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ABSTRACT

The ion magnetron is an experiment in which a plasma is created in a geometry similar to that of the well-known electron magnetron tube. An electron sheath forms about the central anode, and most of the applied-voltage drop occurs in this sheath region. Ionization of neutral molecules in the sheath provides an irreversible mechanism for injecting high-energy ions into the containment region. Experimental observations on the device are described, followed by a short discussion of some of the processes involved in its operation.

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INTRODUCTION

The work to be discussed in this paper had its beginning in February of 1957, with the accidental discovery of a rather strong charged-particle-trapping effect in certain combinations of static electric and magnetic fields. The trapping effect was found in the course of the development of an ion source, and proved so interesting to the authors that work was diverted to an experimental investigation of the properties of gaseous discharges in the presence of crossed electric and magnetic fields. The ion magnetron[1] described in this report resulted from further development of this trapping effect. It is unnecessary to trace here the steps in this development. Therefore, we begin with a bare description of the concept.

In the early nineteen twenties, A. W. Hull[2] demonstrated that stable charged-particle orbits can exist in a region bounded by charged coaxial cylinders and containing an axial magnetic field. If the ratio B_z/E_r is made sufficiently large, ionic particles emitted from the surface of one charged cylinder cannot reach the other. Ions or electrons formed in the space between the cylinders, in a region differing in potential from that found on the cylinders, may be trapped in such a way that, in the absence of perturbing forces, the orbit will fail to intersect either electrode surface.

The critical magnetic field required to produce cutoff is easily shown to be independent of the radial potential distribution, but is not independent of the direction of the electric field resulting from the application of potential. A much larger value of B is required to cut off the flow of particles accelerated radially inward than to cut off the flow of similar particles accelerated radially outward.

We have found experimentally that an electron sheath forms on a positive electrode whose surface is parallel to the magnetic field, if an appreciable ion density is available. (This is because the electrons are the particles of low radial mobility in a plasma in a strong magnetic field, and is the reverse of the usual gaseous-discharge situation.) The electron sheath serves to ionize gas molecules incident thereon and the radial electric field accelerates such particles into the surrounding space. If there were no background of particles--that is, if a perfect vacuum existed in the space between the coaxial cylinders--the only interactions would be between the particles injected, and would occur at points of intersection of the orbits. Further, the orbits, though intersecting, would be highly ordered, and the ratio of tangential velocity to axial velocity would be extremely high. This suggests the possibility of efficient magnetic containment, and we would reasonably expect to be able to contain the particles for a time long enough to observe mutual interactions. In fact, only the mutual interactions could disturb the orbits sufficiently to result in particle loss.

If the product of the magnetic field and radius is made large, ions of very high energy can be contained, and it is well known that the scattering cross sections decrease with increasing energy, while the nuclear reaction cross sections increase. In the limit of perfect vacuum, where the only particles in the space are the fast ions, an interesting operating condition can be found, at least in principle. On the basis of this simple idea, our program of research was undertaken in May 1957.

EXPERIMENTAL GEOMETRY

The experimental geometry is shown in Fig. 1. Both the magnetic field and applied voltage are dc. The solenoidal magnet is 48 inches long and has an inner diameter of 9 inches. The middle half of the magnet winding is connected to one power supply, and the end windings are connected to another supply, so that the magnetic mirror[3] ratio can be varied. Some operation has been carried out with equal currents in the middle and the end coils, which gives a solenoidal magnetic field. At each end of the magnet there is a circular iron plate 2 inches thick with a 9-inch hole in the center. The outer surface of the coils has a 1-inch-thick iron sheath. This iron is needed to confine the magnetic field within the active volume so that spurious discharges do not occur in the vacuum pumping systems. The strongest mirror field available is 12 kilogauss, and the strongest central field is 8 kilogauss.

An 8-inch-diameter water-cooled stainless steel pipe called the liner is inserted inside the magnet. One end of the liner has a quartz port through which the discharge can be observed, while the other end is connected with the vacuum pump. In a later modification both ends of the liner were pumped. A water-cooled copper rod 5/8 inch in diameter is supported on the axis of the machine. The end of the rod nearest the viewing port is not supported, so that the rod is free to oscillate as a pendulum. The center rod is at a potential of a few kilovolts positive with respect to the liner.

The vacuum system consists of an oil diffusion pump with liquid nitrogen traps. The base pressure at the liner as measured on the VGIA ionization gauge is 5 to 10×10^{-7} mm Hg. Metal vacuum gaskets are used in order to avoid introduction of organic contaminants.

The dc high-voltage supply is capable of 4 amperes at 12 kilovolts. An RC filter with 1000 ohms and 18 microfarads is used to protect the supply from surges.

Deuterium gas at pressures of up to 1 micron flows into the system from many small holes in the center rod. Alternately the gas can be supplied through a tube connected at the port end of the liner.

Some experimental work was done with a smaller machine, similar to the above except for having a 6-inch-diameter liner, a weaker magnetic field (which could be on for only 30 seconds because of insufficient magnet cooling), and a vacuum system with rubber gaskets and a base pressure of 5×10^{-6} mm Hg.

EXPERIMENTAL OBSERVATIONS

In early experiments with the smaller machine described above, it was observed that the electrical discharge in the device could produce radial oscillation of the center rod. Under certain conditions of magnetic field and discharge current, the magnitude of the oscillation was sufficient to cause the center electrode to strike the liner. Since the force constant of the rod was 100 grams per centimeter, it was clear that considerable forces were acting on the rod. The frequency was approximately the natural frequency of the rod, which was a few cycles per second. The current was about 1 ampere while the rod was centered, and 0.5 ampere while the rod was off center; the pressure was 1 micron, the potential 5 kilovolts, and the magnetic field 1 to 2 kilogauss. The stronger magnetic field seemed to inhibit the oscillations.

The magnitude and direction of the force acting on the center rod could not be clearly measured by studies of the oscillation. A related experiment, however, led to what appears to be a useful hypothesis concerning the origin of the forces. This experiment was carried out by deliberately positioning the electrode about 1 inch off axis. A discharge running with a steady current of about 1 ampere was established, and the motion of the electrode as a function of the magnetic field intensity was observed. With the rod well off center, the tendency toward oscillation was greatly minimized. It was found that the rod was first displaced toward the center of the liner with increasing magnetic field but that, beyond a certain value of magnetic field, the radial force began to decrease. As the magnetic field was further increased, the displacing force became very small, and the rod returned to its original position. The actual motion of the rod did not lie in a plane. The motion of the tip described a roughly circular path in space over the range of magnetic field involved. This effect could possibly be explained in terms of the forces resulting from ions circulating in magnetronlike orbits about the center electrode. Asymmetry in the system would result in an unbalance in the electrostatic forces that result from the reflection of ions at the positively charged electrode. One ampere of 5-kilovolt deuterons being reflected would exert a force of about 2-1/2 grams.

To test whether the forces on the rod were motor forces ($\vec{J} \times \vec{B}$) or electrostatic forces, the quartz port was removed. With the system at room pressure, a fine wire was attached to the free end of the rod, and returned electrically to ground through a resistor, so that the same voltage and current could be applied to the rod, with of course the same magnetic field. The fine wire did not inhibit the motion of the rod, yet no movement was observed under these conditions.

In order to test the circulating-ion hypothesis further, a vane two inches long in the axial direction and 1 inch in the radial direction was inserted in the liner, supported on a tube which ran through a Wilson seal (Fig. 2). As the vane was pivoted from a position parallel to the liner to a position perpendicular to the liner, where it could intercept ion orbits, the center rod moved toward the vane.

A "flag" was then inserted in the liner, of the same size as the vane, but pivoted so it could swing freely, and made of very light material so that a fraction-of-a-gram force could move it. The flag and the vane were 60 degrees apart in azimuth, and initially were both mounted in the center of the machine. When the vane was parallel to the liner so that it would not intercept ion orbits, the flag was deflected a few degrees in the $\vec{E} \times \vec{B}$ direction. If the magnetic field was reversed the flag deflection reversed. When the vane was turned to the perpendicular position, where it could intercept ion orbits, the flag deflection decreased. With the flag at the center of the machine, the vane was withdrawn axially, and the test was repeated in order to observe the axial motion of the ions. With the vane 12 inches away, the flag would still respond to a rotation of the vane. For these tests the center rod was placed so that it did not move.

Since the above observations indicated that an interesting ion density might be present, the larger machine described above was constructed. It was baked out at high vacuum, and then deuterium gas at a pressure of approximately half a micron was flowed through the liner. When a voltage of 5 kv was turned on, the region of strong magnetic field was filled with a diffuse glow, together with one or two bright cylindrical shells, and there was a dark space on the order of 1 to 3 millimeters thick surrounding the center rod. As the rod oscillated the bright rings and the dark space remained approximately concentric with it. For the magnetic field available the magnetron cutoff voltage would be about 50 kilovolts for deuterons and 25 kilovolts for the molecular ion D_2^+.

With the dc magnetic field on and deuterium gas flowing through the liner, the dc high voltage was switched on. The effects on the gauge pressure, tube current, and tube voltage are shown in Fig. 3. If the gas flow has been set correctly, the pressure and tube current stabilize; however, if the gas flow is too great the pressure and tube current build up until the power supply can no longer furnish the current.

Neutron emission from the magnetron has been investigated by using seven BF_3 counters in a paraffin moderator. The moderator was encased in cadmium sheet to reduce the background of thermal neutrons, and this was in turn surrounded on five sides by 8 inches of boron-paraffin which moderated and absorbed epithermal and moderately fast neutron background. When the geometry shown in Fig. 1 was modified to include pumping at both ends of the tube, the neutron rate increased by an order of magnitude, so that with steady operation at a tube voltage of 10 kilovolts and a tube current of 1 ampere, the neutron production was a few times 10^4 per second. Figure 4 shows the variation of neutron yield with tube voltage, and Fig. 5 illustrates the effect of a change in the symmetry of the system produced by displacing the central anode away from center.

An attempt has been made to determine the electron density in the region external to the sheath by microwave phase-shift measurements. An 8-mm wave guide was mounted inside the center rod, which radiated through a number of slits cut in the rod wall. A horn was mounted in the liner to receive the signal. This procedure yielded no positive evidence for the existence of a plasma; however, the method was sufficiently crude that one cannot exclude a plasma effect possibly as great as half a fringe ($N \sim 10^{12}$ electrons/cc) averaged over the radial distance. The plasma did not cut off the microwaves; therefore the average electron density was certainly less than the cutoff density, which is 1.5×10^{13} electrons/cc.

DISCUSSION

The formation of the central anode sheath is fundamental to the operation of this device. When the voltage is first applied to the tube its distribution is that of a vacuum field. Any ions that exist are accelerated outward, and ions that have collisions while they are near the outer wall may be lost to the wall. Ions may also be lost to the end walls by traveling along magnetic lines under the action of the electric field. The electrons, on the other hand, are restricted to radial excursions much less than a millimeter and thus remain at the radial position at which they are born. As further ionization proceeds, with some ions being lost to the walls, a negative space charge is built up inside the tube and the potential is depressed with respect to the vacuum field. This leads to the formation of a sheath of electrons around the central conductor, across which most of the applied voltage appears. Simple considerations suggest that the sheath thickness should be roughly equal to the magnetron cutoff length for electrons, although visual observation suggests that the sheath may be several times as thick. If the sheath thickness is equal to an electron magnetron cutoff distance, then the sheath density N_e is given by

$$N_e = \frac{B^2}{4\pi mc^2} \quad \text{electrons/cc},$$

where m is the electron mass. For our typical operating conditions N_e is approximately 10^{13} electrons/cc.

The "stability" of the sheath is not well understood; however, we may note that there are approximately 10^{14} electrons in the entire sheath, and so with typical steady-state operation at 1 ampere (6×10^{18} electrons per second produced) the mean lifetime of an electron need by only of the order of 10 microseconds.

The initial ionization of the plasma can be understood in terms of the drift of neutral molecules into an already established sheath. Once the electron sheath has been established, but prior to the establishment of a high degree of ionization, the sheath surface is penetrated by a flux of neutral gas molecules from the outer region. With an initial density of 3×10^{13} molecules per cc we calculate the neutral flux to be $f = Nv/6 = 5\times10^{17}$ molecules/sec/cm^2, where f is the flux, N is the density, and v the thermal velocity at 300°K. The surface area of the rod is about 500 cm^2, and therefore the total number of molecules incident on the rod is 2.5×10^{20} molecules/second. If these molecules are efficiently ionized in the sheath, the initial fast D_2^+ current is

$$\frac{2.5\times10^{20}\text{ molecules/second}}{6.25\times10^{18}\text{ charge/ampere}} = 40\text{ amperes.}$$

These fast D_2^+ ions will charge-exchange with the neutral gas, resulting in the burial in the wall of fast neutrals, and leaving behind slow ions. The charge-exchange process can transfer at the most one-half of the initially present gas to the walls. Since the total volume of the vacuum system is 90 liters ($= 2.7\times10^{18}$ molecules at a pressure of 1 micron) and the ionization rate is 2.5×10^{20} molecules/second, the characteristic removal time is about 6 milliseconds. These numbers are in approximate agreement with the magnitude and duration of the initial pulse of current observed when high voltage is applied to the center electrode, as shown in Fig. 3.

The efficiency of ionization of the sheath can be estimated on the following basis. We have indicated above that the sheath electron density is about 10^{13}/cm^3. We do not have a detailed knowledge of the distribution of electron energies in the sheath; however, the ionization rate is not very sensitive to the electron velocity distribution, since the ionization cross section can be approximated as being inversely proportional to electron velocity. The product of the ionization cross section and velocity for electron ionization of D_2 to D_2^+ is about 6×10^{-8} cm^3/sec. Then the ionization rate for deuterium molecules in the sheath is $N_e\overline{\sigma v} = 10^{13}\times6\times10^{-8} = 6\times10^{5}$ ionizations/sec/molecule, so that the mean life of a deuterium molecule is about 2 microseconds. Since a neutral molecule moving with thermal velocity takes a time of the order of a microsecond to penetrate the sheath region, the probability of ionization is substantial. It will be desirable to increase the ionization efficiency of the sheath so that fast ions can be introduced into the system without concomitant neutral injection.

A D_2^+ ion formed in the sheath region is accelerated outward by the strong electric field. With reasonably low ion or gas density outside the sheath region, the ion makes a normal magnetron orbit and re-enters the sheath. The time spent in the sheath on the initial transit, after ionization, is given by

$$t = \left(\frac{2Ms}{eE}\right)^{1/2},$$

where M is the D_2^+ mass, s is the distance from the point of ionization to the outer boundary of the sheath, e is the electronic charge, and E an average electric field in the sheath. For our operating conditions this time averages about 10^{-9} second. Because the time available for further interaction with sheath electrons is short, an ion made in the sheath will almost certainly leave as a D_2^+ ion. This ion follows a circular path and re-enters the sheath, thereupon to be reflected. The time spent in the magnetron orbit in substantially field-free space can be closely approximated by using the cyclotron orbit period, which is energy-independent. For our conditions this is about 2×10^{-7} second. At the end of the first orbit, the D_2^+ ion re-enters the sheath and requires two sheath transit times to be slowed to zero velocity and reflected back into a new orbit. Thus, neglecting possible interactions with the plasma surrounding the center rod, a molecular ion created in the sheath spends about 1% of its time inside the sheath.

We must now examine the mean time for charge exchange of a fast D_2^+ ion with a neutral molecule. The charge-exchange cross section is of the order of 7×10^{-16} cm^2 for D_2^+ ions of a few kev energy. The maximum charge-exchange rate can be calculated if we assume that the neutral density outside the sheath remains at its initial value of $3\times 10^{13}/\mathrm{cm}^3$. Then the time for charge exchange is

$$t_{CE} = \frac{1}{N_D \sigma_{CE} V} = 10^{-6} \text{ sec},$$

where N_D = neutral density, σ_{CE} = charge-exchange cross section, and V = the D_2^+ ion velocity.

Since the steady-state tube current is about 1 ampere, as compared with 40 amperes calculated above by assuming a neutral density of $3\times 10^{13}/\mathrm{cm}^3$, we might assume that the neutral density outside the sheath during steady-state operation is $1/40$ of $3\times 10^{13}/\mathrm{cm}^3$. Then the mean time for charge exchange would be about 4×10^{-5} sec. By comparing this time with the magnetron orbit period calculated above as 2×10^{-7} sec, we can estimate that the circulating current is about 200 times as large as the tube current. Clearly it is desirable to improve the vacuum pumping capacity and thus increase the circulating current.

A reasonable origin of the observed neutrons is head-on collisions between D_2^+ ions in the central region beyond the sheath. The magnitude of the neutron yield and the shape of the yield-vs-voltage curve (Fig. 4) are in approximate agreement with this mechanism. The rapid decrease in yield when the central rod is moved off center (Fig. 5) indicates that the yield does not come from bombardment of an adsorbed layer in the cylinder wall; however, the process causing this decrease is not understood in detail.

Acknowledgments

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Figure Legends

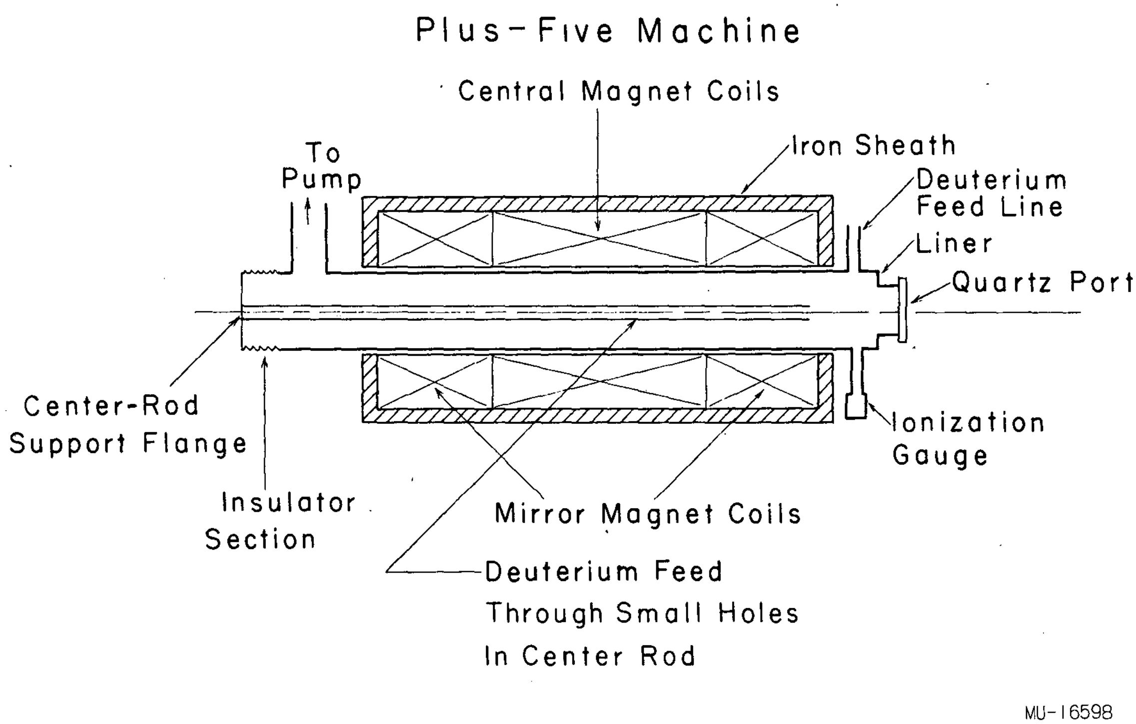
Fig. 1. Experimental geometry.

Fig. 2. Vane geometry.

Fig. 3. Plots of pressure, current, and voltage vs. time for pulsed operation.

Fig. 4. Neutron yield vs. applied voltage.

Fig. 5. Neutron yield vs. center rod displacement.



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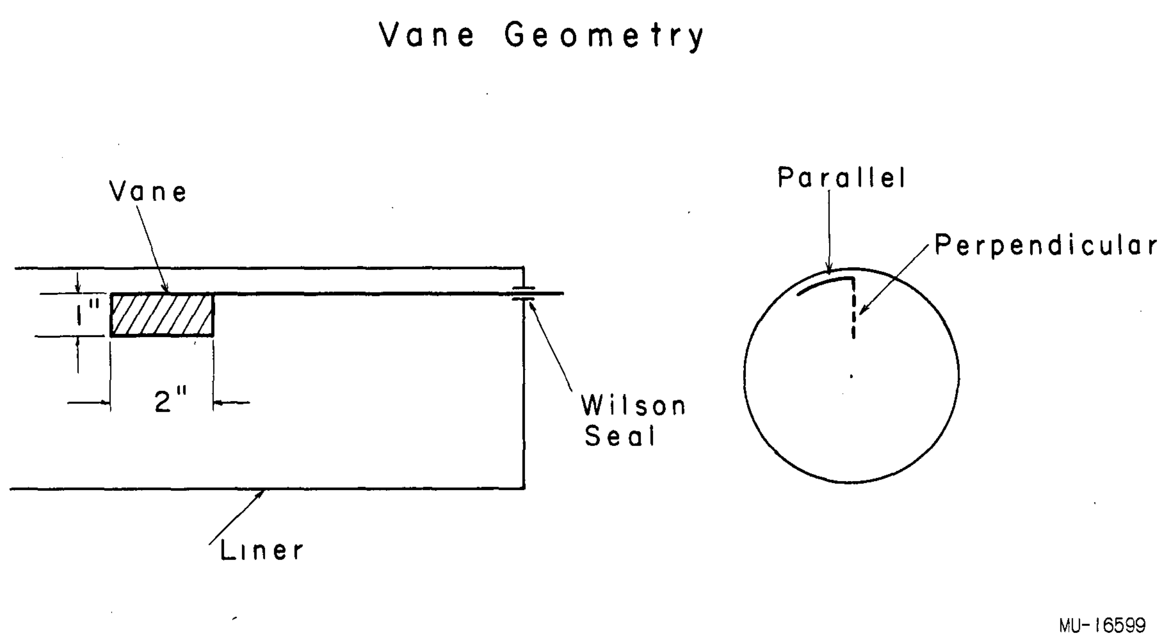

Fig. 2. Vane geometry.

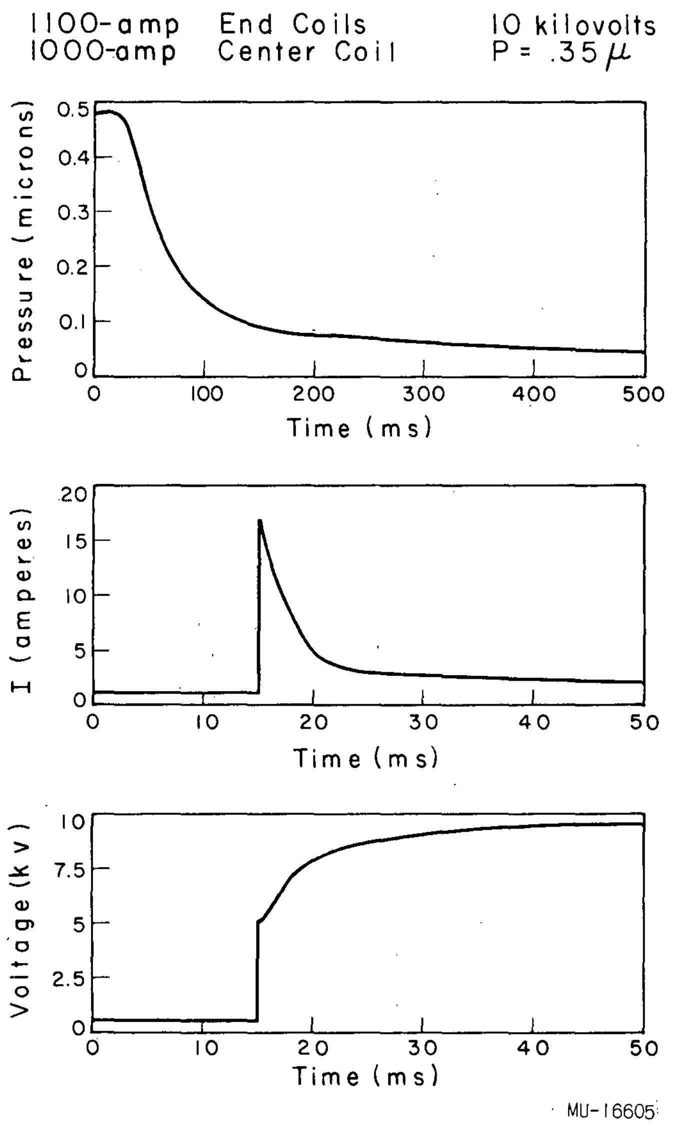

Fig. 3. Plots of pressure, current, and voltage vs. time for pulsed operation.

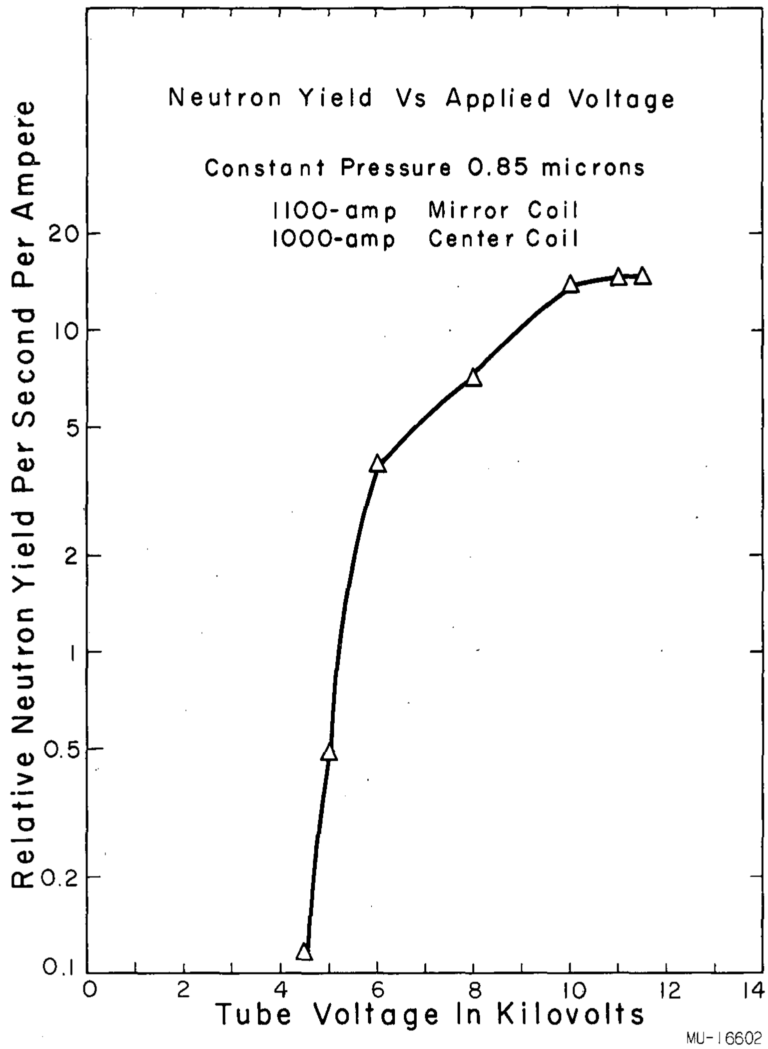

Fig 4. Neutron yield vs. applied voltage.

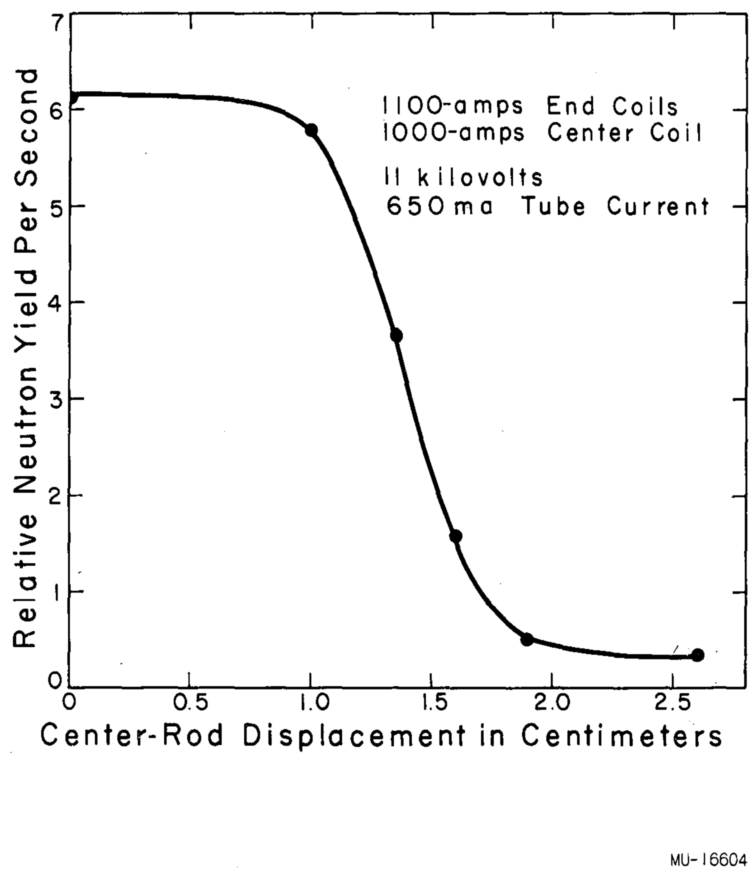

Fig. 5. Neutron yield vs. center rod displacement.