Acceleration of Plasma into Vacuum

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The first part of this paper is a discussion of the magnetic acceleration of plasma. The second part contains a description of some experiments which have been performed.

Work similar in some respects to that described here has been reported by Thonemann, Cowling and Davenport,\textsuperscript{1} by Bostick\textsuperscript{2} and by Kolb.\textsuperscript{3, 4} Thonemann and his collaborators studied the effect on a plasma of a radio-frequency traveling wave in a capacitor-loaded helical delay line. They found a net negative electric current to flow in the direction of the traveling magnetic waves, presumably because the electrons in the plasma were dragged along more efficiently than were the ions.\textsuperscript{5} Bostick has developed a source capable of propelling puffs of plasma into vacuum at speeds of the order of $10^7$ cm/sec. His plasma gun employs a vacuum spark between gas-loaded titanium electrodes. The plasma, which consists of a mixture of ions of titanium and the gas with which the source is loaded, is driven away from the source by the magnetic field of the current flowing through it. Kolb has used programmed external magnetic fields to accelerate shock waves. Since his shock waves move through a gas which is initially at low temperature, dissipative processes are involved and the result is the heating of plasma rather than its acceleration to high velocities.

In the work reported here the intention is:

1. To produce a burst of gas in vacuo.
2. To ionize the gas and heat it to such an extent that it becomes a good electrical conductor.
3. To accelerate the plasma thus produced into vacuum by the use of external time-varying magnetic fields.

MAGNETIC ACCELERATION OF PLASMA

Let us consider a cylindrical tube surrounded by a solenoid, carrying current so as to provide an axial magnetic field, and containing a hot plasma. The plasma might form a cylindrical body down the axis of the tube excluding by its diamagnetism and surface eddy currents, the magnetic field produced by the solenoid. Such a situation actually can exist just after the passage of a sufficiently strong shock wave in an axial direction along the tube. Now let us imagine a wave of increased axial magnetic field to move along the tube. The magnetic lines of force, as the wave approaches a given position, are pushed inward toward the axis of the system, and expand to their original position again as the wave passes. Thus the lines of force ahead of the magnetic wave diverge so as to produce a forward component of force on the plasma ahead. Inside the magnetic wave the magnetic pressure is high and, in the case of equilibrium, so would be the plasma pressure. If the magnetic field is high enough it will exert enough pressure on the plasma trapped at the center to drive the plasma forward ahead of the field, and thus to carry along a considerable mass of plasma at the speed of the magnetic wave. The situation is superficially quite similar to peristalsis in the gastro-intestinal tract of an animal. In the same way that a contractile wave along the esophagus of a giraffe can propel a gulp of water from ground level up to its stomach, so can a wave of increased magnetic field propel a mass of plasma along the axis of our tube.

As an example of the pressure which can be exerted on a plasma by a magnetic field let us consider a field of 30,000 gauss. This is approximately the strength of the magnetic piston employed in some of the apparatus to be described below. $B^2/8\pi$ for this field strength is $3.58 \times 10^7$ dynes/cm$^2$ or about 35.4 atmospheres. Ordinarily one might expect to accelerate rather small masses of plasma so that a 35-atmosphere pressure, if exerted over a suitable distance, should lead to respectable velocities.

The most convenient method of producing a moving magnetic piston appears to be the discharge of a capacitor bank into one end of an artificial delay line composed of a solenoid loaded with capacitors at intervals along its length. The velocity of such a line is given by $v = 1/\sqrt{(L' C')}$ and its characteristic impedance by $Z_n = \sqrt{L' C'}$. Here the velocity will be in cm/sec and the impedance in ohms if $L'$ and $C'$, the series inductance and shunt capacitance per unit length, are expressed respectively in henries/cm and farads/cm. It is quite plain that the parameters $L'$ and $C'$ can vary as a function of distance along the line, so as to produce an accelerating magnetic piston, exerting a constant force over a considerable distance.
It is not inconceivable that really high plasma velocities could thus be achieved.

Let us again use our example of a 30,000-gauss piston, and compute the velocity which could, in principle, be given to a lump of plasma of reasonable mass. Assume that the piston velocity is so adjusted as to exert the full pressure of a 30,000-gauss field against the plasma over a distance of 50 cm. Assume that the plasma to be driven corresponds to 0.02 cm³ of deuterium at normal temperature and pressure for every square centimeter of area. This would amount to about 3.5 μg of plasma per cm². These particular numbers are chosen because they correspond to an amount of plasma which has been driven in this work, although not under these ideal conditions. Remembering that the velocity attained under constant acceleration a through a distance s is given by \( v = \sqrt{2as} \), and substituting an acceleration of 3.6 × 10² (dynes/cm²)/3.5 × 10⁻¹⁶ (g/cm³) × 10⁹ cm/sec², we compute a velocity of approximately 3 × 10⁷ cm/sec. The kinetic energy of the plasma jet would be approximately 180 joule/cm², and its momentum about 100 g cm/sec per cm² of area.

The system of a magnetic piston driving a lump of plasma has phase stability similar to that which a nuclear particle accelerator, such as a synchrotron or a linac, must have in order to operate successfully. The plasma rides on the front of a wave as does a surfboard. If the plasma at some point should be moving more slowly than the wave, it will drift backward relative to it and find itself riding higher where there is more force available to drive it. If it should move faster than the wave, it will get ahead; the force will decrease and the wave will catch up again. Thus the speed of the piston does not have to be precisely adjusted. The plasma will tend to adjust its speed and to stay ahead of the piston. However, if the accelerating process relies on phase stability, the full pressure of the magnetic piston cannot be used. The plasma must necessarily ride part way up the wave. If it should pass over the crest and find itself on the back of the wave, it will be decelerated somewhat and left behind.

Somewhat more latitude for error in the matching of piston and plasma speed can be provided by the use of a piston with a flat top. This can reduce the danger of the slipping of the plasma on to the back slope of the wave. The resistance of the lump of plasma to the penetration of magnetic field implies that if the piston tends to catch up on the plasma, the plasma will make a hole in the magnetic field and thus automatically adjust its rear boundary to move at the maximum possible acceleration. A flat-top piston, of course, requires more energy than does a peaked one of equal strength.

If the back end of the plasma mass rides imbedded in the front of the piston, however, it will be compressed sideways by the magnetic pressure in the piston and its cross-sectional area will be reduced, as for instance has been observed in the Los Alamos experiments on shock channeling. This will tend to limit the amount of plasma which can be driven.

With such an arrangement, really appreciable fractions of the energy of a magnetic piston might be transferred to the jet of plasma. Of course as energy is taken out of the piston, its strength will decrease and, to produce the effect described, means would have to be found to feed more energy into the piston as it drives the plasma.

From the point of view of efficiency of energy transfer, the traveling wave magnetic piston is nearly ideal. The magnetic wave carries all the energy of the driving capacitor bank (assuming negligible resistive losses) and in principle should be able to transfer a large fraction of it to the plasma. The traveling wave, however, is not the only method of producing such a piston. Another method would be to have a large number of separate coils arranged along the acceleration system and excited from separate capacitor banks in a programmed manner. Also it would be possible in principle to use a long coil, tapered in such a way as to produce a magnetic field larger at one end than at the other. If the current through the coil is raised slowly the effect is, to some extent, that of a moving piston. In both of these alternate methods, the energy required to produce the magnetic field is much larger than in the traveling wave method.

In order to drive plasma electromagnetically it must be highly ionized and heated to a high enough temperature so that there will not be serious penetration of field during the driving process. What appears to be a satisfactory method of heating and ionizing is the passage of an intense shock wave along the tube just before the piston circuit is energized. A convenient method of generating such a shock wave is to discharge a capacitor through a one-turn coil looped around the acceleration tube. The shock wave, as it passes through the gas, ionizes it and incidentally imparts to it an initial velocity in the direction in which it is to be accelerated.

Quick-acting Valve

A mechanical valve has been developed for producing the burst of gas at the input end of the plasma acceleration system (Fig. 1). Basically what the valve has to do is to admit something of the order of 1 cm³ of gas to the system in a time of the order of 100 μsec. In 100 μsec, deuterium, which is the gas used in most of the experiments described here, moves approximately 10 cm at the molecular velocities characteristic of room temperature. Thus it becomes possible to have a pressure of deuterium gas of about one millimeter of mercury in the input end of the system while the rest of the system remains temporarily at high vacuum. Under these conditions the plasma produced by the ionization of the gas can be accelerated unimpeded through the system.

The valve is very simple and differs very little from an ordinary mechanical valve such as might be used as a water faucet. The main differences are that it is held shut by a spring, that it uses a teflon (polyperfluoroethylene) gasket, and that it is opened by a hammer blow. The spring tension on the valve...
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Figure 1. Quick-acting valve. One of the many possible arrangements for such a valve. Gas flowing through the leak into the small plenum in the valve stopper can be admitted to the system by allowing the hammer to fall and strike the anvil block.

Figure 2. Electromagnetic hammer. Spiral coil wound of copper ribbon is potted solidly in epoxy resin so as not to be distorted by its own blows. Magnetic lines of force are crowded by skin effect so as to pass through 0.3 mm gap between coil face and anvil block. Hammer blow effect in steel rod is produced by discharging 2-3 kv capacitor through coil by means of an igniton.

Electronic delay unit started by an electric contact made by the hammer in striking the anvil.

In some experiments it is inconvenient to have all functions of the apparatus timed to start after the hammer blow, and it becomes expedient to use some substitute for the falling weight which can be timed precisely after other events. For this purpose an electromagnetic hammer has been built (Fig. 2). It consists of a small coil in close proximity to an aluminum anvil block. A capacitor is discharged through the coil by means of an ignitor, and the magnetic pressure of the field generated by the low inductance coil produces an impulse similar to that produced by a hammer blow. The design of the coil is such that most of its inductance is due to the high concentration of magnetic field where it is squeezed between the coil and the anvil block. Since this gap is originally very small, the inductance is also small at the beginning of the current pulse and the complete impulse can be delivered in less than 50 µsec.

Three methods are readily available for regulating the amount of gas admitted by the valve. They are control of (1) the volume emptied by the valve (this implies that the valve is opened far enough to empty the volume involved), (2) the pressure of the gas behind the valve and (3) the impulse delivered to the valve stopper and, therefore, the degree to which it opens. The first method, which involves an adjustable plenum just behind the stopper, is an attractive one in that the valve may bounce and open more than once without affecting the amount of gas admitted. For most purposes, however, a combination of the second and third methods is easier and appears to be capable of giving highly reproducible results from shot to shot. In most cases, it turns out to be unimportant...
The apparatus used in studying this phenomenon (Fig. 4) has been a glass tube approximately 125-cm long connected at one end to a vacuum system and at the other to the quick-acting valve. Over most of its length, the tube was of approximately 10-cm outside diameter and was wound with a solenoid which could be connected to a capacitor bank through an ignitron so as to produce an axial magnetic field. At each end the tube was reduced through conical transition sections to a 5-cm diameter, and a two-turn shock driving coil was located about halfway along the transition at the end near the quick-acting valve. The shock driving coil could be connected by means of a spark gap to a 22.5 µf capacitor bank, charged to 20 kv. The timing of this spark gap and of the ignitron on the axial field ($B_z$) bank could be accurately controlled by a variable electronic delay circuit triggered by the hammer blow of the quick-acting valve.

The shock wave is launched from the shock driving coil described above by magnetic interaction of the primary current in the coil and secondary currents induced in the low pressure gas inside it. Experimentally it is observed that the gas will break down only at times at which the magnetic field inside the coil is passing through zero. At such a time the gas can whether or not the valve opens more than once. Everything of interest for one shot is over long before the valve has a chance to bounce open again.

Plasma Jets from Shock Wave Blow-off

It has been mentioned above that an intense shock wave provides a convenient method of preheating and ionizing the gas. Actually the passage of a shock wave through a gas which decreases in density, so that the shock runs into vacuum, is in itself a method of introducing a jet of plasma into vacuum. Presumably the plasma jet consists of the particles more or less within the last mean free path of the gas. Since these particles have no more particles in front with which to collide, they simply keep on going. If the shock wave and the blow-off plasma jet are arranged to move parallel to a magnetic field, along the axis of a current-carrying solenoid for instance, any sideways motion of the ions is averaged out and the jet tends to move along the lines of force. Neutral gas, however, which may accompany the jet or be produced therein by recombination, is unaffected by the magnetic field and consequently is lost through the sides, leaving the jet fully ionized.
be ionized by the back emf produced by the rapidly changing flux inside the coil. A ring gas current results, of such magnitude and direction as to shield the regions inside the discharge from the field of the coil. The magnetic pressure external to the discharge drives the plasma toward the axis of the system, picking up gas ahead of it, pinches it off and squirts it out axially in both directions away from the coil. The effect is as if there had been an explosion, and shock waves are produced traveling along the tube in both directions.

The shock driving coil and the capacitor bank which drives it constitute a resonant system which rings so as to produce a train of damped oscillations. Generally a new shock wave is generated each time the current in the coil passes through zero; at least this is true so long as there is gas present to be driven. At very high voltages applied to the coil, the gas appears to be swept out completely by the magnetic field and only one shock wave is generated, but with the arrangement described here, a long series of shock waves is produced. In order to make the apparatus generate a shock wave on the first half cycle of the train of oscillations, it is necessary to pre-ionize the gas. This is done with an electrode brought into the tube in the vicinity of the shock driving coil and connected to a small capacitor through a current limiting resistor, the capacitor being charged to a potential of 10 kv relative to ground. Without pre-ionization the first shock wave appears after one half cycle and on a number of successive half cycles thereafter.

The propagation of the shock wave and of the plasma jet which it produces is conveniently observed by photomultiplier telescopes connected to a multibeam oscilloscope. Each photomultiplier is arranged with a lens and a slit so as to be exposed to light from just one point along the axis of the tube. With such an arrangement, it is observed that the shock wave accelerates as it moves into gas of lower density and that it becomes less steep. Presumably the sharpness of the shock front is related to the mean free path of the particles under the conditions prevailing at that point and with that particular shock intensity. When the shock runs out into vacuum, the jet that it produces begins to separate into slow and fast plasma; the fast particles moving out in front, leaving the slow particles behind. In the absence of particle–particle collisions, this would have the effect of reducing the temperature in the forward and backward degree of freedom, while leaving the sideways degrees of freedom unaffected.

Unfortunately very little data have been taken which can contribute to a quantitative study of the phenomenon. This is partly the result of pressing onward toward the problem of acceleration with a moving magnetic piston, and partly because of the non-existence of instrumentation for the measurement of the rapidly changing gas densities and velocities involved.

Systems identical with that described in this section have been adapted or are being adapted as plasma injectors for thermonuclear machines. One has been in operation for some months on Ixion, the crossed electric and magnetic field spinning plasma machines under development at Los Alamos. Another is being installed on a large linear pinch machine which is being studied currently.

Magnetic Piston

As mentioned above, the most convenient method of producing a moving magnetic piston appears to be the use of an artificial delay line consisting of a coarse solenoid loaded at intervals with capacitors. The line currently in use consists of a solenoid of 2.7-cm radius, with the turns spaced 3.8 cm. It is loaded with one 7.5 µf capacitor for each turn. Such a line has an inductance of $2 \times 10^{-8}$ henry/cm, and a phase velocity for low frequencies of $5 \times 10^6$ cm/sec. A low impedance source of emf $V$ applied suddenly to one end of this line should produce a magnetic field rising in a step to a value $B = 3.30 \, V$. This would mean that a 20 kv capacitor discharged into the line would produce a $6.6 \times 10^4$ gauss field falling off exponentially after a sharp rise with a time constant given by $\tau = RC$, where $R$ is the 0.1 ohm line impedance and $C$ is the capacity of the bank. Actually the rise time of the signal is lengthened by the imperfections of the line, so that a 22.5 µf capacitor bank produces only about half the magnetic field in the wave front that one would compute.

In order to simplify the effects observed and also to lengthen the life of capacitors and spark gap, the line is terminated at its output end with a 0.1 ohm resistor. This reduces reflections from the end of the line and makes it so that the current in the line can be described as a single pulse moving at line velocity from one end to the other. Some difficulty was encountered in developing a resistor suitable for this service. It must be capable of carrying pulse currents of at least $10^5$ amp, have low inductance and absorb the full energy of the capacitor bank each time the equipment is pulsed, 1500 joules for the present arrangement. Also it should be of thin enough material so that skin effect does not materially affect its resistance for the important frequency components of the pulse. A successful design consists of nichrome ribbon clamped between brass plates with teflon insulation. The teflon appears to be able to stand the momentary high temperatures and the brass plates provide good mechanical support as well as a low inductance return current path.

Each capacitor as well as the terminating resistor is connected to the line through 4 parallel 30 ohm coaxial cables about 70 cm in length so as to achieve low inductance. The central wires of each group of four cables connect to one turn of the solenoid while the outer conductors connect to a ground return strap. The return strap is as close as is practical to the connection in the axial direction between solenoid turns so as to reduce inductance and avoid distortion of the field. Insulation between turns and from the turns to the ground return strap is of teflon and the whole coil is potted in epoxy resin with glass tape.
reinforcement so that it will be strong enough to withstand the electromagnetic forces. The coil in use at present has 10 turns and has a total length of about 38 cm.

**Shock Driving Circuit**

The shock wave which pre-ionizes and heats the gas to be driven by the magnetic piston is, in the present arrangement, produced by a one turn coil connected through a spark gap to a 0.88 µf capacitor which has been operated as high as 60 kv. The inductance of the coil is approximately 0.065 µh while that of the entire circuit is computed from the ringing frequency to be 0.285 µh. Thus only 22% of the voltage applied to the capacitor appears across the coil. A good fraction of the parasitic inductance of the circuit is in the spark gap, which is of the four electrode type and is operated in air at atmospheric pressure. The spark gap is triggered from a 0.1 µf capacitor through 3 ignitrons connected in series so as to be capable of withstanding 50 kv.

**PERFORMANCE**

The apparatus in its present form appears to be capable of driving appreciable masses of plasma at the speed of the magnetic piston. The speed is measured by photomultiplier telescopes focused at intervals along the axis of the drift tube into which the piston drives the plasma. An accurate measure of speed is somewhat difficult using this technique because of the diffuse nature of the plasma jet. However, gross features of the luminosity vs. time curve can be followed from telescope to telescope (Fig. 5), and it appears that within 20% or so the plasma moves with piston speed.

The momentum acquired by the plasma has been observed by two methods. One of them employs a capacitor microphone and the other a ballistic pendulum. The capacitor microphone is placed on the axis of the system on a probe extending well into the solenoid which provides the axial magnetic field in the drift space. A grounded aluminum foil, stretched in front of a high impedance pick-up electrode charged to 300 v, is exposed to the plasma and the electrode voltage is registered on an oscilloscope by means of a cathode follower. Since the ringing period of the microphone foil is long compared to the blow given it by the plasma, its behavior is really that of a ballistic pendulum, the initial ringing velocity being proportional to the impulse. However, its period is short compared to the time for un-ionized gas to reach it from the quick acting valve, and so it can separate the two impulses.

With the capacitor microphone (Fig. 6) it is observed that the neutral gas admitted by the valve arrives more or less with a sharp front at the other end of the tube, and that it moves at a velocity of approximately 1250 m/sec. The plasma is observable as a considerably larger impulse arriving long before the gas. The capacitor microphone is somewhat difficult to calibrate accurately because of the complicated response of its diaphragm to the plasma.

A ballistic pendulum method has been developed to measure momentum transfer from the plasma. The pendulum is suspended in vacuum with a bifilar support beyond the end of the B₄ solenoid, but with a disc on an extension arm inside the solenoid to receive the impulse from the plasma. The pendulum has approximately a 1.6 second period and a mass of 17.5 g. The disc which receives the impulse is 4 cm² in area and is non-conducting so as not to be affected by the electromagnetic forces of pulsed magnetic fields.

Impulses of up to 80 g cm/sec have been delivered to each unit area of the pendulum by a shot. The valve alone, with no electrical apparatus triggered, delivers about 16 g cm/sec per unit area of the pendulum disc. This is very nearly equal to the momentum which would be carried if all of the 2.25 cm² atmos of gas admitted in one shot were to move at the 1250 m/sec observed gas front velocity. Actually, of course, all of the gas will not move at this speed but, on the other hand, the molecules will recoil from the disc and deliver probably twice their axial component of momentum to it.

Subtracting the effect of the neutral gas we are left with an impulse of 64 g cm/sec delivered by the plasma to each unit area of the disc. At the observed
speed of $5 \times 10^6$ cm/sec (which is also the speed of the magnetic piston) this would be the momentum carried by about 13 $\mu$g of plasma or a little more than 3 $\mu$g/cm$^2$. If the plasma jet were of the same cross-sectional area as the tube in which it moves, it would have a total mass of about 50 $\mu$g and would correspond to somewhat more than 0.25 cm$^3$ of deuterium gas at normal temperature and pressure.

It has been found necessary to use rather high voltage on the preheating shock driving coil. Initial attempts with a low voltage system, like that used in the shock wave blow-off experiments described above, were not very successful in driving large amounts of plasma. A considerable amount of momentum is imparted to the plasma by the high-voltage shock alone and, if the present state of the apparatus were the final one, there might be no point in the use of the magnetic piston. This report is written, however, at an intermediate stage in the development of the technique and it is hoped that it may be possible, in the future, to accelerate plasma jets in this way to considerably higher velocities.

Preliminary observations have been made of a phenomenon which may be quite interesting. A search coil was inserted into the end of the system on a movable probe so as to generate an emf proportional to the time derivative of the $z$ component of the magnetic field along the axis of the system. With the output from the search coil integrated electrically so as to display $B_z$ on an oscilloscope, very complicated but highly reproducible patterns were obtained. The effect was strongest just outside the end of the $B_z$ solenoid, but was still observable approximately 20 cm farther out. It appears to be due to some sort of magnetohydrodynamic oscillation induced when the plasma jet crosses the diverging lines of magnetic force at the end of the solenoid.

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