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"STRATIFICATION" EFFECT AND MAXIMUM EFFICIENCY OF A MULTICAVITY POWER KLYSTRON

V.I. KANAVETS, O.I. PAVLOV, A.N. SANDALOV

ABSTRACT

The bunchers of multicavity power klystrons with drift tubes of various lengths are considered. The stratification approximation is used for finite-perveance inhomogeneous beams. Results are reported on the optimization of the parameters of klystrons with solid and annular streams and with one or several supplementary cavities tuned to the second harmonic of the primary signal.

1. *INTRODUCTION*

The efficiency of multicavity power klystrons usually is at the level of 40-50%. When the klystron parameters are optimized by means of a conventional one-dimensional model, the efficiency does not exceed 65% [1]. The present work develops the position that methods of controlling stratification must be worked out to increase the efficiency of klystrons.

The stratification effect is basically caused by the field inhomogeneity of gridless gaps, by the transverse depression of potential, and by the variation of Coulomb forces over the beam cross section. Radial stratification occurs in most modern instruments using axisymmetric beams and quite hard focusing. By changing to annular beams and using extra cavities tuned to the second harmonic of the input signal, stratification can be reduced.

When the changeover is made to annular beams, the radial variation of the rf fields and the transverse depression of potential are reduced. All this contributes to a reduction of stratification. For an output signal of specified power, however, annular beams must not be too fine, otherwise the phase separation of the bunch will increase because of the increase in the unreduced plasma frequency, and the bunching will deteriorate [2]. Klystrons with a high-perveance narrow hollow beam have low efficiency [3].

The use of cavities at the second harmonic in bunchers makes it possible to control the effect on the layers and to improve the cross-sectional homogeneity of bunching [4-6]. The important role of supplementary modulation at the second harmonic was commented on in Ref. [7], where the creation of a power klystron with an efficiency reaching 70% was reported. However, in the theoretical part of the work the authors confined themselves to presenting the results of the investigation only in the one-dimensional approximation. Stratification was not considered.

It follows from Refs. [4-6] that supplementary modulation at the second harmonic in two-cavity and three-cavity klystrons reduces stratification. However, a slight gain in efficiency was obtained in these works. This is a peculiarity of the designs considered. In a buncher with a large number of cavities the influence of stratification is increased and the use of additional cavities provides a significant advantage.

Among various modifications of the bunching systems of multicavity klystrons, we may single out bunchers with shortened and lengthened drift tubes. The lengths of the first drift regions are selected equal to approximately 1/8 the reduce plasma wavelength. However, the optimization of klystron parameters in the one-dimensional approximation has made it possible to find optimal conditions for the bunching of electrons into nearly ideal bunches that can be achieved when the lengths of the first drift regions are increased, becoming close to or even exceeding the plasma quarter wavelength [8,9].

The enhancement of bunching at long lengths is related to the excitation of space charge waves at the first and higher harmonics. Stratification effects may disrupt these processes. The use of long lengths in real systems therefore requires additional substantiation.

When allowance is made for stratification, the optimal conditions found in the one-dimensional approximation may not be optimal. The feasibility of optimal conditions in the stratification approximation requires special consideration.

Compensation for stratification in bunchers of various lengths should have distinctive features. Use of an annular beam can produce a major effect at increased lengths, since the bunching conditions in annular-beam systems approach the one-dimensional conditions. In systems with shortened drift tubes it is desirable to use modulation at the second harmonic. In this case enhanced bunching and reduced stratification will be observed, even when one supplementary cavity is used. In bunchers of extended length the use of one cavity does not produce the desired effect and more complicated systems must be employed [4-6]. To determine the selection of buncher lengths, the degree of compensation for separation, and the efficiencies obtained, calculations should be made using the methods of analysis of stratification in finite-perveance homogeneous beams with layers of different area [10]. In connection with the large volume of computations, the concept of the Q-factor, which makes it possible to assess not only the amplitude of the first harmonic of the current, but also the electron velocity spread, should be used. When a klystron operates with microperveance of order unity near the optimum, the Q-factor usually is close to the electronic efficiency [11].

2. BUNCHERS WITH SHORTENED DRIFT TUBES

Analysis of the bunching process in the one-dimensional approximation for systems with one supplementary cavity at the second harmonic has showed that enhancement of bunching and compensation for stratification occur in systems with shortened drift sections [5]. The length of the section where the 2ω cavity is placed should be approximately half the optimal length obtained by considering bunchers not containing cavities at frequency 2ω. This length is somewhat greater than $1/8\ \lambda_q$, where λ_q is the reduced plasma wavelength. On this basis let us consider the buncher of a five-cavity klystron with one supplementary cavity at the second harmonic, placed in the center of the second drift region $0.138\ \lambda_q$ long (Fig. 1a). Allowing for the gradual shortening of the drift sections with increasing number, we obtain the following sequences of lengths (in terms of λ_q): 0.186, 0.069, 0.069, 0.096, 0.1.

Let us consider a beam with near-zero microperveance. The beam is characterized by the ratio of the unreduced plasma frequency to signal

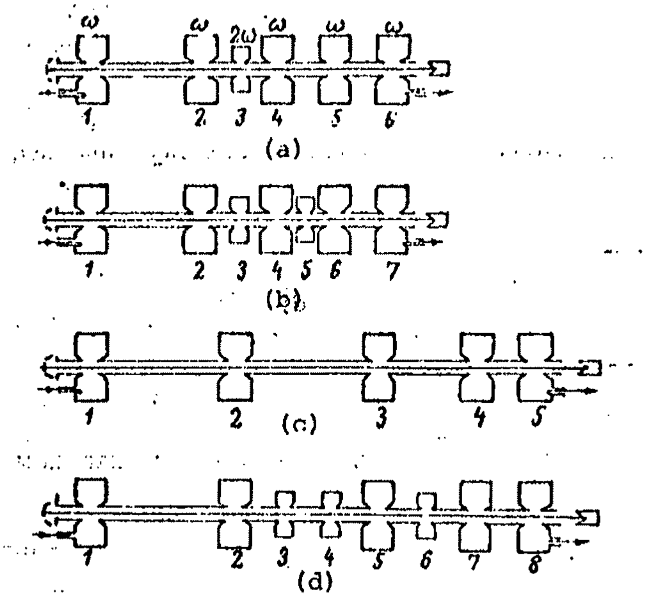

Fig. 1. Schematic diagrams of klystrons with shortened (a,b) and lengthened (c,d) drift tubes.

frequency $\omega_p/\omega = 0.22$ and by the reduced radius $\gamma_e r_r = 0.67$ (the parameter of the decrease in Coulomb forces is $k = 2/\gamma_e r_r \approx 3$). Cavities at the fundamental frequency are characterized by the reduced gap width $\gamma_e^{(\omega)} d = 2.4$ and cavities at frequency 2ω by the reduced width $\gamma_e^{(2\omega)} d = 3.4$. In calculations allowance is made for the variation of the modulation factor across the layers on the assumption that the gaps are formed by thin tubes. To reduce machine time, an approximation of the amplitude and phase of the gap fields was used. The phases were assumed near-optimal. The amplitudes were varied until the maximum Q-factor was obtained at the location of the output gap. The relative values of the amplitude of the first harmonic of the current were computed in the calculations for each of the layers I_{1i}/I_0, where i is the number of the layer, I_0 is the constant component of the current, and the average value of the amplitude is

$$\left(\frac{\bar{I}_{1l}}{I_0}\right)=\frac{1}{N_0}\left|\sum_{l=1}^{N_0}\frac{\hat{I}_{1l}}{I_0}\right|, \tag{1}$$

where N_0 is the number of layers.

The Q-factors of layer bunching also were determined:

$$\eta_{\text{rp}\,l}=\frac{1}{2}\frac{I_{1l}}{I_0}\frac{v_{\text{min}\,l}}{v_{0l}}, \qquad (2)^*$$

where $\frac{v_{\min i}}{v_{0i}}$ is the ratio of the minimum electron velocity in a layer to the constant component of velocity, and the averaged Q-factors of the layers $\bar{\eta}_{bu\ i}$ and of the beam $\bar{\eta}_{bu}$ are:

$$\bar{\eta}_{\text{rp}\,l}=\frac{1}{2}\left(\frac{\bar{I}_1}{I_0}\right)\frac{v_{\text{min}\,l}}{v_{0l}},$$

$$\bar{\eta}_{\text{rp}}=\frac{1}{N_0}\sum_{l=1}^{N_0}\eta_{\text{rp}\,l}. \tag{3}$$

The Q-factors characterize the bunch at the inlet to the output cavity and, as a first approximation, may be assumed proportional to the klystron's efficiency.

Voltage optimization in the one-dimensional approximation made it possible to find the maximum Q-factor in the system without supplementary modulation and with the effect at frequency 2ω (Fig. 2). In the absence of supplementary modulation, the Q-factor does not exceed 0.67. It is significantly less than the factor for a klystron with the same number of cavities and with optimized lengths ($\eta_{bu} \approx 0.8$ [9]). Introducing a voltage at the second harmonic in antiphase to the voltage of the fundamental

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* [translator's note: in this and subsequent equations and figures, read η_{rp} as η_{bu}]

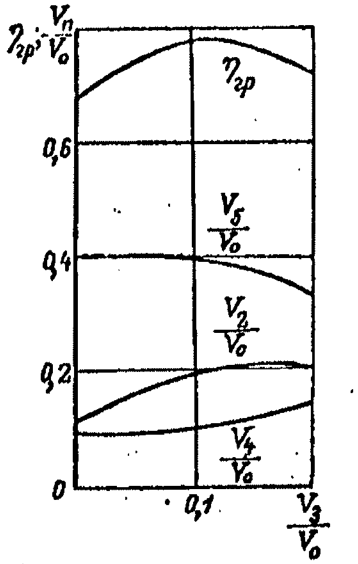
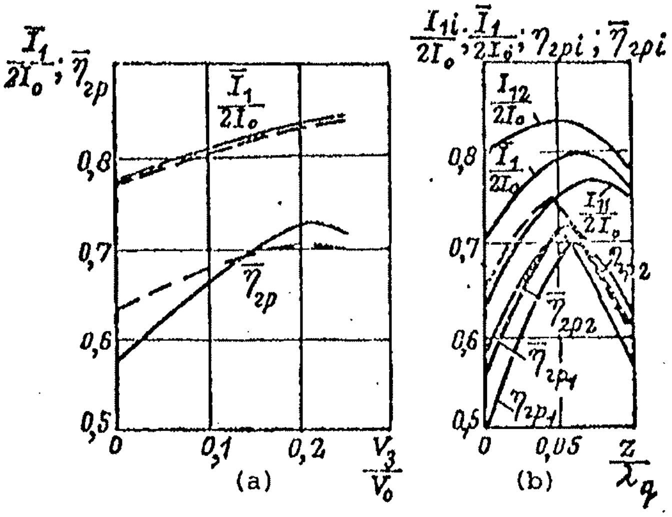


Fig. 2. Maximum values of Q-factor η_{bu} and of corresponding gap voltages V_n/V_0 versus voltage at second harmonic V_3/V_0 for the one-dimensional model of the beam.

frequency in the region of the center of the bunch increases the Q-factor. For a specific selection of voltages, the increase may be significant, and the Q-factor rises to a value of 0.78, which is close to the Q-factor of a klystron with optimized lengths. The Q-maximum occurs at the relative value of the voltage amplitude at the second harmonic $V_3/V_0 \approx 0.1$, where V_0 is the accelerating voltage. The dependences of the optimized voltages on V_3/V_0 are given in Fig. 2 for all buncher gaps except the input gap. In the first drift region the alternating components of current and electron velocity are small and the voltage variation in the input gap, in the approximation of specified gap field amplitudes and phases for the remaining cavities, has practically no effect on the efficiency of the device.

Stratification worsens the characteristics of the bunchers. The current amplitude of the first harmonic and the Q-factor are reduced. Let us consider the results of a calculation in the two-layer approximation (Fig. 3).



(a) (b)

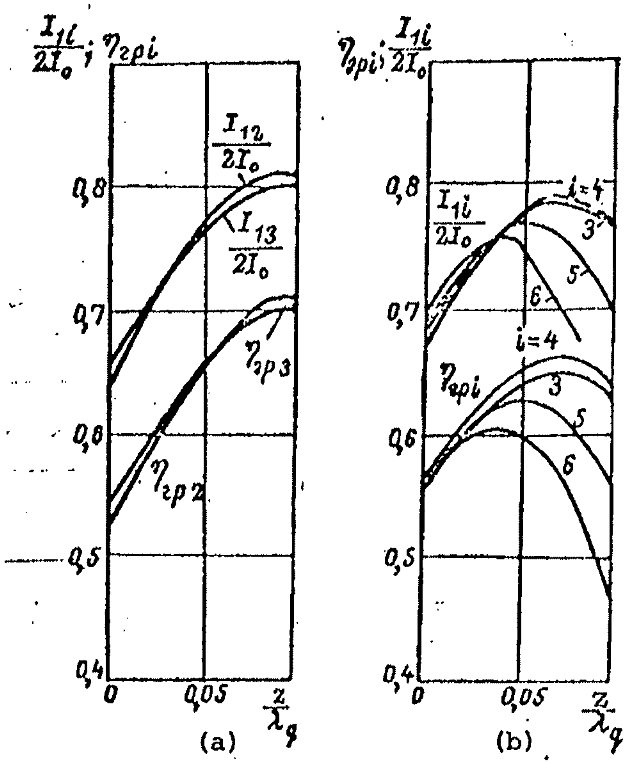
Fig. 3. Dependences of average values of current amplitude of the first harmonic $\bar{I}_1/2I_0$ and of average Q-factor $\bar{\eta}_{bu}$ at maximum on voltage at second harmonic V_3/V_0 for the four-layer model of an annular beam (- - -) and the two-layer model of a solid beam (———) (a); dependences of amplitudes $\bar{I}_{1i}/2I_0$ and $I_1/2I_0$ and of factors $\eta_{bu\ i}$ and $\bar{\eta}_{bu\ i}$ on the coordinate z/λ_q for the two-layer model at the optimal value of V_3/V_0 (b).

If $V_3/V_0 = 0$, then the average values of the Q-factors of the layers $\bar{\eta}_{bu\ 1}$ and $\bar{\eta}_{bu\ 2}$, at optimum are close to 0.57 and are much lower than the Q-factors given by one-dimensional theory. Including supplementary modulation enhances bunching, and the average value of the current amplitude of the first harmonic is increased and the velocity spread is reduced. The maximum average value of these factors is close to 0.72 and is reached at an alternating voltage $V_3/V_0 = 0.2$ exceeding the voltage calculated from one-dimensional theory. The Q-factors are somewhat lower than the values obtained from one-dimensional theory, which indicates compensation for stratification. Analysis of the dependences of the first harmonic of current and of the Q-factors of different layers on the coordinate in calculations using the multilayer model ($N_0 > 2$) shows that electrons in the inner layers drop out of the bunch somewhat. When a changeover is made to an annular beam, further enhancement of bunching may be anticipated.

To ascertain the peculiarities of the use of an annular beam in the klystron under consideration, electron bunching in a beam with an inner aperture having an area 1/3 the area of the solid beam was investigated. Voltage optimization in the absence of modulation at the second harmonic in the two-layer approximation showed that there exist regimes of almost complete compensation for stratification with a maximum value of 0.7 for the Q-factor, which is approximately equal to the Q-factor obtained in the one-dimensional treatment, and with an average current $\overline{I}_1/I_0 = 1.61$ (Fig. 4a).

The two-layer treatment gives exaggerated values for the currents and Q-factors. To obtain refined data a four-layer model of an annular beam or a six-layer model of a solid beam with zero current in the first two inner layers was used. Voltage optimization was carried out. Fig. 4b shows the dependence of the quantities $I_{1i}/2I_0$ and $\eta_{\text{bu}\,i}$ on the coordinate z/λ_q. This dependence characterizes the bunching of layers in the optimal regime. As can be seen from the figure, stratification is practically absent up to the point where maximum compaction of the bunch is achieved. Stratification due to the action of Coulomb forces is manifested thereafter. The average value of the Q-factors at maximum is close to 0.63.

Including supplementary modulation at the second harmonic contributes to the enhancement of bunching. However, stratification in the region of a bunch



(a)

(b)

Fig. 4. Dependences of current amplitudes of first harmonic $I_{1i}/2I_0$ and of Q-factors $\eta_{bu\,i}$ on the coordinate z/λ_q for the two-layer (a) and four-layer (b) models of an annular beam.

is not fully compensated. Fig. 5 shows the dependences of the amplitudes of current $I_{1i}/2I_0$ and factors $\bar{\eta}_{bu\,i}$ on z/λ_q in the final drift region; the Q-factors at maximum are close to 0.7. The average value of the current $\bar{I}_1/I_0$ reaches 1.63. The dependences of $\bar{I}_1/2I_0$ and $\bar{\eta}_{bu}$ on the voltage of the supplementary cavity are shown in Fig. 3a by the dashed line. The voltage in the input cavity was assumed equal to 0.006 which provides a gain of more than 40 db. The best bunching is achieved at $V_3/V_0 = 0.2$, as before. The unbroken

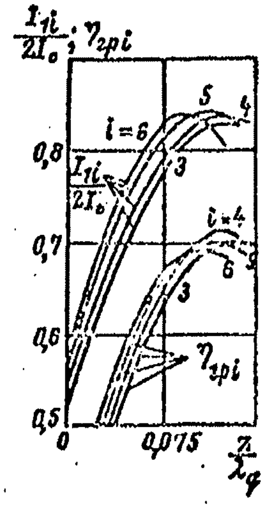


Fig. 5. Dependence of current amplitudes of first harmonic $I_{1i}/2I_0$ and of Q-factors $\eta_{bu\,i}$ on the coordinate z/λ_q in the final drift region for a four-layer annular beam with additional action at the second harmonic.

line of the dependence $\overline{\eta}_{bu}(V_3/V_0)$ initially runs below the dashed line, then rises above it. Consequently at low values of modulation at frequency 2ω, the use of an annular beam provides a substantial advantage. At optimal voltage $V_3/V_0 = 0.2$, if it is taken into account that the two-layer model gives an overstatement of approximately 10%, changing to the annular model also produces a gain, which however is smaller since the effect of modulation at frequency 2ω itself compensates quite well for stratification.

A calculation of a buncher with a four-layer annular beam having specified voltages and a broad variation of phases has established that the Q-factor remains in the range 0.6-0.7. Since for small stratification at optimum the Q-factor is close to the efficiency, conclusions may be drawn as to the anticipated values of the klystron's efficiency. The efficiency of a klystron with shortened tubes, a solid beam, and no cavity at frequency 2ω should reach 50%, while that of a klystron with an annular beam should reach 63%. At optimal voltage at frequency 2ω in the gap of the supplementary cavity, the efficiency of a solid-beam klystron should reach 63% and that of an annular klystron should reach 70%.

The investigation of a klystron with an annular beam and two cavities at frequency 2ω (Fig. 1b) (the second supplementary cavity is placed in the penultimate drift region) has showed that the effect of the second cavity changes the distribution of the quantities I_{1i}/I_0 and $\eta_{bu\,i}$ over the layers in the region of the bunch. However, no significant increase in Q-factors could be obtained. The use of the scheme shown in Fig. 1b apparently does not have advantages over the scheme shown in Fig. 1a if the required alternating voltage amplitudes and phases at frequency 2ω can be obtained by using one cavity.

It should be noted that if after the transition to a real klystron and to the self-consistent problem in any of the cavities at frequency 2ω considered above the required voltages cannot be obtained, a supplementary cavity also tuned to frequency 2ω that does not alter the nonlinear picture of bunching but that does make it possible to drive oscillations with the required amplitude and the necessary phase in the next cavity should be placed in front of the cavity referred to above.

3. BUNCHER WITH LENGTHENED DRIFT TUBES

The optimization of the parameters of a multicavity klystron in the one-dimensional approximation has made it possible to recommend increased lengths for the first drift regions. There may arise objections that at large lengths the influence of stratification is increased. However, the opposite mechanism of reducing stratification is known that is exhibited at increased lengths. In traveling-wave tubes at elevated perveances, for signals not too strong and lengths comparable to the plasma wavelength, self-fields of electron waves are established with maximum of the alternating components

components on the beam axis. This compensates for stratification due to the action of the rf field of retarding structure [12]. The same effect may be exhibited, albeit partially, in the first drift regions of klystrons. In this case using large lengths will not reduce efficiency. These results apply to the case of a strong longitudinal magnetic field greatly exceeding the Brillouin field.

Let us consider a five-cavity klystron with beam parameters $\omega_p/\omega = 0.4$ and $k = 4$ (microperveance close to 1). Let us take the following reduced cavity gap widths at the fundamental frequency $\gamma_e^{(\omega)}d = 1.45$ and at the second harmonic $\gamma_e^{(2\omega)}d = 1.6$. First we will analyze the processes in a klystron constructed after the scheme shown in Fig. 1c. Let us assign the lengths and voltages that are optimal according to the one-dimensional theory [9]. The first voltage is set at $V_1/V_0 = 0.006$, which ensures a gain of over 40 db. The results of a calculation in the approximation of the three-layer and six-layer models for a solid beam have demonstrated the necessity of lowering the voltage somewhat in the penultimate cavity. If the optimal value according to the one-dimensional theory, $V_4/V_0 = 0.55$, is adopted, then the electron velocity spread, which is not compensated by the action of space charge fields as a result of the stratification effect. turns out to increased in the bunch. Reducing the voltage V_4/V_0 has scant effect on the current amplitude of the first harmonic, but does increase the Q-factors.

Fig. 6a shows the dependences of $I_{1i}/2I_0$ and $\eta_{bu\,i}$ on z/λ_q in the final drift region for the three-layer model ($V_4/V_0 = 0.45$). They are extremely specific. The lines in the graph for the middle and outer layers runs almost side-by-side, whereas the lines for the inner layer are much

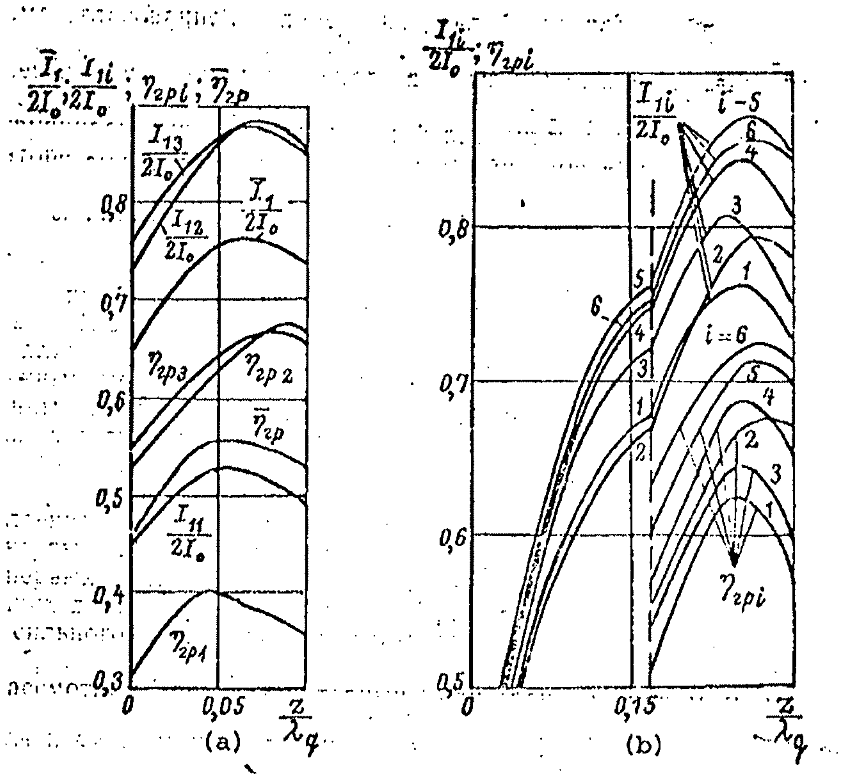


Fig. 6. Dependences of current amplitude of the first harmonic $I_{1i}/2I_0$ and of Q-factors $\eta_{bu\,i}$ on the coordinate z/λ_q in a klystron with lengthened drift tubes for the three-layer (a) and six-layer (b) model of a solid beam (the last two drift regions).

lower. The average values of the amplitude of the first harmonic of current and of the Q-factor at maximum are 1.5 and 0.58 respectively. The difference in the bunching of layers indicates that in the three-layer approximation the nonlinear effects of layer interaction are calculated with insufficient accuracy, and the results must be verified with a model having a large number of layers.

Fig. 6b presents the results of the calculation for an analogous klystron design in the six-layer approximation. In the first two drift regions the stratification is small. It increases as the transition is made to the final drift region. The difference in the currents I_{1i}/I_0 of different layers is much less than for the three-layer model. A tendency toward enhancement of the bunching of inner layers is noticeable.

Thus, more precise allowance for Coulomb forces in the beam indicates the existence of some compensation for stratification, due to the interaction of layers at large drift region lengths. This is analogous to the reduction of stratification in traveling-wave tubes. The average value of the current amplitude of the first harmonic reaches $\overline{I}_1/I_0 = 1.65$, and the average value of the Q-factor is close to 0.65. This value of the Q-factor is much higher than that of a klystron with the shortened drift tubes considered in Section 1 ($\eta_{bu} \approx 0.5$ for the multilayer model). Moreover, it should be taken into account that the plasma frequency of the electron beam of the klystron with lengthened tubes was assumed to be somewhat higher in the calculations, and the optimized efficiency decreases with increasing plasma frequency [2].

Thus, the use of lengthened drift tubes in a buncher is advantageous and should result in increased efficiency.

Let us consider the effectiveness of utilizing an annular beam. Fig. 7 gives the calculated results for a klystron constructed after Fig. 1c with a four-layer annular beam and the previous value $\omega_p/\omega = 0.4$. An aperture having an area 1/3 the area of the solid beam is made at the center of this beam. As can be seen from the figure, use of an annular beam increases somewhat the average Q-factor, which approaches 0.7. Changing to an annular beam in a klystron with lengthened tubes has less effect than in the case of a klystron with shortened tubes.

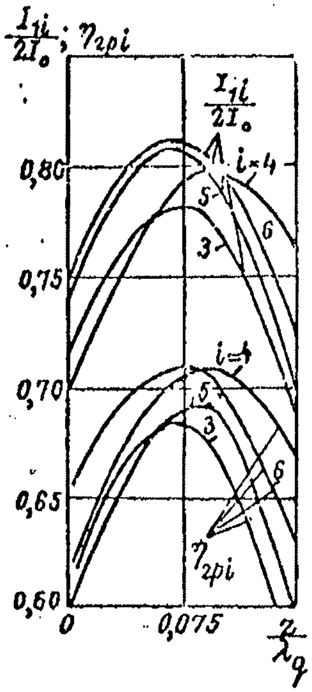


Fig. 7. Dependences of current amplitudes of first harmonic $I_{1i}/2I_0$ and of Q-factors $\eta_{bu\,i}$ on the coordinate z/λ_q for a four-layer annular beam in a klystron with lengthened drift tubes.

Let us examine the use of supplementary cavities at frequency 2ω in a klystron with lengthened tubes. As follows from an examination of the one-dimensional model [5], several supplementary cavities should be used to change the nonlinear process in a buncher with increased lengths. Calculations with one supplementary cavity placed at the center of the second drift tube have confirmed this conclusion. Introducing modulation at frequency 2ω does not lead to an appreciable increase in I_{1i}/I_0 and $\eta_{bu\,i}$. Consequently, the effect of supplementary modulation will show in its influence on processes directly in several drift regions. The cavity arrangement shown in Fig. 1d with three supplementary cavities was adopted for further calculations. The calculations that the voltage in the two penultimate klystron gaps should be somewhat less than that indicated by one-dimensional theory.

A typical picture of the variation of currents I_{1i}/I_0 and of Q-factors $\eta_{bu\,i}$ for the four-layer model is shown in Fig. 8. The average value of current amplitude of the first harmonic $\overline{I}_1/I_0$ reaches 1.8, and the average value of the factor $\overline{\eta}_{bu}$ approaches 0.72. Modes with a value of $\overline{\eta}_{bu}$ close to 0.75 are possible.

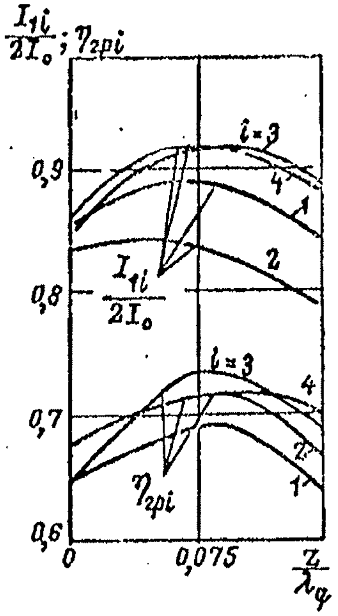


Fig. 8. Dependences of current amplitudes of first harmonic $I_{1i}/2I_0$ and of Q-factors $\eta_{bu\,i}$ on the coordinate z/λ_q for the four-layer model of a beam in a klystron with three supplementary cavities.

Thus, the use of several supplementary cavities in a buncher with first drift regions of increased length leads to the highest efficiencies among all the systems considered. This result is determined by the good electron bunching in lengthened drift tubes.

4. CONCLUSIONS

Stratification effects in multicavity power klystrons disrupt the process of electron bunching with a small velocity spread, reduce the efficiency of the klystron, and change the optimal parameters obtained in the one-dimensional treatment using a disk model of the beam.

The stratification effect in klystron bunchers can be reduced or fully compensated by introducing supplementary cavities excited at the signal's second harmonic, or by using an annular electron beam.

In bunchers with drift tubes of shortened length, stratification is compensated by introducing just one supplementary cavity at frequency 2ω. In bunchers with drift tubes of increased length two or more cavities at the second harmonic are required.

The use of an annular beam is more effective in bunchers with shortened drift tubes. An annular beam can be used in conjunction with cavities at frequency 2ω.

The anticipated electronic efficiency of five-cavity klystrons with supplementary cavities at frequency 2ω reaches 70% in klystrons with shortened tubes. In a klystron with lengthened tubes the anticipated efficiency is somewhat higher (up to 75%) because of the additional reduction of stratification and the enhancement of bunching in the wave regime.

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* [translator's note: SGU probably indicates either Saratov State University or Smolensk State University]

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