Experimental investigation of a compact relativistic magnetron with axial TE_{11} mode radiation

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As one of the relativistic electron tubes having compact configuration and high efficient output, the relativistic magnetron with direct axial radiation is very attractive in pulsed power and high power microwave fields for industrial and military applications. In this paper, the experimental investigation of a relativistic magnetron with axial TE_{11} mode radiation is reported. Under a total length of ~ 0.3 m, volume of ~ 0.014 m^3, working at an applied voltage of 508 kV and a magnetic field of ~ 0.31 T, the relativistic magnetron radiates a microwave of 540 MW with the TE_{11} mode at 2.35 GHz in the axial direction. The power conversion efficiency is 15.0%. After a lot of shots, the detected amplitudes of microwaves are nearly the same. The fluctuations of wave amplitudes are less than 0.3 dB.

Keywords: relativistic magnetron with axial radiation, modified magnetic field distribution, compact configuration, high power microwave

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1. Introduction

The relativistic magnetron with axial radiation (MAR), known as a magnetron with diffraction output,[1−13] is a compact high efficient crossed field microwave device. Under the proper crossed $\boldsymbol{E} \times \boldsymbol{B}$ fields, electron flow in the azimuthal slow-wave structure converts its energy into microwave energy. Then, the exited microwave is directly radiated in the axial direction. Compared with other crossed field relativistic electron tubes, such as magnetically insulated transmission line oscillator (MILO),[14−16] the MAR has a more compact configuration and higher power conversion efficiency. With attractive features such as a simple structure, compact magnetic coils and low magnetic field strength, the MAR has the priority to meet the needs of the modern high power microwave field for a compact and portable high power microwave tube in industrial and military applications.

Recently, the investigation of the MAR focused on efficiency improvement and compact operation. By adding another open angle in the microwave extraction space, the output power efficiency of the TE_{31} mode is increased from 3% to 37% by computer simulation.[2] Using a transparent cathode,[12] a power conversion efficiency of 70% has been achieved in simulation.[4] In our laboratory, the MAR is investigated both in theory theoretically and experimentally. Through many modifications,[3,8] theoretically the MAR has a compact configuration and high efficient output with TE_{11} mode radiation. In this paper, we present the detailed experimental results. The rest of the present paper is organized as follows. In Section 2, we give a brief description of the MAR and the diagnostics used in the experiments. In Section 3, the experimental results are presented and analysed. Finally, some conclusions are drawn from the present study in Section 4.

2. Experimental setup

The compact MAR is composed of a beam-to-microwave interaction region and a microwave radiation region which are shown in Fig. 1. The first region has an A6 magnetron configuration. The cathode radius is $R_c = 1.58$ cm. The anode radius is $R_a = 2.88$ cm. The cavity radius is $R_d = 4.88$ cm. The microwave radiation region has a special waveguide structure. The inner open angle is $\alpha = 25°$ and the outer open angle is $\beta = 90°$. Two transition sections each with a radius of $r = 9.0$ cm and a length of $z = 7.6$ cm are inserted into the tapered cavities for improving the radiation pattern.[3] The output port has a radius of $R_o = 13.0$ cm. The magnetic field in

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the inner space of the MAR is produced by a pair of solenoids, which have the same power supply but opposite magnetic field directions.[8] The magnetic fields produced by the two solenoids could confine the electrons in the inner space of the MAR to efficiently achieve the beam-to-microwave conversion. The side view and in te front view photos of the MAR are shown in Figs. 2 and 3, respectively. The total length of the device is ~ 0.3 m, and its volume is ~ 0.014 m^3.

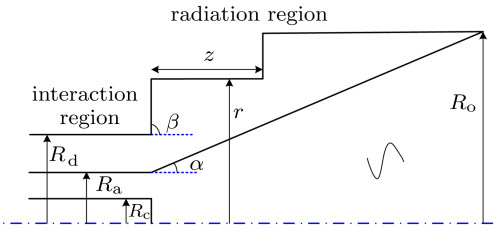


Fig. 1. (colour online) Geometry of the MAR with the inner parameters.

Figure 4 shows a schematic plot of experimental setup for microwave diagnosis. Microwave signals are received simultaneously by two horns which are far from the output port on the axis of the MAR and have the same height from the ground. Horn I is fixed at the location of $\Phi = 0°$. Horn II is movable at $\Phi = \pm 5°$, $\pm 10°$, $\pm 15°$, respectively, along the circumference. The signals received from horn I and horn II are transmitted by an attenuating cable, attenuated by fixed coaxial attenuators, demodulated by fast point-contact microwave crystal detectors and then recorded by a high speed digital oscilloscope. The diode voltage and current are measured by a capacitive divider and a Rogowskii coil, respectively.

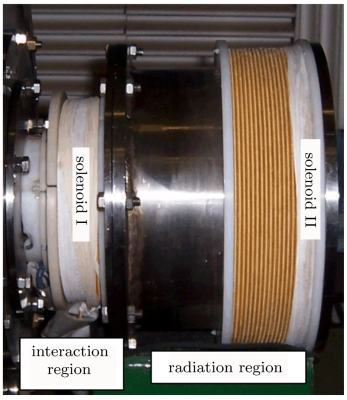


Fig. 2. (colour online) Photo of the side view of the compact MAR.

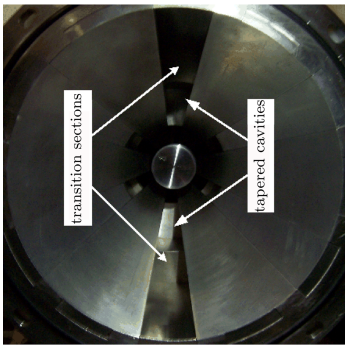


Fig. 3. (colour online) Photo of the front view of the compact MAR.

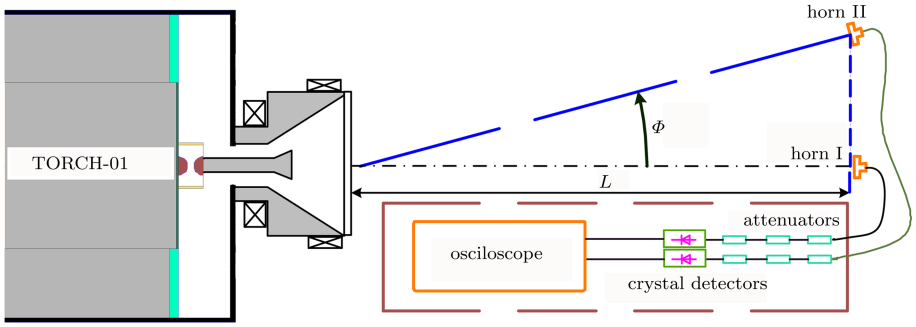


Fig. 4. (colour online) Experimental setup for microwave diagnostics.

3. Experimental results

The experiments are performed on the accelerator "TORCH-01" located in our laboratory. The applied voltage and the axial magnetic field on the MAR are fixed at 500 kV and ~ 0.31 T, respectively.

3.1. Frequency measurement

Without using the crystal detector, the received microwave from horn I is transmitted from attenuators, cable, and is then recorded by a high speed digital oscilloscope TDS7154. Figure 5 shows the mi-

crowave signal. The time-dependent microwave waveform and its fast Fourier transform (FFT) demonstrate that the microwave has a certain pulse duration and pure frequency spectrum. The microwave frequency is 2.35 GHz which is in agreement with the π mode frequency obtained by theoretical expectation and computer simulation. In a lot of shots, the frequency is stable at 2.35 GHz.

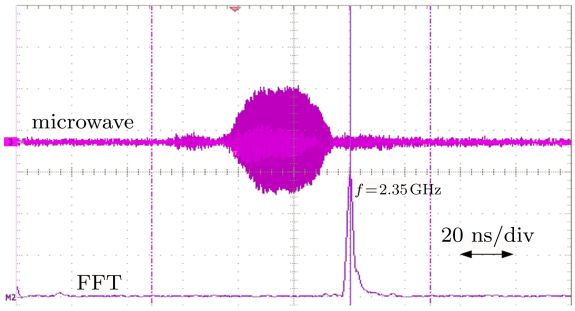


Fig. 5. (colour online) Time-dependent microwave and its fast Fourier transform.

3.2. Mode measurement

The crystal detectors are employed in the two receiving horns. The narrow walls of the receiving horns are parallel to the electric field polarization direction of the output port. With horn I fixed at $\Phi = 0°$, horn II is moved at $\Phi = \pm 5°$, $\pm 10°$, $\pm 15°$, respectively, along the circumference. The signals received from the two horns are recorded in the oscilloscope. With the voltage and magnetic field kept unchanged, all received microwave signals are normalized and plotted in Fig. 6. Figures 6(a) and 6(b) indicate that the measurement results are in agreement with the calculation results of the TE_{11} mode.

3.3. Microwave power measurement

Avoiding all kinds of reflection, the power measurement space is surrounded with microwave absorbers. The ground is paved with two-layer man-made grass. The microwave power is detected using the far-field measurement method.[16] The radiated microwave power is given by

$$P_{\rm out} = \frac{4\pi L^2}{D_{\rm E}} \frac{P_{\rm hm}}{S_{\rm eff}}. \quad (1)$$

Here, L is the distance from the horn to the device, $D_{\rm E}$ is the directivity coefficient of the horn antenna, and $S_{\rm eff}$ is the effective area of the horn at 2.35 GHz. $D_{\rm E}$ is given in the measurement of the microwave mode by interpolation and prediction functions. $P_{\rm hm}$ is the microwave power which is measured by horn I in the main-lobe zone. In order to diminish the uncertainty of power measurements as much as possible, the attenuating cables, fixed coaxial attenuators, and crystal detectors are calibrated immediately after the experiments.

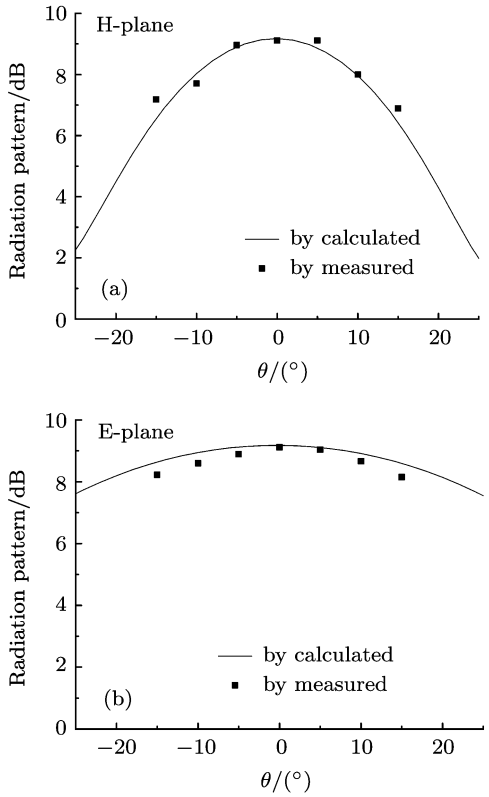


Fig. 6. Radiation patterns of the MAR in (a) H-plane and in (b) E-plane.

Figure 7 shows the waveforms of the diode voltage, the diode current, and the output microwaves. The microwaves are received by horn I at $\Phi = 0°$ and by horn II at $\Phi = 5°$, respectively. The amplitude of the diode voltage is 508 kV. The diode current is 7.06 kA. The microwave power received by horn I is $\sim$ 540 MW. Thus, the power conversion efficiency is $\sim$15.0%. Figure 7 also shows that the microwaves have the flattop time being the same as that of the diode current. This phenomenon illuminates that obvious breakdown or pulse shortening does not take place in the inner space of the MAR.

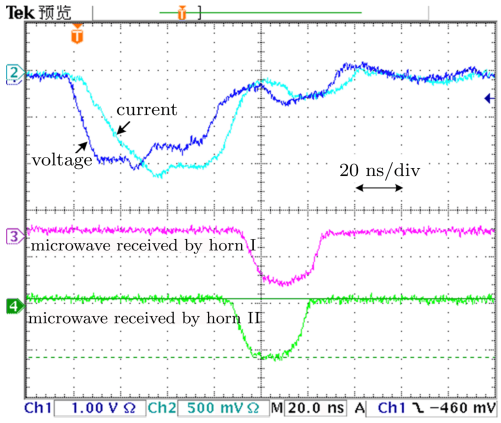


Fig. 7. (colour online) Waveforms of the applied voltage, the diode current, and the output microwave.

Furthermore, in order to validate the operating stability, after many shots, the waveforms of microwaves received by horn I are recorded and then summarized in Fig. 8. Figure 8 shows 10-shot results. It is seen that although a little jitter exists in the pulsed duration, the microwave amplitudes are nearly the same. The fluctuations of wave amplitudes are less than 0.3 dB.

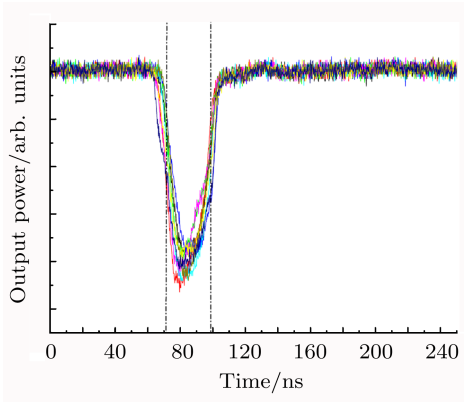


Fig. 8. Waveforms of the radiated microwaves after 10 shots.

4. Conclusions

Experimental investigation of a compact MAR with a directly radiating TE_{11} mode in the axial direction is reported in this paper. With a total length of ~ 0.3 m and the volume of ~ 0.014 m^3, an MAR working at 508 kV and ~ 0.31 T produces a 540-MW microwave at 2.35 GHz with TE_{11} mode in the axial direction. The corresponding power conversion efficiency is 15.0%. After a lot of shots, the detected microwaves are nearly the same. The fluctuations of wave amplitudes is less than 0.3 dB.

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