https://doi.org/10.46813/2024-151-079

RADIATION IN THE MICROWAVE RANGE AT PULSE ACCELERATORS WITH VIRTUAL CATHODE GENERATOR

V.V. Katrechko[1], D.V. Vinnikov[1,2], O.V. Manuilenko[1,3], O.M. Ozerov[1], I.N. Onishchenko[1], V.I. Tkachev[1], V.B. Yuferov[1], S.V. Marchenko[1]
[1]NSC "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine;
[2]O.Ya. Usikov Institute for Radiophysics and Electronics of the National Academy of Sciences of Ukraine, Kharkiv, Ukraine;
[3]V.N. Karazin Kharkiv National University, Kharkiv, Ukraine
E-mail: katrechko1609@gmail.com

The energy and design parameters of some vircator systems are considered. Calculated cutoff frequencies for the main E and H modes of the DIN-2K accelerator waveguides with electron beam parameters: ~ 15 kA and ~ 185 kV. The characteristic frequencies of oscillations of the virtual cathode depending on the distance of the anode-cathode gap were calculated. Experimentally obtained amplitude-frequency spectra (up to 6 GHz) in the far zone of electromagnetic radiation (Fraunhofer zone) for a horn antenna.

PACS: 29.17.+w, 41.75.Fr, 84.30.Jc, 84.70.+p

INTRODUCTION

The development of powerful microwave generators, such as the virtual cathode generator (vircator), magnetron, klystron, and gyrotron, is essential for advancing sources of powerful microwave radiation. These generators are used to heat plasma, accelerate particles, create powerful radar systems, and meet various scientific, industrial, and military needs [1, 2].

Due to its high power, broad frequency tuning capabilities, and conceptual simplicity, the vircator stands out among other microwave sources. It can generate microwaves with power ranging from tens of MW to several GW and at frequencies from hundreds of MHz to tens of GHz, achieving an energy conversion efficiency into radiation of up to 10% [3]. Measuring the power and frequency spectrum of such signals poses a challenge due to the short pulse durations, typically ranging from hundreds of picoseconds to hundreds of nanoseconds, and the inertia of traditional sensors. Consequently, there is increasing attention on sensors based on semiconductor elements [4]. These are capable of measuring both the peak and average radiation power across a broad range of frequencies and pulse durations.

OVERVIEW OF THE PARAMETERS OF SOME VIRCATOR SYSTEMS

Modern research on varactors primarily focuses on increasing their output power and stabilizing either one- or two-mode generation. Most coaxial systems consist of cathodes, usually tubular in shape. When a pulsed negative voltage of 150…500 kV is applied, the process of explosive emission begins, leading to the formation of an electron flow. This flow moves toward the anode, which may be a grid or a thin foil galvanically connected to an external chamber. When certain critical conditions, dependent on the electron beam current and the system's geometry, are met, a virtual cathode forms behind the grid or foil. The oscillations of electrons in this area generate radiation in the HF and UHF ranges. Vacuum conditions are essential for the operation of a vircator; in most systems, the pressure is approximately $(1…5)\cdot10^{-5}$ Torr.

As energy sources, the following can be used: Tesla transformers [5], SOS diodes (a type of semiconductor diode made using silicon deposited on a sapphire substrate, providing high electrical insulation and improved characteristics in high-frequency modes), Marx generators [6], plasma current switches [7–11].

The experiments detailed in [7] demonstrate that a vircator equipped with a plasma erosion switch can generate microwave radiation at frequencies close to the plasma frequency of the electrons in the injected beam. This advancement opens up new possibilities for simplifying the design and enhancing the efficiency of microwave generators by eliminating the need for focusing magnetic fields and metal anodes. At the same time, the maximum radiation power of the device reaches (50±10) MW within a frequency range of 2.5 to 3.0 GHz. Meanwhile, the frequency of the electron beam achieves 2.4 GHz at an energy level ranging from (1±0.15) MeV.

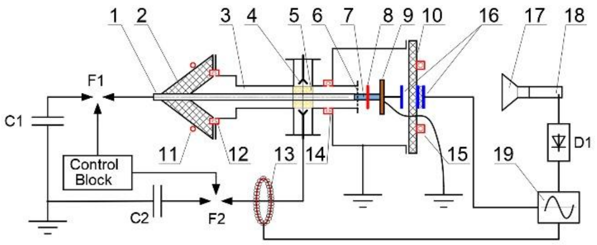
In [12], comprehensive research, including simulations (PIC modeling) and experiments, was carried out to evaluate the influence of the position of the ring reflector on the power of microwave radiation in a system with a coaxial vircator. The distance between the anode and the reflector varied from 6 mm to 24 mm in steps of 3 mm. It has been shown that optimization of the hole diameter of the ring reflector in the axial vircator can increase the microwave power by 2.1 times, reaching a peak power of 23.67 MW at a hole diameter of 120 mm, with frequency generation ranging from 5.3 to 5.8 GHz.

Separate studies were conducted with different types of cathodes. For example, in [13], the Marx generator was used as an energy source with a beam voltage of 245…300 kV and a current of 17…19 kA. Cathodes made of two materials were compared: graphite and polymer corduroy. The study indicated that the corduroy cathode showed better results, attributed to a higher peak power of microwave radiation (specific values were not provided). The authors also noted that the maximum power is achieved due to the anode-cathode gap, which is equal to 12.5 mm.

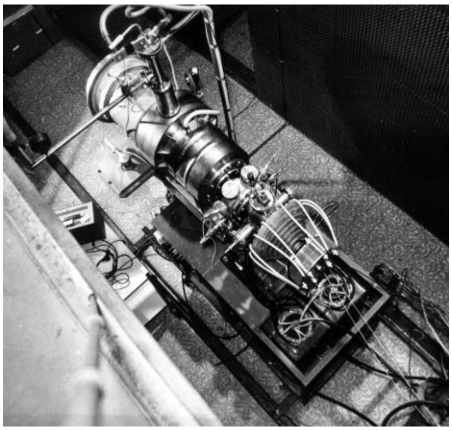
In [14], a system consisting of a vircator with an anode grid, which has a transparency of 65%, is presented. To increase the output power and control frequencies, a resonant cavity was utilized: a movable disk plate with a central hole located at a certain distance from the anode. The authors noted that this configuration of the resonator installation helps increase the output power by 15% and achieve a two-mode operation (suppressing non-resonant frequencies and sharpening the band of microwave radiation).

GEOMETRY AND RADIATION CHARACTERISTICS OF THE DIN-2K EXPERIMENTAL INSTALLATION

A schematic diagram depicting the placement of the diagnostic equipment and a photograph of the accelerator are shown in Fig. 1.



a



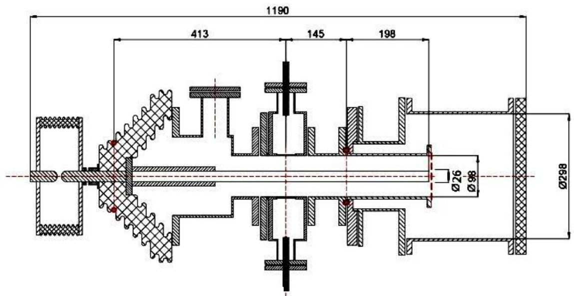
b

Fig. 1. Accelerator with vircator (a – schematic diagram with location of diagnostic equipment, b – photo, top view):
1 – Tubular cathode with a diameter of 26 mm;
2 – High-voltage insulator; 3 – Camera body (anode of the coaxial line); 4 – Radially located plasma guns;
5 – Plasma current switch formation point;
6 – Anode mesh; 7 – Electron beam; 8 – Virtual cathode; 9 – Beam collector; 10 – End flange made of organic glass; 11–15 – Rohovsky belts; 16 – Capacitive voltage divider; 17 - Receiving horn antenna;
18 – Coaxial waveguide transition; 19 – Oscilloscope; C1 and F1, C2, and F2 – Capacitance and air-controlled discharger of plasma guns (PG) and pulse current generator (PCG);
D1 – Microwave diode; Control Block – Control block

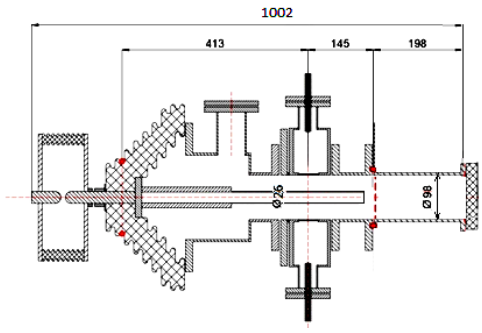
The experimental installation is an accelerator with an inductive energy accumulator and a plasma current switch, with the following parameters:

- Maximum PCG current: ~80 kA;
- Beam current: ~8…15 kA;
- Voltage on the high-current diode: ~200 kV.

The vacuum chamber of the accelerator serves as a waveguide emitting electromagnetic waves in the HF and UHF ranges into the external environment. Currently, there are 2 systems with different geometric dimensions, as shown in Fig. 2.



a



b

Fig. 2. The schematic of the accelerator with marked overall dimensions. Panel (a) corresponds to a system with an output diameter of 298 mm, while panel (b) corresponds to a system with a diameter of 98 mm

The configuration system depicted in Fig. 2,a features a cascade waveguide geometry with a transition in diameters from 98 to 298 mm. The transition to a larger diameter reduces the critical current required for the formation of a virtual cathode behind the grid anode. A notable feature of the system is the generation of radiation in multimode mode, while a drawback is the difficulty in achieving high vacuum levels in the area of virtual cathode formation.

The configuration system depicted in Fig. 2,b features a waveguide without diameter differences (d = 98 mm), as well as a shorter cathode.

The cut-off frequencies of the main modes are defined by:

$$f_c = \frac{c}{2\pi}\frac{\eta_{mn}}{R}, \quad (1)$$

where f_c is the cut-off frequency, Hz; c is the speed of light, m/s; η_{mn} is the m-th root of the n-th Bessel function for E-modes and the first derivative of the Bessel function for H-modes; R is the waveguide radius, m.

The calculated values for both types of waveguides are shown in the graph of Fig. 3.

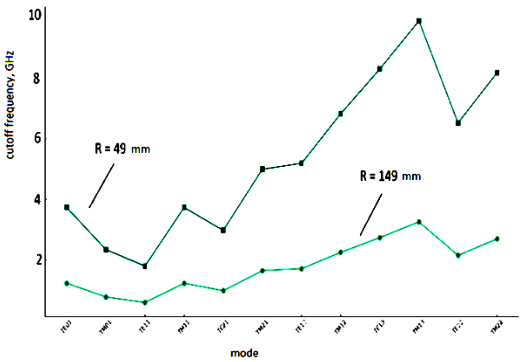


Fig. 3. Cut-off frequencies of the fundamental radiation modes for different configurations of the vacuum chamber – accelerator wavecode with a vircator

At the same time, it should be noted that an axially symmetric beam is capable of exciting only TM modes. To ensure the excitation of microwave radiation in a single-mode mode (for example, in TM01), it is necessary for the oscillation frequency of the virtual cathode to be higher than the cut-off frequency for the TM01 mode and lower than the cut-off frequency of the TM02 mode. Thus, the TM01 mode will be excited, and the TM02 mode will be suppressed, since the frequency of the virtual cathode will fall within the range between these two frequencies.

FREQUENCY OF OSCILLATIONS OF THE VIRTUAL CATHODE OF THE ACCELERATOR

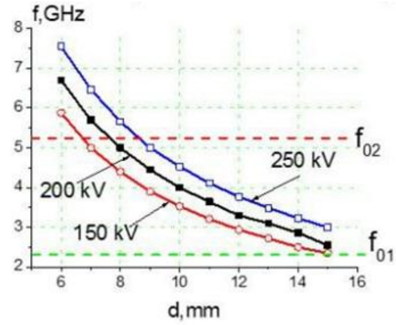
As indicated by experiments and numerical simulations [1, 2], a reliable estimate for the beam oscillation frequency, depending on the parameters of the high-current diode, can be expressed as follows:

$$f_W = c\ln(\gamma + \sqrt{\gamma^2 - 1})/2\pi d. \qquad (2)$$

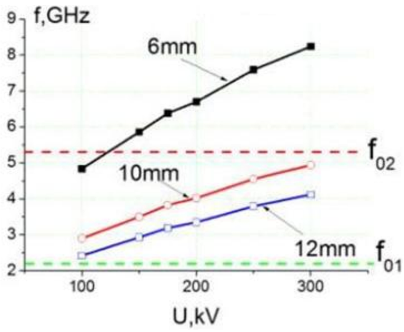
Thus, to excite microwave oscillations in an axially symmetric vircator with a frequency f, at a given beam voltage U, it is necessary to determine the distance d between the cathode and the grid of the high-current diode such that the frequency of the virtual cathode oscillations is close to the frequency f. This can be achieved using equation (2):

$$d = c\ln(\gamma + \sqrt{\gamma^2 - 1})/2\pi f \ , \qquad (3)$$

where $\gamma = 1 + U/m_e c^2$. Using (2), we can estimate the operating frequency of the vircator for the waveguide chamber with a radius R = 49 mm, depending on the voltage parameters of the high-current diode and the anode-cathode gap distance (Fig. 4).



a



b

Fig. 4. The dependencies of the oscillation frequency of the virtual cathode on the length of the anode-cathode gap (a) and the voltage on the high-current diode (b)

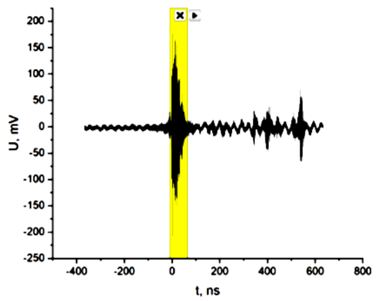
As can be seen, the optimal anode-cathode gap distance for the available voltage values on the diode is approximately d ~ 8…12 mm.

EXPERIMENTAL ANALYSIS OF THE FREQUENCY SPECTRUM OF THE RADIATION OF THE ACCELERATOR

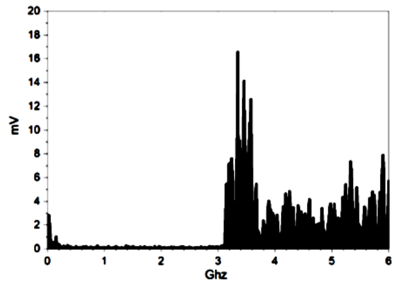
To analyze the generated frequency spectrum of discharge, an external measuring path located in the far zone (Fraunhofer zone) was utilized. It consisted of:

- Receiving antenna: waveguide (aperture 72x34 mm for a chamber with a radius of 149 mm (f_c ~ 2.08 GHz), and aperture 47x22 mm for a chamber with a radius of 49 mm (f_c ~ 3.1 GHz);
- Shielded coaxial cable RK-50;
- Oscilloscope with a bandwidth of 6 GHz.

The Fast Fourier Transform was used for the analysis under the experimental conditions of U = 150…180 kV and a distance of d = 12 mm between the cathode and the mesh anode. The results for both types of accelerator vacuum chamber-waveguide geometry are presented in Figs. 5 and 6.

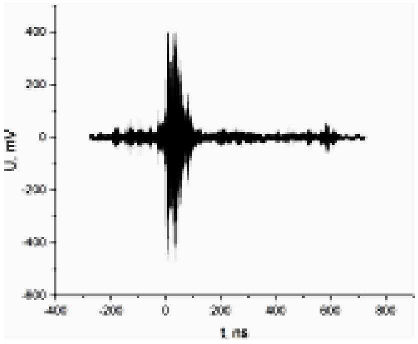


a

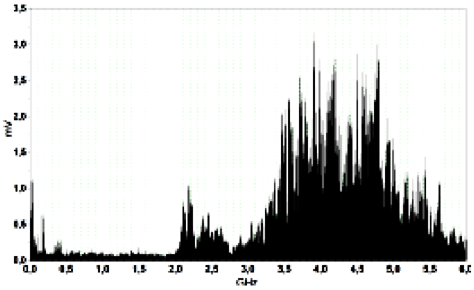


b

Fig. 5. Oscillogram (a) and frequency spectrum of the signal (b) for the chamber with a radius of R = 49 mm



a



b

Fig. 6. Oscillogram (a) and frequency spectrum of the signal (b) for the chamber with a radius of R = 149 mm

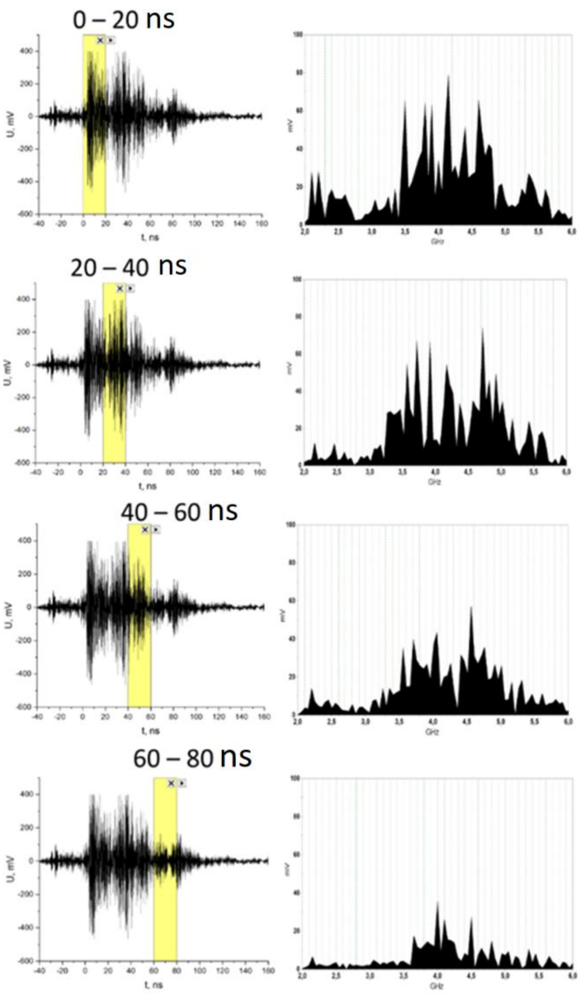


Fig. 7. Displays the time-stretched oscillogram and corresponding spectra with a 20 ns step, covering the range from 0 to 80 ns

From the oscillograms, it can be observed that the duration of the microwave pulse is approximately 80…100 ns, which coincides with the duration of the current interruption, and hence, with the duration of the induced voltage and, consequently, with the duration of the beam pulse. Fourier analysis revealed that in the microwave spectrum, when using a waveguide with R = 149 mm, frequencies in the range of 3…5 GHz predominate, and the spectrum itself has a broadband shape. Conversely, when using a waveguide with R = 49 mm, the frequency spectrum is more pronounced in the range of 3.5…4 GHz.

Depending on the selected time interval of the microwave pulse of the vircator generation, its carrier microwave frequencies must vary. The shape of this dependence should correspond to the shape of the electron beam current pulse.

In Fig. 7, the time-stretched signal and the corresponding frequency spectra with a 20 ns step for the waveguide chamber with R = 149 mm are depicted.

In Fig. 8, a graph depicting the dependence of the main carrier frequency on the generation pulse time is presented.

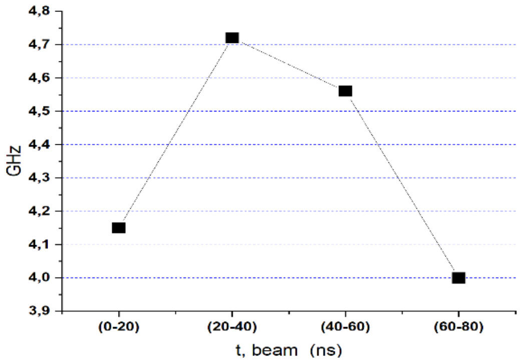


Fig. 8. Graph of dependence of maximum frequencies on the time interval of radiation generation

As evident from Figs. 7 and 8, the main carrier frequency fluctuates within the range of 4 to 4.7 GHz throughout the entire pulse duration, peaking at around 40…50% of the total pulse length, and roughly mirroring the shape of the electron beam current pulse.

CONCLUSIONS

A bibliographic review of systems based on a vircator revealed that the generation of electromagnetic radiation necessitates an electron beam possessing the following parameters: U ~ 150…500 keV and I ~ 4…20 kA under vacuum conditions of P ~ (1…5)·10^{-5} Torr, with an anode-grid or thin foil positioned at a distance of 6…12 mm from the cathode.

Resonators featuring diaphragms of specific apertures, cascade geometries, dielectric inserts, polymer cathodes, gas injection, among other techniques, are employed to enhance efficiency and selectively choose individual modes.

For an accelerator equipped with a DIN-2K plasma current switch:

- Cutoff frequencies of the main radiation modes were calculated and compared for different waveguide geometries (R = 49 and 149 mm).

- The optimal distance between the anode and the cathode for virtual cathode (VC) generation in single-mode mode was determined at operating voltages, ranging from 8 to 12 mm.
- Experimental oscillograms and frequency spectra of microwave radiation from the accelerator discharge, lasting approximately 80…100 ns, were obtained. For the waveguide with R = 149 mm, frequencies in the range of 3…5 GHz predominated, with a broadband spectrum shape. Conversely, when using a waveguide with R = 49 mm, the frequency spectrum was more pronounced in the range of 3.5…4 GHz.
- It was observed that the main carrier frequency throughout the entire pulse duration approximately mirrored the shape of the electron beam current pulse.

REFERENCES

1. *HighPower Microwave Sources and Technologies* / R.J. Barker and E. Schamiloglu, Eds. New York: Wiley-IEEE Press, 2001.
2. J. Benford, J. Swegle, and E. Schamiloglu. *High Power Microwaves*. New York: Taylor & Francis, 2007.
3. D.J. Sullivan, J.E. Walsh, and E.A. Coutsias. Virtual cathode oscillator (vircator) theory // *High Power Microwave Sources* / V. Granastein and I. Alexeff. Eds. Norwood, MA: Artech House, 1987, p. 441.
4. Rishi Verma, Rohit Shukla, Surender Kumar Sharma. Characterization of High Power Microwave Radiation by an Axially Extracted Vircator // *IEEE Transactions on Electron Devices*. January 2014, v. 61, issue 1, p. 141-146.
5. Jiancang Su, et al. An 8-GW long-pulse generator based on Tesla transformer and pulse forming network // *Rev. Sci. Instrum*. 2014, v. 85, p. 063303; https://doi.org/10.1063/1.4884341
6. H. Zhang, T. Shu, S. Liu, Z. Zhang, L. Song, H. Zhan. A compact 4 GW pulse generator based on pulse forming network-Marx for high-power microwave generation // *Rev. Sci. Instrum*. 2021, v. 92, p. 064707; DOI: 10.1063/5.0040111
7. А.Г. Жерліцин, В.С. Лопатін, О.В. Лук'янов. Віркатор з плазмоерозійним розмикачем // *Листи в ЖТФ*. 1990, т. 16, в. 11, р. 69-72.
8. D.V. Vinnikov, V.V. Katrechko, O.M. Ozerov, V.I. Tkachev, S.V. Marchenko, V.B. Yuferov, O.V. Manuilenko, Influence of the energy parameters of the primary circuit on the current characteristics of the din-2k accelerator // *Problems of Atomic Science and Technology*. 2023, N 4(146), p. 36-40.
9. O.V. Manuilenko, I.N. Onishchenko, A.V. Pashchenko, I.A. Pashchenko, V.B. Yuferov. Current Flow Dynamics in Plasma Opening Switch // *Problems of Atomic Science and Technology.* 2021, N 4(134), p. 6-10.
10. O.V. Manuilenko, I.N. Onishchenko, A.V. Pashchenko, I.A. Pashchenko, V.A. Soshenko, V.G. Svichensky, V.B. Yuferov, B.V. Zajtsev. Magnetic Field Dynamics in Plasma Opening Switch // *Problems of Atomic Science and Technology.* 2021, N 6(136), p. 61-66.
11. O.V. Manuilenko, I.N. Onishchenko, A.V. Pashchenko, I.A. Pashchenko, V.B. Yuferov. Plasma and Magnetic Field Dynamics in POS: PIC simulations // *Problems of Atomic Science and Technology*. 2022, N 6(142), p. 55-59.
12. S.-H. Kim, C.-J. Lee, W.-I. Kim, K.-C. Ko. Experimental Investigation into the Optimum Position of a Ring Reflector for an Axial Virtual Cathode Oscillator // *Electronics*. 2021, v. 10, p. 1878; https://doi.org/10.3390/electronics10161878
13. Reghunatha Menon, Amitava Roy, S.K. Singh. High power microwave generation from coaxial virtual cathode oscillator using graphite and velvet cathodes // *Journal of Applied Physics.* 2010, v. 107, issue 9.
14. Tsukasa Nakamura, et al. *Output Evaluation of Microwave Pulse Emitted from Axially-Extracted Vircator with Resonance Cavity* / Hasegawa, Jun (ed.). Tokyo Institute of Technology, Tokyo (Japan), Jan 2018, p. 55-60.

Article received 30.04.2024

ВИПРОМІНЮВАННЯ У НВЧ-ДІАПАЗОНІ НА ІМПУЛЬСНИХ ПРИСКОРЮВАЧАХ З ВІРТУАЛЬНИМ КАТОДНИМ ГЕНЕРАТОРОМ

В.В. Катречко, Д.В. Вінніков, О.В. Мануйленко, О.М. Озєров, І.М. Оніщенко, В.І. Ткачов, В.Б. Юферов, С.В. Марченко

Розглянуто енергетичні та конструктивні параметри деяких віркаторних систем. Розраховано частоти відсічки для основних Е- та Н-мод хвилеводів прискорювача ДІН-2К з параметрами електронного пучка: ~ 15 кА та ~ 185 кВ. Обчислено характерні частоти коливань віртуального катода у залежності від відстані анод-катодного проміжку. Експериментально отримано амплітудно-частотні спектри (до 6 ГГц) у дальній зоні електромагнітного випромінювання (зоні Фраунгофера) та рупорну антену.