ary, though there is a small displacement of the minimum.

Furthermore, as is evident from Fig. 3, it is possible to obtain an analytic representation for $B_y(x)$ valid very close to the point where $B_y=0$ in the plasma. If the $B_y(x)$ profile is symmetric, then by iteration the entire profile may be deduced from a numerical fit with the observed polarization results.

For experiments in which narrower spatial density profiles are obtained, we expect increasing applicability of the method (of course, the upper hybrid resonance must remain accessible). Finally, we suggest an experiment that can indicate whether a local or an integrated effect is being measured for the wave polarization. In this experiment the relative phase of the second-harmonic ordinary and extraordinary waves is measured. A small phase difference implies $|\psi| \ll 1$, and hence Eq. (8) is applicable (the difference must of course be less than 2π).

We mention briefly another method, using an incident ordinary wave, that may be appropriate to experiments having sufficiently narrow density profiles.

The frequency of the wave is chosen such that the ordinary wave must cross a point in the plasma, x_0, where $\nu = \nu_{co}$ (cutoff frequency for the extraordinary wave), i.e., $N_x(x_0)=0$. The $E_\perp$ component generated for $x<x_0$ is absorbed at the upper hybrid resonance (or converted into longitudinal waves). If wave tunneling is small, then very close to the cutoff, $E_\perp=0$ and $E_y=\theta(x_0)E_\parallel$. As before, if conditions for $x>x_0$ approach those of free space we again have a local determination of the magnetic field direction from a polarization measurement of the transmitted wave, $E_y(b)/E_z(b)=\theta(x_0)$. The utility of this method is more restricted than the harmonic technique as free-space propagation is more readily obtained in the latter case for $x>x_0$.

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Electrostatic Confinement of an Alkali-Metal Plasma*

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The imposition of a hollow longitudinal beam of 2-kV electrons about a Q-machine potassium plasma column serves to deepen the radial potential well across that column. Transverse plasma flux is consequently decreased, while the peak ion density and end-plate collector current rise an order of magnitude. A calculation is made of the transverse flux of ions in the plasma column with energy sufficient to surmount the potential well.

Until quite recently, research aimed toward improving plasma confinement has concentrated largely on magnetic field geometries and schemes. Some attention has been given to electrostatic confinement; for example, a device has been proposed (and a forerunner built) to strip and confine heavy ions by immersing them in a relatively dense cloud of fast electrons which, in turn, are confined by a toroidal magnetic field (heavy-ion plasma accelerator HIPAC).[1,2] Stix has also proposed a device to electrostatically confine ions by surrounding them with an envelope of electrons in a magnetic field of toroidal or PIG geometry.[3,4] The experimental studies presented here are concerned with electrostatic confinement of ions in a Q-machine plasma column.

A 50-cm-long potassium plasma column is produced in a Q machine,[5] operating single or double ended, with a grounded tungsten cathode heated to 2000-2500°K. A grounded limiter with a 1.9-cm circular aperture is placed 0.64 cm downstream from the cathode. Diagnostics include a Langmuir probe, inserted at column center to obtain radial profiles of saturation ion current/density and floating potential, and a plasma camera to visually record an instantaneous distribution of plasma density at the column end.[6] A radial particle collector, similar to that used by Buchel'nikova,[7] opposite the probe is used to measure transverse plasma current $I_\perp$; and a terminal particle collector, similar to that used by Decker *et al.*,[8] is used to measure transverse flux by measuring plasma loss along the column.

Two basic kinds of terminal-electrode assemblies were employed; one, the conventional plasma-generating type,[5] and another which used an impregnated cathode ring emitter to inject a hollow 2-kV longitudinal electron beam of 2.6 cm diam through a 1.6-mm-wide annular gap surrounding the plasma column (generated at the opposite end).

In single-ended operation, cellular phenomena have been noted and previously reported at fields between 100 and 320 G.[9] In this range of magnetic field, the peak ion density n_p and end-plate collector current[9] I_c are an order of magnitude greater than at higher fields (Fig. 1). The cause of the cells has been assigned to a beam of energetic electrons from the bombarding filament streaming around the cathode and entering the column.[10,11] This beam current I_s has been measured with a collecting plate biased to collect electrons, located 1 cm from the limiter when no neutral flux impinges on the cathode. The electron current (<2.1 mA) collected by this plate with the cathode cold is taken to be this beam current. Below 400 G, I_s varies with magnetic field in the same way as n_p (Fig. 1); above 400 G, I_s was too small to measure.

Measurements of $I_\perp$ with the radial particle collector show $I_\perp$ to be minimal at the field at which n_p is maximal (Fig. 1). Terminal particle collector measurements show transverse flux to vary with the field in the same manner as $I_\perp$. While all floating-potential profiles indicate a radial potential well (for ions) across the column,[5] emergence of an energetic electron beam into the the column, in addition to creating cells, deepens and steepens a formerly flat-bottomed well into the well shown in Fig. 2 at 175 G. This well depth ΔV attains its greatest value in the range of magnetic field at which n_p, I_c, and I_s are greatest and $I_\perp$ and $I_\perp/n_p$ are lowest (Fig. 1).

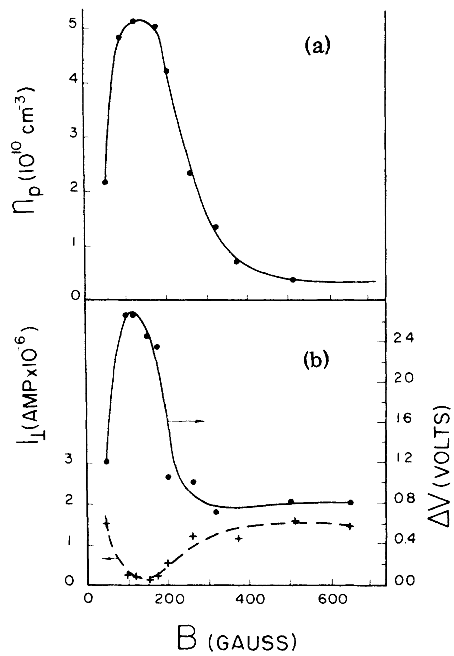

FIG. 1. (a) Peak ion probe density n_p (probe bias −55 V) and (b) well depth ΔV as measured from the floating-potential profiles, and transverse plasma current $I_\perp$, measured 25 cm from the cathode, versus magnetic field for a fixed uniform plate temperature of 2320°K, cold collector bias −55 V, and column length of 50 cm.

Insertion of a boron nitride (BN) shield between limiter and cathode to keep energetic electrons out of the column results in establishment of the usual Q-machine phenomena[10]: no cells, n_p and I_c rising monotonically with B.

The Q machine was operated double ended to investigate the effect of surrounding a conventional plasma column (BN shield, plasma generating end, 2300°K) with a cellular beam of energetic electrons (nongenerating end, 2300°K). The same phenomena as those observed and

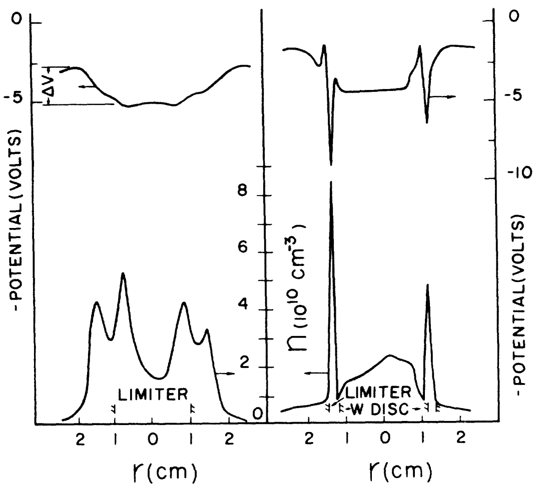

FIG. 2. Density and floating-potential profiles, probe bias −55 V, (a) for 175-G single-ended–mode cellular beam and (b) for 2400-G double-ended mode with beam from impregnated cathode. For both cases the plasma-generating cathode temperature is 2320°K.

measured for the single-ended case were reproduced.

The increase in plasma density and decrease in transverse flux as a result of the cell-forming electron beam in single- or double-ended cases occur only over a range of magnetic fields that permit this beam, I_s, to emerge.[10] An impregnated cathode electron gun, described above, was installed to permit a thin cylindrical 2-kV electron beam to surround the plasma column, generated at the opposite end by the beam-shielded assembly, at any magnetic field. Imposition of this beam results in the creation of a relatively deep and narrow annular potential well at the beam site and in a tenfold to twentyfold increase of ion density in this region. Density elsewhere is diminished as if the ion population were drawn into the beam (Fig. 2, at 2400 G). With this beam surrounding the column, $I_\perp$ is cut at least in half. All this takes place in the full 0.4–2.85-kG range of magnetic field B employed in these experiments. When the impregnated cathode electron beam was run at lower magnetic fields, below 0.3 kG, $I_\perp$ was diminshed by at least an order of magnitude as compared to the BN-shielded plasma column. This decrease in $I_\perp$ for the impregnated cathode beam plasma was equivalent to that for the cell-generated plasma, Fig. 1.

In all single-ended experiments in which the plasma camera was used, the photographs show the increase in ion density detected by the probe, thus verifying that this apparent density increase is not simply due to an increase in probe current caused by acceleration of ions through an electron-dominated cathode sheath as such a sheath is formed. Several independent checks have been made to ascertain that the apparent increase in ion density is not due to secondary emission of electrons from beam-bombarded current collecting surfaces. One such experiment consists of biasing the probe and end-plate collector to reflect the energetic electron beam. Collector current was found to vary with B in the manner reported previously.

The close correlation of $I_\perp$ and $I_\perp/n_p$ with ΔV strongly suggests that the well serves to confine the ions and, with them, the electrons in the plasma. The confining effect of the potential well is calculated with the aid of a model. The plasma of mean density n is assumed to lie at the bottom of a potential well of depth ΔV. The current $I_\perp$ collected by the radial particle collector is derived from that fraction of the ions, assumed to have a Maxwellian distribution of transverse kinetic energy w at the cathode temperature T, that can energetically surmount the potential well. This current is $qa\int v_r\,dn$, where a is the effective collecting area of the radial particle collector, q is the electronic charge, and v_r is the radial ion speed. Since

$$dn_w = (2n/\sqrt{\pi})(kT)^{-3/2}\sqrt{w}\exp(-w/kT)\,dw, \qquad (1)$$

we have

$$I_\perp/n = qa(8kT/\pi m)^{1/2}(1+q\Delta v/kT) \times\exp(-q\Delta v/kT), \qquad (2)$$

where m is the ion mass and k is Boltzmann's constant. This $I_\perp$ is the ion current; for a meaningful comparison with experimental $I_\perp$, the additional ambipolar electronic current collected by the radial particle collector must be known and a mean geometrical factor inserted to account for the cylindrical configuration. It is assumed that the ion-electron current ratio and the mean geometric factor are invariant to ΔV. Comparison of experiment and theory is made with a minimum number of assumptions by considering ratios of $I_\perp/n$, whereby these factors cancel. For two well depths ΔV_1 and ΔV_2 with identical cathode temperatures of 2320°K, the

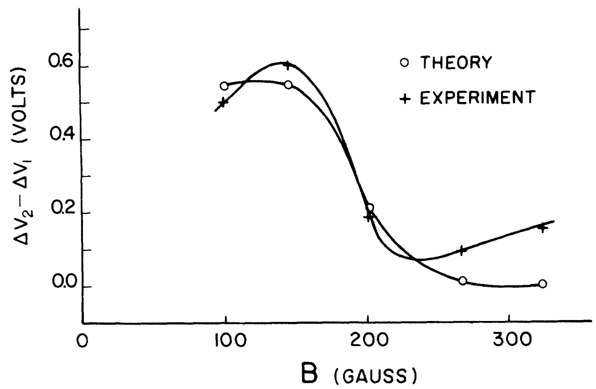

FIG. 3. Experimental and predicted difference in the well depths (single ended) ΔV_1, the no-beam case, and ΔV_2, the cellular-beam case, versus the magnetic field; plate temperature 2320°K.

logarithm of this ratio is given by

$$\tfrac{1}{5}\left[\ln\left(\frac{I_\perp}{n}\right)_1 - \ln\left(\frac{I_\perp}{n}\right)_2\right] = \Delta V_2 - \Delta V_1 + \tfrac{1}{5}\ln\left(\frac{1+5\Delta V_1}{1+5\Delta V_2}\right). \quad (3)$$

The third term on the right-hand side of this equation is small (~10%) compared to $\Delta V_2 - \Delta V_1$, and is neglected in comparing theory with experiment. Values of $I_\perp/n$ and ΔV were assembled from experimental runs; case 1, with the column shielded from electron entry, and case 2, in which the cell-forming electron beam entered the column. $\Delta V_2 - \Delta V_1$ obtained from Eq. (3) and $\Delta V_2 - \Delta V_1$ obtained from experimental data are plotted versus magnetic field in Fig. 3. Agreement is seen to be good despite the simplifying assumptions made in the derivation of this equation.

It is evident from the correlation of n_p and I_c with ΔV, the negative correlation of ΔV and $I_\perp$, and the agreement of theory with experiment that the electron beam serves to increase the well depth and to decrease $I_\perp$. The potential well created by the beam creates an electrostatic barrier to all but the most energetic ions in the plasma.

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