course of their self-resonance acceleration within the volume of a cylindrical anode (oscillating electron region) [6].

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SUPERHEATING INSTABILITY IN A PULSED XENON DISCHARGE

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It is shown that previously obtained conditions for superheating instability substantially vary if we take into account secondary xenon ionization. Instability completely vanishes if the density of heavy particles in the discharge is kept constant and whenever a discontinuous time variation of temperature T in a restricted region between $15 \cdot 10^{3}$°K and $20 \cdot 10^{3}$°K is possible for a constant effective pressure. The development of instability is studied numerically by a ranging method. Stationary temperature distributions possessing a high contrast as a local temperature passes through a given range of instability with constant pressure are presented.

The possibility of discontinuously varying the temperature in a strongly radiating pulsed discharge under the effect of superheating instability has recently been widely discussed [1-4], such instability arising when the relative increment of plasma emissivity φ (T) becomes less than the relative increment in electric conductivity σ(T). The reliability of the theoretical prediction of this difference effect substantially depends on correctly taking into account details in calculating σ and φ and thus requires experimental verification. For example, such instability has been detected experimentally [5] for a discharge in a vapor plasma in the range of temperatures T between $16 \cdot 10^{3}$°K and $24 \cdot 10^{3}$°K and also in [6] for a discharge occurring in erosion products from quartz glass.

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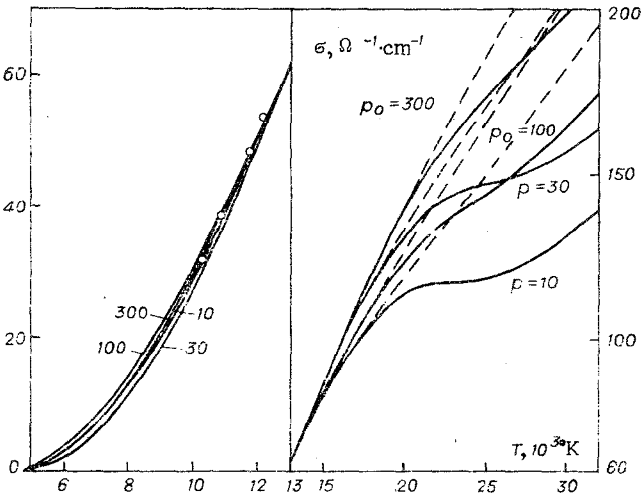

Fig. 1

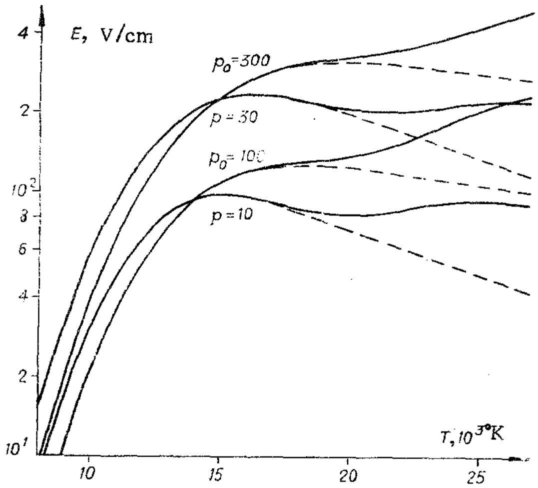

Fig. 2

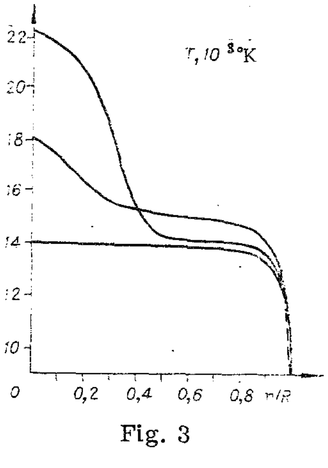

Fig. 3

The lower boundary of stability in the region $T \geqslant 16 \cdot 10^{3}$°K for $p = 10-30$ atm has been indicated in one work [7] that dealt with the calculation of the characteristics of an electric discharge in xenon, taking into account only primary ionization. However, such instability in xenon flash lamps, including under high-power conditions [8, 9], have not been experimentally noted. The purpose of this work is to analyze in more detail conditions under which instability arises and to investigate its development within the context of a nonstationary and nonequilibrium discharge model, taking into account secondary ionization; the model is convenient for calculations beyond the stability boundary.

The system of equations includes separate equations for the electron T_e and heavy particle T temperatures, radiation transport equations to take into account the nonequilibrium population of the atomic levels (approximation of a block of excited states), and an equation for the density of singly charged ions, taking into account collision ionization and recombination, photoelectric processes, and particle diffusion on the wall. Secondary ionization that occurs in the central zone of the discharge, in which all gradients are low, is assumed to be balanced. The density of neutral atoms is determined from the condition that pressure is constant along the radius. This system of equations has been solved on a computer by the range method [10].

The numerical solution demonstrated that nonequilibrium effects are substantial only in plasma layers near the wall when T is between $10 \cdot 10^{3}$°K and $30 \cdot 10^{3}$°K and $p \geqslant 10$ atm. The plasma is nearly in equilibrium in the central zone of the discharge, in which instability may manifest itself. Let us therefore discuss only the equation for T_e which has the form

$$c_e \frac{\partial T_e}{\partial t} = \sigma(T_e) E^2 - \varphi(r, T_e) - \operatorname{div}(\mathbf{q}_e - \mathbf{q}_I) - Q_\Delta, \tag{1}$$

where c_e is volume specific heat, $\mathbf{q}_e = -\varkappa_e \nabla T_e$ is electron heat flow ($\varkappa_e$ is electron thermal conductivity), $\mathbf{q}_I = (5/_2 k T_e + I_1)\mathbf{j}_I$ is convective heat flow, $\mathbf{j}_I$ is ambipolar diffusion flow, I_1 is the effective ionization potential and $Q_\Delta \sim (T_e - T)$ is the rate of heat exchange with heavy particles.

The first two terms are the chief terms in the right side of Eq. (1) in the central zone of the discharge. We therefore obtain the equation

$$c_e \frac{\partial \Delta T_e}{\partial t} - (\sigma' E^2 - \varphi')\Delta T_e = -\sigma E^2 \left(\ln \frac{\varphi}{\sigma}\right)' \Delta T_e, \tag{2}$$

in which the "prime" denotes the derivative with respect to T_e for small deviations of temperature ΔT_e from the stationary solution under constant field (E) conditions.

The solution of Eq. (2) has the form

$$\Delta T_e = \Delta T_e^0 \exp(-t/\tau_e^0); \; \tau_e^0 = \frac{c_e}{\sigma E^2 (\ln \varphi/\sigma)'}$$

and will be stable if the ratio φ/σ or stationary field $E \simeq \sqrt{\varphi/\sigma}$ is an increasing function of temperature (at comparatively low $T \sim 10 \cdot 10^{3}$°K, when, for example, $\sigma \sim n_e$, while $\varphi \sim n_e^2$). Here

$$\left(\ln \frac{\varphi}{\sigma}\right)' \approx \frac{1}{T_e} \frac{I_1}{2kT_e}; \; \tau_e^0 \approx \frac{c_e}{\sigma E^2 (I_1/2kT_e)}.$$

The ratio σ'/σ decreases with increasing temperature, but φ'/φ decreases still more rapidly due to a retardation of the growth, and then the coefficients of continuous absorption also fall for a singly ionized gas, which leads to instability of the initial deviation ΔT_e^0. Temperature increases when $\Delta T_e^0 > 0$ up to the start of secondary ionization, which leads to a new increase in φ/σ. Figures 1 and 2 depict the dependence of $\sigma(T)$ and of the stationary field $(E = \sqrt{\varphi/\sigma})$ with and without taking into account secondary xenon ionization (the unbroken and broken curves, correspondingly, p in atm, p_0 in mm Hg). (The experimental points in Fig. 1 are taken from [11] and the scale is doubled after T = 13.) Bremsstrahlung and recombination radiation on two types of atoms and ions (radiation is assumed to be volumetric) are taken into account in calculating φ (T).

It was assumed $\xi_\nu(T_e) \equiv 1$ [12] for the secondary ion due to the absence of exact data. According to a remark from [7], the nature of the curves substantially depends on which parameter is maintained constant over time – the effective pressure p or the density of heavy particles (initial pressure p_0). When p_0=const (discharge bounded by walls), instability is completely eliminated by taking into account secondary ionization, while when p=const (unbounded discharge) instability for E=const occurs in a finite range of temperatures T approximately between $15 \cdot 10^{3}$°K and $20 \cdot 10^{3}$°K.

Numerical simulation of the development of instability demonstrates that the solution for T_e (r) is established as a function of the sign of ΔT_e^0 at opposite (stable) segments of the curve when T_e^0 is approximately $14 \cdot 10^{3}$°K and $22 \cdot 10^{3}$°K for p=10 atm, selecting E=const in the middle of the decreasing segment of E(T). The solution when p_0=const, giving a monotonically increasing curve E(T) that intersects the curve at p=10 atm at the same point ($p_0 \approx 62$ mm Hg), is stable for E=const at any temperature. The solution is stable also when p=const if the axial temperature is constant.

It is necessary to take into account the dependence of E not merely on axial temperature and radius, but also on the temperature profile in the discharge when absorption is present; the range of instability for p=const may substantially contract when strongly reabsorbed line emission is taken into account. This question requires additional study.

The curves depicted in Fig. 3 (taking into account absorption) demonstrate that a segment with anomalously high gradients T (R=0.25Ω, p=10 atm) manifests itself in the central zone of the discharge with increasing T_e^0 as specified by the axial temperature. This temperature discontinuity approximately corresponds [7] to the region of superheating instability on the curves E(T) and occurs when p_0=const, since radial energy balance holds whenever p(r)=const. Unbalance of σE^2 and φ is compensated by negative divergence of the heat flows. The intermediate region shifts towards the discharge periphery with increasing axial temperature.

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