Operation of a Six-Cavity *S*-Band Relativistic Magnetron at Frequencies in the Range of Its Resonant Response

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***Abstract*— Experimental research on the influence of the frequency characteristic of the anode block on the parameters of relativistic *S*-band magnetron operation is described. A magnetron with a six-vane anode block was powered by a linear induction accelerator (350 kV, 2.5 kA, and 150 ns). It was found that the shift in the resonance frequency of the magnetron anode block cavity into the range of the frequencies obtained during the magnetron operation is affected by the change in the design of the magnetron output and leads to highly efficient ($\eta \geq 40\%$) microwave generation in a relatively narrow magnetic field range. This efficiency remains high during the entire duration ($\tau \approx 100$ ns) of the microwave pulse, and the decrease in the electric field anode–cathode gap during the fall time of the applied voltage does not cause a drift in the frequency of the generated microwaves.**

***Index Terms*— Frequency stability, relativistic magnetron (RM).**

I. Introduction

AMONG the different types of high-current microwave generators, the relativistic magnetron (RM), the operation of which has been described in [1]–[3], can be considered as a powerful and efficient device. An RM can generate microwave pulses with a $\sim 10^3$ times larger power than the commonly used non-RMs with thermionic emission cathodes. However, when an RM is applied, the most important parameters, such as the frequency stability and efficiency of the microwave generation, are significantly worse than those obtained when using magnetrons having thermionic cathodes. There are also other problems specifically related to the RM operation. High-voltage and high-current generators can generate pulses with a duration of several hundreds of nanoseconds. However, the duration of the microwave radiation generated by an RM powered by pulses of such a long duration is significantly shorter. Research on this problem is being conducted at the University of Michigan with an RM powered by the Michigan Electron Long Beam Accelerator [4], [5] and with a recirculating planar magnetron [6]. When an RM is operated with a short (a few tens of nanoseconds) duration voltage pulse, a fast start of the microwave generation with respect to the beginning of the applied voltage pulse becomes important. This problem and ways to increase the efficiency of the microwave generation are being investigated both experimentally and using 3-D numerical simulations at the University of New Mexico [7]–[11]. When an RM is operated with a resonance load, the stability of the frequency of the generated microwaves becomes a crucial issue [12], [13]. In this paper, the results of experimental research on different factors that influence the frequency stability of microwaves generated in a six-vane RM are reported.

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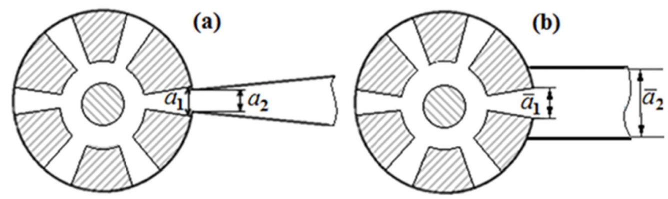

Fig. 1. Schemes of six-vane *S*-band magnetron. (a) Output of the microwave power through linearly expanding waveguide $\Gamma_A = 0.16$. (b) Output of the microwave power through conventional waveguide $\Gamma_B = 0.42$. a_1, a_2, and $\bar{a}_2$ are the heights of the magnetron output slot, linearly expanding waveguide, and conventional waveguide, respectively.

In the description of the operation of a non-RM, its slow-wave structure can be considered as a locked ring-type sequence of resonators. In this system, only the excitation of electromagnetic (e/m) oscillations with frequencies having a phase shift of $2\pi n$ ($n = 1, 2, \ldots$) along the entire length of the slow-wave structure will be realized. Thus, this magnetron presents a resonator with a large Q-factor providing oscillation frequency stability, and respectively, highly efficient transfer of the electron beam energy to the energy of the microwave radiation. The degree to which the magnetron resonators are locked and the value of the Q-factor are mainly determined by the design of the microwave power output: there are magnetrons with radial [14]–[16] and axial (diffraction) [17]–[19] outputs. In this paper, the results of the operation of an RM with radial output of the microwave power are discussed. It is shown that the change in the design of the RM output allows one to achieve significantly more efficient e/m radiation generation and to stabilize the frequency of the generated e/m waves.

In [20]–[22] on an RM with radial output, the microwave power was extracted through a $a_2 = 10$ mm wide slot made in the wall of the anode block [see Fig. 1(a)].

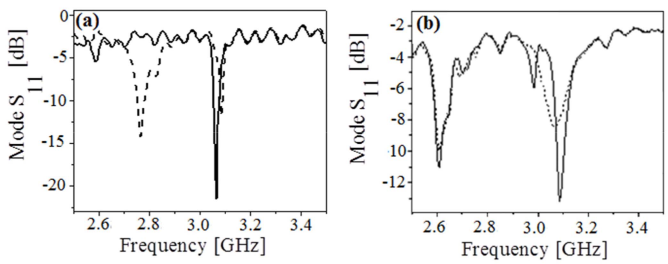

Fig. 2. Frequency response of the magnetron's resonator in the case of power extraction into (a) linearly expanding waveguide and (b) conventional waveguide. The dashed curve represents the case of the anode block without the cathode and the solid curve represents the case with a cylindrical cathode having a diameter of 21 mm.

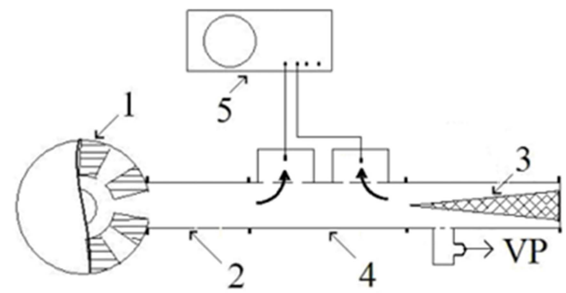

Fig. 3. Experimental scheme. 1—magnetron, 2—standard waveguide with cross section 34×72 mm^2, 3—conical microwave load and VP—vacuum port, 4—cross-guide directional coupler (ARRA 284-A-6-7-50NF) coupling is of −50 dB, and 5—Digitizing oscilloscope (Agilent Infiniium DS080404B, 4 GHz, and 40 GS/s).

The height, $h = 72$ mm, of the slot was the same as the axial length of the anode block resonator having a width $a_1 = 14$ mm. Outside the anode block, the slot was connected to a waveguide; the height of its E-plane wall was increased and its cross section was 34×72 mm^2 at its end, which is typical for a conventional waveguide. The design where the output resonator was practically completely open and the cross sections of the slot and waveguide were almost the same size provided a high electrical breakdown threshold for the output microwave power. However, this slot design decreases the coupling between the anode resonators, and respectively, consideration of the anode block as consequence of locked ring-type resonators becomes questionable. In this case, i.e., when a high level of matched microwave power is realized from one of the anode resonators, one can consider that the RM operates as a nonlocked ring-type slow-wave structure [23]. In this case, the magnetron operates as an M-type traveling wave tube with azimuthally distributed electron emission from the cathode.

One can significantly increase the reflection of the e/m wave from the connection between the resonator output and waveguide while retaining the high breakdown threshold of the electric field. This can be achieved by a completely opened resonator output connected to a waveguide having a height larger than the height of the resonator output slot. For instance, one can use a conventional waveguide with a cross section 34×72 mm^2 [see Fig. 2(b)] for this purpose.

II. Frequency Parameters of the Anode Block Without Electron Beam (Cold Measurements)

The reflection coefficient Γ of the e/m wave from the connection between the resonator output and waveguide can be determined as the reflection coefficient from the connection between two waveguides having different wave impedances ρ_1 and ρ_2. Neglecting waves with high harmonic indexes, one can calculate the value of Γ as [24]

$$\Gamma = (\rho_2 - \rho_1)/(\rho_2 + \rho_1). \quad (1)$$

The ratio between the wave impedances of two waveguides with equal width and different heights (a_1 and a_2) is

$$(\rho_2/\rho_1) = (a_2/a_1). \quad (2)$$

Using (1) and (2), one obtains that, when the microwave power is extracted in linearly expanding and conventional waveguides, the reflection coefficients are $\Gamma_A = 0.16$ and $\Gamma_B = 0.42$, respectively, i.e., the reflection coefficient increases almost three times. Besides increasing the power of the reflected e/m wave, the change in the design of the output slot also changes the phase of the reflected e/m wave. In general, the reflection coefficient is a complex value. The phase of the reflected e/m wave changes the phase shift of the e/m wave along the entire length of the slow-wave structure. Therefore, the change in the reflected e/m wave changes the frequency characteristics of the anode block, which is considered as one resonator volume.

A comparison between the frequency responses of the RM anode block for the considered microwave power outputs is shown in Figs. 2 and 3. The resonance frequencies of the magnetron's resonator were determined by the minimum value of the reflection coefficient S_{11} of the e/m wave reflected from the magnetron input. The measurements of this reflection coefficient were conducted using a Network analyzer (ROHDE & SCHWARZ—ZVL 9 kHz–6 GHz).

The frequency responses of the magnetron's resonator when the power is extracted into a linearly expanding waveguide are shown in Fig. 2(a). One can consider that, without the cathode, the resonator is formed by the waveguide that is rolled into a ring having six cavities. In this case, the anode block cavity has two resonance frequencies, namely, $f_W \approx 2.7$–2.8 GHz and $f_R \approx 3.1$ GHz [see the dashed curve in Fig. 2(a)]. However, when a 21-mm-diameter cathode is placed coaxially inside the anode block, one obtains only one resonance frequency $f_R \approx 3.1$ GHz [see the solid curve in Fig. 2(a)]. This frequency is significantly larger than those of the microwave radiation that were obtained in the recent experiments [21]–[23] with an RM where the microwave radiation was extracted into a linearly expanding waveguide. Here, let us note that with a transparent cathode [8] having the same diameter as the solid cathode, both the resonance frequencies remain, with one of these frequencies in the band of the RM generated frequencies. The frequency responses of the magnetron's resonator when the microwave power is extracted into a conventional waveguide are shown in Fig. 2(b). In this case, the cold lower resonance frequency of the anode block also remained with the cathode, but below the generated frequencies of the RM.

An increase in the value of the reflection coefficient of the e/m wave from the output slot can also be achieved by placing a diaphragm at that location. However, it was found that applying the diaphragm leads to a decrease in the resonance frequency and its shift from the RM generated frequencies. Therefore, in this paper, the RM was not operated with a variable height of the output slot.

III. Experimental Setup

A scheme of the experimental setup is shown in Fig. 3. The anode block consists of six vanes having a 40° span (see item 1, Fig. 3) and resonance cavities expanding at an angle of 20° between these vanes. From the front and back sides, the vanes are closed by ring-type flanges, which limits the resonance cavities in the axial direction. This RM design was used in the first experiments on the operation of an RM powered by a supply with a relatively low output impedance [14], [15], and this design was soon successfully adapted to a power source with high internal impedance [6].

In the present experiments, the RM was powered by a linear induction accelerator [25] [voltage and current amplitudes ≤350 kV and ≤4 kA, respectively and pulse duration $\tau \approx 100$ ns at full-width at half-maximum (FWHM)] operating with a repetition rate of 1 Hz. A calibrated capacitive voltage divider and self-integrated Rogowski coils placed in the vicinity of the RM were used to measure the waveforms of the voltage $U_{\mathrm{AC}}(t)$ applied to the anode–cathode gap of the magnetron and the current $I_B(t)$ of electrons emitted from the boundary of the explosive emission plasma formed at the cathode surface. The external constant magnetic field, varied in the range 0.18–0.5 T, was produced by Helmholtz coils supplied by a dc current. A background pressure of ∼0.8 mPa in the magnetron was maintained by three turbomolecular pumps, one of which was connected to the output waveguide.

The microwave radiation was extracted through the slot made in the anode block into a conventional waveguide with a cross section 34×72 mm^2 (see item 2, Fig. 3). This radiation was absorbed by a conical waveguide load (see item 3, Fig. 3). The microwave radiation power and the control of the matching of the conical waveguide load were obtained using a directional cross-guide coupler (−50 dB) (see item 4, Fig. 3). The parameters of the microwaves were measured and analyzed using a digitizing oscilloscope (Agilent Infiniium DS080404B) with a bandwidth of 4 GHz (see item 5, Fig. 3). The frequency parameters of the microwave radiation were determined using fast Fourier transform (FFT) analysis when only one channel of the digitizing oscilloscope was used, resulting in a sampling rate of 40 GS/s.

IV. Experimental Results

The operation of a magnetron with radial extraction of microwave radiation into a linearly expanding waveguide was investigated rather comprehensively in [10]–[13]. In the current experiments, when the output resonator slot was connected with the linearly expanding waveguide [see Fig. 1(a)], the microwave power increased gradually with the increase in the magnetic field in the range 0.2–0.34 T. At larger values of magnetic fields, a fast decrease in the microwave power and microwave pulse duration was obtained. The duration of the microwave pulse with bell-like form was ≤50 ns at FWHM, even for pulses with maximum microwave power.

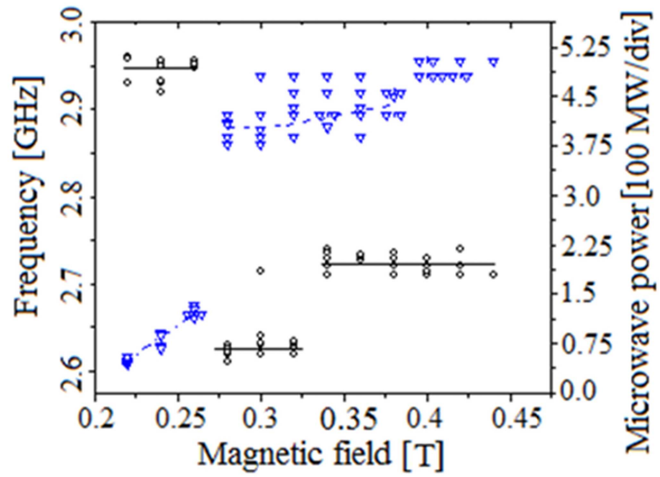

Fig. 4. Dependencies of the microwave power (triangles) and frequency corresponding to the maximum FFT of the microwave pulse (circles) versus the magnetic field when the microwave power was extracted into a conventional waveguide.

The dependence of the RM microwave power on the magnetic field when the power was extracted into a conventional waveguide is shown in Fig. 4 (triangles). One can see that the increase in the magnetic field in the range 0.2–0.26 T leads to a monotonic increase in the microwave power, the level of which is almost the same as in the case of microwave power extraction into a linearly expanding waveguide. However, a further increase in the magnetic field leads to a sharp almost threefold increase in the power of the microwave pulses. Moreover, in the magnetic field range 0.28–0.38 T, one obtains stable operation of the RM with fluctuation $\Delta P = \pm 10\%$ in the peak power, which was calculated as the average value of the power obtained in five single RM pulses. Let us note that the error in the power determination in a single RM pulse was significantly smaller than the measured fluctuation in power. It is important to note that in the magnetic field range 0.32–0.34 T, the duration of the microwave pulse with almost constant power increases, reaching $\tau \geq 100$ ns. Typical waveforms of the cathode current and microwave power obtained at a magnetic field in the range 0.28–0.38 T are shown in Fig. 5(a).

Let us determine the efficiency of microwave generation as $\eta(t) = [P_{\mathrm{MW}}(t)/P_{\mathrm{BEAM}}(t)] \times 100\%$, where $P_{\mathrm{MW}}(t)$ is the microwave power and $P_{\mathrm{BEAM}}(t) = U_{\mathrm{AC}}(t) \cdot I_B(t)$ is the power of the electron beam. The time dependence of the electron beam power and efficiency of the microwave generation when the applied magnetic field is 0.38 T is shown in Fig. 5(b). One can see that the efficiency of the microwave generation is almost constant during ∼70 ns, which corresponds to the duration of the maximum power of the electron beam and that the efficiency is in the range $45 \pm 5\%$. Further increase in the magnetic field leads to a decrease in the duration of the microwave generation. The change in the duration and amplitude of the microwave pulse with the increase in the

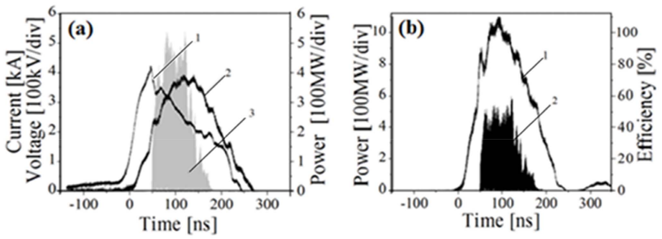

Fig. 5. (a) Typical waveforms of the (1) voltage, (2) current, and (3) microwave power. (b) Time dependence of the (1) electron beam power and (2) efficiency of the microwave generation. Magnetic field is 0.32 T.

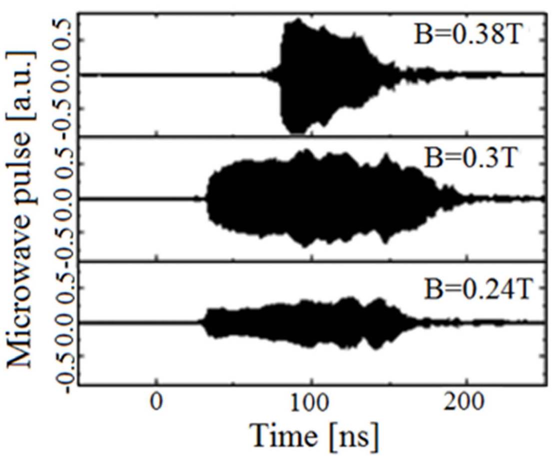

Fig. 6. Time evolution of the microwave pulse obtained from directional cross-guide coupler (see item 4, Fig. 3) at different magnetic field values.

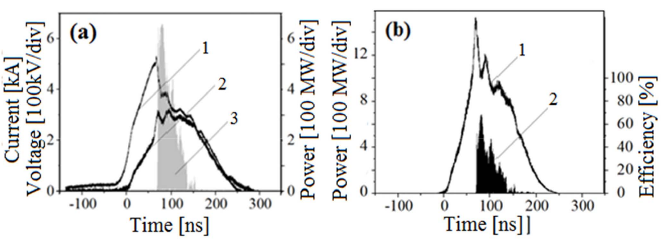

Fig. 7. (a) Waveforms of the (1) voltage, (2) current, and (3) microwave power. (b) Time dependence of the (1) electron beam power and (2) efficiency of microwave generation. Magnetic field is 0.44 T.

magnetic field is shown in Fig. 6. At a magnetic field in the range 0.4–0.44 T, the duration of the microwave generation decreases and does not exceed $\tau < 30$ ns. Typical waveforms of the voltage, current, and microwave power for this case are shown in Fig. 7(a). One can see that similar to the case of magnetic field 0.32 T [see Fig. 5(a)], the beginning of the microwave generation is accompanied by fast increase in the RM current and decrease in the voltage amplitude. This ampere/volt dependence, typical for the RM operation was described in the earlier research (see [15]) and is related to the appearance of the drift of electrons toward the anode leading to an increase in the total RM current. The latter causes the decrease in the amplitude of the voltage because of finite impedance of the linear induction accelerator.

Let us note here that the operation of the RM in the magnetic field range 0.4–0.44 T was characterized by the efficiency of the microwave generation being maximal, namely, $\eta \approx 70\%$ [see Fig. 7(b)]. In addition, one obtains a very fast increase in the e/m wave oscillations in the magnetron, similar to those obtained in [8] where the operation of an RM with a transparent cathode was investigated. In the current experiments, the microwave radiation power $P_{\mathrm{MW}} \geq 400$ MW was increased during $\Delta t \approx 1 \div 1.5$ ns (three to five periods of oscillations). However, the operation of the RM at a magnetic field in this range was not stable. That is, during the operation with a repetition rate of 1 Hz, microwave pulses with a peak power up to 600 MW were interchanged with pulses having negligibly small microwave power. At a magnetic field $\geq$0.46 T, microwave generation was not obtained.

The change in the design of the microwave radiation output also leads to a change in the frequency characteristics of the microwave radiation. In fact, when microwave pulses of a relatively long duration ($\tau \approx$ 50–100 ns) are generated, the frequency stability of the microwave radiation in the sequence of the generated pulses and the dynamics of the change in the frequency during the single pulse are important problems. The stability and dynamics of the frequency of the microwave radiation generated by an RM were studied in [26] using the results of the measurements of the power of 10^4 pulses with a narrow-band filter having a variable step $\Delta f = 5$ MHz. It was shown that the frequency f_{MAX}, which corresponds to the maximum radiated microwave power, is changed from pulse-to-pulse and almost equally distributed in a rather broad band of frequencies $f_{\mathrm{MAX}} = 2800 \pm 50$ MHz. Similar results were obtained in [23], where f_{MAX} was determined as the frequency corresponding to the maximum FFT of the microwave pulse registered by an Agilent Infiniium DS080404B. That is, it was found that the value of f_{MAX} is changed from pulse-to-pulse $f_{\mathrm{MAX}} = 2800 \mp 50$ MHz and does not have a clear dependence on the magnetic field.

In the current experiment, when the microwave radiation was extracted into a conventional waveguide, a sequence of five microwave pulses was acquired at each value of the magnetic field, which was changed with steps of 0.02 T in the range 0.2–0.5 T. In Fig. 4 (solid lines), one can see the values of f_{MAX} (Fig. 4, circles) corresponding to the maximum FFT of the microwave pulse versus the magnetic field. Here, let us note that in half of the analyzed pulses, the value of f_{MAX} was almost the same, and therefore, the number of f_{MAX} values is smaller in Fig. 4. One can see that the dispersion in the value of f_{MAX} decreases by three times as compared with the case where the microwave power is extracted into a linearly expanding waveguide. These measurements showed that at a low magnetic field 0.2–0.26 T, the value of $f_{\mathrm{MAX}} \approx 2950$ MHz, which is $\sim$150 MHz higher than the average value of f_{MAX} obtained in the experiments in which the power was extracted into a linearly expanding waveguide.

An increase in the magnetic field from 0.26 to 0.28 T leads to an increase in the power of the microwave radiation and to a jump in the value of f_{MAX} to a frequency that only slightly exceeds the cold resonance frequency of the anode block [see Fig. 2(b)]. In the magnetic field range 0.28–0.32 T, the value of f_{MAX} does not change. However, in this magnetic

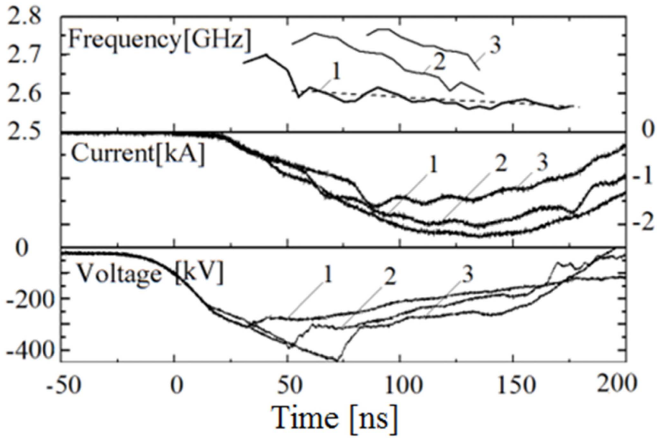

Fig. 8. Time dependence of the frequency of the microwave radiation and waveforms of the current and voltage obtained at (1) 0.28, (2) 0.34, and (3) 0.42 T.

field range, the second maximum FFT was obtained at $f_{\mathrm{MAX}} \approx 2730 \pm 15$ MHz with an amplitude 3–5 dB smaller than that at 2640 MHz. A further increase in the magnetic field ($B > 0.34$ T) leads to the microwave generation at this $f_{\mathrm{MAX}} \approx 2730$ MHz.

The FFT of a microwave pulse describes the time-integrated spectrum of oscillations. To estimate the time-dependence evolution of the frequency, the microwave pulse acquired by an Agilent Infiniium DS080404B digitizing oscilloscope and the average frequency value at discrete-time intervals were used. Let us determine the frequency of oscillations $\bar{f}_i$ averaged during the time ΔT_i, which is the duration of the discrete-time interval, as

$$\bar{f}_i = n_i/(2\Delta T_i) \quad (3)$$

where n_i is the number of half-periods of high-frequency oscillations obtained within time interval ΔT_i. The values of n_i and ΔT_i were determined from the waveform of the squared electric field of the high-frequency oscillations. The beginning and end of the time interval were determined by outside maximums in the high-frequency oscillations at a considered discrete-time interval ΔT_i. In this case, the value of ΔT_i corresponds to the integral number of half-periods of high-frequency oscillations. If one considers that the error δT in the determination of the duration of the time interval is equal to the half of the time between two counts, i.e., $\delta T = 1/(2 \times 40 \cdot 10^9)$ s, in this case, the error in determination of the frequency is

$$\delta\bar{f}_i \text{ (GHz)} = \bar{f}_i \text{ (GHz)}/80\Delta T_i \text{ (ns)}. \quad (4)$$

When $\Delta T_i = 5$ ns, the error in the determination of the frequency averaged during this time interval does not exceed $\delta\bar{f}_i \approx 7$ MHz. The results of the calculation of this frequency $\bar{f}_i$ for the values of the magnetic field, namely, 0.28, 0.34, and 0.42 T, are shown in Fig. 8, together with waveforms of the voltage and current. At a low value of the magnetic field, the analysis was not performed because of the low microwave power (<100 MW) generated at these magnetic field values. One can see that the microwave generation begins and continues during the fall of the voltage pulse.

TABLE I
PARAMETERS OF THE MICROWAVE RADIATION OBTAINED WITH CONVENTIONAL WAVEGUIDE PLACED AT THE OUTPUT OF THE MAGNETRON ANODE BLOCK RESONANCE CAVITY

Magnetic field [T]	Microwave power [MW]	Frequency [MHz]	Microwave pulse duration [ns]	Efficiency of microwave generation [%]
0.2 – 0.26	40-110	2950±50	110±10	10±2
0.27 -0.32	350 ±20	2640±50	140±10	35±5
0.33 – 0.39	420 ±20	2730±50	55±5	45±5
0.4 – 0.44	550±50	2730±50	Peaks pulses	65±5
>0.46	No microwave radiation			

The beginning of the microwave generation is characterized by a typical sharp decrease in the voltage and increase in the current of the magnetron. During this time interval $\tau \approx 5$–10 ns, one obtains an increase in the frequency of the generated microwaves. Furthermore, during the pulse, the frequency of the microwaves decreases to some value of stabilized frequency, which remains slightly above the cold resonance frequency of the anode block.

In addition, one can see that the value of the starting frequency decreases with the decrease in the magnetic field. At a magnetic field in the range 0.28–0.32 T, the starting frequencies were found to be closer to the stabilized frequency. At these magnetic field values, in particular 0.28 T, the duration of the frequency decrease from its starting value to this stabilized frequency is significantly shorter than the duration of the microwave generation (see Fig. 8, curve 1). In these cases, the duration of the microwave generation increases to its maximal values (~125 ns) obtained in the current experiments. Let us note that a similar stabilization of the frequency was obtained in the experiments [23] when an increase in the e/m wave reflected toward the RM was achieved by the increase in the reflection coefficient from the output window of the antenna. At a larger magnetic field, the starting frequency significantly exceeds the stabilized frequency, which results in the termination of the microwave generation before the generated frequency reaches its stabilized value.

V. CONCLUSION

Experimental research on the microwave generation by an RM showed strong dependencies of the duration and frequency of microwaves on the design of the magnetron output slot, which determined the module and phase of the reflected e/m wave. The results of these experiments are summarized in Table I. It was found that when the starting frequency of oscillations is above but close to the resonance frequency of the cold frequency of the anode block, which can be realized by the design of the connection of the anode resonator slot with the output waveguide and by adjusting the magnetic field, the microwave pulse frequency becomes stabilized and the duration of the microwave pulse is maximal.

The change in the module and phase of the reflection coefficient of the e/m wave from the location of the output slot of the magnetron can be considered in two aspects as follows.

1) When one considers the consequence of the anode block resonators as a single resonance volume, the change in the module and phase of the reflection coefficient leads to a shift of the resonance frequency of the anode block to the range of frequencies that are close to the starting frequencies of the microwaves generated by the RM. The operation of the RM is accompanied by a drift in the frequency of the generated e/m waves. If the drift in the frequency is realized toward the resonance frequency of the anode block, the frequency of the microwaves generated by the RM becomes stabilized when it approaches the cold resonance frequency of the anode block. In this case, the duration of the microwave generation increases despite an almost two times decrease in the anode–cathode voltage during the time of the microwave generation.
2) When one considers the consequence of the anode block resonators as an opened ring-type slow-wave structure, the change in the module and phase of the reflection coefficient leads to an increase in the positive feedback of the magnetron. This causes a fast increase in the power of microwave oscillations and short but highly efficient microwave generation. In this mode of operation, one obtains a drift in the frequency of the generated microwaves during the time of microwave generation.

In the current experiments, the choice of the mode of RM operation was determined by the change in the value of the magnetic field. However, this does not allow the starting and resonance frequencies of the RM to be matched. It may be supposed that solving this problem will allow stabilization of the RM frequency during the entire period of microwave generation.

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Authors' photographs and biographies not available at the time of publication.