Stabilized Operation of a Microwave Compressor Driven by Relativistic S-Band Magnetron

Arkady Sayapin, Andrey L. Levin, Uri Dai, and Yakov E. Krasik

***Abstract*— The stabilized operation of a microwave compressor based on a travelling wave resonator, producing at its output microwave pulses with a power of 1.15 ± 0.05 GW and duration of 12 ± 2 ns, is described. The compressor is pumped by a relativistic S-band magnetron generating microwave pulses with a power up to 250 MW and duration of ∼100 ns. To stabilize the frequency of the microwaves generated by the magnetron, a transparent cathode having a limited electron emission surface and double ring-type straps between the anode resonators were applied. It was shown that the application of a phase-shifter between the magnetron and resonator results in the influence of the positive feedback on the magnetron operation beginning within the first 10 ns of the microwaves generation. Finally, the incorporation of symmetrically placed phase-shifters in the compressor's resonator allows the travelling wave phase to be adjusted, and accordingly, reliable ignition of the microwave gas discharge switch.**

***Index Terms*— Microwave compressor, pulse power, relativistic magnetron (RM).**

I. Introduction

HIGH-CURRENT relativistic magnetrons (RMs) can be considered efficient high-power microwave generators, the application of which in different scientific research and practical applications is rather promising [1], [2]. Indeed, an RM powered by voltage pulses with an amplitude ≤400 kV, which can be considered relatively low for relativistic microwave generators, generates microwave pulses with a power up to 500 MW and a pulse duration of ∼100 ns [3]. For applications requiring an increase in the output power of the microwave pulse, for instance, supplies to phase array antennas or resonators of high-energy charged particle accelerators, a very stable microwave radiation frequency is required. The same requirement applies in the case when an RM is implemented for pumping the resonator of a microwave compressor [4]–[6]. Indeed, the first experimental investigations already showed that it is possible to store microwave energy in a microwave resonator powered by an RM and release the energy in the form of a short-duration (several nanoseconds) microwave pulse with power exceeding 1 GW [7]. However, this research showed also that the frequency parameters of the microwaves generated by the RM were not sufficiently steady. This results in the compressor operation being neither stable nor efficient and the duration of the storage phase being less than half that of the supplied microwave pulse. For instance, studies [8]–[10] showed that the frequency of the microwave pulses is characterized by a drift during the microwave generation. In addition, the frequency at which one obtains the maximum radiated microwave power varied from pulse to pulse.

There are several factors that can affect the frequency stability of the microwaves generated by an RM compared with a powerful (up to several MW) but nonrelativistic magnetron operating with thermionic cathodes and supplied by almost rectangular high-voltage pulses having a duration of several microseconds. In almost all experiments with an RM, the microwave generation was obtained when the voltage applied between the cathode and anode was decreasing. This decrease in the voltage can be almost twofold, and therefore, the continuing generation of microwaves is maintained because of the relatively low Q-factor of the RM resonators having a set of modes with a rather dense frequency spectrum. Thus, it can be considered that, during the decrease in the applied voltage, transitions between competing modes maintain the generation of microwaves [5]. Another factor that also can affect the frequency stability of the microwaves generated by the RM is explosive electron emission. Indeed, the extreme power of a modern RM is achieved by virtue of the high-current density of the electron emission from the cathode explosive emission plasma. However, because of the different time- and space-dependent properties of this plasma (spatial uniformity, expansion velocity), this electron emission cannot be considered a steady-state process, and this could be a reason for the variation in the frequency of the generated microwaves. The results of numerical modeling of the RM operation [11] showed a significant change in the frequency of generated microwaves versus the increase in the amplitude of the electron current, as compared with the frequency of the magnetron measured without an electron beam. In addition, in experiments [1]–[3], [8]–[10] the amplitude of the electron current at which the microwave generation begins was almost two times smaller than the maximal amplitude of the electron current obtained during the microwave generation. Thus, the change in the amplitude of the electron current is considered as a reason for the frequency drift. In addition, the results of numerical modeling [11] showed that the increase in the electron current and, respectively, in the electron space-charge, limits the electron flow modulation in the spokes, leaving part of the electrons on the orbits corresponding to the microwave generation at different modes and frequencies.

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The interaction of these electrons with other modes of the electromagnetic (e/m) oscillations increases the competition between the different oscillation modes of the RM. Here, let us note that the influence of the radial expansion of the explosive emission cathode plasma on the stability of the frequency of the generated e/m waves in the RM considered in [4] seems to be insignificant. Recent time- and space-resolved optical and spectroscopic research [12] of the cathode explosive emission plasma showed that this plasma experiences mainly azimuthal drift and its radial expansion velocity does not exceed 2×10^5 cm/s.

Thus, in general, several phenomena can lead to a change and a drift in the frequency of the generated microwaves. However, special measures that could lead to frequency stabilization are limited because of possible electrical breakdowns of the RMs different elements. Nevertheless, such an important application of RMs as a high-power microwave driver for a resonance load, particularly for pumping the microwave compressor resonant cavity, strongly motivates research related to RM frequency stabilization.

In this paper, we present the experimental results of several approaches that allow the frequency of the microwaves generated by an RM to be stabilized and its reliable application as a driver for the microwave compressor. The RM was powered by a linear induction accelerator (LIA) delivering to the RM a pulse with voltage and current amplitudes of $\leq$300 kV and $\leq$2.5 kA, respectively, and duration $\sim$100 ns at full-width of half-maximum (FWHM). A pressure of $\sim$1 mPa inside the experimental system was maintained by three turbomolecular pumps, and an external magnetic field formed by Helmholtz coils was varied in the range 0.22–0.32 T. The parameters of the microwave radiation were measured and analyzed using an Agilent Infiniium DS080404B oscilloscope (4 GHz, 40 GSa/s). For the analysis of the microwaves' frequency (fast Fourier transformer), only one channel of the oscilloscope was used, resulting in a sampling rate of 40 Gs/s. To measure the amplitude-frequency parameters of stabilization systems, a network analyzer, a Rohde and Schwartz-ZVL 9 kHz to 6 GHz, was used.

II. Design Solutions for Stabilization of the Frequency of Microwaves Generated by Relativistic Magnetron

A. Positive Feedback

Because of the high power of the generated microwave pulse and its short duration, the RM anode resonator is characterized by a low Q-factor with maximal coupling of the resonator with the load. In the commonly investigated six-resonator RM with radial output of the generated microwaves, one resonator is almost opened toward the load. The high level of the output microwave power from this resonator decreases its resonance properties, thus increasing the competition between the different modes of the e/m waves. By reflecting back to the resonator a part of the output microwave power, one can either suppress (negative feedback) or intensify (positive feedback) the microwave generation at some of the desired frequencies. To achieve a positive feedback, one has to realize a situation where the phase of the e/m wave reverted to the resonator coincides with the phase of the e/m wave circulating in the resonator and the frequency at which the main power of microwaves in the RM is realized at that time.

Different methods can be applied to increase the efficiency of the positive feedback to stabilize the frequency of the microwaves generated by the RM. For instance, in [13] and [14] microwave power generated by a six-resonator RM was extracted from two oppositely located resonators to the common load. In this case, a part of the microwave power extracted from one resonator was reverted to the magnetron via the diametrically oppositely located resonator. The phase of the e/m wave reverted to the RM was determined by the length of the external coupling waveguides. This length was adjusted to realize positive feedback, that is, the situation where the phase of the reverted e/m wave coincides with the phase of the e/m wave circulation in the resonator. The length of the external coupling waveguides determines the relation between the phases of the electric field in these coupled resonators, and respectively, the mode of the e/m wave oscillations. However, this scheme assumes that there is a natural time delay at the beginning of the positive feedback with respect to the beginning of microwaves generation in the RM. In fact, this time delay, determined by the time of the e/m wave propagation along the waveguide connecting the RMs resonators, is significantly smaller than the total time of the microwave generation by the RM. For instance, in the experiments described in [14], the length of this connecting waveguide was $L \approx 16 \div 17\lambda_0$, where λ_0 is the wavelength of e/m waves in the waveguide. For operational frequency $f \approx 2750$ GHz in the standard waveguide with a cross section of 72×34 mm^2, $\lambda_0 = 12$ cm, and the group velocity of the e/m wave is $v_{\mathrm{gr}} = 16.6 \times 10^9$ cm/s, resulting in a time delay $\tau_w \sim 21$ ns. However, this time delay does not always determine the beginning of the steady operation of the RM. Indeed, frequency stabilization can be achieved by external coupling of the RM resonators. The latter can be considered as equivalent to increasing the Q-factor of RM resonators at the working frequency. However, this frequency stabilization begins only when the temporal drift of the frequency of the e/m waves in the RM becomes insignificant during the time comparable with the feedback time delay. This phase of the RM operation, when the frequency is relatively unchanging, is obtained in the middle of the microwave pulse generation [9], [10]. In addition, because of a relatively slow ($\geq 10^{-8}$ s) increase in the power of the microwaves, there is additional time delay, which one requires to obtain a situation where the power of the reverted e/m waves is significant so that the positive feedback is sufficient to provide e/m wave frequency stabilization in the RM. This additional time delay explained why, in the experiments described in [13] and [14], the frequency stabilization was realized at $\tau_w \geq 45$ ns with respect to the beginning of the e/m waves generation, while the total duration of the microwaves generation was $\sim$80 ns. Thus, one can conclude that this RM frequency stabilization scheme can be effectively used for the operation of an RM with a pulse duration $> 10^{-7}$ s.

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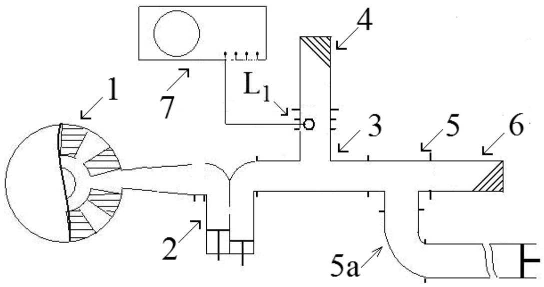

Fig. 1. Experimental setup. 1: Magnetron. 2: Phase shifter. 3: H-plane tee. 4: Matched load. 5: H-plane tee with one of the outputs connected with the waveguide (5a) which is short-circuited by movable plunger. 6: Additional matched load. 7: Oscilloscope (Agilent Infiniium DS080404B). L_1: B-dot loop.

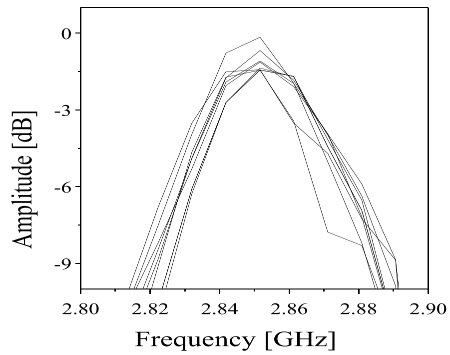

Fig. 2. Frequency spectrum of the pulse train at resonant frequency $f = 2.850$ GHz and magnetic field $B = 0.28$ T.

Considering a relatively broad frequency band (30–50) MHz and a drift of the frequency ±20 MHz/ns that corresponds to the maximal microwave power [9], we investigated the scheme shown in Fig. 1. This scheme allows one to control the frequency at which the positive feedback of the RM is realized. At the output of the magnetron (item 1), a phase shifter was placed (item 2), after which the microwave power was split between the two outputs of the H-plane tee (item 3). One part of the microwave power was dissipated in the main matched load (item 4) and the other part was directed through the additional H-plane tee (item 5) toward the supplementary matched load (item 6). The open output of this tee was connected to the waveguide (Fig. 1, item 5a), which was short-circuited by a movable plunger. This H-plane tee reflects almost completely the incoming e/m wave at a discrete number of frequencies. In fact, this is a well-known method that is commonly used to provide reflection of e/m wave in microwave compressors [4]–[7]. Thus, in the scheme shown in Fig. 1, the H-plane tee (item 5) presents an interference reflector. The latter allows feedback with an RM that has a discrete number of frequencies, with one of the frequencies matching the resonance frequency of the RM at which maximal radiation power is realized. At that desired resonance frequency, a part of the microwave power, after passing the first H-plane tee (item 3), is dissipated in the main matched load (item 4) and the remaining part is reflected back toward the RM. The phase of the reflected e/m is adjusted by the phase shifter (item 2) and is determined by the resonance condition in the new resonance volume (NRV). In this case, the NRV is the space between the H-plane tee (item 5) and the magnetron and includes the volumes of the magnetron and phase shifter. If the electrical lengths of the NRV and the short-circuited end of the tee are not equal to each other, the NRV has resonance only at one of the frequencies corresponding to the total reflection of the e/m wave from the tee. In this experimental setup, for the selected length of the waveguide short-circuited by the plunger, the e/m wave was reflected from the tee at three frequencies in the band 2.7–3.0 GHz. Here, let us note that this band of frequencies corresponds to the band of resonance frequencies typical for an RM operating on a matched load at different values of the external magnetic field. Using the phase shifter (item 2), the electrical length of the NRV was changed to obtain the resonance in the NRV at one of these three frequencies.

Experiments using this scheme (Fig. 1) showed that the RM steadily generates microwaves at two frequencies, depending on the value of the external magnetic field. That is, steady microwave generation was obtained at frequencies $f = 2.848$ GHz and $f = 2.940$ GHz. At each of these frequencies, the maximal microwave power was achieved at different values of the magnetic field. Namely, at frequencies $f = 2.848$ GHz and $f = 2.940$ GHz, the maximal microwave power, measured by a B-dot loop (Fig. 1, L_1), was ∼250 and ∼200 MW when $B = 0.28$ T and $B = 0.24$ T, respectively. Here, let us emphasize that the drift of the frequency during the microwave generation was not obtained. The frequency spectra observed in ten consecutive shots of the LIA are shown in Fig. 2. One can see that the bandwidth of the microwaves is ≤6 MHz and this bandwidth did not change during the total duration of the microwave generation.

The scheme of the aforementioned positive feedback can be used only when there is no reflection of the e/m waves from the main load (Fig. 1, item 4). Such a load can be also a travelling wave resonator excited by the RM via the directional coupler. In [15], a scheme of a microwave compressor where the energy is stored in a travelling wave resonator was suggested, and experiments on charging this resonator by using the microwave pulse generated by the RM were performed with and without an additional interference load. In these experiments, the duration of the charging of the compressor was not constant and did not exceed ∼50 ns, similar to the results of the first experiments [7] on charging the compressor by using an RM powered by the LIA. It was shown that without an interference load the e/m wave amplification in the resonator, that is, the process of charging the resonator, was obtained only in ≤10% of ∼500 shots of the LIA. In contrast, when the interference load and phase shifter were installed, the amplification of the e/m in the resonator was already obtained in ∼80% of the LIA shots. However, the duration of the charging of the resonator was not a constant value from shot to shot varying in the range 40–70 ns and only in some shots was a duration up to ∼80 ns obtained. Therefore, also the maximal amplitude of the travelling e/m wave in the resonator was changed from shot to shot.

Thus, significant stability of the frequency of e/m waves generated by an RM operating with positive feedback was obtained, in particular during the second half of the microwave pulse generation. However, the total efficiency of the positive

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feedback is determined by the generated frequency spectrum and dynamics of the frequency at which the maximal power is obtained during the rise time of the generated microwave pulse and by the duration of this transition phase. Therefore, to improve the efficiency of the positive feedback, in particular at the beginning of the microwave generation, additional special measures were suggested and tested.

B. Transparent Cathode With Limited Electron Emission Surface

In the case where the output of the microwaves generated in the RM is radial, the microwave power is extracted from one of the anode resonators, which is connected by a coupling hole made in the anode wall, with a rectangular waveguide, ∼25 cm in length. The size of the waveguide's wider wall remains constant along the waveguide, allowing propagation of the lowest TE_{10} mode of the e/m wave. The axial size of the anode resonator and coupling hole is equal to the size of the wider wall of the output waveguide. At the resonance frequency, the distributions of e/m fields in the cross section of the connection between the resonator and output waveguide coincide with each other. This allows matched extraction of the generated microwave power from the anode resonator by exciting in the output waveguide only one mode of travelling e/m wave. When the length of the magnetron cathode is equal to the axial length of the anode resonator and uniform electron emission from the cathode surface is realized, electrons emitted from the central part of the cathode interact efficiently with the resonance mode of the e/m oscillations excited in the magnetron's resonant cavities. However, electrons emitted from the cathode parts located close to the cathode edges could effectively excite modes that could have two or more e/m field variations in the axial direction, thus increasing the mode competition. This suggestion concerning the excitation at the RM output not only in the lowest H_{10} mode, was confirmed in our measurements of the space distribution of the microwave radiation when a rectangular horn antenna was used for the extraction of the generated microwave power into the free space; that is, the obtained spatial radiation distribution was not symmetrical with respect to the antenna axis, and moreover, the direction of the maximum of the radiated power was changed during the duration of the microwave radiation.

The effective generation of microwaves by an RM with electron emission only from the narrow central part of a disk-like cathode was reported in [16] and [17]. However, the application of the disklike cathode could lead to a significant change in the electrodynamic parameters of the RM, and thus, make comparison with the commonly used cathode, which has the form of a cylinder, difficult. To keep the electrodynamic parameters of the RM, the cathode length $L = 72$ mm and diameter $d = 20$ mm were not changed and remained as in the preceding experiments, as described in Section II-A. The limitation of the emission surface of the cathode was achieved by manufacturing the central part of the cathode in the form of strips having an onset $\Delta = 0.5$ mm above the cathode surface [Fig. 3(a)]. Time- and space-resolved imaging of the light emission from explosive emission plasma, using an intensified 4QuikE framing camera, was used to obtain the

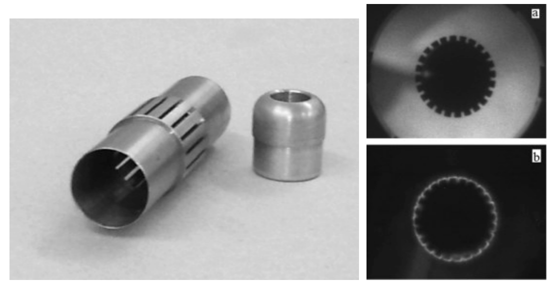

Fig. 3. (Left) Magnetron cathode with striplike central part. (Right) (a) Side view of the cathode. (b) Side view of explosive emission plasma light radiation from the central part of the cathode.

location of the plasma, and thus, the location of the electron emission. A typical image of the explosive emission plasma light radiation is shown in Fig. 3(b). One can see that explosive emission plasma is formed only at the strips' edges and that there is no plasma formation at the smooth and polished parts of the cathode. The results of the test of the RM with this cathode, whose electron emission central part is limited (∼25% of the total cathode surface), showed that the space distribution of the radiation becomes practically constant in time and symmetrical in space with an insignificant increase in the peak power of the generated microwaves.

In addition, we tested the operation of the RM with a hollow cathode having a wall thickness of ∼0.5 mm and strips in the central part (Fig. 3, left). In the grooves of this cathode, slots were made along the total length of the strips. This cathode design provides also a faster beginning of the e/m wave generation in RM [18], thus decreasing the time delay in the beginning of the effective positive feedback.

C. Six-Resonator RM Anode With Two-Ring-Type Connections

In earlier research on an RM where the output of the microwave power is radial, the anode resonators were connected to each other in series by end caps. The results of 3-D numerical modeling using MAGIC software of the microwave generation process by a six-resonator RM with radial output showed that the absence of the coupling between the anode resonators could be the main reason for the frequency jumping and its drift during the microwave generation [19]. In this case, the generation of microwaves with π-mode and 2π-mode occurs in one band of the RM working frequency. Moreover, with π-mode one can obtain the generation of microwaves with two different frequencies. The application of straps connecting the next nearest anode resonators allows one to separate significantly the frequency of the π-mode and 2π-mode to narrow the bandwidth of the generated radiation spectrum, and thus, to increase the efficiency of the magnetron operation.

In RMs, however, strapping of the anode resonators was not used. It was assumed that the application of straps in the case of an RM could be problematic because of inevitable electrical breakdowns at the ends of the resonators. One can suppose, nevertheless, that when the generated microwave pulses are of short duration ($\leq$100 ns), the formation of the microwave discharge, and respectively, plasma formation and

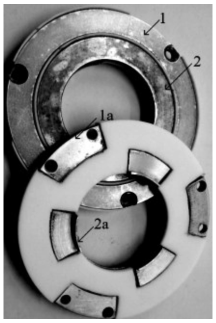

Fig. 4. Two ring-type connections of the six-resonator RM. 1 and 2: external and internal ring-type connections. 1a and 2a: contact surfaces of the external and internal ring-type connections.

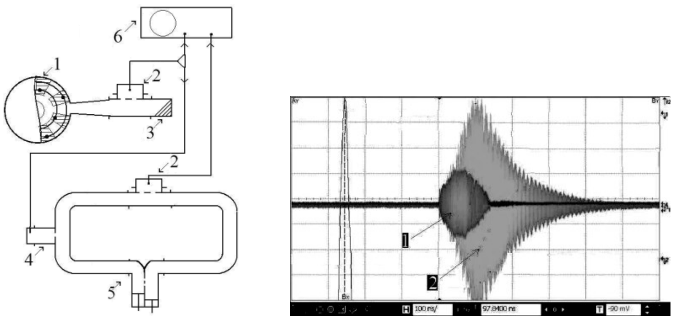

Fig. 5. (Left) Scheme of experiments on estimation of frequency stability of the RM with double ring-type straps between the anode resonators. 1: magnetron. 2: cross-guide directional couplers. 3: matched load. 4: coupling window of the resonant cavity. 5: resonant cavity with the adjusting phase shifter. 6: oscilloscope (Agilent Infiniium DS080404B). (Right) Waveforms of the microwave oscillations at the output of the RM (1) and in the resonant cavity (2), respectively.

expansion, will be delayed with respect to the beginning of the microwave generation. In this case, the strapping between the anode resonators would not lead to the termination of the generation, at least, during the major part of the driving voltage pulse.

To check this suggestion, we conducted experiments with an RM having at both the ends of the anode double ring-type straps between the resonators. These strap rings (Fig. 4) have three ledges in the form of the vanes of the anode block. The ledges were used to provide the electrical contact of the next nearest anode resonators. Between the ring-type straps and resonators, which were not in contact with these ledges, a 3-mm-thick Teflon plate was placed (Fig. 4).

The frequency stability of the operation of this modified RM with strapped resonators was checked using the ringlike resonant cavity. It is understood that efficient charging of a resonant cavity can be achieved only when the charging source operates with high stability of the frequency of the generated microwaves. Thus, the stability of the frequency of the RM generation was checked by studying the dynamics of the charging phase of the cavity. The experimental scheme is shown in Fig. 5 (left). The microwave power generated by the RM with double ring-type straps between the anode resonators (item 1) was dissipated in the matched load (item 3). Between the magnetron and load, a cross-guide −40 dB directional coupler (item 2) was placed. The largest part of the microwave radiation tapped by this coupler was directed to charge the ringlike cavity (item 5) having quality factor $Q \approx 700$, and

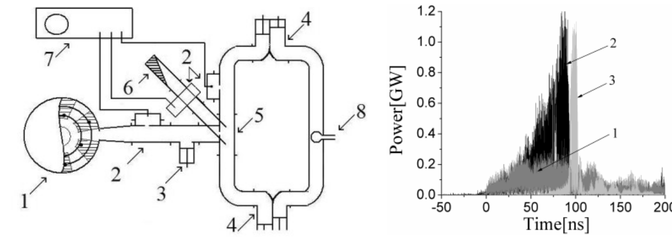

Fig. 6. (Left) Experimental setup of the travelling wave compressor powered by the RM with double ring-type straps between the anode resonators. 1: magnetron. 2: cross-guide directional coupler. 3: tee waveguide with movable plunger. 4: phase shifter. 5: tee waveguide with the resonator coupling hole. 6: matched load. 7: digitizing oscilloscope (Agilent Infiniium DS080404B). 8: microwave gas discharge switch. (Right) 1–3: waveforms of the microwave oscillations at the RM output, in the resonator, and at the output of the microwave compressor, respectively.

the other part was delivered to the digitizing oscilloscope (item 6). The cavity was adjusted to the resonant frequency coinciding with the frequency of the microwaves generated by the RM using a phase shifter (item 5) placed between the two waveguides of the traveling wave resonator. The power of the traveling wave component of the builtup cavity field was monitored by the microwave signal from another directional coupler (item 2) registered by the digitizing oscilloscope. Thus, the stability of the frequency of the generated microwaves can be estimated by the stability and duration of the charging of the resonant cavity.

The waveforms of the microwave oscillations at the output of the RM and the resonant cavity are shown in Fig. 5 (right). One can see that the charging of the cavity continues for almost the whole duration of the microwave pulse generated by the RM; the field buildup in the cavity is terminated only when the power generated by the RM decreases. The dynamics and ∼100 ns duration of the cavity charging thus obtained strongly indicates the stability (sufficient for charging the resonator with $Q \sim 700$) of the frequency of the e/m waves generated by the RM with double ring-type straps applied between the anode resonators. Thus, the experimental positive results concerning stabilization of the frequency of the e/m waves generated by an RM operating on a matched load and the fast beginning of the microwave generation in the RM allows one to realize stabilization also of the energy stored in the resonant cavity of the microwave resonator.

III. Experimental Setup

The final experimental scheme, which was used to study the travelling wave microwave compressor pumping by the RM, is shown in Fig. 6 (left). Microwave pulses generated by the S-band RM (item 1) with radial output were directed to the input of the resonant cavity. The RM resonance system consists of six identical resonant cavities and vanes having an axial length of 72 mm and azimuthal angle width of 20° and 40°, respectively. The anode diameter was 42 mm and the diameter of the resonant cavities was 84 mm. These sizes of cavities and vanes are similar to those used in the RMs that were tested in [20]–[23]. The difference was in the double ring-type straps between the anode resonators (Fig. 5, left), which were used instead of end caps, and in the hollow transparent cathode having a length of 72 mm and a strip-type central part 25 mm in length. The RM was powered by the LIA producing at its output high-voltage pulses with an amplitude $\leq$300 kV and a duration of $\sim$100 ns at FWHM [24]. The voltage and current waveforms were monitored by a calibrated capacitive voltage divider and self-integrated Rogowski coil. The amplitude of the magnetron current was $\leq$2.5 kA. The background pressure of $\sim$1 mPa inside the RM and resonant cavity was maintained by three turbomolecular pumps. An external magnetic field up to $B = 0.35$ T was generated by Helmholtz coils. A change in the magnetic field leads to a change in the frequency and power of the generated e/m waves in the range $f = 2.65$–3.05 GHz and $P = 150$–250 MW, respectively, when the RM is operated with the matched load.

The RM was connected to the travelling wave resonator by the waveguide, which was $\sim$60 cm in length. This waveguide consists of a cross-guide directional coupler (coupling coefficient -40 dB) and an E-plane tee (item 2) with one side short-circuited by a movable plunger (item 3). The resonator was excited by microwaves generated by the RM through the hole made in the wider side wall of the H-plane tee waveguide (item 5). The symmetrical outputs of the H-plane tee were closed using standard E-bend waveguides. Diametrically opposite to the coupling hole, a microwave gas discharge switch (item 8) was placed. This switch comprises a thin wall sphere, 30 mm in outer diameter, connected to a tube with an outer diameter of 6 mm. Both the sphere and tube were made of quartz with a thickness of 1 mm and kept the gas pressure up to 10^6 Pa. The gas was supplied into the sphere through the tube, which was hermitically placed through the waveguide's narrow side wall. In the side parts of the travelling wave resonator, between the locations of the coupling hole and the microwave gas discharge switch, standard phase shifters were symmetrically placed (item 4). The power stored in the resonator microwave was extracted through the side output of the H-plane tee (item 5) and transported to the matched load (item 6) through a cross-guide directional coupler (item 2). The waveforms of the microwave oscillations at the RM output, in the resonator, and at the output of the microwave compressor were obtained from directional couplers (items 2) and registered by a digitizing oscilloscope [Agilent Infiniium DS080404B, bandwidth of 4 GHz (item 7)].

IV. Adjustment of the Travelling Wave Microwave Compressor and Experimental Results

The results of a preliminary test with a matched load of the RM having double ring-type straps between the anode resonators showed that the largest microwave power up to 1.2 GW and the instability of the microwave power $\leq$5% of the RM are obtained at a magnetic field in the range $B = 0.32$–0.34 T.

In this magnetic field range, the RM generates e/m waves with frequency $f \approx 2.85$ GHz. Thus, using phase-shifters (Fig. 6, item 4), the length of the ring-type resonator was adjusted such that one of its resonance frequencies was close to $f \approx 2.85$ GHz. In addition, the application of two phase-shifters in the ringlike resonator of the microwave compressor, placed symmetrically with respect to the microwave gas switch, allows the phase of the e/m wave in the cross section of the microwave gas discharge switch to be changing whereas the resonance frequency remains the same. Namely, by an increase in the resonator phase length by one of the phase shifters and a decrease of the same value in the resonator phase length by the other phase shifter, thus keeping the phase length of the resonator and its resonance frequency the same, one changes the phase of the e/m field in the cross section of the microwave gas discharge switch. During the experiment, the optimal phase of the e/m field was considered to be when the maximal amplitude of the microwave power was obtained at the output of the microwave compressor.

The phase of the e/m wave reflected from the resonator's input that corresponds to the positive feedback coupling between the RM and the load was adjusted by the location of the movable plunger in the input E-plane tee (item 3). The application of an E-plane tee instead of the standard waveguide phase-shifter allows one to achieve a change in the phase of the reflected e/m wave in a relatively small ($\leq 60°$) range. However, this range was sufficient to obtain positive feedback with a time delay $\leq$7 ns of the beginning of the positive feedback's influence on the RM operation with respect to the start of the microwave generation.

The quartz sphere of the microwave gas discharge switch was filled with nitrogen gas. At a pressure $\leq 4 \times 10^5$ Pa, the microwave discharge was initiated prior to the termination of the microwave generation in the magnetron, and respectively, prior to the full charging of the microwave compressor resonator. At a nitrogen gas pressure in the range 4–5 $\times 10^5$ Pa, steady charging of the resonator was obtained with rather reproducible output power $P = 1.15 \pm 0.05$ GW of the microwave pulse with a duration of 12 ± 2 ns. Finally, at a nitrogen gas pressure $\geq 6 \times 10^5$ Pa, a microwave discharge was not initiated and the maximal power in the travelling e/m wave reached $\sim$1.4 GW. Typical waveforms of the microwave oscillations at the RM output, in the resonator, and at the output of the microwave compressor are shown in Fig. 6. Here, let us note that such a reproducible operation of the microwave compressor was obtained only at an LIA operation repetition rate of 0.1 Hz. An increase in the repetition rate led to the appearance of a rather large time jitter in the ignition of the microwave gas discharge in the quartz sphere; that is, earlier gas discharge ignitions were obtained. One can reasonably suppose that this disadvantage can be avoided by providing a constant flow of nitrogen gas through the quartz sphere [25].

V. Conclusion

The experimental results showed that in the case of a relatively slow beginning of the generation of microwaves with a rather wide bandwidth and a frequency drift in the initial stage of microwave generation in an RM, the application of positive feedback leads to the stabilization of the frequency only during the final period of microwave generation for nanosecond time-scale duration pulses.

The application of a transparent cathode with a limited electron emission surface located at the middle of the cathode, together with double ring-type straps between the anode resonators, allows stabilization of the frequency of the e/m waves generated by the RM at a level sufficient for steadily charging the resonator with a relatively low $Q \approx 700$ during the entire period of microwave generation. In addition, it was shown that the application of a phase-shifter between the RM output and resonator allows one to achieve the beginning of the positive feedback influence on the RM operation within the first 10 ns of the microwave generation in the RM. Finally, it was shown that, in these conditions, the travelling wave resonator with incorporated symmetrical phase-shifters, pumped by the RM, which is supplied by voltage pulses with an amplitude $\leq$300 kV, allows one to generate reproducible microwave pulses with power $P = 1.15 \pm 0.05$ GW and a duration of 12 ± 2 ns.

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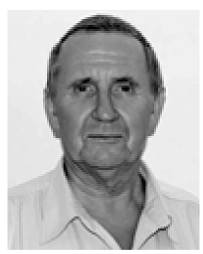

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