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Particle-in-cell based parameter study of 12-cavity, 12-cathode rising-sun relativistic magnetrons for improved performance

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Particle-in-cell simulations are performed to analyze the efficiency, output power and leakage currents in a 12-Cavity, 12-Cathode rising-sun magnetron with diffraction output (MDO). The central goal is to conduct a parameter study of a rising-sun magnetron that comprehensively incorporates performance enhancing features such as transparent cathodes, axial extraction, the use of endcaps, and cathode extensions. Our optimum results demonstrate peak output power of about 2.1 GW, with efficiencies of ∼70% and low leakage currents at a magnetic field of 0.45 Tesla, a 400 kV bias with a single endcap, for a range of cathode extensions between 3 and 6 centimeters. © 2015 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License. [http://dx.doi.org/10.1063/1.4932634]

I. INTRODUCTION

Relativistic magnetrons are among the most powerful, compact, efficient, and low cost sources of microwave radiation,1–5 capable of high output power (GW-class) with applications over a wide range of frequencies.6–8 Several techniques have been reported and discussed for improving the microwave power output and efficiency of multicavity magnetrons. The goals and techniques towards improving the performance are geared towards providing favorable conditions to the electron beam for fast conversion of the potential energy of the electron swarm into electromagnetic energy. These have included: decreasing the startup time $t_s$, reducing the electron leakage from the interaction space by shaping the electric fields through the use of cathode endcaps,9 employing transparent cathodes,10–12 the use of various priming techniques,4,5,13–15 and changing the load characteristics.16 Cathode priming seems particularly advantageous since it requires only changes at the cathode, without modification of the anode block, or the magnetic- and radiofrequency (RF) systems. The priming is achieved by allowing the magnetron cathode to emit charged particles only in selected regions that vary in an azimuthally periodic fashion along the cathode surface.17–19

It has been shown10,12 that the use of a transparent cathode effectively facilitates rapid start-up of the magnetron oscillations and has advantages over priming with solid cathodes. The term “transparent” arises from the fact that the cathode is transparent to the azimuthal component of the RF electric fields that are used as the operating modes of magnetrons. This occurs once the solid cathode is removed since the vanishing-field boundary condition is then eliminated, thus allowing the azimuthal RF electric fields to achieve higher amplitudes in the interaction region relative to the standard-cathode design. Incidentally, the modes can be obtained analytically from the dispersion relation that is derived under the assumptions that: (a) All cavities are closed, and (b) the anode block is infinitely long. These assumptions simplify the derivation considerably and a standard Floquet harmonic analysis20 can be used.

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The use of cathode endcaps has been another performance enhancing aspect studied both through experiments\textsuperscript{21,22} and particle-in-cell (PIC) simulations.\textsuperscript{23} The physics associated with the improvement is based on two aspects. First, the metallic endcaps shape the electric fields and help define the effective electrical length of the cathode. Without such endcaps, the finite size of the magnetron anode block could give rise to competition between different axial modes. In addition, by extending the cathode length beyond that of the anode via such endcaps,\textsuperscript{9} electron leakage currents can be suppressed. One contributing factor towards leakage current suppression is the reduction in the electron swarm width, due to the influence of radial electric fields on the particle trajectories along the extended cathode. Furthermore, the axial electric fields of the electron space charge that fills the interaction space and the azimuthal magnetic field can provide a negative radial drift for electrons that may be leaving the interaction space.

The relativistic magnetron with diffraction output (MDO) is a particularly attractive configuration that relies on axial extraction of radiation using a conical antenna, and is an important development in high power microwave (HPM) technology for compact narrow band sources.\textsuperscript{24–29} An efficiency approaching 70% was demonstrated in the particle-in-cell simulations for the six-cavity MDO,\textsuperscript{30} while experimental data was by obtained by Daimon et al.\textsuperscript{31} although absolute values of the microwave power or efficiency were not reported. The MDO device integrates a mode converter and a horn antenna. Some of its characteristic features include a simple configuration, requirements of relatively low magnetic fields, and stable radiation into the TE11 mode radiation. Moreover, the diffraction output integrates a mode converter and a horn antenna. The vanes and cavities of the MDO are tapered smoothly up to a radius that exceeds the cutoff radius of regular cylindrical waveguide. Tapering works to improve impedance matching and allows enhanced power transfer. Compared to the relativistic magnetron with radial extraction, MDO offers advantages such as compact structure, azimuthal symmetry, and high output power. Other benefits of the MDO include a strong resistance to microwave breakdown, more compact systems for producing the magnetic fields, and the ability to select any eigenmode without mode hopping. In relativistic magnetrons with radial output, it has been shown however, that frequency can be stabilized by partial reflection of the generated microwave power.\textsuperscript{32} In any case, the MDO can directly radiate TE_{31}, TE_{01}, or even the TE_{11} mode which is known to have the best radiation pattern,\textsuperscript{27} based on the numbers of cavities tapered onto the antenna. For this configuration, the use of a cathode endcap with a dielectric coating that is extended downstream of the interaction space, helps reduce leakage currents, thereby weakening the potential for window breakdown\textsuperscript{33} from electron bombardment that can be deleterious.

In the context of magnetron development, the rising-sun configuration was created and designed in the 1940s to achieve mode stability.\textsuperscript{34,35} This device geometry consists of two alternating groups of short and long vanes in angular orientation, that help create greater frequency separation between the modes and prevent mode competition. Another feature of this configuration is that it enables mechanical frequency tunability.\textsuperscript{36–39} Since increasing the number of resonators decreases mode separation, conventional magnetrons cannot be used with a large number of resonators, and so this is an aspect where the rising-sun geometry would be particularly useful. Not only does this geometry have fabrication advantages over designs employing strapping,\textsuperscript{40} its multi-cavity structure can support a number of distinct standing-wave modes. Of these, the π-mode is nondegenerate with only one field distribution at its excitation frequency, and hence preferred for some applications. The device manufacture for the rising sun magnetron though could be a bit more complicated.

A fairly extensive analysis into the efficiency and potential limitations were reported on the basis of PIC simulations some years ago.\textsuperscript{37,39,41–43} However, the performance optimization aspect for a relativistic rising-sun MDO has not been studied in detail. In particular, potential enhancements such as transparent cathodes, axial extraction, the use of endcaps, cathode extensions, and electrical parameters such as the magnetic field and applied bias which could help improve the MDO operation, remain and need to be systematically analyzed. Towards this end, the performance of a 12-cavity rising-sun MDO device is probed in this contribution through particle-in-cell simulations. A comprehensive PIC-based study is presented here to evaluate the effects of altering the geometry, dimensions, and operating field values for increased output power and device efficiency at lower leakage currents. Simulations include various lengths and angular slopes of short vanes, different
extensions of the cathode length beyond the anode, and comparison between cylindrical endcaps and a bulb shaped endcap geometry. The remainder of this article is organized as follows. Section II provides details on the model. Implementation of a particle-in-cell technique to simulate the output power, device efficiency and the time- and spatially-varying electron distributions is also described briefly. Section III describes the results obtained and includes appropriate discussions and analyses. The simulation results serve as a guide towards the selection of an optimized parameter space, and provide a theoretical upper-bound on the MDO performance. Finally, the conclusions are presented in Section IV.

II. MODEL AND METHOD

In order to evaluate and find the optimized geometry and operation conditions of a rising sun magnetron with axial output, computer simulations were performed using the particle-in-cell (PIC) based MAGIC software tool. This software is a well-established commercially available electromagnetic design tool in the plasma, microwave, and pulsed power communities. For the PIC simulations, the well-known A6 magnetron was chosen as the basic starting configuration, and then appropriate changes relating to the anode block and cathodes were implemented for the rising sun geometry. The anode block consisted of 12 sectorial cavities with length $L = 7.5$ cm, maximum radius $R_{\text{cav}} = 4.11$ cm, and minimum radius $R_a = 2.11$ cm. Other details of the magnetron implementation using MAGIC can be found in previous reports.

Two different structures were used for the short vanes of the rising sun magnetron. As shown in Fig. 1 for the first geometry, the outer radii of vanes were fixed and the slope of vanes ($\beta$) was changed. In the second geometry (Fig. 2), the radius of the vanes ($R_v$) was changed while the distances to the point of the vane endings were fixed at 204.6 mm for all six vanes. Thus both models had the basic tapered structure that has been proposed and studied previously. This differs slightly from the configuration used in a very recent report on 12-cavity relativistic magnetrons, wherein the tapered cavity was replaced by a single-stepped cavity. However, the single-stepped design has some drawbacks, and thus was not considered here. For example, one cannot have mode conversion as readily as with a tapered MDO. In addition, one would require larger diameter Helmholtz coils for the single-stepped cavity in order to provide the uniform magnetic field in the interaction space.

MAGIC is a three-dimensional user-configurable numerical simulation code that self-consistently solves the full set of time-dependent Maxwell’s equations and the complete Lorentz force equation to provide the interaction between space charges and the electromagnetic fields. In the code, three-dimensional finite-difference time-domain (FDTD) electromagnetic algorithms are combined with particle-in-cell (PIC) approaches to provide fast, accurate, time-dependent calculations of the fields and particle motion in phase-space. The transparent cathode structure for the simulations was modeled as consisting of 12 discrete longitudinal emitters evenly placed at 8 millimeter from the center ($R_c = 8$ mm) with 2 mm and a 10-degree thickness.

For the MDO, the coaxial antenna for extracting the generated microwave power was modeled to consist of an antenna feed and head without a dielectric vacuum window to maintain vacuum inside the magnetron. The model here included an input port at the lowest $z$-position for providing dc power to the magnetron, and an output port at the highest $z$-position for absorbing the microwave power incident on it. For the PIC simulations, 50-ns voltage pulses of magnitude 400 kV with a 4-ns rise-time were applied. Integrating the angular electric field across each cavity yielded the radiofrequency (RF) voltages. The frequency was obtained through a Fourier transform of an RF-voltage over a time interval in the steady state domain. The simulation time step, on which the time-integration scheme is based, is automatically chosen to meet the Courant-Friedrichs-Lewy stability condition of: $\delta t < \delta x/(c \sqrt{2})$, where $\delta x$ is the smallest cell size and $c$ is the speed of light.

The magnetron was taken to operate with an explosive electron emission model, with electrons created as macro particles from the cathode surface according to Child’s law. Explosive emission results from plasma formation on a material surface. Almost any surface exhibits microscopic protrusions, or “whiskers.” When exposed to large voltages, electric field enhancement at the whiskers can cause significant high-field emission. Subsequently, the whisker may dissipate due to
FIG. 1. Rising sun magnetron with the anode block geometry chosen as the first configuration for quantitative performance evaluation with variable angle for short vanes (angle $\beta$): (a) Cross sectional view in the $r$-$\varphi$ plane. (b) Three dimensional view for $\beta$ equal to 15 degrees. (c) Cross sectional view of the long vanes in the $r$-$z$ plane. (d) Cross sectional view of the short vanes in the $r$-$z$ plane.

Joule heating, resulting in the formation of plasma on the material surface. The MAGIC model used here largely ignores the physical details of the plasma formation process, relying instead on a phenomenological description. Under this approach, breakdown can occur only if the normal electric field at the half-cell, exceeds some user-specified breakdown field threshold. In the simulations, the electron emission was taken to occur at the cathode surface which is a small fraction of the entire cathode length. This restricted area of the beam emission is necessary for the explosive emission modeling in MAGIC because the active region along the axis in which spokes form and reach the anode is shorter than the cathode height. Secondary emission from any surface was ignored, though recently inclusion of such processes has been reported for relativistic magnetron simulations. Neglect of the secondary electron emission can be justified since these effects were not predicted to be very important, due to two contributing factors. First, the relative fraction of secondary electron generation is fairly low due to the high incident energies of the incoming primary electrons that lead to deep penetration and hence, low escape probabilities for any of the secondary electrons generated. In addition, image-charge changes in the surface potential and electric field at the emitting surfaces due to the incoming electron stream would present a repulsive potential, thereby working against strong secondary electron emission. The possibility of any plasma formation arising from release of gases from the surface (i.e., out-gassing) was considered negligible.
FIG. 2. The second anode block geometry chosen for the rising sun magnetron simulations with variable outer radius for short vanes ($R_s$): (a) Cross sectional view in the $\rho-\varphi$ plane. (b) Three dimensional view for $R_s$ equal to 75 mm. (c) Cross sectional view of the long vanes in the $r-z$ plane. (d) Cross sectional view of the short vanes in the $r-z$ plane.

III. SIMULATION RESULTS AND DISCUSSION

Finding an optimized geometry for the anode block of the rising sun magnetron was the initial step in the overall process of evaluating the parameter space through numerical simulations. Figures 1 and 2 show the cut-away views of the magnetron model used. The anode is a rising-sun block comprised of six long and six short vanes. In the first geometric configuration for the anode block, the slope of the short vanes (angle $\beta$ in Fig. 1(d)) was changed from 5 degree to 60 degree in 5 degree increments, while the angle of other six vanes (angle $\theta$ in Fig. 1(c)) was kept fixed at 32 degrees. This fixed value represents an optimized angle as obtained in previous simulations.\textsuperscript{30,46} In the second anode block geometry shown in Fig. 2, $R_s$ was changed from 55 mm to 100 mm in 5 mm steps, while $Z_s$ was kept fixed at 204.6 mm for all six short vanes. It should be noted that the outer radius for the six long vanes was 105 mm at a constant angle of $\theta = 32$ degrees. Three dimensional views of these two geometries (Figs. 1(b) and 2(b)) present a helpful perception of the geometries. Particle-in-cell simulation results for the 12 cavities, 12 cathodes rising sun MDO \textit{without any endcap} for these two different geometries of the anode block are depicted in Figs. 3 and 4. The simulations were carried out at two different applied magnetic fields of 0.42 T and 0.48 T. The output power, device efficiency and leakage current were obtained for different values of $\beta$ as shown in Figs. 3(a) and 3(b), and for various $R_s$ values as in Figs. 4(a) and 4(b).
Figs 3(a) and 3(b) show the output power, device efficiency and leakage current for different angles of the short vanes for applied magnetic fields of 0.42 T and 0.48 T, respectively. Figs 4(a) and 4(b) show the output power, device efficiency and leakage current for different values of $R_s$ (corresponding to the anode geometry of Fig. 2) for same two values of the applied magnetic fields. Comparing Figs. 3 with Figs. 4 shows that the first geometry (i.e. changing the angle $\beta$) appears to have a better performance as compared to changing $R_s$ within the second geometry. The magnetron with the geometry of Fig. 1 is predicted to work at an efficiency of about 57% at 0.42 T, and an efficiency of about 59% at 0.48 T. Here the efficiency $\eta$ refers to the electron beam-to-microwave power conversion efficiency, $\eta = P/(UI_a)$ where $P$ is the radiation power, $U$ is the applied voltage, and $I_a$ the anode current. On the other hand, the second geometry at best is predicted to work at efficiencies of about 50% and 54% for magnetic fields of 0.42 T and 0.48 T, respectively. In addition, the output power in the first geometry is higher than that of the second geometry. For example, the first structure has a maximum output power of about 2.1 GW at 0.42 T and 1.45 GW at 0.48 T, while the second geometry has maximum output powers of about 1.7 GW and 1.2 GW at 0.42 T and 0.48 T, respectively. Clearly then, the geometry of Fig. 1 is preferable from the standpoint of better performance and was therefore chosen for further analysis.

After selecting the geometry for the rising sun MDO, a choice for the best slope (angle $\beta$) was made based on the simulation results already obtained. Simulation data of Fig. 3 suggests an optimum operating range for $\beta$ between 40- and 50-degrees from the standpoint of efficiency and output power. In this range of angles, a 57% efficiency and a 2.1 GW output power, as well as a 59% efficiency and a 1.4GW output power were obtained at magnetic fields of 0.42 T and 0.48 T, respectively. Therefore, $\beta = 45$-degrees was chosen as the optimized angle for the short vanes of the rising sun MDO, with a 56.4% efficiency and 2.13 GW output power at 0.42 T, and a 59.1% efficiency with a 1.47 GW output power for the 0.48 T field. It may be noted that at this chosen angle, the device has relatively low leakage current compared to the other angles at both simulated magnetic field values.
Next, PIC simulations for the rising sun MDO with one comprehensive endcap encompassing all twelve cathodes were carried out for different values of the applied magnetic field. Two different shapes of the endcap were used in the simulations: a bulb shape and cylindrical shape. The radius of endcap for both cases was taken to be 25 mm with the thickness of the cylindrical endcap set at 15 mm. The radius of bulb shape endcap was taken to be 30 mm, while the radius of cylindrical endcap was taken to be 25 mm with a thickness of 15 mm. The geometry for these two comprehensive endcaps used is shown in Fig. 5. It should be mentioned that these two types of endcaps were added to optimized geometry (including the $\beta = 45$-degrees angle) obtained in the previous steps.

The output power, device efficiency and leakage currents were obtained once again with the endcaps, as a function of the applied magnetic field. Figure 6 shows the results. The increase in efficiency is quite significant as compared to the previous results of Fig. 3. For instance, comparing the results of Fig. 3 for a $\beta$ value of 45-degree with Fig. 6 at a 0.42 T magnetic field, shows the efficiency increasing from about 56% without an endcap, to about 65% and 66% with a bulb shaped and cylindrical endcap, respectively. The results at a different magnetic field of 0.48 T also verified this rising trend in efficiency. At 0.48 T, the efficiency is predicted to increase from 59% for an MDO without an endcap, to about 69% with either a bulb shaped or cylindrical endcaps.

In addition to efficiency increases, the sharp drop-off in leakage current with the presence of an endcap is another important benefit of adding endcaps. Fig. 7 compares the leakage current for three different conditions: without any endcap, with a bulb-shaped cap, and with a cylindrical cap. This figure shows that the leakage current to have decreased significantly upon adding endcaps for the cathodes. Specifically, the leakage current values dropped from about 1.5 kA to less than 200 A for magnetic field higher than 0.4 T. Besides, the values were quite close to zero at operating magnetic fields in the 0.41 T to 0.43 T range. Therefore, based on the simulation results of Figs. 6 and 7, one might select the cylindrical endcap at an operating magnetic field 0.43 T as the optimized geometry and operating condition for enhanced efficiency and output power, coupled with low leakage currents.
The role of the cathode length and its extension beyond the anode dimensions was probed next. The length of the anode block $L$ was 7.2 centimeters, and different cases were simulated with cathode lengths ranging in the interval: $5.7 \text{ cm} < L < 13.2 \text{ cm}$. The simulations were carried out at incremental steps $dz$ of 7.5 mm. PIC simulation results for the 12-Cavity Rising-Sun MDO with a cylindrical endcap for different lengths of the cathode are shown in Fig. 8. The magnetic field was taken to be 0.43 T. The output power, device efficiency and leakage current were obtained as a function of cathode length. From the standpoint of high efficiency and output power, coupled with low leakage currents, a cathode length of $L + 5dz$ appears to be a good optimal choice based on the simulation results of Fig. 8. PIC simulations were also carried out for different cathode lengths at a slightly higher magnetic field of 0.45 T with the cylindrical endcap. This second set of simulations at a slightly lower magnetic field of 0.45 T were carried out based on the results already
FIG. 6. PIC simulation results for the 12-Cavity Rising-Sun magnetron with endcap. The output power, device efficiency and leakage current are shown as a function of the applied magnetic field for: (a) a bulb shape endcap, and (b) a cylindrical endcap.

obtained in Fig. 6. Though the device output power was slightly lower (2.15 GW at the 0.45 T magnetic field), but a slightly higher 68% efficiency was predicted at this magnetic field. The PIC simulation results as a function of cathode length at 0.45 T are given Fig. 9. The results of Fig. 9 are somewhat similar to the curves at 0.43 T in Fig. 8. That is, the efficiency appears to have been raised slightly with increasing cathode length. It is seen to surpass 70% efficiency for the interval: 17.25 cm < L < 18.75 cm at 0.45 T. Thus, taking into consideration both Figs. 8 and 9, the best choice in terms of the highest efficiency and output power, with the lowest leakage current would appear to be an extended cathode with a length of \( L + 6 \, \text{dz} \) (\( L = 18 \, \text{cm} \)) and an bias magnetic-field of 0.43 T or 0.45 T. At 0.43 T, the device operates with a 68% efficiency and 2.35 GW output power, while the MDO works at a 70.5% efficiency and 2.14 GW output power at 0.45 T. It may additionally be mentioned that the leakage current in both these cases is at about 150 A which is

FIG. 7. Leakage current of 12-Cavity Rising-Sun Magnetron for three different cathode structures. These structures were without any endcap, with a bulb-shaped cap, and with a cylindrical endcap.
FIG. 8. PIC simulation results for the 12-Cavity Rising-Sun MDO with a cylindrical endcap for different lengths of the cathode at an applied magnetic field 0.43 T. The output power, device efficiency and leakage current are shown as a function of cathode length.

FIG. 9. Simulation results for the 12-Cavity Rising-Sun Magnetron with cylindrical endcap for different lengths of the cathode at magnetic field 0.45 T. The output power, device efficiency and leakage current are shown as a function of cathode length.

FIG. 10. MAGIC-based simulation results for the 12-Cavity Rising-Sun Magnetron with a cylindrical endcap and 18 cm cathodes (L + 6dz) at a 0.45 T magnetic field. The figures show: (a) Efficiency, (b) Output power, (c) Total current, and (d) Anode current.

significantly lower than without any endcaps. In the former case, leakage currents as high as 1.5 kA were calculated.

Next, Fig. 10 depicts the MAGIC-based PIC simulation results for the temporal evolution of various quantities of interest within the 12-Cavity Rising-Sun magnetron. A cylindrical endcap and
FIG. 11. Snapshots at 4.99 ns, 20.038 ns, and 39.442 ns showing the evolution of the electron swarm and formation of spokes in the 12-Cavity 12-cathode Rising-Sun Magnetron without and with a cylindrical endcap at 0.45 T magnetic field and 400 kV applied voltage. The various figure are the $r$-$z$ plane cross sectional view of magnetron without any endcap at: (a) 4.99 ns, (b) 20.038 ns, and (c) 39.442 ns. The $r$-$\phi$ plane cross sectional view of the MDO at $z = 17.04$ cm, without any endcap at: (d) 4.99 ns, (e) 20.038 ns, and (f) 39.442 ns. The MDO cross sectional view in the $r$-$z$ plane with cylindrical endcap at: (g) 4.99 ns, (h) 20.038 ns, and (i) 39.442 ns. Cross-sectional snapshots in the $r$-$\phi$ plane of magnetron at $z = 20.08$ cm with cylindrical endcap at: (j) 4.99 ns, (k) 20.038 ns, and (l) 39.442 ns. Finally, snapshots in the $r$-$\phi$ plane of the magnetron at $z = 17.04$ cm, with a cylindrical endcap at: (m) 4.99 ns, (n) 20.038 ns, and (o) 39.442 ns, respectively.

18 cm cathodes ($= L + 6dz$) at a 0.45 T applied magnetic field was used. The efficiency is seen to reach 70% within about 20 ns. The output power is predicted to be about 2.36 GW with a current of $\sim 8.4$ kA. Moreover, snapshots of the electron distributions within the cross sectional structure of the magnetron without and with a cylindrical endcap at three different time instants of 4.99 ns, 20.038 ns, and 39.442 ns for a 0.45 T magnetic field are shown in Figs 11(a)-11(o). Comparison of the figures, with and without an endcap, demonstrates the role of the endcap in suppressing electrons leakage current and contributing to higher efficiency. For instance, figures 11(d)-11(f) and 11(m)-11(o) represent snapshots at exactly the same position and time the MDO with and without endcap, respectively. Most of the electron flux is blocked by the endcap and is predicted not to reach the vanes and output window. It should be noted that figures 11(m)-11(o) are cathodes with endcap, but this intersection (at $z = 17.04$ cm) is below the endcap, and hence the endcap cannot be seen in the figure.

For completeness, results for the frequency of the magnetron operation are briefly discussed. Figure 12 shows the output voltage spectrum for the 12-Cavity Rising-Sun Magnetron at an applied
FIG. 12. Output voltage spectra for the 12-Cavity Rising-Sun Magnetron at an applied magnetic field 0.45 T for various cases. (a) Without endcap and 13.5 cm cathodes, (b) with a cylindrical endcap and 13.5 cm cathodes, and (c) with a cylindrical endcap and 18 cm (= L + 6dz) cathodes.

magnetic field 0.45 T, with and without the use of endcaps. Different cathode lengths were simulated, and the results shown correspond to 13.5 cm long (Figs. 12(a) and 12(b)), and 18 cm long (Fig. 12(c)) cathodes. In all cases, a frequency of about 2.66 GHz was obtained despite the variation in cathode length and structure. Thus, based on the results obtained the system appears quite stable.

Finally, the issue of secondary electron emission deserves some comment and is briefly discussed for completeness. The role of secondary emission was not found to be very strong for the A6 magnetron\textsuperscript{51} though it did lead to some (a few percent) lowering of the device efficiency. A similar trend was reported more recently for the 12-cavity MDO,\textsuperscript{50} along with effects of secondary emissions on pulse shortening. This aspect of secondary emission was ignored in this contribution, but would be probed in the future. It remains a germane issue since the possibility of electrons with high energy striking the anode block, and thereby leading to secondary and backscattered electrons, cannot be eliminated in an MDO regardless of the geometry chosen. Outgassing from electrodes upon impact by high energy particles would be another practical aspect that would need evaluation. Energy release from the incoming high energy electrons via inelastic phonon scattering would cause localized heating and formation of spatial thermal gradients at the electrodes. The out-gassing (particularly of hydrogen or nitrogen) due to Arrhenius-type enhancements of the diffusion coefficients would then be expected,\textsuperscript{54,55} and this aspect will be addressed in a future study.
IV. CONCLUSIONS

Particle-in-cell simulations have been performed to provide a numerical evaluation of the efficiency, output power and leakage currents in 12-cavity, 12-cathode rising-sun magnetron with diffraction output. The central goal was to conduct a parameter study of a rising-sun magnetron that comprehensively incorporated performance enhancing features such as transparent cathodes, axial extraction, the use of endcaps, and cathode extensions. In reality the parameter space is really large, and so for convenience the basic dimensions and geometry was confined to that used in recent reports of the A6 relativistic magnetron and the different conditions analyzed for optimized shape and angle of short vanes. Our results, in keeping with previous reports, demonstrate the definite advantage of having endcaps. The simulations here also demonstrated peak output power in excess of 2 GW, with efficiencies on the order of 68% for B-fields in the 0.42 T - 0.46 T range.

For further optimization, the role of the cathode length and its extension beyond the anode dimensions was probed. The results show the efficiency in excess of 70% and peak output power on the order of 2.1 GW for a 18 cm cathode length at 0.45 T magnetic field and 400 kV applied voltage.

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