Powerful, self-stabilized, longitudinal, multiatmospheric-pressure discharge

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A powerful periodic-pulse longitudinal discharge at multiatmospheric pressure in mixtures of helium with metal vapors was produced and investigated. It was shown that as an impurity-controlling ionization, the metal vapor ensures that a uniform discharge will function in large-diameter tubes (~3 cm) at least up to mixture pressures of 5 atm and per-unit-length excitation power ~25 kW/m. The discharge obtained is used to pump powerful metal-vapor ion lasers. © *1995 American Institute of Physics.*

1. In the wake of the discovery of lasers, the physics of gas discharges has developed rapidly in many directions in the last 25–30 years. We have in mind, on the one hand, the development of the physics of powerful (tens and hundreds of kilowatts) continuous discharges, which are used to pump ion lasers and occur at low gas pressures (less than 100 Pa),[1,2] and, on the other, the investigation of the physics of high-pressure (greater than 1 atm) discharges with large energy input in a single pulse ($E \geqslant 1$ J/cm^2).[3-6] It is believed that the problem of developing powerful high-pressure lasers is more a problem of organizing the discharges than of searching for the working medium.[7]

In the present paper we report the results of the observation and study of one other type of discharge suitable for excitation of lasers — a powerful longitudinal periodic-pulse discharge at multiatmospheric pressure. The most interesting and promising property of such a discharge is its internal capability of preserving the volume (noncontracted) character of the discharge in large-diameter tubes at high pressures and high per-unit-length pump powers. Such a discharge combines, to some extent, the advantages of discharges produced under very different conditions.[1-6]

2. A periodic-pulse discharge with high average power is mainly used to pump lasers on self-limited transitions in metal vapors. The average lasing power reaches hundreds of watts with an efficiency[8-10] of 1–3%. The conditions for excitation of lasing with an increase of the average pump power per unit length are maintained in such lasers by acceleration of recombination processes in the interpulse interval by introducing molecular impurities (for example, hydrogen),[11] extending the inner surface of the tube,[9] or using compounds of metals with electronegative gases.[8,10]

Both continuous and periodic-pulse longitudinal discharges are subject to contraction as a result of increase of any characteristic parameter, for example, the tube diameter d, the gas pressure p_{He}, the pump power P per unit length, the current amplitude I in the pulsed or the average current in the continuous regime, etc. Figure 1 shows the results

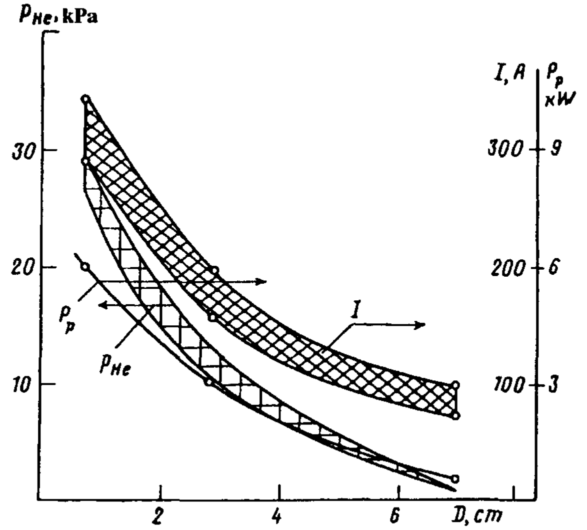

FIG. 1. Maximum values of the parameters for a volume discharge in helium — gas pressure p_{He}, power per unit length P_p, and current amplitude I — versus the tube diameter D.

obtained in the present work which give an idea of the sharp narrowing of the region of existence of a noncontracted volume discharge in helium with increasing tube diameter. The contraction of a longitudinal discharge is due mainly to the ionization-overheating instability.[11]

3. The introduction of an easily ionizing impurity should radically change the properties of a periodic-pulse discharge. As a refinement of the standard definition,[13-15] we mean by this term an impurity whose ionization potential is much lower than that of the main gas. For example, in a mixture of helium with strontium (the working medium of a He–Sr$^+$ recombination laser) or europium (the working medium of a He–Eu$^+$ collisional laser), the ionization potentials of the mixture components differ by more than a factor of 4. The optimal working pressure of the metal vapor in these lasers is ~ 10 Pa with a helium pressure of ~ 1 atm. Under these conditions, the ionization-overheating instability can be completely neutralized.

The suppression mechanism works as follows. Any local change of the electron concentration N_e is produced by ionization of the metal atoms. The character of the radial distribution of the electron density is thereby determined by the distribution of the metal-vapor atoms. When $N_e \sim N_a$ (N_a is the initial concentration of metal atoms) is reached, the current flowing through the gas-discharge tube can increase further only by propagation of the discharge along the total transverse cross section or multiple ionization of the metal atoms. The double ionization potential is much higher than the single ionization potential (for strontium, correspondingly, 11 eV and 5.7 eV), and the electron energy distribution function at high pressures is strongly depleted of fast electrons.[16] It can be assumed, therefore, that the current flowing through the tube will increase not as a result of a nonlinear increase of the electron concentration in a narrow conducting channel (contraction of the discharge), but by expansion of the discharge into the regions where N_e is low. Therefore the discharge self-stabilizes, counteracting the development of the ionization-overheating instability. It is clear *a priori* that the action of this mechanism of decontraction should operate for any reasonable values of the tube diameter, main-gas pressure, and discharge current.

4. The experiments were performed with the mixture He–Eu in a 2.7-cm-diameter beryllium oxide tube with cylindrical tantalum foil electrodes, adjoining the inner wall of the tube. The interelectrode distance was 15 cm. The tube was placed in a metal jacket, filled with nitrogen up to a slightly higher pressure than the working pressure. This precaution made it possible to perform the experiments with mixture pressures of up to ~ 10 atm and temperatures ~ 1000 °C. The discharge was excited by discharging a capacitor with the capacitance $C = 16.3$ nF through the tube and a thyratron with pump pulse repetition frequencies of 1–10 kHz.

The uniformity of the discharge along the cross section of the tube was checked 1) visually, 2) by measuring the distribution of the spontaneous emission intensity along the section of the tube (integrated and separate lines), and 3) by measuring the transverse distribution of the lasing power in the $\lambda = 1.0019$-μm line of the europium ion. The experiments were performed mainly under conditions where the lasing power was maximum. The experimental helium pressures ranged from the lasing threshold $p_{\rm He} \approx 0.3$ atm up to $p_{\rm He} \approx 5$ atm. Under these conditions, a noncontracted discharge occurs only when metal vapor is introduced into the tube. The character of the discharge is appreciably different for pressures up to 1.2–1.3 atm and above. For $p_{\rm He} \leqslant 1.3$ atm a volume discharge exists both at low europium-vapor pressures (up to the lasing threshold, $p_{\rm Eu} \sim 1$ Pa) and at high europium-vapor pressures (up to vanishing of lasing and at higher pressures). At $p_{\rm He} > 1.3$ atm the threshold concentration of europium atoms required to maintain a volume discharge starts to increase rapidly. The optimal Eu-vapor pressure for lasing and the voltage required for maintaining the discharge also increase (Fig. 2).

It was found that in contrast to discharges below atmospheric pressure,[17] not only the metal-vapor pressure but also the pump pulse repetition frequency F must exceed threshold values in order for the discharge to remain a volume discharge. Specifically, for $p_{\rm He} \approx 3.5$ atm the discharge becomes unstable and indications of contraction appear at $F \leqslant 1$ kHz. As $p_{\rm He}$ increases, a simultaneous increase of the frequency, voltage, and current (Fig. 2) leads to an unavoidable increase of the power input per unit length (up to ~ 25 kW/m) and to an overheating of the tube. In the construction employed, overheating causes the europium vapor pressure to increase above the optimal value and lasing stops at $p_{\rm He} > 5$ atm. However, the volume nature of the discharge remains.

5. Our experiments have shown that the assumption, made in Sec. 3, of the possibility of self-stabilization of a multiatmospheric-pressure discharge is correct. We can therefore actually regard such a discharge as occurring in a low-pressure metal vapor, and in this sense such a discharge is similar to powerful discharges of the type used in Refs. 1 and 2 in one-component gases.

High-pressure discharges of the type presented in Refs. 4–6 , including a discharge with a so-called easily ionizable impurity,[13–15] are very sensitive to the shape of the electrodes, the average and pulsed pump power, and so on. In contrast, the fact that a

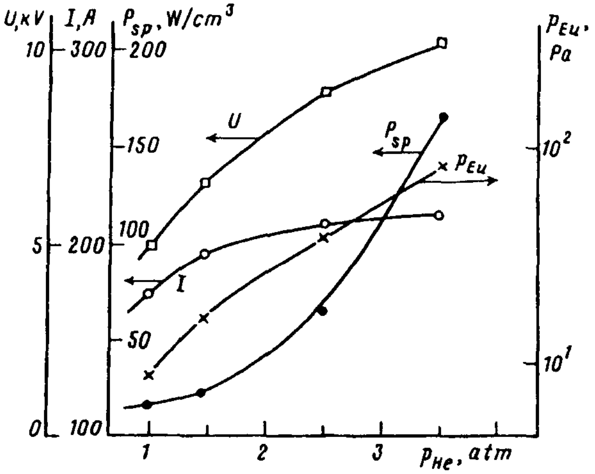

FIG. 2. Specific quasicontinuous lasing power P_{sp}, optimal europium-vapor pressure P_{Eu}, pulsed voltages U, and current I versus the helium pressure p_{He}.

discharge with an easily ionizable impurity is in principle powerful, i.e., it self-stabilizes only with a high average and pulsed excitation power, was somewhat unexpected. We believe that under conditions where no measures are taken to set up a uniform electric field at the electrodes, the necessity for using a high pump power (in other words, high pulse repetition frequency) is dictated by the fact that in order for a discharge to remain a volume discharge, substantially incomplete recombination of the plasma in the interval between pulses is also necessary. In this respect, such a discharge is the opposite of the

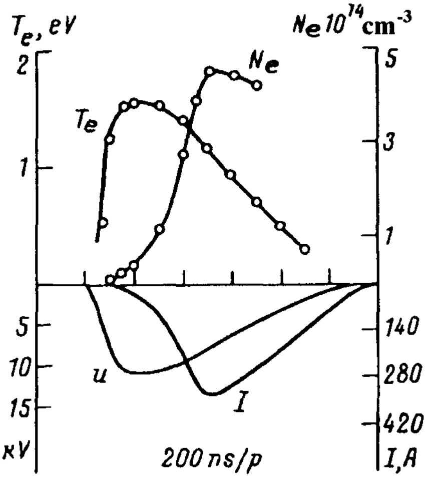

FIG. 3. Typical oscillograms of the voltage and current pulses and the time dependences of the electron density N_e and temperature T_e at $p_{He} \approx 3.5$ atm.

periodic-pulse discharge studied in Sec. 2. We attribute this circumstance to the fact that the residual N_e (actually, this is the pre-ionization electron density in the terminology of Refs. 3–6) must exceed the level required for fast overlapping of electron avalanches at the discharge development stage.[18]

6. While maintaining its volume nature at pressures far above atmospheric pressure and at high pump powers, the discharge investigated is also "good" (well-behaved[3]) with respect to a more stringent criterion, specifically, with respect to the suitability for excitation of lasing on ionic transitions of the metal atoms. Figure 2 demonstrates the rapid growth of the residual quasicontinuous lasing power of a He–Eu$^+$ laser as a function of the helium pressure. Figure 3 shows the time dependences of the main parameters of the excitation and lasing pulses at $p_{\mathrm{He}}=3.5$ atm. It is evident from the figures that the conditions for excitation of quasicontinuous lasing are maintained over a wide range of helium pressures.

The collection of discharge characteristics, which differ markedly from those of other discharges, suggests a separate name for such a discharge. With respect to its physical essence, this is a discharge with an ionization-controlling impurity or, briefly, an ICI discharge. In the English variant the terms KEEP-discharge and KEEP-admixture also correctly express the essence of the discharge self-stabilization process.

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