The New Generation of High-Power Multiple-Beam Klystrons

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Abstract— **A number of drawbacks of single-beam transit klystrons (i.e., narrow band, high voltages, high weight) limit their use in some applications. Multiple-beam klystrons, operating in the fundamental resonator mode, offer the possibility of dramatic improvements in performance. This report describes the advantages of multiple-beam klystrons with regard to power supply voltages, weight and bandwidth. Characteristics of production prototypes are also presented.**

I. Introduction

THE WIDE use of klystrons for some critical applications has been constrained by a number of drawbacks, including unsatisfactory weight/dimension characteristics, high operating voltages and comparatively narrow bandwidth. The elimination of these drawbacks in a single or one beam klystron (OBK) appears impossible due to principal physical limitations. The possible solution is the use of multiple-beam designs.

The concept of using several electron streams appeared after the transit klystron invention [1]–[3]. In the 1950s and, particularly, in the 1960s, multiple-beam klystrons (MBK) were examined in the USA operating on higher resonator modes [4] and in multiple-beam travelling wave klystrons (MBTWK) [5]. While allowing a decrease in the operating voltage, the two versions suffered certain disadvantages. The higher mode MBKs do not give any increase in bandwidth when compared with the OBK, and satisfactory performance of waveguide MBTWK was obtained only for rather high output power levels (up to several MW). Judging by the publications, the work on these two classes of multiple-beam klystrons did not receive a large development effort in the USA. A. Staprans *et al.* announced in a comprehensive publication dated 1973, that multiple-beam klystrons were not being used at the time [6].

From the standpoint of improving performance, MBKs operating in the fundamental resonator mode appear more attractive.

RPC "Istok" has been performing research and production development of MBKs based on the fundamental resonator mode for more than two decades. The major contribution to this effort was made by S. V. Korolyov, who unfortunately suffered an untimely death.

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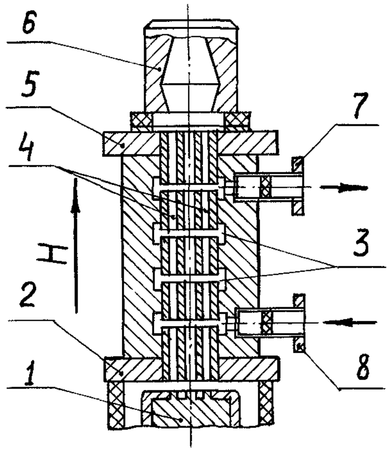

Fig. 1. The scheme of the multiple-beam fundamental rezonator mode klystron: 1—cathode; 2—steel screen; 3—resonators; 4—drift tubes; 5—steel screen; 6—collector; 7—energy output; 8—energy input.

II. Performance of the Fundamental Resonator Mode- Based MBK

Fig. 1 is the outline of the MBK design which is based on the fundamental mode operation of the klystron resonators. Its peculiar feature is the use of several metal wall-separated channels located in a single multichannel drift tube. Each channel conducts its own electron beam. Unlike conventional transit klystrons with grid gaps, there is no connection between separate beams in the drift region, which is the main advantages of the MBK. Low perveance and low current electron beams are focused, bunched and give up energy more readily. The desired output power is achieved by the summation of power, extracted from the multiple low-current beams. The operating voltage can be reduced significantly, thereby reducing dimensions and weight of the klystron and power supplies. In addition, the bandwidth can be increased by the increase in total perveance.

In a somewhat simplified sense, the MBK represents a return to the klystron based on grid gaps and large diameter beam with the advantages of high perveance and efficient interaction. At the same time the splitting of a single beam into many isolated partial beams avoids the main drawback of the grid klystron, i.e. the deterioration of electron bunching in large diameter/perveance beams.

The number of beams, defined by dense "packing" of channels in the MBK usually corresponds to the standard discrete series of values: N = 7, 19, 37, 61 . . . ,which provide

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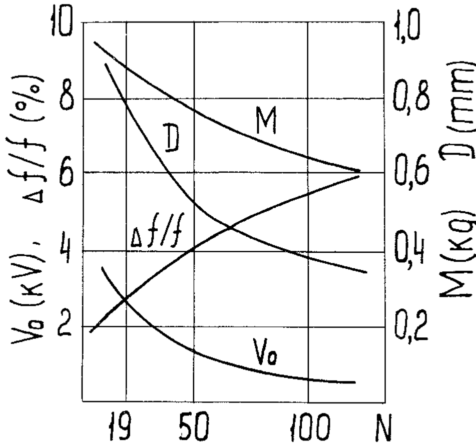


Fig. 2. The klystron parameters as function of the beam number N The operating wavelength is 3 cm, output power—500 W, current density from the cathode—15 A/(cm * cm); V_o is the operating voltage, $\Delta f/f$—the bandwidth, M—the magnet weight, D—transit channel diameter.

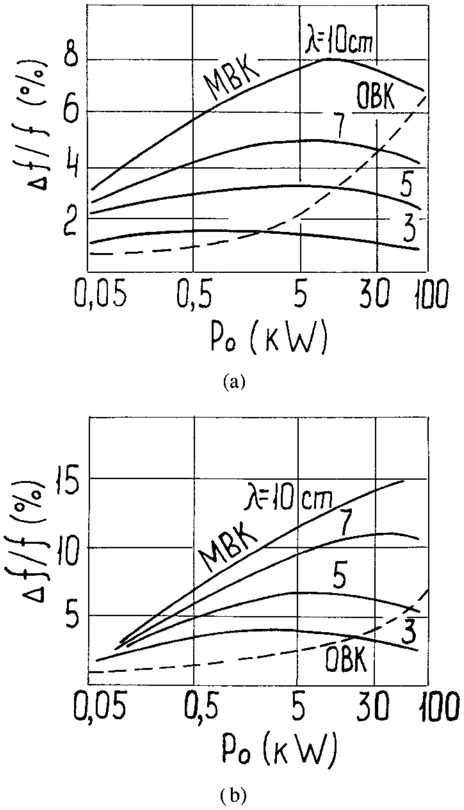


Fig. 3. The bandwidth as function of the output power of one-beam and 19-beams klystrons for various wavelength at current density from the cathode of 15 A/(Cm * Cm) (a) and 45 A/(Cm * Cm) (b) (single-gap output resonator).

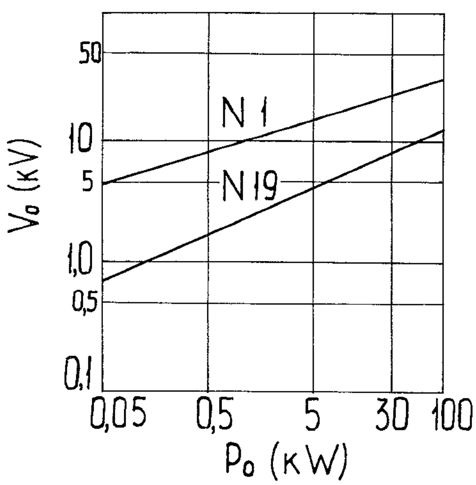


Fig. 4. The generalized dependences of optimum operating voltage of the broadband klystrons on output power levels for the one-beam and multiple-beam designs.

the most close "packing" of the channels in the drift tube. In some cases (e.g. when thermal and other problems arise) other numbers of channels can be used.

The fundamental mode MBK including multiple-beam electron gun, resonator system, focusing magnet and collector, is a highly sophisticated system to design with electric and magnetic fields that are three-dimensional. It has an additional degree of freedom—the number of beams, N, that drastically increases possible variants and achievable compromises. The RPC "Istok"—devised set of programs (CAD) has played a crucial role in the development and optimization of the MBK. Below are a few illustrative analytical estimates and results of computer calculations that characterize some parameters of the MBK.

In the case of equality of MBK- and OBK-beam powers ($P_{O1} = P_{ON\Sigma}$), beam perveances ($\mathcal{P}_1 = \mathcal{P}_n/N = \mathcal{P}_{\text{part}}$) and equal normalized radii of the channels, the MBK bandwidth is 2–2.5 times more than that of the OBK. It is due to the fact that as the beam number grows, the characteristic impedance of the resonator decreases more slowly (due to the smaller contribution of the side capacitance) than the overall conductance of the multiple beam increases. MBK voltage decrease is estimated in accordance with the relationship $U_{O1}/U_{ON} \simeq N^{2/5}$. If the value of the summarized area of the drift tubes cross-sections of the MBK is equal to the area of the OBK's drift tube cross-section, the MBK bandwidth becomes even greater and is 6–9 times more than that of the OBK. In this case MBK, however, requires higher current density in the beams, $j_{ON}/j_{O1} \simeq N^{2/5}$.

Figs. 2–4 show the calculated design dependences that characterize the band growth, voltage decrease and focusing magnet weight reduction for increasing beam number. Achievable band levels and generalized voltages are also shown as a function of output power for broadband MBKs and OBKs based on single gap resonators. The broadband MBK designs provide bandwidth up to 3% in the shortwave part of centimeter range for moderate values of output power—from hundreds of W up to several tens of kW. The operating voltage decreases simultaneously by a factor of 2–3. A supplementary factor of 2–3 increase in band broadening is obtained by utilization of 2 or 3-gap resonators and coupled resonator system (filter) in the output klystron stage. For decimeter range, the MBK band estimates give values close to an octave.

Weight and dimensions of the transit one-beam klystron are defined by its magnetic focusing system. As a rule, the magnet weight is 4 ... 30 times more than that of the klystron. The design work on the MBK and magnetic systems has shown that the fundamental resonator mode MBKs allow a substantial decrease (by a factor of up to 10) in the weight of the magnet and klystron as compared to its OBK analogue, primarily due to significant reduction of the power supply voltage and the summarized lengths of the drift channels [7]. Thus, the transition to MBK solves not only the problem of klystron miniaturization, but also results in the integrated miniaturization of equipment. Simultaneously it eliminates the need for using lead screens against X-ray radiation in high power MBKs.

The physical justification and the achievable parameter estimates are given above for the most commonly used MBK structure based on the fundamental resonator mode. All useful versions of the fundamental resonator mode MBK, however, are not reduced to this design. Some of them are mentioned below.

One of the ways of increasing pulsed and average power is the usage of MBK scheme on higher modes in which every single beam is replaced by a multiple-beam assembly.

Another unique version of the fundamental mode MBK is a dual mode klystron. The structural concept is the integration of two klystrons into a single device using common assemblies: electron optical system, energy output, and magnetic focusing system. The MBK mode would be used for generating high peak power, and the OBK mode for generating CW power. A typical relationship between peak and average output power might be $100 : 1$.

Thus, theoretical evaluation and experiments show: it is possible to obtain improved performance using MBKs based on the fundamental resonator mode. Practical implementation, however, requires the solution of serious structural and technological problems.

III. The Properties of the MBK Assemblies

Typical design of a fundamental resonator mode MBK is shown in Fig. 5. A highly difficult task is the development of an electron gun producing N-beam streams with close to laminar structure. A commonly used gun design (see photo in Fig. 6) includes an isolated focusing and modulating electrode with N-holes aligned with holes in the anode. Separate cathodes with emitting spherical surfaces are frequently used to improve beam laminarity. The crucial factors for producing multiple-beam guns is accurate small diameter hole alignment, thorough monitoring of distances, optimum selection of materials, and development of process operations for producing the cathode/grid structure.

Due to close location of separate channels in the MBK, the beam convergence in the gun is not large, and it is necessary to take off high current densities from the cathode for certain parameter relationships. The high current density requirement resulted in the development of highly effective cathodes, e.g., metal porous cathodes with current density of 30–40 A/cm^2 for pulsed mode and 10 A/cm^2 for CW-mode. The requirement for high current densities limits some applications of the MBK.

The overall microperveance of high power, broadband MBKs can be more than 10 times that of the OBK and achieves $(10 \cdots 30) \cdot 10^{-6}$ A/V$^{3/2}$. When a common collector is used for all the beams, significant decrease of potential in the collector

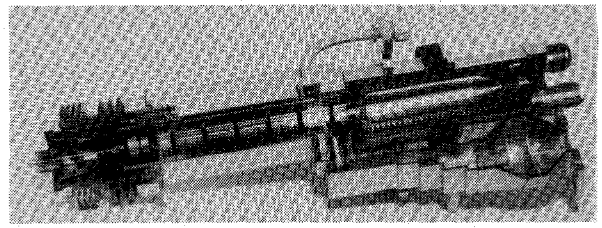


Fig. 5. The multiple-beam klystron cross-section.

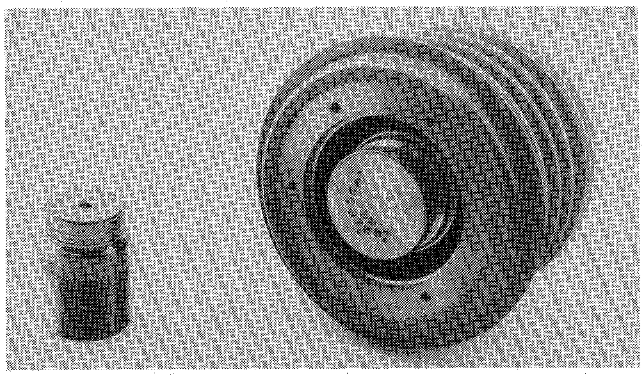


Fig. 6. The general view of the multiple-beam klystron cathode (left) and the cathode stem (right).

cavity can cause the formation of a virtual cathode. As a result, return electrons cause parasitic device excitation and signal spectrum deterioration. A number of collector designs have been developed, to eliminate this problem. These include:

- collector with optimized shape of the inner surface
- multichamber collector (a separate chamber for each beam)
- collector with a special electrode to remove slow electrons from the electron stream entering the collector.

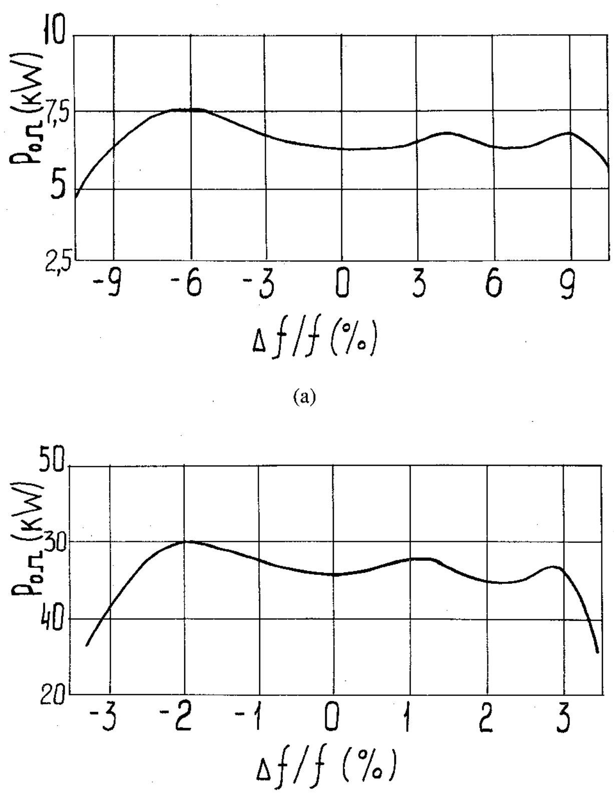
Critical factors affecting MBK collector design are selection of materials for the collector and coatings, thermal design, production and assembly technology.

The presence of off-axis peripheral beams causes problems when designing magnetic focusing systems in order to provide uniform field across the whole area occupied by the beams. Very stringent requirements are placed on the inhomogeneity of the longitudinal and transverse field. As a rule $B_{\perp}/B_{\parallel} \leq 0.01 \ldots 0.02$ is required for 99% propagation in the static mode and up to 96% in the dynamic mode. In some cases, the homogeneity can be improved using iron magnetic field "rectifiers", which have been used in other types of microwave tubes.

The output parameters are primarily determined by the resonator system. Various types of resonators are used in the MBKs, e.g., conventional toroidal single gap resonators, two- and multigap resonators, and systems of coupled resonators (filter). The selection of a resonator is determined by the output requirements, i.e., bandwidth, pulsed and average power, wavelength, etc. The MBK design places a number of limitations on the resonators used, in particular, the capacitor bulge diameter is limited by the condition: $D_{\rm cap}/\lambda \leq 0.5$. Sometimes this problem can be solved using a circular resonator. Optimum selection of spacings between gaps of multigap resonators makes it possible to reduce the sensitivity of output parameters to voltage variations to values that are typical of conventional klystrons.

TABLE I
SOME PARAMETERS OF THE MULTIPLE-BEAM KLYSTRONS

Mode	Pulse				CW	
λ (cm)	> 10	< 10	< 10	< 10	> 10	< 10
P_o (kW)	6	500–700	15–30	150–300	0.3	0.1
$\Delta f/f$ (%)	1.8	6	2–6	2–3	1.5	1.5
V_0 (kV)	2.7	30–32	10–14	20–27	1.7	1.2
η (%)	40	40–50	30–40	30–40	≥40	≥ 35
G (dB)	40	40	40	40	30	40
Focusing	Solenoid	Solenoid	PM	Solenoid	Solenoid	PM



(b)

Fig. 7. Amplitude-frequency response of the broadband multiple-beam pulsed klystrons: (a) $N = 61$, decimeter wave band; (b) $N = 7$, short-wave part of the centimeter wave band.

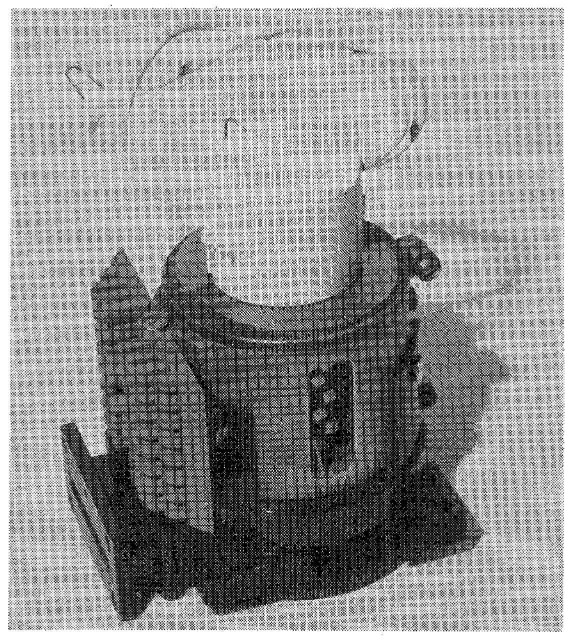


Fig. 8. The general view of the KU-179 ($N = 18$) klystron used in communication devices. Its operation parameters: Frequency range—5.8–6.3 GHz; output power—0.1 kW; band by 3 dB level—50 MHz; input power—0.025 W; efficiency—25%. Cathode: voltage—1.2 kV; current—0.35 A; cooling—forced air; mass—1.3 kg.

The complexity of MBK design necessitated the development of special equipment (e.g., electrical-discharge machines, etc.) for manufacturing resonator units for the MBK. This is also true for other MBK assemblies and for the device as a whole.

At the same time, a lot of industrial equipment and many technological processes commonly used for manufacturing vacuum microwave devices are successfully utilized for producing the multiple-beam klystrons.

IV. SOME RESULTS OF THE EXPERIMENTAL RESEARCH OF THE MULTIPLE-BEAM KLYSTRONS

A number of fundamental resonator mode MBKs have been developed with a wide collection of parameters for various frequency ranges and power levels (Table I). The klystrons use from 6–7 to several tens of electron beams. Fig. 7 shows experimental amplitude-frequency characteristics of the MBK for the short-wave part of centimeter and decimeter ranges. Fig. 8 contains the photograph and parameters of the miniaturized MBK of centimeter range having power of ~100 W.

The high-power MBKs developed at RPC "Istok" have pulsed power of hundreds of kW and average power up to 20 kW. The amplification bandwidth exceeds 5–6%. The voltage and weight are 2–3 times less than similar OBKs.

Klystrons with pulsed power in tens of kW and average power about units of kW provide the bandwidth about 6% in the short-wave part of centimeter range, which is comparable with TWT-band in the coupled resonator chain. At the same time the klystrons have far higher electronic efficiency (~40%) and lower phase sensitivity when compared to TWTs.

The 61-beam klystron based on single-gap resonators provides a bandwidth of 18% for output power of several kW in the decimeter range (Fig. 7).

V. Conclusion

The multiple-beam klystron design based on the fundamental resonator mode represents a powerful means of improving all the klystron parameters. For some applications it can provide better performance than the OBK or TWT based on the coupled resonator chain.

MBKs based on the fundamental resonator mode represent a highly effective new generation of high power microwave tubes.

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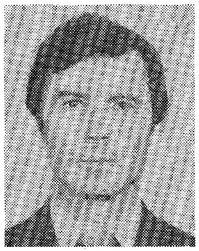

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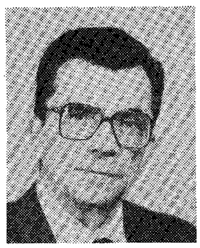

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