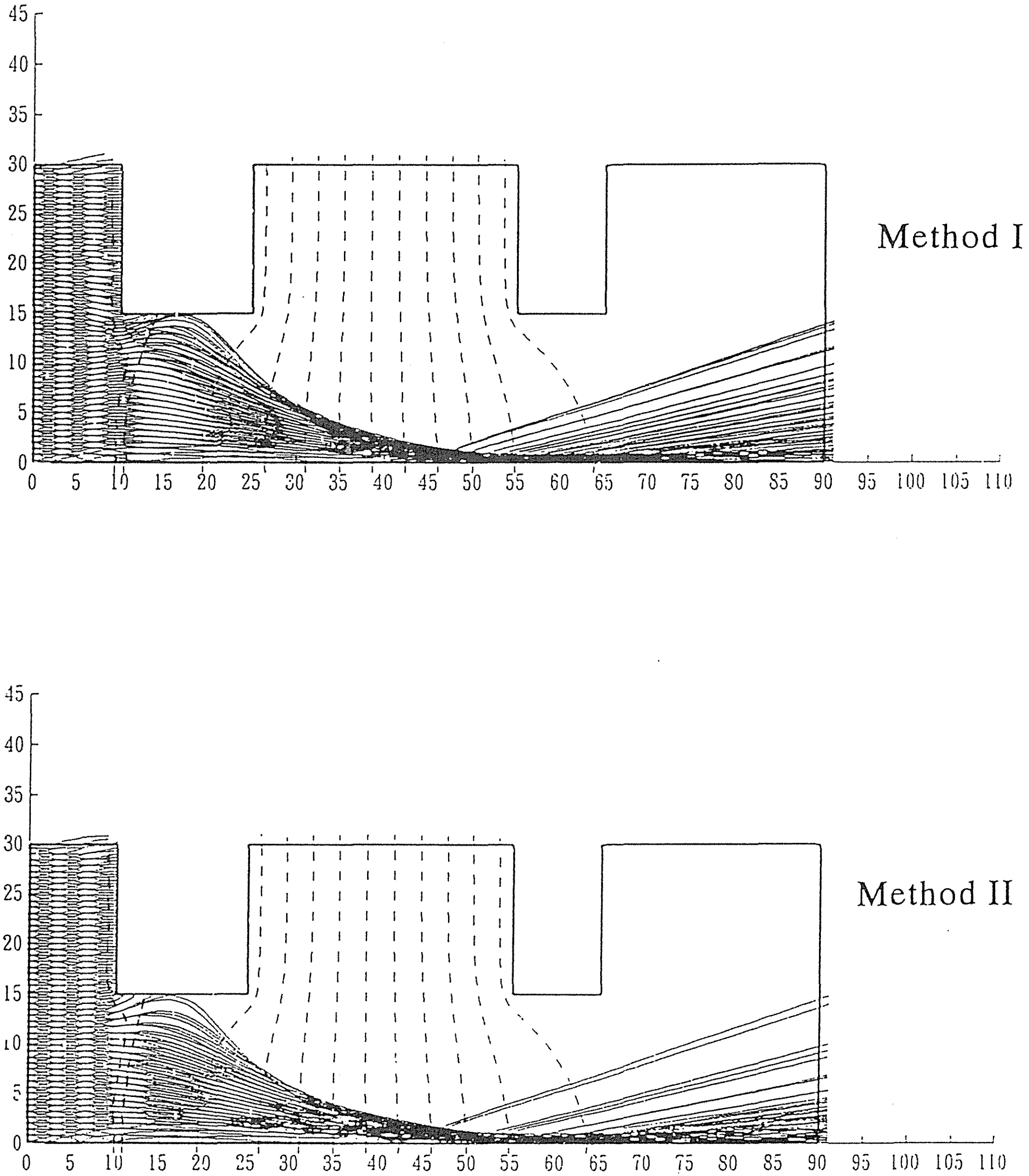


Figure 7. Two methods generate almost the same results when sheath is nearly plane surface

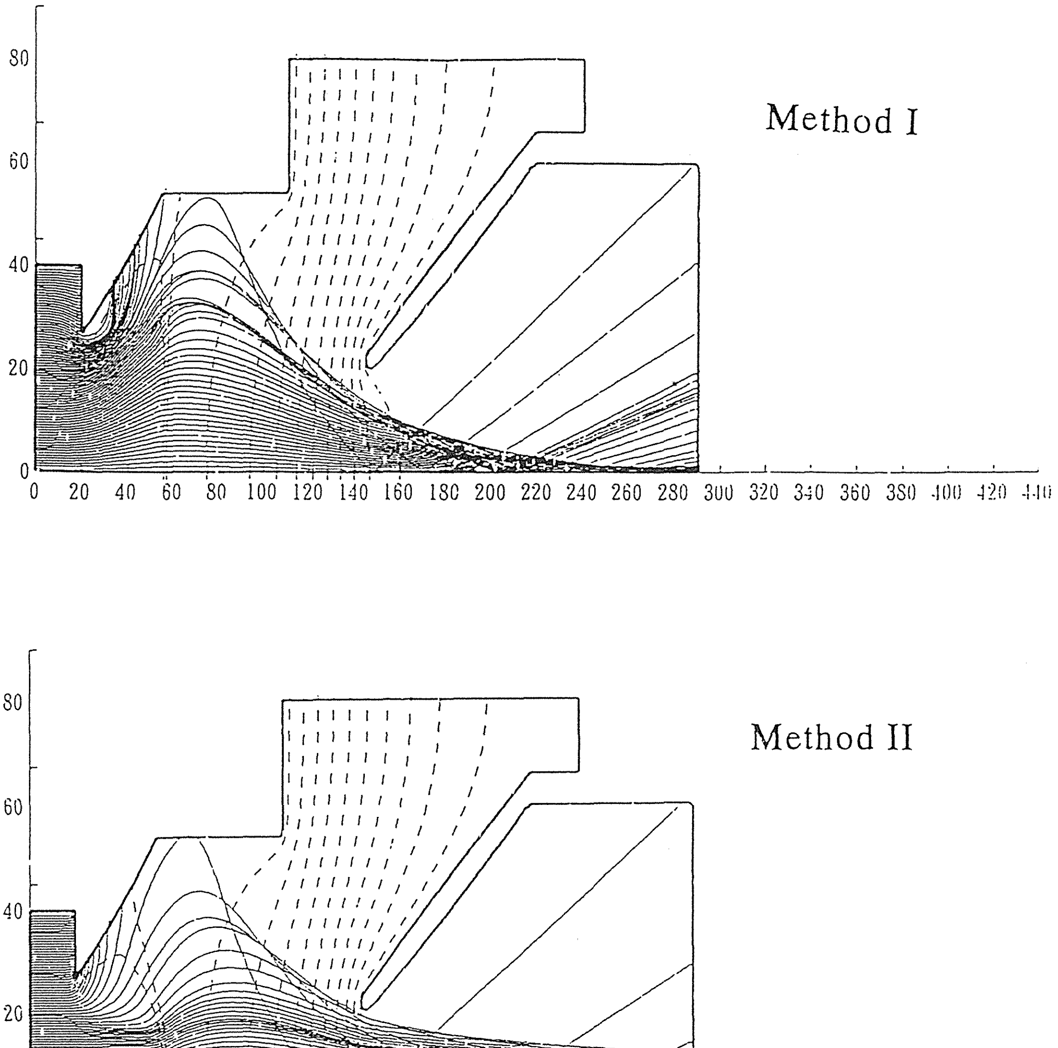


Figure 8. Two methods generate different results when sheath is very much curved.

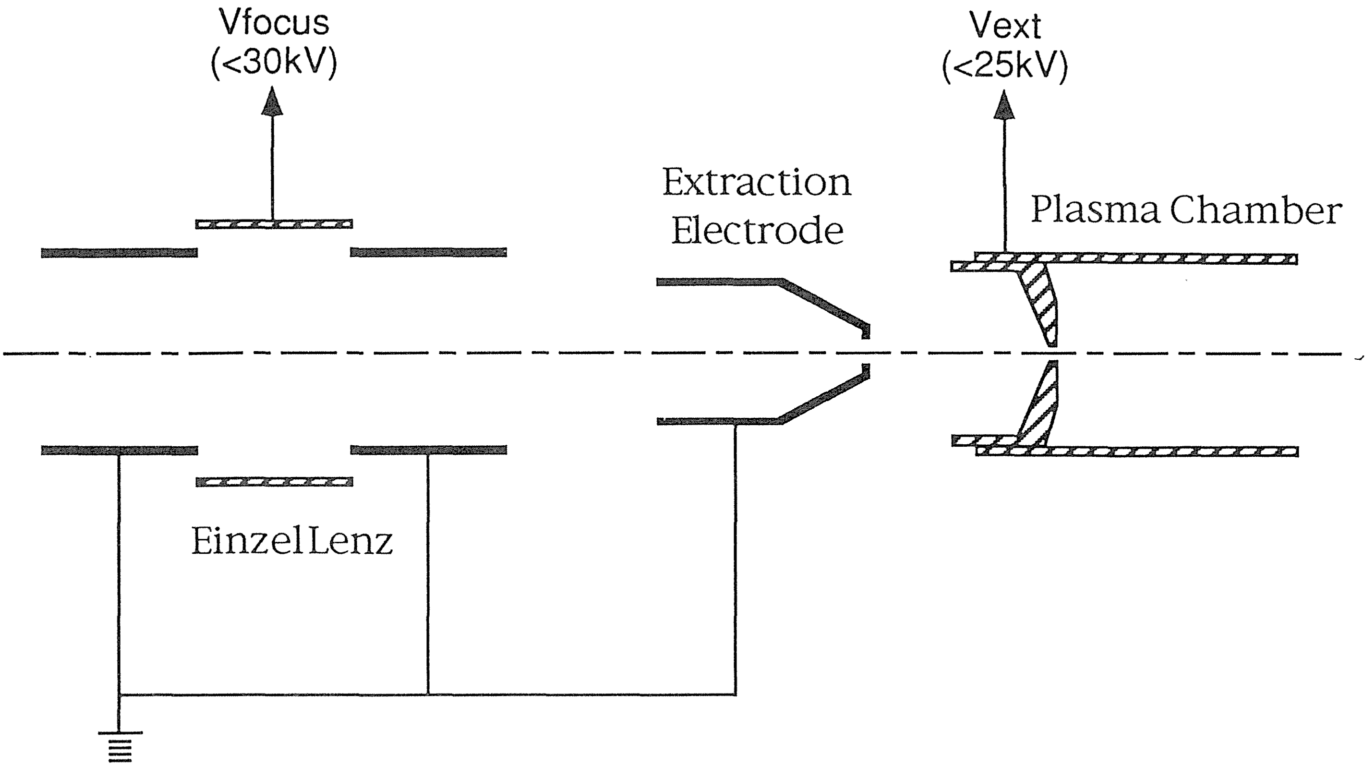


Figure 9. Sketch of the extraction system of NIRS-ECR ion source

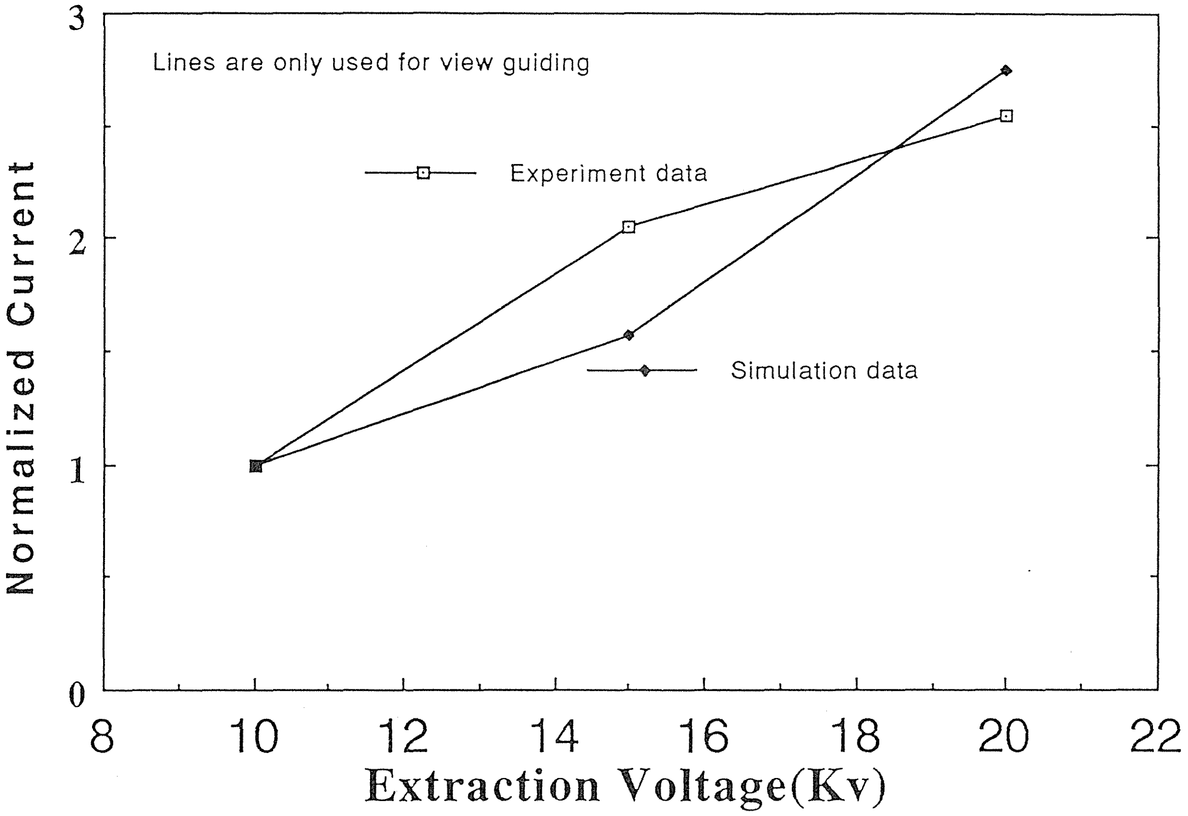


Figure 10. Current Dependence on Extraction Voltage

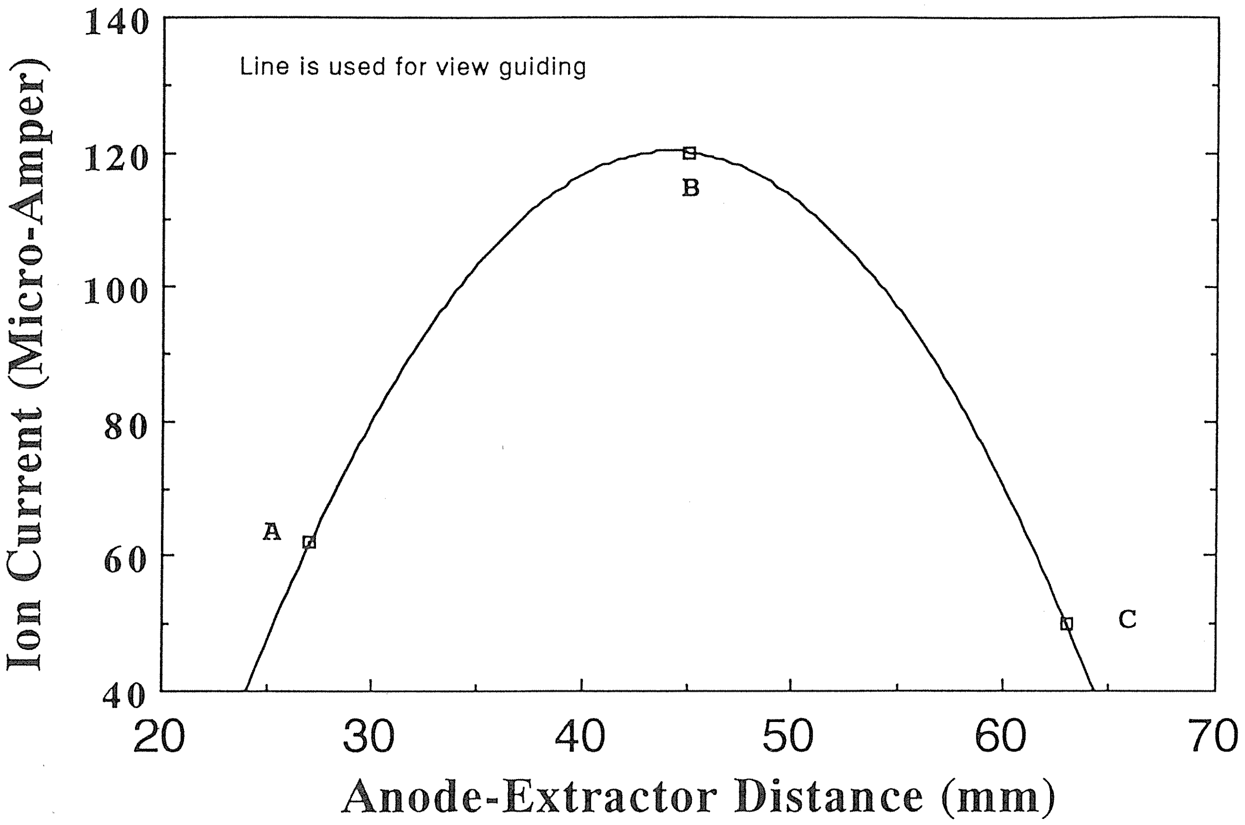
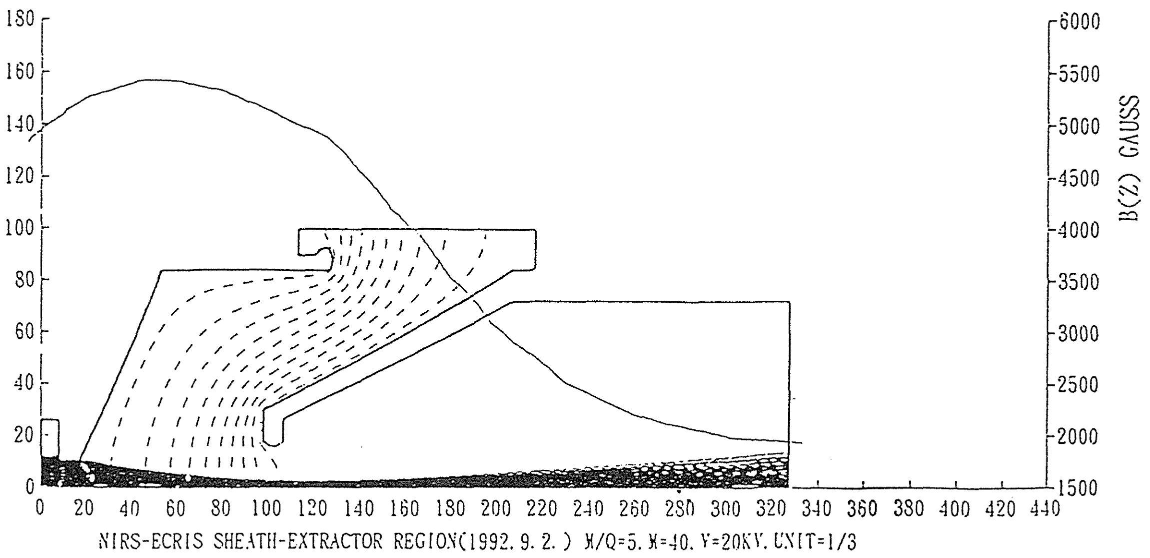


Figure 11. Test results of current dependence on extractor position



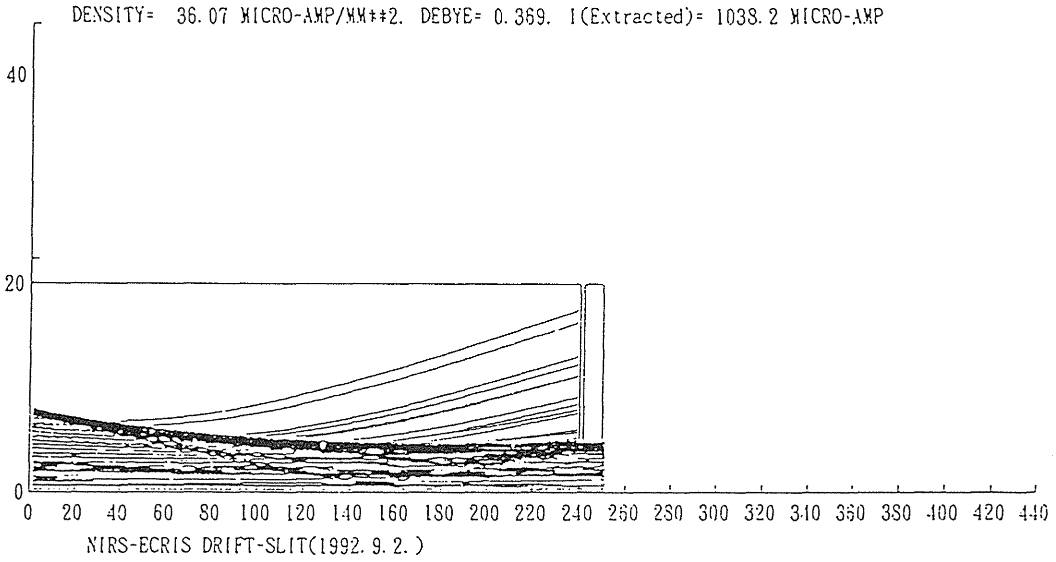
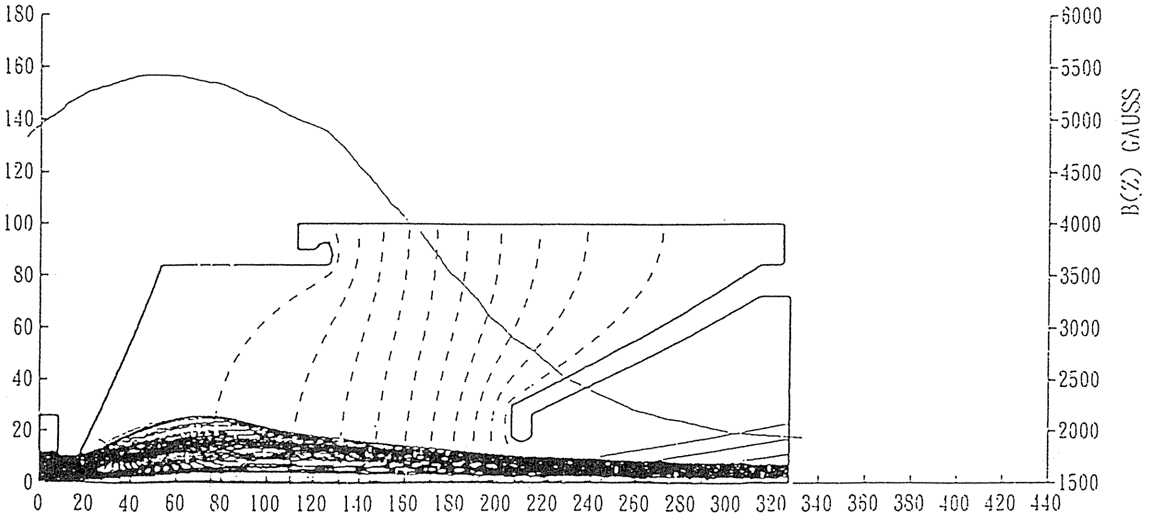
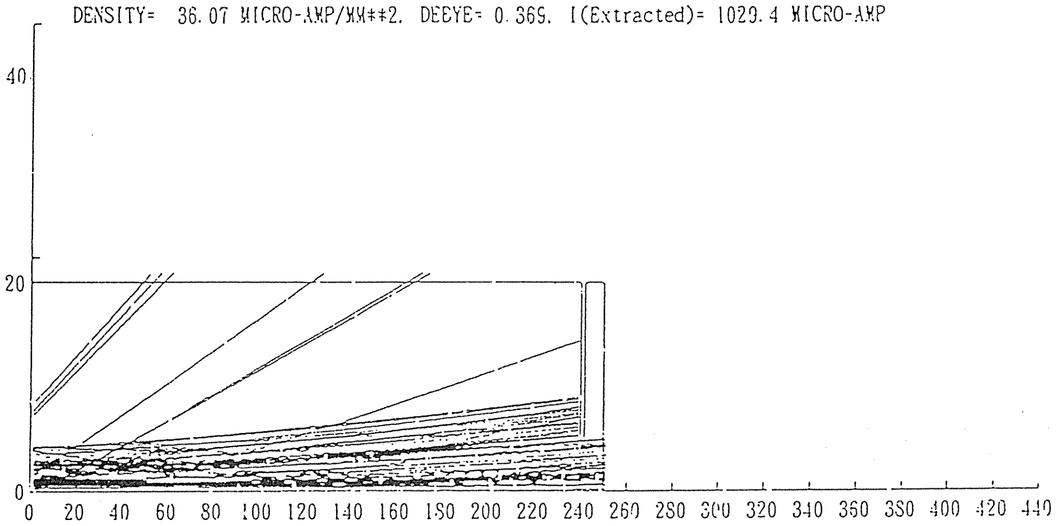


Figure 12. The extractor is too close to the outlet electrode (corresponding to A point in Figure 11)

Between the two figure there is an Einzel lens which is adjusted to the best voltage for maximum current out of the slit in the lower figure.



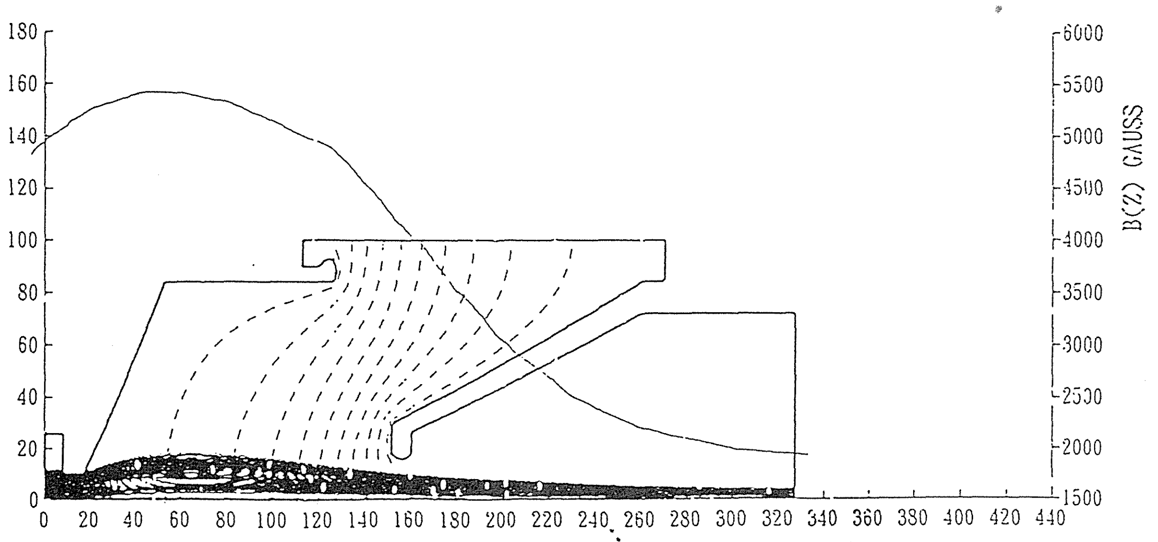
NIRS-ECRIS SHEATH-EXTRACTOR REGION(1992. 9. 2.) M/Q=5. M=40. V=20KV. UNIT=1/3



NIRS-ECRIS DRIFT-SLIT(1992. 9. 2.)

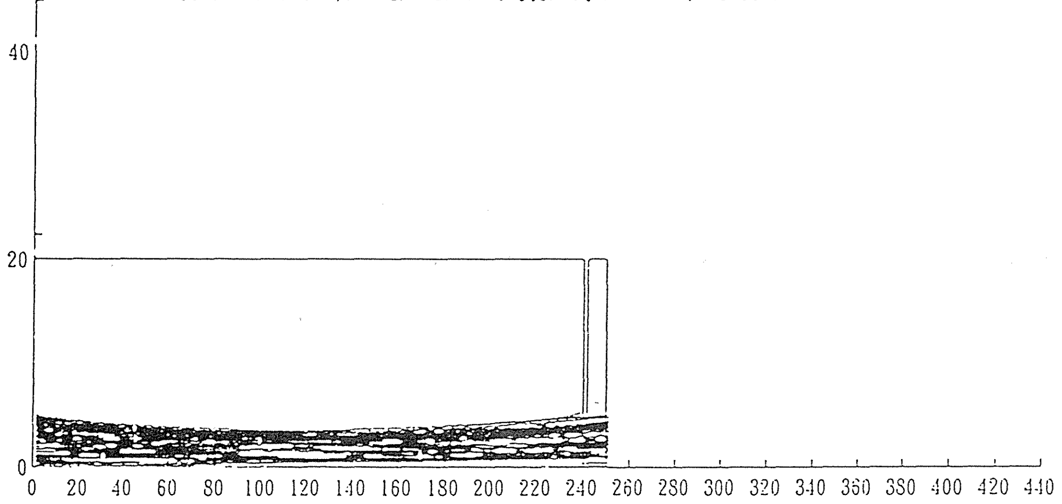
Figure 13. The extractor is positioned too far
(corresponding to C point in Figure 11)

Between the two figure there is an Einzel lens which is adjusted to the best voltage for maximum current out of the slit in the lower figure.



NIRS-ECRIS SHEATH-EXTRACTOR REGION(1992. 9. 2.) M/Q=5. M=40. V=20KV. UNIT=1/3

DENSITY= 36.07 MICRO-AMP/MM**2. DEBYE= 0.369. I(Extracted)= 1038.2 MICRO-AMP



NIRS-ECRIS DRIFT-SLIT(1992. 9. 2.)

Figure 14. The extractor is located properly (corresponding to B point in Figure 11)

Between the two figure there is an Einzel lens which is adjusted to the best voltage for maximum current out of the slit in the lower figure.

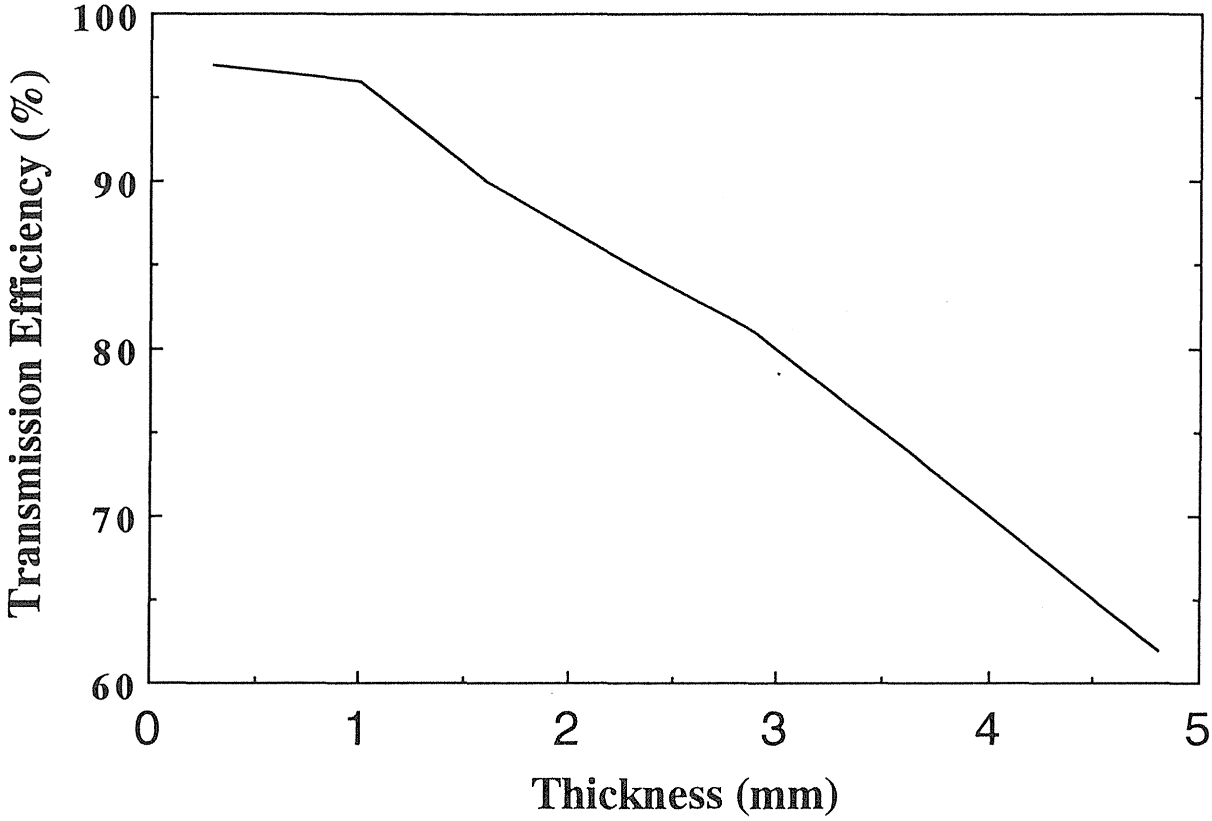


Figure 15. Transmission efficiency dependence on thickness of the anode

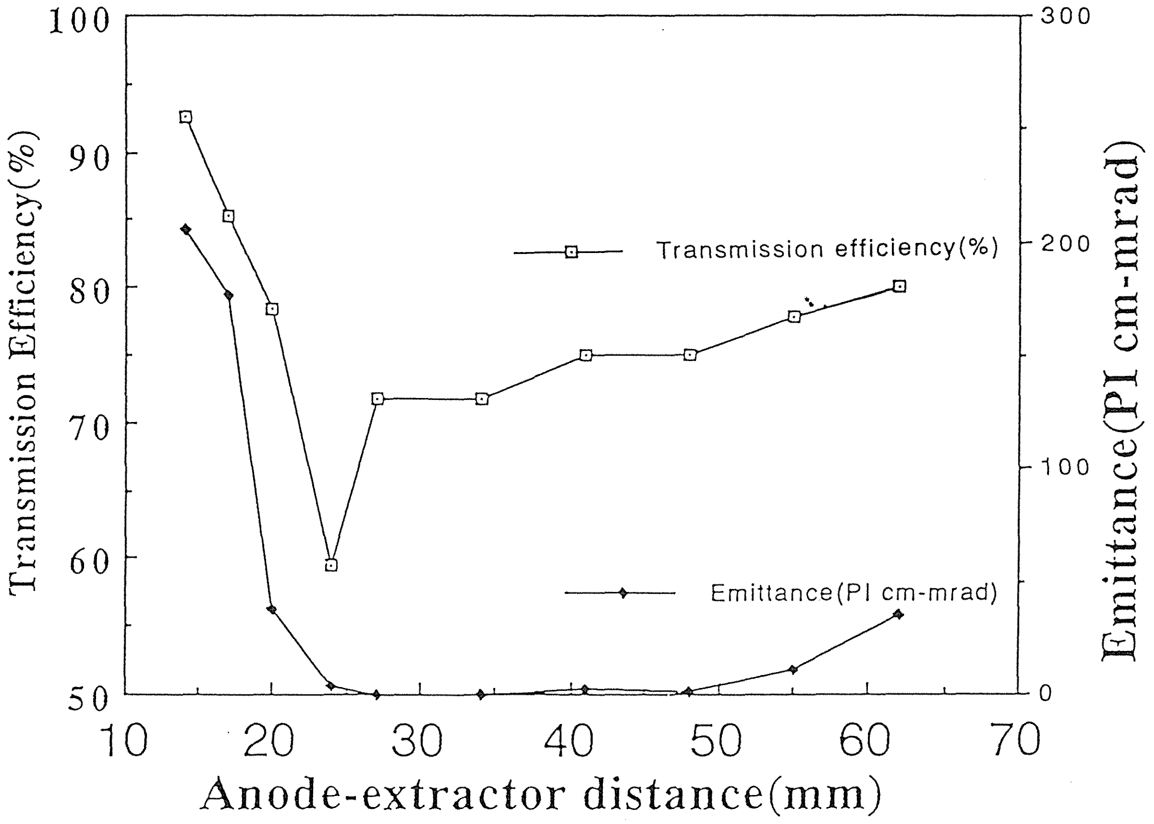


Figure 16. Dependence of Emittance and Transmission Efficiency on the Position of Extractor

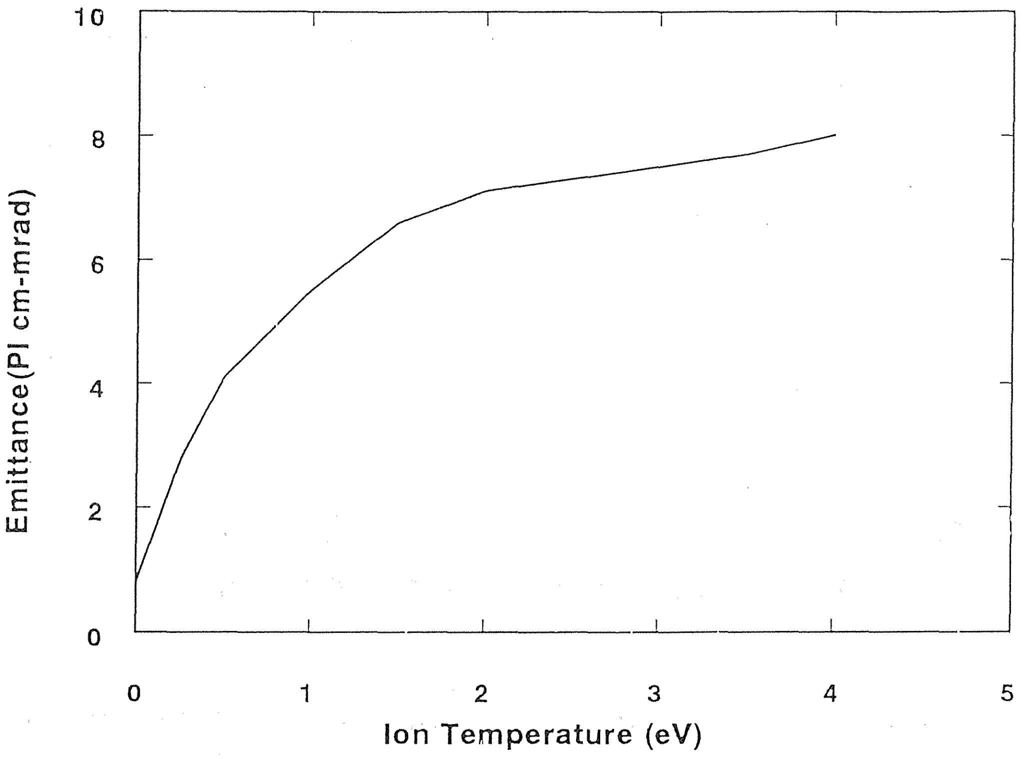


Figure 17. Emittance dependence on ion temperature

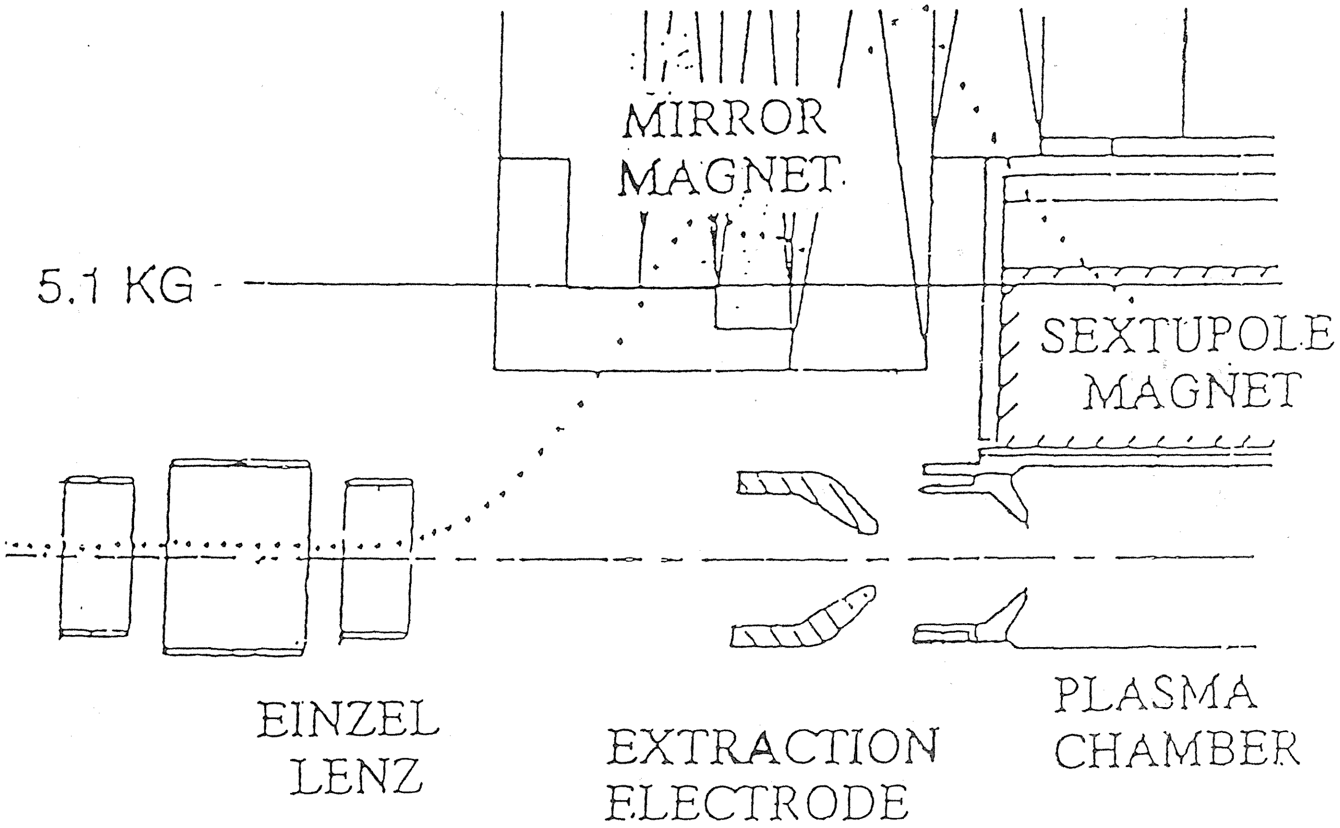


Figure 18. Sketch of the extracion system of HYPER-ECR ion source

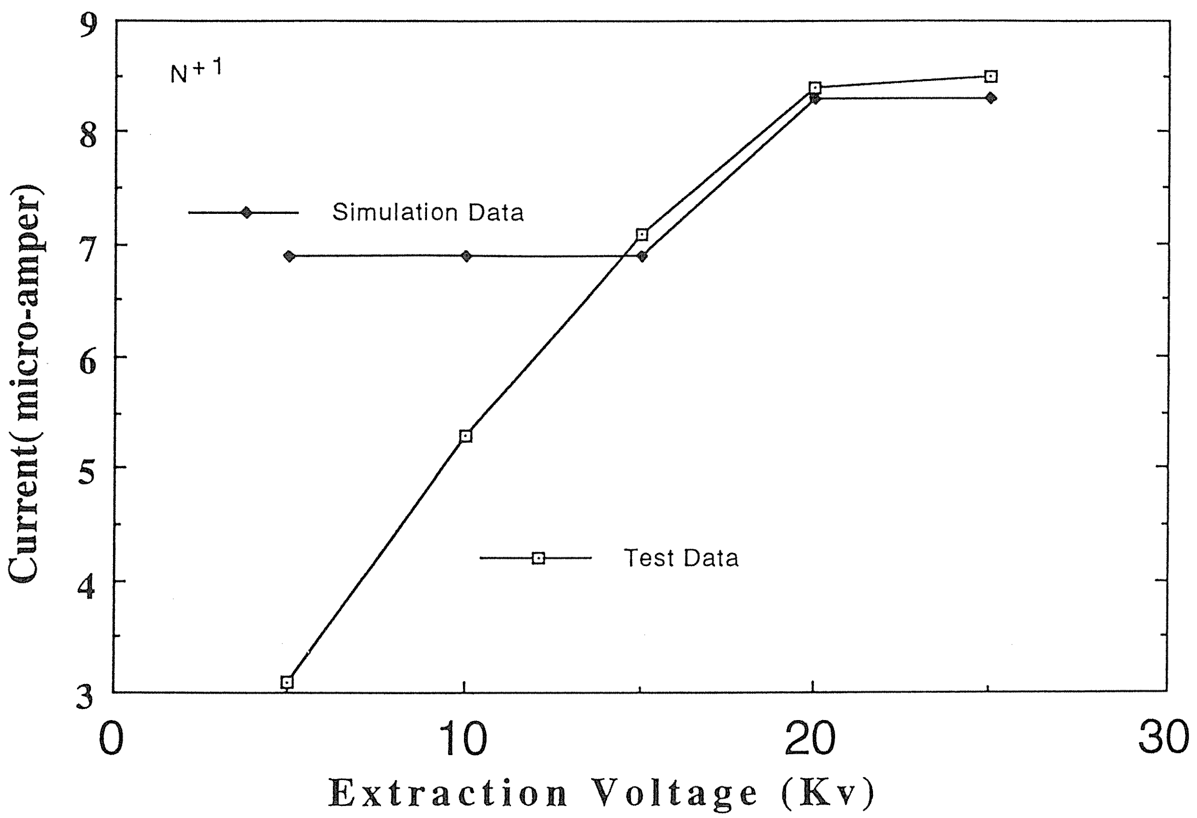


Figure 19 Comparison between test and simulation data at low current

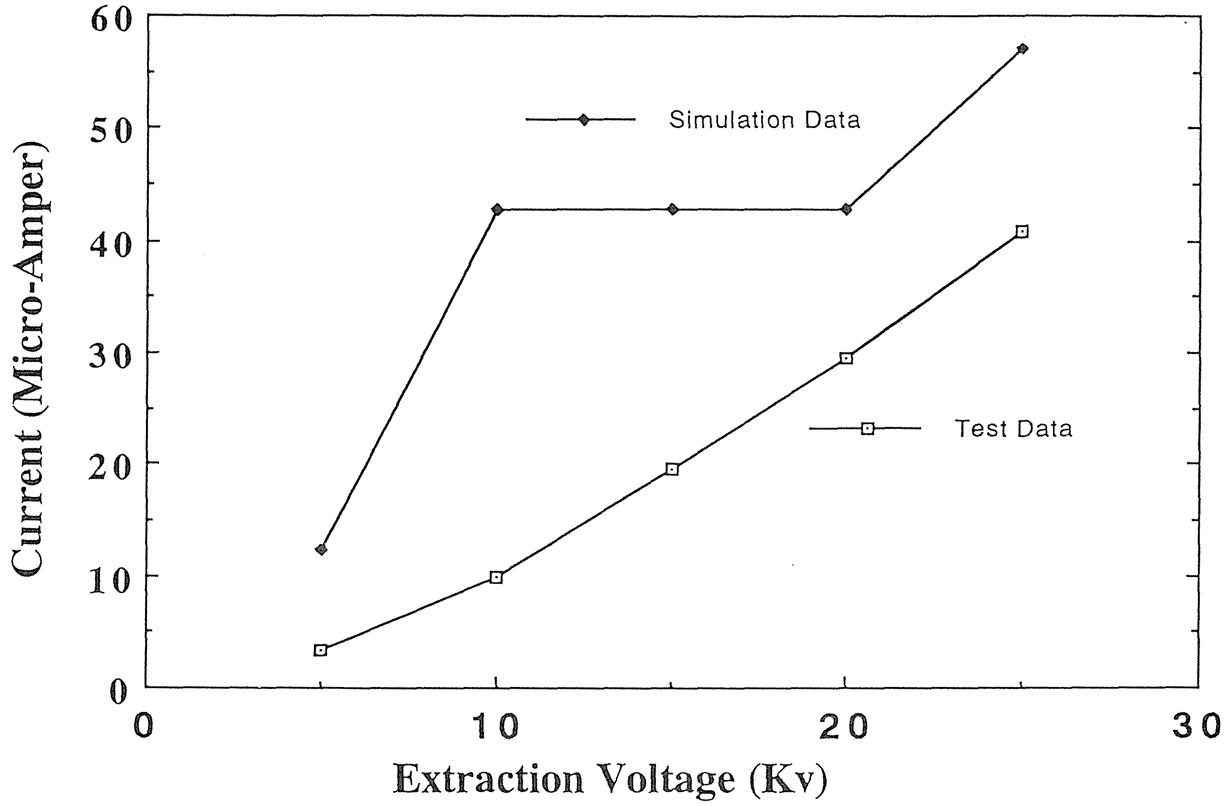


Figure20. Comprison between test and simulation data at middle current

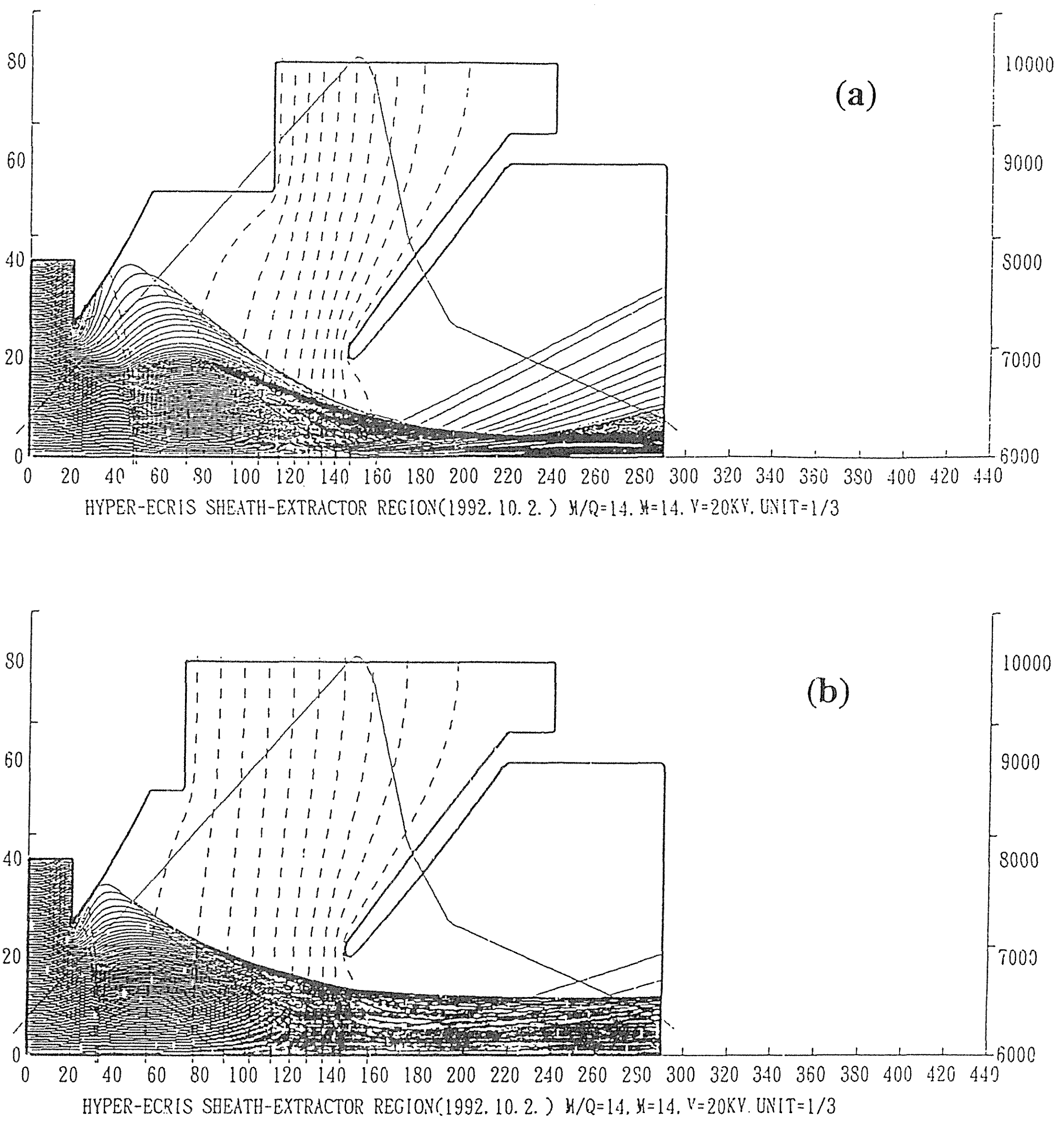


Figure 21. Field Shielding Effect of the Focusing Bar of Outlet Electrode on Beam Optics.

(a). The bar is longer and the abberation is larger.
The extracted beam spreads greatly

(b). The bar is shorter. The beam has less aberration
and is nearly parallel.