Electrostatic–magnetostatic hybrid probe for measuring the electron distribution function in a magnetized plasma

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A probe has been developed which measures the density (in a magnetized plasma) of electrons with a given parallel energy and also with a given ratio of perpendicular energy to parallel energy. This is done by imposing two noninteracting criteria for electron collection. The electron must first pass an adjustable magnetostatic barrier (a magnetic mirror) which selects electrons according to perpendicular to parallel energy ratio; then the electron must surmount an electrostatic barrier which is well removed behind the mirror; this discriminates on the basis of the electron's original parallel energy. This probe is straightforward to build and easy to use. A simple formula for obtaining a distribution function map from the data provided by this probe is derived.

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INTRODUCTION

Direct measurement of the electron distribution function has been a complicated task in most plasmas. In ionospheric studies[1] the distribution function may be found by unfolding data taken by probes whose dimensions are small compared to, or on the order of, the Larmor radius of the particles being collected. In a remarkable achievement, Stenzel *et al.* developed a technique, similar in principle to that used in the ionosphere, for measuring the distribution function in a laboratory plasma.[2] This technique makes use of a microchannel plate whose smallest dimension is small compared to, or on the order of, the Larmor radius of the particles being collected. Current is collected by this probe at a variety of geometric orientations, and the data is unfolded by a powerful computer.

Our technique for measuring the electron distribution function in a magnetized laboratory plasma differs from the above techniques in that we do not employ a material barrier as a discriminator and, therefore, no rotation of the probe is necessary nor is it required that any dimension of the probe be smaller than, or on the order of, the Larmor radius. As a result, our probe is relatively simple to construct and operate. The data which results from the operation of this probe is analyzed by a formula which is sufficiently simple that a qualitative analysis of the raw I vs V plots may be done by eye, although a quantitative analysis of the data is most easily done on a computer (though the computer requirements are very modest). The basic principle of operation of this probe is the elementary result that whether or not an electron is reflected by a magnetic "mirror" depends on the relative magnitudes of the mirror ratio R_m and $W_\perp / W_\parallel$, i.e., the electron's perpendicular energy divided by its parallel energy.[3]

I. THEORY

A schematic design of the probe is given in Fig. 1. The two variable parameters are V, the potential on the collector, assumed here to be referenced to the plasma potential, and R_m, the mirror ratio within the probe. It is very important that the collector be located sufficiently far in back of the mirror that the magnetic field at the collector is essentially the uniform field value B_0. This restriction plays a key role in the decoupling of pitch angle ($W_\perp / W_\parallel$) information from parallel energy ($W_\parallel$) information. If the scale length of the probe magnetic mirror is large compared to the Larmor radii of the electrons being analyzed then the magnetic moment $\mu = W_\perp / B$ of each electron will be essentially invariant.[3] This, along with conservation of total energy for each electron (i.e., no collisions within the probe) implies that any electron approaching the collector will do so with the same values of $W_\perp$ and $W_\parallel$ that it had before entering the probe. Therefore, ideally, the mirror has no net effect on those electrons (the ones in the loss cone) which cross it and approach the collector. Consequently, the mirror affects electron collection in a particularly simple way: electrons in the loss cone, i.e., electrons for which $W_\parallel > W_\perp (R_m - 1)$, suffer no net effect while the rest of the electrons are reflected by the mirror and, hence, are not collected. Of course, not all electrons in the loss cone are collected. Electrons whose parallel energy $W_\parallel$ is less than eV will be reflected by the retarding potential on the collector (the pitch angle of the reflected electrons will be conserved, therefore, the electrons will be able to cross the mirror again on their way out of the probe). Each electron must meet two independent criteria in order to be collected: the electron must satisfy $W_\perp < \alpha W_\parallel$, where $\alpha \equiv (R_m - 1)^{-1}$ and it must also satisfy $W_\parallel > eV$. Thus, the current density striking the collector may be written

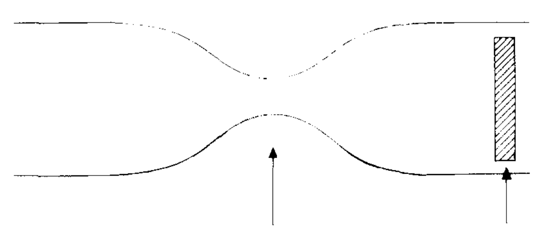

FIG. 1. Schematic drawing of magnetic field lines within the probe. Note that the collector is sufficiently far in back of the mirror that the field lines there are essentially straight.

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$$J = -e\int_{W_\parallel = eV}^{\infty} dW_\parallel \left(\frac{2W_\parallel}{m}\right)^{1/2} \int_{W_\perp = 0}^{\alpha W_\parallel} dW_\perp f(W_\parallel, W_\perp). \quad (1)$$

Equation (1) is just the equation $J = -e\,\overline{nv_\parallel}$ (where $v_\parallel = \sqrt{2W_\parallel/m}$) with the conditions for collection incorporated as limits to the integrals. Thus,

$$\frac{\partial J}{\partial(eV)}\bigg|_{V=V'} = e\left(\frac{2eV'}{m}\right)^{1/2} \int_{W_\perp = 0}^{\alpha eV'} dW_\perp f(eV', \alpha' eV')$$

and

$$\frac{\partial}{\partial(eV')}\left(\frac{\partial J}{\partial(eV)}\bigg|_{V=V'}\right)_{\alpha=\alpha'} = e\left(\frac{2eV'}{m}\right)^{1/2} f(eV', \alpha' eV').$$

Moving all the constants to one side we get

$$f(eV', \alpha' eV') = \left(\frac{m}{2eV'}\right)^{1/2} (e^3 V')^{-1} \frac{\partial}{\partial \alpha}\left(\frac{\partial J}{\partial V}\bigg|_{V=V'}\right)\bigg|_{\alpha=\alpha'}$$

or, to use a simpler (although somewhat abusive) notation convention:

$$f(eV, \alpha eV) = \left(\frac{m}{2e^7}\right)^{1/2} V^{-3/2} \frac{\partial^2 J}{\partial \alpha\, \partial V}.$$

The parameter we directly vary experimentally is the magnetic field ΔB produced by the coil inside the probe.

$$\Delta B = B_0(R_m - 1) = B_0/\alpha,$$

therefore,

$$d\alpha = d(B_0/\Delta B) = -B_0/(\Delta B)^2 d(\Delta B)$$

and our equation for the distribution function may be rewritten

$$f(W_\parallel = eV,\ W_\perp = \alpha eV) = \left(\frac{m}{2e^7}\right)^{1/2} \frac{(\Delta B)^2}{V^{3/2} B_0} \frac{\partial^2 J}{\partial(\Delta B)\partial V}. \quad (2)$$

II. DESIGN

The two principal concerns in the practical design of a probe for measuring the electron distribution function are secondary electron emission and dissipation of the Joule heat from the magnet coil. Secondary emission problems in one-dimensional energy analyzers are usually dealt with by using a negatively biased screen in front of a solid positively biased collector.[4] With this arrangement secondaries emitted by the collector are reflected by the screen back onto the collector. The negative bias on the screen is variable and the screen acts as the analyzer.

The effect of such a screen on collected current is (unfortunately) not isotropic in velocity space. The analyzer screen will be perpendicular to the magnetic field, therefore, particles at high pitch angle $\theta \equiv \arctan(v_\perp/v_\parallel)$ will be more likely to hit the screen than will particles at low pitch angle. Since it is the pitch angle *at the screen* which is important (and since that is a function of $W_\parallel$ at the screen), incorporating into the probe a screen whose voltage will be swept can greatly complicate the analysis of the data (the effect of the screen may be neglected if $r_L \ll a \ll \lambda_d$, where r_L is the Larmor radius, a is the radius of the perforations in the screen, and λ_d is the Debye length; or if $t \ll a \ll \lambda_d$, where t is the thickness of the screen). Another problem is simple loss of signal due to the imperfect transparency of the screen. Unfortunately, the very thin screens needed to satisfy the above requirements ($t \ll a \ll \lambda_d$) tend to have low transparency.

For our prototype probe we chose to suppress secondary emission by a simpler method, one that would keep our effective collection area high. We coated the collector surface with soot (lamp black) and eliminated the screen. The soot coating greatly decreases the secondary emission rate,[5] so the electron collection efficiency is close to one everywhere within the range of interest. Thus, the error current due to secondaries is small (about 10%) and the main effect of this error is to reduce the measured distribution function everywhere in phase space by about the same factor. Consequently, relative values should be off by much less than 10%, so the *shape* of the measured distribution function should not be greatly altered by the secondary emissions. Indeed, in the sample data presented below, ordinary plasma noise appears to be a more important error source than does secondary emission.

Our second major concern was the joule heat generated by the coil which produced the mirror field within the probe. This is an important consideration: we are limited to mirror ratios which may be produced by currents which do not overheat the coil. Since we may only make distribution function measurements of particles which lie outside the loss cone at the maximum mirror ratio, data are not obtainable for values of $W_\perp/W_\parallel$ smaller than $(R_{max} - 1)^{-1}$. Thus, there will always be a small wedge along the $W_\parallel$ axis (or $v_\parallel$ axis, for phase space plots) which is not accessible with this technique. This wedge can be reduced only be increasing R_{max} (the maximum mirror ratio obtainable). In order to do this, the additional joule heat produced in the coil must be dissipated.

In the prototype probe, copper was used throughout and the number of junctions was minimized to ensure good heat transfer away from the probe coil. No active cooling was used, although this remains a possibility for future designs. Ordinary varnished magnetic wire was used in the coil. The probe magnetic field must stay constant for a few seconds before a voltage sweep is taken to allow the plasma to return to quiescence after the magnetic diffusion and reconnection which occur when the field is changed. This extends the time at which the probe coil must be operated at high current, but it is still possible to safely make short excursions to currents which would be damaging if used over long periods.

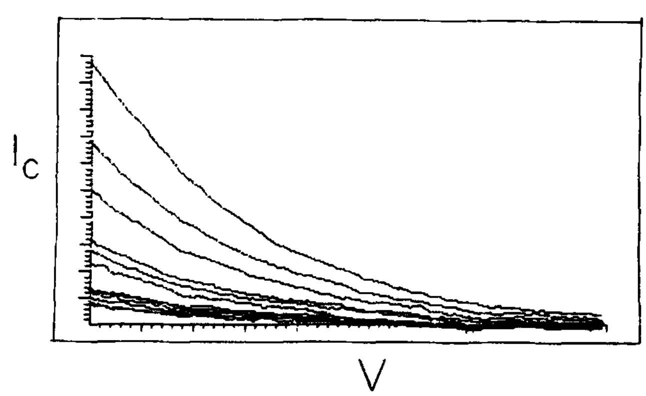

FIG. 2. Collected current (arbitrary units) vs retarding potential on collector (arbitrary units, the range is from 0 to about 30 V).

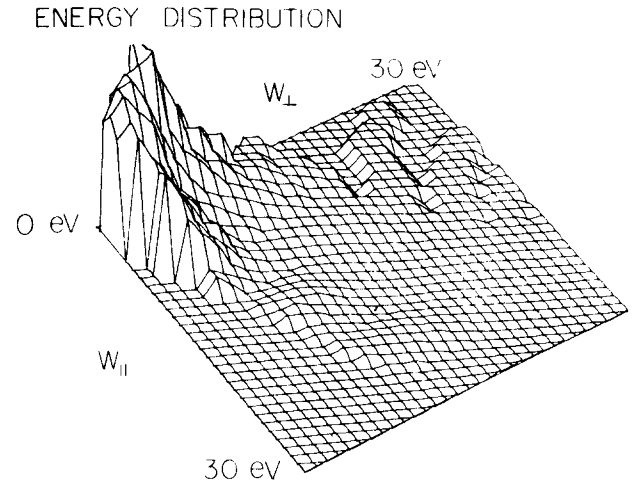

FIG. 3. The map of $f(W_\parallel, W_\perp)$ derived from the data represented in Fig. 2.

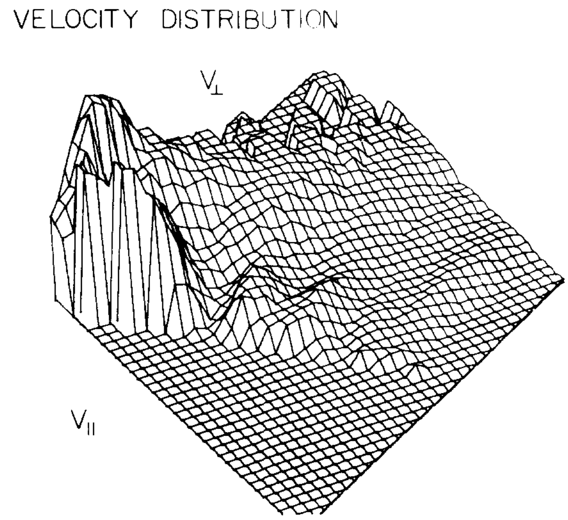

FIG. 4. The map of $F(v_\parallel, v_\perp)$ acquired by translation of the $f(W_\parallel, W_\perp)$ result.

III. RESULTS

The prototype was tested in a (hot cathode) continuous discharge plasma. I vs V (i.e., collected current vs collector voltage) curves were taken on an X–Y plotter for ten different values of probe coil current (in other words, ten different values of mirror ratio). The curves were digitized and fed to a routine which calculated $\partial I/\partial V$ through a linear regression of all points in the neighborhood $V - \Delta V/2$ to $V + \Delta V/2$; since this involves averaging all points within ΔV, high-frequency noise is suppressed. Optimal results were obtained using $\Delta V = 5$ V. At a fixed voltage, the $\partial I/\partial V$ values corresponding to the ten different mirror ratios were fit with a fourth-order polynomial from which the $\partial^2 I/\partial(\Delta B)\partial V$ values were obtained. From this, Eq. (2) gives $f(W_\parallel, W_\perp)$. $F(v_\parallel, v_\perp)$ is obtained by noting that

$$F(v_\parallel, v_\perp)dv_\parallel\, dv_\perp = f(W_\parallel, W_\perp)dW_\parallel\, dW_\perp$$
$$= (m^2 v_\parallel v_\perp)f(W_\parallel, W_\perp)dv_\parallel\, dv_\perp.$$

Raw data (as digitized) from a sample run is presented in Fig. 2. Plots of $f(W_\parallel, W_\perp)$ and $F(v_\parallel, v_\perp)$ are given in Figs. 3 and 4. As was noted above, there is a wedge shaped region along the $W_\parallel$ (or $v_\parallel$) axis for which no values are given: electrons in this wedge are in the loss cone even for maximum coil current and, therefore, cannot be precisely located (in phase space) using this method.

IV. DISCUSSION

This probe was fairly easy to construct. Operation of the probe simply consists of taking I vs V curves for a number of different coil current values. Using an X–Y plotter, it now takes about 10 min to take the data required for a distribution function map. Once the raw data is digitized and in the computer, analysis (exclusive of graphics) takes about 1 min more. When the entire process (including current and voltage sweeping and data acquisition) is done directly by the computer, we hope to be able to produce distribution function maps much faster. We believe that the simplicity, speed, and wide range of applicability of this technique make it a useful plasma diagnostic.

ACKNOWLEDGMENT

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