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Gas injected washer plasma gun

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Abstract A plasma gun similar in geometry to the washer plasma gun has been operated with gas injected externally. Hydrogen, nitrogen and argon plasmas have been ionised and accelerated to velocities of the order of 10^7 mm s^{-1} and densities 10^{11} mm^{-3}. Higher parameter range is possible with higher electrical input power.

Plasma guns find a variety of applications in plasma physics and controlled fusion research. They provide the target plasma in mirror experiments (Coensgen *et al* 1975), help in the initiation of toroidal discharges (Prater *et al* 1976), provide high density plasmas for ion extraction (Dembinski *et al* 1979) and can be used to accelerate pellets for fuelling fusion devices (Buller *et al* 1979). A variety of plasma guns using electromagnetic and other types of propulsion have been developed and are in use.

The titanium occluded washer plasma gun, developed first in the Lawrence Livermore Laboratory is a very reliable plasma source (Coensgen *et al* 1959), although the mechanism of its working is still poorly understood and it has been developed to the present state mainly by empirical methods (Nexsen 1977). A set of titanium washers are heated to around 1000°C in a hydrogen atmosphere where they undergo an exothermic reaction with hydrogen and form titanium hydride. The hydrogen loaded titanium washers are stacked with insulator separation. A trigger electrode placed in the vicinity of the cathode provides an initial quantity of electrons which are then accelerated by the voltage applied between the cathode and the anode. Electrons striking the washers deposit their energy, causing localised heating and desorption of trapped hydrogen which is then ionised and ejected through the anode. The acceleration mechanism may be ambipolar expansion due to the thermal pressure of the plasma inside the gun or may be electrostatic, provided by a cloud of unneutralised electrons accelerated towards the anode or mixture of both.

The occluded gas gun has a number of disadvantages. Firstly the process of loading the washers with hydrogen or deuterium is quite cumbersome. Replacement of the washers is frequently necessary due to ageing resulting in hydrogen starvation after a number of shots. As the gun initially is in hard vacuum, a trigger pulse is essential to provide electrons which will further release the occluded gas and initiate the discharge. Once the discharge is started there is little control over the quantity of neutral gas released. The gun is also unsuitable for operations requiring plasma ions heavier than deuterium. Heavy gases such as nitrogen and argon do not react at all, or react poorly during the loading process.

With an aim to overcome some of these difficulties and specifically to test the suitability of the gun for heavy gas plasmas, we have made a number of modifications in this plasma source while retaining the basic geometry. The source, as shown in figure 1 consists of a number of stainless steel (Copper or brass washers also have been used) and nylon washers with an internal diameter 22 mm and thickness 5 mm stacked together alternately and housed inside a metallic tube. The glass tube around the washers insulate them from the metallic wall and inhibits radial arcing. The first washer acts as the cathode and the last washer is connected to the ground through the metallic wall. The gas to be ionised is let into a nylon plenum and then into the gun with the help of a slow pulsed electromagnetic valve and enters near the cathode. The electromagnetic valve consists of a light aluminium piston contained in a gas manifold sitting over an orifice with an O-ring seal. The sealing is done by the pressure difference between the manifold and the experimental chamber. A small piece of mild steel is attached to the aluminium piston. A coil surrounds the mild steel piece. A low voltage capacitor bank is fired through a thyratron to generate a magnetic field in the vicinity of the mild steel piece and the resultant magnetisation of the mild steel piece lifts the piston to allow the opening of the orifice and entry of the gas into the plasma gun. A typical trace of the ion current in a nude ionisation gauge kept in the

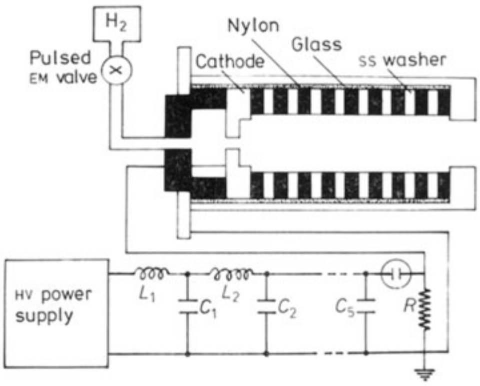

Figure 1 Schematic diagram of the gas injected washer gun. $L=2{\cdot}2$ μH, $C=2{\cdot}4$ μF. The impedance compensating resistor is not shown in the figure.

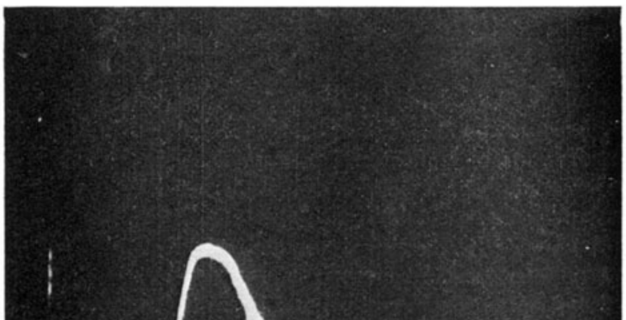

Figure 2 Response of a nude ionisation gauge to gas injected by the electromagnetic valve. The gas pressure in the gun peaks at around 2 ms.

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experimental chamber immediately after the plasma gun (figure 2) shows the time behaviour of the gas entering the plasma gun. The pressure inside the gun reaches its maximum in a time of typically 2 ms.

The gun is energised by a five stage pulse-forming line formed of 2·4 μF low inductance capacitors and 2·4 μH inductors switched through a thyratron. Since the gun impedance was a fraction of an ohm (0·3 Ω), a series resistor was used to match the line-impedance. The thyratron was fired approximately when the neutral gas pressure inside the gun was maximum. This time was estimated by measuring the neutral gas pressure just outside the gun outlet using a fast nude ionisation gauge. The discharge pulse duration was about 40 μs and for an applied voltage of 10 kV the discharge current was about 3 kA, limited mainly by the impedance-matching resistor, which was a 1 Ω resistor made of nichrome strip. We have estimated that about 24% of the energy stored in the pulse forming line gets dissipated in the gun.

The synchronisation of the thyratron triggering *vis-à-vis* the development of the gas pressure was not critical, indicating that the gas was not fully ionised at the voltages and currents in the gun circuit. The plasma discharge current as measured using a Rogowsky coil was constant over a range of gas pressures. The gun did not operate without the injection of external gas.

The experimental study of the plasma produced by this source was done with the help of a Faraday cup consisting of a collector with a grid in front, placed inside a metallic tube. While the data are fairly repeatable there is some question as to whether the collector of the Faraday cup was sufficiently biased to be in the ion saturation region. Even 25 to 30 V applied to the collector caused an arc over in the collector. This necessitated keeping the Faraday cup well away from the gun (typically 200 mm for a voltage of 10 kV and maintaining the bias voltage at not less than −30 V). Therefore the calculated values could be taken only for the lower limit of the densities. A conventional multigrid energy analyser was also used for measuring the ion kinetic energy distribution.

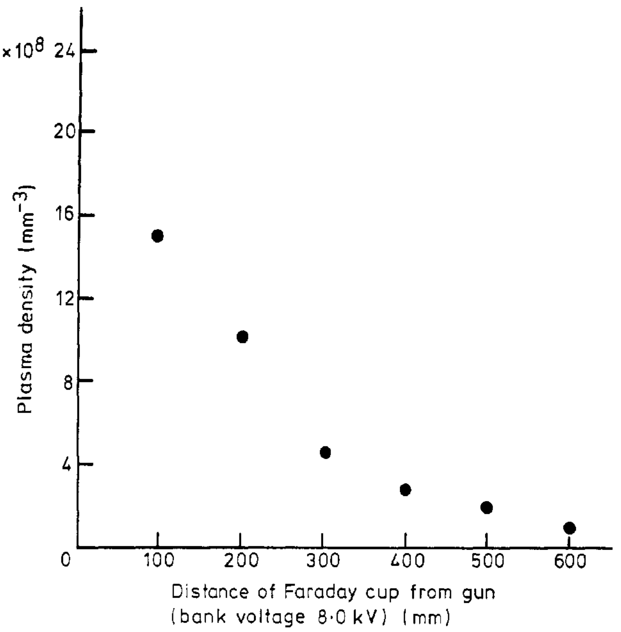

Figure 3 Hydrogen plasma density as measured by a Faraday cup against distance of the collector from gun.

To reduce the ambiguities from the Faraday cup results due to ion acceleration, breakdown etc, we also used a 25 GHz microwave interferometer to supplement the time-of-flight measurements. The density measurements using the signal cutoff (corresponding to 6×10^9 mm^{-3}) shows that the actual density is higher by a factor of 5 than the densities measured by the Faraday cup.

The plot of the obtained values of hydrogen plasma densities against the distance of the collector from the source (see figure 3) shows that the dependence is slower than the inverse of r^2 which indicates that the propagation is not just a thermal expansion. The dependence of the density with the discharge voltage as shown in figure 4 shows that even at 12 kV the density is still increasing with the voltage. The plot of particle flux against the discharge voltage also indicates a similar tendency. These curves guarantee the capability of this gun giving higher densities and fluxes at higher input power.

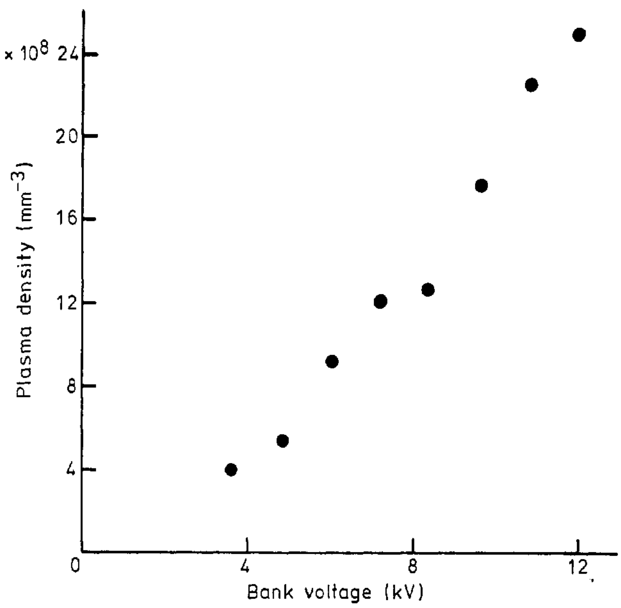

Figure 4 Plasma density as a function of the capacitor voltage. Voltages smaller than 4 V did not induce gas breakdown.

To simulate the conventional washer gun performance, we modified the stainless steel electrode near the exit of the gun such that gas could be introduced through radially drilled holes. However, in this mode, although the electrical characteristics were similar to the case when gas was introduced near the cathode, the plasma velocity was reduced to about half. This may be due to excessive collisional deceleration of the plasma by the neutral gas.

The experiments were repeated with other gases like nitrogen and argon to evaluate the capability of the gun to accelerate heavy ion plasmas. The variation of plasma flux and velocity were qualitatively similar for all gases. The time-of-flight measurements obtained using the microwave propagation techniques are tabulated in table 1. We notice from the interferometer signals that for the same power input; hydrogen gives larger densities (by a factor of two to three) than heavier gases. This is probably due to the fact that, the inlet pressure being constant, much more gas is puffed into the gun when operating with a light gas. The velocities are independent of the pulse duration as verified by operating with 15 μs and 40 μs pulses.

Table 1 Plasma velocity for different species.

Gas	Velocity (mm s^{-1})
Hydrogen	$1 \cdot 2 \times 10^7$
Nitrogen	8×10^6
Argon	7×10^6

The fact that plasmas generated by introducing different gases like hydrogen, nitrogen and argon have different parameters such as density and velocity is indicative that non-hydrogenic plasmas are being produced by the gun. However, the possibility of the evolution of hydrogen within the gun and its subsequent ionisation, even when heavier gases are injected cannot be totally ruled out. To verify that heavier gas plasmas are indeed produced, a simple time-of-flight mass spectrometer was constructed and operated in conjunction with the plasma gun. The mass spectrometer consisted of an assembly of two grid accelerators separated by 20 mm, a 1 m long drift tube and a collector at the end of the drift tube. Ions were accelerated through known potential differences and their time of flight was used to identify the ion mass. As the plasma gun was pulsed the accelerating voltage was kept steady. Experiments were done by injecting argon into the plasma gun and the measured ion time of flight (figure 5) identified the plasma species as argon. All the experiments were done at acceleration voltage less than 100 V as higher voltages caused breakdown in the acceleration region and drift space, possibly due to photionisation and other unidentified sources.

In figure 5, the two traces correspond to the currents from ion collectors. The first large peak in both the traces appear during the discharge duration and is not affected by mass spectrometer accelerating voltage. The peaks appearing at 52 and 100 μs respectively in the two traces are the ion current signals from the mass spectrometer. The differences in polarity and amplitude are instrumental. The dispersion in time in the second trace is due to the fact that the ions are post accelerated from a plasma with finite energy dispersion.

To summarise, we have operated a washer gun by externally injecting gas and have shown that high density plasmas can be produced and accelerated in this mode. Specifically, in contrast to the conventional mode of desorbed gas operation this mode allows ionisation and acceleration of heavy ion plasmas such as nitrogen and argon.

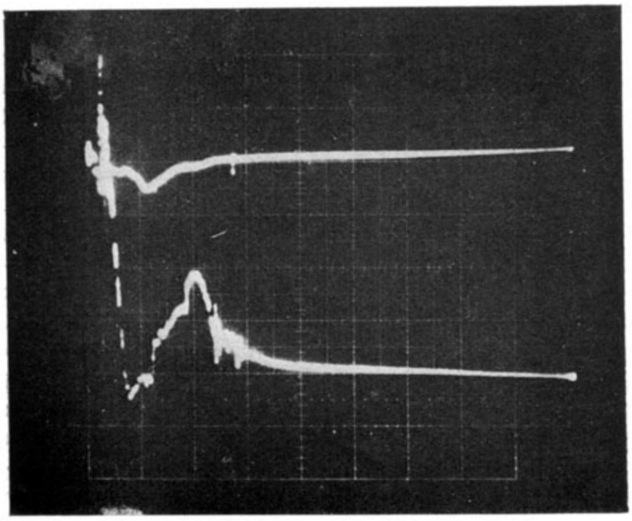

Figure 5 Ion currents collected by two collectors of the time-of-flight mass spectrometer separated by 1 m. Ions are accelerated by 60 V. The horizontal divisions are 50 μs.

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