A Compact Relativistic Magnetron with a TE_{10} Output Mode

Di-Fu Shi, Bao-Liang Qian, Wei Li, Hong-Gang Wang, and Lin Lian
College of Optoelectronic Science and Engineering
National University of Defense Technology, Changsha, Hunan 410073, China

Abstract— An S-band compact A6 relativistic magnetron which operates in the π-mode is proposed, and its radiation can be extracted as a TE_{10} mode axially through a rectangular waveguide which is designed to match radially with the anode. Compared with the magnetron with diffraction output (MDO), the magnetron of this structure can reduce the dimension of the output port of the magnetron, and therefore reduce the volume of the coil of the applied magnetic field, and also reduce the distance between the electron dump and the anode block so that both the diameter and the axial length of the magnetron can be minimized. In addition, as a result of the limit to the dimension of the output waveguide, such a simple converter of the magnetron can provide a much purer radiated mode. The softwares of high-frequency field analysis and CHIPIC particle-in-cell (PIC) simulation have been used to analyze and optimize the operating performance of the magnetron proposed in this paper. Simulation results show that under the condition of the applied voltage of 360 kV, the input power of 1.87 GW and the applied magnetic field of 0.4 T, the output microwave power is 409.2 MW and the power conversion efficiency can reach 21.9%, while the resonant frequency of π-mode is 2.5 GHz and the radiated mode is TE_{10} in the rectangular waveguide.

1. INTRODUCTION

The relativistic magnetron, for the reasons of its simple structure, high-power capability, suitable application for long pulse, and high pulse repetition rate, as well as its tunability, has become one of the most promising devices of all high power microwave sources [1]. In recent years, it was explored extensively, including transparent cathode [2–4], electric or magnetic priming [5–9], axial diffraction output [10–13], compactness [14–16], and so on. A compact relativistic magnetron radiating with the lowest order mode is usually required for commercial and military applications. The magnetron with diffraction output (MDO) in which the anode vanes and cavities are tapered radially outward at an optimal angle in the form of a conical horn antenna can be used for mode conversion from the operating π-mode to different TE modes [10]. And modified magnetic field distribution makes the MDO more compact in axial dimension, however, at the expense of increased radial dimension [13]. Recently, a compact A6 relativistic magnetron is proposed which operates in the π-mode and whose radiation is extracted axially as a TE_{11} mode through a cylindrical waveguide with the same cross section as that of the anode block, although with reduced efficiency [14].

In this paper, we describe an S-band compact A6 relativistic magnetron which operates in the π-mode, and its radiation can be extracted as a TE_{10} mode axially through a rectangular waveguide which is designed to match radially with the anode.

This configuration has several advantages: the magnetron of this structure can reduce the dimension of the output port of the magnetron, and therefore reduce the volume of the coil of the applied magnetic field, and also reduce the distance between the electron dump and the anode block so that both the diameter and the axial length of the magnetron can be minimized. In addition, as a result of the limit to the dimension of the output waveguide, such a simple converter of the magnetron can provide a much purer radiated mode.

2. SIMULATION SETUP

The three-dimensional fully electromagnetic and particle-in-cell (PIC) code CHIPIC [17] is used to investigate the performance of the compact relativistic magnetron with TE_{10} output mode. The structure of the well-known A6 magnetron [18] is adopted in this study. Fig. 1(a) shows the schematic diagram of the horizontal cross section of the A6 magnetron with three protrusions alternating with three recessions. Fig. 1(b) shows the 3D view of the converter connecting the A6 magnetron with the rectangular waveguide.

As shown in Fig. 1(a), the structure of the magnetron consists of 6 sectorial ($\theta = 20°$) cavities with height $H_m = 7.2$ cm. The radii of the cathode, the anode, and the cavities are $R_c = 10.0$ mm, $R_a = 21.0$ mm, and $R_v = 42.1$ mm, respectively. In order to improve the output power and reduce the startup time, protrusions and recessions on the inner surface of anode vanes are utilized in the simulations. The angular width of the protrusions and recessions are $\theta_p = 5°$, and $\theta_r = 5°$, respectively. The protrusion and recession radii are $(R_a - \Delta r) = 20.0$ mm and $(R_a + \Delta r) = 22.0$ mm, respectively, where the radial variation $\Delta r = 1$ mm is same for protrusion and recession.

As shown in Fig. 1(b), at the end of the A6 magnetron, two diametrically opposite cavities and the interaction space of the magnetron are converted axially to a rectangular waveguide. And the other cavities are tapered radially inward at an optimal angle ($\alpha = 68.8°$). The length and width

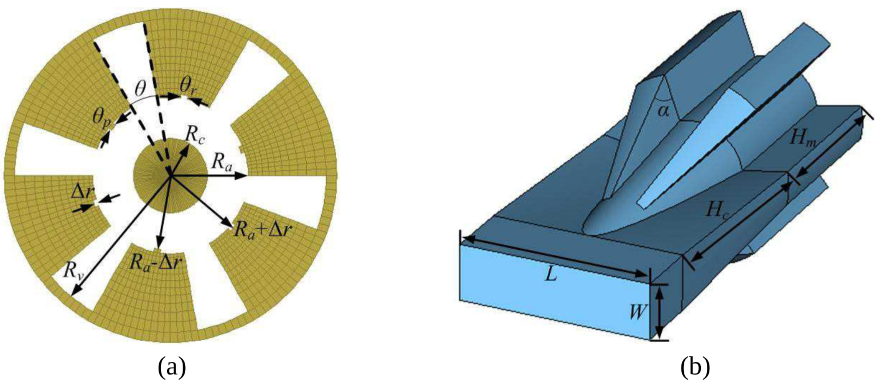

Figure 1: (a) Schematic diagram of the horizontal cross section of the A6 magnetron with three protrusions alternating with three recessions. (b) 3D view of the converter connecting the A6 magnetron with the rectangular waveguide.

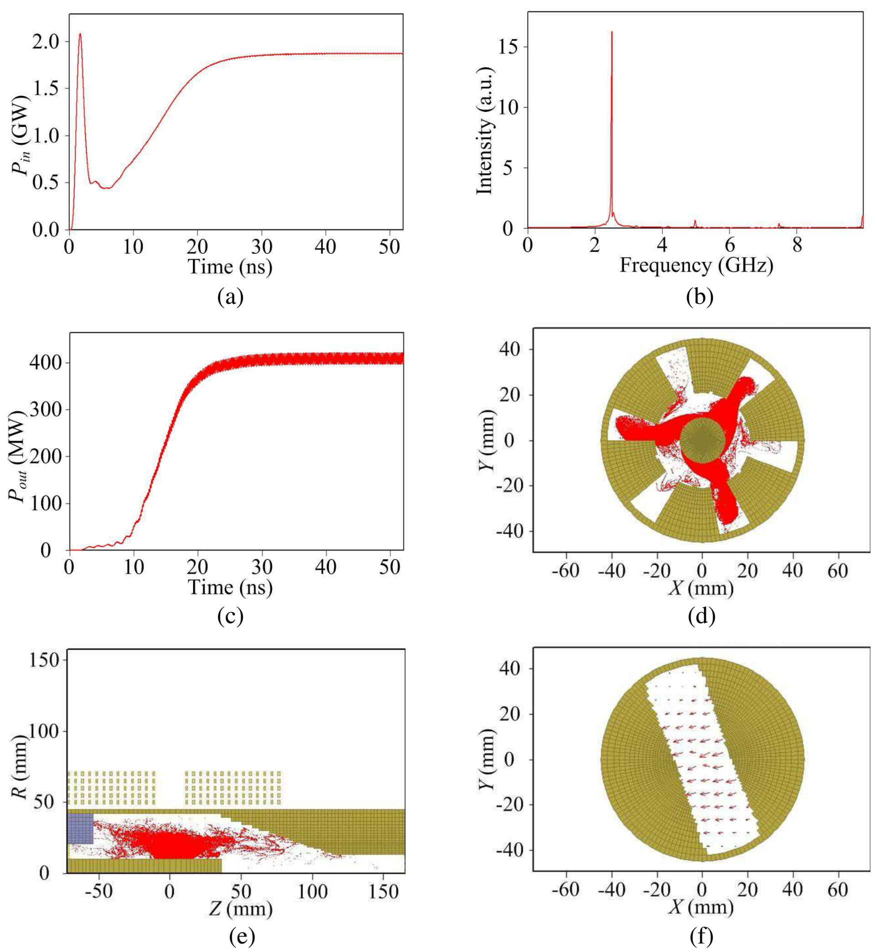

Figure 2: (a) Input power versus time. (b) Spectrum of electric field in resonant cavity. (c) Output power versus time. (d) Electron spokes in the magnetron in the r_θ plane. (e) Particle plot of the electron flow in the magnetron in the r_z plane. (f) Radiated mode of output port.

of the rectangular waveguide are $L = 84.2$ mm, $W = 24.0$ mm, respectively. The distance between the A6 magnetron and the rectangular waveguide is $H_c = 100.0$ mm.

In our simulations, the applied voltage has a rise time of 3 ns after which it maintained a constant amplitude of 360 kV for a duration of 50 ns, and the applied axial magnetic field for interaction space is 0.4 T.

3. SIMULATION RESULTS

According to the simulation setup described in Section 2, the compact magnetron model is investigated by 3D PIC, CHIPIC. And Fig. 2 gives the simulation results.

Figure 2(a) indicates that the input power maintain a constant amplitude of 1.87 GW after 25 ns. Fig. 2(b) indicates that the spectrum of the electric field in resonant cavity is very pure, and the resonant frequency is 2.5 GHz, which is greater than the cutoff frequency for the rectangular waveguide. Fig. 2(c) indicates that the output power of 409.2 MW reaches to saturation at 25 ns, corresponding to the power conversion efficiency of 21.9%. And we believe that further design and optimization could reduce the startup time and increase the power conversion efficiency. Fig. 2(d) shows the electron spokes in the magnetron in the r_θ plane at 30 ns, and it indicates that the magnetron operates at π mode.

Figure 2(e) shows the particle plot of the electron flow in the magnetron in the r_z plane at 30 ns, and it indicates that most leakage electrons from the interaction space can be captured by the converter before the microwave window. Compared with the magnetron with diffraction output (MDO), as shown in Fig. 3, the magnetron of this structure can reduce the dimension of the output port of the magnetron, and therefore reduce the volume of the coil of the applied magnetic field, and also reduce the distance between the electron dump and the anode block so that both the diameter and the axial length of the magnetron can be minimized.

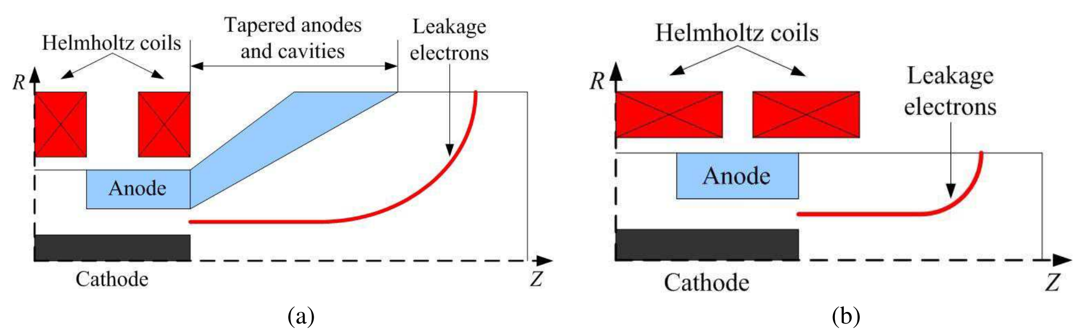

Figure 3: (a) Schematic diagram of the MDO. (b) Schematic diagram of the compact magnetron.

Figure 2(f) indicates that the radiated mode of output port is TE_{10} mode, which is the lowest order mode in the rectangular waveguide. As a result of the limit to the dimension of the rectangular waveguide, only TE_{10} mode can propagate in the rectangular waveguide, so that a pure radiated mode can be obtained.

4. CONCLUSION

In conclusion, a compact relativistic magnetron with TE_{10} output mode is proposed in this paper. The magnetron operates in the π-mode, and its radiation can be extracted as a TE_{10} mode axially through a rectangular waveguide which is designed to match radially with the anode. This design not only makes both the diameter and the axial length of the magnetron minimized, but also provides a much purer radiated mode in the output waveguide, and the magnetron can operate with acceptable efficiency (about 21.9%), although we believe that the further design and optimization of the magnetron may lead to higher efficiency, such as using transparent cathode to increase the efficiency and reduce the startup time, using strap to promote stable generation of the π mode, and using cathode endcap to reduce the leakage electrons from the interaction space.

REFERENCES

1. Benford, J., J. Swegle, and E. Schamiloglu, *High-power Microwaves*, 2nd Edition, Chapter 7, 259–320, Artech House, Norwood, MA, 2006.

2. Fuks, M., S. Prasad, and E. Schamiloglu, "Increased efficiency and faster turn-on in magnetrons using the transparent cathode," *Proc. Int. Conf. CAVMAG*, 76–81, 2010.
3. Schamiloglu, E. and M. I. Fuks, "The transparent cathode: Rejuvenator of magnetrons and inspiration for new RF sources," *Proc. IET Conf. High Power RF Technol.*, 1–5, 2009.
4. Fuks, M. I. and E. Schamiloglu, "70% efficient relativistic magnetron with axial extraction of radiation through a horn antenna," *IEEE Trans. Plasma Sci.*, Vol. 38, No. 6, 1302–1312, Jun. 2010.
5. Kim, J. I., J. H. Won, and G. S. Park, "Electron prebunching in microwave magnetron by electric priming using anode shape modification," *Appl. Phys. Lett.*, Vol. 86, No. 17, 171501-1–171501-3, Apr. 2005.
6. Baiburin, V. B. and K. V. Kaminskii, "Effect of an azimuthally varying magnetic field on the noise level in a multicavity magnetron," *Tech. Phys. Lett.*, Vol. 35, No. 6, 582–584, Jun. 2009.
7. Neculaes, V. B., M. C. Jones, R. M. Gilgenbach, Y. Y. Lau, J. W. Luginsland, B. W. Hoff, W. M. White, N. M. Jordan, P. Pengvanich, Y. Hidaka, and H. L. Bosman, "Magnetic priming effects on noise, startup, and mode competition in magnetrons," *IEEE Trans. Plasma Sci.*, Vol. 33, No. 1, 94–101, Feb. 2005.
8. Hoff, B. W., R. M. Gilgenbach, N. M. Jordan, Y. Y. Lau, E. J. Cruz, D. M. French, M. R. Gomez, J. C. Zier, T. A. Spencer, and D. Price, "Magnetic priming at the cathode of a relativistic magnetron," *IEEE Trans. Plasma Sci.*, Vol. 36, No. 3, 710–717, Jun. 2008.
9. Maurya, S., V. V. P. Singh, and P. K. Jain, "Three-dimensional particle-in-cell simulation of fast oscillation startup and efficiency improvement in a relativistic magnetron with electric priming," *IEEE Trans. Plasma Sci.*, Vol. 40, No. 10, 2686–2692, Oct. 2012.
10. Fuks, M. I., N. F. Kovalev, A. D. Andreev, and E. Schamiloglu, "Mode conversion in a magnetron with axial extraction of radiation," *IEEE Trans. Plasma Sci.*, Vol. 34, No. 3, 620–626, Jun. 2006.
11. Daimon, M., K. Itoh, G. Imada, and W. Jiang, "Experimental demonstration of relativistic magnetron with modified output configuration," *Appl. Phys. Lett.*, Vol. 92, No. 19, 191504-1–191504-3, May 2008.
12. Li, W. and Y.-G. Liu, "An efficient mode conversion configuration in relativistic magnetron with axial diffraction output," *J. Appl. Phys.*, Vol. 106, No. 5, 053303-1–053303-3, Sep. 2009.
13. Li, W., Y.-G. Liu, J. Zhang, D.-F. Shi, and W.-Q. Zhang, "Experimental investigations on the relations between configurations and radiation patterns of a relativistic magnetron with diffraction output," *J. Appl. Phys.*, Vol. 113, No. 2, 023304-1–023304-4, Jan. 2013.
14. Leach, C., S. Prasad, M. Fuks, and E. Schamiloglu, "Compact relativistic magnetron with Gaussian radiation pattern," *IEEE Trans. Plasma Sci.*, Vol. 40, No. 11, 3116–3120, Nov. 2012.
15. Li, W., Y.-G. Liu, T. Shu, H.-W. Yang, Y.-W. Fan, et al., "Experimental demonstration of a compact high efficient relativistic magnetron with directly axial radiation," *Phys. Plasmas*, Vol. 19, No. 1, 013105-1–013105-4, Jan. 2012.
16. Li, W. and Y. G. Liu, "Modified magnetic field distribution in relativistic magnetron with diffraction output for compact operation," *Phys. Plasmas*, Vol. 18, No. 2, 023103-1–023103-4, Feb. 2011.
17. Zhou, J., D. Liu, C. Liao, and Z. Li, "CHIPIC: An efficient code for electromagnetic PIC modeling and simulation," *IEEE Trans. Plasma Sci.*, Vol. 37, No. 10, 2002–2011, Oct. 2009.
18. Palevsky, A. and G. Bekefi, "Microwave emission from pulsed, relativistic e-beam diodes. II. The multiresonator magnetron," *Phys. Fluids*, Vol. 22, No. 5, 986–996, May 1979.