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It has been proposed that gated field emitters could be used in place of conventional thermionic cathodes to control the current injection in a magnetron, both temporally and spatially. Since gated field emitters have to be fabricated on flat surfaces, a faceted cathode would be used to implement this approach. A 2D ten cavity, rising sun magnetron has been modeled using the particle-in-cell code VORPAL. Cylindrical, five-sided, and ten-sided faceted cathodes were modeled to study the variation of magnetron operation due to the cathode shape. This work shows the results of the device performance employing three different cathode geometries with a typical continuous current source. The cathode voltage is -22.2 kV; magnetic field is 0.09 T; and linear current density is 326 A/m. The three models oscillated at the π -mode, at a frequency of 960 MHz for the cylindrical cathode and 957 MHz for the faceted cathodes. Simulations show a faster start up time for the ten-sided faceted cathode. This resulted in a reduced overall startup time of the device from 200 to 110 ns. A strong current instability was observed in the five-sided cathode case with a periodicity range from 250 to 350 ns. This instability was limited to the start-up period of the ten-sided cathode model; hence the ten-sided case was more stable. © 2014 American Vacuum Society.

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I. INTRODUCTION

Magnetrons have been studied and developed in the military, commercial, and plasma physics research communities since the 1940s. There has been a continuing interest in improving performance such as efficiency, power density, start-up times, phase locking, and high frequency operation.^{1–7} In general, conventional magnetrons use thermionic cathodes. Thermionic cathodes are widely used and very reliable, but they do have some disadvantages. Thermionic cathodes do not offer a method to temporally control the electron injection. Ungated field emission cathodes rely on the anode to cathode field for emission, yet they do not provide temporal or addressable control of the current injection. On the other hand, gated field emission cathodes can be temporally modulated and spatially addressed. This paper presents the foundational work for the use of gated, vacuum field emitters in place of the thermionic cathodes.¹ Because the gated field emitters need to be fabricated on flat plates, the proposed cathode would be made up of five or ten facet plates containing the gated field emission cathode. Five or ten sides were chosen to make the number of cathode facets symmetric with the number of magnetron cavities and spokes, ten and five, respectively. This idea was presented in a previous work,¹ and that research included the simulation of the faceted cathode structure in a ten-cavity rising sun magnetron. The simulation was completed using the 3D

particle-in-cell (PIC) code ICEPIC. This paper describes the simulation of a 2D model of a ten-cavity rising sun^{8–12} magnetron using the PIC code VORPAL.¹³ This paper only covers the analysis of the 2D simulation of the ten cavity, rising sun magnetron for the cylindrical and faceted cathodes (five- and ten-sided) using a typical current source which we refer to as a “continuous” current source. This simulation work was performed in order to provide a reference case for the typical continuous current source model and to verify the correct operation of the device by comparing the three different cathode geometries. Future work will describe the use of a modulated cathode⁷ to control current injection.

II. MODELING AND SIMULATION SETUP

VORPAL is used to model a ten cavity, rising sun magnetron in 2D. The rising sun magnetron was chosen for the simulation because the primary mode of oscillation is the π -mode, so the device can be modeled in 2D as no strapping is needed. The geometry in Fig. 1 shows a 2D layout of a rising sun magnetron with two cathode geometries: cylindrical and faceted. As shown in Fig. 1 and Table I, the radius of the cathode is 1.0 cm, and the inner radius of the anode is 2.24 cm. Long cavities have an outer radius of 10.0 cm and opening angle of 10° . Short cavities have an outer radius of 6.0 cm and opening angle of 10° . These geometrical properties control the operating frequency of the cavity, which for this design is 960 MHz for the cylindrical cathode and 957 MHz for the faceted cathodes (five- and ten-sided).

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FIG. 1. (Color online) Rising sun magnetrons using (a) cylindrical cathode, (b) five-sided faceted cathode, and (c) ten-sided faceted cathode, respectively, in VORPAL simulations.

One long cavity is loaded with an absorber to simulate the RF power dissipation in the device as well as the output power coupling. There is no internal loss associated with the structure. This absorber acts as a loading parameter that is

used to tune the quality factor, Q , of the magnetron, which is 404 for this case. A meaningful calculation of the device output is not feasible for the 2D simulations as axial power loss is not calculated, and there is no actual output port. However, the power density at the absorber was used to estimate the efficiency of the magnetron. Therefore, this cavity power density is only used for reference.

A typical simulation is set up with a grid of 102×102 cells with a length of 20.4 cm in the x-direction and 20.4 cm in the y-direction. However, for the ten-sided case, the grid must be increased to 202×202 to account for the needed spatial resolution of the finer facets and the emitter sections. The time step size is typically 2.3×10^{-12} s, and the simulation total run time is 600 ns. VORPAL implements the Dey-Mitra¹⁴ cut-cell boundary algorithm to model curved boundaries, and the algorithm is known to be second order accurate.¹⁵

After calibrating the model and based on previous work,¹ the operating parameters for the cathode geometries were set up as follows: a cathode–anode voltage (V_{ca}) of -22.2 kV, applied magnetic field (B) of 0.09 T, and a total linear emitted current density (J'_e) of 326 A/m. Different sets of simulations were completed to check calibrated parameters, such as varying the cathode–anode voltage, varying the B-field, and varying the total emitted current density. These simulations were performed by varying one parameter at a time while keeping others constant, then changing a second parameter while varying the first. These results were also used to study the startup time of the device, the cavity power, and efficiency. Based on these simulations, the reference parameters described above were found to give the best performance for the faceted cathode geometries. At other values of cathode voltage and magnetic field, the electrons spokes were unstable, or the device would try to oscillate at 650 MHz. Although the rising sun design does increase the mode separation,⁸ during the transient period, all modes can be excited. Fortunately, this lower frequency mode (650 MHz) has a lower magnitude (approximately 20 dB) lower than the π mode and can be considered as noise. Furthermore, after ringing the π mode, the resonance is stabilized, and this mode is no longer observed.

III. RESULTS AND DISCUSSION

A. Cylindrical cathode

The cylindrical cathode model gave an operating frequency of 960 MHz. The start-up time can be determined by plotting the frequency of the cavity voltage oscillation versus time. This plot helps to confirm when the magnetron starts oscillating at the frequency of operation (π mode). The spoke formation is also used in conjunction with this plot to estimate the start-up time of the magnetron. Figure 2(a) shows the output frequency versus time for the cylindrical cathode geometry, and Fig. 2(b) shows the fast Fourier transform (FFT) of the cavity voltage oscillation as simulated in VORPAL. Figure 2(a) shows a start-up time of ≈ 150 ns, and the FFT shows the frequency of operation of the π -mode at 960 MHz. Figure 3 shows the spoke formation from startup

TABLE I. Rising sun magnetron dimensions for cylindrical, five-sided, and ten-sided faceted cathodes.

Cathode radius (cm)	Anode radius (cm)	Facet width (cm)		Small cavity outer radius (cm)	Large cavity outer radius (cm)	Cavity angle (deg)
		Five-sided	Ten-sided			
1.0	2.24	1.18	0.618	6.0	10.0	10.0

through oscillation, showing stabilized oscillation after 150 ns with the five spokes of the π mode.

Figure 4 shows the total anode linear current density versus time. This diagnostic can also be used to determine startup of oscillation and to look for stability issues in the oscillations. It is also useful for calculating the input power density of the device. The linear power density at the loaded cavity was calculated to be 1.0 MW/m for this configuration. In Fig. 4, the anode linear current density for the cylindrical cathode averages to approximately 60 A/m. An analysis of the startup current was also studied. The total emitted linear current density (J'_e) was varied from 81.5 to 652 A/m. Figure 5 shows a graph of start-up time versus the total emitted linear current density of the device for the cylindrical cathode and five- and ten-sided faceted cathodes. This result illustrates the variation in the startup time of the device for the different cathode geometries. It is observed that the start-up time is relatively constant at 100 ns for current densities above 500 A/m. Space charge effects will limit the start up times for high current densities; as the current increases, the space charge effects become more significant, and the hub will get closer to the anode. For the cylindrical cathode, start-up below 250 A/m was not observed, and the lower frequency (650 MHz) mode of the device would try to oscillate.

B. Five-sided faceted cathode

The five-sided faceted cathode model was shown to oscillate at a frequency of 957 MHz. Figure 6(a) shows the mode switching during start-up. Again, there is a 650 MHz mode

FIG. 2. (Color online) (a) Cavity voltage frequency vs time to showing the start-up time of a typical magnetron simulation in VORPAL for the cylindrical cathode ($V_{ca} = -22.2$ kV, $B = 0.09$ T, and $J'_e = 326$ A/m). Stable oscillation is observed around 150 ns, (b) FFT of the cavity voltage oscillation over the entire simulation time.

before the stabilized operation. Figure 6(b) also shows the FFT of the cavity voltage oscillation with a clear peak at 957 MHz. The linear power density at the loaded cavity was calculated to be 1.2 MW/m. The spoke formation results are shown in Fig. 7. Figure 7 shows the preoscillation state and the spokes forming after oscillation. The total emitted linear current density was varied from 81.5 to 652 A/m. A graph of the start-up time of the device versus the total emitter linear current density is shown in Fig. 5. From the curve, it is observed that the five-sided faceted cathode magnetron starts up at 200 ns for the reference parameters (326 A/m), while the cylindrical cathode shows a startup time of 150 ns. The start-up time levels off above 400 A/m. The startup time increases dramatically below 400 A/m, and it will not start below 250 A/m.

The five-sided case shows an unstable oscillation. Figure 8 shows the anode linear current density versus time when the device is in operation. It was found that there is an instability in the five-sided cathode oscillations. As observed in Fig. 8, this instability results in a current spike to the anode and subsequent collapse of the spokes. Figure 9 shows the transition of the spokes before the current spike occurs, at the current spike, and after the current spike, when the spokes collapse. For this particular example, the time between 119.8 and 143.5 ns was selected. It can be observed that the shape of the spokes changes during the current spike with the electrons forming a more concentrated cloud or clump; then, the clump extends to the anode when the spike

FIG. 3. (Color online) VORPAL simulation results of the rising sun magnetron with a cylindrical cathode for $V_{ca} = -22.2$ kV, $B = 0.09$ T, and $J'_e = 326$ A/m. The red dots represent electron macroparticles.

Fig. 4. (Color online) Continuous anode linear current density vs time for the rising sun magnetron with a cylindrical cathode.

occurs. The result is a large increase in anode current followed by a loss of a large percentage of available electrons. Then, the spokes disconnect and collapse. Following this mechanism, the spokes will form again. As can be seen in Fig. 8, this current spike has a periodic behavior. The spike occurs every 250–350 ns. Hence, every time the current spike occurs the spokes will collapse and reform again. The causes of this instability are mainly attributed to the cathode shape as it does not occur with the cylindrical cathode, but further studies are needed to completely understand it. The electron trajectories are perturbed at the facet joints (corners) because of the nonuniform fields at the joints, these perturbations affect hub formation. Eventually, this nonuniformity results in “clumps” of synchronous electrons which give up energy and transit to the anode in a few RF cycles. In addition, simulations of the loading effects have been performed, and a model where all cavities are loaded has been simulated. This symmetric technique seems to reduce the current instability but not eliminate it. However, further studies still need to be completed, and these results are beyond the scope of this paper. On the other hand, by implementing a ten-sided cathode geometry (increasing the number of facets), this problem was greatly reduced. It should be noted that the faceted cathode was rotated to change the orientation of the facet plates with respect to the anode. These simulations would show varying degrees of instability in the spoke formation, but the exact relation with the orientation was not clear. Changes in the simulation parameters (mesh size) did not seem to affect the results.

Fig. 5. (Color online) Start-up time vs continuous total emitted linear current density for rising sun magnetrons employing different cathode geometries: cylindrical, five-sided, and ten-sided.

Fig. 6. (Color online) (a) Cavity voltage frequency vs time showing the start-up time of a typical simulation in VORPAL for a rising sun magnetron employing a five-sided faceted cathode ($V_{ca} = -22.2$ kV, $B = 0.09$ T, and $J_e = 326$ A/m). Stable oscillation is observed around 200 ns, (b) FFT of the cavity voltage oscillation.

Fig. 7. (Color online) VORPAL simulation results of the rising sun magnetron employing a five-sided faceted cathode for $V_{ca} = -22.2$ kV, $B = 0.09$ T, and $J_e = 326$ A/m. The red dots indicate electron macroparticles.

Fig. 8. (Color online) Continuous anode linear current density vs time for the rising sun magnetron employing a five-sided faceted cathode. The periodic current spikes are followed by spoke collapse.

FIG. 9. (Color online) Five-sided faceted cathode showing the transition of the spokes during the current instability. Spokes are shown (a) before current spike at 119.8 ns, (b) at current spike at 121.32 ns, and (c) after spokes collapse at 143.5 ns.

C. Ten-sided faceted cathode

The ten-sided faceted cathode geometry was chosen to minimize the current spike problem. Similar analysis to the cylindrical and five-sided cases was completed for this configuration. Figure 10 shows the start-up time for this device at approximately 110 ns; it also shows the FFT of the cavity voltage oscillation. The FFT plot in Fig. 10 indicates the π -mode operation at a frequency of 957 MHz; the 650 MHz peak is still present in this configuration. The linear power density at the loaded cavity was calculated to be 1.2 MW/m, which was the same as for the five-sided cathode. Figure 11 shows the anode linear current density versus time when the device is in operation. These results indicate a behavior very similar to the anode current for the cylindrical cathode

FIG. 10. (Color online) (a) Frequency of cavity voltage vs time showing the start-up time of a typical simulation in VORPAL for the rising sun magnetron employing a ten-sided faceted cathode ($V_{ca} = -22.2$ kV, $B = 0.09$ T, and $J_a = 326$ A/m). Stable oscillation is observed around 110 ns, (b) FFT of the cavity voltage oscillation.

geometry (see Fig. 4), but the large current spikes are not present as in the five-sided cathode model. Instead there is one large spike at ≈ 110 ns, and then the oscillations are more stable. This initial spike could also be attributed to a combination of the cathode geometry and loading effects. However, this needs further study. Overall, the use of the ten-sided cathode geometry reduces the current instability.

The simulation for this case was also run for various emitted current densities, and the start-up times were determined from the frequency versus time plots in VORPAL. From Fig. 5, it can be seen that the ten-sided cathode geometry has a startup of 110 ns for the reference parameters. As can be seen, the startup time increases for lower current densities and decreases for higher current densities as expected.

From this plot, the three cases: cylindrical, five-sided, and ten-sided cathodes show very similar startup times for the reference parameters; however, as the linear current density is decreased (below 326 A/m), the startup times are not so similar depending on cathode shape. It is also noticeable that the cylindrical cathode does not start for current density values below 230 A/m. It was found that for this geometry there is an increase in mode competition between the 650 MHz mode and the 960 MHz (π -mode); therefore, for values below 230 A/m, the device switches to the lower mode and does not start in π -mode. The nature of this behavior for this particular case needs further study and analysis.

FIG. 11. (Color online) Continuous anode linear current density vs time for the rising sun magnetron employing a ten-sided faceted cathode.

TABLE II. Current densities, power densities, and efficiencies for various cathode geometries: cylindrical, five-sided, and ten-sided cathodes for the reference parameters $V_{ca} = -22.2$ kV, $B = 0.09$ T, and $J'_e = 326$ A/m.

Cathode	Anode current density J'_a (A/m)	Pin (MW/m)	Loaded cavity power density (MW/m)	Efficiency η (%)
Cylindrical	60.81	1.35	1.0	74.3
Five-sided	69.36	1.54	1.2	77.9
Ten-sided	67.56	1.5	1.2	80.0

D. Power and efficiency

An absorber was used in one of the large cavities to create a load for the RF power generator. This absorber sets the quality factor, Q , of the magnetron which is 404 for the case studied in this paper. Table II shows a summary of results of the linear anode current density, the calculated input power density, the loaded cavity power, and the calculated efficiency for the different cathode geometries at the reference parameters $V_{ca} = -22.2$ kV, $B = 0.09$ T, and $J'_e = 326$ A/m. The linear anode current density, J'_a , is determined by averaging the anode current from the simulation over a period of 100 ns after oscillation is stable. The product of the cathode voltage and the linear anode current density gives the linear input power density. From Table II, it is observed that the loaded cavity power is higher (15%) for the two faceted geometry cases (1.5 MW/m) compared to the cylindrical cathode (1.35 MW/m). Similarly, the linear anode current density is about 15% higher for the faceted cases. The reason for this difference is not clear but appears related to the trajectories associated with the faceted cathode. These results also show device efficiency in the range of 74%–80% for the three different geometries. It is important to note that this efficiency should not be taken as absolute value. There is no real output port; therefore, this power density is not the real coupled output power, and there are no axial losses. However, these results can be used as relative estimation of the power output level at the loaded cavity.

IV. CONCLUSIONS

This paper presented results from a study of a 2D model rising sun magnetron with cylindrical and faceted cathodes with a continuous current source. From the results, it was observed that all three models operated at the π -mode with frequencies of 960 and 957 MHz, respectively. A current instability was found in the five-sided faceted cathode. This current instability resulted in current spikes, which led to spokes disconnecting and collapsing. The use of a ten-sided faceted cathode reduced the current instability and improved the overall start-up time of the device from 200 (five-sided

cathode) to 110 ns for the reference current density; in addition, as the linear current density is decreased below 326 A/m, the start-up times are not so similar but depend on cathode shape. Overall, the ten-sided cathode minimized the current instability and reduced the start-up time of the magnetron. Although the results are 2D with no output port, the loaded cavity power was used to estimate the RF power generation. Because the simulation was 2D, axial losses are not included. This work provides a reference case for the future discussions on using a modulated, gated field emitter array to control magnetron startup and phase.

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