Infocommunications and Radio Technologies, vol. 5, no. 1, pp. 93–100, 2022.
Инфокоммуникационные и радиоэлектронные технологии. 2022. Т. 5, № 1. С. 93—100.
ISSN: 2587-9936
DOI: 10.29039/2587-9936.2022.05.1.07

UDC 621.385.632.1

On Prospects of Output Power Increasing in Low-Voltage Multibeam Klystrons for Electron Accelerators

A. V. Galdetskiy
Scientific and production enterprise "Istok" n. a. A. I. Shokin, JSC
Vokzalnaya st., 2A, Fryazino, Moscow region, 141190, Russian Federation
bogdanov_sa@mail.ru

Received: May 22, 2022
Peer-reviewed: June 5, 2022
Accepted: June 5, 2022

Abstract: *Physical principles of output power limitation in low-voltage multibeam klystrons are considered. It is demonstrated that metamaterial consisting of array of metal inductive inserts and located in the cavity's interaction region makes possible significant increasing of phase velocity of transversal wave in the gap. This reveals the opportunity to enhance uniformity of the RF field interacting with the beams in the gap, interaction region diameter, beams current and power of the klystron without cathode voltage increase. Resonators in S and Ka bands are analyzed.*

Keywords: *multibeam klystron, metamaterial, phase velocity, annular resonator, dispersion.*

For citation (IEEE): A. V. Galdetskiy, "On Prospects of Output Power Increasing in Low-Voltage Multibeam Klystrons for Electron Accelerators," *Infocommunications and Radio Technologies*, vol. 5, no. 1, pp. 93–100, 2022,
doi: 10.29039/2587-9936.2022.05.1.07.

1. Introduction

Ultra-high power klystrons and klystrodes (IOTs) are traditionally employed as sources of microwave power for electron linear accelerators [1–3]. Usually klystron output power increase is accompanied with significant rising of power supply voltage, which can achieve hundreds kilovolts in single-beam tubes. To obtain high electron efficiency in klystron it is required suppression of the space charge influence, which is provided by restriction of electron beam perveance at level 0.1–0.8 $\mu A/V^{3/2}$ and results in further voltage increasing. High cathode voltage decreases reliability of klystron, requires strengthening of ionizing radiation protection, isolators enlarging, discharges elimination. One of the possibilities of voltage lowering is the use of multibeam design, which makes possible total current enlarging at limited perveance of partial beam by means of beams number increasing. This approach was successfully realized in variety of works [4, 5], making possible to achieve output power 7 MW at power supply voltage ~60 kV. They employed annular resonators operating on fundamental, axially symmetrical mode E_{010}, providing rf field uniformity on all beams and sufficient frequency separation of fundamental and nearest parasitic modes. Annular resonator diameter is directly proportional to number of beams, so further diameter enlarging for klystron power growth is restricted by dimensions of cathode, acceptable for fabrication, and reduction of frequency separation.

In conventional multibeam toroidal cavity the number of beams is proportional to square of diameter of interaction region, but the diameter is restricted by value ~0.42 λ because of worsening of rf field uniformity in interaction region [6]. Multi-barrel designs operating on high order modes enable some increase of power, however it implies significant distances of beams from magnetic system axes, resulting in significant transversal components of magnetic field, enlarged current intercept and remarkable thermal problems.

Thus, conventional designs of klystron cavities limit further increase of beams number and output power at fixed voltage. Investigation of opportunities of further power rising of klystrons is of great scientific and practical interest.

2. Physical reasons of rf field nonuniformity in interaction region of toroidal cavity and influence of metamaterial on rf field structure

In axially symmetric toroidal cavity having interaction gap $d \ll \lambda$ (and neglecting channels' influence) electric field component E_z in a gap is described by expression $E_z\left(r,\varphi\right)=E_{0z}J_m\left(kr\right)\exp\left(jm\varphi\right)$ in cylindrical coordinates, where J_m – Bessel function, $k=\frac{\omega}{v}$ – wave number, m – azimuthal index (usually $m=0$). This is pattern of radial standing wave, which exists between two conducting planes of interaction gap. Wave number k and resonance frequency ω are determined by wave phase velocity $v=c$ and impedance, represented by peripheral “inductive” part of the cavity on the ends of interaction region. Thus, rf field structure of axially symmetric fundamental mode inside gap is defined by Bessel function $J_0\left(kr\right)$, which is almost constant at $kr\le 1$, which fundamentally restricts radius of interaction region R_i

$$kR_i \le 0.7 \qquad (1)$$

However if interaction gap is filled by a material to provide diminishing of wave number *k* by means of phase velocity *v* increasing, then according to (1) radius of interaction region R_i can be significantly enlarged without field uniformity degradation. Such artificial material can be realized in the form of periodic or aperiodic array of inductive elements (in simplest case – straight conductors) connecting opposite sides of the gap. Properties of such metamaterials were actively investigated by many authors [7–9], including applications to klystron cavities [10–12]. However in recent case metamaterial was used mainly for field localization in the vicinity of the beam, but not for increasing of dimensions of area with uniform field.

Let's consider field uniformity increasing due to metamaterial influence on example of one-dimensional continuous transmission line model with distributed reactances and resonator based on it. It demonstrates qualitative peculiarities of the oscillations which are also inherent to three-dimensional structures. Relying on equivalent circuit of the line segment having length *dx* (Fig. 1a) dispersion equation can be easily derived:

$$k(\omega)=\sqrt{\frac{L}{L_1}\left(\frac{\omega^2}{\omega_{cut}{}^2}-1\right)} \qquad \omega_{cut}={}^{1}\!\Big/\!\sqrt{L_1C} \tag{2}$$

where *L* [Hn/m], *L*1 [Hn·m], *C* [pF/m] – specific values of reactances of the line (Fig. 1b).

Apparently line with metamterial possesses cut-off frequency ω_{cut}, which depends on inductance of inserts *L*1. If line having length *l* is loaded at both ends by impedances *Z*(*ω*), then the turned out resonator has wave number k_2 and resonance frequency ω_{res} satisfying dispersion equation

$$Z(\omega_{res})-jZ_w(\omega_{res})ctg\left(\frac{k(\omega_{res})l}{2}\right)=0 \qquad Z_w(\omega)=\omega\sqrt{\frac{\omega_{cut}{}^2L_1L}{\omega^2-\omega_{cut}{}^2}} \tag{3}$$

If the ends are open-circuited $Z=\infty$, then the solution of dispersion equation is $\omega_{res}=\omega_{cut}$, $k_2 = 0$, and electric field of the mode will be uniform along all length of the resonator. If impedance of the loads is inductive (Im *Z*(*ω*) is positive), then resonance frequency $\omega_{res}>\omega_{cut}$, solution of equation (3) k_2 is real (Fig. 1b), and electric field distribution along line is described by function $\cos(k_2x)$, which drops down from the center of resonator to its ends. The case is similar to field distribution in conventional toroidal cavities. If impedance of the loads is capacitive (Im *Z*(*ω*) is negative), then resonance frequency $\omega_{res}<\omega_{cut}$, solution of equation (3) k_2 is imaginary (Fig. 1b), and electric field distribution along line is described by function $\operatorname{ch}\left(\left|k_2\right|x\right)$, which increases from the center of resonator to ends. In any case insertion of inductances $L1$ results in decreasing of absolute value of wave number $\left|k_2\right|<\left|k_1\right|$ (Fig. 1b) and field uniformity is enhancing.

3. Resonator with metamaterial for klystron in K_a-band

Practical designs of resonator use array of discrete, but not distributed, inductances. This doesn't qualitatively reshape field structure with respect to previously considered distributed one-dimensional analytical model. In millimeter wave band inductive inserts should have small inductance and can be realized by straight conductors. As example we can consider rectangular ferruleless 21-beam cavity (Fig. 2a) having dimensions 16×16×0.8 mm. Beams are located in region with dimension 12 mm (1.5λ!). Channels are placed with pitch 3 mm, thickness of inductive inserts is 0.5 mm. Frequency of fundamental mode is equal to 37.74 GHz. Adjacent high order mode has frequency 39.01 GHz, separation 1.27 GHz supposed to be sufficient for excluding of influence of high order mode on induced field structure on frequency of fundamental mode.

Uniformity of electric field on all channels is excellent (Fig. 2b). Interaction impedances ρ in 13 channels are in range 3.02–3.13 Ohm (±1.8%) and in 8 «corner» channels impedances drop to 2.74 Ohm (–22%). We can point out, that inductive inserts facilitate localization of electric field around channels and increasing interaction impedances.

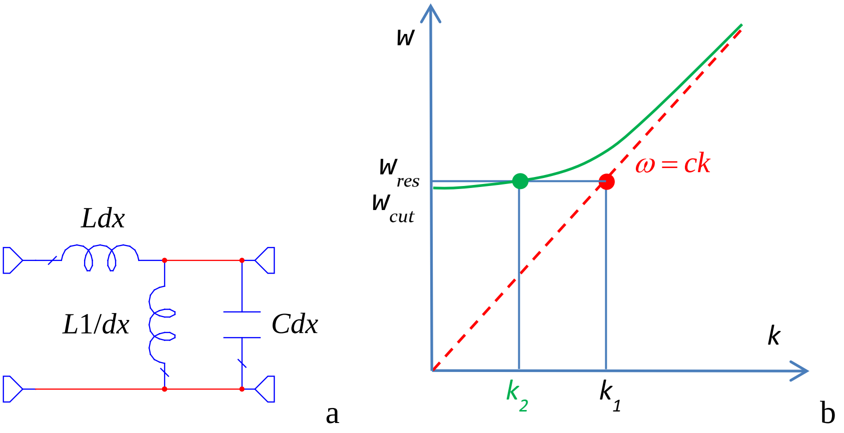

Fig. 1. a – equivalent circuit of transmission line segment of length *dx*;
b – dispersion of the waves in line: with metamaterial realized by inductive inserts $L1$ (solid line) and without metamaterial (dashed line)

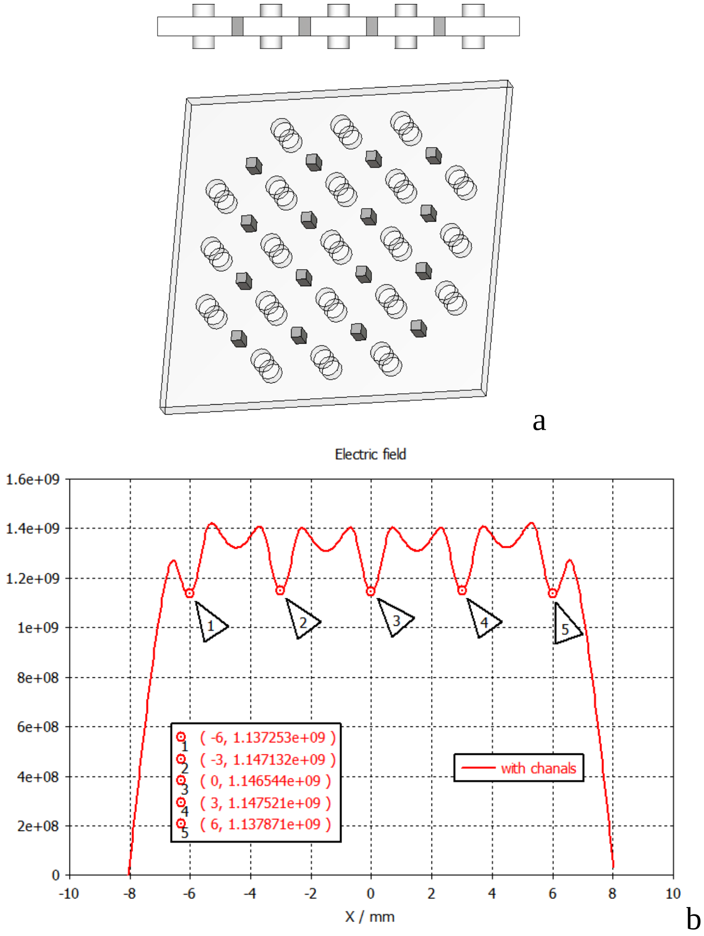

Fig. 2. a – 21-beam cavity for Ka band; b – distribution of longitudinal component of electric field amplitude along central plane of the cavity. Markers show locations of channels axes.

A figure of merit (FOM) of multibeam resonator can be defined as $FOM = \rho N_{beam}$. It describes quality of resonator – potential for achieving large bandwidth. In considered cavity $FOM = 62$ Ohm, which is much greater than $FOM = 23.7$ Ohm of cavity without metamaterial, but using high order mode at the same frequency.

4. Resonator with metamaterial for klystron in S-band

Resonators at frequency 2.856 GHz are widely used in klystrons for electron accelerators. Low operating frequency implies use of inductive inserts having large inductance, which can not be realized by straight conductors. Enlarged inductance can be achieved in helix design, but location of helixes between channels results in significant increasing of diameter of interaction region (and cathode), and also in interaction impedance diminishing. We proposed design with helixes embracing each channel area. This approach provides significant inductance at minor enlarging of interaction region diameter. As example we considered 37-beam cavity (Fig. 3a), where channels form dense hexagonal structure. Each channel has individual helix, embracing beam area, and ferrule, which decreases electric field in the vicinity of the helix (Fig. 3b). Channels diameter is equal to 7 mm, channels pitch 14 mm, partial emitters have diameter 13 mm (beam compression is 3.7). Thus, total cathode diameter is 98 mm, and interaction region diameter is 91 mm (0.87λ). Enlarged helix conductor cross-section 0.7×1.5 mm provides effective cooling of helix through the body of klystron. Helix can be fabricated precisely using laser cutting.

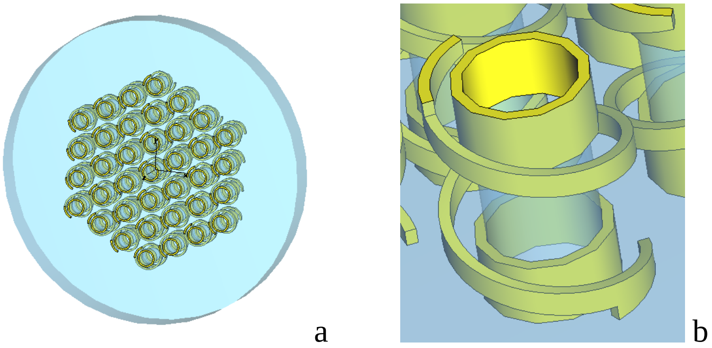

Fig. 3. 37-beam cavity for S band (a); area of partial channel gap with ferrule and helix (b)

Electric field amplitude distribution of fundamental mode in central plane (Fig. 4) demonstrates good equality through all channels.

Interaction impedances in 37 channels are in the range 11.46–11.92 Ohm. Adjacent high order mode is located at frequency 3.11 GHz. Separation 243 MHz (8.5%) is acceptable at narrow operation bandwidth ~0.2%.

On a base of considered resonator high-power klystron in S-band was designed having specifications shown in Table 1.

In that way, klystron output power can be enlarged from 7 to 30 MW at moderate increase of cathode voltage from 52 to 85 kV and fixed cathode diameter 98 mm at expense of slight emission current density growth from 8.2 to 14.9 A/cm^2 and more efficient utilization of cathode area. At the same cathode diameter emission surface area is 2.1 times greater than in annular cathode in prototype klystron. At larger cathode diameter the advantage in current and power becomes even more significant.

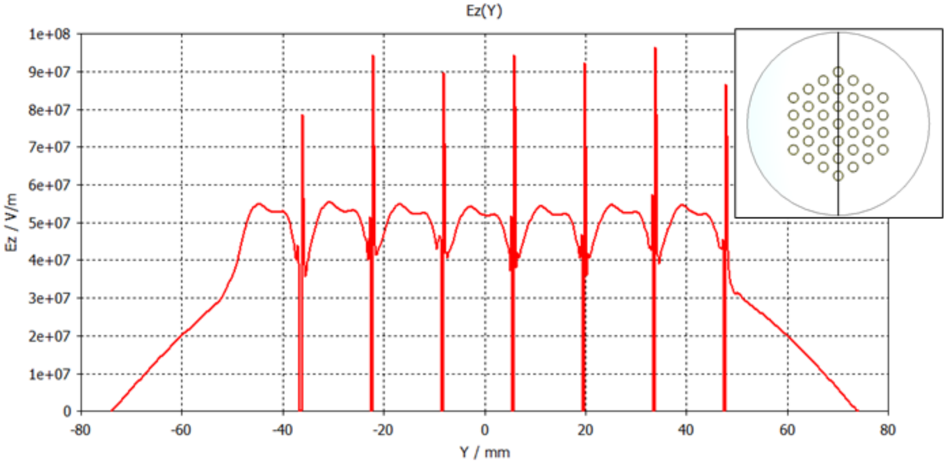

Fig. 4. Amplitude of longitudinal component of electric field vs coordinate Y along resonator’s diameter (see line on inset)

Table 1. Specifications of klystrons

Parameter	**Prototype [4, 5]**	**Considered design**
Power, MW	6–7	30
Number of beams	40	37
Partial beam current, A	4.75	19.83
Cathode voltage, kV	52	85
Total current, A	190	734
Perveance per beam, $\mu A/V^{3/2}$	0.40	0.80
DC power, MW	10	62
Efficiency, %	60	54
Channels diameter, mm	7	7
Partial emitter diameter, mm	8.6	13
Emission current density, A/cm^2	8.2	14.9

5. Conclusion

Analysis of considered examples of resonators demonstrates prospects of metamaterial employing for significant expansion of area of interaction region in multibeam klystron and, therefore, increasing of output power (up to 30 MW in S band) without cathode voltage rising. Number of beams, total current and output power grow proportionally to square of interaction region diameter (and cathode diameter). Such dependence distinguishes this design from conventional annular resonators, where number of beams depends linearly on cathode diameter. In contrast to cavities with high order modes and annular cavities beams in considered design are located more closely to common axes of magnetic system providing small transversal components of magnetic field effecting on electron beams and small current intercept.

Resonators with metamaterial (which can be referenced as metaresonators) can be easily adjusted to frequency of second harmonic of signal facilitating increasing of klystron efficiency and power at operation in high efficiency regimes.

Array of inductive inserts can be designed to be aperiodic making wide opportunities for designers to control rf field distribution in interaction region of klystron.

References

[1] G. Caryotakis, “High energy microwave device research at the Stanford Linear Accelerator Center,” *Proceedings International University Conference*, doi: 10.1109/uhf.1999.787870.
[2] G. Caryotakis, “The future of klystrons,” *Abstracts. International Vacuum Electronics Conference 2000 (Cat. No.00EX392),* doi: 10.1109/ove:ec.2000.847388.
[3] G. Scheitrum, G. Caryotakis, R. Phillips, D. Sprehn, and R. Fowkes, “High power microwave research at SLAC,” *IEEE Conference Record – Abstracts. 1996 IEEE International Conference on Plasma Science*, doi: 10.1109/plasma.1996.551442.
[4] I. Freydovich and M. Vorobiev, “Pecularities of characteristics of annular resonators for multibeam klystrons,” *Electronika. NTB*, no. 2, pp. 9–14, 1998. (in Russ.).
[5] I. A. Guzilov, O. Y. Maslennikov, and A. V. Konnov, “A way to increase the efficiency of klystrons,” *2013 IEEE 14th International Vacuum Electronics Conference (IVEC)*, 2013, doi: 10.1109/ivec.2013.6571181.
[6] A. N. Yunakov and V. I. Pugnin, “Problems and prospects of creation of high-power wideband multibeam klystrons in the middle part of centimeter wave band,” *Electronnaya technika, ser. 1, “SVCh-technika”*, vol. 519, no. 4. pp. 64–67, 2013. (in Russ).
[7] S. E. Bankov, *Electromagnetic crystals*. Moscow, Fizmatlit, 2010. (in Russ).
[8] L. Solymar and E. Shamonina, *Waves in Metamaterials*. Oxford University Press, 2009.
[9] M. V. Davidovich, J. V. Stephuk, and P. A. Shilovskii, “Electrophysical properties of metallic wire photonic crystals,” *Technical Physics*, vol. 57, no. 3, pp. 320–327, 2012, doi: 10.1134/s1063784212030036.
[10] A. Smimov, D. Newsham, and D. Yu, “PBG cavities for single-beam and multi-beam electron devices,” *Proceedings of the 2003 Bipolar/BiCMOS Circuits and Technology Meeting (IEEE Cat. No.03CH37440),* doi: 10.1109/pac.2003.1289636.
[11] A. Smimov, D. Newsham, and D. Yu, “PBG cavities for single-beam and multi-beam electron devices,” *Proceedings of the 2003 Bipolar/BiCMOS Circuits and Technology Meeting (IEEE Cat. No.03CH37440),* doi: 10.1109/pac.2003.1289636.
[12] V. Tsarev, “New Fractal and Photonic Crystal Resonators for Multi-Beam Microwave Vacuum Devices,” *2018 International Conference on Actual Problems of Electron Devices Engineering (APEDE),* 2018, doi: 10.1109/apede.2018.8542362.

Information about the author

Anatoly V. Galdetskiy, Ph.D., head of division, JSC RPC “Istok” n. a. A. I. Shokin, Fryazino, Russian Federation.