OPERATION OF MASS SPECTROMETER PROBES

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March 1979

Task II-2235

This report is unclassified.

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I. DEFINITION OF THE PROBLEM

To measure the relative concentrations of ions of different charge-to-mass ratios in a plasma in a strong magnetic field, a probe of the construction shown in Fig. 1 has been tried. In an argon-uranium plasma, it has been found that the U^{++} species is apparently more abundant than usually thought. We wish to examine the question of whether relative probe currents are indicative of relative concentrations, without making detailed calculations.

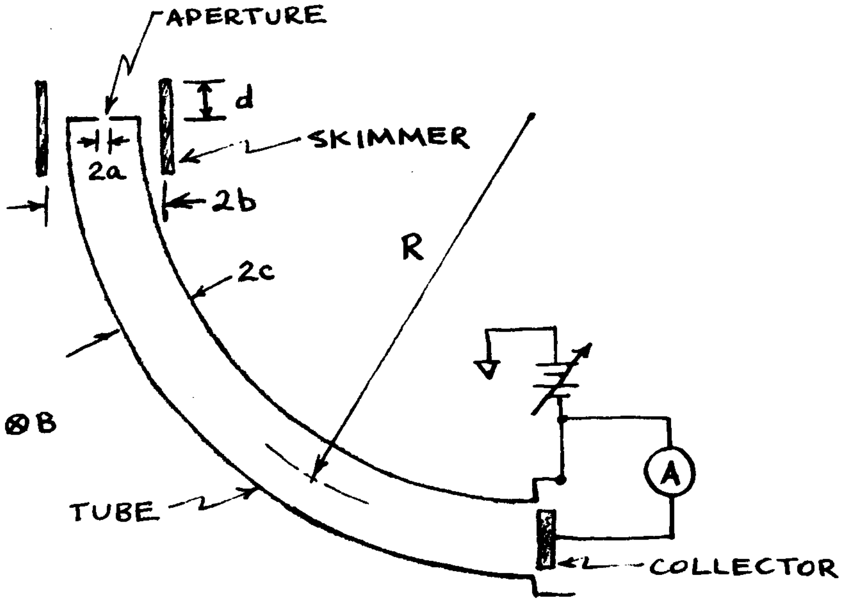

Figure 1

In Fig. 1, the skimmer is a floating cylinder for removing electrons; the aperture and tube are biased to a large, variable, negative potential -V; and the collector measures the current of ions that have been accelerated by the potential, have entered the aperture, and have the proper Larmor radius to follow the curve of the tube.

The probe has been tried in a test plasma under the approximate conditions given below, together with the dimensions of the probe.

Probe: $a = \frac{1}{8}$ mm
$b = 1.5$ mm
$c = 1$ mm
$d = 1$ mm
$R = 1.1$ cm
$V \simeq 100\text{-}200$ volts

Plasma: $p = 4 \times 10^{-4}$ torr Argon
$n_A \approx 10^{12}$ cm^{-3}
$n_u << n_A$
$T_e \approx 3$ eV
$T_A \approx 0.2$ eV
$T_u >> T_A$
$B = 20$ kG

From these numbers we can estimate the Debye length λ_D and the various Larmor radii r_L using the formulas

$$\lambda_D = 740\ (T_{ev}/n)^{1/2}\ \text{cm, and}\ r_L = 0.144\ (AT_{ev})^{1/2}\ B_{kG}^{-1}\ \text{cm},$$

where A is the mass in amu.

$r_{Le} = 2.9 \times 10^{-4}$ cm
$\lambda_D = 1.3 \times 10^{-3}$ cm
$r_{LA} = 2.0 \times 10^{-2}$ cm (0.2 eV)
$r_{LA} = 4.6 \times 10^{-1}$ cm (100 eV)
$r_{Lu} = 5.0 \times 10^{-2}$ cm (0.2 eV)
$r_{Lu} = 3.5 \times 10^{-1}$ cm (10 eV)
$r_{Lu} = 1.1$ cm (100 eV)

These lengths are therefore quite different in magnitude from one another. Collision mean free paths involving neutrals or electrons are all greater than 10 cm and can be neglected. Using formulas from

Dave Book's NRL Plasma Physics Syllabary, we find that the ion-ion mean free path for ions above a few eV is >> 1 cm and can therefore be neglected. However, if the argon ions are really as cold as 0.2 eV, their mutual mfp is only 0.4 mm, comparable to both their Larmor radius and the probe dimensions. The effect of argon-argon collisions is mainly to change the scale length of the pre-sheath and would not greatly affect the operation of the probe.

The major uncertainty in interpreting the data is due to the small magnitude of the analyzer currents. The saturation ion current collected on the top plate is of order 1 mA. Taking the hole in the plate to be about 1/10 the diameter of the plate, one would expect an ion current of 10^{-5} A to enter the hole. Of this perhaps 1/10 would be uranium ions if a non-negligible fraction of the plasma consists of the uranium species. If all the U's entering the hole reached the other end of the curved tube, the analyzer current would be of order 10^{-6} A. On the other hand, currents of order 10^{-8} A are observed. Though this current shows the proper resonances corresponding to the U^+, U^{++}, U^{+++}, and A^+ gyroradii equalling 1.1 cm as the acceleration voltage is varied, the worry is that these peaks would not have the proper relative heights if the collector currents are controlled by incidental effects which have caused the loss of 99% of the available current. We therefore examine the collection problem to see if the 99% can be accounted for.

II. POTENTIAL DISTRIBUTION NEAR PROBE

The problem of the disturbance in density and potential caused by a large obstacle in a plasma in a strong magnetic field has not, to my knowledge, been solved in an elegant fashion by anyone since David Bohm made the first pass at the problem in the 1940's. The reason is that cross-field diffusion and mobility are essential parts of the problem, and anomalies in these transport coefficients have always plagued plasma physicists.

We can get a qualitative picture of the potentials around the probe by adopting the following model: The skimmer is infinitely thin, the electron gyroradius is infinitely small, the ions make no collisions, and there is no secondary emission. Consider the potentials around a skimmer which consists of two parallel semi-infinite half-planes (Fig. 2).

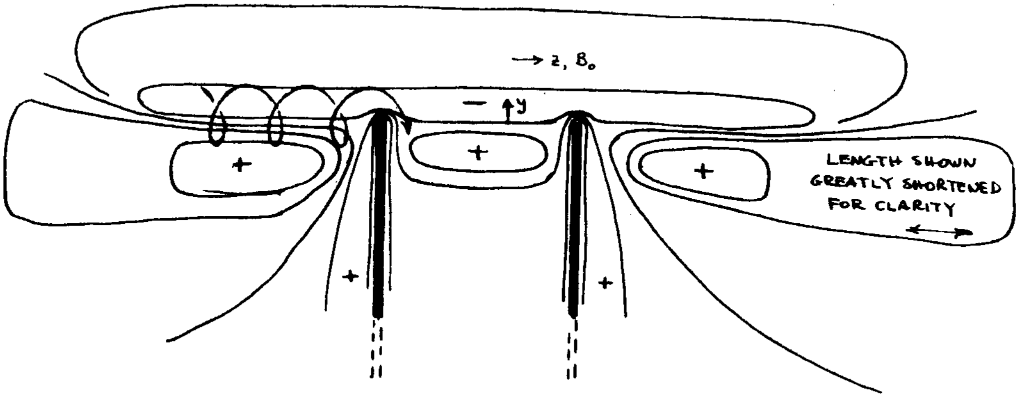

Figure 2.

The orbit of a typical argon ion is shown. Above the skimmer edge $(y > 0)$, the supply of electrons is not interrupted by the obstacles. In the region up to one Larmor diameter above the edge $(0 < y < 2r_{LA})$, there will be a depletion of ions, since this region is partly populated by ions with guiding centers between $y = \pm r_{LA}$, and these have a finite probability of striking the skimmer and being absorbed there. There is therefore a negative space charge in the region just above the edge.

In the region inside the skimmer, there can be no electrons if they have $r_{Le} = 0$. On the other hand, some ions can spiral in if they have the proper phase to miss the thin obstacle. There is thus a positive space charge in the region $-2r_{LA} < y < 0$ inside the skimmer.

Far below the edge, we have essentially a plane wall bounding a plasma. There is therefore the usual pre-sheath, accelerating ions up to an energy $\frac{1}{2} KT_e$, going smoothly into a monotomic Bohm sheath with a positive space charge.[1] The density at the sheath edge is about half that of an unobstructed plasma. As one moves toward the skimmer edge in the outside region, the situation becomes complicated. The ions will develop a bi-directional distribution function, since some ions will

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[1] F. F. Chen, "Thickness of Combined Bohm-Langmuir Sheaths," Task II-2186.

manage to miss both obstacles and pass through the skimmer. Hence, in the region $-2r_{LA} < y < 2r_{LA}$, the ion density will vary smoothly from about $\frac{1}{2}$ to about 1 times the density far away. The electrons, on the other hand, will have a sharp discontinuity in density. For instance, if we imagine that the plasma is generated by two sources at the far right and the far left, we see that one source will be blocked by the skimmer below its edge; and the supply of electrons is only half as large as in an unobstructed plasma. The situation is not nearly as bad as this, however, because the sheath on the floating barrier will reflect nearly all the incoming electrons; only a flux equal to the ion flux can be lost to the skimmer. The resulting potential pattern looks something like that in Fig. 1.

The iso-potential lines shown in Fig. 1 are in reality very elongated along the magnetic field. If the barriers are not infinite but have a dimension L in the x-direction, the iso-potential lines will reconnect at a distance many times L along B_0. The exact distance depends on the diffusion rate of plasma across B_0; that is, on how fast the plasma can fill in behind the barrier. Normally, in a strong field it is the electron cross-field diffusion rate that is the limiting factor. However, if the plasma has ends where there are endplates or sources, electrons can cross the B lines there, rather than in the plasma. Thus it is impossible to calculate the extent of the perturbation without specifying the entire experiment.

The magnitude of the space charge fields described here will be greatly affected by electron trapping. Inside the skimmer, for instance, any electrons that stray into the ion-rich region can be trapped longitudinally by the electric field and radially by the magnetic field. This effect will partly cancel the space charge but cannot change its sign. Since $T_i << T_e$, it would seem that the maximum potentials that can be built up will be less than KT_i/e, except in the Bohm sheath. It is clear that the argon ion orbits will be greatly affected by the space-charge fields, so that the self-consistent fields would be very difficult to calculate even if one neglected trapping and diffusion.

III. ION COLLECTION

Fig. 3 shows the potential distribution of an MS probe with an aperture plate biased to 100-200 volts. The drawing is approximately to scale. The thickness of the combined Bohm-Langmuir sheath has been shown[1] to be comparable to the recess of the aperture plate behind the skimmer edge. The negative potential of the aperture blends smoothly into the negative potential in the plasma just above the skimmer. Since the argon ions are so cold, their orbits will be sensitive to the details of the self-consistent potentials, as explained in the previous section. However, an approximation to the argon flux can be made by assuming that the argon ions are accelerated to $\frac{1}{2}KTe$ energy in a pre-sheath and are then dragged across the magnetic field by the large electric field (the Larmor radius is 4.6 mm at 100 eV). The argon ion current is then given by the Bohm formula

$$J = \frac{1}{2} n_o e \, (KT_e/M)^{1/2} \tag{1}$$

This yields $J \simeq 21$ mA/cm^2, which is compatible with the previously quoted figure of 1 mA measured to the plate. On the other hand, if one were to assume the complete absence of electrons in the 1 mm setback region, the Child-Langmuir formula[1] would be applicable. This yields a space-charge limited flux of only about 1mA/cm^2. Thus it is clear

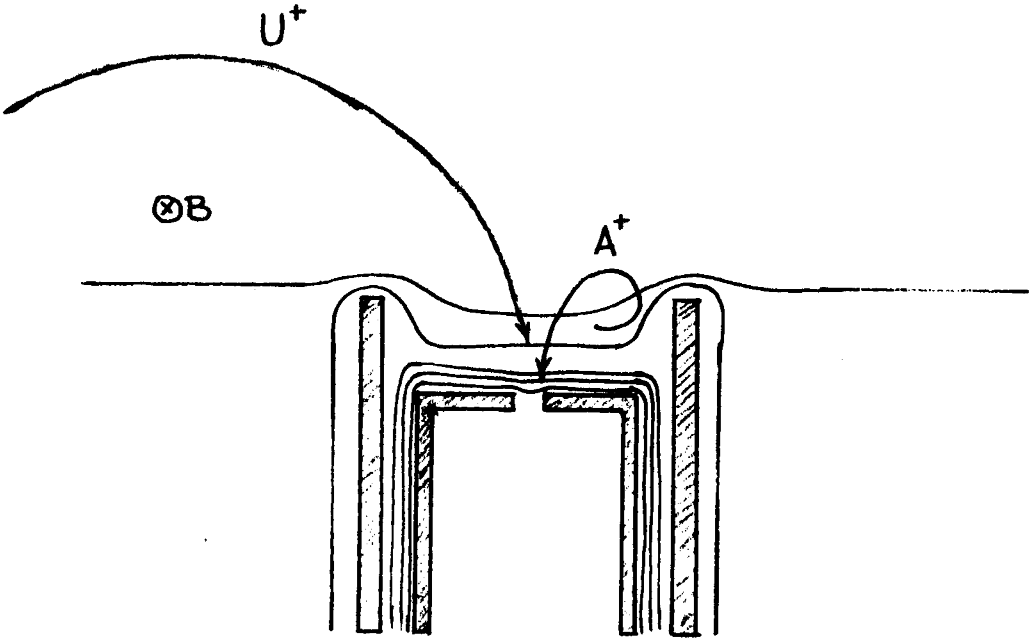


Figure 3.

that electrons do leak into the gap and get trapped there by the sheath on the skimmer. It is only the combined Bohm-Langmuir sheath that extends to the edge of the skimmer; the Child-Langmuir sheath itself does not.

Since the temperature of the argon ions is less than T_e, it would be difficult to calculate the A^+ current collected by the probe. The argon ion orbits would be determined by the shape of the pre-sheath electric fields, which are impossible to calculate. After acceleration to about 1.5 eV in the pre-sheath, the argon ions would have a Larmor radius of about 0.6 mm, which is comparable to the skimmer size; hence, the scrape-off of ions by the skimmer would depend on the exact shape of the ion orbits. Fortunately measurement of the ratio of U^+ to A^+ density is not a requirement of the MS probes.

As for the collection of U^+ and U^{++}, the situation is much simpler because the temperature of the U species is presumably larger than T_e. In this case, the pre-sheath fields have little effect on the U orbits; and one may, to lowest order, assume that the U ions are scraped off geometrically according to their unperturbed orbits. If the U ions have energies much larger than KT_e, which is the magnitude of pre-sheath potentials, only a relatively minor contribution to the collected flux will come from ions whose orbits have been greatly altered by these potentials. Thus the MS probe can yield data which can be interpreted with reasonable confidence only if the collected species have energies larger than KT_e.

We next wish to make a crude calculation of the loss of U^+ ion current during transit along the thin tube. Assume that the population of U^+ ions is not depleted by the presence of the probe. This would be true if the Larmor radius of thermal U^+ ions were much larger than the skimmer radius; the actual situation is marginal. We may then assume that the random flux of U^+ ions entering the skimmer is

$$n\bar{v}/4 = n(KT/2\pi M)^{1/2},$$

where all quantities pertain to the collected species. Once inside the surface defined by the skimmer edge, the U^+ ions are accelerated by the strong electric field of the aperture plate, and the ions hit the plate at nearly right angles. Those that enter the hole have approximately 100 eV energy and therefore have a Larmor radius corresponding to the tube curvature. A large fraction of the available current is lost to the tube walls because of the spread in energies, however. Consider first the motion along the B-field ($\hat{z}$) direction; this velocity component is unaffected by the acceleration field. If the tube radius is c, and the transit time in the 90° tube is $\pi/2\Omega_c$, where Ω_c is the ion cyclotron frequency, the maximum allowable $|v_z|$ would be $|v_z| = 2R_c c/\pi$. For U^+ with c = 1 mm, we have $|v_z| \leq 5 \times 10^4$ cm/sec. For a 10-eV Maxwellian distribution, 20% of the ions are in this range. Similarly, there will be a range of initial $v_\perp$'s which will be collected; those with too large a $v_\perp$ will have too large a Larmor radius and will hit the tube wall. This turns out to be a negligible loss for the parameters taken here. Specifically, suppose that the U^+ flux impinging on the sheath is a unidirectional Maxwellian distribution with KT = 10 eV. The maximum flux will be due to those ions with maximum $v \exp(-v^2/v_{th}^2)$, that is with energy 5 eV. Peak current will be collected if the accelerating voltage is adjusted to 93 volts, giving these ions 98 eV energy and 1.1 cm Larmor radius. The tube will accept r_L between 1.0 and 1.2 cm. This tranlates to ions between 81 and 116 eV, or all ions initially below 23 eV. The flux due to ions above 23 eV is only 10% of the total flux. Thus, perhaps 18% of the flux falling on the aperture should find its way to the collector. We have not accounted for ions entering the sheath at an angle. Because the accelerating voltage is large, this should also be a minor effect. Thus at best we can explain only a factor of 10 loss in collected current, rather than the observed factor of 100. The other factor 10 may be due to a) defocussing effects of a non-planar sheath, b) an error in the measurement of saturation ion current to the aperture plate (due to probe damage), c) imperfections in the tube geometry or d) the space charge effect discussed below.

We must also consider the space charge problem inside the tube. To get an idea of the magnitude of the spreading due to space charge, suppose that we have a current of 10^{-8} A of 100-eV U^+ ions uniformly distributed over a tube 1 mm in radius. Then the current density J is 3.18×10^{-7} A/cm^2, and the ion density is 2.2×10^6 cm^{-3}. Poisson's equation then gives a radial electric field of 0.2 V/cm at the beam edge.

The most that an ion can be accelerated radially in a quarter of a cyclotron period is then $\Delta r = (1/2)at^2$, where $a = eE/M$ and $t = \pi/2\Omega_c$. This yields $\Delta r = 1.5 \times 10^{-3}$ cm, which is much less than the tube radius. Thus, although the spreading rate is faster when the beam has the diameter of the aperture, it slows down to a negligible rate by the time the beam fills the tube. Even if the collected current is increased ten-fold by eliminating unnecessary losses, Δr would increase only to 1.5×10^{-2} cm, which is still very small. However, the argon ions could cause appreciable charge blow-up, since they have Larmor radii almost half as large as R and therefore could travel about one-fourth of the way down the tube before being lost on the wall. If 1 mA of argon current falls on the aperture plate, this corresponds to a current density of 31 mA/cm^2, or a charge density of 9×10^{10} cm^{-3} after acceleration through 100 volts. The electric field inside the tube just below the aperture would then be 1000 V/cm. This large field quickly blows the ion beam up to fill the tube, but even then the radial electric field would be 128 V/cm. A U^+ ion in a field of 100 V/cm would be accelerated a distance of 0.5 mm in 1/16 of a gyration period, so that the argon space charge could be large enough to affect the collection of U^+ current.

Neutralization of the argon ion space charge may occur naturally if electrons are produced inside the tube by ionization of residual gas or by secondary emission off the walls. Electrons would be trapped by the electrostatic well and could oscillate along the magnetic field lines between the tube walls. It may be desirable to build good secondary emitters into the front end of the tube to provide a source of neutralizing electrons. Other schemes to avoid the space charge problem are to use a smaller aperture, thus cutting down on the ion density inside the tube, or to use a series of two apertures, with the second one adjusted so as to scrape off the argon ions but admit the uranium.

IV. RELATIVE ABUNDANCES

Relating the collected U^+ current to the ion density in the plasma is much more difficult than measuring the relative abundances of U^+, U^{++}, and U^{+++}. The MS probe is most useful when employed for relative measurements. We list here various effects that may influence the apparent ratio of abundances. The higher charge states, of course, carry more current per particle, so that the raw data will always have a bias in favor of the high-Z peaks.

1. Scrape-off by the Skimmer. The fraction of collectible ions scraped off by the skimmer increases with decreasing Larmor radius. For very large Larmor radius, those ions headed for the aperture come from far away and have almost straight trajectories which will miss the skimmer. For very small Larmor radius, the skimmer can prevent all ions from reaching the aperture. Since U^{++} has half the Larmor radius of a U^+ ion of the same energy, one would expect that this effect will favor the collection of U^+ over U^{++} or U^{+++}.

2. Change of Sheath Thickness. In order to collect U^{++}, one has to double the accelerating voltage from the U^+ value to about 200 volts. This change of the voltage will cause the sheath thickness to increase by about $8\lambda_D$, or 0.1 mm[1]. More of the fringing field will leak past the skimmer edge and tend to pull in ions whose orbits would otherwise miss the aperture. However, the potential at the sheath edge is so small compared with the U^+ or U^{++} energy that this bias in favor of U^{++} collection is expected to be negligibly small.

3. Change in Electrostatic Focussing. The curvature of the equipotential surfaces near the aperture causes a defocussing effect, which acts to spread out the ion beam and cause some of it to strike the walls of the curved tube. This effect may be appreciable here, since the sheath thickness is comparable to the aperture diameter. The ion trajectories will be independent of q/M; but for U^{++} collection, the sheath thickness is increased, so the equipotential surfaces will be more planar and the defocussing somewhat smaller. One would expect a small bias in favor of U^{++} collection over U^+.

4. Transit Time. Since all collected ions must spend 1/4 of their cyclotron period in the tube, U^{++} ions would spend half as much time as U^+ ions. This means that there is less chance for a U^{++} ion to run into the wall of the tube due to its motion parallel to B. The high-$v_{||}$ cutoff is higher for U^{++} than for U^+, and this would give a non-negligible and calculable bias favoring U^{++} collection.

5. Space Charge. The sideways deflection given a uranium ion by the space charge of the argon ions in the tube will be smaller for U^{++} than for U^+. This is because $s=(1/2)\,at^2$; the acceleration a in given field is twice as large for U^{++}, but the time t to travel a given distance is

half as long, since the cyclotron frequency is twice as large. As for the space charge field due to the uranium beam itself, the current density is $J = nqv$. If J is kept constant, n is one fourth as large for U^{++} as for U^{+}, since q and v are each twice as large. Hence, the space charge field is down a factor of 4. On both counts, then, U^{++} is less likely to be affected by space charge than U^{+}.

6. Secondary Emission. The U^{++} ions strike the collector with four times the energy the U^{+} ions do, and hence are more likely to cause secondary emission. This would give an enhancement of the measured U^{++} current. The magnetic field probably suppresses emission; but in any case a simple remedy exists: the collector should be biased a few volts positive with respect to the tube.

In conclusion, there is one effect tending to enhance the U^{+}/U^{++} ratio, and five effects tending to decrease it. However, only effect (4) is likely to be important, and this can be eliminated by proper design of future probes. We do not believe that an observation on the relative abundance of U^{++} and U^{+} in discharge plasmas can be reversed by the effects discussed above. It would be quite reasonable to have a larger amount of U^{++} than U^{+}, since the ionization potential of U^{++} is only 11.9 eV, as compared with 15.7 eV for A^{+}. If the electrons are hot enough to ionize argon, they should be hot enough to turn U^{+} into U^{++}.

V. INDICATED IMPROVEMENTS

The foregoing considerations suggest the following improvements in the design of MS probes: (1) The tube should be elongated in the B-field direction to allow a greater range of $V_{||}$ to be accepted; (2) The collector should be biased a few volts above the tube and aperture potential, so as to suppress secondaries, and (3) The first few mm of the tube interior, just behind the aperture, should be covered with a good secondary emitter, such as any oxide. Figure 4 shows how an improved MS probe might look. The tube is rectangular, with 2 x 6 mm inner cross section; this length should be sufficient to eliminate all but 1% of the ion loss due to fast parallel motion. The aperture is a 10-mil diameter hole (as it is now) placed close to one end of the rectangular aperture plate. This will allow only ions coming from the right to be collected. Those coming from

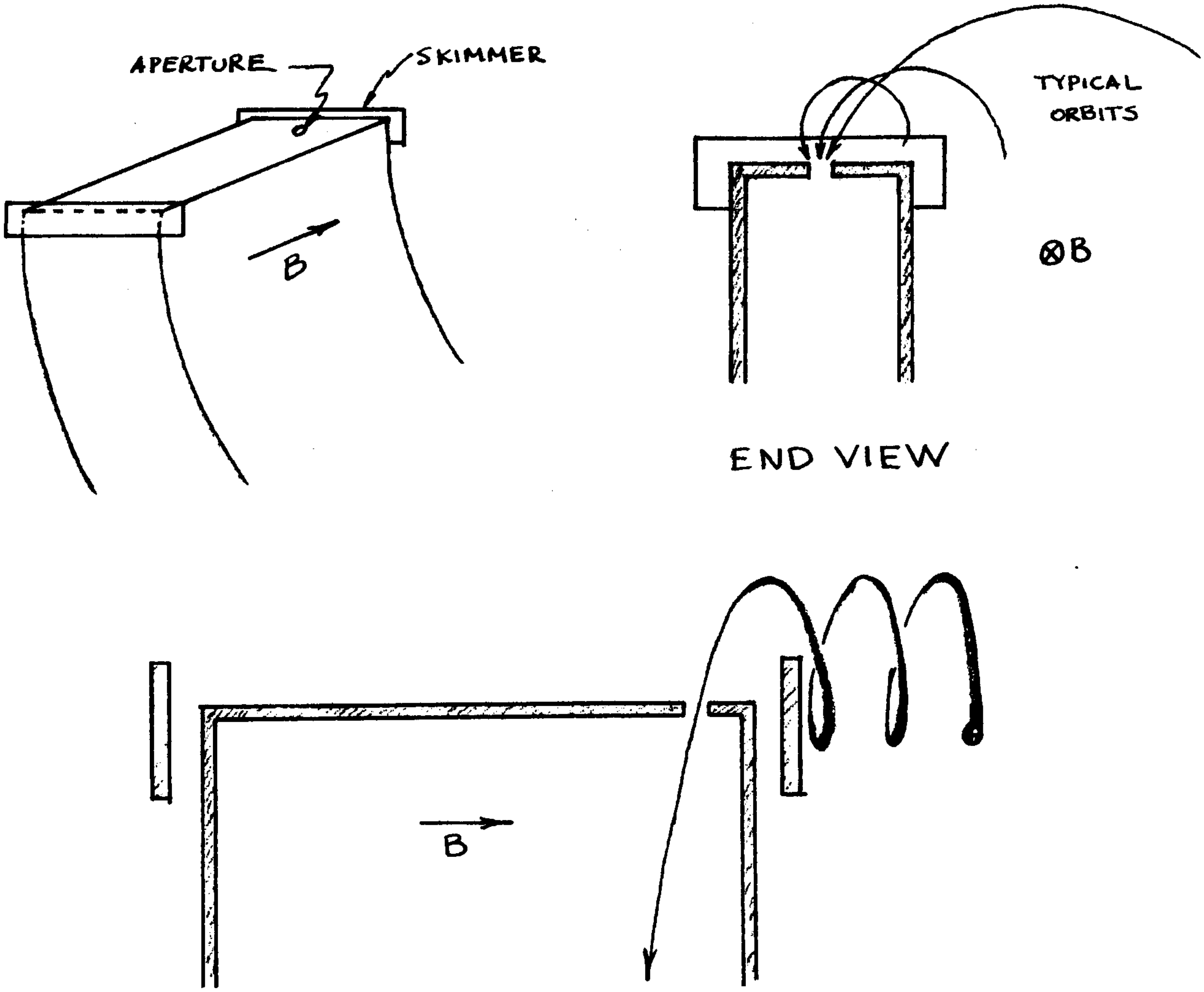
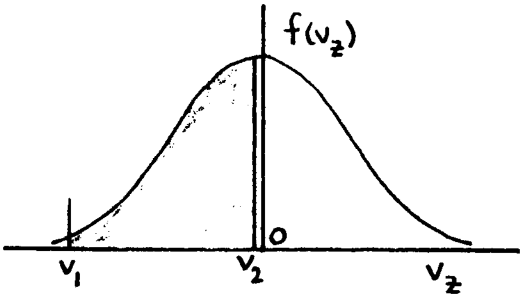


Figure 4.

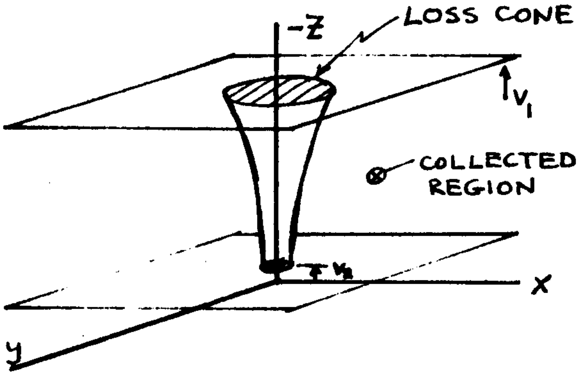
the left will run into the wall of the tube. In principle, a drift of the ion distribution along B can be detected by making another aperture at the other end and dividing the collector into two separately metered halves. The entire distribution $f(v_z)$ can be measured, in principle, if the collector is divided into many segments, each connected to a separate lead, and if one aperture is used at a time.

The setback of the aperture plate below the skimmer edge should remain at 1 mm, which is approximately the sheath thickness. The skimmer need only cover the ends of the rectangular tube, but for structural purposes it could be a rectangular band insulated from the pipe. The pipe itself should have an insulating coating to prevent the high voltage from leaking into the plasma.

A computation of the expected current would be carried out as follows. Assume that a Maxwellian distribution is incident on the sheath edge above the aperture, and consider the one-dimensional distribution in the B direction (Figure 5). Those with $v_z > v_1$ will strike the far wall inside the tube before reaching the collector. Those with $v_z < v_2$ will not be able to clear the skimmer. Hence, regardless of $v_\perp$, there are limits on collectible values of v_z. Now consider the distribution of $v_\perp$ at the sheath edge. For each energy and pitch angle, we can work backwards along the orbit to see if it intersects the skimmer. This will depend on how far below the skimmer the sheath edge is, and on whether the skimmer has side panels as well as end panels. It is clear that ions with too shallow a pitch ($v_\parallel >> v_\perp$) will strike the end panel as we work backwards along the orbit. There is thus a loss cone that is not collected. In general, the loss cone angle will depend on energy, so the loss region will be horn shaped, as shown in Figure 5b. The flux incident on the sheath edge is $n\bar{v}/4$, and the portion that is collectible is shown in the velocity space diagram of Figure 5b. Of course, an exact calculation is not easy. In addition, after the ions enter the sheath, they will be accelerated and have orbits that depend on the defocussing effect of the curved equipotential surfaces. Some will be given large enough $v_\perp$ that they will stroke the side wall of the tube and be lost. Thus, an accurate calculation of the expected current is difficult to make, but by proper design one can hope to collect almost half of the available flux $n\bar{v}/4$; namely, those with the proper sign of v_z.



(a)



(b)

Rather than depend on a calculation, one can more easily do a calibration by introducing a known percentage of xenon into the argon plasma and looking at the Xe^+ peak. As for relative abundances of different charge states, the imporved probe should make the relative efficiencies almost identical.