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ABSTRACT

The use of an EXB type of discharge as a source of ions has been investigated. For standard applications, this use appears limited because the ions obtain energy while still within the arc structure. If the proper polarities are used, the ions exhibit the interesting characteristic of self-extraction. The EXB geometry also operates as an effective ion pump for light gases. Discharge conditions and ion output characteristics are discussed.
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INTRODUCTION

When, in a vacuum, an electric field exists normal to a magnetic field, charged particles under the influence of these forces will migrate trochoidally in a direction normal to both forces. If the combination of electric gradient (E) and magnetic field strength (B) is such that electrons are able to gain ionizing energies, a discharge can result which, depending on the gas pressure, can range from a weak drain to an intense arc discharge.

In most glow-discharge or ion-source geometries utilizing electric and magnetic fields, this combination of E X B will inadvertently exist in some portion of the system. In the past, this effect has resulted in insulator breakdown, voltage-holding difficulties, and parallel discharges which in many cases were difficult to observe or understand. An example of a parallel discharge resulting from E X B geometry is illustrated in Fig. 1.

Figure 1 is a photograph of the filament region of an experimental, hot-cathode ion source. Although the desired discharge took place, as evidenced by the sputtered filament, a second discharge of the E X B type is also indicated by the wavy lines normal to B that mark the filament support lines. These markings, which seem to characterize this type of discharge, are found on the negative electrode. The ion-source anode, which is not shown, served also as the anode for the parallel discharge, and when in place it prevented the parallel discharge from being visually observed.

Insofar as the E X B type of discharge is generally encountered in varying degrees in most ion-source geometries, it was decided to study its operational characteristics to determine if a discharge of this type could be effectively utilized as a source of ions. This short investigation was specifically directed toward the use of this type of discharge in geometries small enough to be termed practical for use as an ion source. Extraction of ions in all cases was normal to the magnetic field, and no attempt was made at axial ion extraction.

Two E X B ion-source geometries which differed little other than in physical size were constructed for test. Figures 2 and 3 are a photograph and a cross-sectional drawing respectively, of the first source structure that was built. This unit, which will be referred to as the "1/2-in. geometry" has a 0.250-in. -diam copper center-rod which is held coaxially in the center of a 1/2-in. -diam copper cylinder by means of fired-lava insulators. Both electrodes are water-cooled by means of "squirt-tubes" which, in turn, form the mounting structure. The lower support rod has an epoxy cover to allow electrical insulation at the entrance support flange. Gas is fed through a 1/8-in. -diam pipe into the center of the arc structure.
Fig. 1. Region of parallel $E \times B$ discharge.
Fig. 2. Photograph of the 1/2-in. geometry.
Fig. 3. Cross section of the 1/2-in. test geometry.
Initial arc operation was with the center rod negative, and the small disk-like extensions at either end of this rod were included to provide a more positive strike or starting of the discharge. These negative extensions are in line with the magnetic field and the positive region of the cylindrical anode and form a Phillips ion gauge (PIG) geometry which prevents the escape of initiating electrons. With the center rod negative, this geometry would operate without the cathode extensions. However, it was often necessary to wait for several minutes for the discharge to strike, and after a short period of operation, the exposed region of the lava insulators would become coated with a thin layer of sputtered copper, which gave the same electrical appearance as the cathode extensions.

Operation of the 1/2-in. geometry with a positive center rod was never successful. The disk extensions were removed because they allowed arc-initiating electrons to escape along the magnetic field lines. Even though clean insulators were used, the arc refused to strike and thus the geometry pictured in Fig. 4 was constructed. This unit, which will be referred to as the "1-in. geometry," was designed to operate regardless of the polarity of the central rod. The inner diameter of the cylinder was increased to 1 in. to allow disks to be soldered at either end. Thus a PIG starting geometry is present regardless of electrode polarity, and no difficulty in starting was encountered. Although some PIG geometry seemed necessary to strike the discharge, it appeared to play no part after the discharge was in operation. This was evidenced by the fact that the electrode extensions never suffered sputtering effects.

Both source geometries were equipped with a 1/2-in.-by-3/64-in. ion-exit slit located through the side of the outer copper cylinder. The small triangular carbon blocks shown in the picture are dumping blocks for external E X B electrons which are formed in the region of ion extraction.

OPERATION

In a modern cyclotron, an ion source must be capable of operating in the presence of magnetic-field levels ranging from about 10 to 20 kgauss. Thus one of the first parameters investigated was the effect of increasing magnetic-field strength on the discharge. Arc operation was stabilized at an arbitrary level, and then the magnetic-field strength was increased. Figure 5a and b indicate the results obtained. In all cases, the arc impedance increased with increasing magnetic field. This effect is not surprising, as one would expect the electron energy to be a definite function of the magnetic field.

If the geometry is such that the average electron energy should fall near or below the ionization potential of the gas involved, then the arc impedance would increase markedly. For simplicity, let us consider the parallel-plane E X B situation illustrated in Fig. 6. As electron starting at the surface of the negative electrode will describe a trochoid normal to both the crossed electric and magnetic fields. The electron energy will be greatest at the point where \( Z \) is a maximum. For the electron starting with 0 energy, the distance \( Z_{\text{max}} \) can be determined from

\[
Z_{\text{max}} = \frac{2E}{[B^2(e/m)]}. 
\]

The energy that the electron will acquire at \( Z_{\text{max}} \) can be determined by \( V_i = 2E^2 m/B^2 \). In the absence of a plasma,
Fig. 4. Cross section of the 1-in. test geometry.
Fig. 5. Arc current vs magnetic field for (a) helium with 1/2-in. geometry, negative center rod, and 1000-v arc, and (b) argon with 1-in. geometry, positive center rod, and 2000-v arc.
Fig. 6. Parallel-plane $E \times B$ considerations. A magnetic field $B$ is assumed perpendicular to the paper.
an electron starting with no energy in the 1-in. geometry operated with a potential of 2 kv and in a magnetic-field of 2 kgauss, would obtain a maximum energy of about 13 ev. This energy would decrease to less than 1 ev should the magnetic field be increased to 8 kgauss. The distance normal to the magnetic field that the electron would travel ($Z_{\text{max}}$) would be $2.3 \times 10^{-3}$ and $1.4 \times 10^{-4}$ in. respectively. The presence of plasma will alter the distribution and magnitude of the electric gradient, and in general electrons will start with some finite energy. Thus the maximum electron energy will be greater than that calculated.

The same relations can be used to indicate the action of the ions, should one know the place of birth within the arc structure. For example, ions of He$_4$ would have a $Z_{\text{max}}$ ranging from 1 to 16 in. under the same magnetic-field conditions, if they received the full arc potential. It thus becomes apparent that in geometries of the size tested, even ions of very low energy will be rapidly lost to the cathode surface, and the action of the discharge will be primarily that of an electron magnetron.

Because of the degenerative effect of high magnetic-field levels on the discharge, the remainder of tests run with the two geometries was at or near the lowest magnetic-field level that the magnet regulator would allow. In general, this was about 3 kgauss.

Aside from magnetic-field effects, the arc impedance was always a function of the gas flow rate to the arc. In general, arc current could roughly be doubled by increasing the gas flow rate by a factor of two.

Arc impedance was also found to be a function of geometry. Under comparable conditions, the impedance of the 1/2-in. geometry was always less than the 1-in. geometry. Because the vacuum system had to be taken to air to change from one geometry to the other, a precise duplication of parameters was difficult. However, a factor of at least two could easily be observed, with the 1/2-in. geometry producing the higher arc current.

In the case of the 1-in. geometry, which would operate with either polarity on the center rod, the arc impedance was always less with the center rod negative. In general, a factor of from three to four increase in arc current resulted when the center-rod polarity was changed from positive to negative.

**GAS PUMPING**

When the 1/2-in. geometry was first operated with helium gas, the vacuum-system pressure dropped considerably as the discharge was initiated. When the discharge was stopped, the chamber pressure immediately returned to normal, indicating that no change had occurred in the gas flow rate as determined by the needle valve. Apparently a substantial amount of helium gas was being pumped into the arc structure.

The gas flow rate of helium into the system, as measured by the leak detection apparatus shown in Fig. 7, was plotted versus the vacuum system ion-gauge reading. As the pumping speed of this system was known to vary slightly from day to day, a plot of the type shown in Fig. 8 was made
Fig. 7. Gas-metering arrangement.
Fig. 8. Gas flow in cm$^3$/min STP vs ion-gauge reading.
Fig. 9. Helium pumping rate vs arc power for 1/2-in. geometry with center rod negative.
just prior to initiating the discharge. The flow meter was an integral part of the gas line, and thus flow rates could be determined during the time the arc was in operation.

The data shown in Fig. 9 were taken with the 1/2-in. geometry operating with a negative center rod and with helium gas. As the power to the arc was increased, chamber pressure as indicated by the ion gauge decreased. The gas flow rate was rechecked to make certain that it had not changed, and the amount of gas that was being pumped by the arc structure could be obtained by noting the change in flow rate that would be needed to obtain the \( \Delta p \) indicated by the ion gauge. In Fig. 9 the pumping rate of the source structure is plotted versus arc power for lack of a better parameter. The arc was able to pump over half the input gas in the two cases shown. In the one case, almost 1.7 cm\(^3\)/min. STP of helium gas was pumped into the arc structure.

If the source can pump gas to the extent shown in Fig. 9, the gas pressure within the source should decrease. As mentioned previously, a decrease in pressure within the source should result in a higher arc impedance, and thus the arc impedance should increase as the pumping rate of the source increases. As shown in Fig. 10, this is precisely what happens.

Of the three gases investigated (He, \( N_2 \), and \( A \)), only helium pumped to the extent shown. This indicates that the pumping action is one of moderately hot ions burying themselves into the metal structure of the negative electrode. In this case, the negative electrode (Fig. 3) was the 1/4-in. -diam copper center rod.

Although evidence of sputtering certainly existed, pumping action by means of gettering by the sputtered material must have been negligible, or nitrogen would have been pumped instead of helium.

The arc current and voltage characteristic for operation with argon is shown in Fig. 11. The arc impedance is about the same as that shown for helium operation in Fig. 10, although the gas flow rate is considerably smaller. No great change in arc impedance is present, and little if any pumping of argon gas was observed. In the case of argon, some pumping could be observed by increasing the arc voltage to above 5 kv.

It is rather interesting to note that if 50% of the input gas was pumped, at least 50% of the gas had to be ionized. We can thus establish a lower limit to the degree of ionization within the discharge. Also a comparison of the number of atoms of gas pumped to the number of electrons represented by the arc current reveals that each electron pumps approximately one gas atom in the case of Fig. 9.

No lengthy runs were made with the arc pumping helium, and thus it is not known how long the effect would continue. It was noted in the case of the 1-in geometry, however, that after several changes of polarity in which both electrodes were exposed to sputtered porous coatings, the pumping effect with helium was drastically reduced.

Although hydrogen and deuterium operation was never checked, there is no reason to believe that these gases would not be very readily pumped by the geometry described.
Fig. 10. Arc characteristics for helium operation with 1/2-in. geometry, $B = 4.5$ kgauss, and negative center rod.
Fig. 11. Arc characteristics for argon operation with 1-in. geometry, B = 3 kgauss, and a gas flow of 0.264 cm$^3$/min STP.
Fig. 12. Source structure inside vacuum system.
ION OUTPUT

A grounded extractor electrode was located near the ion-exit slit and the entire source structure was made positive in an attempt to extract positive ions from the discharge. Figure 12 is a photograph of the 1-in. geometry in position inside the vacuum system. This photograph, taken through a view port, does not include the extractor electrode but does show the moveable Faraday cup at the 180 deg focal plane.

With the center rod negative, few if any ions were ever extracted. No ion beam was ever observed visually, although later observations indicated that a continuous beam of certain gases, such as nitrogen, could easily be discerned, even if only a few microamperes of ions were present. With the center rod negative, ions formed in the discharge region are directed to the center rod. This directed motion is of course opposite to the intended direction of extraction. Even though up to 20 kv was used, the extraction gradient was unable to compete successfully with the reverse internal gradient.

With the positive-ion motion controlled by the direction of the internal electric field, it is obvious that if the polarity is reversed, some of the positive ions now directed toward the outer cylinder should pass through the slit in this electrode. If no external electric fields exist to decelerate the ions, they should emerge from the slit without the necessity of any additional extraction potential. Figure 13 is a photograph of ions emerging from the slit under the conditions described. This photograph was taken through the view port, and can be compared with Fig. 12 for perspective. The outer cylinder of the ion source and vacuum vessel are at the same potential. It is interesting to note the weak E X B discharge running about the exposed metal nut which is attached to the now positive center rod (Fig. 4). The indicated vessel pressure at the time this photograph was taken was 1.8X10⁻⁶ mm Hg.

An ion current roughly equal to the arc current divided by the ratio of outer cylinder area to the slit area was metered. Additional extraction potential did not greatly increase this basic ion current. At no time was a factor-of-two increase noted, and this reading was clouded by the drain of the parallel external E X B discharge.

Because ions in this arrangement exhibit the interesting characteristic of inherent self-extraction, it was decided to attempt to determine their exit energy. By operating the arc with nitrogen gas and at low magnetic-field levels, the Faraday cup shown in Fig. 12 could be used without additional acceleration potential. The minimum cup-to-source distance was a little over 3 in., and thus ions with low energy or high charge-to-mass ratio could not be discerned.

The Faraday cup is moved along the 180 deg ion foci by means of a 1/4-20 lead screw. The collimating slit for the cup is 0.1-in.-wide, and thus two turns of the lead screw are needed to move the cup one slit width.

Figure 14 is a spectrum taken with the 1-in. geometry source operating with a positive center rod. The arc voltage was 2 kv and the discharge
Fig. 13. Ion beam emerging from slit in negative electrode.
was run with nitrogen gas. The Faraday cup was used to obtain several bits of information. First, the total ion current vs radius was read by means of a sensitive ammeter, and then the ion energy vs radius was determined by means of an electrostatic voltmeter. Readings were observed for each two turns of the lead screw to determine any fine structure. Changes in the readings were very gradual, however, and thus data were recorded and plotted only at 1/2-in. changes in radius.

A somewhat unexpected action occurred while taking the initial ion-energy spectrum. The ion energy, as indicated by the voltage to which the electrostatic voltmeter would charge, increased with radius to a point at which it dropped quite suddenly, only to increase again as the Faraday travel continued. This action was very reproducible, regardless of the direction of cup travel. The fact that the charge of the electrostatic voltmeter could be reduced indicated a loss mechanism within the Faraday geometry. This loss mechanism was not a function of electrical drain in the metering circuit, because the RC discharge time (1/e) of the meter and Faraday circuit was in excess of 10 hr if the magnetic field and ion source were turned off. It was determined that the loss mechanism was most probably due to a weak EXB drain within the Faraday geometry. The geometry of this cup is not unlike that of the source being tested, and the voltages to which the cup is charged are quite high.

Insofar as the physical distances involved and operating magnetic-field level were known, the expected positions for molecular and atomic ions of nitrogen at energies up to 2 kv were calculated and plotted (Fig. 14). It was then apparent that the electrostatic voltmeter was attempting to indicate the positions of these two ion states quite accurately.

By carefully biasing the Faraday cup to reflect the molecular ions, the amount of the total ion current that was contributed by the atomic nitrogen ions was obtained.

Figure 14 shows that most of the ion current is made up of molecular nitrogen ions. This is perhaps surprising in that the ionization potential for atomic ions is less (N\texttwoeight\textsuperscript{+} = 15.51 ev; N\textlargesix\textsuperscript{+} = 14.54 ev). This indicates that, once ionized, the ion starts moving to the wall and does not remain in the discharge region long enough to suffer additional ionizing collisions.

The ion energy is a broad spectrum ranging from below 200 v to very near full arc potential. The ion-current intensity also shows a broad maximum which starts to decay quite rapidly as the ion energy exceeds 1 kv. This is true for both ion states.

A second nitrogen spectrum was taken with the ion source operating at 5 kv. This increase in arc potential is reflected in the ion-energy spectrum (Fig. 15). The Faraday cup was not biased to determine the magnitude of the atomic-nitrogen ion current; however, molecular ions were detected in excess of 11 in. from the source, which corresponds to an energy of almost 3 kv.
Fig. 14. Nitrogen spectrum with a 2 kv arc at a 10 ma, 1-in. geometry, positive center rod, and \( B \approx 2.75 \) kilogauss.
Fig. 15. Nitrogen spectrum with a 5 kv arc at 8 ma, 1-in. geometry, positive center rod, B = 2.9 kgauss and a gas flow of ~0.1 cm³/min STP.
CONCLUSION

As an ion source for use in an accelerator, the E X B geometry of the type tested seems to offer very little promise. With freedom to choose all parameters, it is probable that a rather efficient discharge could be attained. Complete freedom, however, is generally impossible, because the ion source must operate in an environment that is a function of other machine parameters. Even if one could integrate the source and its surroundings, the inherent difficulty of ion extraction remains. That ions obtain energy within the arc structure is the basic ill of the geometry. Ion extraction is an extremely inefficient process with the center rod negative. With a positive center rod, extraction is no problem, however, and the ions emerge with an extremely broad energy spectrum. Thus only a small percentage of this ion could be employed if monoenergetic ions were required.

The inherent characteristics of this geometry may be useful in circumstances where the requirements differ from above. Because the ions can be made self-extracting, this geometry represents an extremely simple source of hot ions. The geometries tested were not designed to operate at very high voltages, however, a properly designed geometry, pulsed with potentials in excess of 100 kv, might serve as an extremely simple neutron source. No vacuum pump should be required, because deuterons would be actively pumped into the arc structure. Additional gas would be required between pulses to restore the proper operating pressure.

The ability to pump may allow the E X B geometry to be advantageously employed as an ion source for polarized protons. In this case, it is important that all polarized ions that strike surfaces within an arc structure be removed so that they do not return to the discharge region as unpolarized atoms and contaminate the discharge. This one advantage of the E X B geometry may well be of sufficient magnitude to override its disadvantages.

As far as ion-source improvement in general is concerned, however, the results of these tests have been negative. No further work with E X B geometries is planned now.

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