# A Large Double Plasma Device for Plasma Beam and Wave Studies

R. J. Taylor, K. R. MacKenzie, and H. Ikezi*
*Department of Physics, University of California, Los Angeles, California 90024*
(Received 29 June 1972; and in final form, 14 August 1972)

The DP (or double plasma) device consists of two essentially collisionless plasmas that are separated from each other (for electrons only) by a negatively biased grid. Large cross section beams of ions are produced in one plasma by raising the potential of the other. Ion waves or shocks are produced in one plasma by oscillatory or large sudden (or ramp) potential changes in the other. Electrons emitted from two electrically separate spatial arrays of small filaments produce the two plasmas with densities in the range from below $10^8$ to $\sim 10^{10}$ ion/cm$^3$ with noise levels $\langle \delta n/n \rangle \approx 5\times 10^{-4}$.

## INTRODUCTION

In this paper we describe the production of a large volume quiescent plasma in a DP (double plasma) device.[1] It consists of two separate plasmas (as the name suggests) housed in a common vacuum chamber but separated (for electrons only) by a negatively biased grid. This arrangement makes it possible to generate large cross section plane ion beams,[2] large cross section plane ion waves, and large amplitude ion acoustic shocks[3] in zero or weak magnetic fields ($<30$ G) by simply varying the potential of one plasma with respect to the other. Densities are typically in the range from $10^8$ to $10^{10}$ ions/cm$^3$ in background pressures around $2\times 10^{-4}$ Torr, implying that the plasmas are essentially collisionless for most experiments of current interest. $T_i$ is of the order of 0.1–0.2 eV, while $T_e$ is controllable between 0.5 and 5 eV. Throughout this range the noise level $\langle \delta n/n \rangle$ is typically about $5\times 10^{-4}$. The uniformity is very good, due to the combination of a large volume and a multiplicity of surrounding sources of ionization. In some cases the density varies by not more than 2% over a volume of 28 liters. The gas is usually argon, but helium and xenon are also used.

## I. APPARATUS

The device, in its original form,[2] is shown in Fig. 1. Two vacuum chambers (not necessarily identical) are separated by a negatively biased grid. Plasma is generated in both chambers by electron bombardment from a multiplicity of short filaments held at a negative bias of the order of 40 V. Separate power supplies are employed, permitting both chambers (including the filament and emission power supplies) to be completely insulated from each other. Potential differences can thus be applied between the two plasmas. This essential feature is made possible by the presence of the separation grid which is held at a negative potential (usually at least $-30$ V). The potential of this grid is sufficient to prevent the cross flow of the plasma electrons (not necessarily the ionizing electrons) between the two chambers. The ions, of course, flow freely back and forth through the grid except for a small interception loss due to the finite wire size. Since the grid is biased highly negative, the ions, as they cross the grid, experience acceleration and deceleration over a region of several Debye lengths. A typical grid is cut from stainless mesh (usually 0.0025 cm wire spaced 40–80 wires/cm) and held taut by small peripheral springs.

The geometry of Fig. 1 uses an inconvenient insulated vacuum seal between the two chambers. Figure 2 shows a modification used in our three subsequent DP devices. The metal vacuum housing is at ground potential and common to both plasmas. Separation of the plasma potential from the housing potential is achieved by an internal cylindrical stainless steel mesh anode. The mesh spacing has varied from 2 to 5 wires/cm on different machines with no obvious indication that there is an optimum. In this design the power source, which applies the potential difference between the two plasmas, must be capable of supplying the plasma ionization current that flows to the vacuum housing (typically 3–10 A). The filaments have been placed both inside and outside the mesh anode. Filaments placed inside seem to produce a more stable plasma potential, at the expense of an increase in plasma noise by roughly a factor of 2.

The number and disposition of filaments is governed by four factors:

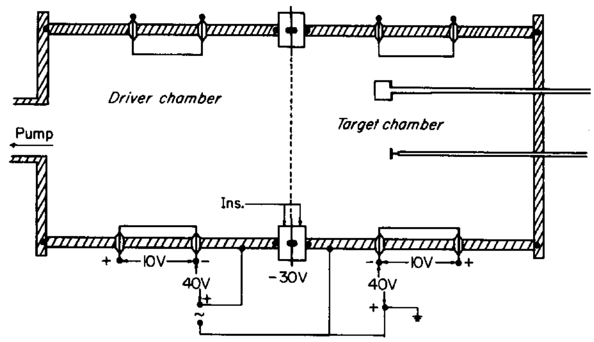


FIG. 1. Original form of the double plasma device with two insulated chambers and power supplies. Signals are applied between chamber 1 and ground. Chamber 1 is often referred to as the driver chamber and chamber 2 as the target chamber. Dimensions are 30 cm diam by 60 cm in length.

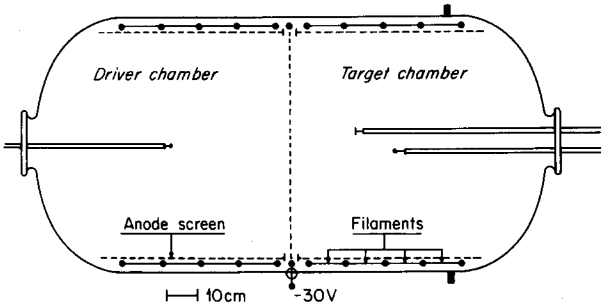


FIG. 2. Large common vacuum chamber, 90 cm diam by 180 cm, with internal separation grid, separate filaments and anode screens, and separate power supplies that can be insulated from ground for application of driver signals.

(1) The voltage drop along any single filament (typically 10–15 V) should be significantly smaller than the applied bombardment voltage.

(2) The filaments emitting the ionizing electrons should be disposed symmetrically around the chamber in the interests of uniformity.[4]

(3) The emission per unit length must be held below some critical value (which varies from 10 to 30 mA/cm in our devices) to avoid the onset of a noise instability due to the density of streaming electrons.

(4) In accordance with this emission limitation, filaments must be added in parallel until enough emission is obtained to provide the desired density without the onset of noise. It is this feature which permits operation in the $10^9$ ions/cm$^3$ range at a noise figure $\langle \delta n/n \rangle$ as low as $5\times10^{-4}$. In the large device shown in Fig. 2, an emission limit of 5 A at 40 V from 120 filaments 15 cm long and 0.020 cm diam produces a density of $3\times10^9$ ions/cm$^3$ at a neutral pressure of $2\times10^{-4}$ Torr in argon. Tantalum filaments are used in this large device instead of tungsten to minimize heating of the vacuum vessel. However, tungsten is used in the smaller devices and has a longer life. Thoriated tungsten filaments are also a possibility but require special heat cycling for proper operation and are very sensitive to ion bombardment.

## II. OPERATION

The large amount of heating power required for the multiplicity of filaments means that cooling and pump down times are important factors. In the above large chamber, the walls are allowed to rise to about 70°C during a bake-out period of some 6–10 h. Then cooling water is turned on.

Whenever it is necessary to break the vacuum to replace filaments (after 50–100 h of operation), or make other changes, variations in operating parameters are usually introduced due to electrical changes in surface layers. The electron temperature, for example, may change from 0.5 to 2 eV during pump down to base pressure. Our vacuum systems are all evacuated by oil diffusion pumps with refrigerated baffles. Nevertheless the small amount of backstreaming contributes a vapor contamination that decomposes in the plasma and together with any initial contamination forms a thin surface layer on the walls and electrodes that often has a very high electrical resistance. When flat surfaces are used as the anode, it is suspected that the electron collection occurs over random open patches in this film. This suspicion is partially confirmed by the fact that mesh anodes (with the electron collection concentrated over a small area) give more reproducible operation. Presumably the concentration of current and bombardment either cleans the surface or lowers the effective film resistance, either by heat, or possibly by fragmentation.

Recently we have found a method of controlling the electron temperature that is relatively independent of surface conditions. A small secondary anode is held at potentials between 0 and 100 V. The current collected depends on the area introduced but typically is a maximum of about 15% of the main anode current. This anode raises the plasma potential, making the whole plasma a deep potential well for electrons (typically 4–7 V in depth with respect to the main anode screen).

In addition to this effect, we have found that if the secondary anode is composed of fine wires, we can achieve higher electron temperatures.[5] Operation is also more dependable (presumably because of lack of surface contamination on the small wires, which run red hot at the higher voltages). When held at positive potentials the small wires are surrounded by cylindrical sheaths, and cold electrons are collected, which, under normal operating conditions in the absence of the wires, cannot reach the walls. In addition, electrons with appreciable angular momentum with respect to the wires (principally the hot electrons) orbit the wires and return to the plasma. We call this phenomenon our Maxwell demon method, due

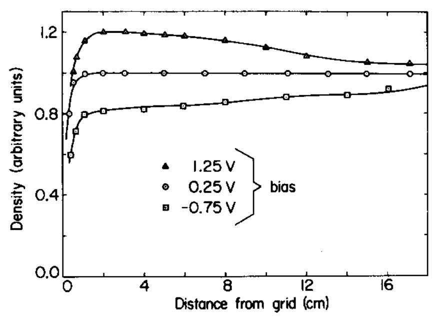


FIG. 3. Plasma uniformity in chamber 2 for three differential potentials in chamber 1. A flat profile is produced by raising chamber 1 by +0.25 V. This compensates for the interception loss by the 0.0025 cm diam grid wires with a mesh spacing of 0.025 cm. Each chamber is 30 cm diam by 30 cm in length. The density for this case is $10^9$ ions/cm$^3$ in argon at $3\times10^{-4}$ Torr. $T_e=1.5$ eV and $T_i=0.15$ eV.

to its similarity to the classical (but forbidden) Maxwell demon method of heating a gas.

When such a fine wire anode is used at a potential between 20 and 100 V with respect to the main anode screen, the plasma potential may assume a value of +5–15 V with respect to the screen. The floating potential however, remains at −30 V or lower (and dependent on probe orientation) due to the small high energy ionizing tail of the distribution function contributed by the filaments at −40 V or more. (This large negative value for the floating potential means that the negative potential of 20–30 V on the separation screen is usually realized in practice by simply allowing it to float). The maximum potential that can be applied to the "demon" is set by the onset of noise and may occur below 100 V when the density is raised to $10^{10}$ ions/cm$^3$. Below this limitation, no noise is introduced, and the plasma uniformity is not affected.

Figure 3 gives an indication of the plasma uniformity in chamber 2 as measured with an electron collecting probe. The drop in electron density next to the grid occurs in a nonneutral region where ions are being accelerated through the grid and electrons are being repelled.[6] Beyond this local region, if chambers 1 and 2 are both held at the same potential with equal densities, there is a slight gradient away from the grid. This is caused by a small interception loss as ions pass from chamber 1 into 2. This gradient increases to a maximum when the potential of chamber 1 is made −0.75 V or lower. In this situation the 0.15 eV ions in chamber 1 cannot surmount the potential barrier. Hence there is a net drift of ions in chamber 2 toward the grid, and an axial gradient of approximately −0.75%/cm for the conditions shown in Fig. 3. The radial gradient has approximately this same value near the walls. On the axis the radial gradient is zero.

As seen in Fig. 3, the gradient in the axial direction can be essentially removed by a slight increase in the potential of chamber 1, causing an ion flow which compensates for the interception loss on the grid. In the large chamber shown in Fig. 2, the density can be made constant within 2% over a cylindrical volume 30 cm diam by 40 cm (∼28 liters).

## III. BEAMS AND ION WAVES

### A. The Beam Mode of Operation

When both plasmas are at the same potential and of equal density, the net flow of ions across the separation grid is zero. If, however, chamber 1 in Fig. 1 is raised to a positive potential $\phi$ with respect to chamber 2 (held at ground potential), all ions in chamber 2 with energies less than $e\phi$ will be reflected. The result is an ion beam in chamber 2 with maximum energy $e\phi$ as shown in Fig. 4. If the densities are unequal, the zero net flow condition

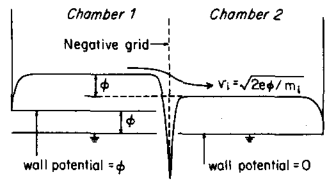


FIG. 4. Potential profiles in the two chambers showing how a beam of ions can be produced by a differential potential $\phi$.

occurs at a finite potential difference, provided it is less than $kT_e/e$.

Beam densities are controllable over wide limits. Beam densities exceeding the plasma density in chamber 2 are easily produced by lowering the filament voltage in chamber 2, thus reducing the plasma density, while allowing enough extra emission (typically a few milliamperes) to neutralize the space charge effect of the entering ion beam.[2] Such beams (with energies up to 80 eV) are currently being employed in studies of beam-plasma interactions.[7]

### B. The Ion Wave Mode of Operation

Plane ion waves are generated when time varying voltages are applied to chamber 1. For example, with both chambers at the same potential, a periodic excitation signal $\phi \cos\omega t$ applied to chamber 1 causes a periodic flow of ions with maximum energy $e\phi$ in both chambers. The flow is neutralized by the plasma electrons within limits set by the electron pressure. Provided that the flow velocity is less than the ion acoustic speed, the residual electric fields are essentially the same as found in an ion acoustic wave, with the result that the quiescent plasma ions gain momentum from the residual fields and initiate a true ion acoustic wave. However, this energy exchange between incident ballistic ions and ion wave energy is not a resonant energy exchange since the ballistic velocity can be arbitrarily small compared with the wave velocity, depending on the wave amplitude desired.

This generation process (in contrast to the usual grid excitation of ion waves) is extremely efficient. Wave amplitudes are easily reached where steepening occurs. Further increases in amplitude cause the waves to steepen into electrostatic collisionless shocks.[3] Such a shock has a plane wavefront about 6 cm less than the effective chamber diameter (where the effective diameter is the clear interior space, unobstructed by filaments and anode screens).

Ion temperatures in this device, as measured by an energy analyzer with a resolution of about 0.1 eV,[6] are below 0.2 eV. Ion and electron energies therefore yield $T_e/T_i$ ratios ranging from approximately 3 to 25, and occasionally as high as 50. However, it is also possible to produce $T_e/T_i$ ratios as low as $\frac{1}{10}$. With chamber 2 at ground potential, ions with energy of about 10 eV are injected from chamber 1 and are neutralized by electrons from the filaments (at near zero potential) in chamber 2. The injected electron energy is the sum of the filament thermal energy and the energy imparted by the bias supply. This energy can be considerably less than the injected ion beam energy. The ion beam, of course, is not Maxwellian, but it is possible to produce a good approximation to a half-Maxwellian ion distribution function by imposing a high frequency voltage of 3–10 V at 2–5 MHz on the separation grid.[2,8]

All of the above parameters apply to zero $B$ field or fields of the order of the Earth's field. When uniform fields as high as 30 G are applied, the nonuniformity and noise in our present devices reach limiting useful levels. Presumably this is due to channeling of the ionizing electrons from each filament along the field. It is not yet known whether increasing the multiplicity of filaments might increase this limit.

**ACKNOWLEDGMENTS**

The authors wish to acknowledge assistance given by Dr. David Cohn. This work was performed with support from the United States Atomic Energy Commission.

* Now at the Institute of Plasma Physics, Nagoya, Japan.

[1] R. J. Taylor, H. Ikezi, and K. R. MacKenzie, Proc. Intern. Conf. Phys. Quiescent Plasmas, Paris, 8–13 Sept. 1969, pp. 57–66.
[2] H. Ikezi and R. J. Taylor, Phys. Rev. Lett. **22**, 923 (1969).
[3] R. J. Taylor, D. R. Baker, and H. Ikezi, Phys. Rev. Lett. **24**, 206 (1970).
[4] This feature is used in a spherical field-free plasma generator. A. C. Hoog and L. Schott, Rev. Sci. Instrum. **41**, 1340 (1970).
[5] K. R. MacKenzie, R. J. Taylor, D. Cohn, E. Ault, and H. Ikezi, Appl. Phys. Lett. **18**, 529 (1971).
[6] H. Ikezi and R. J. Taylor, J. Appl. Phys. **41**, 738 (1970).
[7] F. V. Coroniti, R. J. Taylor, and K. R. MacKenzie, Bull. Amer. Phys. Soc. **16**, 1263 (1971).
[8] H. Ikezi and R. J. Taylor, Phys. Fluids **13**, 2348 (1970).