Operation Characteristics of 12-Cavity Relativistic Magnetron With Single-Stepped Cavities

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***Abstract*— The possibility of using single-stepped cavities to replace the common tapered cavities was studied using particle-in-cell simulations in an A6 magnetron with diffraction output (MDO). The replacing of the tapered cavities by the single-stepped cavities in a 12-cavity MDO increases the interaction space where the charged particles interact with the induced RF waves. The electronic efficiency of the 12-cavity MDO with single-stepped cavities driven by the transparent cathode [2] of GW output power level can be as high as 73% for $\alpha = 18.2°$, 74% for $\alpha = 17.5°$, and 72% for $\alpha = 12.5°$ at $\beta = 32°$, where α is the angle between the outer wall and z-axis, and β is the angle between the inner wall and z-axis. The depth of single-stepped cavities is changed when α is changed, which results in different frequency range of magnetron operating modes. When a 400-kV voltage pulse of 10-ns duration is applied to a transparent cathode or a solid cathode, the output power can be as high as 1 GW. Without loss of generality, for $\alpha = 12.5°$ at $\beta = 32°$, the peak efficiency around 70% of 12-cavity MDO with single-stepped cavities design occurs at the voltage ($V \sim 400 \pm 50$ kV). The results presented in this paper provide references for relativistic magnetron mode selection or mode switching experiments when choosing the input parameters (magnetic field and accelerating voltage) allowing the magnetron to operate in the desired operation mode.**

***Index Terms*— Diffraction output, magnetron, operation mode, single-stepped cavities.**

I. INTRODUCTION

THE relativistic magnetron oscillator can be a highly efficient device for generating microwaves and a lot of works were done on it so far [3]–[15]. In relativistic magnetrons with axial extraction of microwave power through a horn antenna, which also known as magnetrons with diffraction output (MDO), any mode can be used as the operating mode, unlike in magnetrons with radial extraction of radiation through, for example, one of the cavities of the anode block, when only nondegenerate modes can be used as the operating ones [16]. Recently, researchers at the University of New Mexico demonstrated in simulations that the electronic efficiency of an A6 MDO can be as high as 70% [17], when it is driven by a transparent cathode. In addition, Lemke *et al.* [10] demonstrated that the electronic efficiency of rising-sun magnetrons can be around 40% with 3.7-GW output power. It was demonstrated in simulations by researchers at the University of New Mexico that the mode switching from pulse to pulse in an A6 MDO can be realized using a weak ($\sim 10^5$ W), short ($\sim 10^{-8}$ s), and single-frequency microwave signal [18]. It was shown that the switched mode persists even after switching OFF the RF signal [19].

It was also shown that it is possible to achieve frequency switching between modes that have the same transverse field structure, but different axial distributions [20]. It was demonstrated that, when using a diffraction output with a complicated configuration resulting in reflections from its different cross sections, an opportunity exists for exciting different operation modes with different axial distributions and the same transverse field structure, and that the mode switching between different longitudinal modes can also be realized in this configuration [20]. Compared with the traditional tapered cavity, the single-stepped cavity is easier to manufacture.

In this paper, we explore the possibility of using single-stepped cavities instead of the traditional tapered cavities in a 12-cavity MDO to achieve around 70% of electronic efficiency with gigawatt output power level by optimizing MDO geometrical parameters, such as α, the angle between the outer wall and z-axis, and the cathode emitter length. The particle-in-cell (PIC) simulations of the 12-cavity MDO with single-stepped cavities show that the output power of the TE_{41} mode can be as high as 1.74 GW driven by transparent cathode, and the output power of the TE_{31} mode can be as high as 1.54 GW when a 400-kV voltage is applied to both transparent and solid cathodes (the transparent cathode and the solid cathode with same radius dimension $R_c = 1.0$ cm).

II. PIC SIMULATIONS OF 12-CAVITY MDO WITH SINGLE-STEPPED CAVITIES

The tapered cavities in the 12-cavity MDO [20] are replaced by single-stepped cavities, as shown in Fig. 1. The single-stepped cavities position A in the z-direction is 5.0 cm away from the beginning of the anode block. In this configuration, the interaction space where emitted electrons and induced RF waves interact with each other increases, as shown in Fig. 1(a).

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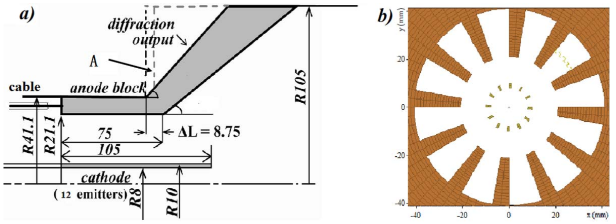

Fig. 1. 12-cavity MDO with single-stepped cavities design. (a) Cross-sectional diagram in the r–z plane. (b) Cross-sectional diagram in the r–θ plane.

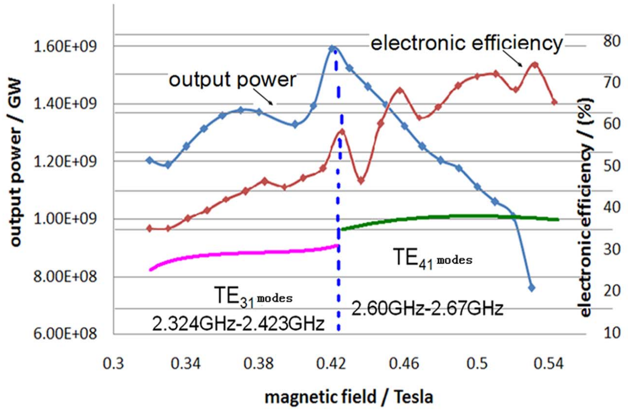

Fig. 2. Separation of modes for different applied axial magnetic fields with $\alpha = 12.5°$ and $\beta = 32°$.

The transparent cathode consisting of 12 separate longitudinal emitters periodically placed around radius $R_c = 1.0$ cm is used in simulations with the PIC code MAGIC [21]. The 12-cavity MDO with single-stepped cavities replacing the tapered cavities is matched to a horn antenna to extract the output power. In our simulations, it can be inferred that R_{ef} is maximum (in the optimized configuration) for modes with azimuthal indices $n = 3$ and $n = 4$, and that the loaded Q-factor is close to the diffraction Q-factor [16]

$$Q \approx Q_{\mathrm{diff}} = \frac{8\pi (L/\lambda)^2}{m(1 - R_{\mathrm{ef}})} \tag{1}$$

where m is the number of axial field variations, L is the length of interaction space, and λ is the operating wavelength. The magnetic field in PIC simulations is varied from $B = 0.32$ to $B = 0.52$ T, with $\alpha = 12.5°$ and $\beta = 32°$, and the cathode emitter length is 10.5 cm. The results of PIC simulation (Fig. 2) show that in this configuration only two operating modes exist, which are the TE_{31} mode (frequency ranges from 2.324 to 2.423 GHz) and the TE_{41} mode (frequency ranges from 2.60 to 2.67 GHz). In addition, it can be observed in Fig. 2 that the electronic efficiency can be as high as 70%, while the output power can be as high as 1.1 GW.

When $\alpha = 17.5°$ and $\beta = 32°$, the mode separation and frequency splitting (two different longitudinal modes appear) is observed, as shown in [20, Fig. 3]. The TE_{31} mode frequency ranges from 2.324 to 2.374 GHz, and the TE_{41} mode frequency ranges from 2.63 to 2.654 GHz, as shown in Fig. 3. In addition, it can be observed that the electronic efficiency is as high as 70%, while the output power is as high as 1.2 GW (Fig. 3).

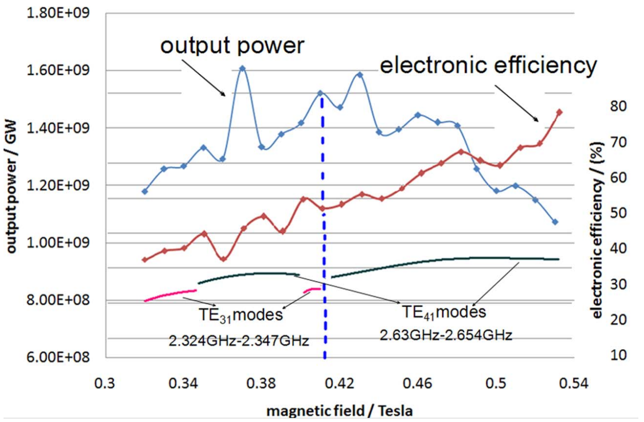

Fig. 3. Separation of modes for different applied axial magnetic fields with $\alpha = 17.5°$ and $\beta = 32°$.

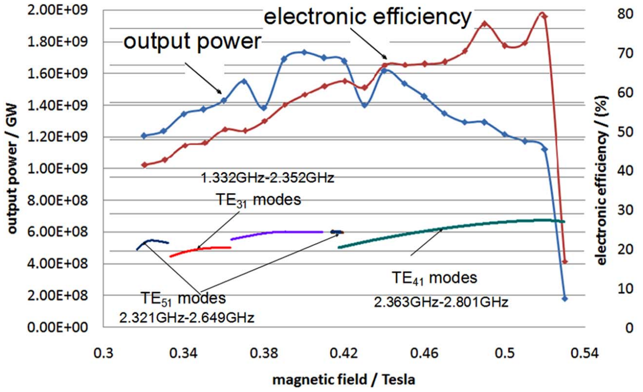

Fig. 4. Separation of modes for different applied axial magnetic fields with $\alpha = 18.2°$ and $\beta = 32°$.

The results of PIC simulations with $\alpha = 18.2°$ and $\beta = 32°$ are shown in Fig. 4. The simulations show the mode separation and the frequency splitting in this configuration, which can also be observed but in a different manner when parameter $\alpha = 17.5°$. He TE_{51} mode can also be observed in Fig. 4. The TE_{31} mode frequency ranges from 1.332 to 2.352 GHz, and the TE_{41} mode frequency ranges from 2.363 to 2.801 GHz. In addition, it can be observed that the electronic efficiency is as high as 70%, while the output power is as high as 1.2 GW (Fig. 4).

The bifurcation of frequency (Figs. 3 and 4) gives the possibility to consider the switching of frequencies at the same transverse mode using common properties of a dynamical system with two stable states separated by an unstable saddle point, as shown in [18] and [19]. The mode priming and the mode switching can also be separately realized in these configurations, as shown in Figs. 2–4.

III. OPERATING MODES FOR A SHORT VOLTAGE PULSE IN A 12-CAVITY MDO WITH SINGLE-STEPPED CAVITIES

The output power of operating modes in these configurations can be optimized by increasing the emitter length.

For example, the output power as high as 1.78 GW in the TE_{41} mode with frequency $f = 2.650$ GHz is obtained (Fig. 5) for the configuration with $\alpha = 18.2°$ and $\beta = 32°$, when the emitter length is increased to 11.2 from 10.5 cm [Fig. 1(a)].

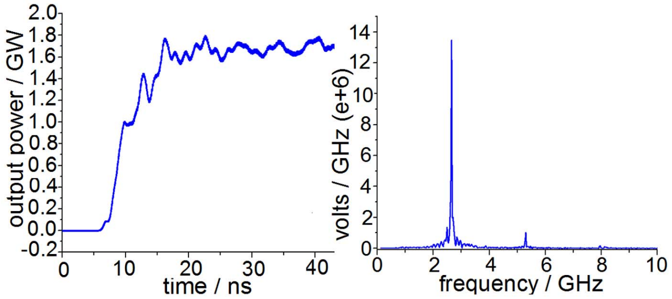

Fig. 5. (a) Output power of the TE_{41} mode at $B = 0.40$ T. (b) Spectrum of the mode with $f = 2.650$ GHz ($\alpha = 18.2°$ and $\beta = 32°$).

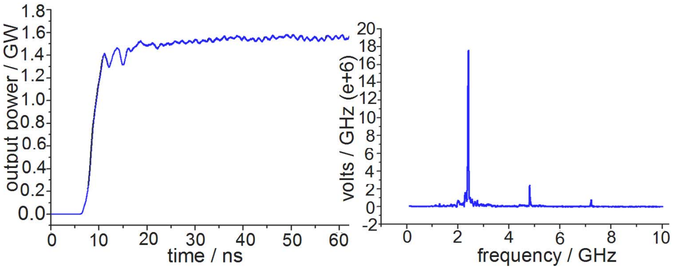

Fig. 6. (a) Output power of the TE_{31} mode at $B = 0.38$ T. (b) Spectrum of the mode with $f = 2.405$ GHz ($\alpha = 12.5°$ and $\beta = 32°$).

In addition, the output power as high as 1.51 GW at the TE_{31} mode with frequency $f = 2.405$ GHz is obtained for $\alpha = 12.5°$ and $\beta = 32°$, when the emitter length is increased to 14.5 from 10.5 cm (Fig. 6).

The electron spokes and the electric field contours for the TE_{41} and the TE_{31} modes are shown in Fig. 7.

Without loss of generality, let us consider the single-stepped cavities position 5.4 cm away from the beginning of the anode block at $\alpha = 12.5°$ (Fig. 2). Since the anode block length increases, $\alpha = 12.5°$ compared with the other angles considered, the emitter length also increases to 20 cm, so that the emitted electrons will exist in the stronger induced RF field in the stepped cavity. The simulation results for 400-kV voltage pulse with a 4-ns rise time for this configuration driven by transparent cathode are shown in Fig. 8. The MAGIC simulations for 400-kV voltage pulse with a 4-ns rise time for this configuration with the solid cathode of length 20 cm are also done; however, for comparison with transparent cathode simply, the solid cathode dimension chosen $R_c = 1.0$ cm, mode competition seriously occurs when magnetic field $B \geq 0.37$ T. So, here only show the clear TE_{31} mode driven by solid cathode when $B = 0.34$ T in Fig. 9. In order to make the solid cathode operate properly, we need to optimize the solid cathode dimension to reduce the mode competition phenomenon in later work.

Top and middle are for transparent cathode, while bottom is for solid cathode.

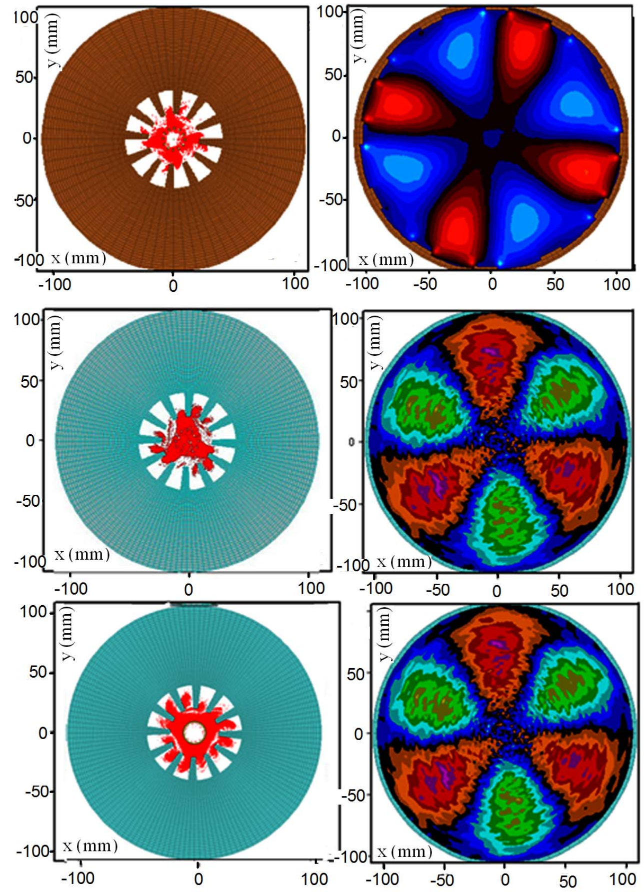

Fig. 7. Top: electron spokes synchrous with TE_{41} mode (left) and azimuthal field structure of generated TE_{41} mode (right). Middle: electron spokes synchrous with TE_{31} mode (left) and azimuthal field structure of generated TE_{31} mode (right). Bottom: electron spokes synchrous with TE_{31} mode (left) and azimuthal field structure of generated TE_{31} mode (right).

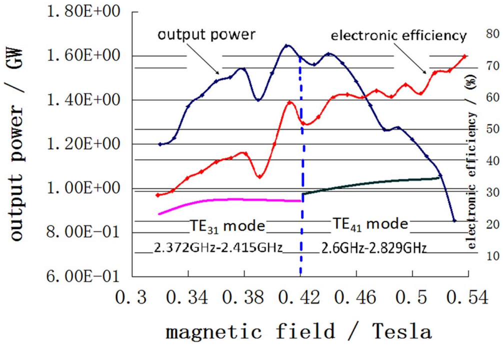

Fig. 8. Separation of modes for different applied axial magnetic fields when the length of the transparent cathode is 20 cm. This is for $\alpha = 12.5°$ and $\beta = 32°$.

In our simulation with $\alpha = 12.5°$ and $\beta = 32°$ (Fig. 2), we also changed the voltage from 350 to 450 kV that is the applied voltage $V \sim 400 \pm 50$ kV, and it was shown through PIC simulation as in Fig. 10 that the electronic efficiency and the output power cannot be obtained the peak value at the same time. The electronic efficiency can be kept around 70% with gigawatt level output power when applied voltage from 375 to 450 kV, and when only considering the electronic efficiency, it can be kept around 70% with applied voltage $V \sim 400 \pm 50$ kV (Fig. 10).

The 12-cavity MDO with single-stepped cavities is a complex oscillator where many different operating modes may exist. The microwave generation originates from noise, which is the sum of eigenmodes with random amplitudes and phases.

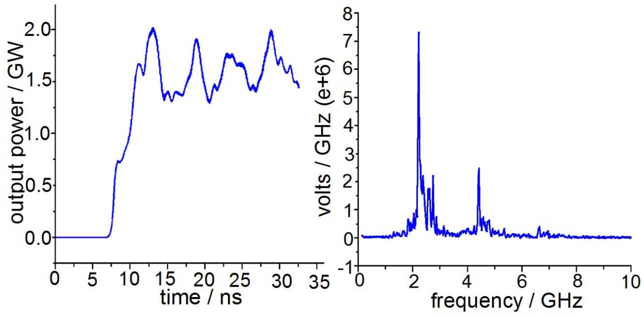

Fig. 9. Left: output power of TE_{31} mode generation when $B = 0.34$ T. Right: spectrum of generation with $f = 2.209$ GHz. This is for configuration $\alpha = 12.5°$ and $\beta = 32°$ with a solid cathode.

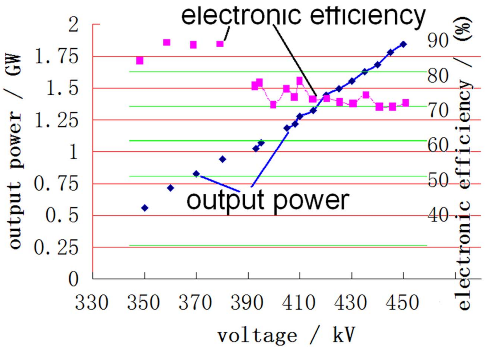

Fig. 10. Output power and electronic efficiency variance with applied voltage.

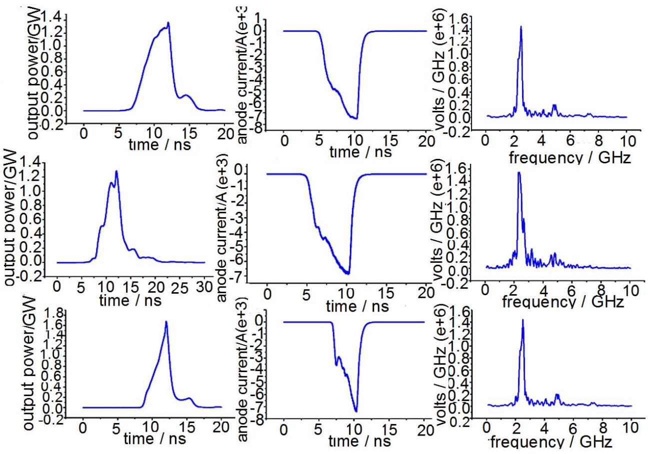

Fig. 11. Top: output power pulse (left), anode current pulse (middle), and spectrum of 10-ns duration voltage pulse for a transparent cathode at $B = 0.40$ T (right). Middle: output power pulse (left), anode current pulse (middle), and spectrum of 10-ns duration voltage pulse for a transparent cathode at $B = 0.41$ T (right). Bottom: output power pulse (left), anode current pulse (middle), and spectrum of 10-ns duration voltage pulse for a solid cathode at $B = 0.34$ T (right).

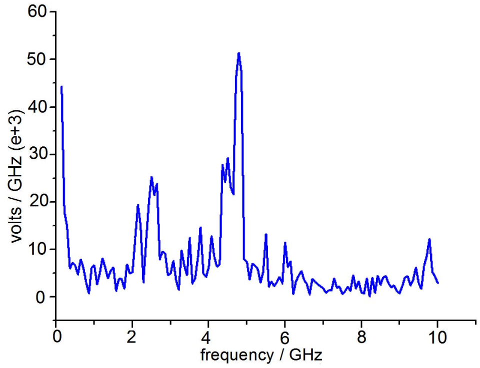

Fig. 12. Frequency spectrum for 12-cavity MDO with single-stepped cavities when driven by a solid cathode in configuration ($\alpha = 12.5°$ and $\beta = 32°$) with $B = 0.38$ T.

When 400-kV voltage pulse of 10-ns duration is applied, when magnetic field $B = 0.40$ T is chosen a little far from neighbor modes boundary $B = 0.42$ T, the PIC simulation shows the output power can be as high as 1 GW with 5-ns pulsewidth (Fig. 11, top) driven by a transparent cathode; and when magnetic field $B = 0.41$ T is chosen, the PIC simulation shows the output power can be as high as 1 GW with 4-ns pulsewidth (Fig. 11, middle) driven by a transparent cathode while driven by a solid cathode, choosing a magnetic field $B = 0.34$ T away from the boundary magnetic field $B = 0.42$ T, the PIC simulation shows the output power can be as high as 1 GW with 3-ns pulsewidth (Fig. 11, bottom).

When the 12-cavity MDO with single-stepped cavities driven by a solid cathode, choosing a magnetic field $B = 0.38$ T near boundary $B = 0.42$ T compared with $B = 0.34$ T, the spectrum in Fig. 12 shows mode competition seriously. The PIC simulation shows that, for short voltage pulse, the transparent cathode is more advantageous than solid cathode when considering high output power and clean operation spectrum.

This is for the configuration $\alpha = 12.5°$ and $\beta = 32$ using transparent cathode and solid cathode with 10-ns duration voltage pulse.

IV. CONCLUSION

We have demonstrated in PIC simulations the operation of a 12-cavity MDO with single-stepped cavities replacing the tapered cavities that the cavity volume is increased along with the interaction space. We found that the electronic efficiency in this magnetron can be as high as 70% at gigawatt output power level. In addition, without loss of generality, for $\alpha = 12.5°$ and $\beta = 32°$, the electronic efficiency can be kept around 70% with voltage from 375 to 450 kV with gigawatt level output power. This means the 12-cavity MDO with single-stepped cavities with a little voltage tolerance, and its efficiency can be as high as 70%. When using a 10-ns duration applied voltage pulse for 12-cavity MDO with single-stepped cavities, the output power is as high as 1 GW. For the same configuration parameters of the MDO, as shown in Fig. 1, given the same cathode radius and cathode length, the transparent cathode is more robust to the disturbances and has a wider range of operating modes as compared with the solid cathode. The research described in this paper allows for the possibility of using a 12-cavity MDO with a higher power pulse to study mode switching phenomena. In addition, the work in this paper provides reference for relativistic magnetron mode selection or mode switching experiments when defining the boundary between magnetron operating modes.

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