DIAGNOSIS OF A HYDROGEN PLASMA BY BEAMS OF HELIUM ATOMS OF DIFFERENT ENERGY

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The underlying theory is described for a method of diagnosing a hydrogen plasma by means of beams of helium atoms of different energy. The range of measured density is 10^{14} to 10^{16} cm^{-3} with a length of plasma section probed ≈ 10 cm. The highest accuracy (≈ ± 20%) is attained in the middle of the range. The accuracy in measuring electron temperature from 10 to 50 eV is no worse than 10–30%. Higher temperatures can be determined with an accuracy of the same order. Methods have been developed in recent years for active diagnosis of a high-temperature plasma using beams of fast neutral particles [1–5]. These methods, in spite of involving somewhat unwieldy apparatus, promise to permit the study of a plasma in the range of parameters difficult to investigate by traditional methods (probes, microwave equipment, and so on). In addition, they have relatively high timewise and spatial resolutions and are noncontact methods in practice.

1. The idea of plasma diagnosis using beams of neutral particles of the same type but having various energies was described first, apparently, in [1, 2]. While the cross section for interaction between the probing particles and the ion, electron, and neutral components of the plasma will vary strongly with change of beam energy, the relative attenuation of beams as they pass through the plasma can be used to determine the plasma parameters: ion density n_i and density of neutral atoms n_0 (more accurately, the thickness of the ion and neutral target: $N_i = n_i l$, $N_0 = n_0 l$, where l is the length of the probed section of the plasma), and the electron temperature T_e.

Fig. 1 shows the cross section for interaction processes between helium atoms and the various components of a hydrogen plasma as a function of beam energy.

The cross section for charged transfer σ_1(He + p → He$^+$ + H) (curve 2) has been taken from [6, 7]. The stripping cross section for the ion σ_2 (curve 4) and for the atom σ' (curve 5) of hydrogen were obtained by extrapolating the data from [8] to the low-energy region, and the results given are in good agreement with the data of [9].

The stripping cross section of a hydrogen molecule (curve 3), computed per target atom, lies somewhat high [10].

The effective cross sections for ionization of helium atoms by electrons ($\sigma_i = \langle \sigma_e v_e \rangle / v_0$) ($v_e$ and v_0 are the velocities of the electrons and beam particles) having a Maxwellian velocity distribution were taken from [11]. Figure 1 shows these as a family of curves, 1a–e, corresponding to the values T_e = 350, 200, 100, 50, and 20 eV, the ordinate here being $\sigma \cdot 10^{16}$ cm^2, and not $\sigma \cdot 10^{17}$ as was shown for curves 2, ..., 5.

The quantity $\langle \sigma_e v_e \rangle = f(T_e)$, calculated by numerical integration on the basis of data for the ionization cross section of the helium atom σ_e by an electron collision [12], was also given in [11]. It can be approximated very well by the expression

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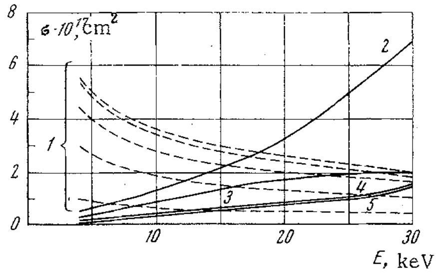

Fig. 1

$$\langle \sigma_e v_e \rangle = -32.2 \cdot 10^{-14} \frac{1}{\sqrt{kT_e}} \operatorname{Ei}\left(-\frac{eU_{ieff}}{kT_e}\right) \tag{1.1}$$

Here $\langle \sigma_e v_e \rangle$ is cm^3/sec, kT_e is in ergs, $U_{ieff} = 1.5U_i = 37$ (eV), Ei is the exponential integral function, and U_{ieff} is the effective ionization potential of helium [1].

Figure 1 shows that the cross sections for integration between the ion $\sigma = \sigma_1 + \sigma_2$ and the neutral plasma component σ' increase continuously with increase of beam energy, while the cross section for ionization by electrons decreases. (Although the maximum charge-transfer cross section $\sigma_1 \approx 2 \cdot 10^{-16}$ cm^2 is reached at a beam energy ≈ 100 keV, it is reasonable in considering the method to restrict ourselves to an energy of 30 keV, since cumbersome apparatus is required to obtain beams of higher energy.)

2. For simplicity we consider the case when the plasma is rotated in a rather strong magnetic field. If probing is performed across the field, the beam current at the entrance I_0 and the exit $I(l)$ of the plasma formation region are related to the plasma parameters as follows [1]:

$$I(l) = I_0 \exp[-n_i(\sigma + \sigma_i) l - n_0 \sigma' l]$$

We write this expression in the form

$$N_i \left(\sigma + \frac{\langle \sigma_e v_e \rangle}{v_0}\right) + N_0 \sigma' = \ln \frac{I_0}{I(l)} \tag{2.1}$$

Simplifying the notation somewhat, we write Eq. (2.1) for three beams ($k = a$, b, c) of different energy as follows:

$$N_i (\sigma_k + A_k \langle \sigma_e v_e \rangle) + N_0 \sigma_k' = B_k \tag{2.2}$$

Solving Eq. (2.2) for N_i, N_0, and $\langle \sigma_e v_e \rangle$, we obtain

$$N_i = \frac{\begin{vmatrix} B_a & B_b & B_c \\ \sigma_a' & \sigma_b' & \sigma_c' \\ A_a & A_b & A_c \end{vmatrix}}{\begin{vmatrix} \sigma_a & \sigma_b & \sigma_c \\ \sigma_a' & \sigma_b' & \sigma_c' \\ A_a & A_b & A_c \end{vmatrix}}, \quad N_0 = \frac{\begin{vmatrix} B_a & B_b & B_c \\ A_a & A_b & A_c \\ \sigma_a & \sigma_b & \sigma_c \end{vmatrix}}{\begin{vmatrix} \sigma_a & \sigma_b & \sigma_c \\ \sigma_a' & \sigma_b' & \sigma_c' \\ A_a & A_b & A_c \end{vmatrix}}, \quad \langle \sigma_e v_e \rangle = \frac{\begin{vmatrix} B_a & B_b & B_c \\ \sigma_a & \sigma_b & \sigma_c \\ \sigma_a' & \sigma_b' & \sigma_c' \end{vmatrix}}{\begin{vmatrix} B_a & B_b & B_c \\ \sigma_a' & \sigma_b' & \sigma_c' \\ A_a & A_b & A_c \end{vmatrix}}$$

For example, we can consider three beams with the following energies: 5, 15 and 30 keV. Assuming that all the cross sections are given to an accuracy of ± 10%, in the numerator of the expression for $\langle \sigma_e v_e \rangle$ we obtain

$$B_a(-0.5 \pm 1.6) + B_b(-0.2 + 0.47) + B_e\ (0.1 + 0.12)$$

The large error results from the almost identical proportional increase of the cross sections σ and σ' with increase of beam energy. It is clear that $\langle \sigma_e v_e \rangle$ and, therefore, T_e cannot be obtained from this expression with the accuracy required in practice.

Analysis of the other expressions also shows that the presence of a relatively large number of cross sections with an average error of ± 10% makes it impossible to use these to determine N_i and N_0 with the required accuracy.

Thus, we can conclude that, with the accuracy of the measured cross sections (±10%), the three-beam method is not suitable in practice for determining three parameters of the plasma.

3. We consider the case of a highly-ionized plasma in which attenuation of the beams in the neutral gas can be neglected, i.e.,

$$\frac{N_0 \sigma_k'}{N_i (\sigma_k + A_k \langle \sigma_e v_e \rangle)} \ll 1$$

Hence,

$$\frac{N_i}{N_0} \gg \frac{\sigma_k'}{\sigma_k + A_k \langle \sigma_e v_e \rangle} = \alpha$$

For T_e = 10 eV and beams with energies of 5 and 30 keV, the quantity α has the values 0.056 and 0.17, respectively. Thus, we can conclude that for $T_e \gg 10$ eV, even with $N_i/N_0 \approx 1$ (i.e., with a degree of plasma ionization of $\beta \approx 0.5$), we can neglect attenuation of the beams in the neutral gas.

Solving the two equations in Eq. (2.2) in this case for N_i and $\langle \sigma_e v_e \rangle$ we obtain

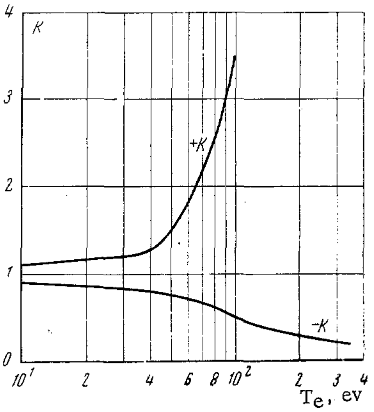

Fig. 2

$$N_i = \frac{A_a B_b - A_b B_a}{A_a \sigma_b - A_b \sigma_a}, \qquad \langle \sigma_e v_e \rangle = \frac{B_a \sigma_b - B_b \sigma_a}{A_a B_b - A_b B_a}$$

4. Figure 1 shows that the most accurate method is that in which beams with markedly different energies are used. Therefore, we consider from now on two beams with energies 5 and 30 keV, respectively. In this case we obtain

$$N_i = \frac{B_b - 0.408 \cdot B_a}{8.18} 10^{17} \ (\mathrm{cm}^{-2}), \qquad \langle \sigma_e v_e \rangle = \frac{4.11 \, (B_a / B_b - 0.07)}{1 - 0.41 B_a / B_b} 10^9 \left(\frac{\mathrm{cm}^3}{\mathrm{sec}}\right)$$

In performing an error analysis of these expressions, we consider that cross sections σ_1 and σ_2 have been measured with an accuracy of ± 10%, while the accuracy of the ratios $I_0/I(l)$ is no worse than 5%.

The relative error in density measurement is then given by the equation

$$\pm \frac{\Delta N_i}{N_i} = 0.1 + \frac{0.855 \cdot 10^{15}}{N_i}$$

from which it can be seen that the error does not exceed 50% for $N_i > 2 \cdot 10^{15}$ cm^{-2}.

The accuracy in determining the value of $\langle \sigma_e v_e \rangle$ in the range of N_i from 10^{15} to 10^{17} cm^{-2} varies roughly from 45 to 20%. Assuming it to average 30%, and using Eq. (1.1), we can calculate the coefficients ±K for the accuracy in determining the electron temperature T_e. Figure 2 shows that the relative error in determining T_e varies from 10 to 30% with increase of T_e from 10 to 50 eV. The error increases sharply for larger values of the temperature, and for $T_e > 50$ eV it can be determined in practice only to orders of magnitude.

5. In the calculations no account was taken of beam attenuation due to elastic scattering of the probing particles by the plasma ions. By making the angular aperture θ of the neutral particle detector large enough, we can minimize this effect. For a rough estimate of the minimum angular aperture θ, we can use the formula for the effective scattering cross section σ_s with a spherically symmetric interaction potential (of the form $U = C/r^n$) for the colliding particles [13]. If we use an interaction potential U(He + H^+) in the calculation, evaluated using the well-known semiempirical rule [14]

$$U_{AB} = \sqrt{U_{AA} U_{BB}}$$

the conditions $\sigma_s < \sigma_1$ for a beam of helium atoms with energy 5 keV will be satisfied with a detector angular aperture of $\theta \gg 6°$. (The interaction potential U (He + He) was taken from [15].) Although the calculation here is nonrigorous and clearly gives a high result, it is nevertheless useful since it at least shows the order of magnitude of the minimum detector angular aperture.

6. Helium has two metastable states, 2^1S and 2^3S, whose lifetimes are far longer than the time of flight of the atom through the region of plasma formation in the actual experiment. The cross sections for stripping and ionization by an electron beam for helium in a metastable state must be larger than the corresponding value for helium in the ground state, and therefore, if there is an appreciable fraction of metastable helium atoms in the probing beam, it will be the main factor in determining beam attenuation. Since this fraction is usually not known, the whole method requires a comparative check.

We give the maximum values of the cross sections for excitation σ^* of metastable states [16] and for ionization σ_i of the helium atoms, existing mainly in the ground state [12] and in metastable states, due to electron collisions. The last two cross sections were computed by the Dravin formula [17], which gives the correct order of magnitude of the cross section:

	$\sigma^*(2^1S)$	$\sigma^*(2^3S)$	$\sigma_i(1S)$	$\sigma_i(2^1S)$	$\sigma_i(2^3S)$
$\max\sigma$ [Å^2] =	0.045	0.061	0.4	32.7	22.7
U [eV] =	33	20.6	126	14	16

(6.1)

The last column of Eq. (6.1) shows the electron energy values corresponding to these cross sections. It can be seen from Eq. (6.1) that the contribution to beam attenuation resulting from excitation of metastable states of helium by plasma electrons (with subsequent ionization) cannot be appreciable, compared to the contribution resulting from helium ionization by electrons from the ground state.

7. The random error resulting from instability in operation of the plasma equipment can be decreased appreciably by conducting simultaneous probing with two helium beams of different energy, followed by ionization in a stripping chamber and separation in a magnetic analyzer for recording purposes [18].

The random error also increases due to statistical fluctuations of beam intensity. We calculate the minimum equivalent current of a beam of energy 5 keV, so that the statistical fluctuations should not exceed 1%. If the resolving time of the electronic recording circuit is $\tau \approx 0.1$ μsec, in that time interval $N = I\tau/e$ particles will be recorded (e is the electron charge).

The relative fluctuations are then given by $1/\sqrt{N}$. From the inequality $\sqrt{e/I\tau} < 10^{-2}$ we obtain the result that the recording beam current should be no less than 0.01 μA. Taking into account that only partial conversion of the neutral beam into an ion beam ($\approx 10^{-2}$) occurs in the stripping chamber, we can conclude that the equivalent current of the primary neutral beam should be of the order 1 μA.

8. The lower density limit of this method is given by the least relative attenuation of beams passing through the plasma which can be observed.

Let this attenuation be 5%. Then

$$\min N_i = \frac{5\cdot 10^{-2}}{\max(\sigma_k + A_k\langle\sigma_e v_e\rangle)}$$

Thus,

$$\min N_i \approx 5\cdot 10^{14}\,\mathrm{cm}^{-2} \text{ for } T_e = 10\,\mathrm{eV},\quad \min N_i \approx 10^{14}\,\mathrm{cm}^{-2} \text{ for } T_e = 350\,\mathrm{eV}$$

However, the accuracy in the density measurements is low. The upper limit in density is more indefinite. It is usually given by the value of density above which elastic and inelastic scattering of the beams by particles of the target can no longer be neglected. If the angular aperture of the detector is ≈ 6 deg, this density value lies in the neighborhood of $\approx 10^{17}$ cm^{-2}.

The lower limit of temperature can be taken as $T_e = 10$ eV, at which a hydrogen plasma is already quite well ionized, so that attenuation of the beam in the neutral gas can be neglected.

The choice of an upper temperature limit depends on the measurement accuracy requirement (Fig. 2).

The resolution time of the method is given by the time of flight through the plasma of the slowest probe particles. Thus, for a path length of ≈ 10 cm, with a 5-keV beam, it is about 0.2 μsec.

In conclusion, we note that, following appropriate relative verification, the above method for plasma diagnosis can be an effective technique for investigating a hydrogen plasma of relatively high density (10^{14} to 10^{16} cm^{-3}).

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