SPECTROSCOPIC INVESTIGATION OF AN INTENSE PULSED DISCHARGE IN HYDROGEN. III

DETERMINATION OF THE PARAMETERS OF A HIGH-TEMPERATURE PLASMA

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The results of a spectroscopic measurement of the parameters of a high-temperature plasma are presented. It is shown that at the time of maximum compression the density of charged particles along the axis of the discharge is 35 — 40 times greater than the original density of neutral atoms. The ionic temperature reaches one or two million degrees.

In the present paper we report the results of an investigation on a test sample consisting of approximately $\frac{3}{4}$ of a liter of high-temperature plasma formed by an intense discharge in hydrogen at the instant of maximum compression. The discharge was produced in a straight cylindrical chamber connected to a pulsed circuit. The circuit and the construction of the apparatus have been described in the literature.[1] We list the circuit parameters: $C = 86\,\mu f$; $V_0 = 35$ kv; $J_{max} = 460$ kiloamp; $dJ/dt = 1.5 \times 10^{11}$ amp/sec (at $t = 0$).

The chief interest of physicists who have been concerned with studying such discharges has been the second compression stage of the pinch, at which time hard radiation is observed.[2,3] The present communication is devoted primarily to the results of a spectroscopic investigation of the first compression stage.

The electronic temperature T_e was estimated from the energy distribution in the continuous plasma spectrum; the absolute intensity of the continuum was used to determine the density of charged particles. As is well known, the spectral densities of the bremsstrahlung and recombination radiation of a hydrogen plasma can be given in the form:

$$I_b(\nu, T_e) = \alpha_1 n^2 T^{-1/2} \exp(-h\nu / T_e)\, L, \qquad (1)$$

$$I_r(\nu, T_e) = \alpha_2 n^2 T^{-3/2} \exp[-h(\nu - \nu_i) / T_e]\, m^{-3}. \qquad (2)$$

Here $n = n_i = n_e$ is the density of charged particles, T_e is the electronic temperature, m is the principle quantum number of the level to which recombination occurs, $h\nu_i$ is the energy of this level, α_1 and α_2 are combinations of constants, L is a correction factor introduced in making quantitative measurements (when $T_e \gg h\nu$ this factor increases logarithmically with increasing temperature[4]). The distribution of the total energy $I_b + I_r$ recorded at low temperatures is determined by the factor $\exp(-h\nu/T_e)$. If this distribution is measured in relative units the slope of the line $\ln(I/I_0) = \varphi(h\nu)$ plotted along the experimental points gives T_e at a given instant of time. Unfortunately, at high electronic temperatures this method is effective only if the measurements are carried out over a wide spectral region. Measurements carried out in the visible and near ultraviolet regions provide only a rough estimate of T_e.

It should be noted, however, that even a very approximate knowledge of the electronic temperature in a high-temperature region does not prevent a relatively accurate determination of the density of charged particles from the intensity of the continuum. As a numerical calculation will show, the quantity that depends on the electronic temperature in $I_b + I_r$ varies very slowly in the visible region if $T_e > 10$ ev. For example it is found that a change of T_e by a factor 30 (from 10 ev to 300 ev) corresponds to a change of 20% in n. Thus, from the intensity of the continuum one can obtain a fairly reliable estimate of n. Obviously the dimensions of the radiating volume of the plasma must be known.

The intensity of the continuous spectrum required for estimating T_e and the measurement of n were made by a photoelectric method. In order to obtain reliable collimation of the light from an isolated radiating volume a monochrometer with an FEU-12 photomultiplier was located at a considerable distance from the discharge chamber (up to 20 m). The apparatus was calibrated with a tungsten filament. The size of the

Line	λ, A	Transitions	Excitation energy, *ev	Line	λ, A	Transitions	Excitation energy, *ev
N V	4945	$6^2G - 7^2H$	90.56	N V	4619.4	$3^2S - 3^2P$	58.98
N V	4943	$6^2F - 7^2G$	90.56	N IV	4057.80	$3^1P - 3^1D$	52.98
N II	4621.39	$3^3_sP - 3^3_pP$	21.06	N IV	3484.90	$3^3S - 3^3P$	50.11
N II	4607.15	,, ,,	21.06	N IV	3482.98	,, ,,	50.11
				N IV	3478.69	,, ,,	50.11

*The excitation energy is computed from the ground state of the corresponding ion.

radiating volume was determined from streak photographs of a luminescent diameter of the discharge channel. Only a narrow spectral region was used for the pictures. These spectral streak photographs are made by combining a monochrometer with a photochronograph.

The ionic temperature was determined from the Doppler broadening of the N IV 3479 (3^3S-3^3P) line by introducing a small amount of nitrogen into the discharge. The observations were carried out along the discharge axis. The broadening of the N IV 3479 line due to the quadratic Stark effect was apparently small. Although the numerical values of the Stark constants for the case considered here are not known to the author the experiments carried out at different hydrogen densities indicate that the effect is small. To within 3% the experimental profile of the line coincides with a Gaussian curve. The Zeeman splitting is apparently less than 0.05 A, and this value lies within the limits of the experimental accuracy. The measurements were carried out by means of the so-called spectral sweep method[1] using an ISP-28 spectrograph with quartz objectives. We may note that the nitrogen "thermometer" on the N IV 3479 line was also used to measure the ionic temperature of a plasma in reference 5.

As has been noted earlier[1] in experiments carried out with a mixture of 95% H_2 + 5% N_2, at maximum compression one observes lines due to highly ionized nitrogen in addition to the continuum. The most intense observed nitrogen lines are listed in the table.

An estimate of the lower limit for T_e, made on the basis of an analysis of the energy distribution in the continuous spectrum, yields $T_e > 10$ ev.

The cross section of the pinch, determined from a photograph with sweep transverse to the discharge axis and from photoelectric observations along the discharge axis at the time of maximum compression, indicate values of 35 – 40 mm. As an illustration, Fig. 1 shows spectral sweep photographs of the discharge.

The density of charged particles for $p_0 = 0.05$ mm Hg reaches $n = 1.2 \times 10^{17}$ cm^{-3}; assuming 100% ionization this figure corresponds to a density along the chamber axis which is 35 times greater than the initial value (in the calculations the value $T_e = 100$ ev is taken). It is interesting to note that the experimental data are in good agreement with the theoretical estimates (cf. for example reference 6). In Fig. 2 is shown the density of charged particles ($n \approx \sqrt{I}$) as a function of pressure. It is apparent that up to a pressure of $p_0 \approx 0.2$ mm Hg the experimental points lie on a straight line. This result may be taken as direct proof that the parameters characterize a hydrogen

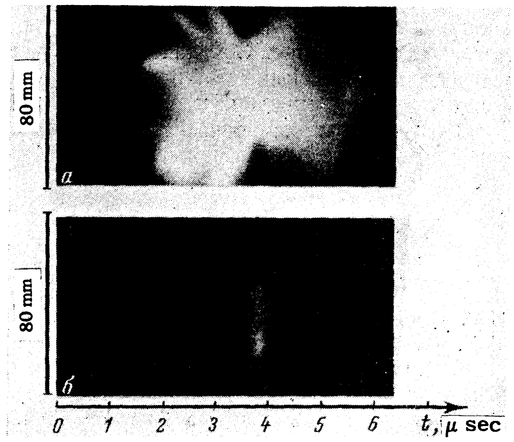

FIG. 1. Streak photograph of the discharge channel with spectrally resolved light at a pressure $p_0 = 0.1$ mm Hg: a) for the spectral region in the vicinity of H_α ($\Delta\lambda$ = 100 A); b) in the region λ = 6400 A ($\Delta\lambda$ = 100 A, continuum). The pictures were taken through a side window with which it was possible to view a portion of the discharge 8 cm in size.

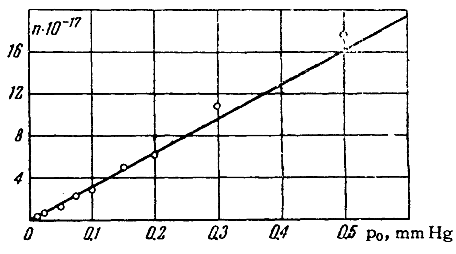

FIG. 2. The density of charged particles ($n \sim \sqrt{I}$) measured at the time of maximum compression as a function of initial pressure in the chamber.

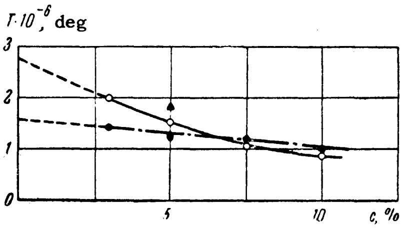

FIG. 3. Ionic temperature measured from the Doppler broadening of the N IV 3479 line at maximum compression of a discharge in deuterium as a function of the concentration of nitrogen impurity: o) $p_0 = 0.05$ mm Hg and the resolution time $\Delta\tau = 1.3$ microseconds; •) $p_0 = 0.1$ mm Hg, $\Delta\tau = 0.9$ microseconds; ▲) discharge in hydrogen (H_2) $p_0 = 0.05$ mm Hg, $\Delta\tau = 1.3$ microseconds. (In the reduction to the same $\Delta\tau$ the curves are displaced vertically).

discharge which is free from impurities. It is possible that at high initial pressures the role of free-bound transitions becomes more important.

The ionic temperature determined from the Doppler width of the N IV 3479 line is 1.2×10^6 °K (for $p_0 = 0.05$ mm Hg). It should be noted that the quantity T_i may be too high if at the first contraction of the pinch most of the particles participate in the directed motion along the axis. On the other hand, the value of T_i can be too low for two reasons: first, even a small admixture of nitrogen causes a large increase in the mass of the gas and this reduces the kinetic energy of the contracting plasma. The second effect is purely instrumental in nature. The resolution time of the spectral sweep is somewhat greater than the time during which the maximum temperature exists in the pinch. Hence the experimental curve is the result of the superposition of instantaneous contours (corresponding to somewhat lower temperatures) and its width is smaller. In Fig. 3, as an example, it is shown that by extrapolating the values of T_i obtained from experiments with impurities it is possible to determine the ionic temperature under "pure conditions". In principle such extrapolation methods allow us to circumvent the numerous difficulties involved in any exact determination of T_i.

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