Title
SOME MEASUREMENTS ON A HIGH-VACUUM HIGH-SPEED ION PUMP

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John Stuart Foster, Jr.

(Thesis)

August 17, 1953

Berkeley, California

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John Stuart Foster, Jr.

Radiation Laboratory, Department of Physics,
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ABSTRACT

A vacuum pump has been developed in which gas particles are ionized and delivered to a higher pressure region by magnetic and electric fields. The active element is a discharge which is collimated by a magnetic field of about 1300 gauss. The discharge is terminated at one end by a hot tungsten cathode and at the other end by a cold reflecting cathode. Gas enters the discharge through an open-wound helix section at anode potential. A current of 5000 amperes is passed through the helix to maintain the axial magnetic field in this region. Ions formed in the discharge are confined radially by the magnetic field and are delivered by the normal plasma gradient to the cathode where they are neutralized and can be removed by a backing pump. The pressure in this region can be as high as 10^{-2} mm Hg. No backing pump is required for gas flows of less than 0.02 cc/sec N.T.P., except for the noble gases. Pumping speeds of 3000 to 7000 liters per sec. and a base pressure of 10^{-6} mm have been obtained. Measurements have been made to determine some of the factors that limit the performance. Operation is automatic, and continuous running has been obtained for periods of at least two weeks.

SOME MEASUREMENTS ON A HIGH-VACUUM HIGH-SPEED ION PUMP

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I INTRODUCTION

The possibility of producing a vacuum by electronic means has been considered for many years. The nature of the problem is such that until the present no scheme has been evolved that showed signs worthy of serious experimental investigation. As a result, most of the literature on the subject is contained in the patent files. Reference 1 lists eighteen of the more pertinent patents which contain a variety of ingenious ideas related to the various problems. However, the pump to be discussed below differs radically from those investigated in the past.[2] Nevertheless, the features that make it successful are easily understood in terms of simple discharge theory, and it is only the combination of well known principles that is new.[3]

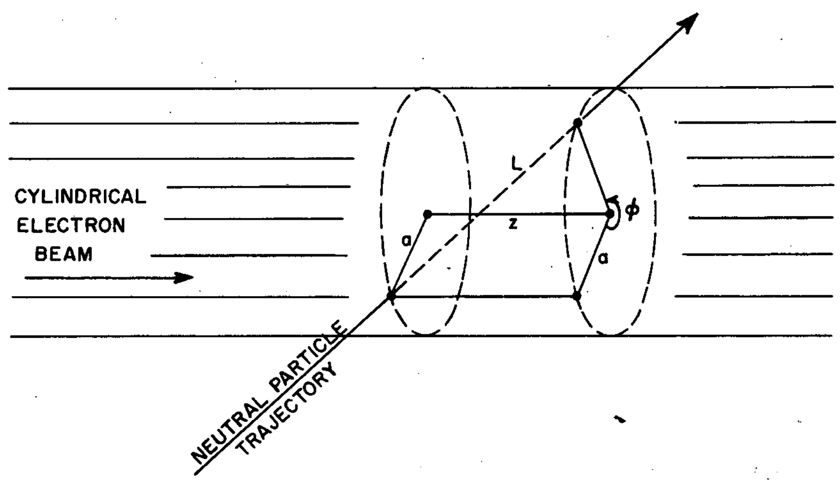

CYLINDRICAL
ELECTRON
BEAM
L
z
a
a
φ
NEUTRAL PARTICLE
TRAJECTORY
MU-6055

Fig. 1

II NATURE OF PROBLEM

This introductory discussion considers a few of the basic problems and magnitudes involved. However, since a successful pump has been developed, the values used in the calculations approximate a situation that can be realized. In general, the idea is to ionize the residual gas in a volume by electron impact and then to remove the ions by the application of electric or magnetic fields.

The first problem is to provide a current of electrons that is sufficient to ionize molecules at a rate that would be useful. We can calculate roughly the efficiency of a given electron current. Consider a uniform beam of electrons traversing a low-pressure volume (Fig. 1). Suppose we consider the beam to be infinitely long and have a diameter equal to 2a. If a neutral particle has a mean free path λ_i in the column before being ionized, then the probability that it will traverse a length ℓ in the column, and be ionized, is $(1 - e^{-\ell/\lambda_i})$. If we assume the incident flux of neutrals is independent of direction, then an expression for the probability that particles incident from all directions will be ionized is given by

$$\overline{P}_i = \frac{a^2}{2\pi} \int_{-\infty}^{\infty}\int_{0}^{2\pi} \left[1 - e^{-\frac{\sqrt{z^2 + 2a^2(1-\cos\phi)}}{\lambda_i}} \right] (1-\cos\phi \, d\phi \, dz)$$

where z and ϕ are cylindrical coordinates relating the points of entrance and exit of a particle's trajectory through the electron beam. Numerical integration was performed with the following result.

If $\lambda_i = 6a$ (Three diameters)

Then $P_i = 0.3$

The total electron current i_e required for this case can be calculated. Suppose the neutral particles are nitrogen molecules, and since the probability of ionization varies with electron energy[4], suppose we choose the most favorable electron energy, ~200 volts. This gives an ionization cross section $\sigma_i = 3.1 \times 10^{-16}$ cm^2. The mean free path is then

$$\lambda_i = \frac{\pi a^2 v_o}{\sigma_i i_e}$$

and v_o the arithmetic average neutral-particle velocity. The total electron current is then

$$i_e \approx 27 \text{ Amps} \qquad \text{for} \begin{cases} a = 2\text{cm} \\ \lambda_i = 6a. \end{cases}$$

There are two striking things about this result. First of all, since the beam ionizes 0.3 of the incident neutral particles, it means that the column represents a very efficient "sink" for molecules. This ionization efficiency can be related to the more familiar notion of pumping speed. If the incident flux density of neutrals entering the column is F, we have

$$F = 1/4\, n v_a \qquad \begin{matrix} n = \text{neutral particle density} \\ v_a = \text{arithmetic average velocity} \end{matrix}$$

One may imagine that each neutral particle is the center of a cell whose volume is just = 1/n. Then the effective volume that enters the column per unit area per second is

$$S = (1/4\, n\, v_a)\,(1/n)$$

$$= v_a/4 \qquad \text{where } v_a = \sqrt{8KT/\pi m}$$

This gives the familiar "aperture speed" of 11.7 liters/cm^2/sec or 75.28 liters/in^2/sec for air at 25°C. Since 0.3 of all molecules entering the column are ionized, then each square centimeter of the electron beam "surface" consumes molecules at the rate of 3.5 liters/sec. Hence the 4-cm-diameter column has a speed of 44.1 liters/sec for each centimeter of length.

The second striking thing about the calculation is that we require a 27-ampere beam of electrons with an energy of 200 electron volts. The electron space-charge potential of such a beam is about 6.7 kv and hence it would not be stable without additional forces. Also, because the density is high, one would need a fine-mesh grid at 200 volts, placed about 0.06 cm from a flat cathode and covering an area of 12.5 sq. cm, in order to obtain the required emission current. Such a grid could of course be constructed, but would be quite impractical.

Both these difficulties are overcome if positive ions are present to neutralize the electron space charge. Indeed, these positive ions could be just those ions resulting from the ionization of the neutral molecules entering the column.

The plasma that results from this neutralization is a medium containing a high density of ions, hence only a very slight electric gradient is required within it to maintain current flow. As a result, most of the voltage drop appears across the sheath that is formed between the plasma and filament. Since the positive ions falling across this sheath are moving relatively slowly, each ion can neutralize many electrons; and in fact the maximum electron-emission current is related to the positive-ion current i_+ by[5]

$$i_e = \gamma \sqrt{\frac{m_+}{m_e}}\; i_+ ,$$

in which γ is a factor that depends on the condition of the filament ($0.1 < \gamma < 1$). In this way the plasma sheath can take the place of an accelerating grid, and the electron emission is mainly limited by the positive ion current to the cathode. Nevertheless, a further development is required to offset a serious limitation of efficiency which naturally occurs at low pressures. As the gas pressure is continuously lowered, reduced ionization efficiency results from the following cycle: lower ion production, lower ion current, lower electron emission, and a further reduction in ion production. This was one of the main limitations experienced by earlier workers. By a suitable geometrical arrangement, the problem is solved, in the present case, by deliberately injecting gas in the vicinity of the cathode, and the geometry is designed so that the gas pressure elsewhere is not increased.

Finally, some method must be found to extract the positive ions. One method is to direct them against the surrounding walls; in this way some may be removed by absorption or chemical reactions. This is, of course, the familiar phenomenon of "electrical cleanup"[6], which is observed when a discharge is run in a sealed-off vacuum system. The method requires that the walls be in good condition, and is not so efficient for the noble gases. At present R. G. Herb[7] and his associates are working on a vacuum pump using a continuous getter that is distilled onto the walls of the vacuum system. The walls then trap some molecules directly and, in the case of noble gases, an attempt is being made to ionize the atoms and accelerate the ions so that they will be driven into the walls. The experimental work to be described below, however, is mainly based on an attempt to displace the gas from a region of low pressure to one of higher pressure, and to maintain the pressure differential by the discharge itself.

In preliminary work a spherical lens was used to focus the ion beam into an exit tube. This method had been used by several investigators and suffers from the following faults. The lens accelerates only those ions which diffuse to it. This means that only a fraction of the ions are pumped. Secondly, the back diffusion from the high-pressure exit tube seriously limits the effective pumping speed and the pressure drop that can be maintained across the lens. These difficulties can be greatly reduced by the use of an axial magnetic field and the proper geometry. The pump to be described below is the result of measurements made on five different ion pumps constructed during the course of development.

III GENERAL DESCRIPTION OF THE EXPERIMENTAL PUMP

A basic arrangement of the pump is shown in Fig. 2. The drawing has been divided into a central section and two end sections. Gas is removed from the low-pressure center section and delivered to the higher-pressure exit sections. The active element in this operation is an intense discharge, which is collimated by a magnetic field and extends from a hot cathode to a cold reflecting cathode. This type of discharge was first used with cold cathodes by F. M. Penning[8], and with a hot cathode by A. T. Finkelstein[9]. Its essential characteristic is an efficient refluxing of the electrons. Electrons emitted from the hot filament are accelerated across a plasma sheath into the discharge, where the magnetic field confines their paths to tight helices, permitting them to pass through the center section and be returned by the reflecting cathode. Thus, the electrons oscillate back and forth through the discharge, losing their energy by excitation and ionization until they are collected on the anode walls. The positive ions made during this process have a very low velocity compared to the electrons and a short mean free path; hence a positive space charge develops in the column. This space charge field moves the positive ions toward the cathode.

We have, then, a discharge containing a large flux of energetic electrons passing through the center section. Hence, gas molecules entering the discharge have a very good chance of being ionized before leaving the discharge column. The ionized molecules are then laterally confined by the magnetic field and delivered to the cathode by the plasma gradient. By means of this process, the gas pressure in the central region is reduced until an equilibrium is reached with inverse processes (which are discussed in section E).

On reaching a cathode, positive ions have several possible alternatives open to them. Some ions combine chemically with the cathode material. Other ions are neutralized at the cathode surface, and then, as neutral particles, they are unaffected by the magnetic field and can leave the discharge and enter the forevacuum system. Neutral particles attempting to travel back up the discharge are ionized again and returned to the cathode. Other neutral particles leaving the cathode are trapped on wall surfaces facing the cathode. These surfaces are constantly receiving cathode material, which is sputtered onto them from the cathode; this sputtered cathode material is the "getter".

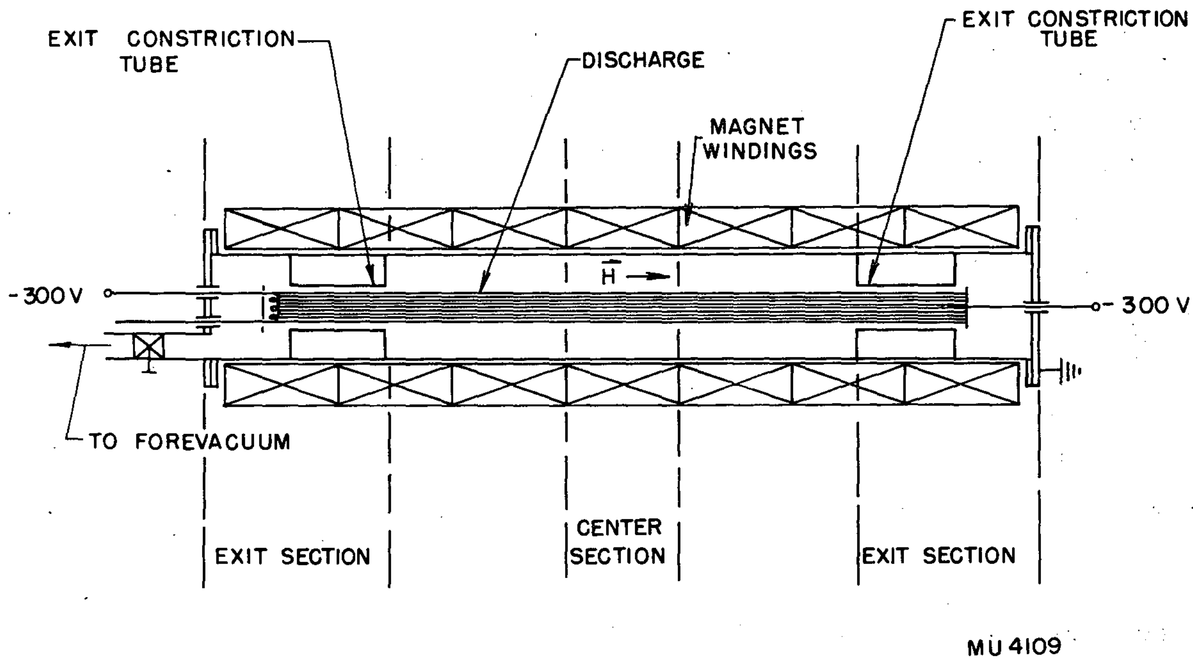

EXIT CONSTRICTION
TUBE
DISCHARGE
EXIT CONSTRICTION
TUBE
MAGNET
WINDINGS
H
-300 V
300 V
TO FOREVACUUM
EXIT SECTION
CENTER
SECTION
EXIT SECTION
MU 4109

Fig. 2

The rate at which air can be removed by adsorption and chemical action is such that for steady operation under normal loads the forevacuum system can be closed off. Adsorption and chemical action do not occur to a great extent when inert gases are used.

The maximum electron current is limited by the positive ion current across the cathode sheath. At low pressures in the central region of the pump, the positive ion supply is insufficient to maintain a discharge of the desired characteristics (10 to 20 amperes at 300 to 400 volts), and it is necessary to introduce gas through a leak into the cathode region. This gas leak is adjusted to keep the pressure in the hot cathode region above 3×10^{-4}mm. The long anode constriction tube near the cathode is designed to confine the high gas pressure to the cathode region. The diameter of this tube is just slightly greater than the discharge itself, hence gas that might diffuse through the tube is ionized and returned to the cathode region. In this way, a large flux of energetic electrons can be sent through the central region even at the lowest gas pressure in the central region of the ion pump. While a minimum exit pressure is necessary to maintain a discharge for light pumping loads, any increase beyond that minimum merely increases the ion bombardment of the cathode. This ion pump is usually operated with an exit pressure of 3 to 5×10^{-4}mm, although exit pressures as high as 10^{-2}mm have been used. Within the range of exit pressures mentioned, the lowest central pressure may vary from 0.8×10^{-6} to 6×10^{-6}mm, and depends on the pump condition, electrical adjustments, and the gas being used.

Electrical and Mechanical Description

The apparatus is represented in Figs. 3 through 8.

Backing Pump

The forevacuum pressure is maintained, when required, by a mercury diffusion pump followed by a mechanical pump. Although the ion pump could be backed directly by a good mechanical pump, the addition of a diffusion pump extends the capacity and pressure range that can be studied. Liquid-nitrogen traps are used on each side of the diffusion pump to reduce the contamination by mechanical and diffusion pumps. Provision was made to pump on either or both ends of the ion pump with or without diffusion pump. It was found that single-ended backing is sufficient.

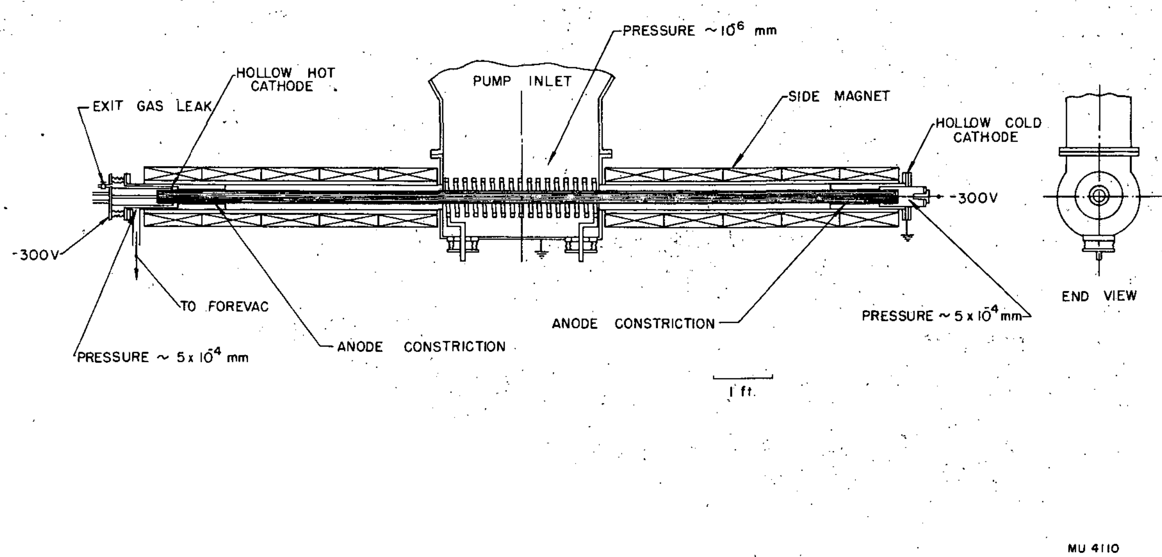
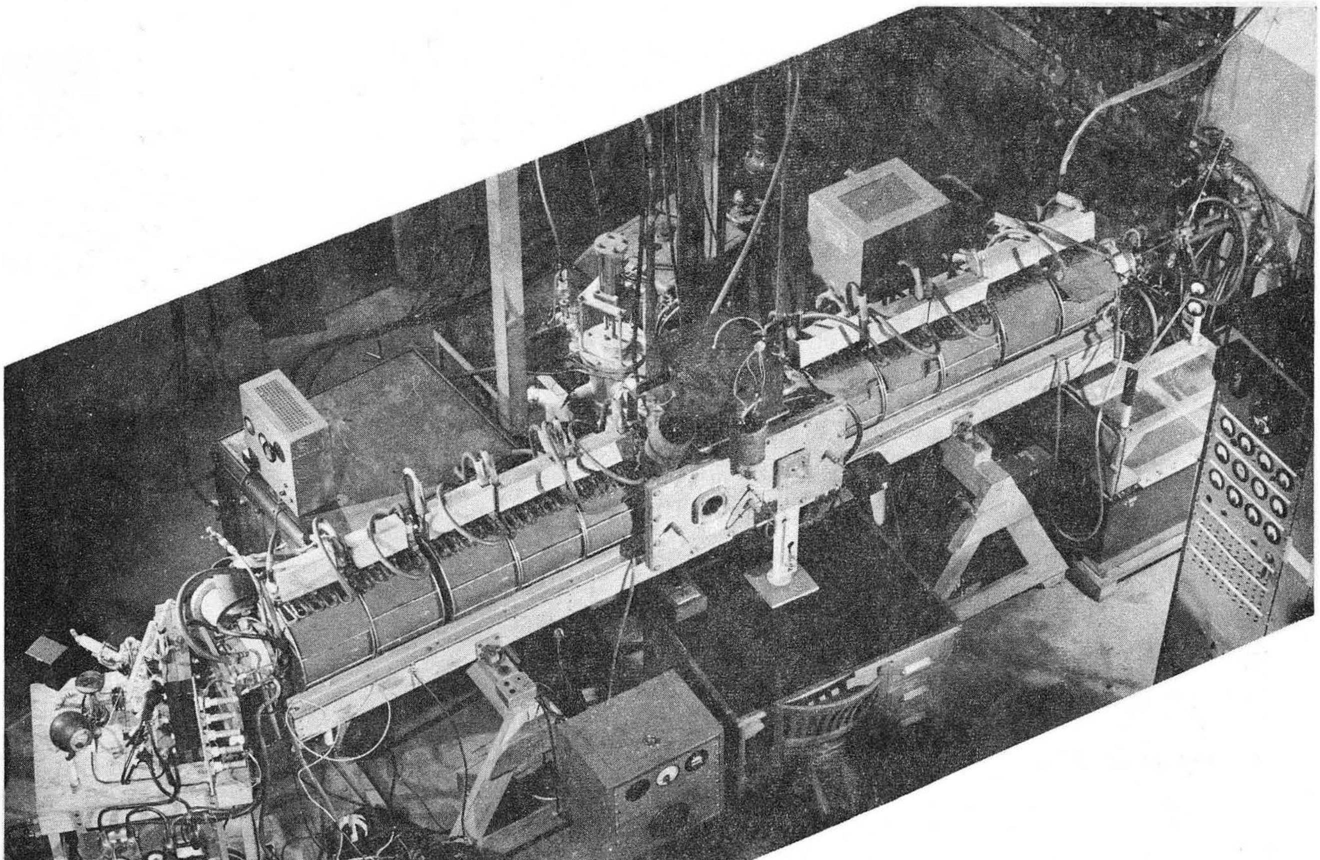

PRESSURE ~ 10^{-6} mm
HOLLOW HOT CATHODE
PUMP INLET
SIDE MAGNET
EXIT GAS LEAK
HOLLOW COLD CATHODE
-300V
-300V
TO FOREVAC
ANODE CONSTRICTION
ANODE CONSTRICTION
PRESSURE ~ 5 x 10^{-4} mm
PRESSURE ~ 5 x 10^{-4} mm
END VIEW
1 ft.
MU 4110

Fig. 3



ZN - 701

Fig. 4

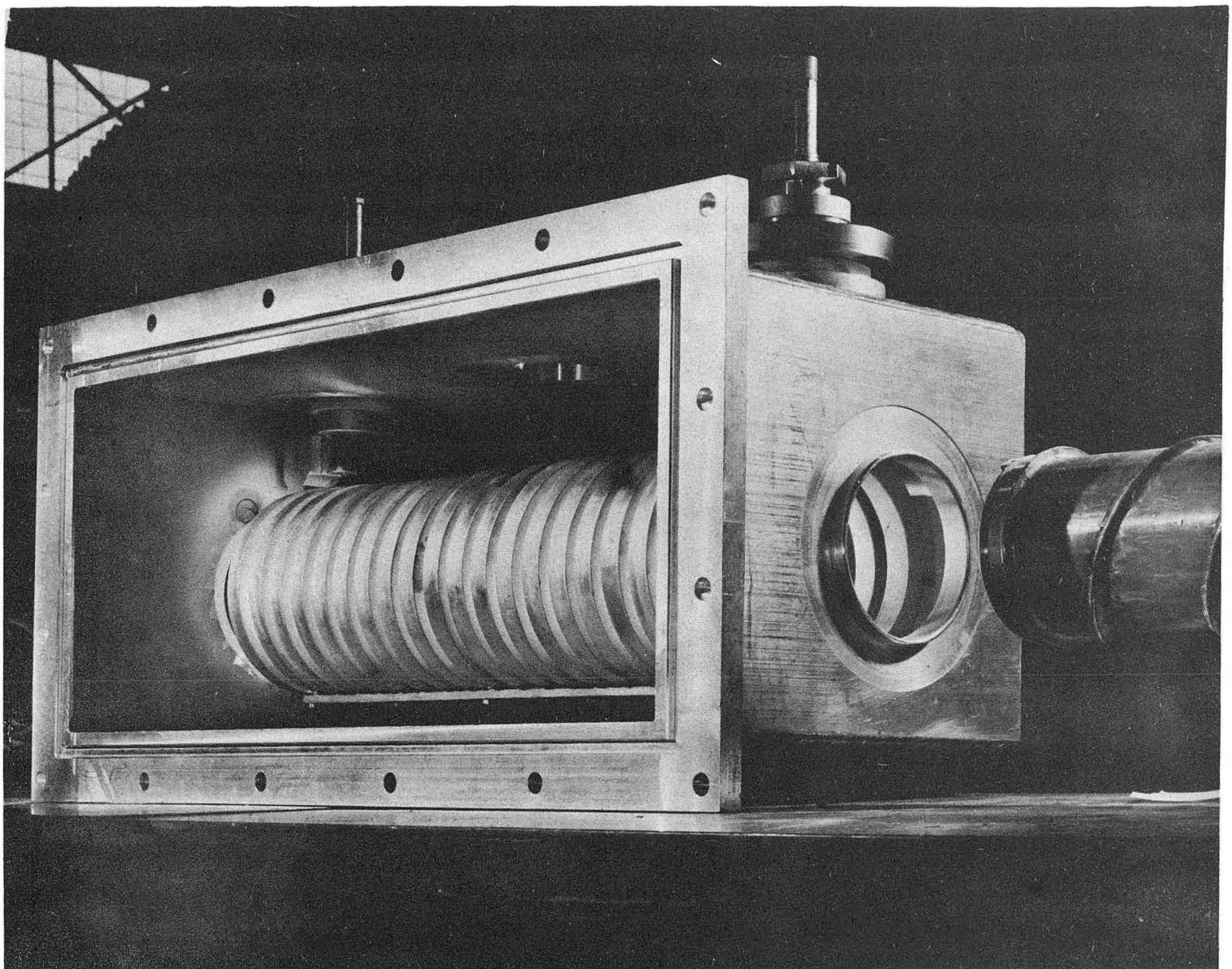


Fig. 5

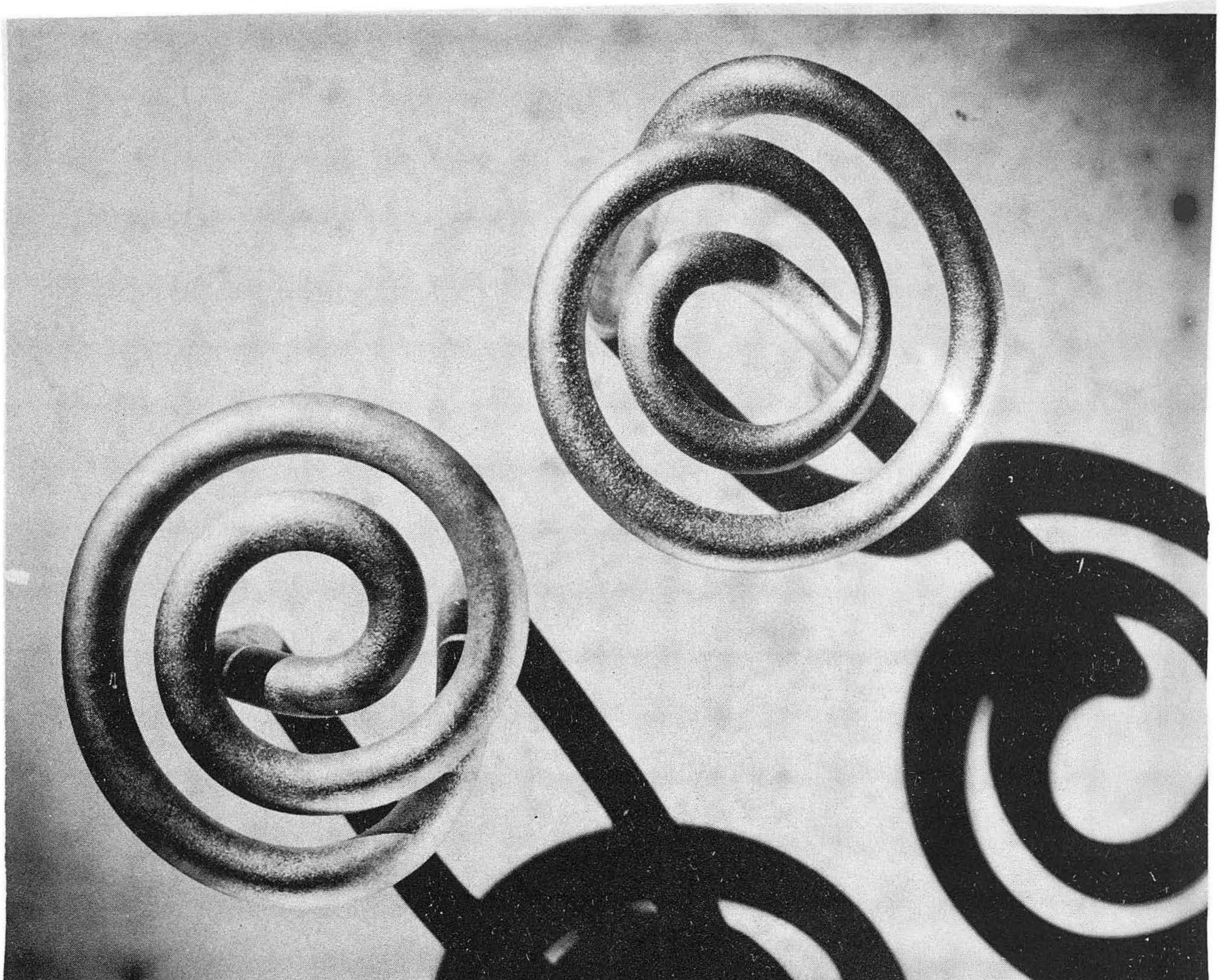


Fig. 6

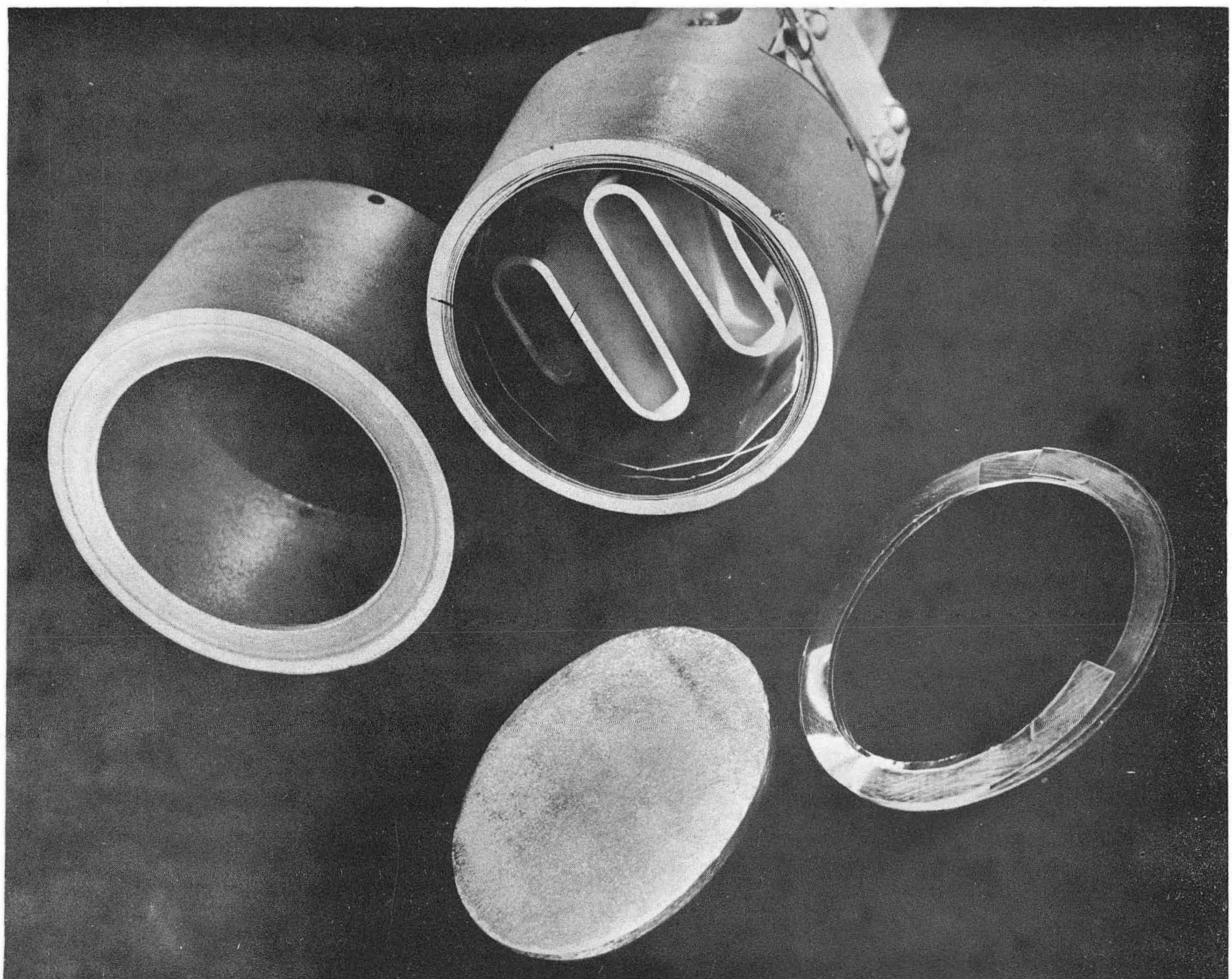


Fig. 7

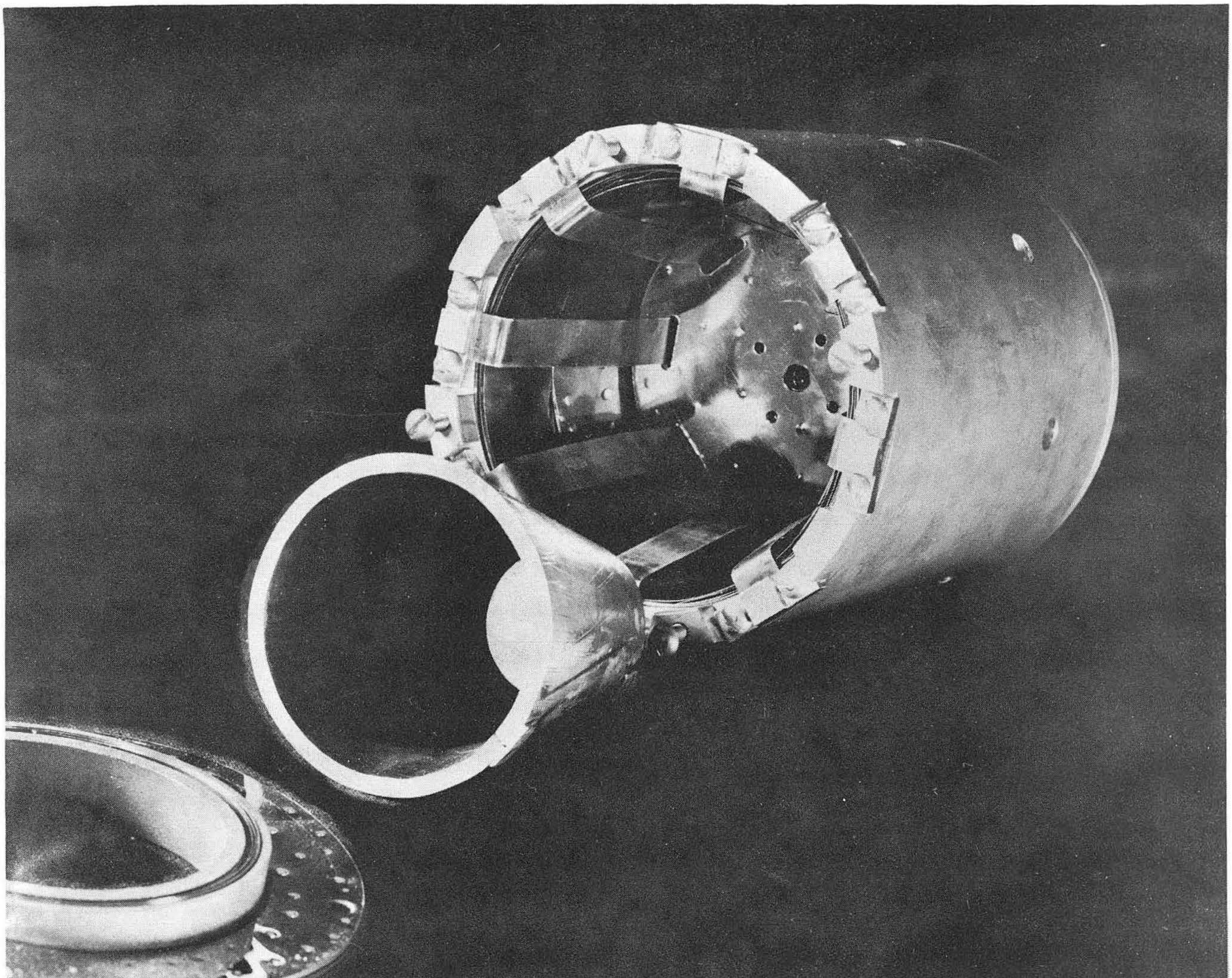


Fig. 8

Magnetic Fields

To maintain the required axial magnetic field throughout the length of the discharge, two different designs are used. In the central region, it is necessary to provide an adequate opening for the flow of gas from the system one wishes to evacuate to the discharge. Several attempts were made to bring the gas between the magnet windings by separating one or more pairs of solenoids. Difficulties arose either because the apertures obtained were too small, or they were so large that the magnetic field became too low in the vicinity of the openings. The present solution is to use an open-wound helix, using hollow copper bar (0.88 in. x 0.88 in.). The helix is water cooled, and a current of several thousand amperes from a selenium rectifier supply permits continuous operation at fields up to 2000 gauss. This arrangement gives a pumping speed for the manifold and helix that is four to five times that of the usable discharge. For the remainder of the pump's length, the magnetic field is maintained by ten water-cooled solenoids, also powered by selenium rectifiers. (Figures 4, 5.)

Cathodes

At present the life of the hot cathode is the most serious limitation to the ion pump. The period of continuous operation depends on the cathode mass. Erosion of cathode material by positive ion bombardment amounts to about 0.8 grams per hour. The cathodes used at present are of two types.

(a) For short experimental runs (~100 hours), involving rapid changes in operating conditions, a bare tungsten filament is used. This filament is made from 3/16 in. or 1/4 in. diameter tungsten rod, formed into a spiral of two to three turns. (Figure 6 shows the effect of approximately 50 hours of operation.)

(b) For continuous operation, an indirectly heated cathode is used. This consists of a 3/8 in. thick disc of tungsten which is radiantly heated by a filament formed from tungsten sheet. Tungsten heat shields are used whenever possible. (Figure 7.)

In an effort to increase cathode life, provision was made to capture the sputtered cathode material. The emitting surface was formed in a hollow cone and heated from the outside. Material sputtered from one point inside the cone is then deposited on another point, since the solid angle for escape is relatively small. Material deposited in this way seems to form a satisfactory emitter, and preliminary results show that the net sputtering rate is reduced by a factor of at least three. (Figure 8.)

The filaments are operated on ac and controlled by an induction regulator. The power required varies over a wide range, but is determined mainly by the positive ion current, which contributes considerable heating by cathode bombardment. In fact, on starting a pump one might use 3 to 5 kw and then reduce the filament power to zero for very heavy discharge currents. The use of a hot filament at each end of the discharge did not change the performance.

An attempt was made to use cold Al cathodes[11] at both ends. On several occasions, pressures below 10^{-5} mm were obtained with these cathodes, but the presence of violent electrical oscillations completely upset the ion-gauge measuring circuits. (In principle it should be possible to eliminate this interference. However, even with careful shielding and the use of supressors, the readings were not reliable for pressures below 10^{-5} mm.) Also, because of the lower ratio of electron emission current to positive ion current, it was difficult to obtain the required discharge current. (Even with 1 kv, only three amperes of discharge current could be obtained.)

When a cold aluminum cathode was used only as a reflector, the rate of wear was much less than for a water-cooled tungsten plate. Here again, however, the oscillations were so bad that pressure measurements were doubtful.

Discharge Power Supply

This power supply is rated at 600 volts, 25 amperes. Since the discharge has a negative resistance characteristic, it is usually necessary to add 10 to 20 ohms in series. The voltage needed between anode and cathode is 300 to 400 volts. For normal gas loads (0.02 cc/sec N.T.P.) a discharge current of 8 to 12 amperes is adequate. Large gas flows (0.08 cc/sec N.T.P.) require 20 to 25 amperes.

Automatic Control

Some form of automatic control is required if the pump is to be left unattended for several hours. It was found that regulation of the discharge current was the best compromise. The current is held almost constant by controlling the filament temperature. This is accomplished by controlling the bias on a saturable reactor in the filament supply. If the gas pressure in the cathode region is set above a minimum value of about 5×10^{-4} mm, then the filament emission is temperature-limited and the automatic control is very satisfactory. Provision is also made to limit the range of filament control and also in the event of a spark, an overload recycle mechanism operates. This control system has made it possible to operate an ion pump on a large vacuum system (48,000 liters) for more than a week without adjustment.

Operating Data

Pumping speed	Air: 4000 to 7000 l/sec H, He, A: 2000 to 4000 l/sec
Base Pressure	0.8 x 10^{-6} to 5 x 10^{-6}mm. (air calibration)
Discharge Voltage	300 to 400 volts
Discharge current	10 to 20 amperes
Cathode Power	4.5 kw (radiantly heated tungsten cathode)
Cathode Life	3 to 4 weeks, continuous operation
Magnet Power	Helix: 12 kw 10 solenoids: 20 kw
Backing Pressure	3 x 10^{-4} to 10^{-2}mm.

Total power input: 42 kw. If the total power is reduced to 25 kw the central pressure will be at least doubled.

IV MEASUREMENTS MADE ON THE ION PUMP

During development, measurements were made on each different model to determine the major effects that limited the performance. In the normal range of operation, the conditions existing in the discharge change a great deal. Hence it is not meaningful to measure any effect to great precision, but it is important to determine its relative magnitude. In the experiments described below, the interpretation within the accuracy required is quite straightforward.

Pumping Speed

Definition

The notion of pumping speed involves the volumetric rate at which gas flowing through a manifold crosses a given plane. However, when applying the term to measure the speed of practical pumps, no specific definition has been universal. Suppose we consider a quantity of gas q at constant temperature.

Then $q = PV$.

If we permit this gas to flow across a fixed plane at a constant rate L,

$$L = \frac{dq}{dt} = P\,\frac{dv}{dt} = PS,$$

where S is the net volumetric rate of gas flow across the plane, and holds for either molecular or viscous flow. In applying this equation to measure the speed of a pump, we could introduce a metered gas leak L, and measure the pressure P at the selected plane. Now in any practical pump, when the measuring leak is reduced to zero the pressure falls to a finite pressure P_o, called the base pressure. This pressure exists because there is always a small flow of gas back from the pump into the vacuum system. (It is assumed that other sources of gas, such as real or virtual leaks in the vacuum system, can be reduced to a point at which their contribution to the pressure P_o is negligible. If this is not so, then they will be considered as part of the leak L.)

The mechanism involved in this leak back depends on the type of pump, but it does constitute a flow of gas back through the pump from the higher-pressure exit to the lower-pressure inlet. <u>This internal gas leak does not contribute to the net flow of gas across the reference plane in front of the pump.</u>

Hence the measured pressure P has two components--a partial pressure P_L due to the intentional gas flow at rate L, and a pressure P_o due to pump imperfection. The partial pressure P_o will be considered a constant since the mechanism of the internal leak and volumetric pumping speed are usually independent of the gas flow if the latter is small. Under these conditions, the equation relating a gas flow L and measured pressure P may be obtained from

$$L = P_L S.$$

But $P_L = P - P_o$, therefore

$$S = \frac{L}{P - P_o}$$

This definition gives the net volumetric rate at which a pump handles an external gas load, and refers to that plane where the pressure was measured. It should be mentioned, however, that one does not know the base pressure very accurately unless the gas composition is known, since the ion-gauge filament emission must be adjusted for a specific gas according to recommendations of the manufacturer.* In the measurements to be described below, the ion-gauge emission was set for the gas to be used in the speed measurement.

Measurement

The flow of gas into the pump was measured by the displacement rate of the butyl phthyalate levels in a U tube. This gas was let in through a blanking plate on the pump inlet. To obtain a reasonably uniform flow distribution, the gas was directed back against the blanking plate by a set of small jets. Since the manifold cross section is very large compared to the discharge surface area, there is very little pressure variation within the manifold, and the point at which the pressure is measured is not very critical. Figure 9 shows the geometry just described, and a pumping-speed curve. The value of pumping speed obtained varies from 3000 to as much as 7000 liters/sec depending on the character of the discharge. From the measured pumping speed one can say that the probability that a neutral air molecule will be ionized once it enters the discharge is about 0.3, and as shown in Part II this gives a mean free path in the discharge of about 4-3/4 inches.

* RCA TYPE 1949

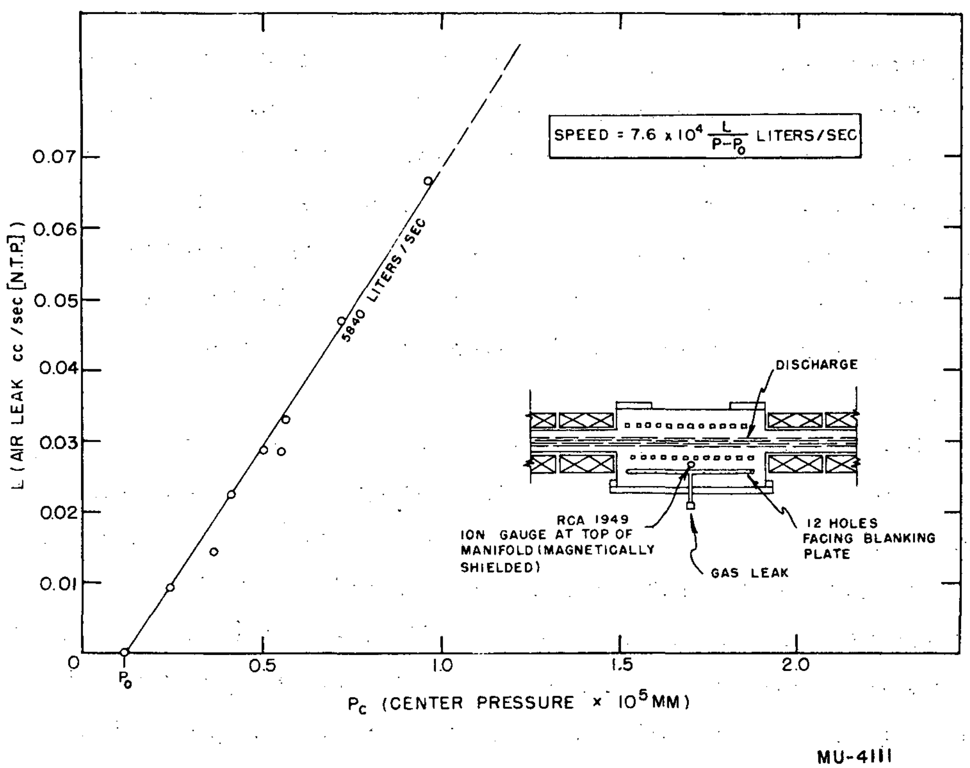

SPEED = 7.6 x 10^4 L/(P-P0) LITERS/SEC
5840 LITERS/SEC
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
L (AIR LEAK cc /sec [N.T.P.])
0.5
1.0
1.5
2.0
P0
Pc (CENTER PRESSURE x 10^5 MM)
DISCHARGE
RCA 1949
ION GAUGE AT TOP OF
MANIFOLD (MAGNETICALLY
SHIELDED)
12 HOLES
FACING BLANKING
PLATE
GAS LEAK
MU-4111

Fig. 9

The pumping speed has been measured for air, H_2, A, He, N_2 and Ne. In general, those gases with a smaller ionization cross section require higher discharge currents. The speed for air and N_2 is about twice that measured for the other gases. It was found necessary to operate a pump on a new gas for a day or more before a reliable pumping-speed measurement could be made. If gases other than N_2 or air are used in the exit leak to maintain cathode pressure, the base pressure may rise above 5×10^{-6}. There is some evidence which indicates that a very clean ion pump of this size (a glass model) would not pump well on H, He, Ne, and A without maintaining the discharge at the exit by an air leak. The reason for this may be the production of neutral particles in the discharge by ion-electron recombination. (E-4)

Energy of the Positive Ions

The energy of positive ions in a plasma is usually measured by means of a technique introduced by Langmuir. This method makes use of a small conducting probe which is inserted into the plasma. While the voltage difference between the probe and the discharge container is varied the probe current is measured. The number of electrons and positive ions that reach the probe depends on the potential of the probe relative to the plasma. In order to relate the applied voltage and observed probe current to the plasma temperature and density, one must make assumptions concerning the nature of the plasma and the disturbance caused by the presence of the probe. In particular, it is necessary to assume that the potential drop between the probe and plasma is static. In the discharge one can detect a radiofrequency potential drop of ~ 15 volts between a probe and the plasma. The presence of these voltage oscillations leads to an estimate of the plasma temperature that is above the true value. Also, the discharge to be studied here is such that when tungsten probes are merely inserted in the edge of the discharge column they run to a white heat. These facts, in addition to the problem of evaluating probe characteristics in the presence of a magnetic field, indicate that the method is not suitable.

The method chosen was to observe the Doppler shift in lines emitted by neutral and ionized atoms within the discharge column. If a particle in the discharge emits light of frequency ν while moving with velocity v_x relative to an observer, the observed frequency is given by

$$\nu^{1} = \nu \frac{(1 \pm \frac{v_x}{c})}{\sqrt{1 - (\frac{v_x}{c})^2}}$$

$$= \nu\,(1 \pm \frac{v_x}{c})\ ;\ v_x << c.$$

The frequency difference is related to a wave-length shift $\Delta\lambda$,

$$\Delta\lambda = -\frac{c}{\nu^2}\ dD$$

$$= -\frac{\lambda}{c}\ v_x.$$

Light coming from the discharge is emitted by particles with some distribution of velocities f(v). The wave length of a particular transition is then observed as a distribution in wave lengths given by

$$F(\Delta\lambda) = F(\frac{\lambda}{c}\ v_x) = \iint f\,(\vec{v})\ dv_y\ dv_z.$$

Hence, by observing the intensity as a function of wave length, one might in principle determine the velocity distribution of the emitting particles.

There are numerous corrections related to the optical system that must be applied before the true intensity distribution of a line can be determined, and the data obtained in this experiment do not have the accuracy required to determine whether or not the velocity distribution of ions in the discharge deviates from a Maxwellian. For this reason the distribution is assumed to be Maxwellian, and only the average energy is measured. If N_v dv is the number of particles with speeds between v and v + dv,

$$N_v\ dv = 4\pi N\ (\frac{m}{2\pi KT})^{3/2}\ v^2\, e^{\frac{-mv^2}{2KT}}\ dv;$$

and then the number with components between v_x and $v_x + dv_x$ along the direction of observation is given by

$$N_x\ dv_x = \left(N\sqrt{\frac{m}{2\pi\ KT}}\right)\ e^{\frac{-mv_x^2}{2KT}}\ dv_x,$$

which gives an intensity distribution radiated by particles with these velocities

$$I(\lambda) \sim N \sqrt{\frac{3m}{4\pi \overline{V}e}} \; e^{\frac{-3m}{4e\overline{V}_x}\left(\frac{c\Delta\lambda}{\lambda}\right)^2} \; dv_x$$

obtained by the substitution

$$v_x = \frac{c\Delta\lambda}{\lambda}$$

$$3/2\ KT = \overline{V}e$$

so that $\overline{V}$ is the average energy in stat volts. The value of $\overline{V}$ that corresponds to half intensity at a given $\Delta\lambda = \Delta\lambda_{1/2}$ is then

$$\overline{V} = \left(\frac{3m}{4e\ \mathrm{Ln}2}\right)\left(\frac{c\Delta\lambda 1/2}{\lambda}\right)^2$$

A Bausch and Lomb medium quartz spectrograph was used to separate the spectral lines, and a Fabry Perot interferometer was used to obtain sufficient dispersion. Light from the discharge leaves the vacuum through a quartz window, and passes through the interferometer. The resulting fringes are focused on the spectrograph slit.

A preliminary examination of the photographic plates indicated that no matter what gas was let in at the center or cathode regions, very strong lines of nitrogen, oxygen and carbon were always found. Helium was chosen as the gas to observe because of the larger Doppler shifts associated with its smaller mass, and one of its ionized lines 4685.8Å, could be isolated from the background. Difficulty also arose because the exposures required were 30 to 45 minutes, owing to poor geometry.* This means that the room temperature and pressure must be constant during this period, and the equipment free from mechanical shock.

*It was not possible to install a collimating lens in the vacuum system close to the discharge, because it would have been rapidly coated with metal sputtered from surrounding metal surfaces.

Reduction of Observations

Figure 10a shows a photograph of a plate taken with He gas in the discharge. The intensity distribution of the fringes was microphotometered on a Leeds and Northrup recording densitometer. These readings were corrected to the true intensity by use of a calibration curve obtained by monitoring the density produced in the same plate by a rotating calibrated logarithmic sector disc placed in front of the spectrograph slit.

The wavelength difference between two successive fringes is deduced directly from the basic interferometer relation for two parallel plates with an air separation d:

$$n\lambda = 2\mu_{air}\, d \cos\theta.$$

If

$$\mu_{air} \simeq 1 \text{ and } \theta \simeq 0,$$

then $$n d\lambda + \lambda dn = 0, \text{ and } \Delta\lambda = \frac{\lambda}{n} \ldots . \Delta n = 1$$

$$= \frac{\lambda^2}{2d}.$$

Since the diameter of each interference ring varies inversely as the square root of the ring number, the wave-length calibration is not constant as one crosses a fringe. Measurements were made on a fringe that was about 12 orders from the center, and a linear wave-length correction scale was used to plot a corrected contour.

Results

The average energy of the un-ionized He line (4437.55Å) was determined by the best fit of a Gaussian distribution to the line profile. Figure 10c shows that an energy $\overline{V}$ = 0.41 volts gives a good fit. In the case of the ionized line, 4686Å, the situation is complicated. This line is the first member of the "Fowler series" and contains fine structure. Figure 10b shows the structure of this line as predicted theoretically by Summerfield and Unsold and observed first by Paschen. In order to obtain a theoretical Gaussian curve to fit the experimental curves, it was assumed that all components had the same Doppler shift and that the relative amplitudes were as predicted theoretically. Figure 10c shows that a Gaussian curve corresponding to an energy of about 0.67 volts gives a fairly good fit.

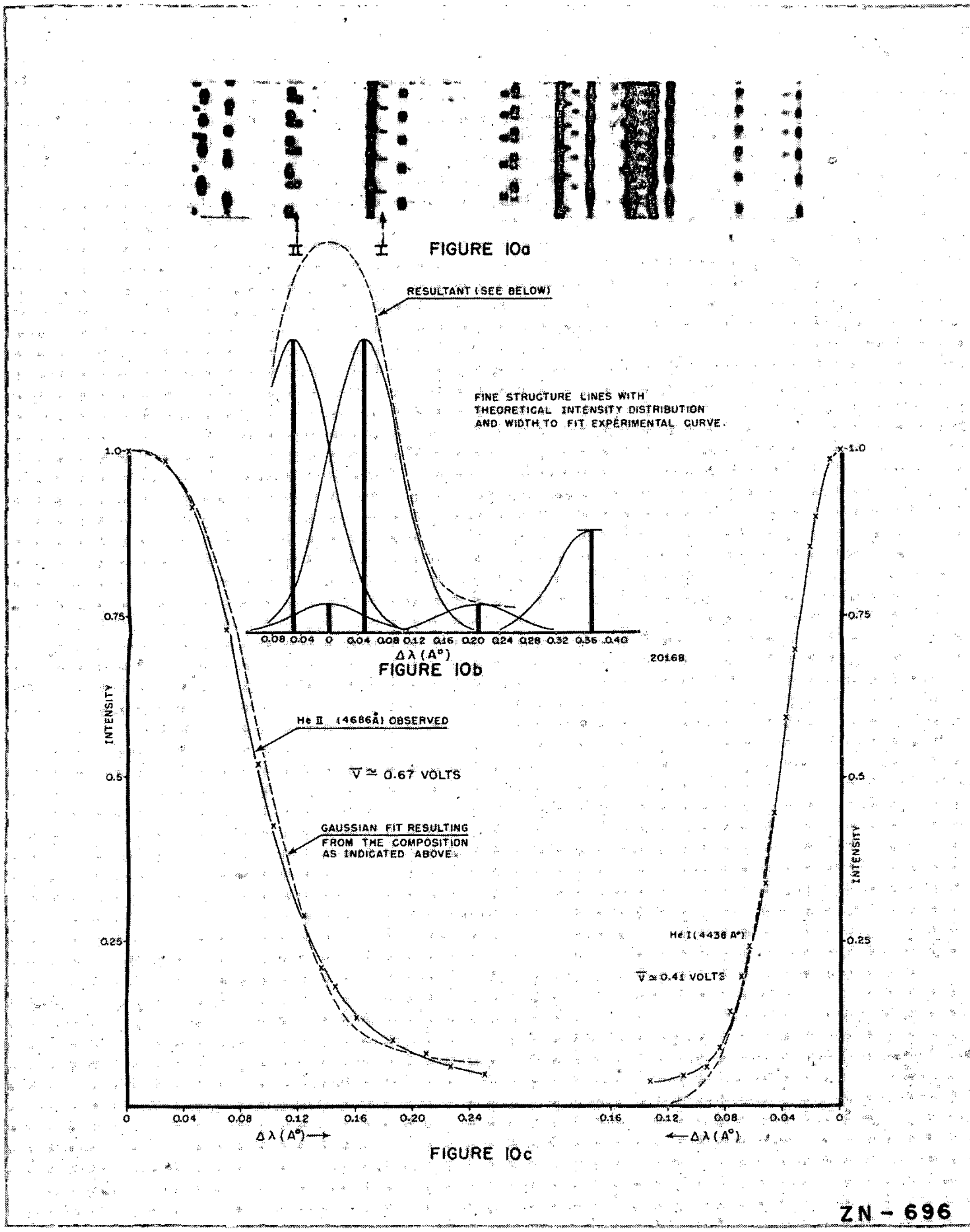


FIGURE 10a

FIGURE 10b

FIGURE 10c

The observed broadening of these lines is not all due to Doppler shift. Some is produced by other mechanisms in the discharge, and some broadening is instrumental, the natural line width being a very small fraction of the observed width (10^{-3}). Since the various effects tend to broaden the line, the observed line width represents a maximum value. A few sources of broadening are discussed briefly below.

(a) Zeeman splitting. The presence of an axial magnetic field gives rise to a Zeeman effect in the lines that were observed. The un-ionized line is a singlet, and hence is split into three components. The side components are displaced about 0.017Å from the central undisplaced component. A profile of the un-ionized line was computed with and without the Zeeman splitting, and there was no significant difference in the resulting curves.

Each component in the ionized line also exhibits Zeeman splitting. Each of these lines is split into three groups of lines with 2 to 6 members in each group. However, since the total amplitude of the splitting is roughly the same as for the un-ionized line, the correction would be small and no calculation was made of the ionized line profile including the Zeeman effect.

(b) Drift of the interferometer and mounting. Runs were made for 5 minutes, 15 minutes and 45 minutes. The line widths obtained were the same.

(c) Interatomic Stark broadening. The local electric fields around an ion produced by its immediate neighbors perturb its electronic energy levels and cause the emitted line to be shifted. This local field can be estimated roughly by considering the average volume occupied by an ion, and computing the average field in this volume. The average field computed in this manner is given by Holtsmark[10] as

$$\bar{E} = 2.6\ e n^{2/3} \quad \text{stat volts/cm}$$

$$\simeq 110 \text{ volts/cm} \quad \text{for an estimated density in the discharge of } n = 5 \times 10^{12} \text{ ions/cc}$$

This random field results in a first-order Stark broadening with a maximum displacement of less than 0.014Å.

(d) Collision broadening. This source of broadening arises when the time between collisions is comparable to the natural lifetime. Under these conditions the radiated wave is damped during a collision, and hence an energy spectrum results. The effect is appreciable only at densities of $\sim 10^{15}$ ions/cc.

(e) Instrumental broadening. Some broadening is introduced by imperfect focusing of the interference rings on the split. This contribution was minimized by careful focusing of the fringes when the interferometer was tilted so as to project the thirtieth to fortieth rings. The resolving power of the interferometer was not checked.

Ion Density in the Column

An estimate of the ion density is made by measuring the ion energy in the central region of the pump and the positive-ion drain current to the reflector cathode. The positive-ion current density i_+ is carried across the last mean free path to the cathode by free motion, and is related to the arithmetical average ion velocity v_a, and the ion density n_+ by

$$i_+ = \frac{n_+ v_a}{4} .$$

The discharge is collimated by a magnetic field. However, this does not affect the velocity distribution, hence the equation for the random current to the cathode still holds. Of course it is necessary to assume that the energy distribution is constant throughout the length of the discharge, and that the magnetic field reduces the radial diffusion so that most of the positive ions reach a cathode.

The normal positive-ion current to the cathode is about 2.0 amperes over an area of 20 sq. cm, and this must be related to the particle current at the cathode. Running on helium, the measured ion current in the the central region of the pump is 96.5% He^+ and about 3.5% He^{++}. In the cathode region, the current of He^{++} was about 2%. An estimate of the ion density can then be obtained, since

$$n_+ = \frac{4i_+}{v_a} = \frac{4i_+}{\sqrt{8KT/\pi m}}$$

$$= 4i_+\sqrt{\frac{3\pi m}{16V e}} .$$

The range of ion currents resulting from the pressure limits of pump operation correspond to a range in ion density of 2×10^{11} to 1×10^{13} ion/cc. Although no energy measurements were made on other gases, it is expected that the energy and hence the density will be quite similar, as the operating characteristics are similar for other gases. Since the base pressure in the central region is about 10^{-6}mm or 3.6 x 10^{10} molecules/cc, this is a discharge in which about 99% of the particles are ions!

Ion Composition in the Discharge

In order to interpret measurements of ion-current drains from the discharge column it is necessary to determine first of all the types of ions in the discharge and their charges. The number of charges per ion may vary along the ion column. For instance, in the central region of the pump the ion motion is restricted to tight helices where ions suffer many electron impacts before reaching a cathode; therefore one may expect to find in the central region some ions that are multiply ionized (N^{++}, N^{+++}, etc). In the cathode region, however, most of the ions are the result of the ionization of molecules from the cathode region. These ions also fall back to the cathode, but since their trip through the discharge is relatively short, one would not expect to find many multiply ionized atoms reaching the cathode. Indeed, the ion ratios here should be quite similar to those found in magnetic ion sources.

Ions in the Cathode Region

A crude magnetic analyzer was first set up at the cathode. Figure 11a shows that ions impinging on the cathode passed through a 0.040 in. diameter hole to be accelerated and focused into a collector cup by a unipotential lens. The ion beam was deflected by a magnetic field and analyzed by varying the magnetic field and observing the current collected in the cup. Observations were recorded by photographing an oscilloscope trace for which the horizontal plate drive was obtained from the magnet voltage and the vertical plate drive from the collected current. The magnet voltage was varied by motor drive, a single sweep requiring about 20 seconds. Owing to the circuit elements used, the horizontal drive was not linear; calibration was obtained by using various gases and several values of ion energy. Results for nitrogen are shown in Fig. 12. The nitrogen was let in only at the analyzing cathode (cold cathode).

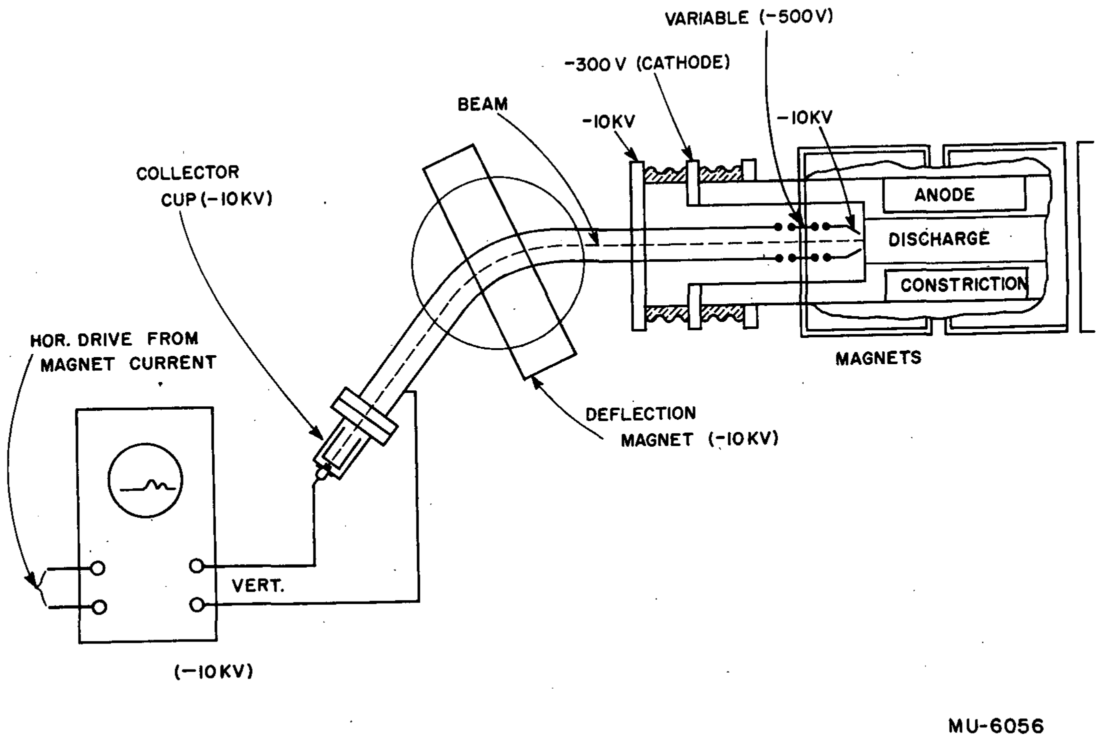

VARIABLE (-500V)
-300 V (CATHODE)
BEAM
-10KV
-10KV
COLLECTOR
CUP(-10KV)
ANODE
DISCHARGE
CONSTRICTION
HOR. DRIVE FROM
MAGNET CURRENT
MAGNETS
DEFLECTION
MAGNET (-10KV)
VERT.
(-10KV)
MU-6056

Fig. 11a

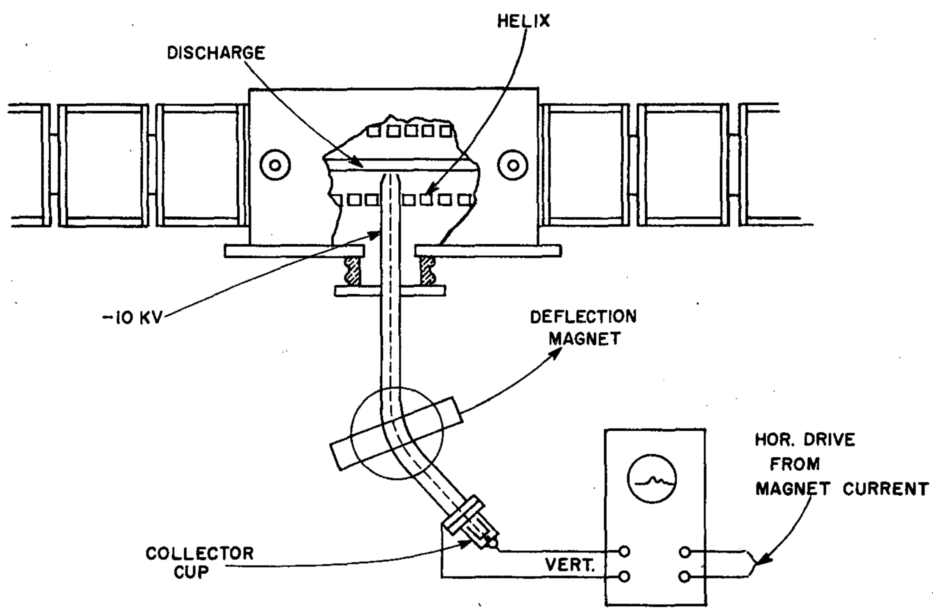

HELIX
DISCHARGE
-10 KV
DEFLECTION MAGNET
HOR. DRIVE FROM MAGNET CURRENT
COLLECTOR CUP
VERT.
MU-6057

Fig. 11b

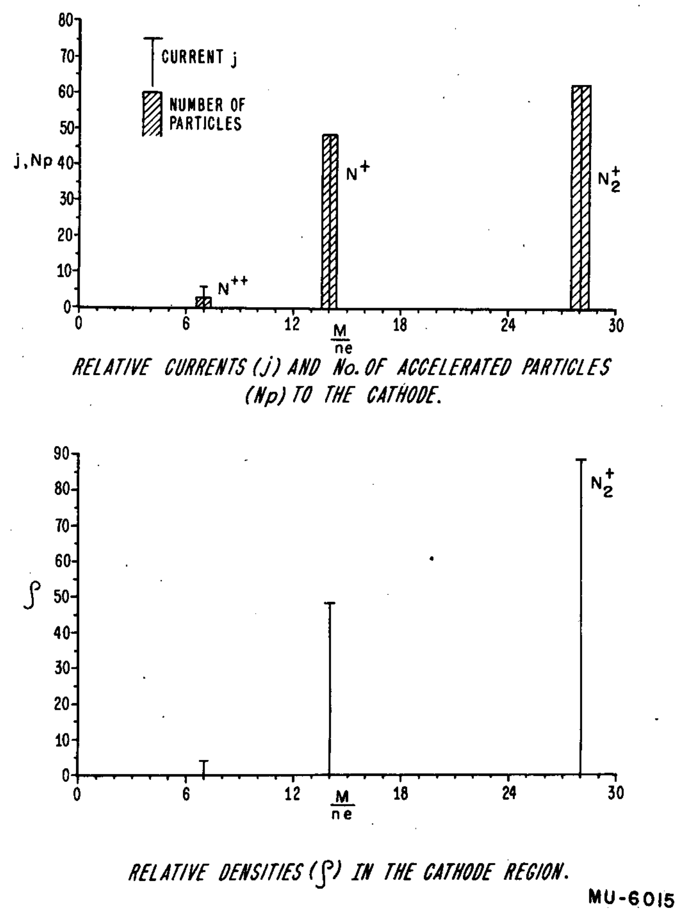

CURRENT j
NUMBER OF PARTICLES
j, Np
N++
N+
N2+
M/ne
RELATIVE CURRENTS (j) AND No. OF ACCELERATED PARTICLES (Np) TO THE CATHODE.
ρ
N2+
M/ne
RELATIVE DENSITIES (ρ) IN THE CATHODE REGION.
MU-6015

Fig. 12

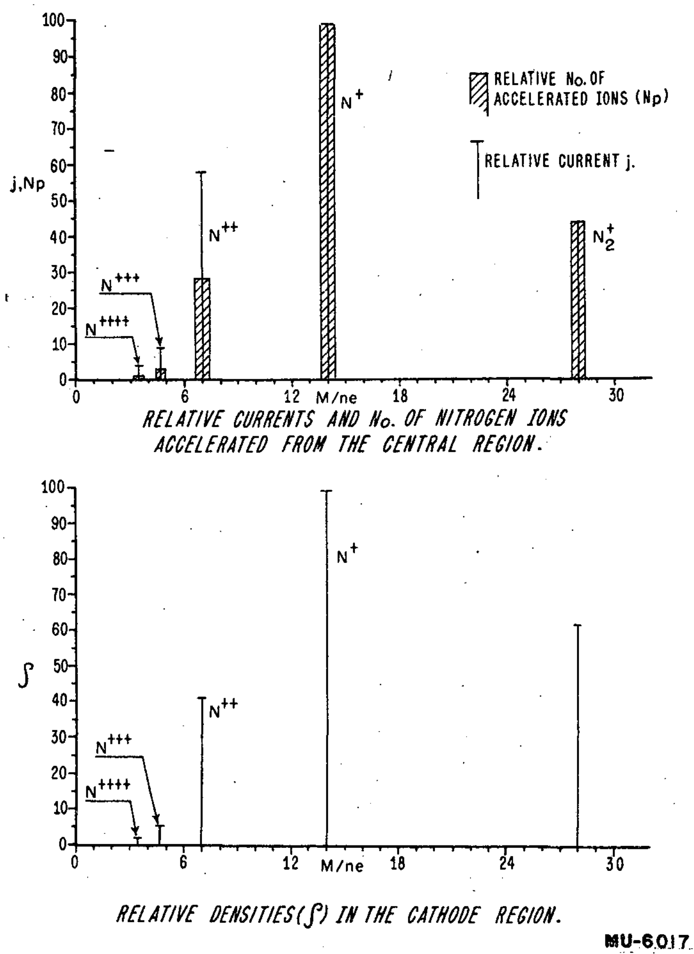

100
90
80
70
60
50
40
30
20
10
0
j,Np
RELATIVE No. OF ACCELERATED IONS (Np)
RELATIVE CURRENT j.
N+
N++
N+++
N++++
N2+
0
6
12
M/ne
18
24
30
RELATIVE CURRENTS AND No. OF NITROGEN IONS ACCELERATED FROM THE CENTRAL REGION.
ρ
N+
N++
N+++
N++++
RELATIVE DENSITIES (ρ) IN THE CATHODE REGION.
MU-6017

Fig. 13

Ions in the Central Region

Extraction at the center was made by inserting an accelerating electrode between two turns of the helix (Fig. 11b). Ample ion current is available, since there is no gas flow problem, hence no focusing was used and the ions were analyzed with the equipment used at the cathode. The results obtained for nitrogen admitted only at the reflector cathode and analyzed at the central region are shown in Fig. 13.

To determine the true relative currents and densities of the various ion types in the discharge, the following procedure was used.

(a) Relative currents. An ion of mass M and charge ne moving in a constant magnetic field H describes a circle of radius R with velocity v. These are related by

$$\frac{Mv^2}{R} = \frac{H(ne)v}{C} ; \qquad v = \sqrt{\frac{2\overline{V}(ne)}{M}} ;$$

$$\therefore \; HR = C\sqrt{\frac{2\overline{V}M}{ne}} ;$$

$$H\Delta R + R\delta H = 0;$$

$$\therefore \; \Delta H = (\text{const})\sqrt{\frac{M}{ne}} ,$$

which gives the relation between corrected peak widths (ΔH) for the various ion types. To determine the total ion current (j) associated with each type, one could integrate over each peak and compare the relative values obtained. However, it was simpler to read off the peak heights A, and multiply by $\sqrt{\frac{M}{ne}}$

$$\text{eg.} \quad \frac{j_{N^{++}}}{j_{N^{+}}} = \frac{A_{N^{++}}\sqrt{\frac{M}{2e}}}{A_{N^{+}}\sqrt{\frac{M}{e}}}$$

(b) Relative densities. We assume that all ion types in the discharge have the same energy and spatial distributions. Then the rate at which ions are accelerated from the plasma into the ion beam is given by Child's Law, and hence varies as $\sqrt{\frac{ne}{M}}$. This means that the densities ρ are related to the true currents j by

$$\frac{\rho_{N^{++}}}{\rho_{N^{+}}} = \frac{j_{N^{++}} \sqrt{\frac{M}{2e}}}{j_{N^{+}} \sqrt{\frac{M}{e}}} .$$

Figures 12 and 13 show that the fraction of multiply charged ions in the central region is much larger than in the cathode region, which was expected. One can compare these current ratios with those obtained in a commercial mass spectrograph. A typical value for a mass spectrograph running on nitrogen is

$$\frac{j_{N_2^+}}{j_{N^+}} \approx \frac{100}{14} ,$$

whereas from the central region of the ion pump one obtains

$$\frac{j_{N_2^+}}{j_{N^+}} \approx \frac{41}{100} . \quad \text{(Fig. 13)}$$

An ion can become multiply ionized if there is a sufficient flux of ionizing electrons and a low enough gas pressure, and if the geometry and electron energy are such that several ionizing events can take place before the ion reaches a wall. In the ion source of most mass spectrographs, the electron flux density is a few ma/cm^2, and the discharge length is less than one inch. In this ion pump, the electron current density is about one amp/cm^2, and the discharge extends for several feet.

Contributions to the Base Pressure

The lowest pressure that can be obtained in the central region of the pump is limited by various sources which contribute neutral particles to the central region. The most important of these arise from the diffusion of ions from the discharge column across the magnetic field to the anode. The axial magnetic field severely restricts the ion diffusion radially, but has no direct effect on axial diffusion.* As a result of this, ions that move out radially from the

* As soon as the discharge has been established, and the pressure in the central region has dropped below, say, 10^{-5}mm, the ions suffer only relatively light electron impacts as they move along the discharge column.

discharge column usually travel at the same time a much greater distance along the axis. The pump is dimensioned so that most of those ions which leave the discharge column strike the anode constrictions before they can reach the tube walls. Ions reaching the constriction surfaces are neutralized, hence these surfaces are a source of neutral gas particles. The gas particles diffuse back up the anode tube toward the central region. In doing so, however, they can be ionized on passing through the discharge and hence trapped in the ion column by the magnetic field. The anode tube is made long enough so that most of the neutrals produced at the exit constriction are re-ionized before reaching the central section. Of course, some migrate radially to the walls of the central region, where they are neutralized and contribute to the central gas pressure. A high magnetic field and careful adjustment of the discharge conditions minimize this effect. Recombination within the discharge, leaks in the apparatus, and out-gassing of the surfaces due to ion bombardment all contribute to the base pressure in smaller amounts. The experiments described below give the magnitude of these effects:

(a) Length of the pump. Since most of the length of the pump is due to the necessity of long tubes on either side of the center section, it is important to determine just what length is needed. This can be done in a variety of ways-and, indeed, several different approaches were used. The method described below is probably the most direct.

A pair of additional anode constrictions was installed in the anode tube (Fig. 14). These constrictions were designed to slide freely in the anode tube and could be moved by pulling on a wire while the discharge was running. The movable constrictions were long enough (8 inches) so that the gas pressure on the side of the constriction was isolated from the gas pressure on the other side. Data were obtained by recording the center pressure as the constrictions were moved. It was found that different positions of the constrictions did not require any change in the operating controls to produce a minimum center pressure. The results for two discharge diameters are shown in Fig. 14. To vary the discharge diameter, the magnetic field at the cathodes was varied, but the field along the rest of the pump was held constant.* From the figure, one

* Since the electrons and ions follow the magnetic field lines, the ratio of the discharge column diameters at two points varies as the square root of the magnetic fields.

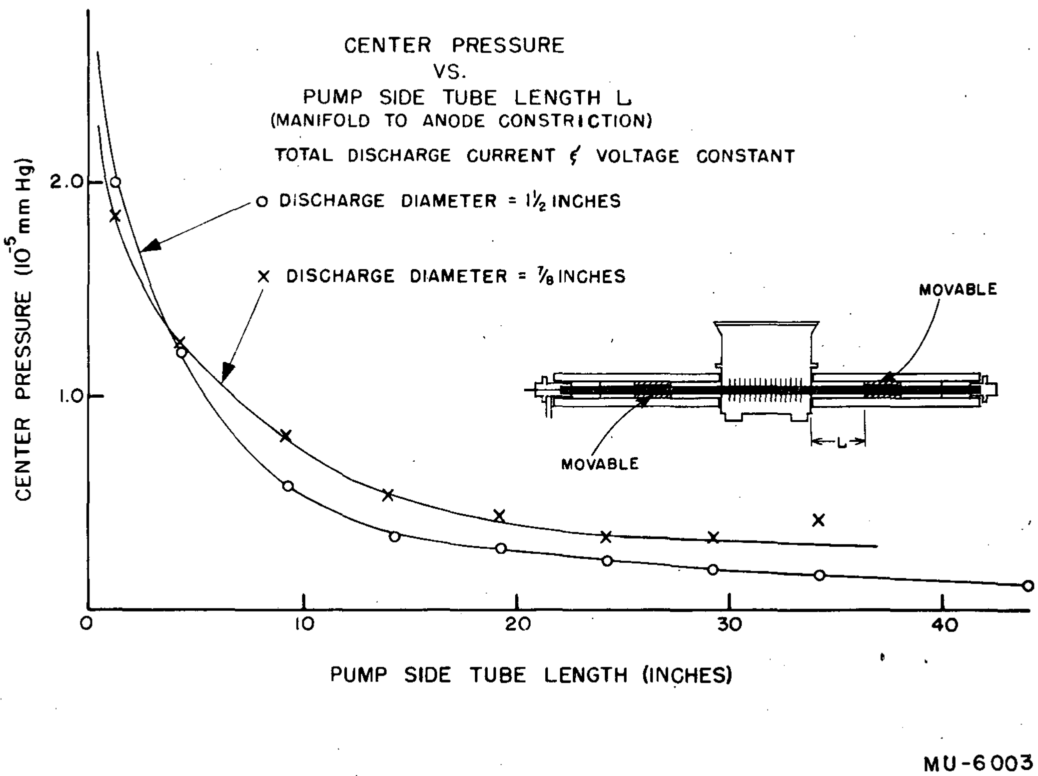

CENTER PRESSURE
VS.
PUMP SIDE TUBE LENGTH L
(MANIFOLD TO ANODE CONSTRICTION)
TOTAL DISCHARGE CURRENT & VOLTAGE CONSTANT
o DISCHARGE DIAMETER = 1½ INCHES
x DISCHARGE DIAMETER = ⅞ INCHES
MOVABLE
MOVABLE
L
CENTER PRESSURE (10⁻⁵ mm Hg)
2.0
1.0
0
10
20
30
40
PUMP SIDE TUBE LENGTH (INCHES)
MU-6003

Fig. 14

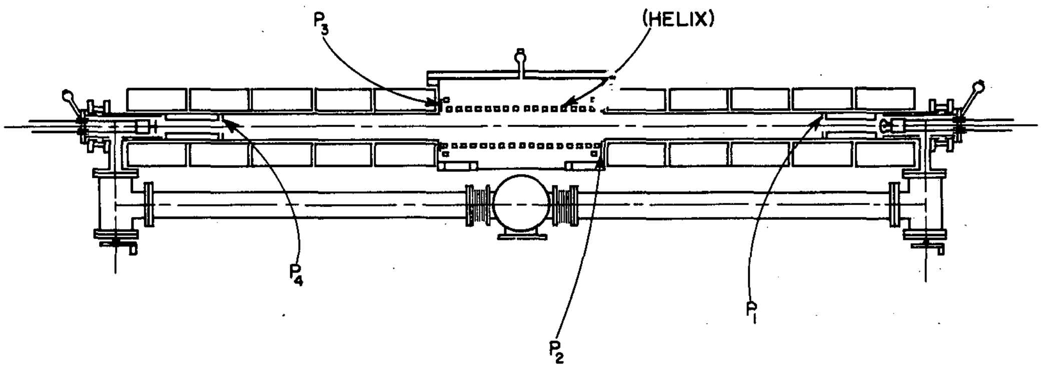
can see that the gas pressure drops off rapidly with distance, and 15 to 20 inches of tubing are certainly required. The inside diameter of the anode tube was 5 inches. Not all the neutral particles diffusing along the anode tube came from the anode constriction; some were the result of recombination along the tube walls. For this reason it is not easy to relate the data given in Fig. 14 to the absorption characteristics of the discharge.

(b) Radial ion drain. To obtain some idea of the contribution to central pressure due to the diffusion of positive ions from the discharge column to the anode, the currents to various regions were monitored. This was accomplished by installing sheets of metal insulated from the wall, and the locations of these drain electrodes are shown in Fig. 15. With the pump in operation, the potential on an electrode was varied, and the current recorded. Normally, when the electrodes are at anode potential* the current of particles reaching them consists of both positive and negative particles. Since we are concerned with the positive-ion component, it is informative to vary an electrode potential so that only particles of one sign are collected. Figure 16 gives the general shapes of curves obtained from the different electrodes. Some of the electrodes are very large, and hence when placed at a high potential they disturb the plasma balance. In principle it would be more accurate to use a small probe, but since the ion drains are not uniform over all the areas, it would be necessary to provide either many probes or complicated mechanical devices. There was little evidence of interaction between the large electrodes, or disturbance of the observed center pressure. A fair indication of the positive drain when the electrodes are grounded is given by linearly extrapolating the positive-ion drain current to zero volts. The effect of photoemission and secondary electrons is to increase the positive-ion current reading.

In order to vary the radial ion drain, the magnetic field along the length of the pump was made uniform and set at several different values. The discharge voltage and total current were kept constant. Figure 17 shows the effect on the central pressure and the extrapolated ion drain to that area. It is seen that as the magnetic field is reduced, the ion drain increases very rapidly and the local gas pressure rises.

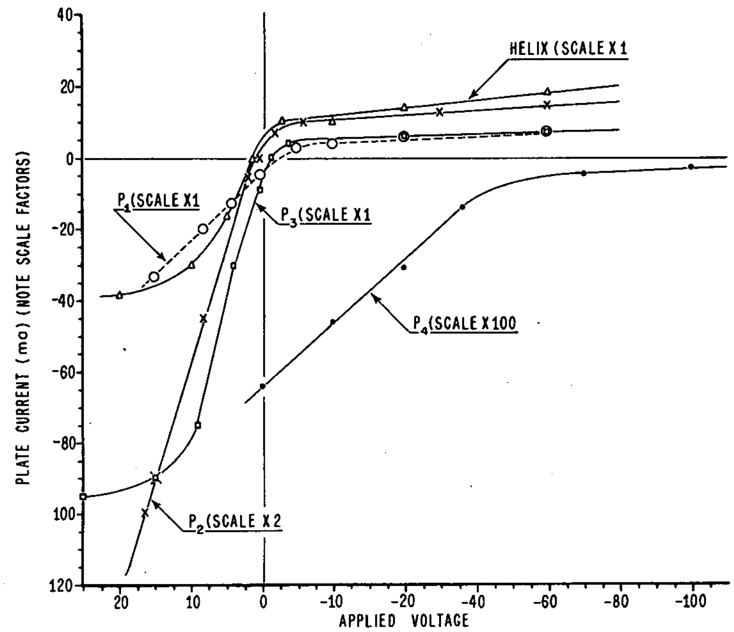
* The anode was grounded and the cathodes operated at a negative potential.

ION PUMP DRAIN PLATE LOCATION



MU-6058

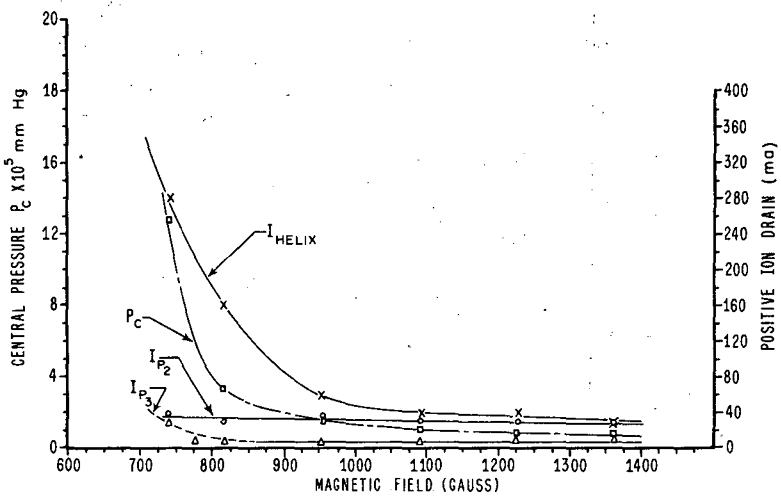
Fig. 15



DRAIN PLATE CURVES FOR OPERATION AT 300 V., 10 A.

MU-6016

Fig. 16



EFFECT OF MAGNETIC FIELD ON ION DRAIN AND CENTRAL PRESSURE.

MU-6013

Fig. 17

One does not know whether or not the ion density in the column is constant for various magnetic fields, and hence a direct calculation on the diffusion across the magnetic field is not simple. However, one can certainly see that an increase in magnetic field decreases the drain and the minimum central pressure. Equating the flow of neutral particles into the discharge to the measured ion drain in the central region, one finds that although the measured current is probably a little high, it fails to account for more than a third of the central pressure rise. Of course not all the ion drain in the central region was measured, and the ion bombardment may release additional gas particles.

(c) Plasma hash.[15] This refers to the observation that the ion pump could be operated so that many watts of noise power were generated. (It was particularly noticeable whenever an effort was made to replace either the reflecting cathode or both cathodes by cold aluminum cathodes[11]). With a hot cathode, the noise amplitude could be varied by slight adjustments to the filament temperature. It was found that the lowest pressure in the central region was obtained when the noise was adjusted to a minimum. In general, most of the noise lay in a band from 10 to 100 kc. However, using an AN/APR-4 Receiver, one can easily pick up strong signals from 70 to 3000 Mc/sec. Many of these signals have a width of several megacycles, and some are less than 300 kc wide. If a small condenser is connected between cathode and anode at one end, then except for a few signals, the frequency distribution is completely changed. The interpretation taken is that the discharge is a noise source and those frequencies associated with certain modes of the container are reinforced. The pressure change is associated with the fact that fluctuating electric fields within the plasma can increase the rate at which positive ions diffuse across the magnetic field to the walls.

(d) Recombination. One may suppose some of the minimum pressure in the central region to be due to the production of neutral particles from ion-electron recombination within the discharge. The rate at which neutrals are made in a unit volume of plasma containing an ion density N is given by

$$\frac{dN}{dt} = \alpha N^2 \quad (N_e \simeq N_+);$$

α is the recombination coefficient.

If one assumes that the minimum central pressure is all due to recombination, one can obtain an upper limit for the coefficient. We then equate the rate of neutral production in the discharge per unit length to the rate at which neutrals are ionized.

$$\alpha N^2 \ A = N_o S_\ell$$

where N_o is the neutral particle density given by the ion-gauge reading set for air, and S is the pumping speed per unit length of discharge whose cross section is A.

for
$$\left(\begin{array}{ll} P_{min} & = 10^{-6}\text{mm}; \ N_o = 3.5 \times 10^{10}\text{mols/cc.} \\ A & = 16 \text{ sq. cms.} \\ S & = 3 \times 10^{4}\text{cc/sec} \\ N & = 5 \times 10^{12}\text{ions/cc} \end{array}\right.$$

$$\alpha < \underline{2.6 \times 10^{-12}}$$

First of all, it should be stated that this coefficient is known for only a few special situations. Recently, Biondi and Brown[12] have obtained the following electron-ion recombination rates by microwave techniques:

$\alpha_{He} = 1.7 \times 10^{-8}$ $\qquad$ $\alpha_{H2} = 25 \times 10^{-7}$

$\alpha_{Ne} = 2 \times 10^{-7}$ $\qquad$ $\alpha_{N2} = 14 \times 10^{-7}$

$\alpha_{A} = 3 \times 10^{-7}$ $\qquad$ $\alpha_{O2} = 3 \times 10^{-7}$

These measurements were made in the temperature region between 77^{o} and 300^{o}K. The noble gases showed no temperature sensitivity, while the coefficients for the molecular gases varied approximately as T^{-1}. These experimental conditions involve only molecular ions and low energies. The ion pump discharge contains mainly atomic ions, and the average electron energy is a few volts. It is clear of course that such large coefficients would certainly prevent this ion pump from reaching a low pressure.

Recombination coefficients in low-pressure arcs have been measured for some time.[13] An order of magnitude for the values obtained with various gases is

$$\alpha \simeq 2 \times 10^{-10} \qquad (T \simeq 3000^{o}\text{C})$$

and the observers usually found some pressure dependence, which indicates something other than the postulated two-body problem.

For hydrogen-like atoms, when the kinetic energy of the electrons is small relative to that of the level into which the electron falls, the recombination coefficient α_n for that level is given roughly by[13, 14]

$$\alpha_n \simeq \frac{5.94 \times 10^{-13} A_n}{V^{1/2}} \qquad (1) \qquad \begin{array}{l} V = \text{electron energy (e. v.)} \\ A_n = \dfrac{0.326}{n} \quad \text{for } n \geq 3. \end{array}$$

When the electron's kinetic energy is much greater than that of the level n, (Oppenheimer)

$$\alpha_n \simeq \frac{6.3 \times 10^{-11}}{V^2 n^3} \qquad (2)$$

Equation (1) is used for $n < n_o$ where

$$n_o = \left(\frac{13.54}{V}\right)^{1/2}$$

and equation (2) for $n > n_o$;

Now $\alpha = \sum_{1}^{\infty}{}_n \; \alpha_n$

and if we take $V = 4$ ev,

$$\alpha \simeq 8 \times 10^{-13}$$

with most of the contribution coming from equation (2). This is quite close to the value of α obtained on the assumption that <u>all</u> the base pressure was due to recombination, i. e. $\alpha < 2.6 \times 10^{-12}$.

Some experimental information that might lead one to believe that recombination is playing a limiting role is as follows. In order to obtain low base pressures, one needs to operate at voltages above 300 V. The current used is not critical so long as it is above the minimum determined by the total gas flow into the pump. The voltage (300 V) is well above that value for which the ionization cross section is a maximum--and indeed, the pumping speed is not very sensitive to the operating voltage. A possible explanation is that the base pressure is being limited partly by recombination, and since operation at higher voltages raises the average electron energy, the recombination rate is reduced. (The average electron energy is estimated at 2 to 4 volts.[15])

In addition, there is some evidence indicating that this type of pump will not pump well when operated completely on hydrogen. However, if the discharge is sustained by an air leak at the cathode instead of a hydrogen leak, one then obtains a good base pressure and a good pumping speed for hydrogen. The explanation offered is based on the supposition that the recombination rate for oxygen and nitrogen is less than for hydrogen. The hydrogen-ion density in the discharge column is less when air is used to sustain the discharge, and hence the recombination rate is reduced.

Relation Between Gas Flow and Discharge Current

Cathode Current

Having obtained some information about the ion ratio in the discharge, one can relate the flow of neutral particles into the discharge to the current flowing in the cathode leads. Current measurements were made only on the reflector cathode and every effort was made to keep the gas pressures and magnetic fields symmetrical.

It has been found that the discharge contains several types of ions, involving a combination of one or two atoms and having one or more charges removed, e.g. N_2+, N_1+, N_1++, etc. These ions are separated and identified by a magnetic field, and the current i_j associated with each type j is measured. We wish to determine the average number $\bar{n}$ of charges per atom in the extracted beam.

$$\bar{n} = \frac{\text{Total collected charge}}{\text{Total number of atoms}}$$

$$\bar{n} = \frac{\sum_j i_j}{\sum_j \frac{i_j}{q_j} n_j}$$

where q is the number of charges on the ion and n_j is the number of atoms in a type j ion.

Using the results of the ion analysis made with nitrogen gas at the center and cathode of the pump, one obtains values of $\bar{n}$ which are $\bar{n}_c = 0.98$ and $\bar{n}_k = 0.66$. The subscripts c and k refer to central and cathode regions respectively.

In the general description it was stated that the neutral particles in the central region are ionized and delivered by the discharge to the cathodes. At the cathodes the ions are neutralized but in attempting to leave the discharge some are re-ionized and returned to the cathode. To determine the positive-ion cathode current associated with a given gas leak at the center of the pump, it was necessary to first set the reflector cathode sufficiently negative so that no electrons would be received. Figure 18 is a plot of the positive-ion cathode current found for various cathode potentials, and indicates what voltage must be applied so as to be on the flat portion of the curve. (The ratio of secondary electron current to bombarding positive-ion current is < 0.1 at these energies and will be neglected).

A cathode bias of -400 V was selected. First a fixed leak of 0.03 cc/sec. was admitted at the center of the pump. Then to determine the contribution to the cathode current due to the local cathode gas pressure, the pressure at each cathode was set at several values, while leak and voltage were held constant. The results are given in Fig. 19 and the extrapolated current at zero cathode pressure gives a cathode current of 0.7 amperes for a total center leak of 0.03 cc/sec. (23.3 amps/cc). The cathode pressures are made equal so that the diffusion of positive ions from the central region to each cathode will be roughly the same.

As a check on the above result, the cathode pressures were held fixed, and the central leak was varied. These measurements are recorded in Fig. 20 and the slope gives a value of 22.5 amps/cc/sec, which is considered to be in good agreement with the first result.

The above values seem rather high when one realizes that if the molecules were ionized to singly charged atoms and simply delivered to each cathode the current would be 8.7 amps/cc/sec. A factor that contributes to the cathode current is the fact that some ions that are neutralized at the cathode and attempt to go some distance through the discharge are re-ionized and returned without leaving the discharge column. Each time this recycling in the cathode region is repeated, a charge of $\bar{n}_c$ per atom must be supplied to the cathode.

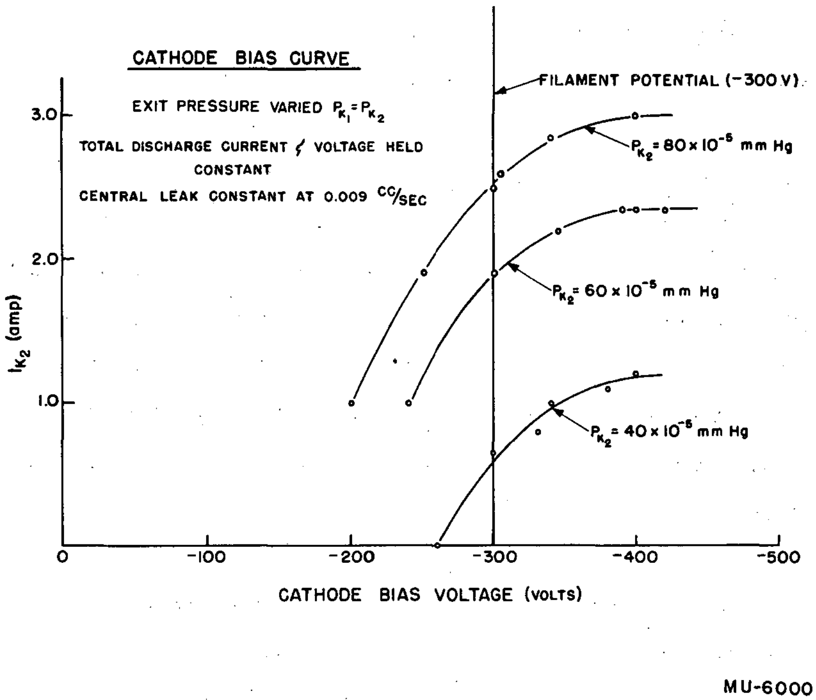
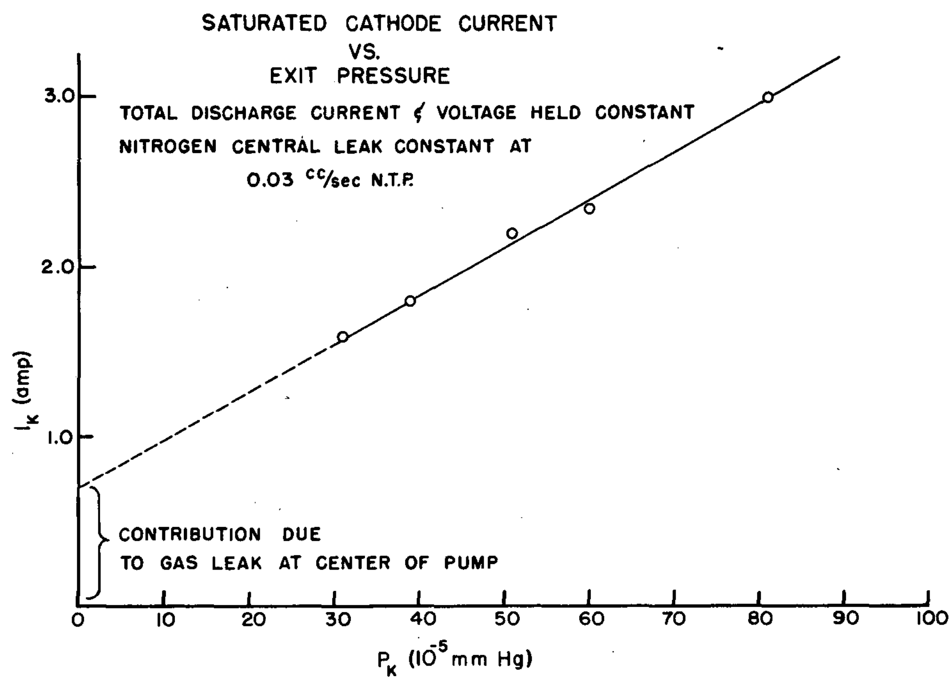
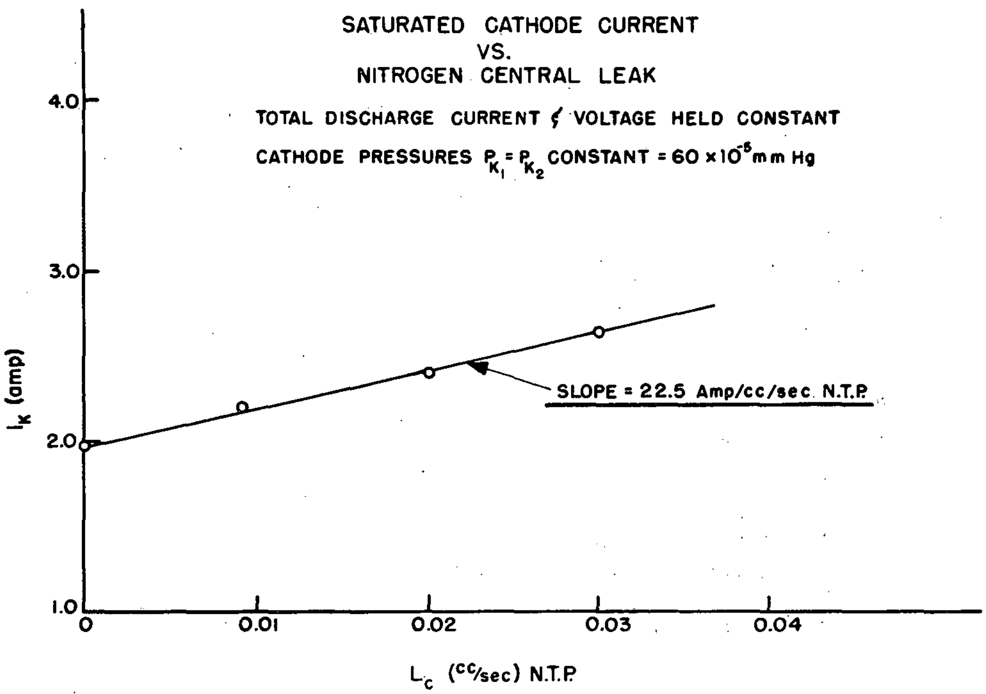

CATHODE BIAS CURVE
EXIT PRESSURE VARIED $P_{K_1} = P_{K_2}$
TOTAL DISCHARGE CURRENT & VOLTAGE HELD CONSTANT
CENTRAL LEAK CONSTANT AT 0.009 CC/SEC
FILAMENT POTENTIAL (−300 V)
$P_{K_2} = 80 \times 10^{-5}$ mm Hg
$P_{K_2} = 60 \times 10^{-5}$ mm Hg
$P_{K_2} = 40 \times 10^{-5}$ mm Hg
I_{K_2} (amp)
3.0
2.0
1.0
0
−100
−200
−300
−400
−500
CATHODE BIAS VOLTAGE (VOLTS)
MU-6000

Fig. 18



MU-6001

Fig. 19



MU-6002

Fig. 20

One can then equate the number of gas atoms which are let in at the center due to the central leak L_C, to the neutralizing current at the cathode I_K (amperes)

$$L_C \times 5.44 \times 10^{19} = \frac{I_K \times 6.24 \times 10^{18}}{\bar{n}_c (1 + R)}$$

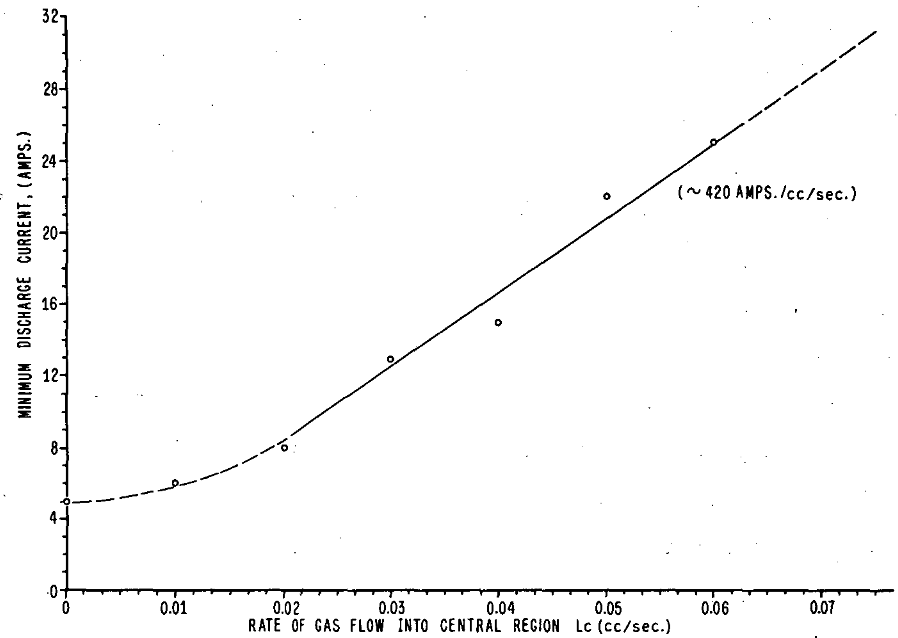
where R is the number of times the incident particle is re-ionized and returned to the cathode. (There are 5.44×10^{19} atoms/cc. N.T.P. and 6.24×10^{18} charges per sec/amp). If the values for I_K, L_C, and $\bar{n}_c$ are inserted, the value obtained for R is ~1.7. It is assumed here that the number of charges and atoms in a particle is <u>not</u> altered from what it had on initially striking the cathode. Therefore the value of R = 1.7 means that after striking the cathode, the particles on the average reenter the discharge 1.7 times to be re-ionized, and then leave the discharge column to contribute to the exit gas pressure, or is lost by absorption or chemical action. This value seems reasonable considering the geometry; no attempt was made to change the geometry in the cathode region to verify the interpretation.

<u>Net Discharge Current</u>

This is the current that must be supplied by the discharge power supply, and it does not refer to the total current in the discharge column. The net discharge current used depends on the pump geometry, discharge diameter, and the central and exit pressures. In general this current has a minimum value, but higher values may be used without changing the central pressure. Figure 21 gives values of current required for different gas loads.

One can measure the effectiveness of the reflector cathode by running it at anode potential. Under these conditions the electrons are not reflected and one can obtain approximately the same base pressure, but the net discharge current must be increased by a factor of 5 to 20*. This factor cannot be used as a direct measure of the number of trips made by an electron when both cathodes are at the same potential, but it does indicate the advantage of using a reflector cathode.

* The factor is highest when the central and exit pressures are low, so that an electron has fewer collisions between cathodes.



MINIMUM DISCHARGE CURRENT AS A FUNCTION OF GAS LOAD.

MU-6014

Fig. 21

V CONCLUSIONS

1. It is difficult to predict the degree of success that will be reached finally, since this development is less than a year old and a certain amount of engineering development remains to be done to achieve long-term reliability and lower operating costs. The greatest advantage of the ion pump over diffusion pumps is the complete absence of any working fluid other than the gas let in at the cathode. In some applications it is very important to avoid contamination from pumping fluid, and elaborate and costly baffles must be provided. In evaluating the ion pump, the comparison should be made with conventional pumping systems, allowing for the reduced speed due to baffles and the increased operating cost (including refrigerants). This ion pump compares favorably with a 32 inch mercury-diffusion pump with liquid-nitrogen baffles.

2. The ion pump cannot be considered as an ideal experimental setup to investigate fundamental properties of discharges in magnetic fields. It is nevertheless, a new example of their application, and it was possible to measure a few effects that limit the pumping speed and base pressure.

3. A measurement of the ion energies by Doppler shift gave an upper limit to the average ion energy of only 0.7 ev. This value is only about one fifth of what was expected.

4. The ion density was found to be about 10^{12}, as one could predict from the work of Massey and Bohm.

5. An interesting property of the discharge is that in the central region almost 100% ionization is obtained. Most intense discharges have only 15 to 20% of the particles ionized. The basic reason for this, of course, is that the effects of recombination on walls and cathodes were reduced by a combination of magnetic field and special geometry.

6. Great improvements in performance and simplicity can certainly be made by further development.

7. The gas discharge conditions in this ion pump are rather unusual, and one is prompted to apply the techniques to other problems. The discharge contains a high ion density and low neutral density. In addition, a good many of these ions are multiply ionized. One suggestion is to use a small version of the ion pump as an ion source, with extraction from either the central or cathode regions. Two other possibilities are outlined in Appendices 1 and 2.

VI ACKNOWLEDGMENTS

It is a great pleasure to express my thanks to Professor Ernest Lawrence for the initiation and overall direction of this work. I would also like to thank my group leader, Dr. E. J. Lofgren, and other members of his group, particularly Paul Byerly, Bruce Cork, Warren Eukel, and Forrest Fairbrother. Professor Jenkins, John Howard and Ervin Woodward kindly provided optical equipment and gave valuable help and suggestions. Marion Jones supervised the electrical installation and maintenance.

APPENDIX A: THE PRODUCTION OF PULSED NEUTRONS

An experiment was made to demonstrate another possible application of this type of discharge. The general idea is to take advantage of the conditions that exist in the central region of the pump. In particular, there is a well defined column of ions in a region of very low gas pressure ($\sim 5 \times 10^{12}$ ions/cc; $\sim 10^{11}$ neutrals/cc).

Neutrons were produced by using the reaction

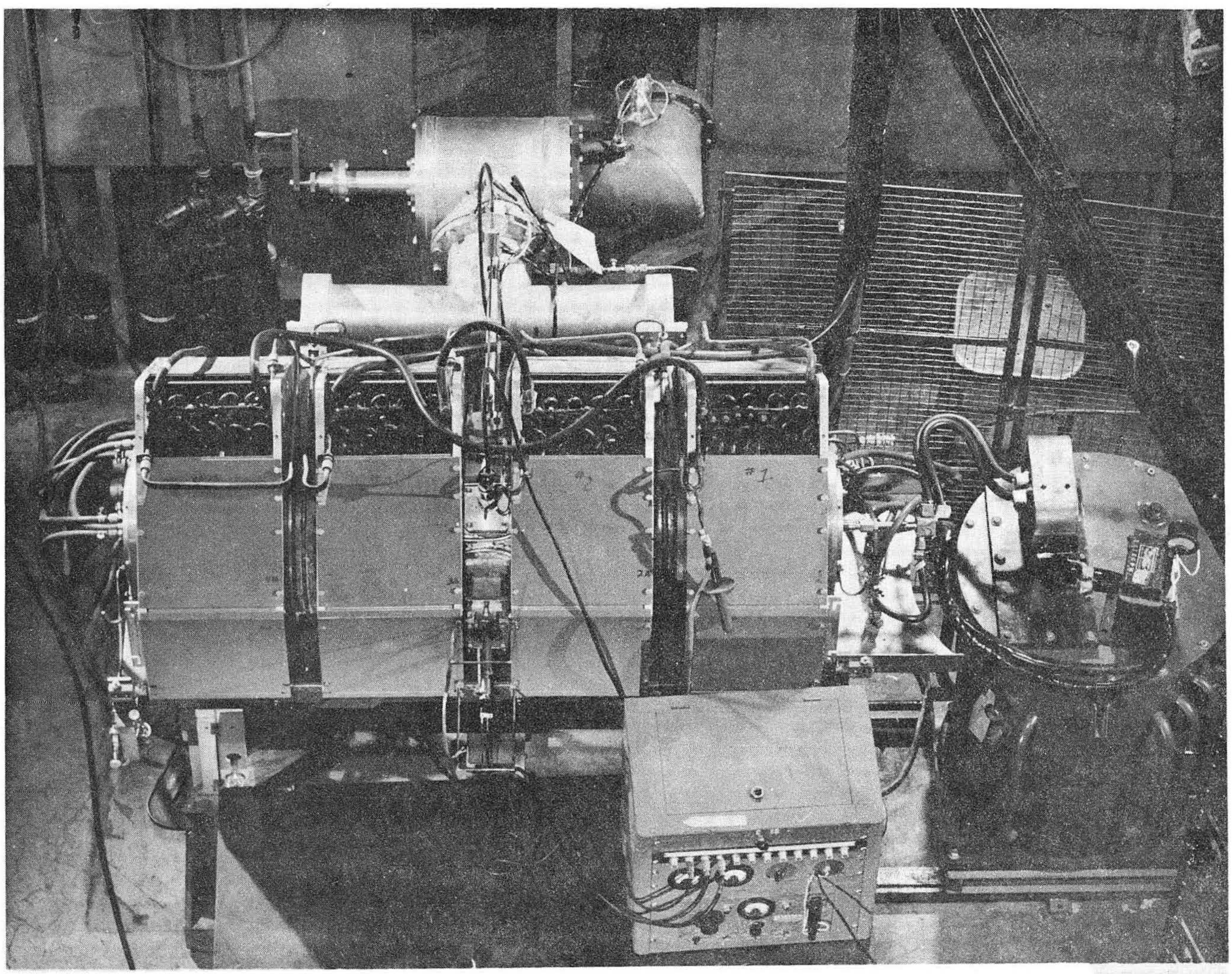
$$D + D \rightarrow n + He^3 + 3.25 \text{ Mev}.$$

The arrangement used is shown in Figs. 22a and 22b*. An electrode was placed close to the cylindrical ion column, and insulated so that a -100 kv pulse reached full voltage in about 3×10^{-7} sec, and had a length of about 10^{-6} sec. A titanium plate was mounted on the pulsed electrode, and faced the discharge. This plate was "loaded" with deuterium, and the discharge was run with deuterium gas. When the target is pulsed negatively, D^+ ions are accelerated from the surface of the discharge and collide with D atoms in the target. Neutrons from the reaction leave with approximately spherical symmetry and are detected by a Geiger counter wrapped with a silver foil and surrounded by 1-1/2 in. of paraffin moderator. The detector counts the beta activity of the silver nuclei.

The detector arrangement was calibrated by means of a known RaBe source placed at the target position. Using a -100 kv peak pulse, 2.5×10^5 neutrons were produced per pulse. The pulse rate was limited by the charging supply to about 2 pulses per second. A pulse rate as high as 10^3 pulses/sec is believed possible.

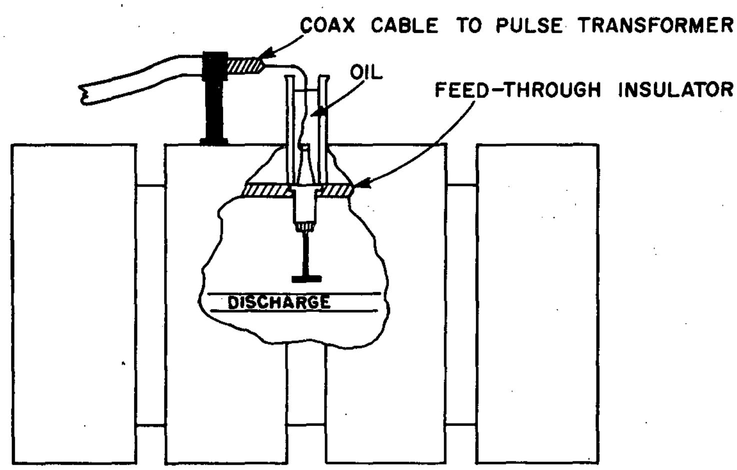
For pulsed neutron work, it is desirable to obtain a short pulse ($< 10^{-6}$ secs), containing as many neutrons as possible. The pulse length has a minimum value determined by the electrical circuit. The free rise time of the circuit used was $\sim 2 \times 10^{-7}$ secs. If the target area is increased in an effort to increase the neutron yield, the capacity of the system is increased, and hence the pulse length increases. However, the target area should be increased until it represents a good fraction of the total capacity.

* For the pump shown in Fig. 22a, the base pressure was only 10^{-5}mm, and best results were obtained at $\sim 2 \times 10^{-4}$mm.



ZN - 700

Fig. 22a



MU-6059

Fig. 22b

A figure of merit for such a source might be given by $Y/\Delta T$, the total neutron yield per pulse divided by the pulse length. In this connection it is of interest to investigate very briefly some of the events that take place during the pulse of ion extraction. Since the energy of ions in the discharge is less than 0.6 volts, their velocity is $< 8 \times 10^5$ cms/sec, and hence during a 3×10^{-7} sec pulse rise time they move less than 0.24 cm. Suppose, however, that we consider these ions to be stationary, so that as ions are removed from the surface of the discharge a "cavity" with an increasing depth x is created. Electrons, with their high mobility, migrate from the volume very quickly. We can then equate the ion current density flowing to the target for a time interval dT to the ion density and volume element of "cavity" created.

i.e: $$I\,dT = n_+ e\,dx$$

but $$I = \frac{KV^{3/2}}{x^2} \qquad \text{(Child's Law)}$$

and if $$V = \alpha T \qquad \text{(linear voltage rise)}$$

$$x^2\,dx = \frac{KT^{3/2}}{n_+ e}\,dT$$

$$x^* = \left(\frac{6\,K\,\alpha^{3/2}}{5\,n_+ e}\right)^{1/3} t^{5/6}$$

In the experiment, the voltage rose to 100 kv in about 3×10^{-7} secs, and the ion density was about 5×10^{12} ions/cc. This gives a "cavity" depth of 0.9 cms after only 3×10^{-7} secs. Since ions within the plasma move about 0.24 cms during this time, it indicates that for ion densities $< 5 \times 10^{12}$ and pulse lengths $< 10^{-6}$ secs, the notion of a cavity formation is good.

From the space charge relation one sees that ion current varies inversely as the square of the plasma-target separation. Since the neutron yield increased both with ion voltage and current, it is important to have a fast voltage rise.

* Provided it is assumed that the electrode was initially at the space potential of the plasma so that x = 0 at T = 0.

With a fast rise, the voltage corresponding to a large D-D cross-section is reached before the plasma-target separation becomes large, and hence a large ion current can be drawn. The notion can be expressed in the figure of merit for a pulsed source, and with crude approximations as given below.

$$\frac{Y}{\Delta T} = \int_{-\infty}^{\infty} \frac{1}{\Delta T} \left(\begin{matrix}\text{Number of neutrons}^{*} \\ \text{per deuteron}\end{matrix}\right) I dt$$

We now obtain an expression for x^2

$$I = ne \frac{dx}{dt} = \frac{KV^{3/2}}{x^2}$$

$$x^2 dx = \frac{KV^{3/2}}{ne} dt$$

Assume $V = V_o \sin(\frac{\pi}{\Delta T} t')$

$$\text{Then} \int_o^x x^2 dx = \frac{K V_o^{3/2}}{ne} \int_o^t \sin^{3/2} (\frac{\pi}{\Delta T} t') dt'$$

$$x^3 = \frac{3KV_o^{3/2}}{ne} \left(\frac{\Delta T}{\pi}\right) \int_o^t \sin^{3/2}\left(\frac{\pi t'}{\Delta T}\right) d\left(\frac{\pi t'}{\Delta T}\right)$$

$$\therefore \quad x^2 \sim V_o (\Delta T)^{2/3}$$

Hence

$$\left[\frac{Y}{\Delta T}\right] \sim \frac{V_o^{7/2}}{V_o (\Delta T)^{2/3}} \int_o^{\Delta T} \text{Sin}^{7/2} \left(\frac{\pi}{\Delta T} t\right) d\left(\frac{\pi}{\Delta T} t\right)$$

$$\left[\frac{Y}{\Delta T}\right] \sim \frac{V_o^{5/2}}{(\Delta T)^{2/3}}$$

* E. Fermi, Nuclear Physics, p. 180.

Pulse transformers with a peak voltage of 300 kv and a rise time of 5×10^{-8} sec. can be built. Using these values and the above scaling law, one would predict an estimated yield of 10^7 neutrons per pulse. The experiment described above was performed to indicate the possibilities, but no time was available to experiment with the various parameters. This system is much simpler than similar types described in the literature which involve an ion source, accelerating and focusing electrodes, target, and vacuum system as separate units.*

* W. H. Zinn and S. Seely, Phys. Rev. 52, 919 (1937).

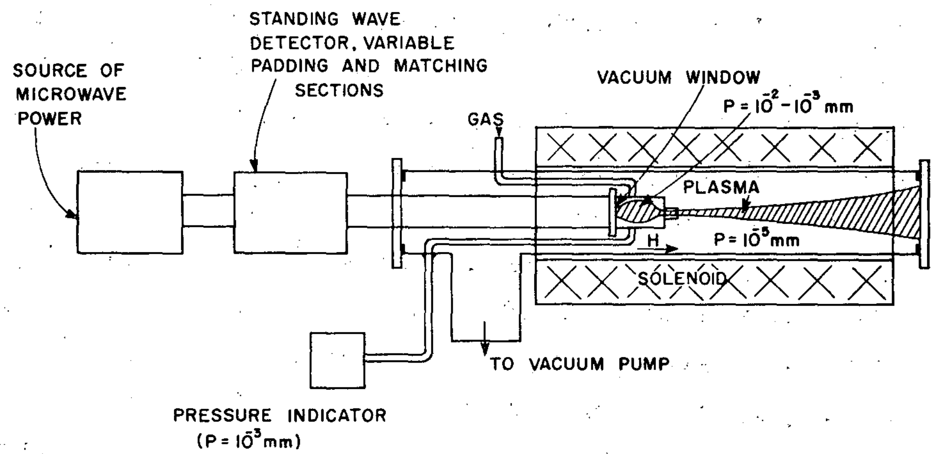
APPENDIX B: SUGGESTION ON A "PLASMA GENERATOR"

The rate at which positive ions and electrons in a plasma diffuse across a magnetic field is of great interest. Simple theory predicts a H^{-2} dependence, while many observations give a H^{-1} dependence.[16] The most common reasons advanced to explain the experimental results are the presence of high neutral-particle densities and plasma oscillations. In the case of plasma oscillations, it is believed that they are associated with the column of ionizing electrons used to maintain the discharge (Bohm-Backus[11]).

It would be very helpful if one had a "black box", which would deliver a plasma that was free of electron beams and neutral particles. Then one might be able to measure the interaction of charged particles in a magnetic field with and without electron beams and appreciable neutral densities. The notions involved in the design of the ion pump suggest the following scheme. A plasma is formed in a region of relatively high gas pressure, and then guided to a region maintained at a relatively low gas pressure. In a sense, this is just what takes place in the ion pump discussed here. (The discharge is formed in the higher-pressure cathode region, and the charged particles can move along the magnetic field into the low-pressure central region). One can accomplish this with the simple geometry suggested schematically in Fig. 23. The output power from a magnetron is sent in the TE_{10} mode through a power divider, standing wave detector, and matching section, and finally it passes through a vacuum window to enter a half-wave-length section of waveguide at low pressure (10^{-2} to 10^{-3}mm). The magnetic field that passes through the final section of guide as shown in the figure is adjusted so that the cyclotron frequency for electrons F_c is equal to that of the magnetron F_m.

$$F_c = \frac{eH}{2\pi m_e c} = F_m$$

Under these conditions, electrons in the low-pressure section receive the most energy from the electric field, and a plasma can be produced with only a few watts[17]. With sufficient power and gas pressure, the ion density in the plasma, n, is expected to increase until the electron plasma frequency F_p approaches the magnetron frequency[18].



MU-6060

Fig. 23

$$F_m \geqslant F_p = \left(\frac{ne^2}{\pi m_e}\right)^{1/2} = 8980\, n^{1/2}$$

If $$F_m = 3000 \text{ mc/sec.} \quad (\lambda = 10 \text{ cm})$$

$$n_{max} \simeq 10^{11} \text{ ions/cc.}$$

Plasma formed in the waveguide diffuses out through the short section of small-diameter tubing into a region maintained at lower pressure (10^{-5}mm) by a diffusion pump. The purpose of the short section of tubing is to reduce the rate of gas flow from the waveguide section, and because of the magnetic field, it has little effect on the charged particles.

Hence, in the low-pressure region one has a low-temperature plasma, drifting along the magnetic field, without the presence of an electron beam or frequent collisions with neutral particles. The development of such a device is under way and it is hoped that it proves to be a useful tool.

Note added in proof: The "generator" described above is now in operation. Preliminary observations indicate that the plasma from the generator has the expected density.

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