Experimental Examination of Diode Features in a High-Power Magnetron with a Transparent Cathode

Hoshiyuki YAMAZAKI and Weihua JIANG

Extreme Energy-Density Research Institute
Nagaoka University of Technology, Nagaoka, Niigata 940-2188, Japan

(Received 16 November 2007 / Accepted 2 April 2008)

A Magnetron is a high efficiency microwave source, although the energy conversion efficiency of a pulsed-power magnetron with a relativistic electron beam is less than that of a non-relativistic magnetron. We studied the possibility of increasing the energy conversion efficiency of a high-power magnetron using a transparent cathode. The conversion efficiency is controlled by the resonance efficiency between the electron beam and microwave oscillation, and initial rise time of the oscillation. In particular, the initial rise time of interaction with the pulsed-power generator is important. The transparent cathode can lower start-up times and enhance the oscillation efficiency. It consists of independent cathode strips, each of which produces an azimuthal magnetic field. The radial drift velocity of electrons emitted from this cathode is accelerated more than that of electrons emitted from a normal cathode. In particle-in-cell electron simulation, the availability of the transparent cathode was indicated. We investigated the experimental effect of the transparent cathode. The experimental setup of the relativistic magnetron is operated with "ETIGO IV," which is a 400-kV-class repetitive pulsed-power generator. The start-up time of magnetron with the transparent cathode is shorter than that with a traditional cathode. We expect that the transparent cathode method will be advantageous over the current method.

Keywords: high-power microwaves, relativistic magnetron, transparent cathode, combined efficiency, rapid start-up, long pulse

DOI: 10.1585/pfr.3.S1025

1. Introduction

Recently, reduction in the device scale and weight is expected in many fields of study. The region of high-power microwaves is no exception. Of course, the energy conversion efficiency and output power are important. In addition, minimal modification reduces development costs, and past knowledge and equipment can be well utilized. The magnetron is one of the main candidate devices with high efficiency. Magnetrons have been studied for several years, and come into play at the non-relativistic to relativistic region in radars, electrical power transmission devices, microwave ovens, etc. Magnetrons display average efficiency in regions of high-power microwaves, although their operating frequency is limited to lower microwave regions; that is, gyrotrons can output more high-frequency than magnetrons. Some characteristic features of magnetrons include high oscillation efficiency and a low demand for external magnetic fields [1, 2]. The external magnet consists of permanent magnets, and it can reduce the input power to the magnetic field and the space of magnetic coils, which may require a cooling system. In general, the efficiency of high-power microwaves is determined by momentary output energy and momentary input energy measured at the time of peak oscillation. Recent studies have considered the total efficiency to the total input-output energy ratio [1], i.e., the enhanced combined efficiency has been investigated. Among the candidate procedures to enhance magnetron oscillation efficiency, such as magnetic, cathode, and anode priming [3–5], numerical simulations have demonstrated the potential of transparent cathodes [6, 7]. Transparent cathodes consist of independent cathode strips, as opposed to the solid column found in conventional cathodes. Figure 1 (a) shows the model of a transparent cathode. Each strip induces an azimuthal magnetic field, and the radial drift velocity of electrons is accelerated to more than that of electrons emitted from the general cathode shown in Fig. 1 (b). In addition, the azimuthal electric field penetrates the cathode strips. Crossed field devices like magnetrons function based on interactions between azimuthal electric motion and electromagnetic waves. Therefore, transparent cathodes lead to rapid spreading of electrons, which implies a rapid start-up, and the penetrating electric field leads to higher efficiency interaction. The shorter start-up also increases the interaction term in pulsed electron beams, and enhances the combined efficiency. The transparent cathode can improve the start-up time and operation efficiency. Our aim is enhanced combined efficiency by simplification of the magnetron structure. Our approach is to reduce the start-up time to achieve enhanced efficiency. In this study, we investigate the use of a transparent cathode for rapid start-

author's e-mail: yamazaki@etigo.nagaokaut.ac.jp

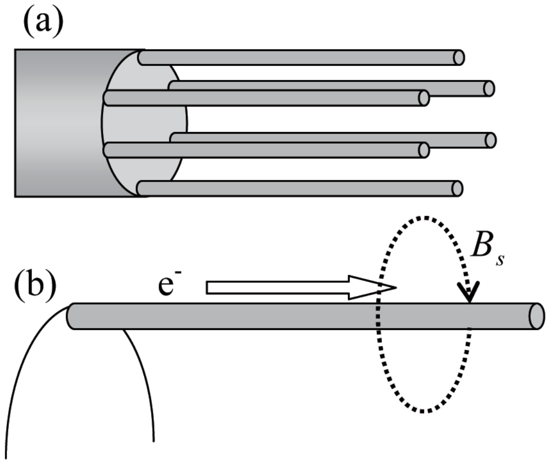

Fig. 1 Transparent cathode model showing the independent cathode strips (a), and the magnetic effect near a strip (b).

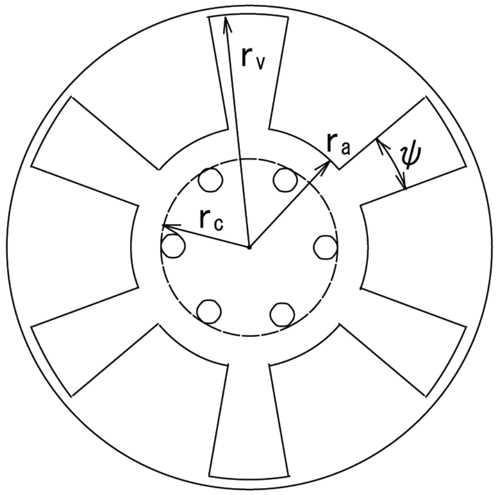

Fig. 2 Schematic of a magnetron.

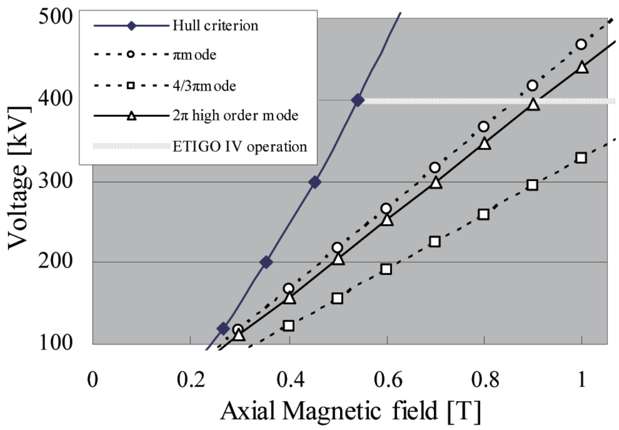

Fig. 3 Magnetron operating region.

up. The experimental conditions are provided by ETIGO IV, a 400 kV class repetitive pulsed power generator.

2. Schematic of Magnetron and Transparent Cathode

The crosssection of a magnetron is shown in Fig. 2. The magnetron comprises a cylindrical anode surrounding a coaxial cylindrical cathode. The broken lines within the conventional cylindrical cathode represent the transparent cathode. The anode has spaces such as resonator vanes. Electrons emitted by the central cathode are subjected to an axial magnetic field B_z and drift due to the Lorentz force. The drifting electrons interact in the space between the two electrodes with a characteristic mode formed by the structure of the resonator vanes. In the case of a magnetron with a transparent cathode, the current flowing through each cathode strip causes the azimuthal magnetic field B_s.

$$B_s = \frac{\mu_0 I}{2\pi r_s}$$

The radial drift velocity of electrons v_e is given by

$$v_e = \frac{cE_0}{\sqrt{B_z^2 + B_s^2}}.$$

The electrons are accelerated faster compared with the acceleration by a traditional cathode. Therefore, the transparent cathode causes rapid spreading of electrons and rapid start-up.

The characteristic dimensions are adopted from the type A6 magnetron, which has been studied as a relativistic magnetron [8]. The parameters considered are the cathode radius $r_c = 15.8$ mm, anode radius $r_a = 21.1$ mm, gap in resonator vanes on the side of the anode $\psi = 20°$, and the depth of the resonator vanes $r_v = 41.1$ mm. The number of resonator vanes is $M = 6$. The external radius of the transparent cathode is the same as that of the conventional magnetron cathode r_c. The number of strips is that same as the number of resonator vanes, M. The effect of the number of vanes is reported by numerical simulation [6, 7].

3. Experimental Setup

Figure 3 shows the features of magnetron operating region. The lines show the Hull cutoff and Buneman-Hartree resonance conditions [9] for the A6 magnetron. The power source is a repetitive pulsed-power generator ETIGO IV [10], which is capable of delivering, to a matched load, an output pulse of 400 kV in voltage, 13 kA in current, and 130 ns in pulse width, at a repetition rate of 1 Hz. The diamond dots and the line represent the Hull criterion. In general, the Hartree voltage is less than the Hull cutoff voltage magnetic insulation. The other dots and lines show the Hartree voltage for several oscillation modes. We consider the main operating modes as the fundamental π-mode (2.34 GHz) or the high order 2π-mode (4.6 GHz). The Hartree voltage corresponds to the breakdown voltage of the magnetron in the presence of a rotating perturbation field. The electrons interact the most with magnetron cavity modes near the Hartree line, and fall across the cathode-anode gap by emitting energy. The potential energy of the electron efficiently interacts with and provides the electromagnetic wave. For this device, the A6 relativistic magnetron requires an external magnetic field of about 0.5 T to 1.0 T.

The experimental setup consists of a stainless steel (SUS304) vacuum chamber. This chamber is covered with external magnets; we adopt the Helmholtz coil system. These magnets form a constant axial magnetic field covering the magnetron resonator. It can be controlled by an outer power source and can form a maximal 1.0 T magnetic field. The anode blocks are composed of aluminum and the cathode blocks of carbon graphite. Compared to aluminum, graphite as a cathode has the advantage of good field emission characteristics and small excitation delays [11] as well as resistance to discharge. The axial body length is 125 mm, as decided by the wavelength of the operating electromagnetic wave, 2.34 GHz, and avert discharge from converging electric. The anode blocks also remove the sharp edges to avoid discharge. The stick of the transparent cathode is made of graphite shapes like rounded trapezium due to manufacturing defects. Graphite is breakable.

4. Experimental Result

Our magnetrons were run at a constant diode input power that has a wide margin for discharge, rather than at the maximum rated power. Figure 4 shows the voltage and current characteristics of our magnetron as a function of the external axial magnetic field B_z. Full and hollow dots show the voltage and current values, as a function of magnetic field. Diamonds indicate values measured with the traditional cathode, and triangles indicate values measured with the transparent cathode. The voltage and current shapes with the traditional cathode are the same as those of the typical magnetron [8]. The transparent cathode shows a higher resistance than the traditional cathode. In particular, in the lower magnetic field, the current with the traditional cathode varies extensively, but that with the transparent cathode is more controlled. On the other hand, the current with the transparent cathode increases at a high magnetic field. This increase occurs at the final phase of the pulse. It seems that the transparent cathode is high in impedance and pools more electrons in the space in the cathode strips; therefore a plasma sheath may be formed at the final phase of the pulse. Figure 5 shows the diode voltage, diode current, and microwave pulse by an oscilloscope. The waveforms from the magnetron with the transparent cathode show full lines, and those from the magnetron with the traditional cathode show dashed lines. Heavy and normal lines represent the diode voltage and current, respectively. The top lines show the output microwave pulses. The distance from the output window to the observation point is 2.5 m. The operating regions are assumed to be about S-band to C-band, mainly 2 to 5 GHz. We use the horn antenna admitting nearly S-band; this ensures a calibration coverage of 2.45 to 4.6 GHz. The microwave pulse lengths of the magnetron with ETIGO IV are greater than 100 ns. And the pulse widths (half to half) of voltage and current are about 150 and 160 ns, respectively. This is enough time to reach static state magnetron operation. Our experimental setup may examine the steady oscillation region, even when the power source is a pulsed power device. The peak voltage is less than the rated capacity, because the plasma sheath is formed at the circumferential cathode, which cannot be analyzed at the particle in cell simulation. The current with the transparent cathode increases instantaneously, as plasma or electron sheath are

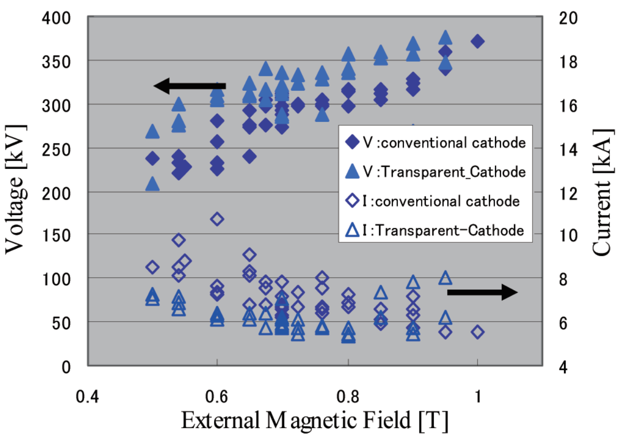

Fig. 4 Voltage-current characteristics of the magnetron as a function of magnetic field. The diamond dots denote measured values with the traditional cathode. The triangle dots denote measured values with the transparent cathode.

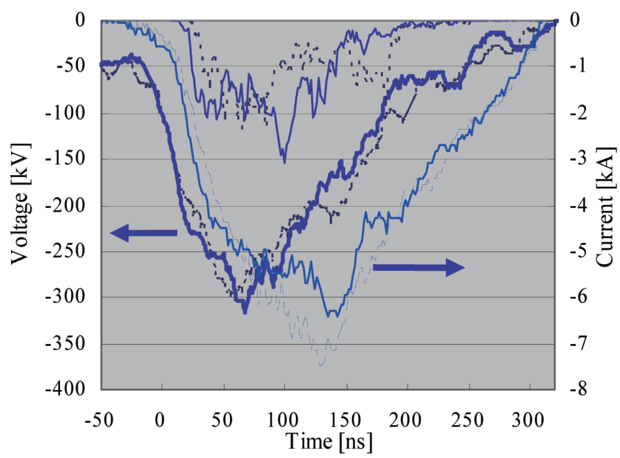

Fig. 5 Voltage, current, and microwave pulses at 0.76 T. Full lines show operation with the transparent cathode. Dashed lines show operation with the traditional cathode. Heavy lines represent the diode voltage. Normal lines represent the diode current. Top lines represent the microwave pulses.

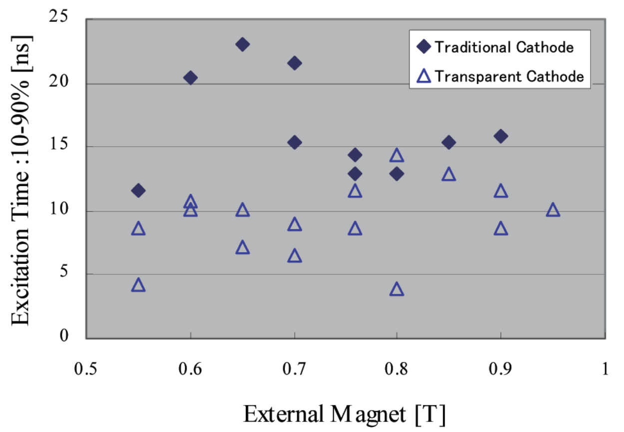

Fig. 6 Excitation time until the first peak: 10% to 90% time. Diamonds represent the excitation time with the traditional cathode. Triangles represent the excitation time with the transparent cathode.

formed and the diode impedance decreases at the last pulse phase. This problem is magnified as the external magnetic field increased, because the electrons are constrained and the electron sheath is thickened. These problems can be resolved by redesigning the cathode. Optimization of diode impedance for this experimental setup can lead to an increase in diode voltage and stabilize the pulse forms. The peak value of output power is determined by mode stability, which is dependent on the situation of electron emission. Because the oscillation modes are approximate in Fig. 3, and the diode voltage fluctuates according to elapse in same pulse, the oscillation mode also fluctuates. The output power is not significant until occasional modes are determined. The excitation times until first peak, 10% to 90% time, are shown in Fig. 6. Diamonds indicate the start-up time with the traditional cathode, while triangles indicate the excitation time. The excitation time seems to be influenced by the oscillation mode, which may vary according to the external magnetic field. In general, the same mode is operated by the same external magnetic field. On average, the start-up times of oscillation with the transparent cathode are more rapid than those with the traditional cathode. However, rapid start-up occurs in the oscillation mode when the voltage increases. In many cases, the first oscillation mode is not the most efficient resonance mode. Accuracy measurement and mode control may allow for higher peak power and enhanced efficiency.

5. Discussion and Summary

The transparent cathode results in a high impedance diode at the same external diameter cathode. In particular, for lower magnetic fields nearly Hull cutoff the magnetron with transparent cathode is stabilized. The frequency and operating modes with the transparent cathode may differ from the traditional magnetron; therefore, we want to investigate these futures experimentally. The detected microwave intensities with the transparent cathode are of the same level as that with the traditional cathode. We will examine the operating modes and explain the maximum power and efficiency of interaction with/without the transparent cathode. The relativistic magnetron with the transparent cathode may cause rapid start-up compared with the traditional cathode. The combined efficiency against all input power can be enhanced by the transparent cathode.

Our experimental setup shows a long pulse over 100 ns, in the region of high-power microwaves. This pulse length is enough to consider a full-time oscillation magnetron such as an over-the-counter microwave oven. In the last phase of the pulse, the magnetron with ETIGO IV can operate in a static state. Static-state high-power magnetron operation should be examined further using the pulsed power source.

[1] J. Benford and J. Swegle, *High-Power Microwaves* (Artech House, Norwood, MA, 1992).
[2] S.H. Gold and G.S. Nusinovich, Rev. Sci. Instrum. **68** 11, 3945 (1997).
[3] J.I. Kim, J.H. Won and G.S. Park, Appl. Phys. Lett. **86**, 171501 (2005).
[4] V. Bogdam, C. Jones, R.M. Gilgenbach, Y.Y. Lau, J.W. Luginsland, B.W. Hoff, M.White, N.M. Jordan, P. Pengvanich, Y. Hidaka and H.L. Bosman, IEEE Trans. plasma **33**, 94 (2005).
[5] M.C. Jones, V.B. Neculaes, W.M. White, Y.Y. Lau, R.M. Gilgenbach, J.W. Luginsland, P. Pengvanich, N.M. Jordan, Y. Hidaka and H.L. Bosman, IEEE Trans. Electron Devices **52**, 858 (2005).
[6] M. Fuks and E. Schamiloglu, Phys. Rev. Lett. **95**, 205101 (2005).
[7] M.C. Jones, V.B. Neculaes, Y.Y. Lau, R.M. Gilgenbach, W.M. White, B.W. Hoff and N.M. Jordan, Appl. Phys. Lett. **87**, 081501 (2005).
[8] A. Palevsky and G. Bekefi, Phys. Fluids **22**, 986 (1979).
[9] R.V. Lovelace, T.F.T. Young, Phys. Fluids **28**, 2450 (1985).
[10] A. Tokuchi, N. Ninomiya, W. Jiang and K. Yatsui, IEEE Trans. Plasma Sci. **30**, 1637 (2002).
[11] R.K. Parker, R.E. Anderson and C.V. Duncan, J. Appl. Phys. **45**, 2463 (1974).