S-band microwave radiation by a high-impedance diode with an A6 anode block

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(Received 3 October 2017; accepted 19 November 2017; published online 5 December 2017)

The results of experimental research of the intensity distribution of microwave fields in the resonant cavities of an A6 anode block with a high-impedance ($\geq$120 Ω) magnetically insulated electron diode powered by a Linear Induction Accelerator (LIA) ($\sim$350 kV, $\sim$2.5 kA, 150 ns) are presented. The power and duration of the microwave pulses obtained from one cavity varied in the range of 200–300 MW and 120–50 ns, respectively, depending on the charging voltage of the LIA and the value of the axial magnetic field. It was found that the field intensity in cavities adjacent to the extraction cavity differs by $\sim$3 times and that the field intensity gradually increases along the series of cavities. The direction of this increase coincides with the direction of the electrons' $\mathbf{E} \times \mathbf{B}$ drift, i.e., the change in the magnetic field direction results in the change in the direction of the increase in the intensity of the field in the cavities. *Published by AIP Publishing.*
https://doi.org/10.1063/1.5007804

Research carried out in the last few decades showed that the microwave power generated by different types of relativistic microwave tubes can exceed $\sim 10^3$ times the power of microwaves generated by conventional microwave tubes.[1] Relativistic magnetrons (RMs) operating with explosive-emission cathodes generate microwave pulses with power up to several GW.[1–3] Extraction of microwave power from a RM can be realized in either the radial or the axial (diffraction output) direction. The latter case[4,5] has its advantages, in particular, because the distribution of the microwave power between the magnetron cavities is uniform. In addition, magnetrons with diffraction output better withstand microwave breakdown at their output, their magnetic field system is more compact, and it is possible to select the radiation mode. In recent research,[5] efficiency up to 72% of microwave generation was reported.

On the other hand, one of the main advantages of the RM with radial output is the possibility of multi-channel output of the generated microwaves. In addition to phase synchronization of the microwave beams generated by different magnetrons, one can use the different output channels of a single magnetron as a supply for an antenna array.[6–10] The extraction of the microwave power through several output channels of the RM following coherent interference of the microwave beams at the desired distance allows one to obtain power densities multiple times larger than those from a single output channel. During the last decade, significant improvement in the efficiency, pulse duration and amplitude, and frequency stability of the microwaves generated by RMs was demonstrated. It was shown that RMs powered by modest generators (voltage 250–350 kV) generate microwaves of $\sim$500 MW, pulse duration of 10–30 ns, and power efficiency comparable with the efficiency of conventional magnetrons.[11–13]

Earlier research[14–16] of high-impedance ($\geq$50 Ω) RMs with radial microwave power output showed its high microwave power efficiency ($\sim$60%). Recently,[17–21] we demonstrated the increase in the microwave pulse duration up to $\sim$150 ns with the same high efficiency. However, for long ($\geq$100 ns) microwave pulses, RMs have some specific features not typical to conventional magnetrons. Namely, the power of the microwave pulses and the frequency vary significantly with very small changes in the reflection coefficient of the microwaves from the load;[19] the microwave generation continues despite a significant decrease (to a half) in the applied voltage and the microwave frequency drifts (by $\sim$10%) relative to their value at the beginning of the oscillations.[20–22] In addition, in RM experiments[10] with multi-channel microwave output, the power radiated from the open resonant cavities adjacent to closed cavities was found to depend on the direction of the external axial magnetic field. These results show that the operation of this high-impedance magnetically insulated electron diode with an A6 anode block differs significantly from the conventional description of magnetrons. In spite of the fact that this problem has undergone many years of research,[1–7] our work shows that it is far from being completely understood and additional research is required to understand the phenomena governing the operation of relativistic magnetrons, which could also be relevant for conventional magnetrons.

In Ref. 19, it was suggested that when the microwave power is obtained from a single open cavity connected with negligible reflections to a linearly expanding waveguide, the high impedance RM can be considered as an open-end chain of cavities with effective interaction of the electron flow and the electromagnetic wave at a lower voltage. In the present paper, we study the same RM[19] and we report direct measurements of the high-frequency magnetic field inside the resonant cavities during the operation of the RM. A Linear Induction Accelerator (LIA) produces output pulses with the duration at a FWHM (Full Width Half Maximum) of $\tau \sim 150$ ns and voltage and current amplitudes of $U \leq 350$ kV and $I \leq 3$ kA, respectively. The voltage and the current were measured using a capacitive voltage divider and a self-integrated Rogowski coil, respectively. The dc axial magnetic field varied in the range of 0.22–0.32 T and was produced using a Helmholtz coil pair. The vacuum, $\sim$0.9 mPa, in the system was maintained by three turbo-molecular pumps.

The experimental setup and external view of the RM's anode block are shown in Figs. 1(a) and 1(b), respectively. The anode block of the RM has six radial vanes expanding at an angle of 40° [Fig. 1(a), item 1]. The resonator cavities, formed between two azimuthally adjacent vanes expand radially at an angle of 20°. The external and internal vane's radii were 42 mm and 21 mm, respectively, and the vane's height was 72 mm. A 72 mm long 21 mm diameter brass cathode with uniform azimuthally distributed grooves was placed coaxially with the anode block. The vanes were closed by 6 mm thick ring caps at both ends of the anode block. In the cap furthest from the LIA, two holes of 6 mm diameter with centers separated by an azimuthal angle of 60° were prepared [Fig. 1(b) items 3 and 4]. Two B-dot loops were inserted in these holes with $\sim$1.5 mm between the cap margin and the loop to protect their from interacting with electrons, which can lead to microwave breakdown and short-circuit in the loops, respectively. The microwave power was obtained through a slot ($10 \times 72\,\text{mm}^2$) made in the wall of one of the cavities. The width of the cavity's external wall was 14 mm, that is, one may consider this resonator as almost open. Outside the anode, the slot continues as a waveguide [see Fig. 1(a), item 2]; the height of its E-plane wall is increased, and its cross-section at its end is $34 \times 72\,\text{mm}^2$, typical for a conventional waveguide.

The obtained microwaves propagating through a waveguide directional (-50 dB) coupler [see Fig. 1(a), item 3] were absorbed by a matched graphite load [Fig. 1(a), item 4]. Microwave signals registered by the B-dot loops and the waveguide directional coupler were acquired using an Agilent Infiniium DS080404B oscilloscope (4 GHz) [Fig. 1(a), item 5]. For frequency characteristic analysis, that is, a fast Fourier transform (FFT), only a single channel of the digitizer was active, resulting in a sampling rate of 40 Gs/s.

Two B-dot loops, azimuthally separated by 60°, allow high-frequency magnetic field measurements in two adjacent cavities, and by rotation of the back-side cap, one can cover all six cavities, two at the same time. We denote as cavity 1 the cavity open to the extraction system and number the other cavities clockwise up to 6. In Fig. 2, the waveforms registered by the B-dot1 loop in cavity 1 and those measured at the waveguide coupler showed coincidence during $\tau \approx 100$ ns of the microwave generation. However, at $\tau > 100$ ns, when the microwave signal from the directional coupler becomes almost zero, the B-dot signal showed a sharp second short high-power microwave pulse. Frequency analysis showed that this second microwave pulse is characterized by a frequency of 2.11 GHz, which is close to the extraction waveguide's cut-off frequency of $f_C = 2.08$ GHz. Here, let us note that at frequencies close to f_C, one obtains an increase in the Ohmic losses in the extraction waveguide walls. In addition, negligibly small signal from the directional coupler is related to a significantly smaller (-70 dB) coupling coefficient at this frequency than -50 dB in the range of RM's working frequency range $\Delta f = 2.6$–3.95 GHz.

The power and duration of the obtained microwave pulses varied in the range of 200–300 MW and 120–50 ns, respectively, depending on the LIA charging voltage and external axial magnetic field (see the details in Refs. 17 and 19). Waveforms of the high-frequency magnetic field measured in adjacent cavities of the anode block are shown in Fig. 3. Here, let us note that the ratios between the intensities of fields in adjacent cavities are independent of the amplitude of the applied voltage or that of the axial magnetic field. One can see in Figs. 3(a)–3(d) that the intensity of the field in the cavities increases gradually along the series of cavities coinciding with the electron $\mathbf{E} \times \mathbf{B}$ drift direction. Reversing the direction of the axial magnetic field [Figs. 3(e)–3(h)] results in the change in the direction of the intensity decrease of the field in the resonant cavities. The intensities of the field in the 2nd and 6th cavities, which are adjacent to the extraction cavity (cavity 1), differ by a factor of 3, corresponding to a ratio of $\sim$10 in the microwave energy densities.

This non-uniform distribution of the electromagnetic field intensity in the resonance cavities confirms our suggestion that the electrodynamic structure of a single open cavity high-impedance A6 RM with a relatively large anode-cathode gap cannot be considered a single resonance structure. These data strongly indicate that the RM operates as a chain of five consecutive resonance cavities ending by a cavity where most of the generated microwave power is obtained.

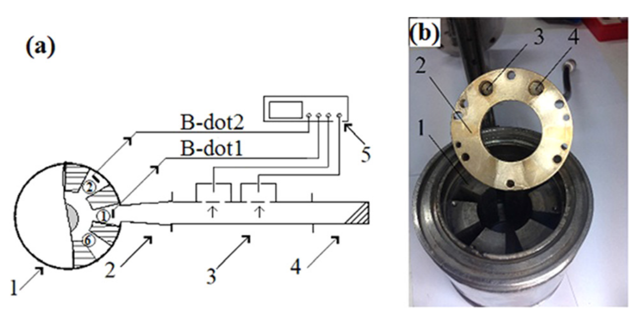

FIG. 1. (a) Schematic of the RM with the B-dot1 and B-dot2 loops installed in the 1st and 2nd resonant cavities. 1—A6 anode block; 2—output waveguide; 3—waveguide directional coupler (-50 dB); 4—matched load; 5—digitizing oscilloscope Agilent DS080404V (4 Hz, 40 GS/s). (b) Appearance of the A6 anode block with the back-side cap. 1—A6 anode block; 2—the back-side cap; 3 and 4—built-in B-dot loops.

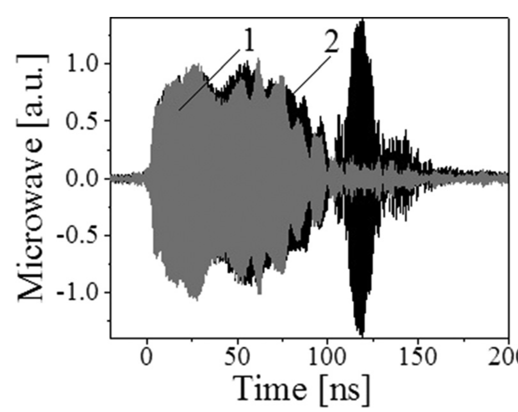

FIG. 2. Waveforms of the microwave pulses: 1—from the waveguide coupler (gray color) and 2—from the B-dot loop inserted in the output cavity (black color).

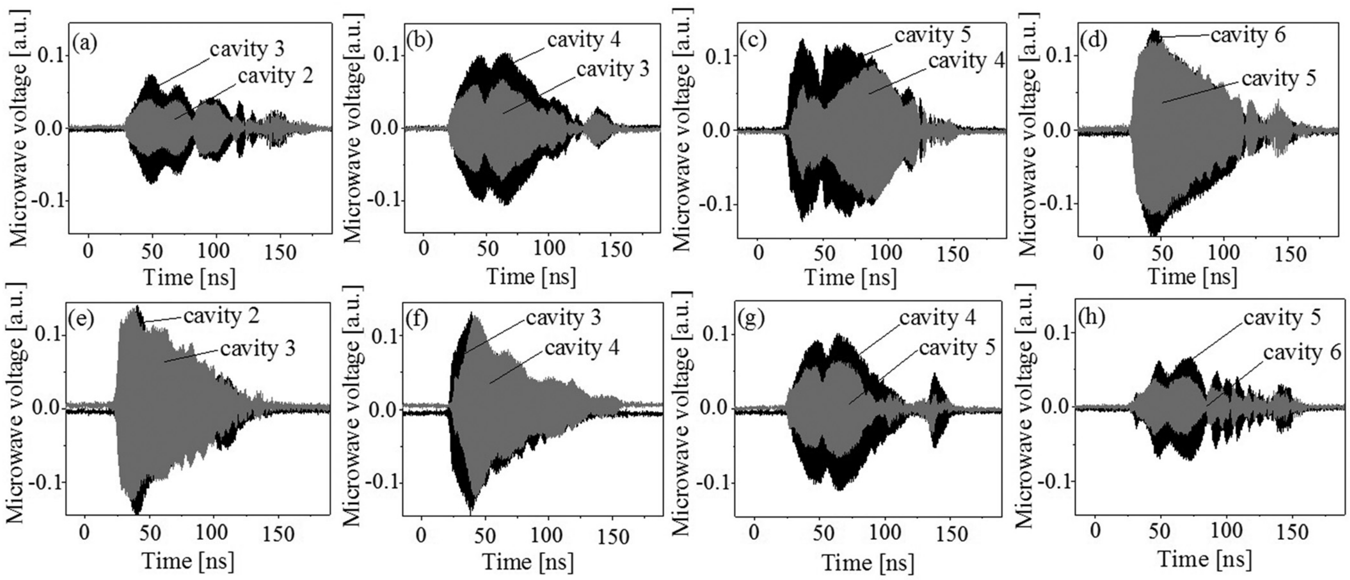

FIG. 3. (a)–(d) Waveforms of the microwave intensities measured in adjacent cavities. The electron drift coincides with the direction of the increase in the numbering of the cavities; (e)–(h): the same but the direction of the axial magnetic field is reversed.

The results obtained also explain the continuous drift in the frequency of the microwaves generated in this complex resonance structure. In Fig. 4, one can see the frequency characteristics of the A6 anode block closed by two front- and back-caps and with a 21 mm diameter, 72 mm long cathode. In the same Fig. 4, we present the change in the frequency during the microwave generation. The minima in the reflection coefficient S_{11} of the electromagnetic wave from the RM output determine the resonant frequencies of the anode-cathode volume as a single resonant structure. Here, let us note that the resonant frequencies of this RM differ very little from those obtained when the RM cathode diameter was 30 mm and the A6 anode block was not closed by end caps.[23,24] The time dependence of the microwave radiation frequency was determined using waveforms of the microwaves acquired using a 40 GS/s resolution digitizing oscilloscope. Namely, the frequency was calculated as an average value during the time interval of 10 microwave oscillation periods. One can see in Fig. 4 that the frequency drift is quite large up to $\sim$10% of the frequency at the beginning of the microwave generation. Also, the microwave generation occurs at frequencies which do not coincide with the resonance frequencies of the magnetron.

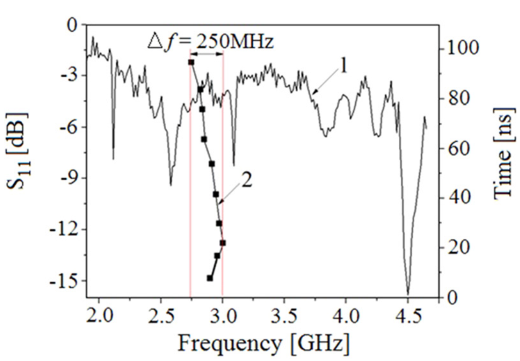

FIG. 4. 1—Frequency response of the cavity of the A6 anode block closed by two end caps and a 21 mm diameter, 72 mm long cathode; 2—evolution of the frequency during the microwave generation.

The first M-type microwave generator[23,24] was invented after successful research of low-impedance magnetically insulated high-power (several GW) electron diodes.[25] The design of this multi-resonator RM was very similar to the design of magnetically insulted diodes with a cylindrical anode. The resonant cavities were separated by six wide vanes in the form of expanding segments with an expansion angle of 40°. Thus, the main part of the anode block was formed by the vane's surface. The latter allows this multi-resonator RM having an anode-cathode gap of 5.4 mm to have an impedance of $\sim$4.5 Ω, close to the properties of the coaxial diode with a cylindrical anode. In later work,[12,13] the same RM as in Refs. 23 and 24 but with an increased anode-cathode gap up to 13 mm was used to match to the high impedance of the LIA ($\geq$100 Ω) power supply.

It is possible that the results obtained in the present research correspond only to the high impedance mode of the RM operation because the increased anode-cathode gap leads to a decrease in the coupling between the anode block cavities adjacent to the extraction cavity. The data obtained allow one to consider the investigated electrodynamic structure as an open series of five coupled resonators. This electrodynamic structure permits the effective interaction of the electron beam with the generated electromagnetic waves at frequencies different from the RM resonance frequencies during the anode-cathode voltage decrease. The decrease in the voltage and consequently the decrease in the electron azimuthal drift velocity change the frequency of the electromagnetic waves, which is now not limited by the discrete spectrum of resonance frequencies of the closed wave structure.

The generation of electromagnetic waves in such RM resonators can be achieved by the space-charge modulated electron beam without electromagnetic energy transfer in the direction of the azimuthal drift of electrons similar to the case of a klystron operation. Also, one can consider that the coupling between the RM resonance cavities is achieved by a travelling wave which transfers electromagnetic energy in the direction of the electron drift. The latter is similar to the operation of the M-type travelling wave tube with an azimuthally distributed electron source. Thus, the understanding of the mechanism responsible for the operation of such high-impedance RM is important for a proper design of multi-resonator multi-channel output magnetrons.

The authors are grateful to Dr. J. Leopold, Professor E. Schamiloglu, and Dr. A. Andreev for fruitful discussions and comments. This work was supported in part by the Center for Absorption in Science of the Ministry of Immigrant Absorption.

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