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Highly Ionized, SteadyState Plasma System

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The term involving $\bar{F}_e + \bar{H}_e$ cancels. Also from Eqs. (A10) and (A11)

$$\sum_i F_i + H_i^* = E(u) - \frac{\pi}{k^2} \sum_i \omega_{pi}^2 (\bar{F}_i' E + F_i' \bar{E}),$$

$$F_e + H_e = \frac{F_e}{\epsilon} - \frac{\pi\omega_{pe}^2}{k^2} F_e'(\bar{E} + iE),$$

$$\begin{aligned} T(u) = F_e + \frac{\pi\omega_{pe}^2}{k^2} (\bar{F}_e' - iF_e') & \cdot\left[E - \frac{\pi}{k^2} \sum_i \omega_{pi}^2 (\bar{F}_i' E + F_i' \bar{E})\right] \\ & - F_e + \frac{\pi\omega_{pe}^2}{k^2} F_e'(\bar{E} + iE) \\ & \cdot\left(1 - \pi \sum_i \frac{\omega_{pi}^2}{k^2} \bar{F}_i' - i\pi \sum_i \frac{\omega_{pi}^2}{k^2} F_i'\right) \\ & - \frac{\pi\omega_{pe}^2}{k^2} (\bar{F}_e' E + F_e' \bar{E}) \left(1 - \pi \sum_i \frac{\omega_{pi}^2}{k^2} \bar{F}_i'\right) \\ & + \frac{\pi\omega_{pe}^2}{k^2} \sum_i \frac{\pi\omega_{pi}^2}{k^2} F_i' (\bar{F}_e' \bar{E} - F_e' E) = 0. \end{aligned}$$

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Highly Ionized, Steady-State Plasma System

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A system is described which produces a steady-state helium plasma with greater than 95% ionization. The primary plasma is generated in a modified Phillips ion gauge discharge and diffuses along a magnetic field ($B \sim 1$ kG) through a region in which neutral particles are preferentially removed. In the downstream region a plasma density of $\sim 2 \times 10^{13}$ cm^{-3} and ion temperatures up to 10 eV have been achieved. The present paper describes the over-all physical assembly, the operating characteristics of the system, and the nature of the plasma that is produced. In addition, a discussion of processes believed important in its operation is given.

I. INTRODUCTION

THIS paper and its companion[1] describe a system which produces a highly ionized steady-state plasma whose properties include the following features (based on operation with helium as the parent gas): ion temperature up to 10 eV; nearly complete ionization (> 95%); plasma density 1–2 $\times$ 10^{13} cm^{-3}; small macroscopic electric currents in the working plasma; steady-state operation. The plasma density and percent ionization are in a region of much interest (for example, in controlled fusion research). The density is intermediate as compared with densities of the more familiar steady-state plasmas, e.g., the high-pressure arcs studied in Germany and elsewhere,[2] and the low-density, weakly ionized plasmas of conventional discharge work.[3,4]

The development of the system (earlier code-named P-4) has been reported in a series of unpublished memoranda and reports,[5–14] most of which are available in limited numbers from their authors. In the present article we present a description of the

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[1] A. L. Gardner, W. L. Barr, R. L. Kelly, and N. L. Oleson, Phys. Fluids **5**, 794 (1962).

[2] W. Finkelnburg and H. Maecker, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1956), Vol. 22, p. 254.

[3] L. B. Loeb, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1956), Vol. 21, p. 490.

[4] S. C. Brown, *Basic Data of Plasma Physics* (The Technology Press and John Wiley & Sons, Inc., New York, 1959).

[5] C. M. Aplin, N. W. Carlson, A. L. Gardner, L. S. Hall, W. D. Kilpatrick, and H. H. Vandermark, "Plasma Source Results," UCRL-4857 (1957), or TID-7536, part 2, book 1 (1957), p. 178.

[6] L. S. Hall and A. L. Gardner, "Preferential Pumping and its Application to the P-4 Experiment," UCRL-4905 (1957).

[7] C. M. Aplin, A. L. Gardner, L. S. Hall, and H. H. Vandermark, "P-4 Plasma Source," UCRL-5113 (1958), or TID-7558 (1958), p. 463.

[8] A. L. Gardner, L. S. Hall, and D. E. Edwards, Bull. Am. Phys. Soc. **5**, 313 (1960).

[9] N. L. Oleson and D. M. Gall, Bull. Am. Phys. Soc. **5**, 313 (1960).

[10] W. L. Barr and R. L. Kelly, Bull. Am. Phys. Soc. **5**, 314 (1960).

[11] A. L. Gardner, W. L. Barr, D. M. Gall, L. S. Hall, R. L. Kelly, and N. L. Oleson, "P-4, a Steady-State Plasma Source," UCRL-5904 (1960).

[12] A. L. Gardner and N. L. Oleson, Bull. Am. Phys. Soc. **6**, 190 (1961).

[13] L. S. Hall, A. L. Gardner, R. L. Kelly, and N. L. Oleson, Bull. Am. Phys. Soc. **6**, 201 (1961).

[14] A. L. Gardner, "Diagnostic Measurements of a Highly Ionized Steady-State Plasma," Second Symposium on the Engineering Aspects of Magnetohydrodynamics, Philadelphia, March 9–10, 1961.

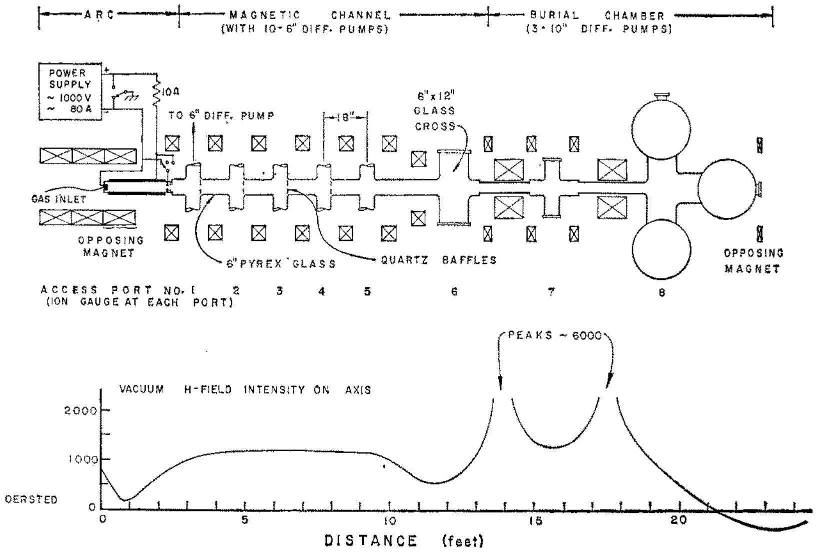

FIG. 1. Schematic drawing of the system (plan view).

over-all physical assembly, the operating characteristics of the system, and the nature of the plasma that has been achieved, along with a discussion of what we believe to be the important processes in its operation as a plasma source. An account of the detailed diagnostic work that went into the establishment of the properties of the plasma is given in the companion paper.[1]

II. GENERAL FEATURES

The basic idea of the experiment is to achieve a highly ionized plasma by preferentially eliminating the neutral particles from a dense plasma in which they initially predominate. This is accomplished in steady-state fashion by allowing the charged particles to diffuse along magnetic field lines through a region where the neutral particles may be pumped away with diffusion pumps or may become ionized by electron collisions in the plasma (ion pumping). At the downstream end, one attempts to reflect as much of the plasma as possible and to dispose of the rest without causing an undue rise in neutral-particle density.

The system in its present form is shown sche-

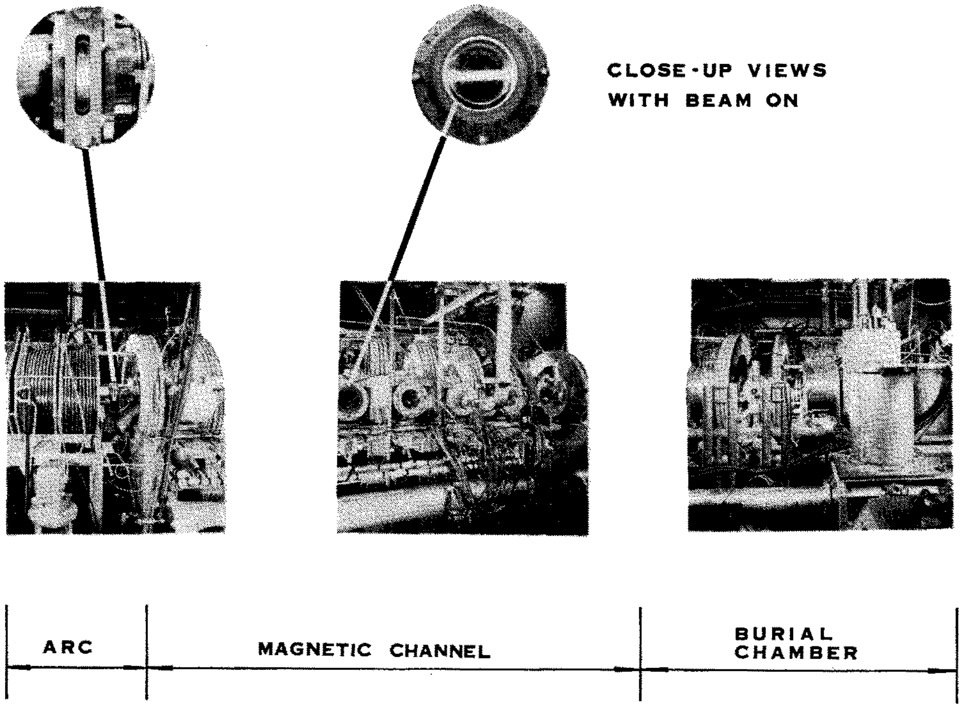

FIG. 2. Composite photograph of the system.

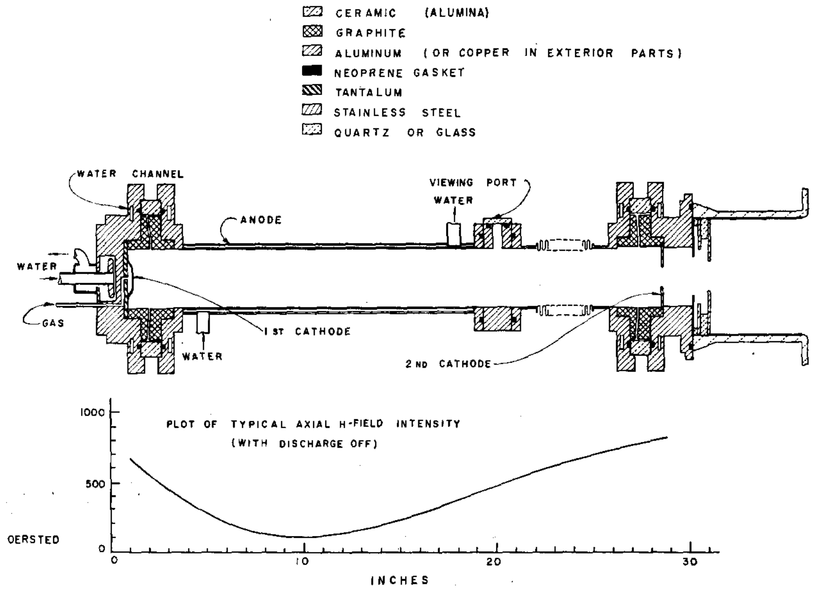

FIG. 3. The arc-discharge region.

matically in Fig. 1 and photographically in Fig. 2. There are three principal elements of the physical assembly: (a) *the discharge region*, which is the prime source of plasma for the device; (b) *the magnetic-channel region*,[15] in which the plasma is guided along magnetic field lines ($\sim 10^3$ Oe) past a series of five pumping stations,[16] to preferentially remove neutral particles from the incompletely ionized plasma[6]; and (c) *the burial chamber*, for disposing of ions leaking out of the downstream end of the system.[17]

The system has normally been run on helium. The base pressure of impurity gases is about 10^{-6} mm Hg in the magnetic-channel region and drops to about 10^{-7} mm Hg in the burial chamber. When running, the pressure of neutral helium from port 5 to the burial chamber (see Fig. 1) is typically in the low 10^{-5} mm Hg range, having dropped from a few microns in the discharge chamber. For use of the system as a plasma *source*, one is most interested in the characteristics of the plasma in the vicinity of ports 5 and 6 of Fig. 1, and in this region one is able to obtain a quiescent plasma[18] of greater than 95% (probably greater than 98%) ionization with a measured electron density of $1\text{–}2 \times 10^{13}$ particles/cm^3. The electron temperature (from Langmuir-probe measurements) is about 20 eV on the axis of the plasma column and decreases to around 8 eV at a position 1 cm from the axis. (Spectroscopic observations indicate that an appreciable number of electrons with energies of at least 77 eV occur in the plasma core.[10]) Depending upon conditions of operation and axial position in the channel, ion temperatures up to 10 eV (measured by Doppler broadening) can be achieved in the 1- to 2-cm-diameter core of the plasma column.

III. ARC DISCHARGE

The prime source of plasma for the system is the arc chamber shown in Fig. 3. This operates as a modified PIG (Phillips Ion Gauge) discharge[19] and in many respects resembles a scaled-up version of von Ardenne's Duoplasmatron.[20]

At the gas-input end of the discharge chamber there is a primary cathode of 0.020-in. tantalum with an active diameter of about 1.3 in. During operation, ion bombardment maintains this cathode at a brightness temperature of approximately 2500°K. The second "cathode" at the opposite end

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[15] It is in this region that most of the diagnostic measurements are made, and the cylindrical rod of plasma occurring therein is referred to as the *plasma column*.

[16] Each consisting of two 6-in. oil diffusion pumps.

[17] The burial chamber consists of a pair of magnetic mirrors, to reflect as much of the plasma as possible, together with three 10-in. oil diffusion pumps to remove the neutrals formed when the plasma which leaks past the mirrors recombines at the walls of the chamber. (The opposing magnet shown in Fig. 1 protects the quartz window at the end of the assembly by dispersing this stray plasma.)

[18] That is, no large electric currents, no marked turbulence, etc., appear in the plasma column. This is in contrast with what can occur, for instance, in the discharge chamber proper.

[19] J. Backus, in *Characteristics of Electrical Discharges in Magnetic Fields*, edited by A. Guthrie and R. K. Wakerling (McGraw-Hill Book Company, Inc., New York, 1949), Chap. XI. See also R. G. Meyerand, Jr. and S. C. Brown, Rev. Sci. Instr. **30**, 110 (1959).

[20] M. von Ardenne, *Tabellen der Elektronenphysik, Ionenphysik, und Übermikroskopie*, in two volumes (VEB Deutscher Verlag der Wissenschaften, Berlin, 1956), especially Vol. 1, p. 544.

of the 3-in.-i.d., water-cooled aluminum anode section is an 0.080-in.-thick tantalum diaphragm, of 1-in. i.d., which runs cold and through which the plasma diffuses into the magnetic-channel region. This electrode, when tied to the primary cathode, carries about 10% of the total operating current,[21] although its action is not essential to the operation of the system after the discharge is initiated (since it may then be allowed to float electrically or may even be connected to the anode without appreciably changing the basic features of the central core of the plasma column).

For ease of starting and as a "keep-alive" for the discharge, low-power rf at about 25 Mc was previously applied between the anode and the cathode. Such a modification is not necessary, however, and since the presence of about 30 rms volts of rf reduced the average operating voltage by about 10 volts at typical values of anode current and otherwise tended to interfere with diagnostic measurements, its use has been discontinued.[22]

The axially symmetric external magnetic field in the discharge chamber is not uniform (see Fig. 3). At the primary cathode it has an intensity of 500–600 Oe, decreasing to a minimum value of about 100 Oe at a position approximately 8 in. in front of the primary cathode, and rising thereafter until it becomes about 1100 Oe in the magnetic-channel region (cf. Fig. 1).[23]

The discharge has usually been operated with an anode voltage of 150–175 V and a total current of around 80 A. Helium is introduced through the primary cathode assembly at a flow of 200–400 micron-liters per second, although the "effective" rate of helium input into the plasma is about 10 times this figure, since the neutral atoms produced when ions recombine at the cathode constitute a large virtual source. In particular, approximately 10 A of ions (at 150 V) must flow to the primary cathode to account for the power it dissipates, and this current of recombining singly ionized helium is equivalent to 2000 micron-liters per second of helium gas.

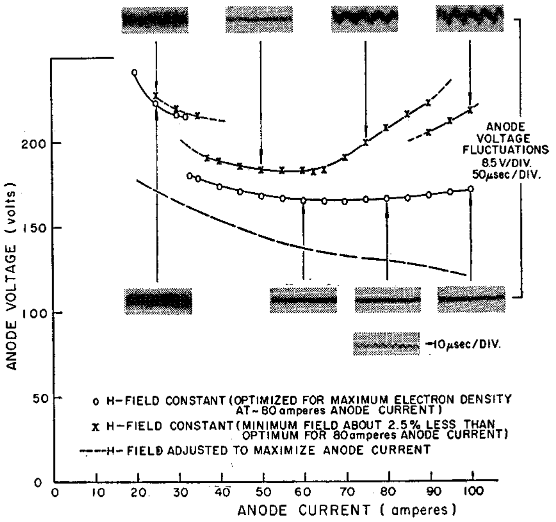

FIG. 4. Voltage-current characteristics of the arc discharge. Helium-gas flow is 340 micron-liters/sec; conductivity of the second cathode for room-temperature helium is 160 liters/sec.

A typical current–voltage characteristic of the operating discharge is indicated by the open circles in Fig. 4. To obtain this curve, the magnetic field in the discharge chamber was optimized at an operating current of 80 A so as to maximize the plasma density in port 6 (see Fig. 1).[24] The magnetic field was then held constant while the anode supply voltage was varied over a wide range.

The effect of small changes in the magnetic field is typified by the characteristic indicated by crosses in Fig. 4. This plot was obtained by a 2% reduction in the current in the center coil of the three arc-chamber magnets shown at the left of Fig. 1. This in turn caused the vacuum magnetic field at the position of field minimum to be reduced about $2\frac{1}{2}\%$.

The dashed line in Fig. 4 shows the operating conditions that occur if the current in the center arc magnet is adjusted at each anode-power-supply setting to maximize the operating current. This maximum-current condition is achieved with the magnetic field slightly higher (at most a few percent) than that required for the "optimum" condition. With still higher fields, not only does the discharge current decrease, but its operation tends to become

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[21] This current is mostly drawn to the downstream side, i.e., it is due to the presence of plasma in port 1 (see Fig. 1) which has diffused radially out to where the ions can come back along magnetic field lines into the second cathode. The magnetic field inside the arc chamber keeps ions from going directly to this electrode (see Sec. IV).

[22] However, the use of the rf under certain conditions materially increases the insulator life. Depending to some extent on the procedures for starting the discharge when the rf is not used, sparking or arcing between the anode and cathode can cause carbon dust to be deposited on the ceramic insulators so that eventually breakdown occurs and the insulators have to be cleaned or replaced.

[23] In order to bring the primary cathode up to operating temperature, a uniform magnetic field is used in the arc chamber at startup. Under these conditions the arc operates in the mode of the conventional magnetically contained PIG discharge (see reference 19). Attainment of the desirable characteristics obtained in the normal operation of the present system does not appear to be possible with a cold cathode.

[24] Actually, the criterion used was the adjustment which provided maximum attenuation of 8-mm microwaves at port 6. Because of possible diffraction effects due to the small size of the dense plasma core (diameter 1–2 cm) this may or may not correspond to a true density maximization.

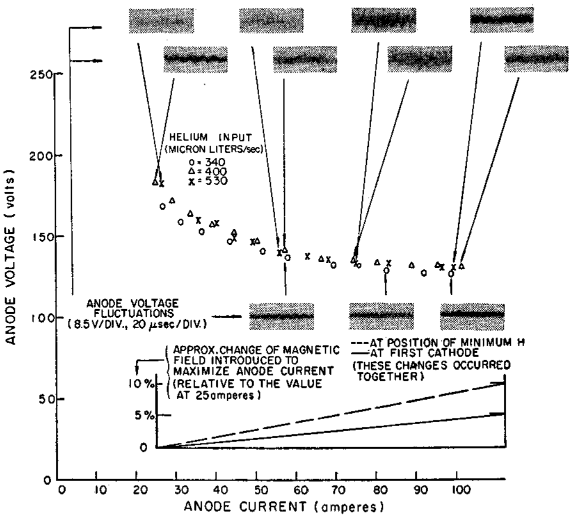

FIG. 5. Voltage–current characteristics of the arc discharge. (Magnetic field adjusted to maximize anode current.) Inset shows approximate change of magnetic field introduced to maximize anode current (relative to the value at 25 A).

unstable. The change in the magnetic field necessary to obtain the condition of maximum current, relative to a maximization at 25 A, is shown in Fig. 5.

Figure 4 also includes oscilloscope photographs of the anode voltage fluctuations which were present under the indicated conditions. Each picture shows many traces that were synchronized with the coherent fluctuations (when these were present). Large-amplitude oscillations were associated with non-optimum conditions—in some cases the amplitude almost equalled the average anode voltage. Near optimum a lower amplitude fluctuation is usually present which is reasonably coherent and occurs at frequencies in the range of 50–100 kc, depending on operating conditions. The photograph with the expanded time scale in Fig. 4, associated with operation at 75 A, shows such an oscillation. Usually, as the optimum adjustment of the magnetic field is approached, the oscillations decrease in amplitude and lose coherence (although they tend to be most coherent just slightly off "optimum"), sometimes becoming undetectable. Typically, however, their amplitude is somewhat less than 3% of the anode potential in normal operation. The frequency of the oscillations increases with increase of pressure of the parent gas (helium) and decreases with increasing magnetic field intensity at the position of field minimum (which simultaneously decreases the magnetic field gradients in the discharge chamber).

The effects of varying the input gas flow are shown in Fig. 5, and it is seen that the maximum-current characteristic (dashed curve of Fig. 4) is relatively unaffected. Although the gas flow produces no sensitive behavior here, it does affect the amount of neutral helium in the plasma column downstream; for this reason the system is ordinarily run at the lowest input flow consistent with stable operation.

IV. QUALITATIVE THEORY OF OPERATION

In this section we summarize qualitatively the mechanisms which we believe to be important to the operation of the system as a plasma source, and which we put forward as a tentative explanation of its behavior. The arc discharge itself has some of the features of the more conventional (magnetically contained) PIG discharge,[19] i.e., electrons are emitted either thermionically or as secondaries from the hot cathode, move out into the discharge proper, and are reflected at the opposite end back into the center of the discharge. However, in the present assembly any reflection at the open end occurs not as a result of an electric field but by the mirroring action of the increasing magnetic induction. In the region near the minimum magnetic induction the plasma material pressure (nkT) is too great to be supported by the magnetic field (it takes an estimated 130 Oe to provide a balance). Thus, except as they diffuse across the magnetic field (a comparatively slow process), the electrons are relatively free to move radially toward the anode only in this vicinity. How the electrons actually move out, however, is a complicated question which we will next examine.

If the plasma were a perfect diamagnet, the magnetic field would be completely canceled out in the region of minimum magnetic field and there would be no barrier whatsoever to an electron's radial motion. However, van Leeuwen's theorem[25] tells us that wall effects tend to cancel out the diamagnetism (e.g., by Hall currents resulting from pressure gradients or electric fields near the anode) so that the magnetic field does not vanish and the radial motion of the electrons is consequently inhibited. Since the energy density of the plasma is slightly greater than that of the vacuum magnetic field, however, there is a tendency for a rather pronounced turbulence to occur in this region, enabling the electrons to be carried to the anode at a rate intermediate to that which would result with ordinary cross-field diffusion and that which

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[25] Miss J. H. van Leeuwen, Dissertation, Leiden (1919) or J. Phys. **2**, 361 (1921); quoted in J. H. Van Vleck, *Theory of Electric and Magnetic Susceptibilities* (Oxford University Press, London, 1932), p. 94 ff., especially p. 100.

would occur if no magnetic field were present at all. In our particular case, turbulence can really be a desirable feature (as long as it does not get out of hand) since it may also provide a way of heating the ions at the expense of the fast electrons coming from the cathode, a cooperative mechanism which we can expect to be more efficient than if we were to wait for this thermalization to occur through Coulomb collisions alone.[26] Experimentally, the actual adjustment of the magnetic field appears to be rather critical,[27] as one would indeed expect on the basis of the above picture, since a really pronounced turbulence should occur only for magnetic fields in which the pressure balance is tipped just slightly in favor of nkT as compared to $H^2/8\pi$. Moreover, the adjustment of the magnetic-field *gradient* may be fairly important in order that a sufficient number of the faster electrons be kept in the arc chamber for the purpose of ionizing the neutral helium, rather than dissipating their energy in the channel, for example through excitation of He II.[28]

A further real advantage of the present system is related to the way in which plasma leaks to the outside and into the areas more useful for experimentation. In our case, the "hole" through which particles diffuse is in velocity space, i.e., a particle's velocity must be properly oriented in order to get up the magnetic hill, and the size of the hole is essentially independent of the radial position of the particle. This means that the effusing plasma is effectively a sample of that throughout the whole discharge. Hence it tends to be hotter than in the case of conventional extraction, where the plasma comes out through small holes near the edges of the discharge and thus is subjected much more to the cooling effects of the walls.

As the plasma moves into the magnetic channel, the diameter of the plasma column is principally determined by the size of the anode bore as it maps along a flux tube from the point inside the discharge chamber where the magnetic field starts to take over, i.e., at the end of the region of turbulent diffusion. From this point on, particles can move radially outward only by cross-field diffusion, which as previously noted is relatively slow.

The actual means of radial diffusion is rather complicated and is probably of a hybrid nature. In the core of the plasma column (that part which maps magnetically into the discharge region) one expects a Simon-type diffusion[29] because of the large number of fast electrons (> 50-eV) whose mean free path is of the order of the length of the system and which therefore provide a high conductivity along the magnetic field lines to the turbulent region of the discharge, in which radial motion is relatively uninhibited. At the edge of the plasma column core ($\frac{1}{2}$–1 cm from the axis) there is a large gradient of electron thermal energy and, since the mean free path drops rapidly with the temperature, at larger radii the electrical short essential to Simon's diffusion mode is in effect removed and the diffusion may be expected to be more in the nature of an ambipolar process.[30]

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the key roles others have played in bringing this plasma source into being. In particular, a great deal of the diagnostic work which has materially aided the understanding of the system has been carried out in collaboration with W. L. Barr (spectroscopy), N. L. Oleson (probe studies), and R. L. Kelly (vacuum ultraviolet spectroscopy) whose work is reported in the companion paper.[1] In the initial phases of the work, W. D. Kilpatrick and C. M. Aplin collaborated in the design and testing of the arc chamber, and R. F. Post, D. E. Edwards, and N. W. Carlson made valuable contributions toward the initial design of the over-all system. The efforts of W. J. Stroh and previously H. H. Vandermark in keeping the com-

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[26] Because of the difficulties involved, no experiments have yet been performed which would definitely establish the presence and extent of such turbulence. Moreover, not all of the heating of ions is done by this mechanism in the present system, since the ions are observed to be heated significantly by the electrons as the former diffuse along the 5-m distance from the source to the burial chamber.

[27] Because of this sensitivity, it is necessary to provide well-filtered dc power to all magnets that appreciably contribute to the magnetic field in the discharge chamber, as even a very small amount of ripple can cause undesirable behavior of the discharge.

[28] Instabilities other than those of hydromagnetic origin associated with the inequality $8\pi nkT/H^2 > 1$ as discussed above may also occur in the discharge, and cannot be ruled out with our present experimental knowledge of its behavior. A possible effect, for example, might be the presence of instabilities of the "two-stream" type [D. Bohm and E. P. Gross, Phys. Rev. **75**, 1851 (1949)] near the cathode. Although the maximum energy density of the two-stream motion is less than 1% of that of the plasma in this vicinity, so that pronounced turbulent effects are unlikely and there should be no direct effect on the plasma, such instabilities may still contribute to an effective scattering of the fast electrons coming from the cathode. This, in turn, could influence the number of fast electrons reflected by the magnetic-field gradient at the second cathode which, as we noted, is important in determining the balance between ionizations and losses in the discharge. Such effects need not be postulated at present for an explanation of the discharge behavior, however, and so are not considered further.

[29] A. Simon, Phys. Rev. **98**, 317 (1955).

[30] W. P. Allis in *Handbuch der Physik,* edited by S. Flugge (Springer-Verlag, Berlin, 1956), Vol. 21, p. 397.

plicated equipment in running condition have been invaluable, and their suggested improvements have resulted in greatly increased reliability of operation.

The continued interest and encouragement given by Drs. C. M. Van Atta and R. F. Post are gratefully acknowledged.

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Diagnostic Measurements on a Highly Ionized, Steady-State Plasma

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Techniques and results are given for various measurements made on a highly ionized helium plasma in a steady-state plasma system (which employs a longitudinal magnetic field of approximately 1 kilogauss). Neutral-particle pressures ranged from about 3×10^{-4} mm Hg near the source to about 10^{-5} mm Hg in the downstream region. Spectroscopic measurements showed principal impurities were C, N, and O ions (up to C^{3+}, N^{4+}, and O^{4+} states). Doppler broadening measurements of He^+ $\lambda 4686$ revealed ion temperatures up to 10 eV. Probe measurements indicated electron temperatures up to 20 eV and maximum ion densities of a little over 10^{13} cm^{-3}. Microwave transmission measurements (at $\lambda = 4$ mm and 8 mm) gave supporting evidence that the electron density exceeds 10^{13} cm.

I. INTRODUCTION

THIS paper recounts various measurements that have been made on a helium plasma produced in the system previously described in the companion paper.[1] A plan view of the system is shown at the top of Fig. 1 on which are indicated the positions where the measurements were made. An axial magnetic field of about 1 kilogauss extends throughout most of the region and no electric fields are deliberately impressed outside of the discharge chamber (shown at the left end of the sketch).

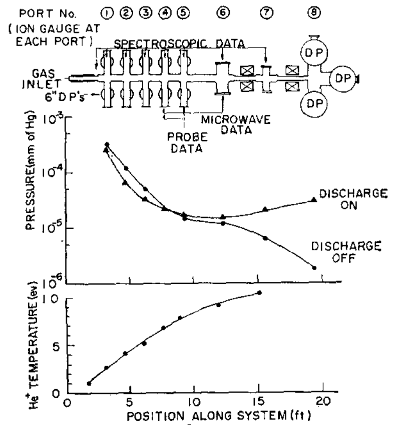

FIG. 1. Observation positions along the system and axial variation of neutral-helium pressure and helium-ion temperature.

The reported measurements do not represent a consistent set for a particular operating condition of the system, since they span a considerable period of time. Nevertheless, the general features of the plasma have proved to be notably reproducible and the data given are representative of typical operation.

II. NEUTRAL DENSITY ALONG THE SYSTEM

Eight ionization gauges (type VG-1A/2, made by Central Electronics Manufacturers, Inc.) were used to determine the neutral-particle distribution along the system. These were mounted vertically above the system axis at each port except 6 and 7 (Fig. 1), where they were mounted on the side flanges.

The gauges at ports 1 through 7 were magnetically shielded so that the presence of the magnetic field caused less than 3% change in the ion-current reading. The gauge at port 8 was unshielded, but its reading was affected less than 15% by the field.

In order to correct for individual variations in sensitivity, the ion gauges were compared against each other in a semistagnant helium atmosphere. This was done by closing off all pumps except that at one side of port 1 and adjusting the input helium flow to yield a pressure well above the base pressure. A typical set of readings is shown in Table I.

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[1] L. S. Hall and A. L. Gardner, Phys. Fluids 5, 788 (1962).