Mechanism of excitation of helium spectral lines at λ = 706.5 and 587.6 nm in the *e*-beam plasma

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The conditions for formation of the population inversion of the energy levels yielding the helium atomic transitions $3^3 S$–$2^3 P$ (λ = 706.5 nm) and $3^3 D$–$2^3 P$ (λ = 587.6 nm) are determined for the He–H_2 plasma excited by a beam of low-energy (2–10 keV) electrons.

Earlier the lasing at excitation of the He–H_2 mixture by a beam of low-energy (2 – 6 keV) electrons was obtained at two new helium atomic lines λ = 728.1 ($3^1 S$–$2^1 P$) and 667.8 nm ($3^1 D$–$2^1 P$) in the visible region,[1] as well as at λ = 706.5 nm ($3^3 S$–$2^3 P$), at which lasing was observed with the use of different pumping methods.[3,4] Under conditions of *e*-beam plasma, amplification and lasing can be obtained at some other transitions in atomic helium, in particular, at λ = 492.2, 447.1, and 587.6 nm. The line λ = 587.6 nm is the most intense in the visible spectral range, and so it is of special interest.

The conditions for formation of the population inversion of the levels of the transition $3^3 D$–$2^3 P$ (λ = 587.6 nm) in the He–H_2 mixture are similar to those for the transition $3^3 S$–$2^3 P$ (λ = 706.5 nm) and can be created by beam pumping. Detailed analysis of the role of kinetic processes in creating population of the working levels $3^3 S$ and $2^3 P$ in the He–H_2 mixture taking into account the rate constants of plasmochemical reactions[2] shows that the decisive factors in de-excitation of the lower $2^3 P$ level are the spontaneous emission and the Penning reaction with the hydrogen molecule. The role of the direct excitation by electrons is also significant. The character of population of the upper level $3^3 S$ determines the set of levels with $n = 3$, which is effectively populated due to processes of recombination at beam excitation, and then it undergoes de-excitation to the lowest level $3^3 S$ due to collisions with the electrons in plasma.

The major part of the electron beam energy in a gas comes to ionization of the medium. Thus, after the current pulse the helium atomic levels are populated due to the triple

$$He^+ + e + e \rightarrow He^* + e$$

and dissociation recombination

$$He_2^+ + e \rightarrow He^* + He.$$

The lower level of the transition depopulates in the Penning reaction with the hydrogen molecule:

$$He^*(2^3 P) + H_2 \rightarrow He + H_2^+ + e.$$

A similar mechanism of level population takes place for the transition $3^3 D$–$2^3 P$. However, formation of population inversion in this transition is hampered by multiplet splitting of the upper level, as well as by its collisional de-excitation at high gas pressure. Our purpose was to find the conditions optimal for formation of population inversion to yield the helium lasing transition at λ = 587.6 nm.

The plasma was excited by a beam of low-energy electrons formed in the discharge with a grid anode.[1] The pressure of the active mixture varied in the range P = 5–20 Torr, the current pulse of the duration at half maximum $\tau_{0.5}$ = 0.5 – 1 μs was formed in the discharge gap at the voltage U = 2 – 6 kV and the beam current density $j \sim 5$ A/cm^2.

The radiation from the He–H_2 plasma was focused with a lens at the slit of an MDR-3 grating monochromator, which allowed the plasma spectrum to be studied in a wide range. Particular spectral lines were selected by turning the diffraction grating. The time behavior of spectral lines was recorded with a FEU-100 photomultiplier tube and an S-74 dual-beam oscilloscope. Thus we could simultaneously observe the radiation at a spectral line and the current pulse.

The amplitude and temporal characteristics of the radiation at the helium lines of λ = 706.5 and 587.6 nm were studied in a wide range of excitation conditions at different helium pressure and composition of the He–H_2 mixture. The level $2^3 P$ is the common lower level for both of these lines. The efficiency of its de-excitation by hydrogen can be judged from the readily achievable mode of amplification and lasing at the transition λ = 706.5 nm. For line at λ = 587.6 nm the conditions of more intense pumping of the upper working level $3^3 D$ or de-excitation of the lower level $2^3 P$ should be provided by selecting proper gas mixtures based on H_2.

Figure 1 shows the time dependence of the intensity of the helium atomic (λ = 587.6 and 706.5 nm) and ion (λ = 468.1) lines. The current pulse (Fig. 1*c*) has a peaked shape. The ion line (Fig. 1*b*) follows its behavior but with the prevailing recombination processes at the intensity decay. Long afterglow of the lines is indicative of this. The maxima of the atomic lines (Fig. 1*a*) are observed after the pump pulse and

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are characterized by longer recombination emission. Consequently, regarding the time behavior of the line intensities, we can speak about the effective recombination population of the levels of the helium atomic transitions λ = 706.5 and λ = 587.6 nm.

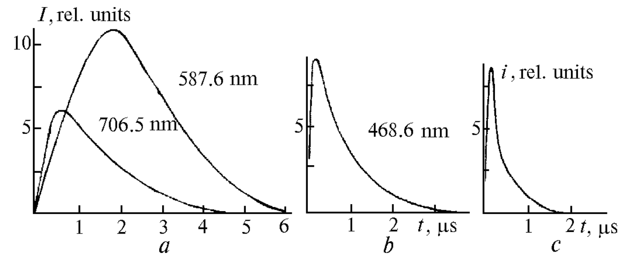

Fig. 1. Time dependence of helium atomic (*a*) and ion (*b*) lines and current pulse (*c*).

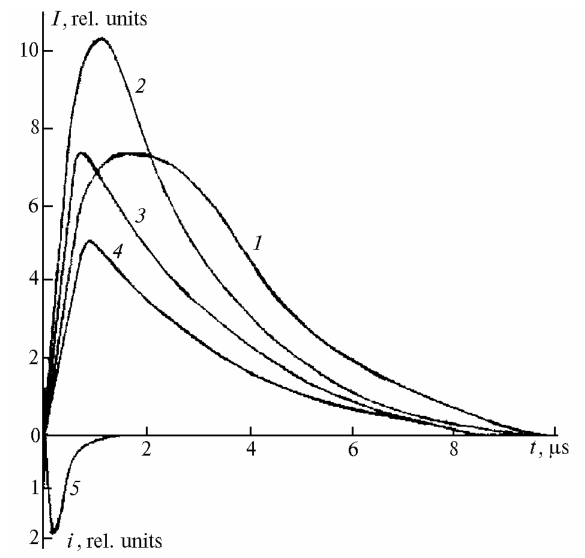

Fig. 2. Dependence of helium atomic line intensity at λ = 587.6 nm on hydrogen pressure in $He-H_2$ mixture at P_{He} = 11.5 Torr: P_{H2} = 0 (*1*), 1 (*2*), 6 (*3*), and 10 Torr (*4*); current pulse (*5*).

The conditions for formation of the population inversion of the levels in the helium atomic transition at λ = 587.6 nm were sought by the time dependence of spontaneous radiation on the concentration of the Penning admixture (Fig. 2). The conditions optimal for the inversion are achieved by the beginning of the sharp decay of the line intensity, what qualitatively characterizes the admixture de-excitation of not only the lower, but also of the upper level of the transition. As this takes place, the conditions of inversion are conserved, when the line intensity is almost halved.

Under conditions of pumping by *e*-beam, the He levels $3^3\,S$ and $3^3\,D$ are populated due to the processes of triple and dissociation recombination. Their efficiency is determined by the most important characteristics of plasma, as the electron concentration and temperature. These parameters can vary in a wide range ($N_e = 10^{13} - 10^{14}$ cm^{-3}, T_e = 0.2 − 0.5 eV) in changing the composition of $He-H_2$ mixture and the pump current. The dynamics of population of the 3^3D level was experimentally studied as a function of the hydrogen concentration (Fig. 3). It was found that the maximum population inversion of the energy levels in the helium atomic transition (λ = 587.6 nm) is achieved with the use of the Penning admixture in the range P_{H2} = 6 − 10 Torr and the helium pressure of 10 − 20 Torr. These values differ significantly from the optimal parameters found in Ref. 1 for the helium atomic transition at λ = 706.5 nm.

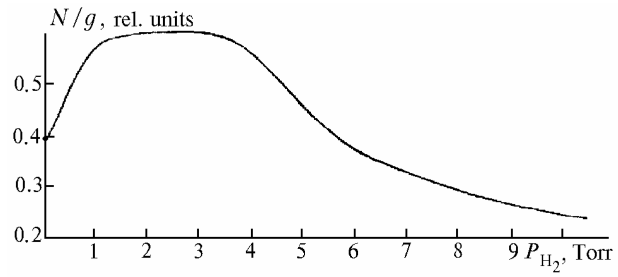

Fig. 3. Dependence of population of the 3^3D level at λ = 587.6 nm on hydrogen concentration at P_{He} = 11.5 Torr.

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