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Zeyang Liu, Yuwei Fan, Xiaoyu Wang, Difu Shi, Ankun Li, and Yuanqiang Yu

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Zeyang Liu, Yuwei Fan, Xiaoyu Wang, Difu Shi, Ankun Li, and Yuanqiang Yu

AFFILIATIONS
College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha 410073, China

Zeyang Liu, Yuwei Fan, Xiaoyu Wang, Difu Shi, Ankun Li, and Yuanqiang Yu

ABSTRACT
Relativistic magnetrons (RMs) are one of the most promising high power microwave devices. A high-efficiency relativistic magnetron (HERM) with a novel all-cavity extraction structure is presented and investigated theoretically and numerically in this paper. Compared with conventional RMs with an all-cavity extraction structure, the HERM has three improved features. First, a single stair is introduced into the HERM. Second, the angular width of the extraction structure is bigger than that of the anode slow-wave structure. Third, the extraction port is set behind the anode vanes in the axial direction instead of being set between two anode vanes. These improved features can enhance the extraction efficiency of the HERM. The typical simulation results are as follows: high-power microwaves of the transverse electromagnetic mode are generated with a peak power of 1.65 GW, a frequency of 1.61 GHz, and a power efficiency of 67.6%, when the voltage is 586 kV and the current is 4.19 kA. The simulation results verify the validity of the novel all-cavity extraction structure.

I. INTRODUCTION
With the advantages of high efficiency, stable operation, and simple structure, relativistic magnetrons (RMs) are one of the most promising high power microwave (HPM) devices. Increasing the output power and increasing the power efficiency are the two major development directions for RMs. The extraction structures of RMs include an axial diffraction output and a radial all-cavity output. In recent years, axial diffraction output RMs (MDO) and transparent cathodes (TCs) have been used to improve power efficiency. A high efficiency (70%) MDO based on TCs has been presented by Fuks and Schamiloglu at the University of New Mexico, and the experimental results have confirmed the feasibility. The axial length of the radial all-cavity output RM is shorter than that of the axial diffraction output RM, which is an obvious advantage in some situations. However, it has had a much lower efficiency (~55%) than MDO until now. In our opinion, it is an important development direction to enhance the extraction efficiency of the radial all-cavity output RM.

In this paper, a high-efficiency relativistic magnetron (HERM) with a novel all-cavity extraction structure is presented and investigated theoretically and numerically. Compared with conventional RMs with an all-cavity extraction structure, the HERM has three improvements. The simulation results show that the power efficiency of the HERM increased to 67.6%, which is an increase of 25% compared with the conventional radial all-cavity output RM. The simulation results verify the validity of the novel all-cavity extraction structure.

This paper is organized as follows: Section II presents the improved design and Sec. III gives the simulation results and discussion. Conclusions are given in Sec. IV.

II. IMPROVED DESIGN
The 3D structural diagram of the HERM is shown in Fig. 1. The HERM can be divided into four parts from left to right. The left side is a coaxial waveguide for electric power input, which includes an upstream cathode endcap. The second part comprises a resonant system for beam–wave interaction and radial all-cavity extraction ports. The third part includes sectorial waveguides arranged in an annulus for microwave extraction and a single stair. The fourth part is a coaxial waveguide for microwave output, which can be transformed into the TE_{11} mode by a compact cross-shaped mode converter.
Compared with conventional RMs with an all-cavity extraction structure, the HERM has three improvements. First, a single stair is introduced into the HERM. Second, the angular width of the extraction structure is bigger than that of the anode slow-wave structure (SWS). Third, the extraction port is set behind the anode vanes in the axial direction instead of being set between two anode vanes. These improvements can enhance the extraction efficiency of RMs.

III. SIMULATION RESULTS AND DISCUSSION

In simulation, the HERM is optimized with the 3-D particle-in-cell (PIC) code CHIPIC. Typical simulation results are as follows: when the diode voltage is 586 kV, the beam current is 4.19 kA, and the magnetic field is 0.344 T; HPMs are generated with an average power of 1.65 GW, a frequency of 1.61 GHz, and a corresponding power efficiency of 67.6%.

For a sectorial waveguide, if the inner radius is fixed and the outer radius is changed, the cut-off frequency of the fundamental mode TE_{11} is the lowest. With a decreasing outer radius, the cut-off frequency of high-order TE_{01} and TE_{12} modes increases obviously. Therefore, reducing the outer radius of the sectorial waveguide as much as possible can ensure better mode isolation, which will avoid mode competition. As mentioned, TE_{11} modes are excited, respectively, in three symmetrical sectorial waveguides, which have the same amplitude and phase. In the coaxial waveguide, TEM and TE_{31} modes exist simultaneously. However, with the length of the waveguide increasing, the higher order mode such as TE_{31} will be suppressed. Figure 2 shows the electric field distribution in different cross sections. Before microwaves get into the sectorial waveguide, it is difficult to distinguish the microwave mode. By adjusting the inner radius and outer radius, a pure TE_{11} mode can be obtained in the sectorial waveguide, as shown in Fig. 2(b). Therefore, the radiated TEM mode of the coaxial waveguide exhibits a fine performance, which is shown in Fig. 2(c).

Figure 3 shows input electron beam power vs time, which remains at 2.44 GW after 28 ns.

Figure 4 plots the time history of the output microwave power in the extractor. The diagram shows that nonlinear saturation occurs at about 29 ns and the average RF output power is 1.65 GW.

Figure 5 shows the frequency spectrum of the HERM. The dominant frequency is 1.61 GHz, and the frequency spectrum is very pure.

Figure 6 shows the electron spokes in the interaction region, which shows that the HERM operates at the $\pi$ mode.

In the HERM, the single stair structure is a key factor to enhance power efficiency. On the one hand, the radius of the stair will affect the amplitude of the reflected microwave. On the other
hand, the axial length of the stair will affect the phase of the reflected microwave. All of these show that a suitable stair structure can enhance extraction efficiency.

If the single stair structure is canceled, the power efficiency is only 33%, which is much lower than the power efficiency of the HERM.

Figure 7 shows the efficiency vs stair radius curve. It can be seen that when the stair radius is changed from 14 mm to 58 mm, the highest power efficiency is more than 70%.

Figure 8 shows the efficiency vs axial length curve. When the axial length is changed from 6 mm to 42 mm, the highest power efficiency is more than 70%.

Furthermore, the dimensions of the radial extraction port, as shown in Fig. 1, are key parameters that can affect extraction efficiency.

First, as the radial depth of the coupling hole increases, the output power decreases. Hence, the radial depth of the coupling hole should be as small as possible.
Second, as shown in Figs. 9 and 10, the axial length $L_A$ and the angular width $\theta_A$ obviously affect power efficiency. Simulation shows that when the axial length is changed from 84 mm to 108 mm, the highest power efficiency is 67.6% at $33^\circ$, which is bigger than that of the SWS ($24^\circ$).

Considering efficiency, output power, and stability, we chose the model with an efficiency of 67.6%, which is the typical result, and the engineering design is being carried out.

Besides the improvements mentioned above, the extraction port is set behind the anode vanes in the axial direction instead of being set between two anode vanes. It directly leads to an increase in efficiency from 57% to 67.6% compared with the structure with the extraction port between two anode vanes.

The experiment is in progress. TM$_{01}$ is a kind of rotational symmetry mode that can be the radiation mode for measurement. We have designed a TEM–TM$_{01}$ mode converter linked with the coaxial waveguide and a horn antenna for radiation. Past experiments certify that the far field method is effective and it will be used in this experiment.

**IV. CONCLUSION**

In conclusion, a highly efficient relativistic magnetron with a novel all-cavity extraction structure is presented and investigated numerically. In simulation, high-power microwaves of the transverse electromagnetic (TEM) mode are generated with a peak power of 1.65 GW, a frequency of 1.61 GHz, and a power efficiency of 67.6% when the voltage is 586 kV, the current is 4.19 kA, and the magnetic field is 0.344 T. The simulation results verify the validity of the novel all-cavity extraction structure.

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