AN EXPERIMENTAL CHECK ON THE THERMALIZATION CONDITIONS FOR AN ELECTRON FLUX AFTER EXPOSURE TO A UHF FIELD

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Temperature measurements are reported for an electron flux exposed to a UHF field and passing through a dense space-charge region. It is shown that certain combinations of UHF frequency and current density cause the perturbation to be transformed into electron heating. The experimental results confirm previous theoretical estimates for the flux thermalization conditions.

In some types of UHF vacuum devices, the electron flux after interacting with the alternating electric field enters a region with a high space-charge density, which occurs in particular in reflected-beam devices, which include the reflection klystron, reflection generators of diffraction radiation, and also electronic detectors and mixers working under conditions of potential space-charge barriers. Estimates [1,2] show that in such cases conditions may occur where perturbations introduced into the electron flux by the UHF field are damped out (they may be considered as the excitation of space-charge waves or simply as electron-velocity modulation). The energy exchange, on the other hand, on interaction with the field makes itself felt as a change in the temperature characterizing the recovered equilibrium electron velocity distribution. This means that the electron flux is thermalized. Indirect experiments such as [3] confirm these concepts, but it is desirable to have a direct experimental check on the thermalization conditions [1], since these conditions have been derived from various assumptions.

The experiment scheme was as follows. The electron beam passed in sequence through a UHF interaction system and an electrode gap, in which there was a space-charge potential barrier, and then passed to an electron-velocity analyzer. The spectra obtained in the presence and absence of the UHF signal show whether the spectrum of the perturbed beam corresponds to a temperature different from the initial value. If this is so, thermalization occurs under these conditions. Since sufficient information is contained in the temperatures with this formulation, it is desirable to use a very simple method of analyzing the spectra: the retarding-potential method.

In that method, one examines not the direct electron velocity (energy) distribution but the integral representation (retardation curves). In the case of a thermalized beam, the current at the collector with retarding potential U_r is $I_{col} = I_0 e^{U_r e_0/(kT)}$ (I_0 is the current entering the analyzer) and the bias curve, i.e., $I_{col} = f(U_r)$, enables one to determine the electron temperature T directly. If on the other hand the beam is exposed to the UHF field but there is no thermalization,

*Deceased.

the reflection of this in the bias curves requires additional discussion.

The following is [4] the maxwellian spectrum for the initial velocities in the unperturbed beam written in kinetic-energy units:

$$dn(\varepsilon_x) = \frac{1}{kT} e^{-\varepsilon_x/kT} d\varepsilon_x, \tag{1}$$

where dn is the number of electrons whose energy lies in the range from ε_x to $\varepsilon_x + d\varepsilon_x$ in accordance with their velocities along the x axis, and k is Boltzmann's constant. The UHF signal produces sinusoidal velocity modulation, which is superimposed on the spectrum of (1). The resulting energy distribution in that case (on averaging over time) is related to (1) as follows [5]:

$$\frac{dn'(\varepsilon_x)}{d\varepsilon_x} = \frac{1}{\pi kT} \int\limits_{\varepsilon_x - E}^{\varepsilon_x + E} e^{-\varepsilon_x'/(kT)} / \sqrt{E^2 - (\varepsilon_x - \varepsilon_x')^2}\, d\varepsilon_x'. \tag{2}$$

Here E is the kinetic energy corresponding to the velocity-modulation amplitude.

The form of the distribution obtained by numerical integration of (2) is shown in Fig. 1a for several modulation amplitudes (curve 1 is the unperturbed distribution of (1)). There are two characteristic features. The first is that modulation substantially transforms the initial region ($\varepsilon_x \leq E$), which in principle differs from the initial stationary distribution and extends up to values $\varepsilon_x < \varepsilon_0$, where ε_0 is the minimal electron energy in the unperturbed beam. The second feature occurs in the region $\varepsilon_x > E$. Here the $dn'(\varepsilon_x)/d\varepsilon_x$ dependence is purely exponential, and the exponent is determined by the same temperature as for the initial unperturbed distribution. Correspondingly, the bias curves for the unthermalized beam should take the form shown in Fig. 1b. We see that the UHF signal shifts the curves on the potential scale by an amount corresponding to the modulation amplitude, and that there is a deviation from a linear relationship near zero retarding potential. However, it is difficult to use these features to determine the beam state, since the same deformation in the bias curves can be observed in the case of an unperturbed beam, although it is true for quite different reasons (the contact potential difference, inhomogeneity in the real electron beam, etc. [6]). It is therefore desirable to utilize the exponential parts of the bias curves (the linear ones in a semilog scale): then a perturbed but unthermalized beam should have a slope in these parts, which is determined by the electron temperature, that should be exactly the same as for the unperturbed beam. Thermalization will alter the slope, i.e., will alter the temperature by a certain amount ΔT from the initial value.

The experiments were based on a special device whose design is shown schematically in Fig. 2a. This consisted of an electron gun (cathode 1 and accelerating grid 2), a two-electrode gap (grids 3 and 4), to which the UHF signal was applied via the coaxial input 5, a gap formed by grid 4 and electrode 6, in which there was a space-charge potential barrier (Fig. 2b shows the distribution of the potential U(x) and space-charge density $\rho(x)$ in this gap), and finally the gap between the electrode 6 and the collector 7, which is a velocity analyzer employing the retarding-potential method. The experiments were performed in the signal-frequency range 0.5-1.0 GHz, where the flight angles are of the order of π in the high-frequency gap (between electrodes 3 and 4 in Fig. 2a). The signal amplitude in the gap was determined from the shift in the bias curves and was a fraction of a volt, i.e., it was of the order of or less than kT/e_0. The cur-

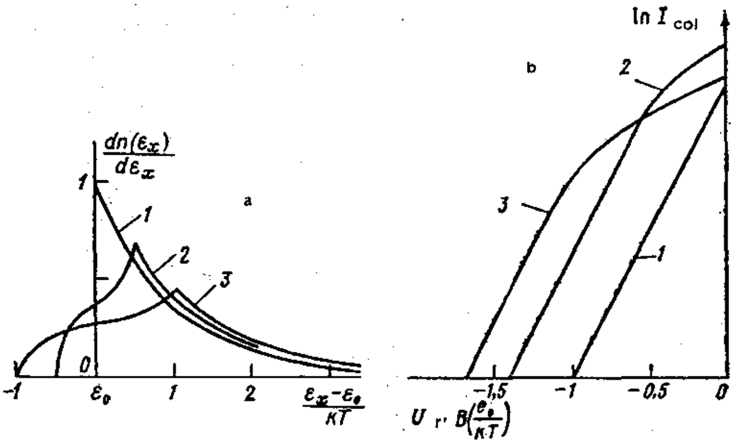

Fig. 1. a) Electron energy distributions: 1) unperturbed beam; 2) modulation with amplitude E = 0.5 kT; 3) with amplitude E = kT; b) bias curves corresponding to the spectra of 1-3 in part *a*.

rent density passing through the high-frequency gap and entering the gap between electrodes 4 and 6 may vary over the range 10-10^3 A/m^2. A check was made on the occurrence of a potential barrier in this gap from the form of the voltage-current characteristics: the dependence of the current to electrode 6 on its potential relative to the cathode.

We found that UHF signals in the above frequency range at current of 10^3 A/m^2 did not alter the electron temperature, i.e., there was no thermalization. As the current density decreased, a point occurred where we could record a certain temperature increase ΔT, and this itself increased as the current decreased further. Figure 3a shows the relationships of the temperature change to the current density. It is clear that the currents at which thermalization begins at each frequency can be determined quite clearly, i.e., the temperature change exceeds the error of measurement. At 1 GHz, there is saturation in the relationship at small currents, which indicates that the conditions for complete thermalization have been attained. To compare the observations on the conditions for the start of complete thermalization with the theoretical forecasts, Fig. 3b shows the calculated diagram derived from [1], which indicates the following ranges in frequency and current density. Region I corresponds to the case where the waves excited in the beam are reflected from the part with the maximal space-charge density without attaining the minimum potential (Fig. 1b). In region II, the potential barrier becomes transparent to the waves, but they propagate with attenuation, which gradually increases as one approaches the boundary between regions II and III. Region III corresponds to complete wave absorption (in a distance of the order of the electron wavelength) in the region of the minimum-potential plane. Therefore, in region II near the boundary with I, partial thermalization should set in, while at the boundary with region III there should be complete thermalization, which corresponds to all the energy from the interaction of the beam with the UHF field being converted to electron heating. We note that these conditions apply only for small perturbations, when the electron-energy change is of the order of or less than the mean thermal energy. Our experiments corresponded to this constraint.

Figure 3b shows points reflecting the experimental conditions for onset of thermalization at 0.6 GHz (A_2) and 1 GHz (A_1) (Fig. 3a) and also the conditions

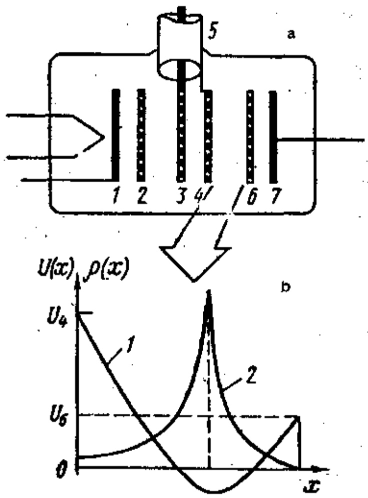

Fig. 2

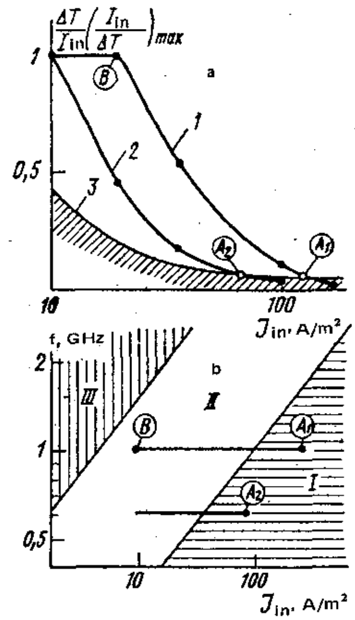

Fig. 3

Fig. 2. a) Schematic device design; b) distribution of the potential U(x) (1) and of the space charge density ρ(x) (2) in the gap between electrodes 4 and 6.

Fig. 3. a) Relative temperature changes caused by UHF fields with frequencies of 1 GHz (1) and 0.6 GHz (2); curve 3 is the error level in the measurements. Points A_1 and A_2 are the onset of thermalization while B represents complete thermalization; b) diagram for the conditions for reflection of beam perturbations from the potential barrier (region I), for barrier transparency (II), and complete absorption (III). A_1, A_2, and B are experimental points.

for complete thermalization found at 1 GHz (point B). There is some deviation of the experimental data from the theoretical estimates because the calculations employed the plasma frequency for an unbounded medium, whereas that frequency is reduced under real conditions. On the whole, through, experiment demonstrates correspondence with the conditions defined theoretically, and the data given here may be considered as the first direct experimental confirmation of concepts on the transformation of UHF perturbations in an electron beam into heating.

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