PASSIVE CORPUSCULAR DIAGNOSTICS OF A HIGH-TEMPERATURE PLASMA

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The diagnostic apparatus, results of calibration of an air-hydrogen stripping chamber for hydrogen atoms in the energy range 0.3-0.5 keV, and technique for analyzing the experimental data to determine the plasma ion temperature are described. Passive corpuscular diagnostics based on charge-exchange neutrals [1-3] is one of the few methods for obtaining information on plasma ion temperature. The apparatus used in this technique consists basically of a device (stripping chamber) which partially transforms neutral particles into charged particles and a differential ion-energy analyzer with a detector. In the present paper we describe this type of diagnostic apparatus which has been developed and used at the Institute of Nuclear Physics of the Siberian Branch of the Academy of Sciences of the USSR, the results of its calibration, and the technique for analyzing the experimental data. In contrast with [1], in which nitrogen was used as the stripping gas, the calibration of the stripping chamber was made using air and hydrogen. We also propose a technique for determining the plasma ion temperature with account for the degree of isotropy of the Maxwellian ion velocity distribution function.

1. Diagnostic Apparatus. A schematic of the diagnostic setup is shown in Fig. 1, where 1 is the deflecting condenser, 2, the stripping chamber, 3, an inlet needle valve, 4, an ion energy analyzer, and 5, an electron multiplier.

For partial transformation of the neutrals into charged particles we use a gas stripping chamber, which is the simplest and most effective device of this type for neutral particles with energy greater than 200-300 eV [1].

The chamber length is 20 cm. Tubes 6 mm in diameter and 5 cm long are provided at the chamber entrance and exit in order to create a differential pressure. Structurally, the chamber is made from an integral piece of Armco iron to protect against the effect of the quasi-stationary magnetic field of the plasma setup on the charged particle beam.

Air and hydrogen are used as the stripping gas. The use of air makes it possible to avoid the use of any gas facilities (other than the inlet needle valve), while the use of hydrogen – in spite of some reduction of the chamber effectiveness – eliminates the danger of distortion of the studied process as a result of entry of foreign gas into the plasma equipment space in the case of insufficient differential evacuation. The usual working pressure in the stripping chamber was $(4-7) \cdot 10^{-4}$ mm Hg.

A condenser which screens out the charged particles traveling together with the neutrals is installed ahead of the entrance to the chamber. The differential electrostatic ion energy analyzer is based on a cylindrical condenser with cone angle 127°57' and is similar to that described in [4]. The instrument is described in more detail in [5].

To record the ions we used an open electron multiplier (EM) of the VÉU-OT-8M type which usually has a gain of order 10^5-10^6. The observed slow reduction of EM sensitivity with time has practically no effect on the results of relative measurements made in the course of a short time interval. A preliminary calibration of the multiplier using an ion source is made in order to carry out absolute measurements of the neutral particle flux.

Novosibirsk Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 11, No. 3, pp. 132-137, May-June, 1970. Original article submitted July 16, 1969.

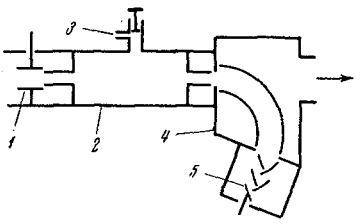

Fig. 1

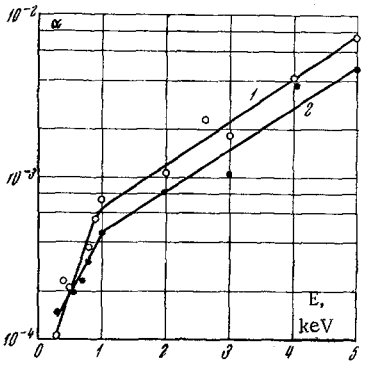

Fig. 2

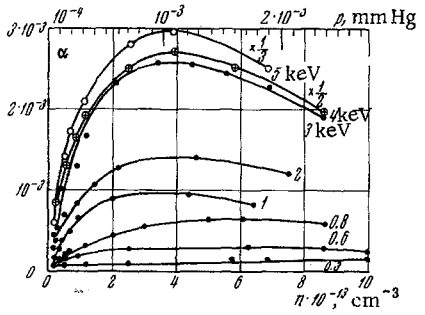

Fig. 3

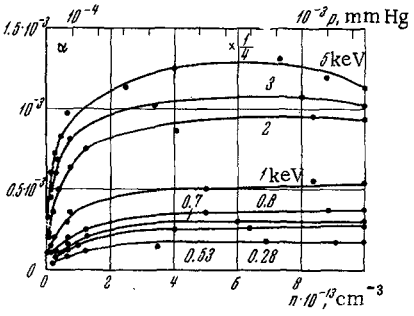

Fig. 4

As would be expected, the dependence of the electron multiplier gain on ion energy is weak, since the ions of all energies receive additional energy on the order of 5 keV prior to striking the surface of the first dynode. Thus, according to [6], the multiplier gain K(E) for protons with energy (the sum of the initial and additionally acquired ion energies) 10 keV exceeds by no more than 30% the K(E) for protons with energy 5 keV.

2. Stripping Chamber Calibration. The stripping chamber calibration was conducted using a neutral particle source similar to that described in [7], which makes it possible to obtain neutral hydrogen atom beams with equivalent current densities on the order of several $\mu A/cm^2$.

A drawback of the source is the fact that in its beam there is in addition to atomic hydrogen also molecular hydrogen, as well as the lower-energy H_0 and H_2 which are formed as a result of dissociation of the particles H_2^+, H_3^+, and H_2 in the source charge-exchange chamber.

However, special studies made using a gas stripping chamber and a magnetic mass analyzer showed that there is a source operating regime (reduced pressure in the discharge bulb of the high-frequency ion source and reduced contribution of high-frequency ion source and reduced contribution of high-frequency power to the discharge [7]) in which the overall impurity fraction in the beam does not exceed 30% over a wide range of variation of beam energy, which makes the magnitude of the calibration error quite acceptable.

The measurement of the equivalent neutral-particle beam current entering the stripping chamber was based on secondary electron emission from a brass target located immediately ahead of the chamber entrance. The target had an area equal to the area of the inlet por', and a small negative potential (–50 V) was applied to the target. With the aid of a bellows drive the target could block the chamber inlet port without disrupting the vacuum. The electron current from the target was measured by a UI-2 direct-current amplifier. The dependence of the coefficient of secondary neutral-electron emission from the brass target on the energy of the bombarding hydrogen atoms was obtained on a special setup. The measurement of the ion current after the stripping chamber was made with the aid of a UI-2 direct-current amplifier with a Faraday cylinder having a grid for stopping the secondary electrons, which was mounted after a cylindrical condenser whose slit energetic width was sufficient to pass the entire beam, which has energy spread of ±30 eV (measured at the half-height). The use of the cylindrical condenser was necessary to screen out the negative ions and secondary electrons coming from the stripping chamber, which distort the

result markedly, particularly for low beam particle energies. Figure 2 shows the hydrogen atom stripping coefficient α versus their energy for a stripping gas pressure $p = 4 \cdot 10^{-4}$ mm Hg (curve 1 is for air, curve 2 is for hydrogen). Here we note that the hydrogen density corresponding to this pressure exceeds the air density by about 2.5 times [8, 9].

Figures 3 and 4 show the stripping coefficient for hydrogen atoms of different energy as a function of the stripping gas pressure – air and hydrogen respectively. We see that the pressure chamber should be in the $(4\text{-}7) \cdot 10^{-4}$ mm Hg range for most stable chamber operation.

3. Analysis of Experimental Data. In studying a pulsed plasma process we usually obtain a series of oscillograms, each of which corresponds to a record of the neutral particles with energies lying in a narrow interval relative to the energy to which the energy analyzer is tuned. In this case the temporal correspondence of the features on the different oscillograms is determined from flight time considerations.

We shall explain the technique for determining the plasma ion temperature from the experimental data obtained. Let us assume that in the plasma there is a region in which ion heating takes place. In real conditions this region is usually surrounded by a "jacket" of colder plasma. From the plasma there is emitted continuously a neutral particle flux, whose magnitude and energy spectrum are determined by both the plasma parameters and the cross-sections of the competing processes which lead to the formation transformation of ions into neutrals and vice-versa.

In studying fast processes in a plasma [3], we can (at least for their initial stage) neglect influx into the plasma of the neutral gas desorbed from the walls, which is in the case of the slow processes [11] the most probable charge-exchange target for the ions. In the fast process case the charge exchange must proceed basically on the plasma neutrals.

The current I at the multiplier output, proportional to the signal amplitude on the oscillograms, is connected with the input current I_1 by the relation

$$I = K(E) I_1$$

where K(E) is the multiplier gain, which as we have noted depends weakly on the ion energy.

We can write for the multiplier input current I_1

$$I_1(E^*) = \int_{E_-^*}^{E_+^*} \frac{dI}{dE} dE \approx \left\langle \frac{dI}{dE} \right\rangle \Delta E \approx \frac{dI}{dE}(E^*)\,\Delta E \qquad \left(E_\pm^* = E^* \pm \frac{\Delta E}{2}\right) \tag{3.1}$$

where

$$\frac{\Delta E}{E^*} = \pm \frac{s}{r_0} = a \ll 1$$

Here E* is the energy to which the analyzer is tuned; ΔE is the energy range defined by the analyzer; s is the average slit width; r_0 is the radius of the ion mean trajectory in the analyzer. Hereafter, considering the smallness of a, we shall drop the averaging symbol $\langle\,\rangle$ in (3.1) to simplify the equations.

We obtain for the multiplier output current

$$I(E^*) = K(E^*)\,\alpha(E^*)\,aE^* \frac{dI_n}{dE}(E^*)$$

Here $\alpha(E)$ is the effectiveness of the conversion of neutral particle flux into charged flux in the stripping chamber (stripping coefficient); $I_n(E)$ is the equivalent neutral particle current at the chamber entrance, satisfying the condition (3.1).

Account for the weakening of the neutral particle beam by a cold plasma in the case of a strong transverse field capable of deflecting from a rectilinear trajectory the ions formed during charge exchange of fast neutrals by ions or during ionization by electrons leads to the result

$$\frac{dI_n}{dE} = \frac{dI_n^\circ}{dE} \exp(-\gamma L), \qquad \gamma = n_0 \sigma_2^n + n_i \left(\sigma_1 + \frac{\langle \sigma v_e \rangle}{v_0} + \sigma_2^i\right) \tag{3.2}$$

Here I_n° is the equivalent neutral particle current at the boundary of the hot and cold plasma, L is the length of the neutral atom flow path in the cold plasma prior to entry into the stripping chamber, σ_2^n, σ_2^i are

the neutral and ion stripping cross sections, $v_0^{-1}\langle\sigma v_e\rangle$ is the effective cross section for ionization by electrons (v_0 is the beam velocity), σ_1 is the neutral atom–ion charge-exchange cross section.

In the case of presence or absence of a longitudinal magnetic field we have

$$\frac{dI_n}{dE} = \frac{dI_n^\circ}{dE}\left[\frac{\beta}{\gamma+\beta} + \left(1 - \frac{\beta}{\gamma+\beta}\right)\exp\{-(\gamma+\beta)\}\right] \quad (\beta = n_0\sigma_1)$$

Using the results of [10] for the conditions of a collisionless plasma ($n_i l \sim 10^{14}$ cm^{-2}, l is the characteristic dimension of the emission region) we can obtain the following connection between the neutral I_n° and ion I_i° currents in the plasma, satisfying the condition (3.1)

$$I_n^\circ(E) \approx \sigma_1 n_0 l I_i^\circ(E)$$

Considering $I_i = qn_i vS$ and (3.1), we can write

$$\frac{dI_n^\circ}{dE} = B\sigma_1\sqrt{E}\,\frac{dn_i}{dE}$$

Here q is the charge of the ion, S is the area of the neutral atom stream, B is a coefficient which is independent of the energy.

Finally, for example, for the case (3.2)

$$\frac{dn_i}{dE} = \frac{I(E)\exp\gamma(E)}{BK(E)\alpha(E)E^{3/2}\sigma_1(E)} \tag{3.3}$$

This expression practically coincides with the analogous expression used in [1], where ion charge exchange takes place on the neutrals coming from the chamber walls.

The ion velocity distribution function is completely defined if the distribution functions for all three velocity projections on the coordinate axes are obtained. It is clear that with the aid of a single analyzer this is possible only in the case of complete anisotropy of the distribution. An example is the distribution function of the collimated ion beam from the ion source. In the general case the distribution function can be found approximately by the trial and error method. To do this we must specify different distribution functions and their degrees of anisotropy, whose selection is based on physical considerations, find the change of their functional dependences on the ion velocity owing to the angular aperture of the instrument, and use (3.3) to compare with the value obtained experimentally and determine the value closest to experiment.

As an example we consider the case of an isotropic Maxwellian ion velocity distribution. We direct the x axis along the system; the y and z axes are perpendicular and parallel to the generator of the cylindrical condenser in the energy analyzer. In this case the maximal values of the velocities along the y and z axes for which the particle can enter the condenser will be related with the velocity along the x axis by the geometric relations

$$\left|\frac{u_y}{u_x}\right| \leqslant \frac{b}{2L} = p_1 \ll 1, \qquad \left|\frac{u_z}{u_x}\right| \leqslant \frac{s}{2L} = p_2 \ll 1 \tag{3.4}$$

Here b is the height of the analyzer inlet slit; L is the distance from the emission region to the analyzer. (In the present case $p_1 \approx p_2 \approx 10^{-2}$.)

Using these conditions, we find the distribution function of the ions which enter the cylindrical condenser in terms of the x velocity component

$$dn_{u_x} = \frac{n}{\pi^{3/2}u^3}\int_{-u_x p_1}^{u_x p_1}\exp\frac{-u_y^2}{u^2}du_y\int_{-u_x p_2}^{u_x p_2}\exp\frac{-u_z^2}{u^2}du_z\exp\frac{-u_x^2}{u^2}du_x\left(u = \sqrt{\frac{2kT}{m}}\right) \tag{3.5}$$

To find the integrals in (3.5) we can use a series expansion of the probability integral [11], from which we see that it is sufficient to use only the first terms when the integration limit $\varphi < 1$.

We assume that in the subject case

$$\varphi_z = \frac{u_x}{u}p = \frac{1}{2}$$

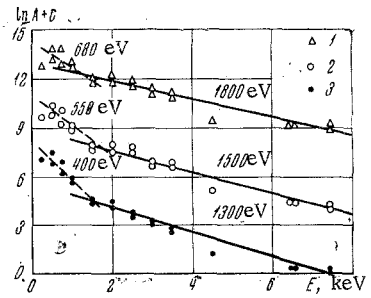

Fig. 5

For $p \approx 10^{-2}$ this will correspond to the velocity ratio $u_x/u \approx 10^2$ and correspondingly the energy ratio $E/kT \approx 10^4$, which means that this approximation can be used for recorded particles with energy of order 10^4 kT. Since there are few such particles in the case of the Maxwellian distribution, the adopted approximation can be considered well justified and we can use only the first term of the expansion (which is proportional to φ).

Integrating (3.5), we obtain

$$dn_{u_x} = \frac{4n}{\pi^{3/2} u} p_1 p_2 \left(\frac{u_x}{u}\right)^2 \exp\left(-\frac{u_x^2}{u^2}\right) du_x \tag{3.6}$$

Thanks to the smallness of the angular aperture the resulting distribution is similar, as we would expect, to the ion distribution with respect to the absolute velocities. In the case of relatively large (except for the case 180° – when we obtain the particle distribution with respect to the velocities along the x axis) angular aperture of the instrument, we cannot restrict ourselves to only the first term of the expansion, and the form of the distribution function of the ions entering the cylindrical condenser will be considerably more complex.

Converting in (3.6) to energy variables, we have

$$\frac{dn}{dE} = \frac{2np_1p_2}{\pi^{3/2}} (kT)^{-3/2} \sqrt{E} \exp\frac{-E}{kT} \tag{3.7}$$

Comparing (3.3) and (3.7), we can write

$$\frac{dn}{dE} = \frac{2np_1p_2}{\pi^{3/2}} (kT)^{-3/2} \sqrt{E} \exp\frac{-E}{kT} = \frac{I \exp\gamma}{K\alpha E^{3/2}\sigma_1 B}$$

Hence the ion temperature is easily found from the cotangent of the straight line slope

$$\ln \frac{I(E) \exp\gamma(E)}{K(E)\alpha(E)E^2\sigma_1(E)} = -\frac{E}{kT} + \ln C_1 \tag{3.8}$$

where C_1 is an arbitrary constant.

Omitting the calculations, we write the analogous expression for the Maxwellian function which is isotropic in two directions (for example, in the φ plane in the case of cylindrical geometry)

$$\ln \frac{I \exp\gamma}{K\alpha\sigma_1 E^{3/2}} = -\frac{E}{kT} + \ln C_2 \tag{3.9}$$

For the anisotropic Maxwellian function, corresponding to the case in which the transverse ion temperature is negligibly small in comparison with the longitudinal temperature, it is easy to obtain

$$\ln \frac{I \exp\gamma}{K\alpha\sigma_1 E} = -\frac{E}{kT} + \ln C_3 \tag{3.10}$$

where C_2 and C_3 are arbitrary constants.

As a rule dearth of statistics makes it impossible to determine from the deviation from rectilinearity of the curves (3.8), (3.9), (3.10) which of the three Maxwellian functions holds in a given case for the ions in the plasma. Therefore the calculation is usually made for all three assumed cases and the lower and upper limit of the ion temperature is determined.

The upper temperature limit yields the case of the anisotropic distribution function, the lower (experience in the calculation using this technique shows that it is about 1.5-2 times lower) yields the isotropic function. We would hope that the possible systematic error does not take the true temperature value outside these limits.

In the absence of a Maxwellian distribution the experimental points should not lie on a straight line in any of the assumed cases.

As an example Fig. 5 shows the curves 1, 2, 3 corresponding to expressions (3.8), (3.9), (3.10), obtained in a plasma study using the UN-6 setup [12] and corresponding to the moment of cumulation of the transverse shock wave at the axis of the system. Here the observed break in the straight lines indicates the presence in the plasma of a two-temperature distribution. We can conclude that the energy spectrum of the "hot" ions approaches the Maxwellian distribution with a temperature of 1.3-1.8 keV.

The authors wish to thank R. Z. Sagdeev and R. Kh. Kurtmullaev for their encouragement in this study.

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