HIGH EFFICIENCY MULTICAVITY POWER KLYSTRONS (OPTIMIZATION OF BUNCHING AND ENERGY EXCHANGE)

MOЩНЫЕ МНОГОРЕЗОНАТОРНЫЕ КЛИСТРОНЫ С ВЫСОКИМ КПД (ОПТИМИЗАЦИЯ ГРУППИРОВАНИЯ И ЭНЕРГООБМЕНА)

V.I. KANAVETS, S.V. LEBEDINSKIĬ, E.I. VASIL’EV, YA.SH. GRANIT, S.V. ZHURAVLEV, V.I. KUCHUGURNĬ AND A.N. SANDALOV

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Summary. The article discusses the results of optimization calculations of six-cavity and eight-cavity klystrons with an electronic efficiency of over 70%, designed in connection with the construction of television klystrons of decimeter range. The electrodynamic systems of the instruments contain two-gap cavities and include one or two cavities of doubled signal frequency. The calculations of the bunches and output cavities are performed by means of an approximate analytical method and discrete models – disk, multilayer and two-dimensional. The Coulomb forces and reverse motion of electrons in the output cavities are considered.

1. Introduction

Theoretical investigations of the problem of raising the efficiency of multicavity power klystrons and experimental studies have shown the necessity of a simultaneous consideration of a large number of factors determining the electron bunching and energy extraction (effect of the space charge, electron
velocity spread, different bunchings over the beam cross section, two-dimensional and return motion of electrons, etc.). These factors are considered most fully in theories based on the use of multilayered two-dimensional discrete models of electron fluxes. However, because of the great complexity of such models, the one-dimensional (disk) model has become most popular. Optimization of klystron parameters with the aid of the disk model has made it possible to obtain regimes with an electronic efficiency up to 80-90%. However, the realization of such high efficiencies in experimental models of the devices has turned out to be difficult. The best experimental results have been obtained with klystrons containing cavities tuned to the second harmonic frequency of the input signal. The Varian Co. has designed narrowband klystrons with magnetic focusing having an electronic efficiency of 70-75%. Experimental models of devices without second-harmonic cavities, built on the basis of results of a one-dimensional optimization calculation, have an electronic efficiency of 55-65% if single-gap cavities are used. The electronic efficiency may reach 70% if the electrodynamic system contains double-gap cavities.

Special studies of the physics of optimum electron bunching in the two-dimensional approximation have shown that in general, the conditions of applicability of the disk model are not fulfilled. For example, when the beam is focused with a fairly strong longitudinal magnetic field, two-dimensional effects manifested as stratification effects lead to a breakdown of the homogeneity of layer bunching. The process optimized in the one-dimensional approximation becomes far removed from the optimum process. Additional action at the fre-
frequency of the second harmonic makes it possible to compensate for the stratification and obtain a bunch of homogeneous cross section.\textsuperscript{13} Excitation of the output cavity by such a bunch makes it possible to obtain the optimum energy extraction and provide for high efficiencies.\textsuperscript{7} In Ref. 8, these questions are not discussed, and the results obtained are largely empirical in character. The importance of achieving a bunching of homogeneous cross section is indirectly confirmed by the results of a two-dimensional (quasi-three-dimensional) calculation of output cavities.\textsuperscript{14} In the excitation of the latter by disks optimally bunched according to the one-dimensional model and first broken up into rings, the optimum energy exchange conditions are met for typical cavity designs. The results of the study made in Ref. 14 are in good agreement with the experimental data of Ref. 8.

Stratification can also be compensated for in optimized bunchers with cavities having different gaps, tuned only to the fundamental frequency.\textsuperscript{7} However, instruments with self-modulation at the second harmonic turn out to be shorter, which is their advantage. At the same time, in the selected design of the instrument, the replacement of single-gap cavities of fundamental frequency by double-gap cavities makes it possible to extend the working frequency band. Energy extraction in the sequence of the gaps leads to an increase of the efficiency of the instrument.\textsuperscript{15, 16}

A special theoretical and experimental study was set up to check the conclusions of the two-dimensional theory (including the stratification theory) and compare them with experimental data. The experimental models were based on a universal klystron model whose design permitted a rapid change of the number of cavities, their parameters, and the parameters of the electron beam, and permitted the introduction of doubled frequency cavities. This article presents the results of preliminary optimization calculations. A comparison of theoretical and experimental data is given in Ref. 17.
The experience in the optimization of the processes and creation of a high efficiency klystron can be used for optimum designing of other O-type devices.

2. Parameters of Klystrons

The working frequency was close to 500 MHz; initial values of accelerating voltage were \( V_0 = 17 \text{ kV} \), and beam current \( I_0 = 1.76 \text{ A} \) (micropervance \( P_\mu = 0.8 \)). The fundamental frequency cavities had two gaps and operated on the antiphase type of oscillations. Their wave impedance was 143 Ω, and the transit angle in the gaps was 42° at a voltage of 17 kV. The transit angle between the centers of the gaps of all two-gap cavities except the output one was 170°. Various transit angles were used in the output cavities. The single-gap doubled-frequency cavity had a transit angle of 50°. Its wave impedance was 100 ohm.

The focusing longitudinal magnetic field increase from the cathode to the output cavity. Its ratio to the Brillouin value reached a factor of 2-3. Conditions of motion with small radial pulsations were produced at the input of the electrodynamic system. The filling factor of the beam in the drift tube was 0.7 in a static regime. The reduced beam radius at 17 kV was \( \frac{\omega}{v_0} r_b = 0.47 \), where \( \omega \) is the signal frequency, \( v_0 \) is the constant velocity component, and \( r_b \) is the beam radius. The corresponding value of the parameter of longitudinal decrease of Coulomb forces \( k = \frac{2}{(\omega/v_0) r_b} = 4.35 \) was within the optimum range.

At current \( I_0 = 1.76 \text{ A} \), the ratio of the nonreduced plasma frequency to the signal frequency was \( \frac{\omega_p}{\omega} = 0.34 \).

The optimization calculations were performed for designs of devices with four, five, six and eight cavities; the last three designs contained second-harmonic cavities (Fig. 1).
In the devices studied, the first cavity and the drift region behind it formed a linear amplifier, and the second and following cavities, except the output cavity, were part of a nonlinear buncher. The initial choice of distances between the cavity gap centers of five-, six- and eight-cavity klystrons was made in accordance with the results of an analysis of stratification effects, obtained in the specified field approximation. Nonlinear bunches of five-, six- and eight-cavity klystrons are equivalent to two-, three- and four-cavity optimized bunchers with fundamental frequency cavities.

The length of the first drift region was chosen to be less than one-quarter of the plasma wavelength. The selection of the distance between the centers of gaps of the doubled-frequency cavity and the gaps of adjacent fundamental frequency cavities was a compromise in order to fulfill the conditions of compensation of stratification and improvement of bunching \[ l/\lambda_q = 0.07, \quad \text{where} \]

\[ \lambda_q = \frac{V_0}{b \omega_p} \sqrt{1 + k^2} \]  

(Ref. 7). Klystrons with four, five and six cavities have the same total length. The technologi-
The requirements being taken into account, the following preliminary sequence of lengths \( (\ell/\lambda_q) \) was obtained for the six-cavity klystron: 0.111, 0.071, 0.071, 0.083 and 0.083.

The following sequence of lengths \( (\ell/\lambda_q) \) was specified for calculations of the eight-cavity klystron: 0.10, 0.08, 0.07, 0.06, 0.07, 0.11 and 0.06. The Q factor of the first cavity was taken as 100, and the Q factors of the intermediate cavities were variable between 100 and 1500.

The electronic interaction coefficients and electronic conductivities of the cavity gaps were calculated from the formulas of Ref. 18 and for cavities at the fundamental frequency were \( M_\omega = 0.92, (G_e/G_0)_\omega = 0.05 \); at the frequency of the second harmonic, \( M_{2\omega} = 0.63, (G_e/G_0)_{2\omega} = 0.164 \) \( (G_0 = I_0/V_0) \).

3. Method of Calculation

The calculation of the klystrons was performed both with the aid of an approximate analytical model and by means of discrete models: one-dimensional, disk, multilayer and two-dimensional. The disks and rings were assumed to be thin and to have the same charge.

The preliminary optimization was based on the analytical model. The minimum of the target function (efficiency of the device, bunching figure of merit) was sought by means of standard programs contained in the BESM-6 file, for example, programs of direct or gradient descent.

The degree of bunching was estimated from the amplitudes of the first harmonic of the current \( I_1/I_0 \) and bunching figures of merit \( \eta_b \):

\[
\eta_b = \frac{1}{2} \frac{I_1}{I_0} \frac{v_{\text{min}}}{v_0},
\]

where \( \frac{v_{\text{min}}}{v_0} \) is the ratio of the minimum electron velocity to the constant velocity component. The figure of merit is close to the electronic efficiency of the optimized output cavity. The efficiency was estimated analytically from the induced current and parameters of the output cavity, the nonlinearity...
of the processes being taken into account:

$$V_{\text{out}} = \frac{V}{V_0}$$

where $V_{\text{out}}$ is the ratio of the variable potential difference across an equivalent output gap to the accelerating voltage;

$$Z_0 = \frac{1}{\rho_0 C_0}$$

$\rho_0$ is the wave impedance of the cavity;

$$C_0 = \frac{z_0}{V_0}$$

is the beam conductivity;

$Q_{\text{out}}$ is the "cold" Q;

$f(\eta)$ is an empirical function allowing for the nonlinearity:

$$f(\eta) = a\eta^3 + ba^2\eta$$

where

$$a = \eta_{\text{max}} - \eta_{\text{b max}}$$

$$\mu = \eta/\eta_{\text{max}}$$

$\eta_{\text{max}}, \eta_{\text{b max}}$ are the maximum values of efficiency $\eta$ according to formula (2) and of the bunching figure of merit in the working frequency band;

$b$ is a parameter of the order of 1.

The values of the resonance frequencies, figures of merit and power of the input signal, obtained by optimization with the analytical model, are used as the initial parameters in computations with the discrete model. The computations showed that for selected drift lengths, the first harmonic of the beam current and efficiency may be fairly high: $k_1/I_0 = 1.7-1.8$; $\eta_e = 80-90\%$.

A further self-consistent optimization calculation using discrete models was performed separately for the bunchers and the output cavities. In the case of beam models consisting of sequences of disks of fixed and variable radii, the maximum of the figure of merit $\eta_b$ (1) was sought.
In calculating bunchers by means of the multilayer model (rings of fixed radius), the bunches are characterized by the first harmonic of the current in the layers $I_{1i}/I_{0i}$ and figures of merit of the layers:

$$\eta_i = \frac{1}{2} \frac{I_{1i}}{I_0} \left(\frac{\nu_{\text{min}}}{\nu_0}\right).$$

(4)

The number of layers is usually equal to 3; the checking calculations were performed with four and six layers. The bunching is considered optimal if the figures of merit reach the required values $\eta_{b_1} > 0.7$.

The optimum bunching regimes found by taking the stratification into account were checked in the two-dimensional (quasi-three-dimensional) approximation allowing for the radial and angular charged disks and rings. The disks and rings could be deformed in the transverse plane.

In calculations with a multilayer model, the coefficient of electronic interaction of the layers $M_i$ and electronic conductivities $G_{el}/G_{0i}$ change along the radius. For two-gap cavities and the three-layer model, the change is slight: $M_1/M_{av} = 0.98$; $M_2/M_{av} = 1.0$; $M_3/M_{av} = 1.02$, where $M_{av}$ is the average value of the coefficient ($M_{av} = M_\omega = 0.92$). For a single-gap double-frequency cavity, the calculations showed a large change: $M_1/M_{av} = 0.92$; $M_2/M_{av} = 1.0$; $M_3/M_{av} = 1.08$ ($M_{av} = M_2\omega = 0.63$).

The calculations of the buncher were performed in phase variables. The phases of electrons and their velocities were determined at the output of the buncher. Their values were used for calculating the processes in the two-gap output cavities. The optimization of energy exchange was performed mainly within the framework of the disk model. Checking calculations were carried out with the one-dimensional multilayer model with allowance made for the two-dimensional motion of electrons. A fixed coordinate system was employed that made it possible to describe the reverse motion of electrons. The establishment of electron trajectories over several oscillation periods was considered.
The checking calculations of the output cavity by means of the multi-layer two-dimensional model were performed by considering the actual two-dimensional distribution of the fields in the gaps. The program makes it possible to perform calculations of cavities with any number of gaps. The high-frequency field of each of the gaps may be given in the form of tables of numbers obtained by means of an electrolytic bath or by calculations using the formulas of Ref. 19. For multigap cavities, the field is equal to the sum of the fields of the individual gaps. The necessary tables are calculated by means of a special subprogram.

The space charge forces are determined by means of the Green function for the model of deformable rings analogous to the rings used in the calculation of the buncher.

The electronic efficiency $\eta_e$ is determined from the kinetic energies of the longitudinal, transverse and angular motion of the rings and the given kinetic energy at the input to the buncher.

Optimization calculations in the one-dimensional approximation for four- and five-cavity instruments showed that the electronic efficiencies do not exceed 65 and 70% respectively. For six- and eight-cavity instruments, the electronic efficiency obtained was appreciably above 70%. Only the latter instruments are discussed below.

4. Optimized Buncher of a Six-Cavity Klystron

The optimum bunching regime obtained by calculations using the disk model is characterized by high figures of merit $\eta_b = 0.79$ and high amplitudes of the first harmonic of the current $I_1/I_0 = 1.8$. The character of the processes is analogous to the optimum bunching obtained in the specified field approximation. 7

Optimum bunching is weakly dependent on the choice of the resonance frequency of the second, fourth and fifth cavities in the presence of mutual
tunings of the frequencies and the corresponding change in the power of the input signal (Fig. 2, a and b). Changing the frequency $\gamma_3$ of the second-harmonic cavity substantially affects the figure of merit (Fig. 2 c). If the cavity is markedly mistuned toward the low-frequency side ($V_3/V_0 \rightarrow 0$), the figure of merit drops to 0.6-0.7. The maximum $\eta_b$ is reached when the tuning $\gamma_3 = 0.9937$ (Fig. 2 c) and the relative voltage in the gap is $V_3/V_0 = 0.15$. The variable voltage of the fifth cavity near the optimum ($\gamma_5 = 1.028$) changes over the range $V_5/V_0 = 0.35-0.45$.

The conclusions of the one-dimensional theory were checked by means of a three-layer ring model. If the optimum values of input power and cavity detunings according to one-dimensional theory are specified, the electron trajectories in the first three drift regions remain practically unchanged. Starting with the third region, a stratification is manifested that is characterized by a diverse change in variable currents and in the figures of merit of the layers along the last drift region (Fig. 3 a). The stratification leads primarily to debunching in the inner layer. The expected electronic efficiency decreases by at least 10%, since according to the results of a study of output cavities, the value of the efficiency is located between the minimum and average values of the figures of merit of the layers. 7

Excessive values of variable voltages correspond to the optimum regime according to the one-layer model. An additional optimization of the parameters is necessary. In the six-cavity klystron under consideration, a certain retuning of the cavities of the buncher is sufficient to compensate for the stratification. The curves of $\eta_b$ vs $\gamma_5$ illustrating this possibility are shown in Fig. 3 b. When $\gamma_5 = 1.0225$, the functions $\eta_b(\gamma_5)$ intersect at approximately the same point, and a bunch of homogeneous cross section is formed at the output of the buncher. A further improvement of the bunching
Fig. 2. Figure of merit of six-cavity klystron (disk model) $\eta_b$ vs tuning of fifth cavity $\gamma_5$ (a, b) and third cavity $\gamma_3$ (c) ($\gamma_1 = \gamma_6 = 1.00$):

- curve 1: $P_{in} = 0.4 \, \text{W}$, $\gamma_2 = 0.998$; curve 2: $P_{in} = 0.3 \, \text{W}$, $\gamma_2 = 0.999$ ($\gamma_3 = 0.999$; $\gamma_4 = 1.04$);
- curve 1: $\gamma_3 = 0.993$; $\gamma_4 = 1.04$; curve 2: $\gamma_3 = 0.994$, $\gamma_4 = 1.044$; curve 3: $\gamma_3 = 0.994$; $\gamma_4 = 1.048$ ($\gamma_2 = 0.999$);
- curve 1: $P_{in} = 0.3 \, \text{W}$, $\gamma_2 = 0.999$; $\gamma_4 = 1.04$.

is obtained by lowering the voltage of the third cavity. A change in the amplitudes of the first harmonic of the current of the layers along the beam in the newly found optimum regime is shown in Fig. 3 c. Up to the fourth cavity, the distribution of $I_{11}/I_{01}$ values corresponds to the main type of space charge wave in the beam with the maximum current in the inner layer. Then the curves intersect, and subsequently the current maximum corresponds to the outer layer. The bunch is practically homogeneous in cross section. The $\eta_{b_1}$ values range from 0.68 to 0.72. The expected electronic efficiency is at the 70% level.
Fig. 3. Figures of merit of six-cavity klystron for a multilayer model \( \eta_{b i} \) (i = 1, 2, 3) vs \( I_5/\lambda_q \) (a) and tuning of fifth cavity \( \gamma_5 \) (b) and optimized curves of \( I_{1i}/I_{0i} \) and \( \eta_{b i} \) vs \( \ell(\lambda) \) (c) at \( P_{in} = 0.3 \text{ W} \); \( \gamma_1 = \gamma_6 = 1.00 \); \( \gamma_2 = 0.999 \); \( \gamma_3 = 0.993 \); \( \gamma_4 = 1.035 \).

Further calculation was performed with the aid of a multilayer two-dimensional model containing deformable disks and rings of variable radius. The parameter of cathodic conditions \( K \) is chosen on the basis of absence of pulsations in the flux at the input to the buncher:

\[
K = 1 - \left( \frac{B_B}{B_{z0}} \right)^2,
\]

where \( B_B \) is the induction of the Brillouin field;

\( B_{z0} \) is the induction at the input to the buncher.

The magnetic field distribution used was the actual one, recorded on the axis of the focusing solenoid. It is shown in Fig. 4 a. As is shown
by the curves of this figure, which were obtained with the aid of the model of deformable disks, the beam initially does not pulsate, and the maximum and minimum radii are similar. Subsequently, the bunching causes the conditions of compensation of radial forces to be disturbed, and a dynamic defocusing arises, but it is slight. Figure 4 b shows the current $I_1/I_0$ and figure of merit $\eta_b$ as a function of the coordinate for models of rigid and deformable disks. The curves run side by side. The radial motion introduces a small correction. Thus, a more significant role in bunching is played by the stratification effect, which in turn is determined by the radial change in Coulomb forces and by the inhomogeneity of the high frequency fields in the gaps.

5. Optimized Buncher of an Eight-Cavity Klystron

The buncher contains two second-harmonic cavities (Fig. 1 d). Its design differs from the one discussed in Ref. 7, and therefore the optimization in the one-dimensional approximation was made by taking the lengths of the drift tubes into account. This design made it possible to obtain very high values of the figure of merit $(\eta_b)_{\text{max}} = 0.83$, with $I_1/I_0 = 1.85$. The curves of $\eta_b$ versus the tube lengths, detunings and power of the input signal near the optimum were fairly smooth (Fig. 5, a, b, c and d). The choice of tunings of doubled-frequency cavities ($\gamma_3$, $\gamma_5$) greatly affects the bunching (Fig. 5 e). The maximum figure of merit is obtained with $\gamma_7 \approx 1.019$, the variable voltage in the gap $V_7/V_0 \approx 0.55$ being somewhat high.

Results of a checking calculation of the optimum regime by means of a three-layer model of rings of constant radius are shown in Fig. 6 a. For comparison, data obtained in calculations with a disk model are also shown. At the buncher output, the current $I_{11}/I_{01}$ and figure of merit $\eta_{b1}$ were far from the maximum values. When the stratification was taken into account, the bunching became nonoptimal.
Fig. 4. Change in focusing magnetic field $B$ and extreme radii of charged rings $(r/r_T)_{max}$ and $(r/r_T)_{min}$ along the device (six-cavity klystron, $P_{in} = 0.4 \, W$) (a). Amplitude of first harmonic of current $I_1/I_0$ and figure of merit $n_b$ of six-cavity klystron versus longitudinal coordinate for two-dimensional (-----) and disk (-----) models.

For a given beam microperveance, the search for stratification compensation regimes required a fairly extensive checking of the resonance frequencies and drift region lengths, as well as a reduction in the power of the input signal. With constant Q factors, the figure of merit of the first layer $n_{b_1}$ could be raised only to 0.6. A detailed examination of the process showed that layer bunching is disrupted, in particular, because of the action of the fields of bunches forming at the end of the first drift region. Raising the Q factor of the second cavity $Q_{c2}$ to 500 and correspondingly decreasing the input signal made it possible to raise $n_{b_1}$ to 0.66. Further variation of the parameters did not improve the bunching. The optimum current distribution over the layers for a given perveance is shown in Fig. 6 b. The stratifica-
tion was not completely compensated, and the expected efficiency was about 70%.

The debunching effect of the beam on the first layer can be reduced by lowering the charge density, i.e., decreasing the plasma frequency of the beam. Let us examine the results of a calculation with a new value of micro-perveance, $P_u = 0.5(\omega_p/\omega = 0.25; k = 4.35)$. A decrease in $P_u$ was achieved by lowering the beam current to $I_0 = 1.1$ A.

The optimized calculation made it possible to find the stratification compensation regimes. At the optimum, the figure of merit for the inner layer $\eta_{b_1}$ was 0.74, with $\eta_{b_2} = 0.76$, $\eta_{b_3} = 0.79$ (Fig. 6 c). The expected electronic efficiency of the instrument was about 75%.

For a given beam current density, compensation of stratification can also be achieved by changing to an annular beam with an aperture amounting to 1/2 of the total area of a full beam. Special calculations with a three-layer model of an annular beam made it possible to obtain regimes characterized by the values $\eta_{b_i} > 0.7$ ($i = 1, 2, 3$).

Thus, in contrast to the six-cavity instrument, stratification in an eight-cavity klystron was successfully compensated only by substantially reducing the beam current. The necessity of reducing the current was also determined from an experimental study of an instrument with two second-harmonic cavities.

A two-dimensional checking calculation of an eight-cavity klystron showed that in the stratification compensation regime, the influence of radial motion is slight, and dynamic defocusing has no appreciable effect (results of two-dimensional analysis are described in detail in Ref. 17).

In regimes with minimum stratification (Fig. 6, b and c), the variable voltage in the gap of the fifth cavity (of double frequency) is low: $V_5/V_0 < 0.05$. The cavity has little effect on the bunching and in principle can be neglected.
Fig. 5. Typical curves of the figure of merit of an eight-cavity klystron $\eta_b$ vs length of fifth $\lambda_5/\lambda$ (a) and sixth $\lambda_6/\lambda$ (b) drift regions, tuning of the sixth cavity $\gamma_6$ (c), power input $P_{in}$ (W) (d) and tunnings of the third and fifth cavities $\gamma_3$ and $\gamma_5$ (e) of an eight-cavity klystron (disk model). $\gamma_1 = 1.002$; $\gamma_2 = 0.998$; $\gamma_4 = 1.030$; $\gamma_7 = 1.019$.

Fig. 6. Amplitudes of first harmonic of layer current $I_{1l}/I_{01}$ and figures of merit of layers $\eta_{b1}$ in an eight-cavity klystron vs longitudinal coordinate $\ell/\lambda$. The cavity number $n$ is also plotted along the abscissa. For a, b and c respectively $P_{in} = 1.9, 0.08$ and $0.01$ W; $P_{m} = 0.8, 0.8, 0.5$; $Q_{c2} = 100, 500$ and $500$. The dashed line pertains to the disk model.
6. Optimization of the Parameters of Output Cavities

In two-gap output cavities, the variable voltage corresponding to the gap is cut by approximately one-half in comparison with the voltage in single-gap cavities. The dynamic defocusing is attenuated, and the disk model or multilayer model with rings of fixed radius should be better suited to estimating the energy exchange.

In calculations of energy exchange, use was made of the two-dimensional distribution of the electric field in the gaps, obtained by modeling on an electrolytic bath; the effect of Coulomb forces was calculated, the reverse and oscillatory motion of electrons was considered, and the change in the potential energy of the bunch was taken into account.

The calculation and optimization of the parameters of the output cavities of six- and eight-cavity klystrons were carried out mainly for one-dimensional electron bunches with figures of merit $\eta_b = 0.718$ and $\eta_b = 0.823$, corresponding to the optimum regimes, for three values of transit angles between the gap centers, $\Theta_{12} = 100, 135$ and $170^\circ$. The calculations gave the electronic efficiencies and values of the real and imaginary parts of electronic conductivity, which determined the tuning of the cavity. Figure 7 a shows typical curves of electronic efficiency versus total variable voltage in the gaps $\xi = V_0/V_0$. The voltage phases used were optimal. As follows from the figure, the electronic efficiency increases as $\Theta_{12}$ decreases; at a transit angle of $135^\circ$, the efficiency is above the figure of merit of the six-cavity klystron and below the figure of merit of the eight-cavity klystron. In the eight-cavity instrument, an even greater reduction of the distances between the gaps is required. However, small transit angles were found difficult to achieve, and transit angles of $135^\circ$ were used in the experimental instruments.

In the optimum regime, the same power is produced on each of the gaps. In nonoptimum phases, the energy exchange in the gaps may differ considerably.
For given bunches, the corresponding detunings of the output cavities were determined. In the eight-cavity klystron with $Q_c = 75$, the optimum detuning was small: $\Delta \gamma_8 = 0.0004$.

Figure 7 b shows the trajectories of electron disks of the same period inside a two-gap cavity at a transit angle $\Theta_{12} = 135^\circ$, transit angles in the gaps $\Theta_1 = \Theta_2 = 42^\circ$ and optimum value of effective voltage $\xi = 0.923$; the longitudinal coordinate, expressed in transit angles, is plotted along the ordinate. In the first gap, the bunch is densified, and subsequently undergoes expansion.

Fig. 7, a. Electronic efficiency $\eta_e$ vs total variable voltage in the gaps of output cavity $\xi$ for various transit angles $\Theta_{12}$ between the gap centers.

--- efficiency of eight-cavity klystron ($\eta_b = 0.823$), --- efficiency of six-cavity klystron ($\eta_b = 0.718$).

b. Trajectories of electron disks in output cavity for optimum regime of eight-cavity klystron ($\eta_b = 0.823$).
As in the buncher, stratification and dynamic defocusing effects are manifested in the output cavity. Calculations showed that in the presence of the acting focusing magnetic fields, the stratification depends on the choice of the frequency within the band. At the central frequency and the optimum, the stratification does not alter the basic results of the calculation obtained by means of the disk model (a similar examination of the effect of stratification is given in Ref. 17).

As an example of a two-dimensional calculation, Fig. 8c shows the change in particle velocities and radii in a two-gap output cavity. The flux is three-layered and contains 24 particles per layer per period. The magnetic field is 2.5 times the Brillouin field. The trajectories of rings of numbers 7 and 20.9 and 12.8 and 19 are shown, pertaining to layers 1, 2 and 3 respectively. The radii of the rings at the input change only slightly. At the output, the pulsations increase, and the beam radius increases by a factor of approximately 1.3. Of the total efficiency $\eta_e = 74\%$, the radial component accounts for $\eta_r \approx 2\%$, and the angular motion, $\eta_\theta = 1\%$. Although the true motion of electrons in the cavity is two-dimensional in character, the electronic efficiency of 74% is close to the figures of merit of the disk and multilayer models (for the buncher operating mode employed, the average value $\bar{\eta}_b \approx 72\%$). In the optimum operating mode of the output cavity, no landing is observed. As the variable field is increased above the optimum value, approximately 2% of the current lands.

7. Conclusions

1. Klystrons with magnetic focusing and high efficiencies should contain optimized nonlinear bunchers, the designs of which are arrived at by studying the physics of action of Coulomb forces, stratification effect, and dynamic defocusing.
Fig. 8. Change in the velocities (a) and radii (b) of rings of a two-dimensional three-layer model in the output cavity of an eight-cavity klystron \( \eta_e = 74\%, \eta_b = 0.72 \). \( i \) - number of layer, \( n \) - number of electron ring.

2. The selection of drift tube lengths and detunings should be made by considering the possibility of compensating the stratification and obtaining a slight dynamic defocusing. Bunchers with "short" drift tubes should contain no fewer than two or three fundamental frequency cavities markedly detuned toward the upper frequencies, and at least one double frequency cavity detuned toward lower frequencies.

3. The optimization of the parameters of the instruments should be carried out with the aid of a set of programs of increasing complexity, based on the analytical, disk, multilayer and two-dimensional models.
4. To save computer time, the optimization calculation of bunchers and output cavities can be performed separately. The degree of bunching is estimated from the figures of merit of the layers.

5. To obtain high electronic efficiencies in klystrons with two-gap output cavities with antiphase type oscillations, it is necessary to use reduced transit angles between the gap centers (100-135°).

6. To obtain electronic efficiencies close to 80% (in an eight-cavity device), it is necessary to use beams of reduced perveance ($P_\mu \approx 0.5$). Only in this case is it possible to compensate the stratification in the buncher.

References


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