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Adjustment of the ion energy distribution in double plasma and other synthesized plasma devices

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Abstract. The parallel ion energy distribution of a synthesized plasma can be readily controlled via plasma potential gradients in the ion source chamber(s). Alternatively, layers of electrically biased metal filaments can introduce an isotropic ion heating.

Keywords. Ion energy; synthesized plasma; double plasma device.

1. Introduction

The low cost and relative simplicity of the double plasma (DP) device (Taylor *et al* 1972) has made it very popular for basic plasma physics experiments. Previous practical devices, although providing electron plasma temperatures adjustable from about 0·05 to a few electron volts (Honzawa 1977) have had rather low, fixed (or nearly fixed) ion temperatures, T_i (Hershkowitz 1975). A number of new experimental applications would immediately come to mind if only one could control the ion energy distribution. Cusp leak width investigations, for instance, depend upon the size of the ion gyroradius and hence the distribution of ion energies (Jones 1979a). Such investigations would benefit from the development of a plasma having widely controllable ion energies. In the present paper we report on several means of varying and increasing the average ion energy spread so that a wider range of experimentation becomes possible. Specifically, it is now possible to produce plasmas having $T_e \sim T_i \sim$eV or T_i/T_e greater than unity.

2. The experimental setup

The experimental device (figure 1) is a large (40 cm diameter, 60 cm long) aluminium double plasma device (Hayzen and Barrett 1977) which can be pumped to a base pressure in the 10^{-7} mm range by a 6 inch oil diffusion pump. The source chamber contains 18 well-distributed, 7 inch long, 0·008 inch diameter tantalum filaments and is surrounded by (1500 gauss) close-packed ceramic magnets (700 gauss in the cusps, measured at the wall surface) except for the face containing the ion extraction mesh. The target chamber contains an array of about 40, 5 inch long, 0·005 inch diameter filaments. Argon is the usual working gas, density fluctuations dn_e/n_e (Jones 1979a) are typically a few $\times 10^{-3}$ and neutral pressure ranges from 4×10^{-5} to

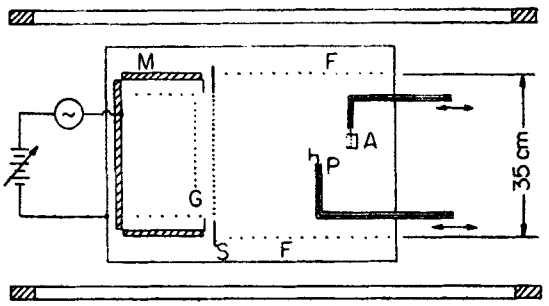

Figure 1. Double plasma device with; F, target chamber filament arrays for neutralising the incoming ion beam; P, Langmuir probes; A, energy analyzer; M, arrays of permanent magnets for plasma confinement; S, separator mesh; and G, auxiliary ion beam control grid.

10^{-3} mm. Plasma densities and temperatures of 10^8 cm^{-3} and 1 eV are typical in the target chamber (where experiments are performed).

The source chamber filaments are biased 70 V negative with respect to the source chamber wall and are heated by a 0–17 V, 0–100 amp power supply. The source chamber can itself be biased (with respect to the target chamber wall) positively by a 0–500 V, 0–500 mamp supply.

If one end of the filaments in the target chamber is at ground potential then the predominant source of ions is the extracted current from the source chamber and the voltage difference between the two chambers is used to introduce a drift in the two components of the synthesized target plasma. Since the source chamber acts like a plasma filled diode the extracted ion current scales as the three halves power of the potential difference between the source chamber and target chamber plasmas. (i.e. low ion-electron relative drift corresponds to lower working target plasma density). Optimal quiescence (Jones 1979b) and near Maxwellian target plasma electron distribution depend upon reducing the target filament electron emission so as to just neutralise the incoming ion beam.

Pressures above a few $\times 10^{-4}$ are usually to be avoided due to the short charge exchange mean free path (argon) while very low pressures lead to higher electron temperatures and noise. A pressure of 2 or 3×10^{-4} is a reasonable choice for a machine of this size and argon gas (Jones 1978a).

3. Discussion and results

In a plasma possessing a finite electron-ion relative drift (and all synthesized plasmas must have some such drift) the ion temperature is defined with respect to the spread in ion velocities:

$$T_i \equiv \tfrac{1}{2}M(dv)^2,$$

while the total kinetic energy of an ion, in the laboratory frame, is defined with respect to the ion velocity in this frame:

$$U \equiv \tfrac{1}{2}Mv^2.$$

From these definitions we find that the ion temperature can be obtained from the ion energy and energy spread, measured in the lab frame, according to the equation:

$$T_i = (dU)^2/4U.$$

with U generally greater than dU.
It is U and dU which are obtained directly from planar gridded retarding field electrostatic energy analysers (Jones 1978b) in our experiments. Strictly speaking, the ion temperature parallel to the relative drift U may well differ from that at right angles to it. For many plasma instabilities it is this 'parallel temperature' which is important (Hayzen and Barrett 1977; Jones 1978c). As we shall see, the ion distribution may differ significantly from Maxwellian. In such a circumstance we can speak of an average ion energy spread rather than a true Maxwellian 'temperature'. We will also discuss means of isotropising T_i later on.

The observed ion temperature, or energy spread dU, can be enhanced by the presence of a potential gradient in the body of the source chamber plasma (Jones 1978d). Such gradients, while usually neglected in simpler theories, actually are unavoidable under certain discharge conditions (Tonks and Langmuir 1929) and when a more complete theory is considered (Caruso and Cavaliere 1962; Jones 1977). (At least in the limit of electrostatic confinement and ionisation supported, at least in part, by plasma electrons.) Since ions created by electron-gas discharge are born nearly at rest and at the local plasma potential (Dunn and Self 1964) ions originating at various spatial locations in the source fall through different potential differences in traversing the extraction region. It has been known since Langmuir's time that the energy distribution so introduced will be quasi-Maxwellian (Langmuir 1961). The total energy spread observed in the target region is approximately:

$$dU = T_i(s) + U_{\text{gradient}}$$

where $T_i(s)$ is the ion temperature in the source plasma and U_{gradient} is the average potential variation over the ion emitting source plasma region. U_{gradient} is of the order of the source plasma electron temperature, $T_e(s)$ which is independent of the target plasma electron temperature (Jones 1977).

It has been found that a simple way to increase dU is to increase the filament power (and, hence, discharge power) in the source chamber. Figure 2 clearly shows the dependence. For a fixed value of the extraction voltage (differential bias between source and target chambers), or U, one also sees a rise in plasma density in the target chamber (and must adjust electron emission there simultaneously). Furthermore, for the highest ion energy spreads obtainable the ion distribution function can differ significantly from Maxwellian. The source discharge power has been raised above the values shown in figure 2 and the ions become successively hotter. Plasma noise increases, however, and may begin to play a role in ion heating. Certainly the distributions observed can differ widely from Maxwellian.

Axially-spaced biasable meshes can be introduced into the source chamber to modify the axial gradient slightly. A single flat grid, 10 cm square, was positioned as shown in figure 1 and biased positively to potential V_g (figure 3). The exact ion distribution which results depends upon the axial positioning of the grid. While the distribution

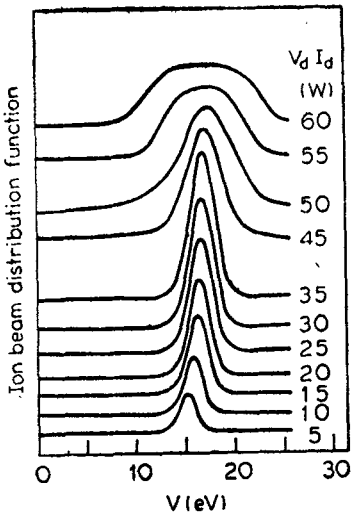

Figure 2. Target chamber ion distribution function versus source chamber discharge power (source plasma density and, hence, target chamber ion beam density also increase with source discharge power).

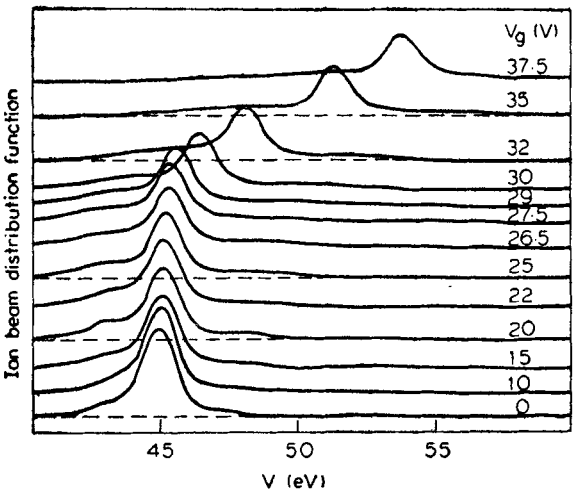

Figure 3. Target chamber ion distribution function versus auxiliary grid bias.

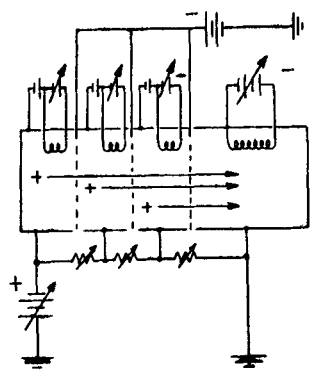

Figure 4. Multi-plasma device schematic diagram.

can be made nearly Maxwellian it more commonly exhibits two energy components as shown in figure 3. (The axial grid location was about 2 cm from the separator grid.) The overall plasma potential in the source is also modified by the bias on the auxiliary grid (as seen by the shift in average beam energy in figure 3).

Alternatively, a 'triple' or, ideally, an n plasma device can be constructed (figure 4) in which a series of tandem ion source plasmas (separated by negatively biased separator meshes) all supply ions to the composite beam. Each of the n ion source plasmas can then be maintained at a different potential and (by adjusting the filament emissions and wall potentials of each of the tandem ion sources) one can taylor a wide range of target chamber ion distributions. (If such beams are input from many directions one can even reduce the ion-electron relative drift to zero.)

The multiple plasma technique has some value as an improved ion source. In the intended ion extraction direction the plasma gradient is a gentle function of axial position and extends for most of the length of the source region (i.e. all n component chambers). In the opposite direction, however, the gradient scale length is much

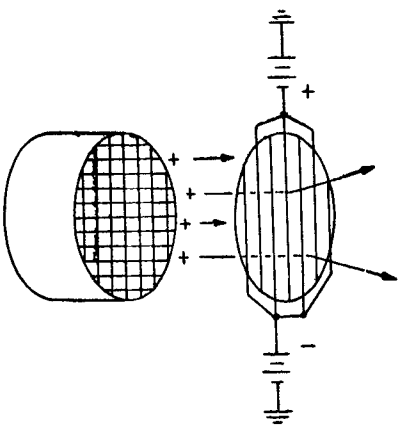

Figure 5. Alternating potential array for deflecting beam ions (array is mounted in the target chamber).

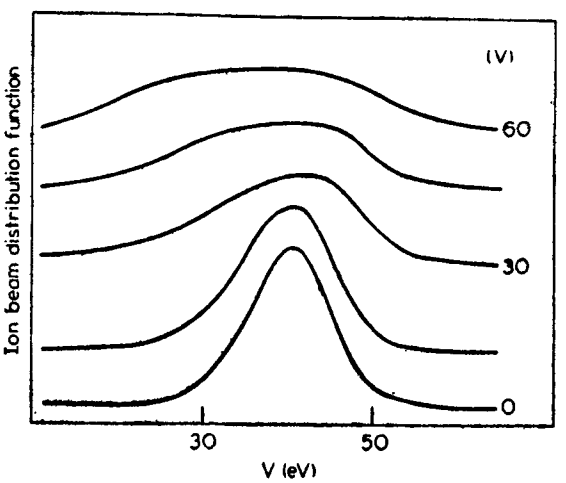

Figure 6. Target chamber ion distribution function versus electrical bias on deflecting array of figure 5.

shorter. Since most ions are created in the region characterised by the long gentle gradient they fall out in the desired extraction direction. Only very few ions are created on the short, steep gradient and are lost to the end wall (as a parasitic loss). Such a system, then, is a nearly unidirectional (reflex 'triode' type) ion source having improved extraction efficiency. (If grid losses can be kept low.)

To produce a radially uniform beam and reduce undesirable space charge effects in the synthesised plasma, a radially variable separator mesh transparancy can be introduced. Such a grid (which can consist of a laminate of several meshes, each of a different diameter) will help to prevent electric fields which act to introduce a radial dependence into the target chamber ion temperatures.

In certain experiments, such as the cusp leakage example (Jones 1979a) quoted in the introduction, it may be desirable to insure an isotropic ion distribution. (In other situations, such as ion beam-plasma instability studies (Hayzen and Barrett 1977) one may be relatively immune to effects of ion distribution anisotropy.) A third technique has been demonstrated which is capable of heating and isotropising the ion beam. A flat array of closely packed parallel metal wires is mounted in front of the ion source (figure 5). The wires (0·008 inch diameter) are spaced just a few Debye lengths apart (i.e. typically about 5 mm) and, when alternatively biased to large electrical potentials, scatter the ion beam transversely (figure 6). Two arrays with conductors at right angles to one another suffice to isotropise the ions as verified experimentally by rotating the axis of the energy analyzer diagnostic (figure 7). Because of the relatively close spacing of the filamentary conductors this technique has only been employed over small diameters (a few cm).

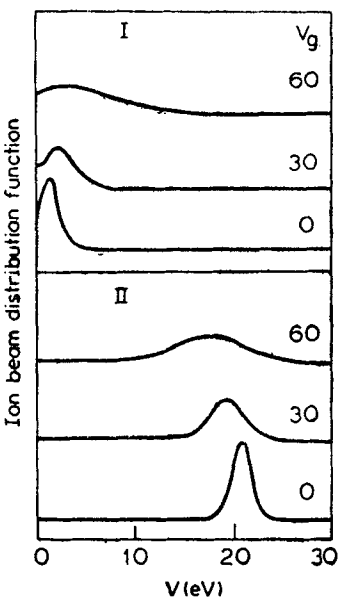

Figure 7. I. Target chamber ion distribution function measured transverse to the beam relative drift and as a function of bias on the deflecting array. II. Target chamber ion distribution function measured parallel to the beam drift and as a function of the bias on the deflecting array.

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