Rapid Start of Oscillations in a Magnetron with a "Transparent" Cathode

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(Received 1 March 2005; published 10 November 2005)

We report on the improvement of conditions for the rapid start of oscillations in magnetrons by increasing the amplitude of the operating wave that is responsible for the capture of electrons into spokes. This amplitude increase is achieved by using a hollow cathode with longitudinal strips removed, thereby making the cathode transparent to the wave electric field with azimuthal polarization. In addition, an optimal choice of the number and position of cathode strips provide favorable prebunching of the electron flow over the cathode for fast excitation of the operating mode. Particle-in-cell simulations of the A6 magnetron demonstrate these advantages of this novel cathode.

DOI: 10.1103/PhysRevLett.95.205101 PACS numbers: 84.40.Fe, 07.57.Hm, 41.75.Fr, 52.75.Fk

Relativistic magnetrons are among the most powerful and compact sources of microwave radiation and are, therefore, very attractive for many applications [1]. Today there is increasing interest in improving the operating characteristics of magnetrons, in particular, decreasing the time-to-start of oscillations, which is critical when short radiation pulses are required as, for example, in high-resolution radars [2].

Of late there have been several schemes suggested to provide a fast start of oscillations in magnetrons. In particular, there have been intensive investigations underway at the University of Michigan where azimuthally modulated electron emission (“cathode priming”) [3,4] and applied magnetic field distribution (“magnetic priming”) [5–7] have been proposed. Both of these approaches, together with the applied radial electric field whose value varies on the cathode depending on whether it is situated underneath cavities or between them, lead to an azimuthally modulated electron flow forming around the cathode in crossed fields: the normal electric field E_0 and the tangential magnetic field $H_0 = \sqrt{H_{0z}^2 + H_{0\theta}^2}$. Here H_{0z} is the applied axial magnetic field, $H_{0\theta} = 2I_z/cr$ is the azimuthal magnetic field of an axial cathode current I_z, c is the speed of light, and r is the radius in the gap d between the cathode and anode with radii r_c and r_a (the A-K gap). The useful effect lies in the fact that the local enlargements of the electron hub over the cathode, which exceed its average thickness, are captured into electron spokes by the stronger synchronous electric field, which exponentially decreases from the anode to the cathode. This leads to a more rapid start and growth of microwave oscillations. The average radial velocity $v_r = cE_\theta/H_0$ of electron motion from the cathode to the anode, accompanied by the conversion of electron potential energy to electromagnetic energy, is determined by the azimuthal electric field of the synchronous wave [8]

$$E_\theta = E_\theta(r_a)\frac{\sinh g(r - r_c)}{\sinh gd} \tag{1}$$

(g is the transverse wave number). The exact synchronism condition for electrons drifting with azimuthal velocity

$$v_{e\theta} = cE_0H_{0z}/H_0^2 \tag{2}$$

and a wave with phase velocity $v_{\rm ph}$,

$$v_{e\theta} = v_{\rm ph} \tag{3}$$

is satisfied at only one radial position because of the different dependencies of these velocities on r. In order to provide synchronism in the entire interaction space, operating magnetrons have, as a rule, a quasiplanar design with $d \ll r_a, r_c$. The electronic efficiency, which is the ratio of radiated power P to the power of electrons moving to the anode,

$$\eta_e = \frac{P}{UI_a} \approx 1 - \frac{\Delta}{d}, \tag{4}$$

is determined by the ratio of the electron sheath thickness

$$\Delta = 2\frac{v_e\gamma_e^2}{\omega_{H0}} \tag{5}$$

to the A-K gap d [8]. Here I_a is the anode current, $\omega_{H0} = eH_0/mc$ is the nonrelativistic cyclotron frequency, v_e is the average electron velocity along the cathode surface, and γ_e is the relativistic factor for the electron drift. To achieve high electronic efficiency Δ must be small. However, in accordance with Eq. (1), the smaller Δ is, the weaker E_θ becomes (see curve 2, Fig. 1) and E_θ is responsible for the speed of energy conversion; that is, this field determines the growth time of oscillations.

Fortunately, in addition to the previous modulation of the electron flow there is an opportunity to provide a strong field E_θ on the electron flow and, therefore, to provide the optimal condition for a much more rapid start of oscillations. In this Letter we report a method to increase the microwave electric field acting on the electron flow over the cathode in a magnetron (the original idea behind this method and preliminary results of its application were reported in Refs. [9–12]). The method is based on removing longitudinal strips from a hollow, thin-walled cathode so that the E_θ field penetrates to the axis. With such a

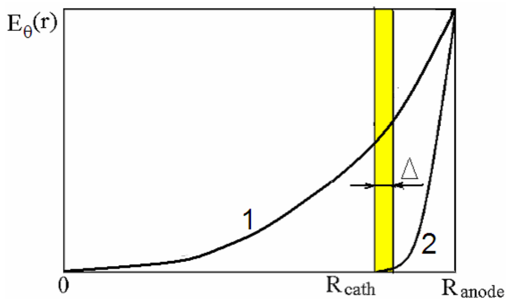

FIG. 1 (color online). Dependencies of the azimuthal electric field of the synchronous wave on radius for a transparent cathode (1) and solid cathode (2).

"transparent" cathode the synchronous azimuthal field with azimuthal index n is distributed as $E_\theta = E_\theta(r_a)I_n(gr)/I_n(gr_a)$ where I_n is the modified Bessel function of the first kind of order n, and this field (curve 1, Fig. 1) is much stronger than the value of Eq. (1) on the electron flow for any Δ in the narrow A-K gap d. In magnetrons electromagnetic energy accumulates mainly in the cavities; therefore, the average amplitude $E_\theta(r_a)$ of the field on the anode surface $r = r_a$ is weakly dependent on the cathode.

The enhancement of the azimuthal field on the electron flow also occurs in the case where there is a small coaxial metal rod within the cathode strips, and the smaller the radius of this rod, the larger the value of the field which penetrates to the surface of the rod. The use of the coaxial inner rod could be advantageous for practical implementation of the transparent cathode (for example, to provide rigidity of a long cathode).

We now consider the operation of the A6 magnetron with a solid cathode that was studied in many earlier works (see, for example Refs. [13–16]), and compare its performance when powered using a transparent cathode (one version is shown in Fig. 2) and cathode priming with same number of emitters.

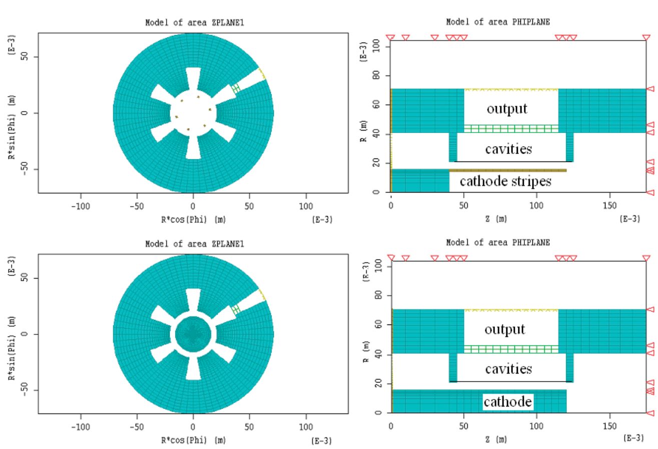

FIG. 2 (color). Examples of an A6 magnetron with a transparent cathode (top) and solid cathode (bottom) in 3D MAGIC simulations.

The original A6 magnetron consisted of a solid cathode with radius $r_c = 1.58$ cm and an anode block with 6 identical cavities closed on both sides (the inner radius of the block is $r_a = 2.11$ cm; the resonant cavities extend 4.11 cm with anode gap openings of 20°). The axial extent is $L_r = 7.2$ cm. The A6 magnetron operating in 2π mode has the best characteristics when the applied voltage $U =$ 350 kV. The measured and calculated [15] powers from earlier studies were $P \approx (0.5$–$0.6)$ GW and the electronic efficiencies were $\eta \approx (7$–$8)\%$. In our study we use the same voltage with a rise time $t_U = 10$ ns, corresponding to Ref. [15]. This value leads to "slow turn-on" because this rise time exceeds the cavity fill time $t_{res} = Q/\omega$ where Q is the quality factor of the resonant system for the mode with frequency ω. The typical fill time for A6 magnetrons is about 4–5 ns, as follows from data [16] and our simulations using the 3D fully electromagnetic particle-in-cell code MAGIC [17]. (Here we emphasize that simulations using a short rise time voltage pulse $t_U < t_{res}$, and long rise time, $t_U > t_{res}$, can have markedly different outcomes [18].) Using MAGIC we verified that the output characteristics of magnetrons with $t_U = 1$ ns are much better than longer rise times, attributed to the absence of any mode competition with modes having lower Buneman-Hartree thresholds than that of the operating mode (a subject of a forthcoming article). Here these results are omitted because magnetrons with such a short rise-time voltage are not typical.

Figure 3 demonstrates faster electron spoke formation in a magnetron with a transparent cathode having 6 emitting strips compared with the original A6 using either a solid cathode or a solid cathode with 6 discrete emission regions (so-called cathode priming). For all cases the leakage current of electrons moving from the cathode edge in the axial direction is 10–15% of the anode current for values of H_{0z} corresponding to the peak radiated power. The modulation of the electron flow in the magnetron with the transparent cathode leads to electron spoke formation during the rise time of the applied voltage, whereas electron spokes do not form even for the nominal voltage 350 kV in magnetrons with a solid cathode or with cathode priming (Fig. 3). Additionally, by selecting the same number of cathode strips as the number of cavities promotes rapid excitation of the 2π mode owing to the symmetry of premodulation of the electron hub. Furthermore, we have verified that, for the transparent cathode, when the number of strips is half the number of cavities, the π mode rapidly grows. (We have not studied magnetron operation for different azimuthal widths of the cathode strips. We have restricted our studies to 5° emitting sectors, reasoning that the smaller width of the emitting region will lead to greater transparency.)

In comparison with magnetic priming and cathode priming in a magnetron with a solid cathode, the discrete regions of electron emission provided by the transparent cathode lead to stronger cathode priming. Firstly, it manifests as rapid formation of prebunched electrons which are

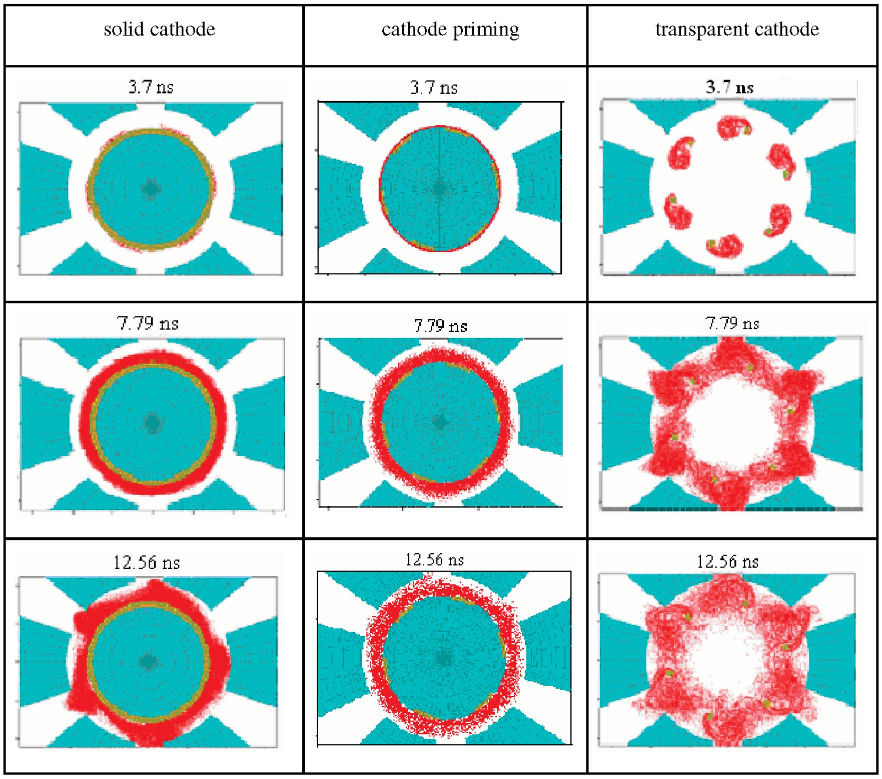

FIG. 3 (color). 3D MAGIC simulations illustrating the formation of electron spokes in the A6 magnetron using a solid cathode (left), cathode priming with 6 emitting regions (center), and a transparent cathode with 6 strips (right) at the same times in the simulation with the same voltage rise.

then swept up by the strong synchronous electric field to the anode as rotating electron spokes (Fig. 3).

Secondly, the choice of the same number of strips as the azimuthal index of the desired operating wave promotes its rapid excitation.

Thirdly, the choice of the azimuthal position of the strips within the interaction space also exerts strong influence on the excitation of oscillations. Figure 4 illustrates the favorable region for positioning the cathode strips with respect to the cavities, providing stable 2π-mode generation with power 0.6–0.7 GW.

Fourthly, the rapid formation of spokes leads to faster formation of anode current (Fig. 5) and excitation of the 2π mode (Fig. 6) than occurs in either the original A6 magnetron using a solid cathode or cathode priming. We note that the transparent cathode and cathode priming with 6 restricted emission regions had the azimuthal location of the emitters in the same position for fair comparison. As follows from a simple analysis of the equations of motion for electrons accounting for the nonuniform radial electric field (microwave fields are absent; the applied voltage does not reach the Buneman-Hartree threshold), the favorable emission regions produce electrons forming local enhancements in the electron flow.

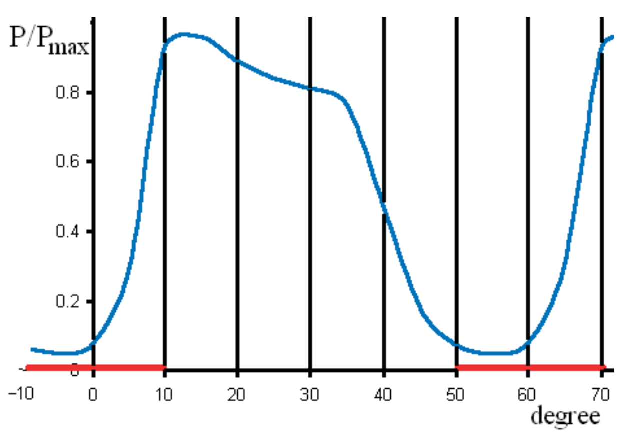

FIG. 4 (color). Dependence of radiated power on the azimuthal position of the cathode strip (for one period of the resonant system) with respect to the cavities (red lines) for a magnetron using a transparent cathode with 6 strips. The electron flow is right-to-left for this case. This was obtained from 3D MAGIC simulations.

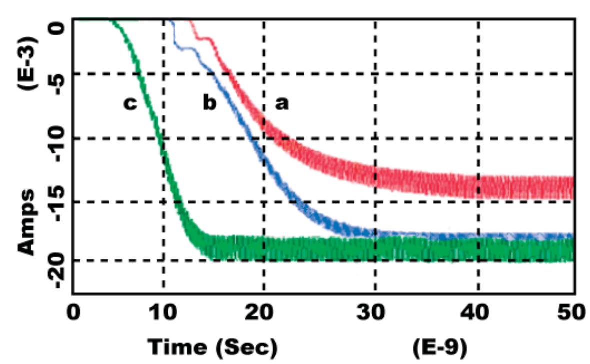

FIG. 5 (color). 3D MAGIC simulations calculating the anode current in the A6 magnetron using (a) solid cathode, (b) cathode priming, and (c) transparent cathode.

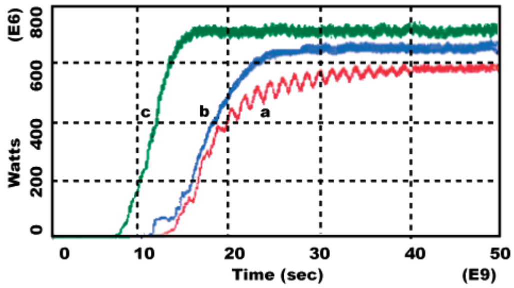

FIG. 6 (color). 3D MAGIC simulations calculating the radiated power of the A6 magnetron using (a) solid cathode, (b) cathode priming, and (c) transparent cathode.

As is shown in Figs. 5 and 6, the cathode priming caused by the nonuniform emission from the solid cathode leads to sufficient shortening of the rise time of generation [Figs. 5(b) and 6(b)] in comparison with the case for uniform emission [Figs. 5(a) and 6(a)]. However, the application of the transparent cathode, which provides both cathode priming and magnetic priming produced by the current along the cathode strips, leads to a faster start of oscillations [Figs. 5(c) and 6(c)] owing to the stronger synchronous field on the electron flow.

In summary, the transparent cathode effectively provides the means for a rapid start of oscillations using both cathode priming and magnetic priming approaches simultaneously and without requiring additional external magnets as in the case of magnetic priming. However, the main effect provided by the transparent cathode is the strong azimuthal electric field on the electron flow around the cathode. For an applied voltage $U = 350$ kV the efficiency of the magnetron with the transparent cathode is comparable to that of the solid cathode—about 12% (Figs. 5 and 6). However, this is a strong function of the value of the applied magnetic field. The efficiency [Eq. (4)] can be increased by concomitantly increasing the voltage and the magnetic field owing to decreasing the thickness Δ [Eq. (5)] (where $\Delta \sim E_0/H_0^2$). However, experimental results and computer simulations for magnetrons with solid cathodes (see, for example, Refs. [15,19,20]) show that the efficiency does not increase in this manner, contrary to expectations. Moreover, as is noted in Ref. [21], this technique leads to unstable generation with degradation of output characteristics. It is assumed that the cause of such behavior is the decreased synchronous field on the electron flow which deteriorates the conditions for capturing electrons to the anode. When the transparent cathode is used instead of a solid cathode the strong field $E_\theta(\Delta)$ for any sheath thickness (Fig. 1) suggests that this technique will in fact lead to improved efficiency.

This research was supported by an AFOSR/DoD MURI Grant on Compact Pulsed Power.

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