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# *SPECTROSCOPIC INVESTIGATION OF TURBULENCE HEATING OF A PLASMA*

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Turbulence heating of a helium plasma was investigated by means of time-resolved spectra obtained with an image converter. The wave penetration into the plasma in turbulence heating was studied by observing the emission of individual spectral lines. The intensity of the spectral lines was used to estimate the electron temperature which was found to be $T_e \approx 100$ eV in a plasma with density $n_e = 2 \times 10^{13}$ cm$^{-3}$. It is shown that under typical experimental conditions the plasma impurities amount to less than 1% of the primary component.

## 1. INTRODUCTION

THE turbulence-heating method developed by Babykin, Zavoĭskiĭ et al[1-5] offers new and interesting possibilities for the production and investigation of high-temperature plasmas. As reported in[1,2], this method makes it possible, by very simple techniques, to heat electrons rapidly to very high temperatures. For example, a temperature of 1.5 keV has been obtained at an electron density of $2 \times 10^{11}$ cm$^{-3}$ and this value is still far from the limit possible with the method.[5] It has also been shown[2-5] that turbulence heating of the electrons produces favorable conditions for effective heating of the plasma ions.

In the present work we report on a spectroscopic investigation of turbulence-heating in a plasma with relatively high electron density. We have investigated the impurity content, a factor that plays an important role in the heat balance of a plasma with hot electrons. The electron temperature has been deduced from the intensity of the spectral lines of helium. From the point of view of understanding the turbulence-heating mechanism we are interested in the penetration of the wave into the plasma, the electron heating rate, and the radial distribution of the electron temperature in the discharge tube. Information on all these characteristics has been obtained from the radial distribution of the emission intensity of individual spectral lines.

In turbulence-heating the energy of the rf circuit is transferred to the plasma in a very short time interval. The time the plasma remains in the high temperature state depends on the density, degree of ionization, and the method of containment. At high densities ($N > 10^{13}$ cm$^{-3}$) and full ionization, conditions that characterize the present experiments, the plasma cools off and decays rapidly because of electron-ion recombination, regardless of the method of containment. It is evident that under these conditions the most valuable information can be obtained by time-resolved spectra, which allow us to trace the dynamic behavior of the spectral lines in each of these phases of a single discharge. For this reason, in the present work we have employed techniques appropriate to the photography of spectra of a weakly emitting short-lived plasma that exploit the image converter described in reference[6].

## 2. EXPERIMENTAL ARRANGEMENT, PREIONIZED PLASMA

The experimental arrangement (Fig. 1) is essentially that used by Babykin, Zavoĭskiĭ et al.[2] The plasma is produced in a glass tube 1 of 3.6 cm diameter, which is first pumped down to $10^{-6}$ mm by an oil diffusion pump. The working gas is helium and the helium pressure in the chamber is regulated by means of a controlled leak.

The rf circuit 2 has a characteristic frequency of 12.5 Mc. The length of the cylindrical turn which serves as the inductance in the circuit is 30 cm. The circuit capacitance, 0.0045 $\mu$F, is charged to 40 kV. With these values the amplitude of the ac magnetic field at the center of the discharge chamber is 560 Oe. The coils 3 (radius 30 cm) produce a fixed magnetic field of 800 Oe which is uniform

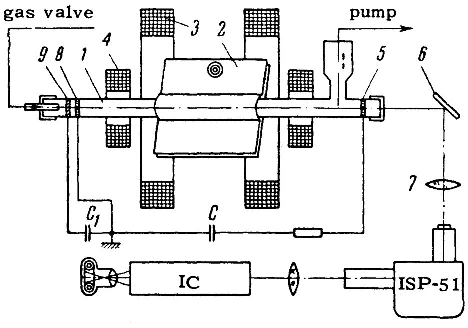

FIG. 1. Diagram of the experimental apparatus.

to approximately 2% in the region of the cylindrical turn of the rf circuit. The mirror ratio is approximately 3.

The light from the discharge chamber is transmitted through a semitransparent end electrode 5; the mirror 6 and the objective lens 7 (f = 30 cm) focus the light on the slit of an ISP-51 spectroscope with a chamber having a focal distance f = 27.0 cm. The time-resolved photographs are obtained by means of the image converter (IC). The pulsed supply for the image converter is obtained from a sweep generator.[7] The generator can be triggered simultaneously with the preionizing pulse or with the pulse to the rf circuit; there is a controlled delay ranging from 3 to 1500 μsec between these two settings.

The preionized plasma is obtained by a direct discharge of a capacitor C = 0.05 μF between electrodes 5 and 8. The discharge is fired between electrodes 5 and 8 by breaking down a small gap between electrodes 8 and 9 from which electrons move freely into the discharge volume in the chamber. Capacitors C and $C_1$, rated 0.012 μF, are charged to 25 kV.

The direct discharge current flows for several microseconds. The plasma becomes 50% ionized in this stage. The density of the freely decaying plasma then diminishes gradually. A curve showing the time variation of electron density $n_e$ is plotted by observing microwave transmission through the plasma at wavelengths of 0.4, 0.8, and 3 cm. The nature of the curve between the points $1.7 \times 10^{13}$ and $1.25 \times 10^{12}$ cm$^{-3}$, corresponding to cutoff of the microwaves at wavelengths of 0.8 and 3 cm, is established precisely by the damping of the spectral line of the plasma afterglow.

A photograph of one of the portions of the afterglow spectrum obtained with a time-resolved sweep is shown in Fig. 2a.[1] This picture exhibits all the characteristic phases of the freely decaying dense helium plasma. Following the initial spectral burst corresponding to current flow there is a dark region followed by the spectrum characteristic of three-body electron-ion recombination.[8] The intensity of the recombination lines reaches a maximum quickly; then, when the lines of singly charged ions appear the intensity is damped in several hundreds of microseconds.

Recombination of the doubly charged $He^{++}$ ions occurs four times more rapidly and the process is terminated before the electron density falls to a value of $1.7 \times 10^{13}$ cm$^{-3}$. Consequently, when $n_e < 1.7 \times 10^{13}$ cm$^{-3}$ the intensity of the lines of He I is proportional to the electron recombination rate; this feature makes it possible to interpolate the curve showing the decay of plasma density in the indicated region. A decay curve for $n_e$ obtained in this way at a pressure of $4 \times 10^{-3}$ mm in helium and the magnetic field of 800 Oe is shown in Fig. 2b.

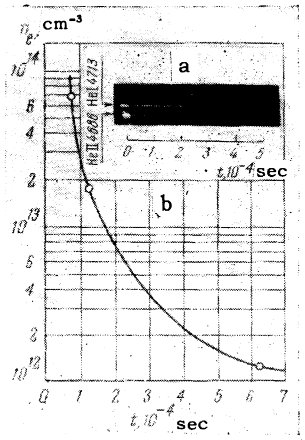

FIG. 2. Curve showing the time decay of the electron density of the preionized plasma. The upper portion of the figure shows a time-resolved spectrum.

It is evident from the above that by introducing a variable delay between the triggering of the preionizing pulse and the triggering of the rf discharge we can switch on the rf discharge at any predetermined degree of plasma ionization.

An investigation was also made of the impurity content of the preionized plasma. It is shown in Sec. 4 that impurities can be neglected under typical experimental conditions.

## 3. PROPAGATION OF INTENSE ELECTROMAGNETIC WAVE IN LOW DENSITY PLASMA. ELECTRON TEMPERATURE

Turbulence-heating is attributed to an anomalous collisionless absorption of an intense electromagnetic wave that propagates across the magnetic field in the plasma.[1,2,4,5] According to the theory this process leads to the development of a beam-type (two-stream) instability with subsequent absorption and thermalization of the plasma oscillations. The characteristic time of the process is appreciably smaller than the period of the rf circuit. Hence, at any given instant of time the electron temperature is determined by the current in the wave and heating can occur essentially only in the first quarter period of the oscillation circuit. In other words, it can be said that even on the wave front the electron temperature should read the maximum value attainable for the given experimental conditions.

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[1] The graininess of the pictures shown here as well as that in Figs. 3, 4, and 6 is due to the high amplification of the image brightness. The individual grains correspond to individual primary photoelectrons that are emitted from the input photocathode of the image converter (cf. [6]).

In connection with this interpretation of the turbulence heating mechanism (which holds for a fixed magnetic field $H_0 < 10^3$ Oe)[5] it is of interest to carry out an experimental investigation of the propagation of the intense electromagnetic wave in the plasma and to measure the electron temperature at the shock front. A series of photographs obtained in experiments with a helium pressure of $1.5 \times 10^{-3}$ mm, an electron density $n_e = 2 \times 10^{13}$ cm$^{-3}$, and with the mirrors switched off, is shown in Fig. 3.

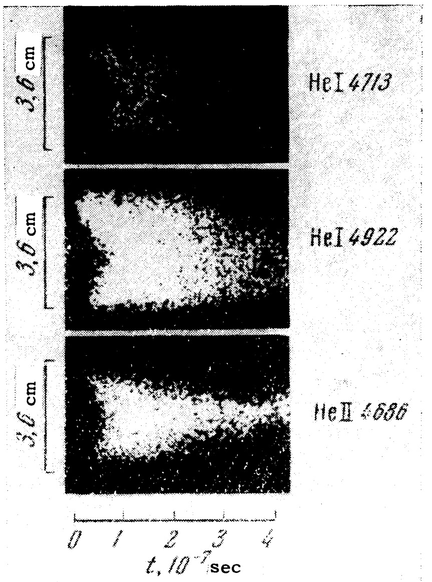

FIG. 3. Time-resolved photograph of the diameter of the plasma cylinder as observed in the light of individual spectral lines of helium showing the penetration of the wave into the plasma in the turbulence-heating process.

It is evident from these photographs that the wave propagates with the Alfvén velocity $v_A = 3.5 \times 10^7$ cm/sec from the periphery to the axis of the discharge tube; this wave is characterized by a clearly defined front at which there develops an intense dissipative process. The electrons are actually heated to the maximum temperature at the wave front. This result is obtained from the intensity ratio of the helium lines $J_{4713}/J_{4922}$ at wavelengths $\lambda = 4713$ Å and $\lambda = 4922$ Å.[9] Photographic analysis of the pictures in Fig. 3 shows that directly beyond the wave front the average value of the ratio $J_{4713}/J_{4922} \approx 0.4$ along the diameter of the plasma column; this corresponds to $T_e > 40$ eV.

The pictures in Fig. 3 have been obtained in three successive discharges rather than in a single discharge. Strictly speaking, the value of $J_{4713}/J_{4922}$ measured in a given discharge can differ from the intensity ratio for $J_{4713}$ and $J_{4922}$ measured in different discharges. However, in control experiments it was found that with uniform experimental conditions it was possible to obtain good reproducibility of the measured results.

In order to check further we took time-resolved photographs of the He 4713 Å and He 4922 Å lines in a single discharge. A picture of the corresponding portion of the spectrum obtained with mirror geometry with a helium pressure $1.5 \times 10^{-3}$ mm and a density $n_e = 2 \times 10^{13}$ cm$^{-3}$ is shown in Fig. 4.[2)] The density of the single electron grains in this picture is such that the photographic analysis can be carried out by counting grains.[6] Results of this photographic analysis are shown in Fig. 5a in the form of histograms. The large sta-

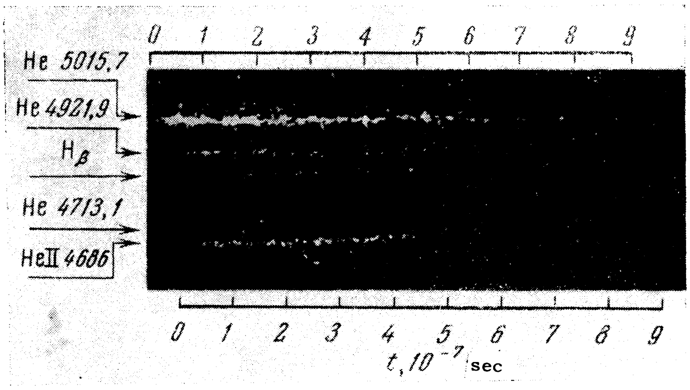

FIG. 4. Time-resolved photograph of a portion of the turbulence-heating spectrum of a plasma containing the lines HE I 4713 Å, He I 4922 Å, and He II 4686 Å.

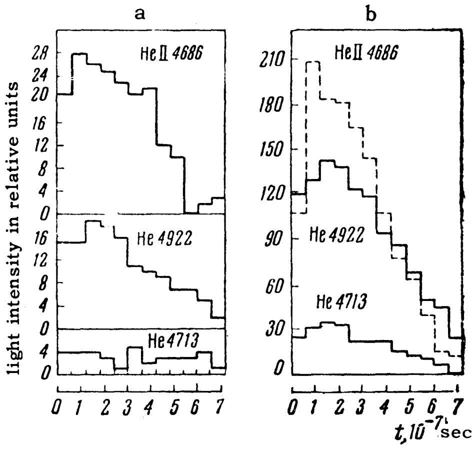

FIG. 5. Histogram of the time dependence of the intensity of the spectral lines He I 4713 A, He I 4922 A and He II 4686 A.

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[2)] In photographing the spectra with the image converter, the rectangular coordinate system of λ and t is distorted into a diagonal coordinate system, as is evident in Figs. 4 and 6. For convenience we have shown two time scales on these figures.

tistical errors characteristic of photographic analysis make it impossible to trace the time behavior of $J_{4713}/J_{4922}$ in a single photograph.

However, it is possible to use these data to compute the value of $J_{4713}/J_{4922}$ averaged over some sufficiently large time interval and to estimate the mean value of $T_e$. The value obtained in this way for $\langle J_{4713}/J_{4922}\rangle$ for the initial time segment $\Delta t = 3 \times 10^{-7}$ sec is 0.2. It is clear that with this value of $J_{4713}/J_{4922}$ we cannot make a very accurate measurement of $T_e$. Extrapolating the calculated curve for the value given by Thoneman[9] to the temperature region above 70 eV, we can state that $\langle T_e\rangle$ is of the order of or greater than 100 eV. The value of $T_e$ obtained from the data of Fig. 3 is lower than that for $\langle T_e\rangle$ because of the absence of magnetic mirrors in the first case.

In Fig. 5a we show the results of photographic analysis of the He II 4686 Å line, which has an excitation potential of 51 eV. The ratio of the intensity of this line to the intensity of the He I 4922 Å line can be used to estimate $T_e$, using the well-known excitation functions for these lines[10] and the densities of neutral and ionized particles in the plasma. In these experiments the rf circuit is switched on after the $He^{++}$ ions have completely recombined while the ionization time for the neutral and singly ionized helium are greater than 2 and 5 μsec respectively. Hence, the density of $He^+$ ions at the time the circuit is operated is equal to the electron density and the intensity of the He I 4922 Å and He II 4686 Å lines can not change because of ionization effects during the time of observation ($7 \times 10^{-7}$ sec). These estimates of plasma electron temperature also yield a value $\langle T_e\rangle \approx 100$ eV.

A more precise record of the intensity of the spectral lines as a function of time can be obtained by averaging the histograms for several discharges. Data of this kind obtained for seven discharges under the same conditions are shown in Fig. 5b. The intensity decay in these histograms yields an additional independent estimate of the maximum value of the electron temperature in the plasma. The emission of the spectral lines can be weakened only by cooling and the escape of plasma from the working volume (the observed damping times are small compared with the ionization time of the atom $\sim 2 \times 10^{-6}$ sec). We now consider these two mechanisms.

Under the present experimental conditions (mirror field, initial atomic density $5 \times 10^{13}$ cm$^{-3}$ and approximately 50% ionization) electron cooling is due primarily to radiation of line spectra in the plasma. This cooling rate (for an optically thin plasma) can be estimated from the Bethe formula:[11]

$$\frac{dT_e}{dt} = -\sum_j \frac{8\pi N_j Z_j e^4}{\sqrt{2\pi m T_e}}\left[\left(\ln\frac{T_e}{I_j}\right)e^{-I_j/T_e} - E_i\left(-\frac{I_j}{T_e}\right)\right],$$

where $Z_j$ is the number of electrons bound to particles of type j, $N_j$ is the density, $I_j$ is the mean excitation energy of these particles, and $E_i(x)$ is the integral exponential function. According to this relation, with an initial temperature $T_e = 100$ eV, the electron temperature falls to approximately 50 eV in a time $3 \times 10^{-7}$ sec while the intensities of the He II 4686 Å and He I 4922 Å lines are reduced by factors of 1.9 and 1.3 respectively (in accordance with their excitation functions). This result is in good agreement with the time behavior of the intensities shown in the histograms in Fig. 5b.

Evidently the damping rate can only increase as the initial value $T_e$ is reduced (because in this temperature region the excitation function falls off sharply as $T_e$ is reduced whereas $dT_e/dt$ is essentially unchanged) and this contradicts the experimental results. For this reason escape of plasma from the volume is compatible with the observed line damping only for initial values $T_e \gg 100$ eV and such values contradict the earlier estimate of $T_e$ obtained from line intensities.

Thus, it appears that the only mechanism for damping of the spectral lines is electron cooling; estimates of $T_e$ on the basis of cooling rates give a lower limit of 100 eV for the initial value of the electron temperature.

## 4. INVESTIGATION OF IMPURITIES

In the present work we have investigated what is essentially a nonequilibrium plasma with hot electrons and relatively cold ions. Radiation losses play a basic role in the heat balance of such a plasma contained in a magnetic field with mirror geometry; in the medium and low temperature region the primary radiation mechanism is the radiation of line spectra of incompletely ionized atoms. The intensity of the line radiation is a linear function of the atomic number Z so that the estimate of the plasma cooling rate due to radiation of atoms of the working gas we have given above may not be valid if the partial pressure of heavy gas impurities is large.

Under the present experimental conditions (as well as the conditions given by Babykin, Zavoĭskiĭ et al[1,2]) the presence of a large amount of impurities in the plasma cannot be discounted a priori. These impurities can be produced in the preionized plasma, which is obtained by a direct discharge between metal (copper, aluminum) electrodes. Impurities can also enter the discharge if the plasma comes in contact with the walls of the discharge chamber. A known impurity fraction (0.03% $N_2$, 0.01% $O_2$, and 0.01% $H_2$) was present in the technical grade helium used to fill the operating chamber.

The impurity content has been investigated by means of time-resolved spectra. The spectrum sweep is triggered by the preionization trigger and the sweep speed is relatively low. As a result, the spectrogram records the entire history of the spectrum including the preionizing pulse, the heating pulse, and the subsequent cooling. A typical spectrogram obtained under the experimental conditions described here (pressure $1.5 \times 10^{-3}$ mm, density $n_e \approx 2 \times 10^{13}$ cm$^{-3}$) is shown in Fig. 6, column I.

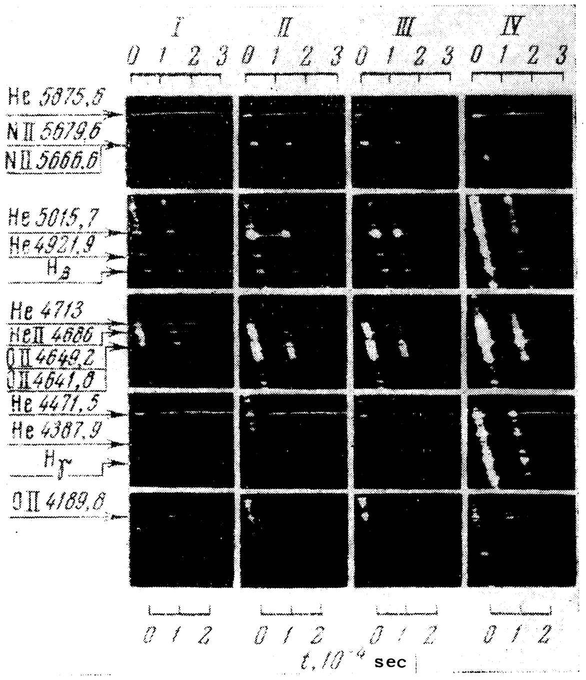

FIG. 6. Time-resolved spectra of the plasma obtained in an investigation of the impurities by the "small-sample" method: I) technical grade helium without additive; II) with 3.5% $N_2$; III) with 6.5% $N_2$; IV) with 5.5% $O_2$.

The complete spectrogram consists of photographs of five individual almost overlapping segments taken under identical conditions. In this spectrogram one can see the peaks corresponding to the helium spectrum in the preionizing discharge and the discharge of the rf circuit in an interval of $10^{-4}$ sec (the recombination emission phase following the rf discharge is cut short).

The strongest impurity lines are the $H_\beta$ lines and the group of lines below He II 4686 Å. There are also weak indications of other impurity lines (near He 5016 Å and in the region below He 4471 Å). Most of these lines are associated with nitrogen and oxygen. A quantitative estimate of the content of these elements was made by the "small-sample" technique. The spectra obtained in this case with samples of 3.5% $N_2$, 6.5% $N_2$ and 5.5% $O_2$ are shown in the same figure in columns II, III, and IV respectively.

It is evident that the addition of small amounts of $O_2$ and $N_2$ results in a sharp increase in the intensity of the corresponding impurity lines. Analysis of the spectrograms in Fig. 6 indicates that the nitrogen and oxygen impurities comprise less than 1% of the primary plasma component. A careful analysis has also shown that the spectrum does not contain lines corresponding to atoms or ions of materials used in the electrodes or chamber walls.

It is important to note that the addition of small amounts of $N_2$ and $O_2$ results in an appreciable reduction of the electron temperature, as evidenced by the sharp reduction in the intensities of the spectral lines of helium both in the radiative and recombination spectra. On this basis we may say that in general the total impurity content in the turbulence-heating plasma experiment is less than 1% of the primary component.

It is also interesting to point out the promising possibility of a quantitative analysis of a high-temperature plasma that is offered by the observation of the time-resolved recombination spectrum. In principle, analysis of the recombination spectrum allows us to estimate the degree of ionization, to determine the partial pressure of the impurities, and to identify the radiative spectrum by virtue of the fact that the recombination rates are different for atoms with different ionization multiplicities.

In conclusion we wish to thank E. K. Zavoĭskiĭ for initiating this work and for his constant support. We also wish to thank L. I. Rudakov for his continued interest and for valuable comments, M. V. Babykin for help in building the experimental apparatus, and P. I. Blinov for help in the microwave measurements.

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[1] Babykin, Zavoĭskiĭ, Rudakov and Skoryupin, Paper No. 209, International Conference on Plasma Physics and Controlled Fusion, Salzburg, 1961.

[2] Babykin, Gavrin, Zavoĭskiĭ, Rudakov and Skoryupin, JETP **43**, 411 (1962), Soviet Phys. JETP **16**, 295 (1963).

[3] Babykin, Gavrin, Zavoĭskiĭ, Rudakov and Skoryupin, JETP **43**, 1547 (1962), Soviet Phys. JETP **16**, 1092 (1963). ibid. **43**, 1976 (1962), Soviet Phys. JETP **16**, 1391 (1963).

[4] E. K. Zavoĭskiĭ, Atomn. énerg. **14**, 57, 1963.

[5] Babykin, Gavrin, Zavoĭskiĭ, Rudakov and Skoryupin, JETP **46**, No. 2 (1964), Soviet Phys. JETP in press.

[6] Bolotin, Zavoĭskiĭ, Oranov, Smolkin, and Striganov, Izv. AN SSSR, seriya fiz. **27**, 872 (1963), Columbia Tech. Transl. p.

[7] Levin, Markov, Plakhov, Smolkin, Sofiev, Stepanov and Shapkin, PTÉ No. **6**, 100 (1962).

[8] E. Hinnov and J. G. Hirschberg, Phys. Rev. **125**, 795 (1962).

[9] P. C. Thoneman, Symposium on Optical Spectrometric Measurements of High Temperatures, Ed. P. J. Dickerman, University of Chicago Press, 1961.

[10] Massey and Burhop, Electronic and Ionic Impact Phenomena, Oxford Press, 1952, (Russian Translation) IIL, 1958.

[11] Mott and Massey, Theory of Atomic Collisions, Oxford Press, 1949, (Russian Translation), IIL, 1957.

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