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A TOROIDAL PLASMA GUN*

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ABSTRACT

A toroidal plasma gun that accelerates a symmetric ring of plasma, containing $1-6 \times 10^{18}$ particles, to a radial velocity of $\sim 2 \times 10^7$ cm/sec, is described here. The device differs from the usual coaxial plasma gun in the use of a pulsed toroidal gas valve and a pair of annular accelerating electrodes instead of coaxial tubes. Enhanced gun efficiency is achieved by the use of a strong toroidal bias magnetic field. In addition, a technique is described for generating a toroidal current of several kiloamperes in the plasma ring. The device has considerable flexibility in that the total number of particles in the ring can be varied over the range of $10^{18}$ to $10^{19}$ particles by simply changing the fill pressure in the plenum of the pulsed gas valve. The dynamics at the gun are such that the total kinetic energy of the plasma ($\sim 200$ Joules) remains roughly constant with different fill pressures. The kinetics of the plasma gun are in good agreement with a simple "snowplow" model for the plasma acceleration. The plasma emerging from the 40 cm diameter gun has a minor diameter of about 3 centimeters that remains approximately constant as the major radius of the ring increases. At least 60% of the accelerated particles are contained in this initial "ring", and little plasma is seen emerging from the gun after the first half cycle of driving current.

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I. Introduction

A toroidal plasma gun that radially accelerates a ring of plasma containing \( \sim 5 \times 10^{18} \) particles to velocities of \( \sim 2 \times 10^7 \) cm/sec is described here. The gun has been developed for the pulsed filling of a Tormac Bicusp experiment, a topic beyond the scope of this paper. The device consists of a pulsed toroidal gas valve (opening time \( \sim 50 \) \( \mu \)sec) that injects a ring of gas between two annular plates (Fig. 1). After a delay of about 100 \( \mu \)sec, to allow time for the gas to distribute itself between the plates, a 2.1 \( \mu \)F capacitor charged to 50 kV is connected across the plates by means of a spark gap switch. The gas breaks down in the resulting electric field and \( \mathbf{J} \times \mathbf{B} \) forces on the plasma ring accelerate it radially outward. This acceleration is enhanced by the application of a bias toroidal magnetic field when the bias field is in the same direction as that resulting from the capacitor discharge. The total number of particles is regulated by the filling pressure of the plenum in the gas valve, and in practice can be varied over the range of \( 10^{18} \) to \( 10^{19} \) particles (hydrogen). The dynamics of the gun, described in the section on theory, are such that the total plasma kinetic energy after leaving the gun is roughly constant for different filling pressures (\( \sim 200 \) Joules). A small poloidal magnetic flux (\( \sim 2 \times 10^{-3} \) webers), generated by a set of coils on each side, links the plasma gun. As the plasma is accelerated outward it crosses these flux lines, generating a toroidal current in the plasma. The magnitude of this current can be adjusted by varying the initial poloidal field strength.
II. Theory

A. Snow Plow Model

An adaptation of the "snowplow" model of Rosenbluth is used to model the dynamics of the plasma gun. The model assumes that plasma current flows in a thin sheet \((\frac{\rho^0 c}{\omega_p})^*\) and that this current sheet (in this case a cylindrical sheet) is accelerated by \(J \times B\) forces (Fig. 2). Gas (or plasma) in the path of the sheet is assumed to be swept up into the thin layer causing the mass to continually increase. Infinite conductivity of the plasma is assumed. A departure from the earlier snowplow model is the inclusion of a toroidal bias field, due to a (quasi) D.C. current through the axis of the system. Since this field adds to the toroidal field generated by the gun current, enhanced plasma acceleration is realized. The equations for the acceleration of the sheet, coupled with the equations for the driving circuit are;

\[
\frac{\partial R}{\partial t} = v, \tag{1}
\]

\[
\frac{\partial v}{\partial t} = \frac{1}{M(R)} \left\{ \frac{\mu_0 I}{4\pi R} \left[ I^2 + 2I \right] - \frac{\partial P}{\partial R} - v^2 m(R) \right\}, \tag{2}
\]

\[
\frac{\partial M}{\partial t} = m(R) v, \tag{3}
\]

\[
\frac{\partial I}{\partial t} = - \left( L_s + \frac{\mu_0 L}{2\pi} \log\left( \frac{R}{R_0} \right) \right)^{-1} \left\{ \frac{\mu_0 I}{2\pi} \left( \frac{I+I_0}{R} \right) v + IR_s + V_c \right\}, \tag{4}
\]

and

\[
\frac{\partial V_c}{\partial t} = \frac{1}{C} \tag{5}
\]

\(R(t)\) is the radius of the plasma sheet, \(V_p\) is the potential energy due to the poloidal magnetic field, \(R_0\) is the initial radius at \(t=0\), \(v(t)\) is the velocity of the snowplow, \(M(R)\) is the total mass swept up by the snowplow when it reaches radius \(R\), \(m(R)\) is the initial mass distribution of gas between the plates and \(I(t)\) and \(I_0\) are the plasma and bias currents respectively. \(R_s\) and \(L_s\) are stray resistance and inductance (unavoidable in a real system) and \(L\) is the separation of the plates. \(C\) is the capacitance of the driving capacitor and \(V_c(t)\) is the voltage across the capacitor.

*where \(c\) is the velocity of light and \(\omega_p\) is the plasma frequency in the current sheet.

+ defined as mass per unit radius integrated over \(2\pi\) radians and along the length \(L\) in the z direction.
Rationalized MKS units are used throughout. The equations have been reduced to a set of first order differential equations to facilitate a computer solution.

Initial conditions for this set of equations are $R(t=0) = R_0$, $v(t=0) = 0$, $M(R_0) = 0$, $I(t=0) = 0$ and $V_c(t=0) = V_0$, the initial voltage on the capacitor. The function $m(R)$ depends on the distribution of gas between the plates. Measurements on the operation of the gas valve, described in the experimental section, indicate that at the optimum time for discharging the gun (100 μsec after the valve starts opening) the gas density is given to a close approximation by the empirical equation

$$m(R) \approx \frac{m_0}{(R-R_0)^2}; \quad (R \geq 1.2 R_v)$$

where $R_v$ is the radius of the valve aperture. This equation is used in the computer program and $m_0$ is a constant determined by the pressure in the gas valve. The gas distribution ahead of the snowplow is essentially constant in time during the operation of the gun since the gas is moving at about 1 mm/μsec, and the plasma acceleration takes less than 1 μsec.

Since the plasma gun is to be used for the pulse filling of a Tormac bicusp device, the desired plasma parameters were fixed, prior to the gun development, at $N = 5 \times 10^{18}$ particles with a directed kinetic energy of several hundred eV per particle. These parameters were chosen to test the operation of the gun in a useful regime and to test the processes of trapping and containment of the injected plasma. The computer program simulating the gun operation was used to optimize the design of the gun, given restrictions on size, cost, voltage limitations, etc. within the framework of the required
plasma parameters. Parameters arrived at in this study are as follows; accelerating plates 40 cm O.D., 20 cm I.D., with a 3 cm separation between the plates; a capacitor spark gap combination identical to those used on the SCYLLAC experiment of 2.1 μF at 50 kV with ~150 nH of stray inductance, and a bias current (I₀) of 0.3 megamperes. Plots of predicted gun performance are shown in Figs. 3-5.

B. Toroidal Current Generation

A technique for inducing a toroidal current in the plasma ring is described herein. Although this toroidal current is not necessary for the operation of the plasma gun, it is needed for the subsequent plasma trapping experiment for which the gun was developed. The technique consists of applying a poloidal magnetic field (B_z, B_R) across the accelerating plates in such a way that, as the plasma ring is accelerated radially outward, it crosses poloidal field lines. This generates a toroidal current in the ring. Stated somewhat differently, a quantity of magnetic flux φ_o links the plasma ring when it is first formed. As the ring is pushed outward by the toroidal magnetic fields the poloidal flux in the ring remains constant (Lenz's law). After leaving the plasma gun this flux is still conserved. The current in the ring at this point is then φ_o/L where L is the self inductance of the plasma ring. This process is illustrated in Figs. 6 a,b,c where poloidal field lines are plotted for various positions of the plasma during this process. The poloidal field shown in these plots corresponds to that used in the experiment. The coils were designed to localize the field to the plasma gun region, so as to not interfere with fields to be used in the later plasma trapping experiments.
The inclusion of the poloidal flux into the plasma requires work to be done on the ring as it is pushed out. The radial force required to expand the ring is calculated to be

\[ F_{\text{pol}}(R) \propto \frac{[\phi_o - \phi_p(R)]}{2 \mu_0 R \log(\frac{8}{\epsilon})} \cdot \left\{ \left[ \frac{\phi_o - \phi_p(R)}{2R} \right] - \frac{d\phi_p}{dR} \right\} \]  

(7)

where \( \phi_o \) is the flux linked by the plasma at \( t=0 \) (breakdown) and \( \phi_p(R) \) is the flux (midplane) produced by the coils at radius \( R \). The aspect ratio of the plasma ring (ratio of major and minor radius) is given by \( \epsilon^{-1} \), and appears in the self inductance of the ring in the above equation. Since time is not contained in the above equation (the coil producing the flux \( \phi_p(R) \) is quasi steady state), \( F_{\text{pol}}(R) \) is a conservative force and can be written as the gradient of a potential \( V_p(R) \) where

\[ V_p(R) = \int_{R_0}^{R} F_{\text{pol}}(R) dR \]

and the aspect ratio of the ring is assumed constant (see Fig. 7). The energy delivered by the gun in overcoming this potential is then stored in the \( \frac{1}{2} L I^2 \) energy in the plasma ring after it leaves the gun. It should be noted that the poloidal field lines are "frozen into" the two gun electrodes and a calculation of the potential should include a correction for the effect of eddy currents in the plates.

The effect of \( F_{\text{pol}} \) on the gun operation is easily included in the computer program described earlier. Shown in Fig. 8 is the snowplow velocity versus time for the same initial conditions as described earlier in Figs. 3-5, but with poloidal flux added. In practice the enclosed poloidal flux \( \phi_o \) is controlled by setting the current in the external poloidal field coils. It can be seen in this figure that the snowplow acceleration is retarded by \( F_{\text{pol}} \).
especially for larger values of $\Phi_0$. The theory predicts a sharp cutoff when $\Phi_0$ approaches $8 \times 10^{-3}$ webers. This value of $\Phi_0$ corresponds to a plasma toroidal current of about 10 kA when the plasma leaves the gun.
III. Experimental Results

A. Apparatus

The experimental apparatus consists of several components: the plasma gun and its associated parts, the toroidal bias field and poloidal coil systems, and various diagnostics. The entire gun and coil structure is supported on the end of a coaxial stalk 1 meter in length in the center of a 2 meter by 2 meter cylindrical stainless steel vacuum vessel. Most of the diagnostic hardware is mounted in the vacuum tank and many of the devices (probes, faraday cups, and interferometer) can be positioned by remote control.

The heart of the plasma gun is made up of the fast gas valve and two annular accelerating electrodes. The 14 cm diameter gas valve\(^2\), which is toroidally symmetric, employs a coil and flux concentrator to deflect an aluminum ring. The valve is energized by ringing down a 10 \(\mu\)F capacitor charged to 3.1 kV through the 12 \(\mu\)H coil. This opens a toroidal plenum to the vacuum, and with a plenum pressure of 8 psia about \(4 \times 10^{18}\) molecules (H\(_2\)) are injected into the region between the plates. Measurements of gas density as a function of radius and azimuthal angle were made using a fast ion gauge. A typical trace of gas density versus time at a radius of 15 cm is shown in Fig. 9. Measurements of the azimuthal variation of gas density at constant radius (20 cm) showed a maximum deviation of \(\pm 10\%\) around the valve at the time of peak density. Great care was taken to assure a uniform gas distribution, since the symmetry of the plasma ring depends on it and the subsequent plasma trapping experiments will require toroidal symmetry. Care was also taken in the design of the accelerating plates and current feeds to insure this toroidal symmetry. The two identical plates were spun into shape from 1.5 mm thick OFHC copper and both the inner and outer edges were rolled over to eliminate sharp edges. Inner and outer
diameters of the finished annuli are 17.8 cm and 38.0 cm respectively. One plate is maintained at ground (vessel) potential, while the other is connected to the negatively charged driving capacitor through teflon coaxial cables and a low inductance feed-through as shown in Fig. 1. In initial tests the gas valve aperture was centered between the plates, but it was quickly found that more reproducible operation was realized when the aperture was in line with the high potential plate. Fast image converter camera pictures (Fig. 11) showed the initial gas breakdown occurring between the valve and this plate, and rapidly (~50 nsec later) spreading to the other plate. These pictures indicated a uniform discharge around the valve. During the early work on the gun, a discharge along the cable insulation was encountered, but proper positioning of the valve and adjustment of the time delay between the valve opening and high voltage switching eliminated this problem. There is evidence that the toroidal bias magnetic field provides some magnetic insulation in this region.

The toroidal bias magnetic field is produced by a coil located inside the vacuum tank and constructed of copper bars. The coil has a rectangular cross-section with an inner (center-post) diameter of 5 cm, an outer diameter of about 80 cm and a length of 28 cm. The center conductors pass through the gas valve and accelerator plates. The coil has 16 segments with four groups of four segments each in a series-parallel arrangement. The current feeds are back wound in such a way as to minimize any stray asymmetric magnetic field. The coil is energized by discharging a 0.4 Farad, 450 volt electrolytic capacitor bank through it. Series switching is accomplished with four ignitrons in parallel and the bank is "crowbarred" by six, 30 kA, solid-state diodes. The risetime (quarter cycle) of the magnetic field is 1.4 msec and the crowbar time constant (e-fold) is about 4 msec.
The poloidal field, used for toroidal current generation, is produced by two coils (Fig. 1) on either side of the accelerator plates. These coils, driven by a 0.1 Farad, 450 volt capacitor bank have a rise time of 4.5 msec and a crowbar time of about 10 msec. Since there are a number of conducting structures around these coils (such as the accelerator plates, the stainless steel casings on the coils, etc.) the field takes sometime to "soak into" the region between the plates. Shown in Fig. 10 are plots of $B_p$ as measured along the midplane of the device at different times. The "soaking in" is evident here in the time evolution of the field shape.

B. Diagnostic Apparatus

Among the various diagnostic tools used to analyze the plasma gun were magnetic probes, Rogowski coils, a laser interferometer, a fast image converter camera and faraday cups. Of the several types of magnetic field probes used, the simplest were small coils encased in 8 millimeter diameter quartz or alumina tubes. The coils were typically 3 mm in diameter by 5 mm long wound with several tens of turns in two layers on a glass core. These were calibrated in a pulsed Helmhotz coil assembly constructed for this purpose. Rogowski coil probes were made in two sizes, the smaller being about 7 mm in diameter and used to measure local plasma current densities, while the larger, 10 cm in diameter was used to measure total plasma currents. Both coils consisted of a form (o-ring) wound with many turns of wire and encapsulated in epoxy resin. These were calibrated with a modified version of the circuit described earlier. Measurements made with the magnetic probes were checked by rotating the probes 180°. Reversal of the signal polarity with no change in waveform was taken as a verification of the measurement.
In some cases a further check was made by enclosing the probe tip in a metal tube (with a magnetic diffusion time long compared to the plasma lifetime) to insure that electrical pickup due to ground loops, etc., was not contributing to the observed waveforms. The probe cables were terminated with a matching impedance (50 Ohm) at the oscilloscopes with no integrating circuit. The only exception to the above was the large (10 cm) Rogowski coil which was used with a passive integrator circuit. Remote probe positioners driven by a selsyn motors and located in the vacuum tank were used for various scans of the magnetic fields.

A gated image intensifier camera (Beckman-Whitley type 501) was used to observe the formation and acceleration of the plasma by looking in radially between the plates. The symmetry of the plasma ring was checked by viewing the plasma gun end-on (axially).

The interferometer which was used to measure the line density of the plasma is of the Michelson type. The He-Ne laser light source (5 mw of power at 633 nm) results in a line density (electrons) of $1.77 \times 10^{17}$ cm$^{-2}$ for a single fringe. The laser is mounted on the interferometer frame hanging over the experiment. This frame is suspended by springs inside a tubular aluminum casing which serves two purposes. It permits the laser and the interferometer structure to be in atmospheric environment, whereas the casing is hung within the experimental vacuum tank. Secondly the case attenuates the pulsed magnetic fields of the experiment. The interferometer structure was made, as far as possible, from non-conducting materials which would eliminate mechanical displacements due to the pulsed magnetic fields. No mechanical displacement of the interferometer structure is observed until 20 milliseconds after the measurements. The arm lengths for the reference and test beams were approximately equal (70 cm). Each beam return mirror was remotely adjustable around two axes through the use of selsyn motors.
The recombined beams were focused onto a 125 micron fiber optic cable. The light was thus transmitted to the detector at the oscilloscope. Because of the size of the fiber it performed the function of a spatial filter for stray plasma light, and yet was big enough to be a few times the focal spot size of the laser beam. In this way no filter was necessary to further reduce stray plasma light. The interferometer light was detected with a silicon photodiode and large bandwidth amplifier (10 MHz). The entire interferometer structure is mounted on rails and can be moved from outside the vacuum tank by a mechanical linkage. The light beam that passes through the plasma gun region is parallel to the axis of the gun and can be moved radially, the minimum radius being the gun muzzle (R ≈ 20 centimeters) and the maximum being the outer toroidal field conductors, (R ≈ 40 centimeters).

For small fringe displacements the sensitivity of the measurements depends on the starting position of the fringe; the most sensitive being halfway between dark and bright where the variation of intensity is approximately linear with phase. Since the interferometer was not stabilized for mechanical vibrations the starting position (phase) changed from shot to shot. Taking this into account the expression giving the line integral of electron density $n_e$ as a function of detected voltage is given by the expression

$$\int n_e \, d\ell \, (\text{cm}^{-2}) = 2.8 \times 10^{16} \left( \sin^{-1} \left( \frac{\Delta V + V_i}{V_o} \right) - \sin^{-1} \left( \frac{V_i}{V_o} \right) \right)$$

where $\Delta V$ is the measured voltage change due to the plasma, $V_i$ is the voltage giving the position in the fringe at the beginning of the plasma detection (zero voltage is taken to be halfway between the extreme values) and $V_o$ is half the total peak to peak voltage swing for a complete fringe. The electron density, $n_e$, is given in $\text{cm}^{-3}$ and the line integral is taken along the path of the laser beam through the plasma.
Various types of probes and faraday cups were developed in the course of the experimental work. The simplest of these was a bare wire probe, biased 300 volts negatively to collect an ion saturation current and placed in the path of the plasma. The second type consisted of a copper cup 1 cm x 1 cm enclosed in a copper shell with a 0.5 mm diameter aperture in front of the cup which was also biased several hundred volts negatively (Faraday Cup).

An attempt at spectroscopic plasma measurements was made, but was unsuccessful because of insufficient plasma light. The arrangement consisted of a 0.3 meter Jarrel-Ash spectrograph modified to operate as a polychromometer (16 channels, 0.49 Å/channel). The light detection system was sensitive enough to detect single photons, but line profiles were barely resolvable for the $H_\alpha$ and $H_\beta$ transitions. In view of the poor statistics (even when viewing the plasma along the longest chord possible) it was decided not to pursue the spectroscopic measurements for the time being. A schematic drawing of the arrangement of various diagnostics is shown in Fig. 21.
IV. Plasma Formation and Acceleration

The initial gas breakdown in the plasma gun was studied using the gated image converter camera looking radially between the plates, and a magnetic probe located at a radius of 15 cm aligned to measure toroidal magnetic field. In early work on the gun a small capacitor bank (60 kV and 3300 pF.), in a Marx configuration, was used to "preionize" the gas between the plates several microseconds prior to turning on the plasma gun capacitor (50 kV and 2.1 μF). Efforts to employ this preionizer bank were singularly unsuccessful; the gun operation was not very repeatable and the current sheet (snowplow) was very diffuse as it moved radially outward. In addition, the plasma velocity as it left the gun was much reduced, in this mode of operation. It was also noted that image converter pictures showed bright discharges along the insulators of the cables feeding current to the gun when the preionizer was used. The preionizer bank was removed from the system once it was found that better operation was realized by switching the main capacitor and allowing the gas breakdown and acceleration to occur simultaneously. Subsequent to this it was found that the position and timing of the fast gas valve were very important to both the repeatability and efficiency of the gun. The optimum position of the valve was found to be when the aperture of the valve was in line with the high voltage accelerating plate (the other plate being at ground potential). In this position the jet of gas from the valve impinges on the plate, and when the high voltage is applied gas breakdown occurs between the plate and the grounded valve. Very quickly after this the plasma is pushed between the plates and the radial acceleration begins. This process is illustrated in Fig. 11 in a series of image converter camera pictures of the breakdown and initial plasma acceleration for the first 300 nanoseconds of the process. After this period the light from the accelerated plasma dies down quickly and it becomes invisible to
the camera. Magnetic probes placed at various radii show, however, that the plasma continues to accelerate outward. In addition to the valve position, the time delay between the opening of the gas valve and the application of the high voltage is critical. A time delay of 95 μsec was found to be optimum, and delays differing from this by more than 20 μsec were found to give erratic results. These difficulties having been overcome, the operation of the gun became both reliable and repeatable, and systematic measurements of the plasma became possible.

The effect of the poloidal field linking the plasma was very pronounced, as expected (Fig. 8), although there is some quantitative disagreement with the computer model. Initially it was planned to have $\phi_o$ (the poloidal flux enclosed by the plasma ring) equal to about $5 \times 10^{-3}$ Webers, but when the gun was operated at this value either no plasma emerged from the gun or it emerged very late in time (several microseconds later). While the computer program predicted that the plasma gun would be "cut-off" at a value of $\phi_o > 8 \times 10^{-3}$ Webers, good (high plasma velocity) operation of the gun could not be achieved with $\phi_o \geq 2.5 \times 10^{-3}$ Webers. This was found to be true whether $\phi_o$ was varied by changing the poloidal coil capacitor bank voltage, or by fixing the voltage and varying the time delay between the poloidal bank and the firing of the gun (in the later case the field shape changes somewhat due to the earlier mentioned "soaking in" of the field.) Two magnetic probes were used in this study, one at a radius of 15 centimeters (between the plates) and a second at a radius of 32 centimeters. The time delay between the arrival of plasma signals at the two probes was used as a monitor of the average radial plasma velocity when $\phi_o$ was varied. Plotted in Fig. 12 is plasma velocity (the distance between the probes divided by the time delay between probe signals) for different values of $\phi_o$. The cutoff point for the plasma gun can be seen at much lower values of $\phi_o$ than predicted.
The applied poloidal field strongly affects the magnetic field profiles in the gun. Shown in Fig. 13 are magnetic probe traces of $B_T$ in the gun ($R = 15$ cm) and $B_p$ outside the gun at $R = 32$ cm (no attempt was made to measure $B_p$ in the gun itself since the magnetic field there is strongly dominated by the toroidal component).
v. Plasma Transport After Leaving the Gun

The properties and behavior of the plasma ring, after it has left the gun, have been studied using the interferometer, magnetic probes and a Faraday cup. The interferometer measurements show that the plasma leaves the gun as a well defined ring with a minor dimension of a few centimeters or less at velocities of the order of 20 centimeters per microsecond. A smaller number of particles, moving more slowly than the initial burst, follows, but quickly falls behind the former. The minor radius of the burst remains roughly unchanged as the ring expands from the gun muzzle ($R = 20$ cm) to the maximum extent of the measurements ($R = 40$ cm). Shown in Fig. 14 is a plot of plasma density as measured by the interferometer versus time at the gun muzzle. The plot is an average of 16 shots of the device and the error bars indicate the relative shot to shot repeatability of the gun. The arrival time of the burst of particles at different radii is plotted in Fig. 15 and a well defined velocity is indicated. Using the interferometer data of Fig. 14, the velocity obtained from Fig. 15 and assuming azimuthal symmetry in the gun the particle flux emerging from the gun can be calculated. Fig. 16 gives the integrated flux of particles versus time, assuming that all the particles travel at the same velocity (25 cm/μsec in this case). This overestimates the number of slower (later) particles, thus it can be stated that at least 60 percent of the particles travel with the fast (initial) particle burst.

Interferometer data was taken with various valve filling pressures and a series of plots similar to Figs. 14, 15, and 16 were made. Estimating that the first 550 nsec of particle flux contains the useful (fast) plasma the total particle number $N_0$ is then found. A summary of these measurements is presented in Fig. 17, a plot of $N_0$ versus valve filling pressure. $N_0$ increases almost linearly with the valve gas pressure. The range goes from
10^{18} to 6 \times 10^{18} particles for valve pressures between 4 to 10 psia. The plasma front velocity decreases over this range from around 20 cm/\mu sec down to about 16 cm/\mu sec. At the lowest pressure the measurement was erratic. Using the plasma front velocity the particle kinetic energy \( E_p \) can be calculated and is included in Fig. 5. This energy is significantly below the theoretical curve, but follows the theoretical trend with increasing particle number. Similarly the total plasma energy, where

\[
E_T = E_p N_0
\]  

(10)

increases with particle number as on the theoretical curve, but also with a lower value. This measurement is dependent on the gun poloidal field. An experimental point for a different poloidal field (included in Fig. 5) shows a higher measured particle and total plasma energy.

A series of magnetic probe measurements is given in Fig. 18 where both toroidal and poloidal components are resolved (the slowly rising bias toroidal field has been filtered out in these pictures). The toroidal magnetic field in the plasma ring is parallel to the bias magnetic field. This should be the case since the initial plasma, formed when the gas breaks down, is born in a region of strong toroidal bias field (~7 kiloGauss) which is "frozen into" the ring and carried out with it. The magnitude of the probe signal indicates an increase in the toroidal field of about 500 Gauss in the plasma ring, a number that remains fairly constant as the ring moves outward. Both the toroidal field carried with the plasma and the poloidal field generated by the toroidal current propagate outward with roughly the same velocity as the particle burst (Fig. 19), with the poloidal signal preceding the toroidal signal by about 200 nsec. This is interpreted in the following way. A conducting ring carrying a toroidal current generates a poloidal field external to the ring that will be detected by a probe prior to the ring intercepting the probe. Any discontinuity in toroidal magnetic field (deviation from \( 1/R \) dependence) on the other hand implies a current density at that spot, by
Maxwell's equations. Thus a signal on a probe measuring toroidal field implies that the probe is surrounded by plasma (current carrier) rather than vacuum. This also explains why the velocity measured from the magnetic probes agrees with that from the interferometer.

It is unclear from the measurements of poloidal magnetic field whether or not poloidal magnetic lines reconnect behind the ring as it propagates out (as illustrated in the idealized plots of Figs. 6a-c). Integration of the $\dot{B}_p$ signals in Fig. 18 indicates only very slight, if any at all, reversal of poloidal field as the ring passes over the probe. Any magnetic probe inserted in a plasma has a magnetic diffusion time associated with it that depends on the plasma conductivity and the probe dimensions. Taking a plasma temperature of 10 eV and the probe diameter of 8 mm the calculated diffusion time is about 0.25 µsec. The probe will thus integrate signals changing faster than this and might well mask the reversal of poloidal field behind the ring. Smaller probes, which have a faster diffusion time were tried, but the smaller coil size gave proportionally smaller signals that were swamped by spurious electrical noise in the system. The question of magnetic reconnection of the poloidal lines therefore remains unresolved.

Total toroidal current in the plasma was measured with the large Rogowski coil (13 cm diam). The coil was positioned so that the plasma ring crossed over and threaded the coil. Since the coil size is much larger than the minor diameter of the plasma it can be assumed that all the toroidal plasma current passes through the ring at one time. Currents of up to 6-7 kiloamperes are measured in this manner. Shown in Fig. 20 is a typical signal from the Rogowski loop. It should also be noted that while a toroidal current was
induced in the plasma the results were not in quantitative agreement with
the theory. Plasma toroidal current can also be inferred from the $B_p$ probe
measurements (although this is less accurate) by modeling the field due
to a current carrying ring and comparing this with the observed fields.
Since both the Rogowskii coil and the $B_p$ probes pass through the plasma
there is a possibility that the probes perturb the plasma being measured
(and vice versa). A check on the above measurement was made by positioning
a poloidal field probe (displaced from the midplane) so that the plasma
passed by it, but did not intercept it. Probes hit by the plasma generated
a bright flash of light (as seen by the image converter camera), and this
probe was moved until no light was seen from the probe tip. The signals
seen on this probe were consistent with the passage of a current ring
carrying several kiloamperes of toroidal current, corroborating the Rogowskii
coil and $B_p$ probe measurements.

A straightforward analysis shows that the toroidal current frozen into
the ring by the flux $\phi_0$ is given by $\frac{\phi_0}{L}$ where $L$ is the self-inductance of
the plasma ring after leaving the gun. For a plasma ring aspect ratio of
10 it is estimated that

$$L \approx 3 \times 10^{-6} \text{ R Henries},$$

where $R$ is the major radius of the ring. For the measured cutoff of
$\phi_0 = 2.5 \times 10^{-3}$ webers a plasma current of $\approx 4$ kA would be expected. Probe
measurements, on the other hand indicate that the toroidal current actually
falls off at higher values of $\phi_0$, instead of increasing linearly with $\phi_0$.
It is postulated that this is due to the resistive decay of the current, since
the more slowly moving plasma at large values of $\phi_0$ take longer to arrive at
the measuring probe. The decay time $\tau$ of the ring is estimated to be
$1/2\sigma \mu_0 a^2$ where $\sigma$ is the plasma conductivity, $\mu_0$ is the permeability of
free space and $a$ is the plasma minor radius. For a plasma with a density of
a few times $10^{14}$ (as seen by the interferometer) and a temperature of a few eV, the conductivity is given by the expression

$$\sigma = 2.0 \times 10^3 T_e^{3/2} \text{ (ohm-meters)}^{-1}$$

Taking the dimension $a$ to be a few centimeters, the decay time for toroidal current is then given by the expression

$$\tau = 0.5 \times T_e^{3/2} \text{ microseconds}$$

$T_e$ (the plasma electron temperature) is expected to be quite low (coaxial plasma guns typically have temperatures of the order of a few eV in the moving plasma frame). In addition the plasma in this device is continually expanding radially, which will lead to adiabatic cooling. The above conductivity assumes a pure hydrogen plasma, and any impurities would quicken the decay even more. Thus it seems quite plausible that the decreased plasma currents near the gun cutoff are due to the currents' decaying before reaching the measuring probe.

Faraday cups were used to measure the time of arrival of the particle burst from the gun. The magnitudes of the signals from these, when biased negatively to collect ions (-300V), were up to two orders of magnitude lower than expected. The flux of ions through the aperture was expected to be $nuA$ where $n$ is the plasma density $u$ is the directed velocity of the burst and $A$ is the aperture area. Since $n$ and $u$ are well known from the interferometer the discrepancy must be due to unexpected complications in the Faraday cups. The most likely explanation is that a dense gas layer, builds up quickly at the cup surface (incident power $\approx 2 \times 10^6$ watts/cm$^2$) and prevents most ions from being collected. In any case the arrival time of the signal measured at various radii gives a plasma velocity that agrees with that from the interferometer.
The toroidal symmetry of the plasma ring was checked both with magnetic probes and an axial (end-on) view with the image converter camera. Fig. 22 shows traces of magnetic probe signals with the three identical probes located at various azimuthal angles around the gun. The probes are all located at the same radius from the coil axis, and although the waveforms are somewhat different (both shot to shot and at the different angles) the arrival time of the signals is nearly constant for the three probes. Since it was found that the toroidal field was carried along with the particles (from the interferometer and probe measurements described earlier) it is concluded that the initial particles move outward with the same velocity independent of azimuthal angle. Figure 23 is an image converter camera picture of the emerging plasma ring. This picture indicates toroidal symmetry, particularly since the picture was made with highly nonlinear, high contrast film (Polaroid type 410). It was found that if the gun was operated with very low gas fill pressures \( N < 10^{18} \) particles, \( p < 4 \) psia) that asymmetries appeared. The source of these effects was not pursued, but it seems likely that the initial breakdown may be responsible. Time resolved side-on image converter pictures show that asymmetries are characteristic of low pressure delays and begin very early in the acceleration process. Above 6 psi these asymmetries are not generally observed.
Conclusion

A toroidal plasma gun, producing a symmetric radially expanding ring of plasma with a toroidal current frozen into it, has been demonstrated experimentally. The operation of the gun agrees well with a modified snowplow model for plasma acceleration. Further study of the effect of poloidal field on the gun operation and the level of impurities in the ejected plasma ring is clearly indicated. Enhanced electrical efficiency for the gun should also be pursued, since the present device converts only about 7 percent of the stored electrical energy in the driving capacitor into useful plasma energy. An improved gun design is currently being developed at the Lawrence Berkeley Laboratory in which the stray inductance is significantly lowered. Efficiency of the order of 40 percent is expected from this effort with over a kilojoule of plasma energy.

The gun, in its present state, has been successfully used for the pulsed plasma filling of a Tormac bicusp experiment, the results of which are to be published in the near future. Potential applications for the device include the pulsed injection of plasma into other types of toroidal plasma devices, such as tokamaks, and the possible generation of field reversal (via the toroidal current) in solenoidal or mirror magnetic fields.
References

Figure 1  Sectional view of the toroidal plasma gun and bias magnetic field coils. The supply for the plasma gun was a 2.1 μF capacitor charged to 50 kV. The toroidal bias field is supplied by a 0.4μf electrolytic capacitor bank. The poloidal bicusp coils shown were not energized.

Figure 2  Schematic of the plasma gun operation: $L_s$, stray inductance; $R_s$, stray resistance; $δ$, plate separation; $δ$, plasma current sheet thickness sweeping up and ionizing the gas (H₂); $I_0$, axial bias current.

Figure 3  Computed plasma front radial evolution using the snowplow model (no poloidal field). Plasma is initially formed at $R_o = 7.5$ cm and accelerated to the outer radius, $R = 20$ cm, of the plates shown by the dots. Curves A through E are for accelerated particle numbers $2, 4, 6, 8$ and $10 \times 10^{18}$ respectively.

Figure 4  Computed plasma front velocity evolution using the snowplow model (no poloidal field). The initial velocity increases from zero until the end of plates is reached (shown by dots). Curves A through E are for accelerated particles numbers $2, 4, 6, 8$ and $10 \times 10^{18}$ respectively.

Figure 5  Computed plasma energy (joules) and particle energy (eV) as a function of the total particle number (no poloidal field).

Experimental values:

\[
\begin{array}{c}
\times, \bigcirc & \text{No Poloidal Field} \\
\times, \bigcirc & \text{Poloidal Bank: 150 volts} \\
\bigcirc & \text{Particle Energy} \\
\_ & \text{Total Energy} \\
\end{array}
\]

Estimated experimental error bars are shown.
Figure 6  Computed poloidal field lines including the accelerated plasma.

Note:  
- poloidal coils (black rectangles)
- gun plates are assumed non-conducting.

a)  Plasma formation; \( R = 7 \) cm at about the \( \times \) point of the poloidal field. Flux in the plasma is assumed to be conserved.

b)  Plasma ring at \( R = 13 \) cm. The ring aspect ratio is assumed to be 20.

c)  Plasma ring at \( R = 19 \) cm. Note the reconnection of field lines behind the ring.

Figure 7  Computed potential energy verses plasma ring positions. The actual values are determined by the current in the poloidal coils (see Equation 7). Plot does not include eddy current effects in the plate or the finite L/R time of the plasma ring.

Figure 8  Effect of poloidal flux on the evolution of the plasma velocity. The total particle number is fixed at \( 5 \times 10^{18} \) for four values of flux, \( \Phi_0 \times 10^{-3} \) Webers.

Figure 9  Gas Valve characteristics:

Sweep: 200 \( \mu \)sec/cm

Top Trace: Fast ion gauge collector current 2 \( \mu \)A/cm

Bottom Trace: Gas valve driver current 2 kA/cm

Note the delay of about 100 \( \mu \)sec between the coil current start and the gas arrival consistent with the thermal velocity of hydorgen at room temperature.
Figure 10  Predicted and measured (mid-plane) poloidal field versus radius
Time is relative to the energizing of the field coils (system
rise time is 6 msec with a 10 msec crowbar decay). The predicted
value (arbitrarily normalized) assumes nonconducting plates.

Figure 11  Side-on photographs of the gun plasma (exposure time 10 nsec
through an H filter of 20 width).
- t = 200 nsec; light front has moved out radially
- t = 500 nsec; light front is further out but obscured by the
toroidal bias field coil (dark streaks)

Figure 12  Exit plasma velocity versus poloidal flux. For the data points
(A) the flux was varied by changing the charging voltage on the
poloidal coil supply. For the data points (B) the supply voltage
was constant but the relative gun operation time was varied.
This compares the effect of flux or of field shape (ref. Fig. 10).

Figure 13  Typical traces of magnetic probe signals for two values of
poloidal flux. The measurement of \( B_T \) at \( R = 15 \) cm were inside the
gun and thus give an indication of the shape of the current sheet.
Vertical scales - top: \( B_T \), \( 2.9 \times 10^9 \) (Gauss/sec) per div.
\( B_p \), \( 6.4 \times 10^8 \) (Gauss/sec) per div.
Bottom: \( B_T \), \( 2.9 \times 10^9 \) (Gauss/sec) per div.
\( B_p \), \( 1.3 \times 10^9 \) (Gauss/sec) per div.

Figure 14  Measured line density evolution averaged over 16 shots. The error
bars show the degree of repeatability (standard deviation) of the
gun. The tail is due to slower plasma streaming out after the
initial burst.
Figure 15  Plasma front arrival time versus radius. Each point represents a shot.

Figure 16  Particle number evolution averaged over 16 shots. Assuming toroidal symmetry and constant velocity the particle number is the integral of the line density of Fig. 14.

Figure 17  Total particle number in the burst as a function of the valve filling pressure. Number is obtained during the first 550 nsec of particle flux out of the gun.

Figure 18  Traces of the time evolution of $B_T$ and $B_p$ at various radii (cm) outside the gun muzzle. The complicated structure near the muzzle simplifies further out. Vertical scale (all traces): $8.1 \times 10^9$ (gauss/sec) per centimeter deflection.

Figure 19  Arrival time at the first zero crossing of $B_p$ as a function of radius. This field structure moves out about the same velocity as the plasma density. A plot using $B_T$ gives the same velocity.

Figure 20  Measured toroidal current.
Sweep Rate: 1.0 µsec/cm  
Top Trace:  Rogowskii loop; 2 kA/cm  
Bottom Trace:  Gun Current; 75 kA/cm

Figure 21  Schematic arrangement of various probes and other diagnostics.
1. He-Ne laser interferometer; the beam is parallel to the experiment axis and can be position radially.
2. Magnetic field probe; some probes were mounted on remote positioners for remote field mapping.
3. Rogowskii coil; aligned as shown to measure toroidal current in the plasma ring.
4. Poloidal field coil; mounted just outside the expanding ring pathway.

5. Faraday cup; mounted for radial positioning to give time of flight measurement of the plasma velocity.

6. Light viewing optics; located to observe plasma light coming from different radial positions.

Figure 22 Traces of three idnetiral probes measuring $B_T$ at three azimuthal angles. The initial burst appears at the same time ($\pm 50$ nsec) on the three probes. Note that later structure is not repeatable. Vertical scale: Approx. $1 \times 10^{10}$ (gauss/sec.) per div.

Figure 23 One microsecond exposure of the gun plasma light taken axially. The dark radial spokes are toroidal field conductors.
Fig. 1
Copper Electrodes

Gas Density Distribution \( m(R) \)

Plasma Current Sheet (I) 
\( \delta = c/\omega_p \)

Coaxial Feed

Bias Current (I₀)

Spark Gap Switch

Toroidal Magnetic Field (bias + gun)

Toroidal Magnetic Field (bias only)

Fig. 2
Fig. 3

Time (microseconds)

Radius (cm)

Fig. 3 XBL 801-7622
Fig. 4
Fig. 5
Fig. 6a
Fig. 7

Radius (cm)

\( Y_p \) (Rel. Units)
Fig. 10
Fig. 12

\[ \phi_0 - \text{Enclosed Flux (Webers)} \times 10^{-3} \]

- Enclosed Flux (Webers) x

- Computed

- A

- B

velocity (cm/\(\text{usec}\))
(a) Shot #1334

\[ \Phi_0 = 3.4 \times 10^{-3} \text{ Webers} \]

\[ \dot{B}_T \text{ at } R = 15 \text{ cm} \]

\[ \dot{B}_p \text{ at } R = 32 \text{ cm} \]

(b) Shot #1347

\[ \Phi_0 = 2.3 \times 10^{-3} \text{ Webers} \]

\[ \dot{B}_T \text{ at } R = 15 \text{ cm} \]

\[ \dot{B}_p \text{ at } R = 32 \text{ cm} \]

\[ t \leftrightarrow 1 \mu \text{sec/cm} \]

Fig. 13
Fig. 15

$V = 25 \text{ cm/\mu s}$
Fig. 16

Particle Number $\times 10^{18}$

\begin{align*}
\text{Time (microseconds)} \\
0 & \quad 0.2 & \quad 0.4 & \quad 0.6 & \quad 0.8 & \quad 1.0 \\
\end{align*}

$P = 8 \ \text{psia}$

$R = 29 \ \text{cm}$

$V_p = 25 \ \text{cm/\mu s}$

XBL 801-7611
Fig. 17

Particle Number \times 10^{13}

(in first 0.55 μs)

Valve Pressure (psia)

\(V_{\text{poloidal}} = 150\)
Fig. 18
Fig. 20
Fig. 21

Plasma Gun

Axis

R Z

Plasma Ring

To Photomultipliers

1

Fig. 21
Shot #1791

Probe #1
\[ \theta = 22.5^\circ \]

Probe #2
\[ \theta = 158^\circ \]

Probe #3
\[ \theta = 293^\circ \]

Shot #1792

Shot #1794

\[ t \rightarrow (500 \text{ nsec/cm}) \]

Fig. 22
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