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ABSTRACT

The cooperative physical processes of ion source and ion beam physics in magnetic fields can be separated into plasma internal motions, motion from the source plasma into the beam, and beam formation. A few experiments demonstrate that these processes are consistent with elementary laws of charge diffusion. Ion beam current limits are almost independent of magnetic field and have magnitudes consistent with classical diffusion processes. Ion current is proportional to applied potential gradient up to high voltage breakdown values which are determined by electrode geometry and secondary electron currents. Beam plasma stability, which is necessary for isotope separation using ion beam technology, depends on the formation of a dense, charge-neutralizing plasma as well as on ion source stability.

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1. INTRODUCTION

High current ion beams are accelerated from dense electronic plasma by high gradient electrostatic fields. Separation of different ion species of isotopes in quantity has been accomplished¹ by focusing these high current ion beams in magnetic fields. The steps in this process are (1) formation of a dense ion plasma, (2) acceleration of these ions from the surface (meniscus) of the plasma by a carefully optimized system of electrodes at high potential, and (3) neutralization of the ion beam-plasma charge forces to permit fixing of ion trajectory.

This study of ion beam limits was made in connection with the large isotope separation facility (the Calutron) at Oak Ridge, TN, which was under the general direction of E. O. Lawrence. Success of that facility in producing large quantities of ²³⁵U from uranium is due to the stability and reproducibility of the ion beam assemblies. This report discusses the nature of those beams and the ion current limiting processes in them.

The different kinds of ion sources—whether developed by high voltage spark, direct current arc, electromagnetic induction, potential traps in a magnetic field, or electron beam currents impinging on a gas—are all similar in structure for high ion density because of the very small energy equilibration time in dense plasma. Moreover, the ambipolar diffusion forces are relatively large in all of these ion sources, and the discharges may be considered to be quiescent, hence the following remarks pertain to all types of gaseous electronic plasma.

Electrostatic fields applied to the surface of a dense plasma cannot penetrate into the body of the plasma. Thus the interaction between applied potential and the plasma surface which produces the ion beam is given by a Poisson equation in which the electron number density is a function of electron temperature, which can be much higher than ion temperature. This is unlike the simpler solution of the equation which gives Child's law as the connection between current, potential drop, and plane electrode spacing. Composition of the ion and gas stream crossing the plasma surface is given to the first order

by Saha's equation for ionic species except when interaction between the applied potential and the electron beam used for plasma ionization begins to cause instabilities. In cases where the total ion current as well as its uniformity and stability are to be maximized, the area of the ion source, the potential gradient ($V^{3/2}/d^2$ in Child's law), and the numerous causes of electrode erosion and ion beam instability must be studied. Efficiency of plasma ionization and ion beam acceleration are generally consistent with optimum overall performance because of the large magnitude of energy dissipation in high current ion sources. It has been found that plasma uniformity and other aspects controlling ion source performance are optimized by the use of a high magnetic field in the ion source and beam regions. In the Calutron, this field is also used to focus different isotopes at the 180° point in an almost semicircular trajectory.

The ion source under consideration uses a hot cathode as a high current electron source to ionize a gas in an adjacent chamber. The assembly is in a high magnetic field (8000 Oe); one side of the chamber is open to a high potential gradient set up by 60 to 120 kV applied to an electrode assembly (Fig. 1). Figure 2 shows a cross section of the ion source and electrode geometry used to control ion current and beam divergence. The magnetic field is parallel to the x-axis in Fig. 1 and normal to the plane of Fig. 2.

Consistent with the space charge limit in the acceleration region, the ion beam is largest when the degree of ionization, pressure, and potential gradients are optimum for an ionic species over the largest possible plasma surface area exposed to the accelerating voltage. These are optimum when the power source is used most efficiently, as the source of ionizing electrons has its own limitations and the largest energy sink is that due to radiative transfer and escape of energetic electrons. This has resulted in the use of a high magnetic field for the most intense sources of useful ion beams. The ions in the

Fig. 1.

Geometry of plasma probe experiment.

Fig. 2.

A typical high density ion beam geometry, the University of California Calutron.

plasma are normally accelerated along an internal electric field E normal to the magnetic field H but with a net flow normal to E along a cycloidal path to the surface of the plasma. Loss of electrons by diffusion normal to a magnetic field may ordinarily be considered small. The third direction, along the magnetic lines of flux, can easily be transformed into an electron trap by inserting a negative potential or an insulated surface at each end. This also increases the plasma uniformity by reducing potential and density gradients from the electron source toward the anode.

Note that electrons must still have an easy mode of egress from the plasma in a magnetic field because the electron current is the source of power. In either the oscillating volume or electron beam power sources, electrons are injected into the body of the arc along H ; therefore an equal electron current, plus the negative charge equivalent of the useful positive charges diffusing out of the plasma, must leave the arc to maintain a stationary condition. Otherwise, the arc will discharge itself by high frequency, random oscillations called "hash," which increase the electron diffusion rate across H . This mechanism has been commonly conceived to be the only mode of

egress and is the process effective in the "Bohm limit" for transverse currents. However, the transverse diffusion velocity on equipotential surfaces, related to the normal velocity by the product of the Larmor frequency ω and the collision period τ , can be sufficiently high to permit the development of stationary electron flow patterns from any point in the arc directly to the high density plasma boundary, where a quiescent current of electrons parallel to H becomes possible.

The following discussion presents the ion beam problem in three parts and describes a fundamental aspect of each. Section II discusses the source plasma, Sec. III ion beam formation, and Sec. IV the acceleration region. Section V compares ion currents along and across the magnetic field.

II. INTERNAL STRUCTURE OF AN ION SOURCE PLASMA

The interaction of a stream of electrons from a hot cathode and a molecular gas evaporated from a boiler at a density of approximately 10^{13} particles/ml results in excitation and ionization of the gas and thermalization of the electrons to a temperature determined by energy balance equations and boundary conditions. These equations are well known; the boundary conditions are indirectly defined by measurement of total ion beam magnitude and stability (determined at a remote focus of the ion beam). These gross measurements are made in addition to gas flow rate and electron current and cathode potential, but plasma and beam processes must be determined by more detailed studies for which the Langmuir probe is useful.

It is well known^{2,4} that a magnetic field cannot change the particle velocity distribution function, however it does introduce large drift velocity equal to cE/H across the magnetic field H in potential gradient E . The drift velocity is normal to H , therefore a probe surface which is also normal to H and properly shielded will measure only the current $I = ne\bar{u} = ne \int_0^{\infty} u f(u) du = ne(kT/2\pi m)^{1/2}$. A retarding potential V on a probe will permit current $I = I_0 \exp(-eV/kT)$ to flow to its surface, and the variation of $d \ln(I/I_0)/dV_{\text{probe}} = -e/kT = 300 V_T$ (practical units) measures charge temperature $kT/e = V_T$ in electron volts. In addition, the plasma density n is determined from the same equation $I(\text{probe}) = ne(eV_T/2\pi m)^{1/2} \exp(-V_0/V_T)$ for I measured at $V_0 = 0$, i.e., at plasma potential. Thus, $n = 3.71 \times 10^8 (I/\text{area})/V_T^{1/2}$ electrons/ml for $V_T(\text{ion}) \ll V_T(\text{electron})$.

Interpretation of probe measurements at the anode end of a plasma for current flowing along the magnetic field is simplified by noting the wear pattern on the walls of the ion chamber. Figure 3 shows a simplified sketch of plasma electron motion in the body of the high density plasma used in this study. In the W direction in Fig. 4, probe measurements show electron concentration (number density) and temperature. Note that the plasma distribution in space, assumed from the wear pattern, is supported by the measurement of the concentration distribution across the plasma. The negative side of the probe position supplies the cold gas input. As the electrons drift, the concentration increases, moving the electronic plasma radially away from the collimated electron beam source, as shown in Fig. 3. On the side toward the meniscus, the drift current adds to the primary electron current to form a maximum in number density. The electron temperature increases in similar fashion, but with a strong decrease near the plasma sheath, or meniscus, due to processes (such as H -directed electron drain to chamber walls and interaction with the ion beam) that increase the rate of energy loss. This fact is demonstrated by Fig. 5 which shows the effect of ion beam acceleration fields on the internal plasma potential. Clearly, the direction of electron drift changes with the sign of E in the drift velocity formula $v = cE/H$, where $E = -\partial V/\partial z$. The magnitude of E (from Fig. 5) is approximately 70 V/cm, the potential at plasma center 4.3 V, and the plasma thickness 0.26 cm.

Fig. 3.
Ion transverse and normal motion in the plasma, both perpendicular to the magnetic field.

Fig. 4.

Electron concentration and temperature across the argon plasma.

Ion current from the plasma sheath must be equal to ion beam current. It is given by $I = n\bar{\omega}W$ where, according to Chapman and Cowling,² the diffusion velocity $\bar{\omega}$ is given by

$$\bar{\omega} = \left(\frac{eE_z}{m} - \frac{1}{nm} \cdot \frac{\partial p}{\partial z} \right) \frac{\tau}{1 + \omega^2 \tau^2}.$$

The terms are conventional and τ is the ion-ion collision period, i.e., the mean time for an ion to accumulate a 90° deflection by Coulomb collisions. This was given by Spitzer⁴ as

$$\tau = \frac{11.4 A^{1/2} T^{3/2}}{nZ^4 \ln \Lambda}.$$

Ion-electron collisions are less effective in promoting diffusion by one order of magnitude.

Fig. 5.

Plasma potential vs probe position.

Probe measurements permit a direct test of ion diffusion rate calculations. Figure 4 magnitudes are consistent with a mean collision period of 4×10^{-5} s and, comparing potential and pressure gradient terms in the diffusion velocity, the potential term denominator. Then $I_w \approx 4.3$ ma/cm² for the measured conditions in which $n = 1.6 \times 10^{12}$, $E = 0.23$ esu/cm, $\tau = 4 \times 10^{-5}$ s, and $\omega = 1.6 \times 10^6$ rad/s. A lower limit to ion temperature of 0.1 eV reduces τ to 3×10^{-8} s and increases I_w to 17 ma/cm². Experiment showed that the ion beam current across the plasma sheath near the probe was 7.0 ma/cm². This agreement was considered excellent.

The transverse velocity $v = cE/H \approx 10^6$ cm s⁻¹ plays an important part in plasma diagnostics if the motion of ions and electrons on these equipotential surfaces moves the individual charges very quickly

across H to the emitting surface of the plasma and to a position where the electrons can move along H to an electrode immediately on formation, as is evidently the case. Because of the presence of the electric gradient E , the charges will clearly move from any point in the plasma toward the outer surface on an equipotential. The very asymmetric density distribution which was experimentally observed for the body of the plasma indicates that, in fact, there is a very small number of transits around the plasma. It is possible that there is only one transit for ions formed upon entrance into the very hot plasma on the side away from the ion beam emitting surface. Thus the residence time for a charge is of the order of 10^{-6} s, small with respect to the thermal equilibrium time of ions and electrons of about 10^{-4} s (Ref. 4, p. 80).

A "streaming" motion normal to H and E (along equipotential surfaces) with a velocity cE/H will supply the ion beam meniscus with a sufficient quantity of ions to be consistent with the ion beam current if the effective collision period is indeed of the order of the values consistent with the self-collision time of Spitzer.⁴ The physical situation is more complex than the assumptions in Spitzer's analysis, because the geometry of the plasma, instead of being effectively infinite (as in stellar physics), is such that a single cycloidal path may cross the plasma radius from zero to large electric gradient values. An ion on the periphery of the plasma will leave the plasma in times of the order of fractions of microseconds (fractions of a period $\tau = 1/\omega$). This being so, and ion normal diffusion being very small across the midplane of the plasma, transverse diffusion (along $v \approx cE/H$) must play an important part in supplying ions to any high electric gradient vicinity such as the ion beam source meniscus. Note that the mean ion energy in the cycloidal trajectory is of the order of the maximum displacement $d = 2cE/m\omega^2$ times the electric gradient E , or $V_T = mc^2E^2/eH^2 \approx 90$ V (practical) for the upper limit of mean ion energy for an infinite geometry and a low ion-ion collision rate. The potential distribution in the plasma must provide an important diffusion mechanism for the ions.

A validation of the ion temperature evaluation may be found indirectly by observing probe potential for the zero net current condition. For this, $I = 0$, or $I_e = I_i$. Thus,

$$\frac{ne \bar{c}_i}{4} = \frac{ne \bar{c}_e}{4} \exp\left(\frac{-4V}{kT}\right),$$

or

$$\bar{c}_i = \bar{c}_e \exp\left(\frac{-eV}{kT}\right),$$

where subscript i signifies ion and e electron. Let $V \approx V_p \approx 170$ V, an average probe potential for $I = 0$. Since $kT_e \approx 20$ eV for the plasma discussed above, and since

$$1/2 M \bar{c}_i^2 \approx \frac{M}{m} \bar{c}_e^2 \left(\frac{-2V_p}{V_e}\right) \text{ from } I_e = I_i,$$

then

$$V_i = \frac{M}{m} V_e \exp\left(\frac{-2V_p}{V_e}\right) \approx 0.1 \text{ eV}.$$

V_i is ion temperature, V_e electron temperature, and V_p probe potential for $I_e = I_i$.

This relationship is very sensitive to probe potential and electron temperature. The mean ratio of $V_p/V_e > 5$ for the ratio of floating probe potential to electron temperature in high density ion sources is commonly found in these high density ion sources.

A. Discussion

The diffusion of low temperature ions out of an electronic plasma cannot be constrained by a magnetic field H with an effectively very small (coulomb) collision period because normal diffusion processes will occur. If the geometry is such that the magnetic field serves to establish a potential gradient E , then ions and electrons will move normal to H and E with relative freedom. Electrons have such a very small cycloidal amplitude that they are relatively immobile along the E vector in spite of a short coulomb collision period. Because of the relative immobility of electrons, as compared to ions, for motion across equipotential surfaces, the most stable high density plasma should be more negative in the center (see "ion beam off" case in Fig. 5) and should be subject to forced oscillations if a high energy electron stream, entering the plasma (along H) to provide an energy source, does not have a stable mode of egress. Both of these situations have been observed in this and associated studies. In fact, the change in direction of internal plasma currents,

upon initiation of plasma hash, has an easily observed effect on ion beam trajectory from the ion source meniscus due to movement of the plasma sheath from more (less) to less (more) concave on the two sides (refer to Fig. 3).

Other means of exciting the discharge were developed in light of the above considerations. An rf discharge using only the magnetic component of the assembly shown in Fig. 1 formed a plasma of the same order of magnitude of density as the dc electron beam most frequently used which has already been discussed. The geometry was simply that of an induction coil whose current flows along the magnetic vector H in vacuum, with a gas-filled discharge chamber immediately juxtaposed. Again, an extension of the Penning ion gage geometry (with a thermionic cathode heated only by the discharge but with a geometrical cross section permitting stability in the sense discussed above) gave a very high density, stable discharge that was used⁵ for ion beam production in the ampere range. Again, a high voltage, high current spark with an oscillating volume geometry gave a high current (16 A) pulse of ions for use in a cyclotron.⁶

B. Conclusions

1. The transverse component of velocity $v = \omega r_w$ is a major component of plasma drift across a magnetic field.

2. Stability, as a characteristic of ion sources required for ion beam focusing (small internal electric gradients), does not limit ion source production, since stability is consistent with high density plasma formation with attention to electric fields which are plasma boundary derived.

3. The Chapman and Cowling equation² for ion drift velocity is consistent with electronic plasma motions.

III. ION BEAM FORMATION

Ions are formed in the ion source plasma and presented to the meniscus electric gradients of the ion beam source. Here, in plane geometry for one charge species, Child's law relates ion current I to accelerating voltage V and electrode spacing d $I = c_1 V^{3/2} d^{-2}$.

In the magnetic field, the meniscus structure is complicated by ion and electron density gradients which, by Poisson's equation, affect ion currents. The magnitude of the effect on the ion currents which are space charge limited, due to the presence

of a velocity distribution, may be seen to depend more on ion temperature than meniscus structure. Since there is an uncertainty connected with this vicinity because of the possibility of effectively high ion temperatures (which are comparable with the kinetic energy change in a cycloidal path of amplitude $V_T(\text{ion}) \sim Ed = 2E^2/m\omega^2$) it is necessary to look for effects due to high ion temperatures, effective (resulting from a large cycloidal amplitude) or real.

The gross effects of ion and electron temperature on ion beam formation are relatively simple to evaluate if there are only very small amplitude transients, and if secondary effects, such as thermionic emission from the material containing and probing the plasma, are small. The particle temperature effects can be shown to be relatively small, without sufficient analytical knowledge of the plasma, if Child's law (which assumes zero initial velocity), derived from the simple Poisson equation, holds. Measurements can be made of a net current through high voltage electrodes from the meniscus in a direction normal to the magnetic field, and the "dark space" between low voltage electrode and plasma parallel to the magnetic field. These were made in a relatively straightforward way which will not be discussed here. One interesting difficulty was due to penetration of high electric gradients into the electron stream exciting the ion source plasma. This caused a very hashy (fluctuating plasma density in the megacycle frequency range) ion source density and a divergent ion beam. An increase in plasma density corresponding to increased accelerating potentials eliminated this effect.

The close approximation of computed to experimental values found in these measurements ($V^{3/2} = c_1 d^2$ and $I = c_2 V^{3/2}$) shows that the charge particle temperature effects are small, and strongly implies that there are no significant plasma oscillations which could cause significant changes in effective particle mean energy.

The validity of elementary ion current theory for ion source evaluation has its limitations. One of these, which provides a real limit of an obscure nature to the voltage gradient possible with ion sources, is the electric breakdown that occurs when a limit is reached. The maximum potential gradient that can be maintained for a wide variety of conditions for one highly developed high current ion source for uranium isotope separation (the Calutron) is 60 kV cm^{-1} . Above this value, high voltage breakdown begins in the threshold sense, for reasons described in Sec. IV. This limit in voltage gradient changes Child's law to the novel form $I_{\text{max}} = K'V^{-1/2} = K''d^{-1/2}$.

IV. ION BEAM ACCELERATION REGION

A. Physical Processes

The ion beam is accelerated in a geometry shown in Fig. 2, by high potential gradients from the ion source meniscus in the presence of a neutral gas density near 10^{13} mol/m. This neutral gas results primarily from incomplete ionization of the gas passing through the plasma. A neutral gas in the acceleration region can be important in ion source performance not only because of ion beam scattering, which is usually small (although charge exchange produces a strong neutral particle beam), but also because of the formation of large circulating (or equipotential surfaces) electron currents in this region. The ion beam itself is relatively ineffective for ionization, since an electron of the same velocity, to use familiar magnitudes, has an energy V_e only of $V_e = (m_e/M_I) \cdot V_I \approx 1$ eV, where V_I is the ion energy and M_I is ion mass, argon in these experiments. Any electron formed in the gas by photoionization or electron scattering is highly ionizing because of its high mean energy in the ion acceleration region. The amplitude of electron cycloidal motion is $d = 2eE/m\omega^2 \approx 1.4 \times 10^{-2}$ cm. Magnitudes of E and ω for electrons in the high current ion sources are near $E \leq 60$ keV cm^{-1} and $\omega = Hc/mc \approx 10^{11}$ for $H = 5000$ to 10000 Oe. The electron maximum energy is $V_e = Ed \approx 1$ keV with an average value of the order of 100 eV. The mean transverse electron velocity in the $E \times H$ field is approximately $\bar{v} = eE/H \approx 10^9$ cm s^{-1} , and the energy of the electrons in the stream consistent with this velocity is approximately $E_{\text{transverse}} \approx 300$ eV.

The electrons formed in the ion beam acceleration region cause further ionization in the neutral gas, and large currents may be formed in electron-conserving systems. This stream is especially troublesome for multiple (parallel) ion beam sources, thus many stratagems have been evolved to reduce inter-ion beam effects. These methods consist essentially of eliminating circulating electron currents by formation of potential gradients E in the direction of the magnetic field that allow the currents to leave the system. The geometrical problem of inserting H -directed E vectors in the ion beam acceleration region generally increases ion beam source separation in multiple systems to approximately one-third of the H -directed length of the ion sources.

A typical effect of the rise of several parallel ion sources is ion beam defocusing which is due to both the large circulating currents and the secondary effects of quantities of ions being formed in the high

electric gradient region, in particular, high voltage arcing and sparking. Extreme conditions can affect ion source electrical stability.

Considerations involving electron multiplication in the acceleration region (which are questionable because of the high velocity and low density expected for the accelerating region transverse electron currents) have been generally validated by increasing and decreasing electron loss rate by electrodes which change loss rates with single and multiple ion beam geometries. No beneficial effects of these currents, such as decreasing ion space charge effects, have been found. Factors of 2 on stable and well-focused ion beam production have resulted from small changes in electrode geometry in the light of these considerations. Conversely, ion sources can be made inoperable simply by use of electron-conserving fields in parallel ion source assemblies.

B. Ion Accelerating System Interaction with Ion Source

The accelerating system of the ion source has a double function: to focus the ion output of the ionic plasma, which permits focusing at the ion beam collector, and to accelerate a high ion current from the plasma. These two factors are not independent: variations in potential gradient at the plasma surface causes changes in curvature of the meniscus that results in a different focusing function for the electrostatic lens set up by the accelerating system. For this reason, it is not possible to calculate in a simple way an ion beam focusing system or to design a system that will work for any given type of plasma or for any magnetic field. Acceleration system geometries are developed empirically.

Maximum production of ions from any given type of arc requires that the potential gradient at the surface of the arc can be no greater than a critical value given by ion diffusion current in the source plasma. Larger values will incite ion source plasma instabilities (see Sec. C). Because this potential gradient determines the position and shape of the meniscus for any ion beam source density and geometry, it is possible to design a satisfactory focusing system using control of electrode voltage and spacing.

C. Ion Source Current Limit Across the Magnetic Field

The plasma of the ion source is optimized for (1) stability, to permit formation of a sharply focused ion beam; (2) temperature, to specify the

quality of the ion beam; (3) thickness and density (consistent with stability), to maximize ion beam for a given supply of source gas; and (4) to minimize erosion of the surrounding apparatus. Controls are cathode temperature and voltage (for plasma excitation control), and voltages required for acceleration of the ion beam to maximum ion current values. Formation of a stable ion beam plasma is important for magnetic focusing reasons, because a high density ion beam must be neutralized, first to form a beam plasma meniscus, and second to avoid extreme space charge disturbance of ion trajectories. Because of long migration distances of electrons, stable ion beam plasma is near the potential of the most positive electrode accessible to the ion beam. Very long operating periods for ion beam production are made possible with these controls which reduce changes due to erosion, etc., in a complex system.

An optimized ion source may produce large controlled changes in ion beam currents up to limits on electric gradients set by acceleration region processes previously outlined, the most important of which is the maximum potential gradient.* Higher gradients incite sparking flurries due to mechanisms which are not completely understood, although a qualitative argument can be made from a description of plasma structure as follows. The internal structure of the ion source plasma consists of a collimated high temperature electron stream coming directly (with many small angle collisions) from the cathode. On this is superposed the ambipolarly diffusing ionic plasma, circulating in a direction normal to H with a velocity magnitude $v \approx cE/H$. Ionization of the gas entering the plasma is conservative, with motion increasing the plasma thickness beyond the collimated electron stream in a direction consistent with plasma potentials which are more negative toward the center (the diffusing electron source). Electrons are essentially trapped in an oscillating volume along H , therefore any electrical or plasma geometry change that reduces the mean diffusion velocity normal to H and E , which permits draining of electrons from the plasma, results in oscillations. One such change is penetration of the meniscus position-sensitive, and thus relatively unstable, ion beam acceleration potentials into the primary electron stream, coupling plasma density with beam space charge effects. Another is an increase in plasma thickness that forces the electron to

increase the transverse diffusion velocity by a hash (radiofrequency oscillations with a wide frequency band) mechanism. Thus, if plasma density and temperature are increased by energy and gas flow rate controls, the plasma thickness increases beyond the experimentally optimized point. Hash is incited. The internal potential gradients change sign and magnitude with different current direction distribution to the ion beam source meniscus. The ion beam changes direction due to the different symmetry of the meniscus. The ion beam diverges because of a change in meniscus position due to the sometimes energetic ion plasma hash. The ion beam plasma is less completely neutralized because of unstable ion currents, and so it diverges because of internal space charge potentials.

The ion source plasma, ion beam acceleration region, and ion beam plasma are sufficiently connected by potential distributions and charge flows that they should be considered as a unit. As an extreme example, the ion beam may impinge on an electrode, such as an ion collector, several meters from the ion source. Potentials on this collector have been seen to affect ion source performance through the ion beam plasma over this long path and through the acceleration region.

D. Ion Beam Plasma

The ion beam from a high intensity ion source must be electrically neutral both for beam divergence reasons and to provide a minimum acceleration electrode spacing for maximum ion current ($I \propto d^{-1/2}$). The ion beam plasma may be formed by the weakly ionizing ion beam at ion energies >10 - 20 keV, and this is the simplest and most used method if there is a sufficient amount of easily ionized and preferably electronegative gas in the ion beam trajectory. Formation of the ion beam plasma attenuates ion beam current, but the mean life of plasma ions and electrons for gas pressure reasonably optimized ($p \approx 10^{-5}$ mm) is sufficiently long that the net attenuation is not large. The relative ease of this method of forming ion beam plasma has reduced interest in ion beam plasma physics, except where a minimum of residual space charge is important, and when lower particle velocity ion beams are in question.

Methods of producing additional neutralization are as follows.

1. Use of an intense source such as a dc arc to produce photoionization of residual gas in the ion beam volume.

*This maximum gradient, as will be seen, depends on geometry to some extent. John Luce, L.L.L., was able to increase the maximum gradient value from 60 to 90 keV cm⁻¹ using a novel grid geometry for ion sources.

2. Use of low ionization potential gases in the beam plasma.

3. Secondary emission by ion beam bombardment of container walls.

4. Thermoelectric emission of container walls or juxtaposed filaments.

These methods have all been shown to have a significant and sometimes very important (for low ion beam particle energy) effect on ion beam particle trajectories, by reduction of space charge.

There are added considerations to condition a choice of neutralization means.

1. Negative charges in the plasma do not move very far along the beam (normal to H).

2. The plasma is normal in every way, including resonance frequencies, a Maxwellian temperature distribution, space charge potential positive with respect to container walls (typically 2 eV). A search with a wave analyzer failed to locate any but thermal low amplitude frequencies characteristic of plasma density and ion species.

3. Plasma density is an order of magnitude greater than average ion beam density.

4. The electron temperature from Langmuir probe measurements is remarkably high: 2-4 eV for a 30 keV argon ion beam.

5. Plasma potential is relatively constant along H and, from Langmuir probe measurements, approximately equal to the electron temperature in electron volts.

6. The plasma space charge is a sensitive indicator of the stability (small rf amplitude) of the ion beam itself. The presence of ion beam density fluctuations adds and removes space charge because of different mobilities of ions and electrons, which introduce potential fluctuations to the order of magnitude of those that would be present with no neutralizing plasma. For example, for orders of magnitude with an argon ion beam, $\nabla^2 V \approx 3 \times 10^{-2}$; $E = dV/dx \approx 0.25x$ esu where x is distance. This will result in strong ion beam divergence, which is observed with an unstable ion source.

An example of the usefulness of these observations was found in the development of a mass analyzer. Whitson⁷ noted in 1950 that the very large and uniform magnetic fields available with the Calutron could be used to determine the mass of heavy isotopes simply by letting a pulse of ions circulate for a long time in the magnetic field. A low voltage (hence, small radii for ion trajectories) ion source was constructed, using a short chop in a continuous ion beam spiral to locate the ion pulse. Only after easily ionized gas (cesium) was used for beam plasma formation did the device work well for beam

pulse position measurement. All methods other than charge scattering for beam neutralization failed to locate the gap because of its closure by space charge effects.

V. MAXIMUM ION CURRENTS FROM A PLASMA

A. Ion Currents

An evaluation of ion currents from an ionized gas can be made more simply by experimental than by analytical means. This is due to a lack of detailed knowledge of actual ion and electron temperatures and internal potential and density gradients. Such an experimental evaluation is significant if the ion currents are controllable as, for example, samples emitted through small collimating slots, and if the currents are connected with a well-understood physical situation.

B. Large Probe Measurements

An experiment was conducted in the light of the plasma structure study (Sec. IV.D) using argon gas and electron beam excitation or heating of the plasma in a magnetic field. Large probes collected saturation ion currents parallel to H through an ion current collimation slot and normal to H through a second slot on a protected probe (see Fig. 1). Ions moved freely (parallel to H) on a stable plasma in one direction ($I = ne\bar{u}$) and slowly (across H) in the other; the rate depended on the self-collision period τ , the plasma internal electric gradients E , and the magnitude of H . The objective of the analysis was to establish systematic trends to enhance a qualitative understanding of the diffusion processes as well as to obtain magnitudes for ion currents. The magnetic field was used to establish a coordinate system for diffusion velocity measurements; it was used because plasma heating by electron currents is most efficient in the oscillating volume easily established by electrodes in a magnetic field. Also, of course, ion current magnitudes have significance in ion source analyses by physical means.

Several questions remain.

1. Do hash phenomena enhance ion diffusion across H and thus increase the ion current magnitude?

2. How are ion currents along and across H actually related?

3. What are the upper limits to ion currents from a plasma into an ion beam?

Two probes which collect I_x and I_z , respectively parallel and normal to H , were juxtaposed, so that the ratio of parallel to normal (perpendicular) currents (with relation to the magnetic field vector) sufficed to evaluate the velocity ratio in these directions. The apparatus simply consisted of a geometry designed to generate a plasma 0.25 x 2.0 cm in cross section normal to H and 20-cm long in the direction of H . An argon gas supply on one side and a vacuum on the other (1.27-cm-wide opening) permitted gas supply and accessibility. One end of the plasma was directly exposed to a cathode filament (tantalum) at controllable temperature and voltage so that plasma heating by electron interaction could be supplied with 0 to 2 kW of power in the form of an electron current from the filament. The anti-cathode end of the plasma terminated through a 1.0 x 0.16 cm² opening on a collector plate at a controlled potential. The side of the plasma exposed to vacuum was also exposed to a 0.56-cm-diam collector plate, protected by a ring at the same potential. Conventional current and voltage circuits permitted control.

C. Currents Along and Across the Magnetic Field

Figures 6-8 summarize the probe ion currents for saturation conditions over the control range of the plasma currents, limited on the lower pressure and power side by plasma extinction. The control range included both stable and bashy conditions as evaluated by relative magnitudes of rf current amplitudes on the electrodes. Stability is consistent in general with parallel- (to H) to-normal current ratios near 2.2.

In Fig. 6 note the remarkable constancy of the ratio $I_u/I_w = 2.2$, where u is parallel and w is normal to H . Larger values are consistent with a higher degree of ionization of the plasma resulting from increased power dissipation. Lower ratios are consistent with lower temperature and density plasma for which the internal electric gradients, resulting from charge interaction with the magnetic field, could be larger.

D. Conclusions

1. The effect of plasma oscillations on diffusion across the magnetic field is apparently small since the ratio of current along H to across H is independent of the presence of oscillations. This observation is consistent with results in Fig. 7 in which high ex-

Fig. 6.
Ion current vs electron beam current.

citation currents, which commonly cause plasma hash, actually decrease the relative current across H .

2. The constancy of the ratio $\bar{u}/\bar{w}$ results in the novel relationship between currents² parallel to (I_u) and normal to (I_w) the magnetic field H :

$$\frac{I_u}{I_w} = \frac{\bar{u}}{\bar{w}} \frac{m}{2E_z} = \frac{Kn}{TE_z} \approx 2.2$$

Lack of knowledge of the dependence of T_{ion} and E_z on plasma density and power dissipation prevents further reduction of this data.

3. The degree of ionization of the plasma, which should affect diffusion in a large way due to the effect on the ion coulomb collision period ($\propto Z^{-4}$), has little effect on plasma currents. This indicates that the plasma ion diffusion processes are in a domain of relative independence of the magnetic field, except in a secondary way by the dependence of E_z on H . This conclusion depends on Chapman's factor $(1 + \omega^2 \tau^2)^{-1}$ on diffusion velocity,² where

Fig. 7.

Ion current vs gas pressure in the ion source.

$\omega = He/mc$ and τ is the mean equilibrium time constant for self-interaction.⁴

4. The essentially linear relationships, shown in Fig. 7, between plasma gas pressure and currents from a plasma, exhibit no definite limitation on currents from a plasma in a magnetic field. Plasma sensitivity to exciting electron current conditions, a familiar phenomenon, is also illustrated in Fig. 8.

VI. REMARKS

Although there is nothing surprising in this report, it can be helpful in ion beam considerations for conventional and novel applications. Development of ion beam devices remains largely an experimental effort. The ideas summarized in this report helped to correlate many Calutron observations in the development of very simple high density ion sources and in the understanding of ion beams and sources now being used in many places. The general problem is that of forming a dense, uniform, stable plasma with most of the excitation energy appearing as heat, so that transport processes into a region of high voltage (for high energy beams), or space for low

Fig. 8.

Ion current vs electron beam voltage for 1 and 2 A electron beam current.

energy neutral beams, are optimum for the particular situation. It is not necessary to invoke a hash mechanism for diffusion across a vector field H and, unless a space-charge-free beam is necessary, one frequently finds that the hash does little but increase parasitic losses in efficiency. The beam formation mechanism is described well by a Child's law type of equation; ion beam neutralization has not been a problem. Details of ion source and beam plasma physics are only determined with difficulty; much remains to be done in this field.

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