MEASUREMENT OF SPATIAL DISTRIBUTIONS OF RESIDUAL GAS DENSITY AND ELECTRICAL POTENTIAL IN A PLASMA

V. N. Bocharov, A. M. Kudryavtsev,
A. F. Sorokin, and Yu. N. Ul'yanov

UDC 53.082.79+533.9.07

In experiments on creation and maintenance of a high-temperature plasma of hydrogen isotopes an important parameter is the concentration of neutral atoms n_a and molecules n_m in the volume occupied by the plasma. The quantities n_a, n_m determine the energy loss in the plasma connected with charge exchange of rapid ions with molecules and especially hydrogen atoms.

Recently studies have appeared on measurement of the spatial profile $n_a(r)$, based on resonant scattering of vacuum ultraviolet by hydrogen atoms in the ground state [1] and on quasiresonant scattering of laser light by excited atoms [2]. Both methods require additional measurements and calculations to determine the populations of various atomic states in the plasma. Moreover, these methods do not measure the residual gas component n_m.

The present study will offer a method of determining n_a and n_m from charge exchange with residual gas of a high-speed hydrogen or deuterium ion beam introduced into the plasma.

A beam with energy W_0, current I_i, and cross section S_0 is introduced across the magnetic field H which maintains the plasma, as shown in Fig. 1. As a result of charge exchange with the residual gas a portion of the ions are transformed into atoms, which, moving along the tangent to the ion trajectory at the charge exchange point P, fall into a high-speed atom detector—analyzer with angular aperture $d\psi$. The flux of these atoms I_0 is proportional to the partial concentrations of residual gas components in the vicinity of the point P,

$$I_0 = I_i/S_0 \cdot Sl[\sigma_a(W_0)n_a + \sigma_m(W_0)n_m], \quad (1)$$

where $S = \min\{S_0, (I_p d\psi)^2\}$; $l = Rd\psi$ (R is the radius of curvature of ion trajectory at point P); σ_a, σ_m are charge exchange sections for atoms and molecules. (The flux of atoms produced by recombination of rapid beam ions with plasma electrons is many times smaller than the "charge exchange" flux over the entire range of plasma and beam parameters of practical interest.)

Since Eq. (1) contains two unknowns n_a and n_m, an additional equation relating these is needed.

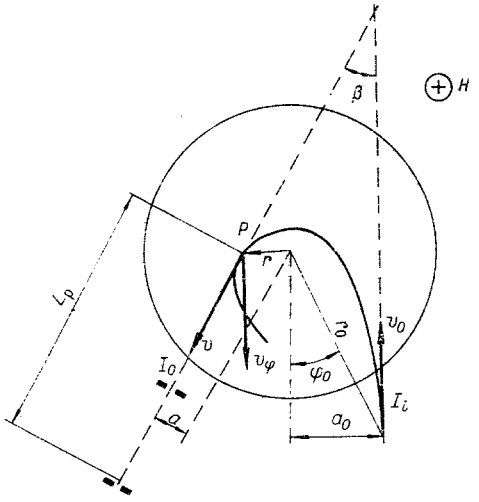

Fig. 1

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 35-40, September-October, 1977. Original article submitted October 15, 1976.

0021-8944/77/1805-0617$07.50

In working with a plasma located in a relatively weak magnetic field an H^+ or D^+ ion beam with $W_0 < 10$ keV may be used. In this energy region the functions $\sigma_a(W_0)$ and $\sigma_m(W_0)$ differ significantly: The resonant section σ_a increases with decrease in W_0, while σ_m falls sharply [3-5]. Thus, from flux measurements $I_0(W_0)$ and $I_0(W_0')$ at two ion energies W_0 and W_0', we can calculate the absolute values of n_a and n_m at any point of the plasma volume.

In working with relatively dense plasma ($n_e \gtrsim 5 \cdot 10^{12}$ cm^{-3}) where all H_2 molecules in the plasma volume are dissociated, n_a is determined directly from Eq. (1).

For high magnetic fields it is necessary to use heavy ions with high energy. In this case, if $\sigma_a \approx \sigma_m$ the total residual gas concentration $n_a + n_m$ is measured.

From measurements of the shift in energy spectrum ($W_0 - W$) of the atoms formed one can find the electrical potential U at the charge exchange point P:

$$eU(r) = W_0 - W(r), \tag{2}$$

where W is the mean energy of charge exchange atoms, measured by the detector–analyzer. By varying the positions of the detector, ion source, and the value of W_0, the spatial distributions $n_a(r)$, $n_m(r)$, $U(r)$ can be examined.

We note that a similar method of determining U(r) from ionization of probe particles by plasma electrons was presented in [6, 7].

For high potentials in the plasma the use of atoms as secondary particles is preferable in our opinion, since ions may, for example, not leave the plasma volume if $U(r) < 0$, $|eU| \geq W_0$.

We will now consider the question of determining the coordinates (r, φ, z) of the charge exchange point P. In the case of an axially symmetric magnetic field and electric potential only the coordinate r need be determined, and it can be found from the condition of conservation of the angular component of generalized momentum P_φ:

$$P_\varphi = -ma_0v_0 + \frac{e}{c} r_0 A_\varphi(r_0) = mrv_\varphi(r) + \frac{e}{c} rA_\varphi(r), \tag{3}$$

where e and m are the charge and mass of the ion; A_φ is the φ-component of the magnetic field vector potential H(r), ($A_z = A_r = 0$) is calculated from H(r) measurements; a and a_0 are the sight parameters of injection and detection points; $v = \sqrt{2W/m}$, $v_0 = \sqrt{2W_0/m}$.

It follows from Fig. 1 that

$$v_\varphi(r) = -va/r. \tag{4}$$

Substituting in Eq. (3) the concrete expressions for $A_\varphi(r)$ and v_φ from Eq. (4), we obtain the equation for r.

To determine the absolute value of I_0 it is necessary to calibrate the measurement system. This can be done easily using molecular hydrogen in the absence of a plasma. However, when using the calibration results with a plasma having significant electrical potential one should correct σ_a, σ_m, and $Rd\psi$ in Eq. (1):

$$\sigma(W_0) \to \sigma(W_0 \pm eU); \quad R = \frac{mcv_0}{eH} \to \frac{mcv}{eH} \frac{1}{1 \mp \frac{v_*}{v}}, \tag{5}$$

where $v_* = (c/H)\,\mathrm{grad}_R U(r)$.

Apparatus was tested and n_a, n_m, and U(r) measurements performed on a stationary Penning discharge plasma in a magnetic field with corkscrew configuration (Fig. 2). The two rings 3 with outer diameter 6 cm serve as discharge anodes with a distance between rings of 3 cm. The cathodes are the walls of the grounded vacuum chamber 1, made of stainless steel.

The magnetic field is inhomogeneous over the radius. The radial dependence H(r) in the plane of symmetry of the device may be approximated with an error of $\lesssim$5% by the function

$$H(r) = H_0 \exp(-r^2/44).$$

H_0 may reach 2 kOe, with a corkscrew ratio of 2.8. Discharge voltage was up to 1 kV with current to 0.3 A. Experiments were performed in helium and hydrogen plasmas at densities $n_e \sim (3\text{-}6) \cdot 10^{11}$ cm^{-3} and electron temperatures $T_e \sim 5\text{-}10$ eV.

The absolute value of n_e was determined from the discharge current since calibration by cutoff of uhf signals with $\lambda = 3$ and 0.8 cm showed that plasma density changes linearly with this current. The temperature T_e was measured by the "helium thermometer" method. Initial gas concentration $n_m^0 \sim (3\text{-}6) \cdot 10^{13}$ cm^{-3}.

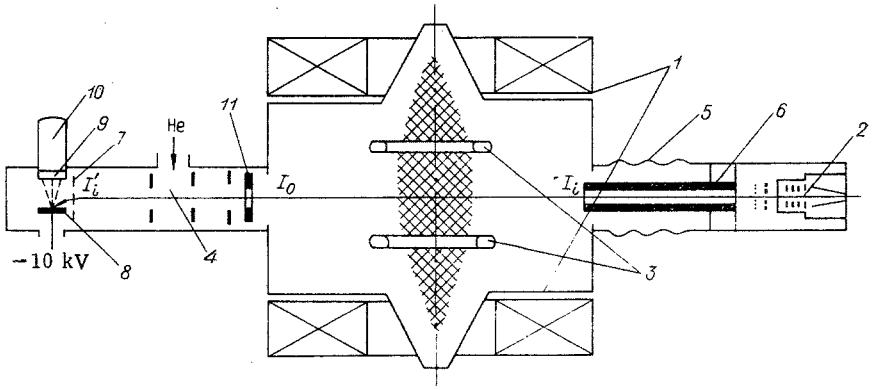

Fig. 2

An impulse arc source 2 was used to generate the ion beam [8]. A beam of protons with energy 1-3 keV at a current of 5-20 μA was introduced into the plasma volume through channel 6, screened from the device magnetic field.

The beam diameter at the channel end, i.e., the injection point, was 8 mm, while the diameter near the system axis was 10 mm. Bellows joint 5 permitted changing radial and angular coordinates r_0, φ_0 (see Fig. 1) of the injection point. The half-width of the proton energy was less than 50 eV with a scattering of 5 eV over various moments. This figure determined the accuracy of the measurement of potential U(r).

Measurements of charge exchange atom flux and their energies were performed by the detector–analyzer (Fig. 2). The H^0 atoms lose electrons at the impulse helium target 4, changing into protons which then pass through the analyzer retarding potential created by grid 7 and are detected by a system consisting of a secondary emission ion–electron converter 8, scintillator 9, and photomultiplier 10. Fine diaphragms are located in the electron stripping channel, ensuring a device aperture over the range of n_a, n_m, U measurement of the order of 6 mm. Scanning over the 3 cm plasma volume is performed by shifting the input diaphragm 11.

The source and detector–analyzer are located in the device symmetry plane with an angle $\beta = 60°$ between them. Measurements were performed in the pulse mode. Duration of the rectangular ion current pulse was 100 μsec, duration of the sawtooth analyzer voltage 50 μsec, time resolution ≤ 10 μsec.

Preliminary measurements revealed that in the absence of a plasma it was always possible to select ion beam input parameters such that the atoms formed fell on the detector. After the beam is located at arbitrary values of H and W_0, the value of H can be changed continuously to that required in the experiment while adjusting W_0, and if necessary, the coordinates of the ion beam injection point.

Figure 3 shows the dependence of photomultiplier current I_{ph}, which is proportional to I_0, on air pressure p within the volume. From the minimum experimental pressure $p = 0.5 \cdot 10^{-5}$ mm Hg up to $p = 1.5 \cdot 10^{-3}$ mm Hg, $I_{ph} \sim p$. Loss of proportionality is connected with attenuation of the ion current at high p due to charge exchange. Extrapolation to the low-pressure region, performed with consideration of loss of detector sensitivity indicates that at an ion beam current of 1 μA it is possible to reliably measure $n_m \sim 10^8$ cm^{-3}.

Figure 4 shows the measured radial distribution of electrical potential in the absence of a plasma at an anode voltage of $U_a = 400$ V (points 1). They coincide well with the calculated distribution (points 2) obtained by the network method. The absolute potential value, as has been noted, is determined to an accuracy of 5-7 V. The spatial resolution is determined in practice by the aperture of the detector–analyzer and comprises 6 mm.

To check possible influence of the plasma on operation of the ion source and the detector–analyzer, on the ion trajectory, etc., measurements of $n_a(r)$ and U(r) were performed in a weakly ionized helium plasma with parameters $n_a^0 \sim 3 \cdot 10^{13}$ cm^{-3}, $n_e \sim (4\text{-}6) \cdot 10^{11}$ cm^{-3}, $T_e \sim$ 5-7 eV, $W_0 = 2.2$ keV. These measurements showed that the value of I_0 at all radii was practically independent of the presence or absence of plasma, i.e., $n_a \sim n_a^0$, of what would be expected from the low degree of ionization [Fig. 5: 1) helium plasma; 2) n_a, hydrogen plasma]. It follows from these same measurements that within the plasma volume there are no impurities with large charge exchange sections. The form of U(r) changes noticeably with plasma present

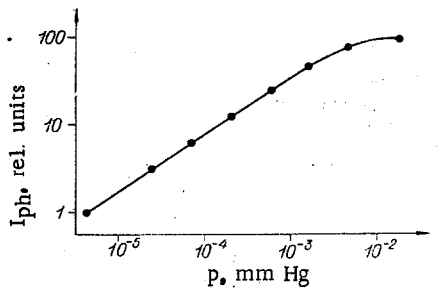

Fig. 3

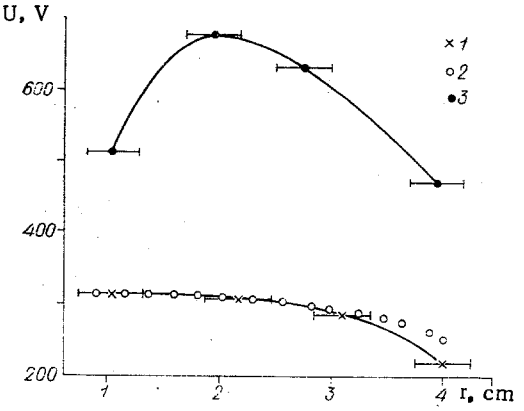

Fig. 4

(Fig. 4, points 3, U_a = 800 V). To prevent deviation of the atom beam away from the detector aperture upon switch-on of the plasma a quite small (∿2-4%) change was made in magnetic field value. The ratio of signal to noise connected with fluxes of slow atoms and ultraviolet radiation generated by the plasma exceeded 3, although no special measures for noise suppression were taken.

In experiments on hydrogen plasma of approximately the same parameters as the helium plasma, it was observed that the atomic flux I_0 increases with switch on of the plasma by a factor of several times, with this effect dependent on r and W_0. The results obtained in one series of such experiments are presented in Table 1.

Comparison with results of similar measurements on helium plasma allows the clear conclusion that the charge exchange atom flux I_0 increases due to the appearance of atomic hydrogen in the plasma volume.

As is evident from Table 1 the contribution to the flux from charge transfer to molecular hydrogen is negligibly small compared to the flow from charge transfer to atomic hydrogen, thus not permitting determination of n_m in our experiment: the atomic hydrogen density

$$n_a \approx n_m^0 \frac{\sigma_m}{\sigma_a} \frac{I_0'}{I_0}.$$

Figure 5 shows the distribution of n_a over device volume with a hydrogen plasma. Dissociation evidently occurs near the device axis, with degree of dissociation $\alpha \sim 65\%$. Beyond the plasma boundaries ($r \sim 4$ cm) the degree of dissociation decreases ($\alpha \sim 40\%$), which indicates the presence of a strong hydrogen atom absorption mechanism in the volume or on the chamber walls.

It should be noted that the accuracy of determining n_a and n_m depends not so much on experimental accuracy as on the accuracy of data from the literature on charge transfer sections. However, we maintain that even at a total accuracy of n_a determination of ∿50% such measurements will be of a certain value in experiments on maintaining a hot plasma. It is of course necessary to attempt to minimize factors which degrade the accuracy of the experiment itself. The most important of these are as follows: a) uncontrolled attentuation of both the "primary" ion beam and the "secondary" atom beam due to charge transfer and electron loss to the residual gas and ionization by plasma electrons; b) scattering of the "primary" ion beam on electric field fluctuations in the plasma.

TABLE 1

W_0, keV	r, cm	U, V	$\frac{I_0(w/o\ plasma)}{I_0'(w\ plasma)}$	Charge exchange section [3-5]
1,75	1	430	4—5	$\sigma_a = 2{,}1 \cdot 10^{-15}$ cm^2; $\sigma_m = 6 \cdot 10^{-16}$ cm^2
1,35	1	430	6—7	$\sigma_a = 2{,}3 \cdot 10^{-15}$ cm^2; $\sigma_m = 4{,}5 \cdot 10^{-16}$ cm^2
1,75	4	350	2—2,5	$\sigma_a = 2 \cdot 10^{-15}$ cm^2; $\sigma_m = 6{,}5 \cdot 10^{-16}$ cm^2

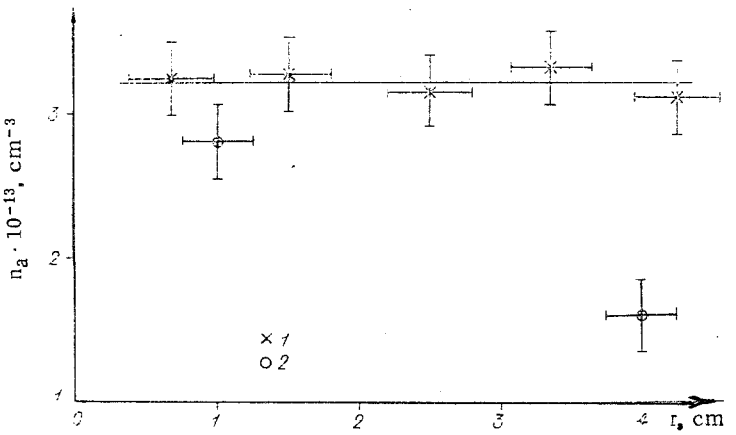

Fig. 5

Simple estimates indicate that at a plasma column diameter of the order of 20 cm with use of an Ar^+ beam with energy of several tens of kV the processes referred to above begin to noticeably affect measurements at n_a, $n_m \gtrsim 10^{14}$ cm^{-3}, $n_e \gtrsim 10^{14}$ cm^{-3}, $E_z \gtrsim 0.5$ kV/cm.

In conclusion, we note that if the magnetic field changes with plasma switch on, while remaining axially symmetric (for example, if $H^2/8\pi n_e T_e > 1$), then by measurements with beams of ions of two different masses one may calculate both the magnetic field vector potential and the electric potential. The equality of generation radii for particles of different mass may be determined by equality in shift of their energy spectra [see Eq. (2)].

LITERATURE CITED

1. C. Breton and R. Papoular, "Neutral density determination by scattering of vacuum-uv radiation," Plasma Phys., 17, No. 5, 309 (1975).
2. H. F. Döbele and K. Hirsh, "Scattering of laser light from excited hydrogen atoms in plasma," Phys. Lett., A54, No. 3, 267 (1975).
3. W. L. Fite, R. T. Brackmann, and W. R. Snow, "Charge exchange proton-hydrogen atom collision," Phys. Rev., 112, No. 4, 1161 (1960).
4. W. L. Fite, R. F. Stebbings, D. G. Hummer, and R. T. Brackmann, "Ionization and charge transfer in proton-hydrogen atom collisions," Phys. Rev., 119, No. 2, 663 (1960).
5. D. W. Koopman, "Measurements of charge-exchange cross section for H^+, H_2^+, and He^+ ions," Phys. Rev., 154, No. 1, 79 (1967).
6. S. A. Vdovin, A. A. Kalmykov, V. A. Naboka, and Yu. I. Pankrat'ev, "Measurement of potential well depth in an electromagnetic trap by a beam of neutral particles," Zh. Tekh. Fiz., 45, No. 3, 563 (1975).
7. F. C. Jobes and I. C.Hosea, "Space potential measurements in the ST tokamak," in: Materials of the Sixth European Conference on Controlled Synthesis [in Russian], Vol. 1, OIYaI, Moscow (1973).
8. G. I. Dimov and G. V. Roslyakov, "A pulse charge transfer source of negative hydrogen ions," Prib. Tekh. Éksp., No. 1, 29 (1974).