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Author
Levine, Morton A.

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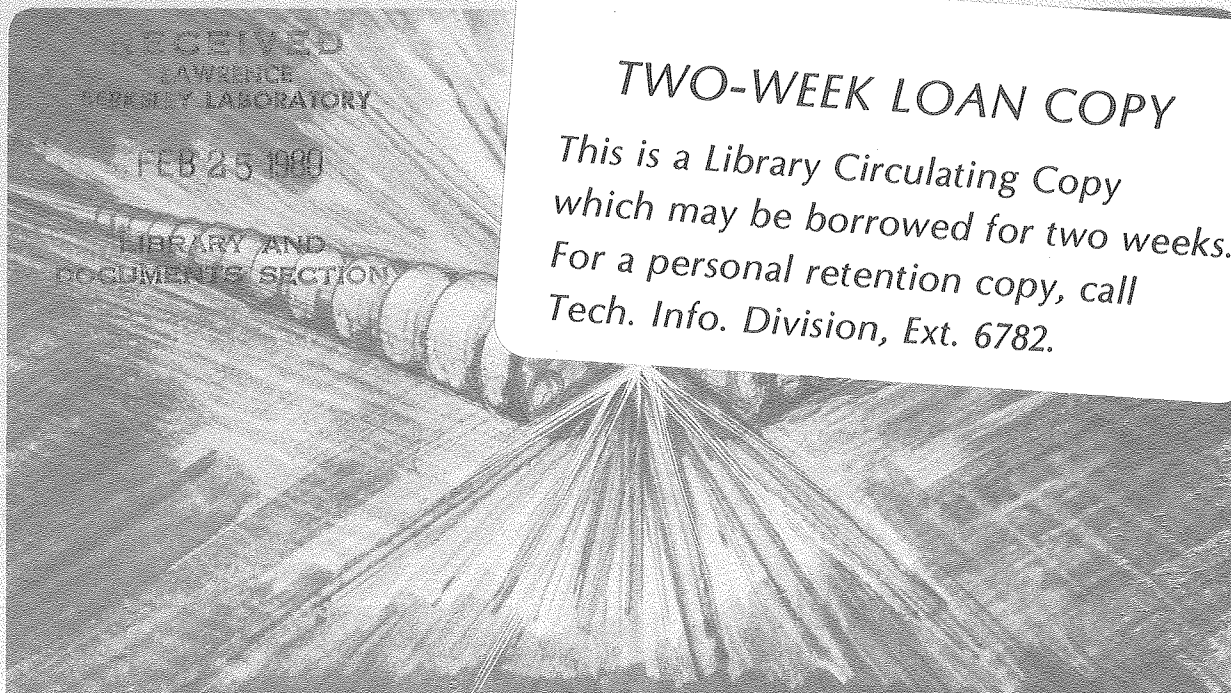## UNIVERSITY OF CALIFORNIA

Accelerator & Fusion
Research Division

FORMATION OF A COMPACT TORUS USING A TOROIDAL PLASMA GUN

Morton A. Levine and Philip A. Pincosy

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FORMATION OF A COMPACT TORUS
USING A TOROIDAL PLASMA GUN

Morton A. Levine and Philip A. Pincosy

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Myers, Levine and Pincosy[1] report results using a toroidal plasma gun. The device differs from the usual coaxial plasma gun[2] in the use of a strong toroidal bias current for enhanced efficiency, a pair of disk-like accelerating electrodes for reduced viscosity and a fast pulsed toroidal gas valve for more effective use of the injected gas sample. In addition, a technique is used for generating a toroidal current in the plasma ring. The combination offers an opportunity to deliver a plasma with a large amount of energy and to vary the density and relative toroidal and poloidal magnetic field intensities over a range of values. It is the purpose of this paper to report further experimental results, to project the gun's applications.to the formation of a compact torus and to propose a simple modification of the present apparatus as a test.

The gun consists of a pulsed toroidal gas valve (opening time - 50 microseconds) that injects a symmetric ring of gas between two annular plates. After a delay of about 100 microseconds, to allow time for the gas to distribute itself between the plates, a 4.4 microfarad capacitor charged to a maximum voltage of 50 kV is connected across the plates resulting in a half cycle time of 0.75 microseconds. Gas breakdown occurs in the breech of the gun in the region where the gas is injected and $J \times B$ forces accelerate a plasma ring outward. This acceleration is enhanced by the application of a bias toroidal magnetic field and its direction is determined by the relative direction of the current in the plasma and the bias current. Thus, normally during the first half cycle of the capacitor discharge the plasma is accelerated radially outward toward the muzzle of the gun and during the second half cycle the gas in the gun is accelerated inward toward the breech which is left open in the gun.
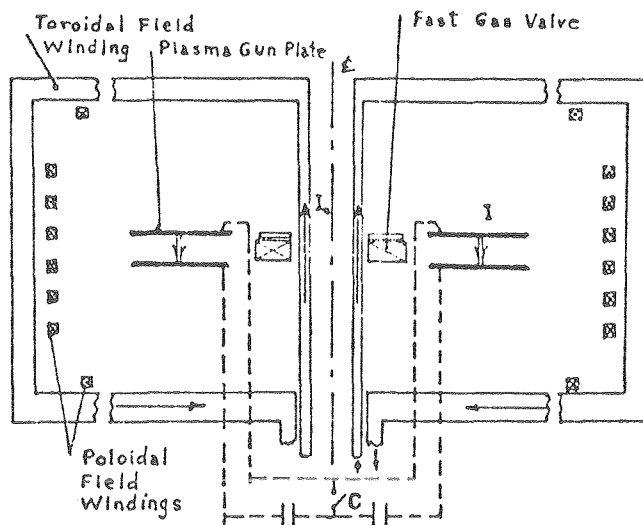
The total number of particles in the plasma ring is regulated by the filling pressure of the plenum in the gas valve and in practice can be varied from 10^{18} to 10^{19} particles (hydrogen).

It has been shown in a computer program which solves a set of coupled equations for the driving circuit that the dynamics of the gun are such that the total plasma kinetic energy after leaving the gun is roughly constant (currently 50% capacitor stored energy) over a wide range of particle number.

$$(1) \qquad \frac{\partial v}{\partial t} = \frac{1}{M(R)} \left\{ \frac{\mu_o d}{4\pi R}[I^2 + 2I\,I_o] - \frac{\partial v}{\partial R}\rho - v^2\,\frac{\partial M(R)}{\partial R} \right\}$$

$$(2) \qquad \frac{\partial M(R)}{\partial t} = m(R)v, \qquad (3) \qquad \frac{\partial R}{\partial t} = v, \qquad (4) \qquad \frac{\partial v_c}{\partial t} = \frac{I}{C}$$

$$(5) \qquad \frac{\partial I}{\partial t} = -\left(L_s + \frac{\mu_o d}{2\pi}\log\!\left(\frac{R}{R_o}\right)\right)^{-1}\left\{\frac{\mu_o d}{2\pi}\left(\frac{I+I_o}{R}\right)v + I\,R_s + V_c\right\}$$

$R(t)$ is the radius of the plasma sheet, V_ρ is the potential due to the poloidal magnetic field, R_o is the initial radius at $t = o$, $v(t)$ 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 per unit length between the plates, and $I(t)$ and I_o are the plasma and bias current respectively. R_s and L_s are stray resitance and inductance and d is the separation of the plates. C is the capacitance of the driver with a voltage $V_c(t)$.

Early data was taken with accelerating plates 38 cm O.D., 19 cm I.D. and with a 3 cm separation. The capacitor driver had a SCYLLAC type spark gap with a 2.1 µF capacitor, 50 kV and 150 nH. The bias current was a 0.3 meg amperes.

In the earlier low energy test, plasma velocities of 15 cm/microsec to 20 cm/microsec were obtained. The accelerated plasma had 10^{18} to 6×10^{18} particles and had a Mach number of the order of 2. In this configuration the plasma could be stopped and trapped using a poloidal magnetic field in the form of a toroidal bicusp.

Measurements were made using magnetic probes, radiation detectors, Faraday cups and a moveable laser interferometer. Particle densities and velocities were inferred by assuming cylindrical symmetry from the interferometer data.

Velocities were measured from a series of shots in which the interferometer was moved. Particle count before the plasma was stopped was inferred from the measured line density of electrons and a velocity inferred from the shot series. These measurements indicated that over 60% of the particles came out of the gun during the first burst. The magnetic probe measurements showed the first burst to contain a paramagnetic plasma with 2 kiloamperes to 6 kiloamperes of toroidal current.

Stopping and trapping the plasma in a poloidal magnetic field depends on toroidal symmetry to close the currents generated in moving into such a field. In fact, when the plasma is known to be assymetric, trapping does not occur. Interferometer data measuring the trapped plasma indicates that essentially all the particles were trapped. This result coupled with the magnetic probe results seemed to justify the assumptions of toroidal symmetry.

More recently, in order to increase the plasma energy, a larger, low inductance driver was installed in the system. This system has a total inductance of 13.5 nanohenries for capacitors, switch, leads and gun; so that the new system shows efficiencies of greater than 50% of the energy in the capacitor delivered to the first burst of plasma. This system under limited tests has given a plasma velocity of 45 cm/microsecond for a burst of 8×10^{18} particles corresponding to a Mach 6 plasma.

The use of a bias magnetic field parallel to the driving magnetic field in a plasma gun has the advantage that it is inherently more efficient and less dirty. This can be seen from equation (1) where the driver term is proprotional to $(I^2 + 2\,I\,I_o)$. I_o is the bias current and I the plasma current. Since the plasma current is introduced through electrodes, this interaction is reduced when I is reduced. Also apparent from equation (5), small values of I leads to higher electrical efficiency for the same drive.

The disadvantage to using a bias current is that the current is closed outside the plasma and the plasma is created within a coil structure. To form a compact torus it is necessary to remove the plasma from the coil by passing through spokes.

Removing the plasma from the coil may not be as difficult as it first seems. Predicting the behavior of the plasma is simplified if the plasma is moving at supersonic velocities. In the experiments so far performed with the toroidal plasma gun there has been a range of Mach numbers of from 2 to 6. Higher energy plasmas can be expected to given even higher Mach numbers.

Consider a toroidal plasma with a toroidal field moving with a Mach number, M. The toroidal field is produced by a current I_o flowing through the center of the system and returned through $\underline{n}$ bars each carrying I_o/n abamperes. We make the approximation that the magnetic field near the bars is given by $B = 2I_o/rn$ Gauss where r is the distance from the center of each bar. The toroidal magnetic field in the plasma is approximately $B_o = 2I_o/R_o$ Gauss. (The actual field is slightly higher due to a paramagnetic effect in the plasma as is characteristic of the Tokamak configuration.)

As plasma approaches the bars the plasma is compressed. However, the disturbance cannot be communicated to the rest of the plasma because of the supersonic flow. A characteristic bow shock then forms with a stand off distance such that the magnetic field pressure near the bar balances the directed momentum of the plasma, i.e. $1/2\ \rho v^2 = B^2/8\pi$ or $v = B/\sqrt{4\pi\rho}$ where v is the velocity of the plasma. Thus going through the bars disturbes a plasma of width 2r where $r = 2I_o/Bn$. In the limit of high Mach number and a thin plasma the fraction of plasma disturbed by the bars is $f = 2nr/2\pi R_o$. Using the fact that $B/B_o = M$ we find $f = 1/M\pi$. Thus for large Mach number, the bulk of the plasma passes through the bars unaffected. However, it is interesting

to speculate on the integrity of the magnetic configuration after passing
through the bars.

Alfvén's theorem states that in a frame of reference, moving with and
within a plasma, the magnetic field remains constant. Thus changes in mag-
netic field geometry are confined to the perturbances created at the bars
where the plasma is cut. Since the cut is very thin, we can assume at some
point down stream that the toroidal magnetic field will be symmetric and
reconnection will have taken place. The question is thus one of asking in
what distance or in what time this reconnection takes place. One notes that
as the plasma flows by the bars, the field lines are bent, the volume available
for the plasma to fill by flow along magnetic field lines becomes larger and
larger. One also notes that there is a magnetic x-point or line in this
region behind the bars. It has been shown[3] that in the region of an x-point
reconnection can take place at the Alfvén velocity if it is accompanied by
flow along magnetic field lines which drains plasma from the region of recon-
nection. Thus, in the region behind the bars reconnection can be expected to
proceed at the Alfvén velocity. Since the plasma in this region can be ex-
pected to be subsonic and reconnection fast, this implies that the magnetic
configuration will be effectively unchanged as the plasma passes through the
bars.

As mentioned above, the current apparatus includes a large toroidal field
coil surrounding a smaller poloidal field coil which is used in the plasma
trapping experiments. The toroidal field coil has 16 turns. These turns can
be shorted using thin rods near the muzzle of the gun. This would then leave
the bias current and the poloidal field coil structure intact. Thus, a plasma
produced by the gun would have to pass through the coil structure before
interacting with the poloidal field. However, after passing through the coil,
if the plasma maintains its configurational integrity it will not be able to
penetrate the poloidal field and a sharp boundary of penetration of the plasma
will be observed. However, unlike the current experiment where the plasma is
trapped in place, in the proposed experiment the plasma can be expected to
bounce back toward the gun. If this experiment is successful a very simple
extension will lead to the formation of a compact torus.

[1] Lawrence Berkeley Laboratory, Report LBL-9507

[2] J. Marshall in "Plasma Acceleration (S. Kash, ed.) Stanford University Press,
Stanford, California (1959).

[3] V. Iunas, Review of Geophysics and Space Physics, 13, 303 (1975).