A Small Electrostatic Retarding Field Energy Analyzer with Compensating Differentiation Circuit

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A small electrostatic retarding field energy analyzer with compensating differentiation circuit

M. Oertl and H. Störi
Institut für Experimentalphysik, Innsbruck University, Innrain 52, A-6020 Innsbruck, Austria
R. Hatakeyama [a)]
Institut Für Theoretische Physik, Innsbruck University, Innrain 52, A-6020 Innsbruck, Austria

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A small electrostatic retarding field energy analyzer is constructed in order to measure locally the ion energy distribution functions parallel and perpendicular to a magnetic field. A compensating differentiation circuit enables it to yield the energy distributions clearly in spite of the smallness of the signal available in a low-density plasma. An application is performed to reveal local anisotropic heating due to a plasma instability.

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I. INTRODUCTION

In recent years the simultaneous measurement of charged particles' energy distribution functions parallel and perpendicular to a magnetic field has been required to estimate the velocity space diffusion or the heating rate in wave heating and in nonlinear wave experiments.[1,2] Historically, large sized electrostatic retarding field energy analyzers were mostly used in magnetized plasmas to find the parallel energy distribution of ions.[3,4] In order to measure both parallel and perpendicular ion distributions, small analyzers have been used, that is to say, analyzers which are small enough to be moved and rotated within the volume of the plasma without disturbing its conditions too much.

The small analyzers known as far, however, mostly yield only integral characteristics[1]; in cases where the analyzer characteristics are electronically differentiated—thus displaying the energy distribution function of the ions directly—the resulting curves are very noisey due to the small signal available.[5] Only in the case of an ion beam experiment, where the large beam current was utilized, was it possible to obtain clear differentiated curves.[2]

A special case of a small analyzer which measures only perpendicular ion distribution functions is the Katsumata probe.[6] It achieves charaged particle separation by utilizing the different gyration radii of ions and electrons in the magnetic field, whereas most analyzers mentioned here use a biased entrance grid for this purpose. Also for the Katsumata probe, only integral characteristics have been reported.

In this paper we describe the construction of a small gridded energy analyzer and its application to a *Q*-machine plasma. The analyzer presented here uses an improved differentiation circuit giving satisfactory differentiated curves for ions even in a low-density range (5×10^7 cm^{-3}). It combines the sensitivity of the large analyzers with the local resolution of the small ones. And, in the application to a current-driven wave heating experiment,[7,8] it reasonably reveals a local anisotropic ion heating.

In Sec. II, the experimental apparatus is described. The experimental results are reported in Sec. III. Conclusions are contained in Sec. IV.

II. EXPERIMENTAL APPARATUS

A. Analyzer

A schematic drawing is given in Fig. 1. The collector (1), a circular disk 4 mm in diameter made of a 0.2-mm tungsten plate, is separated and insulated from the entrance grid (2) by a thin (0.15 mm) ring of ceramic Al_2O_3 material. The grid consists of a fine copper mesh (40 000 25×25-μm holes per cm^2) which, together with a limiting diaphragm (3) of 0.1-mm Molybdenum, is pressed mechanically onto the ring by a loop of 0.2-mm *W* wire. Thus mesh and diaphragm can be removed easily for cleaning or repair of the analyzer.

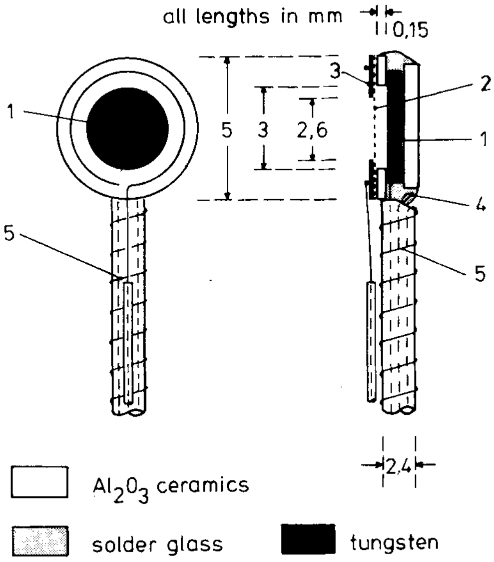

FIG. 1. Construction of the analyzer. Left: Front view (copper mesh and diaphragm removed). Right: Side view. (1) collector, (2) copper mesh, (3) diaphragm, (4) thermocouple, (5) heating spiral.

[a)] On leave from Department of Electronic Engineering, Tohoku University, Sendai, Japan.

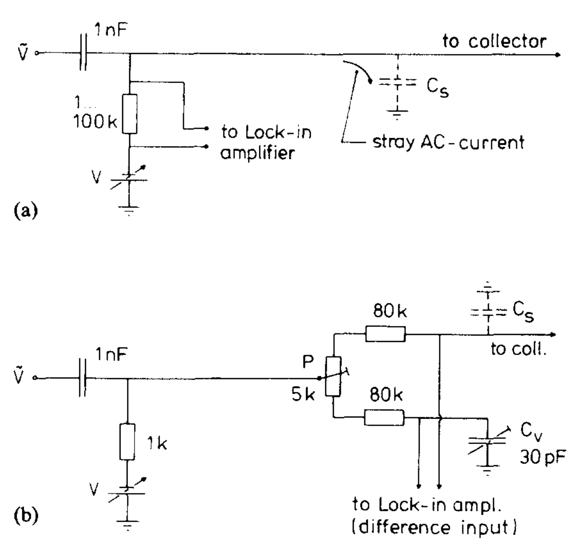

FIG. 2. Analyzer differentiation circuits. (a) Usual circuit, (b) circuit with compensation of stray ac currents. C_s ... stray capacity, C_v ... variable capacitor compensating C_s, P ... potentiometer for resistor symmetry.

During operation, the mesh is biased at a negative voltage $V_M = -4... -9$ V, which ought to be just negative enough to reflect all electrons. The diaphragm improves the constancy of the ion saturation current.

Electrical leads are fed through a four-hole ceramic tube 2.4 mm in diameter around which a heating spiral (5) is wound. The heating of the analyzer is useful in order to reduce the contamination with condensed plasma particles. The ceramic parts forming the body of the analyzer are fastened together by small portions of Dow Corning glass, a solder glass, melted over a Bunsen flame. The use of Corning glass should be kept to a minimum since, when the analyzer heating is applied, it becomes electrically conductive ($R \leqslant 10^{10}\,\Omega$) to an extent that Ohmic leak currents may conceal the collector characteristics. Ohmic currents could be neglected up to an analyzer temperature of 250 °C, corresponding to a heating power of 6 W. The analyzer temperature is measured by a thermocouple (4), mounted close to the collector by use of Corning glass.

B. Electronic differentiation circuit

Following a frequently used method,[3] differentiation of the integral analyzer characteristic is realized by superposition of a small ac-voltage $\tilde{V}$ (in our case, 50 mV peak-to-peak, 172 Hz) onto the dc-bias V of the collector. The resulting ac current is proportional to the slope of the collector characteristic, i.e., it represents a difference quotient of the characteristic. In usual circuits as in Fig. 2(a) there is the possibility of an additional ac current via stray capacities C_s. It turned out that, with the small analyzer, the ac current resulting from the slope of the collector characteristic is about 100 times smaller than this capacitive ac current and therefore no satisfactory differentiation could be performed.

In order to avoid this trouble a compensation circuit was devised and is shown in Fig. 2(b). It can be regarded as two differentiation circuits that are identical with the exception that the second (lower) circuit contains a variable capacitor C_v in place of the analyzer collector. With no plasma present, this capacitor is adjusted to minimum ac signal at the lock-in amplifier which measures the differential ac voltage between the two circuits. Also, the potentiometer P, which is responsible for resistor symmetry, is tuned to minimum signal. The elements of the compensation circuit are mounted to the analyzer as close as possible.

With the adjustments described above, the ac signal produced by stray capacities is eliminated almost completely from the input of the lock-in amplifier. As there remains a noise signal of only about 0.5 μV as compared to an ac signal of 100 μV (at maximum slope of an average collector characteristic at plasma density 10^8 cm^{-3}), differentiation is easily possible. It can be shown by circuit analysis that the ac voltage received by the lock-in amplifier (strictly speaking, the ac voltage portion "in phase" with the applied ac voltage $\tilde{V}$) is still proportional to the slope of the analyzer characteristic as in the case of the simple circuit of Fig. 2(a).

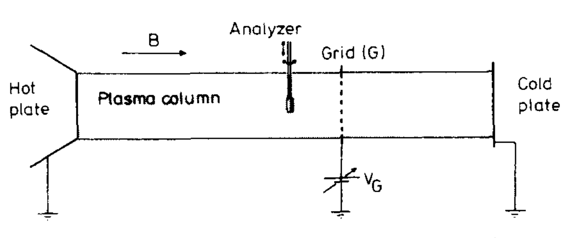

FIG. 3. Experimental set-up.

III. EXPERIMENTAL

A. Experimental conditions

The analyzer is inserted into one of the radial ports of the Innsbruck Q-machine[9] in Fig. 3 and positioned into the middle of the plasma column ($r = 0$ cm). The column is terminated by a large diameter cold plate ("single-ended" Q machine) and operated under "electron-rich" conditions. The plasma, about 2–3 cm in diameter, is produced by sur-

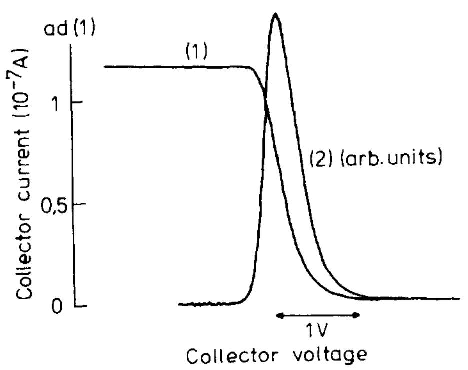

FIG. 4. Typical ion parallel collector curves. (1) Current-voltage characteristic, (2) differentiated characteristic is the parallel ion distribution function. $n = 1.5 \times 10^8$ cm^{-3}, analyzer grid bias $V_M = -5$ V.

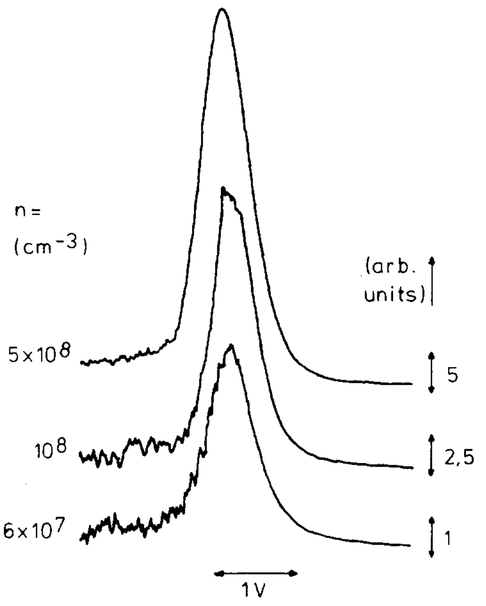

FIG. 5. Ion parallel energy distributions for different densities.

face ionization of sodium atoms on a tungsten plate of 2000–3000 K and confined magnetically ($B = 1.5$ kG). The density of the plasma is $n = 10^7$–10^9 cm^{-3} and the background gas pressure is less than 5×10^{-6} Torr. Thus, collision mean-free paths of charged particles are longer than the plasma column ($= 60$ cm). The electron temperature T_e, 0.2 eV, is measured by a Langmuir probe. The ion Larmor radius r_L is 0.2 cm and the Debye length λ_D is 0.1–0.01 cm.

For the application of the analyzer we excite the current-driven collisionless drift instability by applying a positive bias V_G to an axially movable 6-cm-diam grid (made of 0.2-mm tungsten wires spaced 2 mm apart) with respect to the hot plate. The distance between the hot plate and the grid is set to 35 cm. Parallel electron current is drawn through the whole region of the plasma column (typically 1 mA), resulting in parallel and perpendicular ion heating due to the drift wave turbulence.[8]

B. Measured ion distribution functions

The parallel distribution function $F_{i\parallel}$ is recorded when the surface of the analyzer is perpendicular to the plasma column. The perpendicular distribution $F_{i\perp}$ is measured after a 90° rotation of the analyzer in the magnetic field.[1,2] First, curves are shown for the quiescent plasma, i.e., V_G is left at floating potential. Figure 4 represents a typical parallel current-voltage characteristic of the collector together with the differentiated one [$= F_{i\parallel}(V)$ in a voltage scale] at the plasma center, $r = 0$ cm. The temperature estimated from the exponential slope on the higher energy side of $F_{i\parallel}(V)$ gives a reasonable value of about 0.25 eV which is comparable to the hot plate temperature. For different plasma densities, $F_{i\parallel}(V)$ does not show a big change, as seen in Fig. 5.

When the Q-machine grid is biased positively with respect to the hot plate, the induced electron current strongly enhances the growth rate of a drift instability with $\omega/2\pi \simeq 15$ kHz. The amplitude of this current-driven collisionless drift instability becomes larger with increasing V_G and saturates at about $V_G = 10$ V; simultaneously, its spectrum becomes broader.[7] The corresponding ion distribution functions at $r = 0$ cm are shown in Fig. 6. $F_{i\parallel}(V)$ remains essentially constant. $F_{i\perp}(V)$, however, becomes broader and displays a high energy tail with temperature 2.1 eV in the case of $V_G = 10$ V.

Radially, the drift instablity has its largest amplitude at the positionof maximum density gradient which is at $r \simeq 1.0$ cm. When the analyzer is moved into this position, the heating effects become stronger: $F_{i\perp}(V)$ assumes a one-component Maxwellian with a temperature of about 9 eV at $V_G = 10$ V; $F_{i\parallel}(V)$ now shows tail heating with a temperature of 1.7 eV. The detailed structures and local variations of the distribution functions, which represent the characteristics of drift wave heating, will be displayed elsewhere.[8]

IV. CONCLUSIONS

We have constructed a small electrostatic retarding field energy analyzer and applied it to the Q machine. With the use of the compensating differentiation circuit the disturbing influence of stray capacities is eliminated successfully, and parallel and perpendicular ion distribution functions in the magnetic field are obtained clearly in spite of the small signal available. In the application to the experiment of plas-

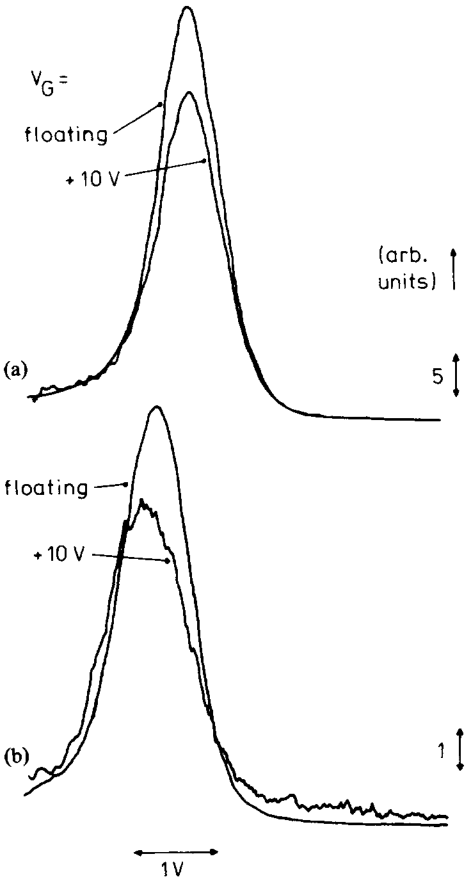

FIG. 6. Dependence of ion energy distributions on Q-machine-grid bias V_G. (a) parallel and (b) perpendicular energy distribution functions. $n = 4\times10^8$ cm^{-3}.

ma heating, the analyzer gives the detailed structure, local variations, and anisotropy of the ion distributions, which physically result from the current-driven collisionless drift instability present in the plasma. Generally, results of this kind are also important in explaining mechanisms of wave heating and nonlinear wave saturation.

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[1] M. Yamada and D.K. Owens, Phys. Rev. Lett. **38**, 1529 (1977); R. Hatakeyama, N. Sato, H. Sugai, and Y. Hatta, Phys. Lett. **63A**, 28 (1977); J.P. Hauck, H. Böhmer, N. Rynn, and Gregory Benford, J. Plasma Phys. **19**, 237 (1978); G.R. Allen, D.K. Owens, S.W. Seiler, M. Yamada, H. Ikezi, and M. Porkolab, Phys. Rev. Lett. **41**, 1045 (1978).

[2] M. Yamada and S.W. Seiler, Phys. Rev. Lett. **39**, 808 (1977); M. Yamada, S.W. Seiler, H.W. Hendel, and H. Ikezi, Phys. Fluids **20**, 450 (1977).

[3] J.M. Buzzi, H. Doucet, and D. Gresillon, Phys. Fluids **13**, 3041 (1970); S.A. Andersen, V.O. Jensen, P. Michelsen, and P. Nielsen, Phys. Fluids **14**, 728 (1971); R. Hatakeyama, N. Sato, Y. Tsunoda, H. Sugai, and Y. Hatta, J. Appl. Phys. **45**, 85 (1974).

[4] D.R. Baker, Phys. Fluids **16**, 1730 (1973); P. Michelsen, H.L. Pecseli, J. Juul Rasmussen, and N. Sato, Phys. Fluids **19**, 453 (1976).

[5] P. Michelsen, Proc. of the 3rd Intl. Conf. on Quiesc. Pl., Elsinore, Sept. 1971 (unpublished).

[6] I. Katsumata and M. Okazaki, Japan. J. Appl. Phys. **6**, 123 (1967); R.W. Motley and T. Kawabe, Phys. Fluids **14**, 1019 (1971).

[7] R. Hatakeyama, M. Oertl, and E. Märk, Phys. Lett. (to be published).

[8] R. Hatakeyama, M. Oertl, and E. Märk (unpublished).

[9] G. Auer, F. Cap, and N. Schwaighofer, Elektrotechnik + Maschinenbau **89**, 49 (1972); R.W. Motley, *Q-machines* (Academic, New York, 1975).