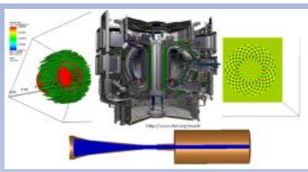

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Design and development of field emission based rising-sun magnetron for industrial applications using CFDTD PIC simulations

Ling Li[1], Kaviya Aranganadin[1], Hua-Yi Hsu[2], and Ming-Chieh Lin[1]

[1]Multidisciplinary Computational Laboratory, Department of Electrical and Biomedical Engineering, Hanyang University, Seoul 04763, South Korea

[2]Department of Mechanical Engineering, National Taipei University of Technology, Taipei 10608, Taiwan

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CONTENTS

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Background and Motivations

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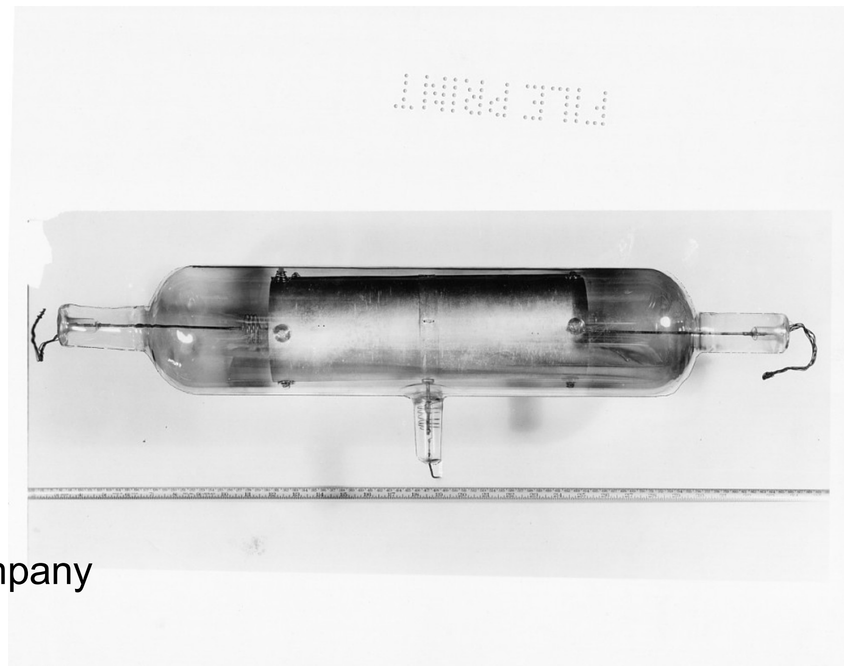
General Electric experimental Hull magnetron



Object Name
  diode
  magnetron
  Electron Tube, Diode

date made
  1921

associated institution
  General Electric

maker
  General Electric Company

Measurements
  overall: 29 in x 4 1/2 in; 73.66 cm x 11.43 cm
  anode: 12 in x 4 in; 30.48 cm x 10.16 cm

ID Number
  EM.315142
catalog number
  315142
accession number
  217661

Credit Line
  from General Electric Research Laboratory, thru Albert W. Hull

https://americanhistory.si.edu/collections/search/object/nmah_1359099

Background and Motivations

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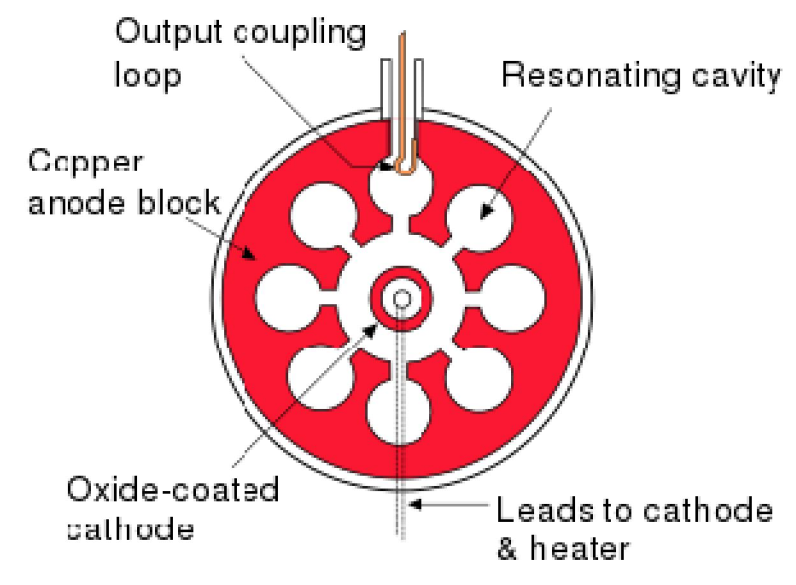
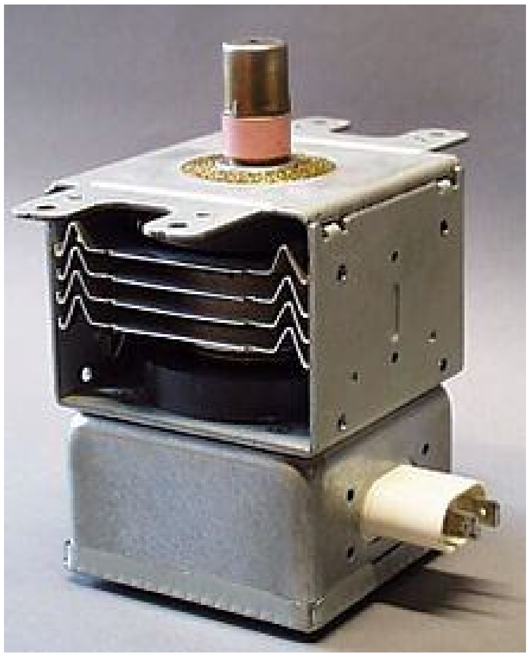
The cavity magnetron is a high-power vacuum tube that generates microwaves using the interaction of a stream of electrons with a magnetic field while moving past a series of cavity resonators which are small, open cavities in a metal block.

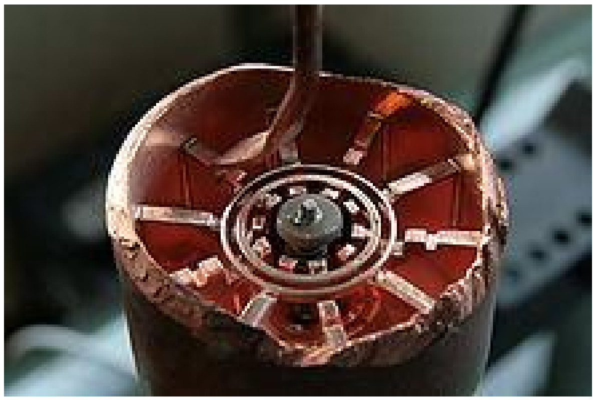


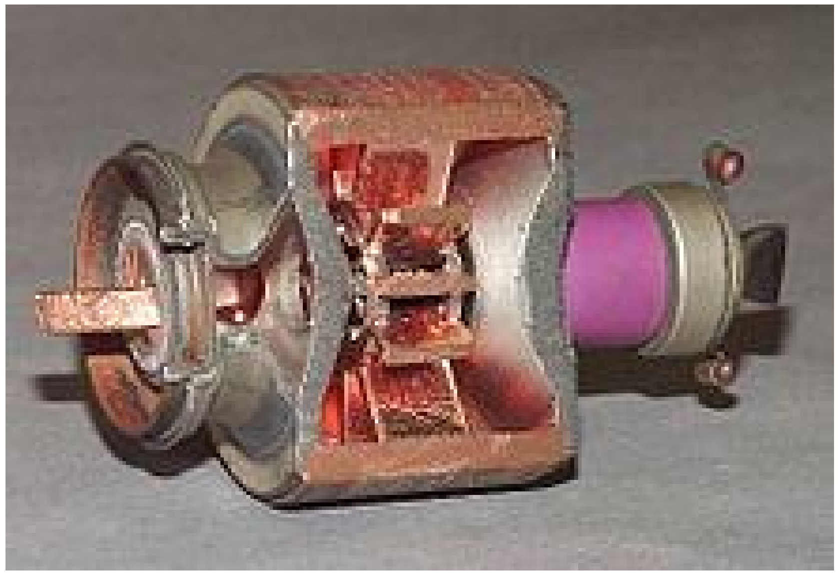
Resonant cavity magnetron high-power high-frequency oscillator

https://en.wikipedia.org/wiki/Cavity_magnetron

Background and Motivations







Magnetron from a microwave oven with magnet in its mounting box. The horizontal plates form a heat sink, cooled by airflow from a fan. The magnetic field is produced by two powerful ring magnets, the lower of which is just visible. Almost all modern oven magnetrons are of similar layout and appearance.

https://en.wikipedia.org/wiki/Cavity_magnetron

Background and Motivations

The cavity magnetron was widely used during World War II in microwave radar equipment and is often credited with giving Allied radar a considerable performance advantage over German and Japanese radars, thus directly influencing the outcome of the war. It was later described by American historian James Phinney Baxter III as "the most valuable cargo ever brought to our shores".

The cavity magnetron is a high-efficiency, high-power, while low-cost vacuum device for generating microwaves and is widely used for applications such as radars, microwave ovens, and industrial heating.
In principle, far exceeding most microwave tubes are capable of and this make magnetrons still the main RF power source for use of microwave heating in daily life and industries.

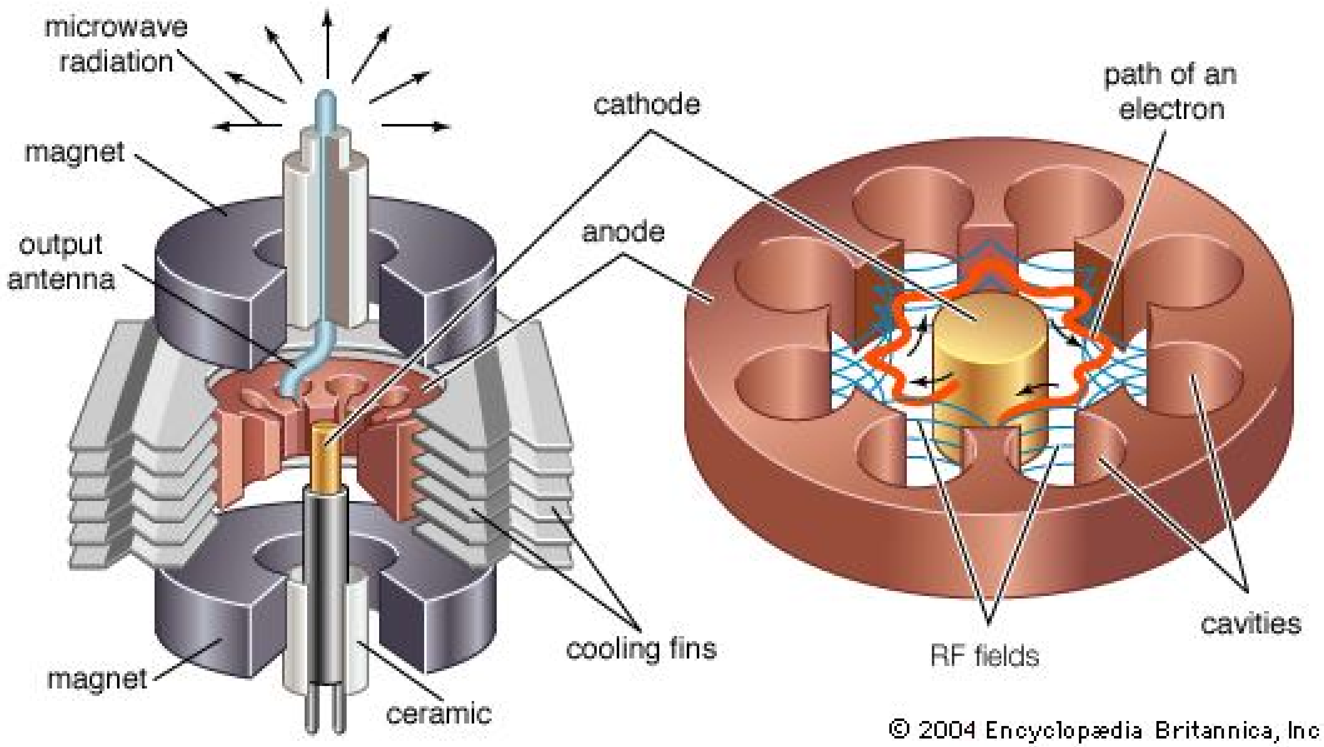
Background and Motivations

https://www.airforce-technology.com/news/raytheon-to-develop-high-power-microwave-system-for-usaf/

https://www.crfs.com/blog/radar-jammers-and-where-to-find-them/

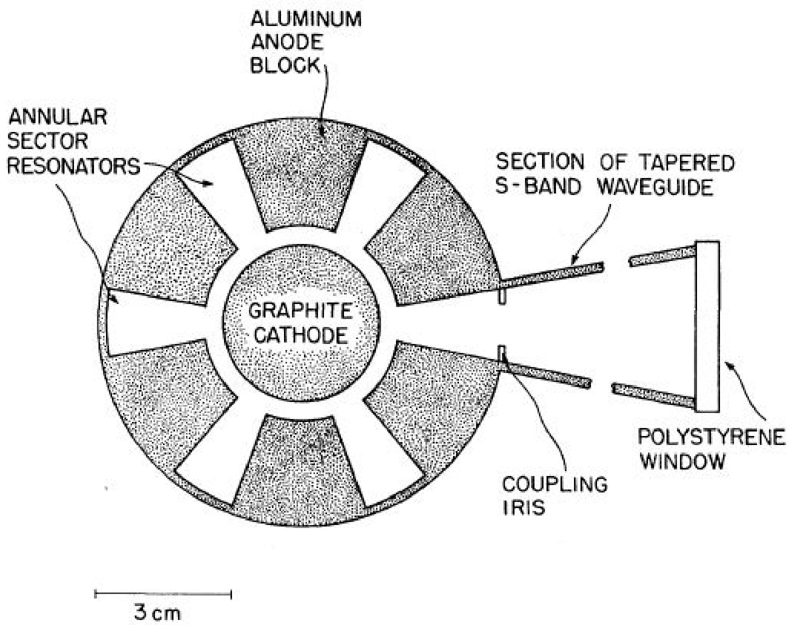
https://www.youtube.com/watch?v=kOvTIKLq6ho

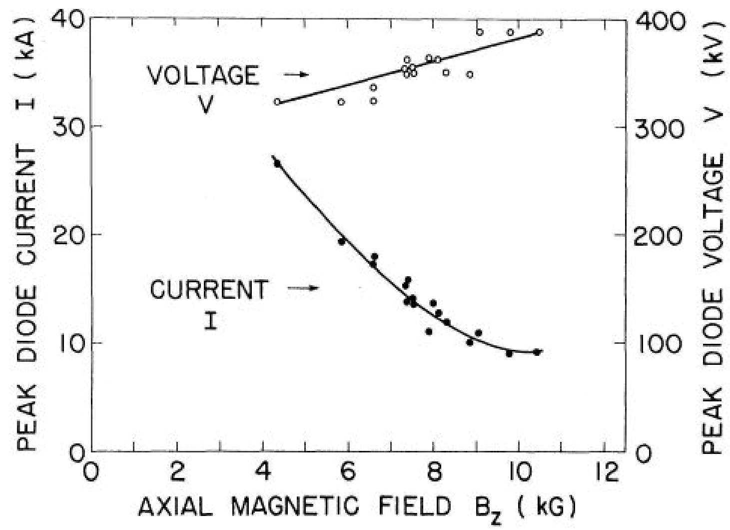
Background and Motivations



Background and Motivations

The S-band **A6 relativistic magnetron** was proposed by G. Bekefi and T. J. Orzechowski of MIT in 1976. With an external voltage of ~360kV, an external magnetic field of ~0.8 Tesla, and a field emission current of ~12 kA, an ultra-large output power of ~1.7 GW can be obtained, with an efficiency of about **36%**.





G. Bekefi and T. J. Orzechowski, "Giant Microwave Bursts Emitted from a Field-Emission,Relativistic-Electron-Beam Magnetrons", Phys. Rev. Lett. **37**, 379 (1976).

Background and Motivations

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A6 Relativistic Magnetron

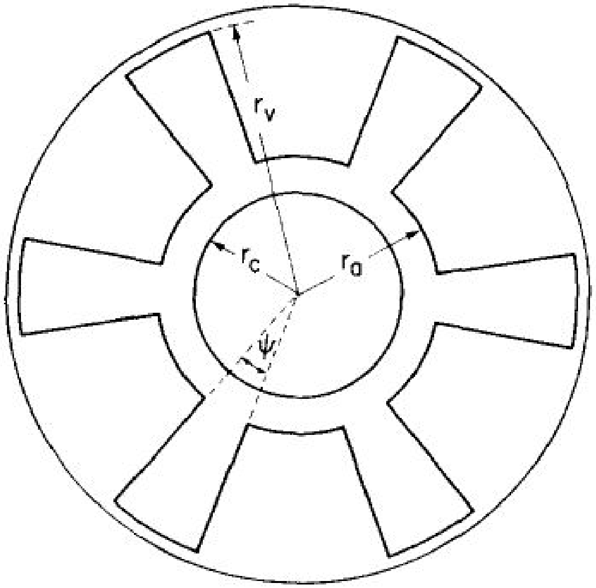
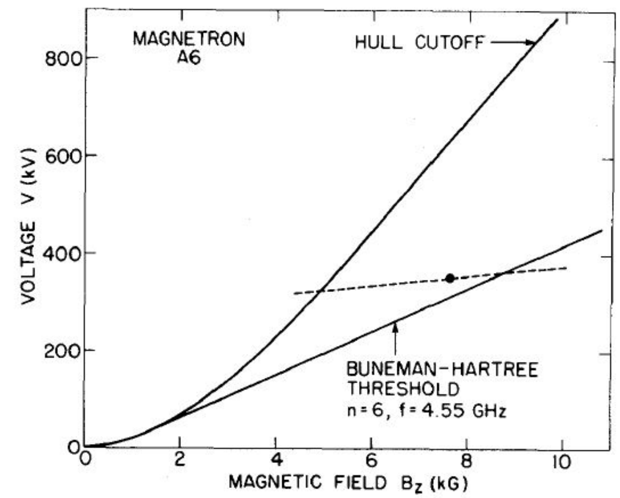


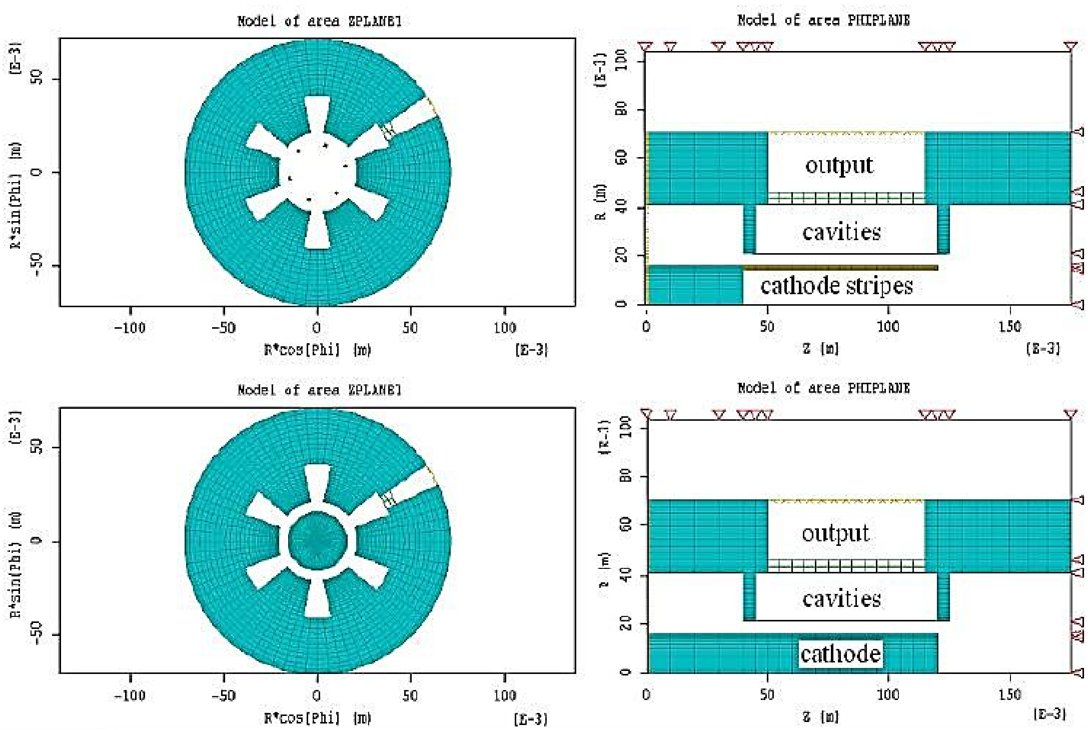
TABLE I. Characteristic dimensions of several relativistic magnetrons. (The frequencies are computed for an infinitely long anode block, see Sec. II.)

Magnetron	r_c (cm)	r_a (cm)	r_v (cm)	ψ (degrees)	N	L (cm)	$f(n=3)$ (GHz)	$f(n=6)$ (GHz)
A6	1.58	2.11	4.11	20	6	7.2	2.34	4.60
B6	[illegible]	2.11	4.11	20	6	[illegible]	[illegible]	[illegible]
D6	1.88	2.46	4.83	20	6	8.42	1.98	4.01
J6	1.69	2.22	3.82	18	6	7.2	2.81	5.27



A. Palevsky and G. Bekefi, “Microwave emission from pulsed, relativistic e-beam diodes, II: The multiresonator magnetron,” Phys. Fluids **22**, 986–996 (1979).

Background and Motivations



In 2005, Professor E. Schamiloglu from the University of New Mexico proposed to replace the traditional solid cathode with a transparent cathode, which can make the relativistic magnetron oscillate quickly.

Transparent cathode

Solid cathode

M. I. Fuks and E. Schamiloglu, “Rapid Start of Oscillations in a Magnetron with a "Transparent" Cathode”, Phys. Rev. Lett. **95**, 205101 (2005).

Background and Motivations

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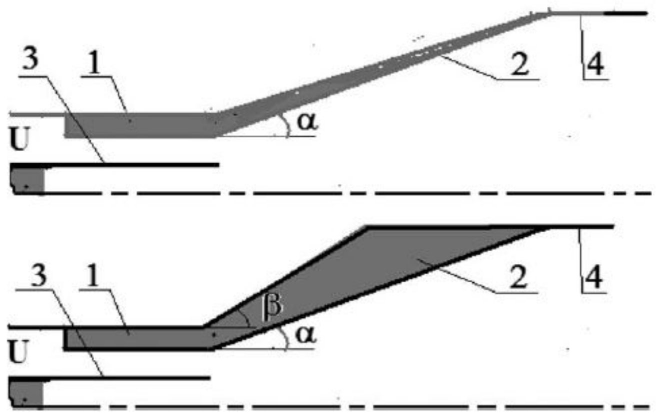
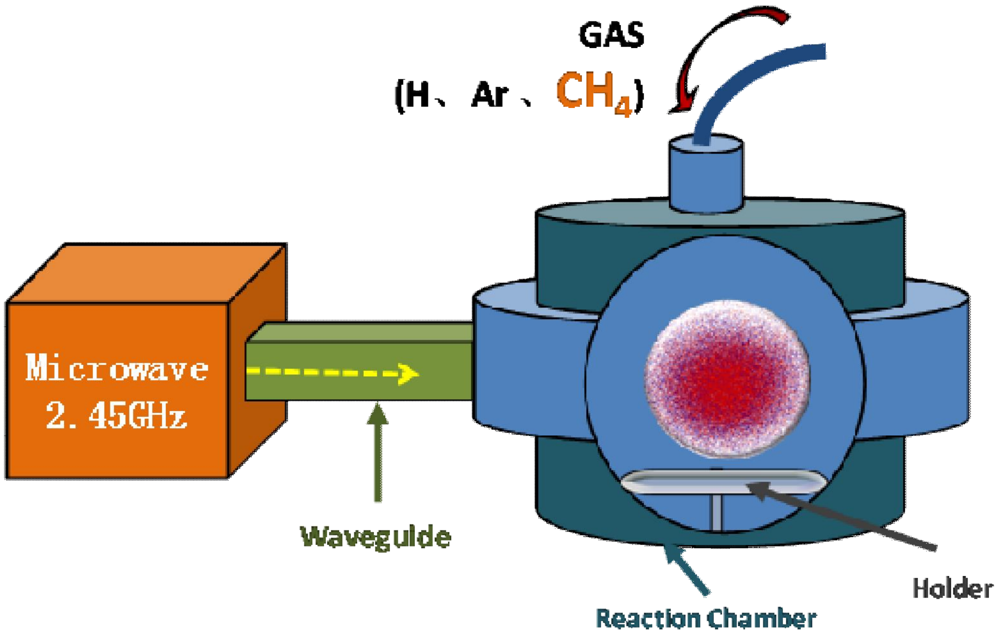
Magnetron with diffraction output (MDO)



In 2010, it was further proposed to use a special diffraction output. The diffraction output structure is to smoothly connect the resonant cavity of the magnetron to the horn antenna in the axial direction, and then use a circular waveguide to output electromagnetic energy from the horn antenna. The efficiency of a relativistic magnetron can be increased to **~70%.**

Edl Schamiloglu et al, “70% Efficient Relativistic Magnetron With Axial Extraction of Radiation Through a Horn Antenna”, IEEE Transaction on plasma science **38**, 1302-1312 (2010).

Background and Motivations



Schematic structure of the MPECVD system

Background and Motivations

- High efficiency and long operating life
- Small magnetic field leakage
- High frequency stability
- Compact and lightweight
- Low anode voltages

Magnetron 2M265-M12WJ

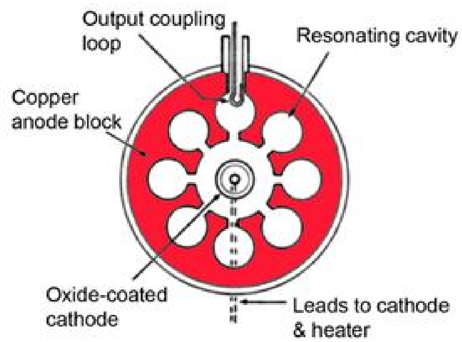
MUEGGE

For industrial use, S-band (2450 MHz)

Output Power (W)	Efficiency (%)
3000	70

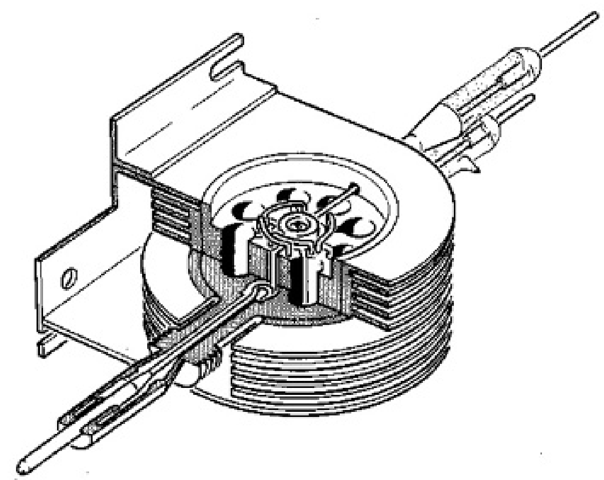
Continuous wave magnetrons are used for plasma processing in the manufacture of semiconductors and in industrial dielectric heating applications.

Background and Motivations



Resonant cavity magnetron high-power high-frequency oscillator

The cavity magnetron is a high-power vacuum tube that generates microwaves based on the interaction of a stream of moving electrons under a crossed electric and magnetic fields with a series of open coupled metal cavity resonators.



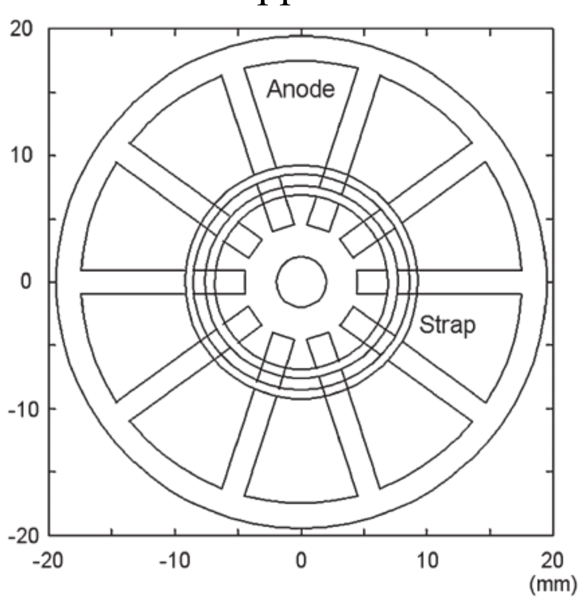
Electrons pass by the openings to these cavities and cause microwaves to oscillate within, similar to the way a whistle produces a tone when excited by an air stream blown past its opening. The frequency of the microwaves produced, the resonant frequency, is determined by the cavities' physical dimensions.

https://en.wikipedia.org/wiki/Cavity_magnetron

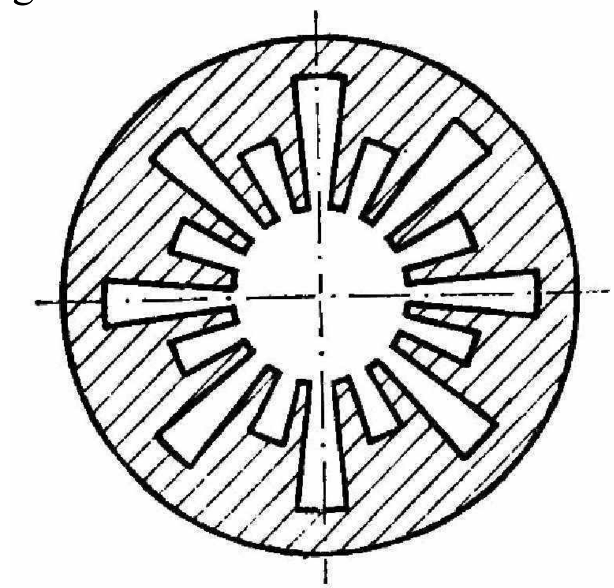
Background and Motivations

· *Rising-sun structure*

In order to further ease the fabrication and reliability, a **rising-sun configuration** is chosen instead of a trapped conventional magnetron.



(a) Conventional magnetron



(b) Rising-sun magnetron

The cavity radius is equal, hence the dispersion of the conventional structure cannot provide enough mode separation from the operating curve interception without straps.

Background and Motivations

· *Thermionic cathode*

In general, all cavity magnetrons produced today consist of a thermionic or heated cathode placed at a high negative potential created by a high-voltage, direct-current power supply while the anode is grounded. Thermionic cathodes in all magnetrons contain a small amount of thorium mixed with tungsten in their filament.

· *Field emisson cathode*

Recently, field emission arrays have been demonstrated being capable of experimentally emitting > 100 A/cm^2 current densities and this makes employing field emission as electron sources or cold cathodes in microwave tubes possible. In this work, a field emission based magnetron is proposed and investigated for industrial applications.
With the use of a field emission cathode to replace a thermionic one, not only the **lifetime** can be extended but the complexity of the **external circuit and assembly process** can be much reduced.

Background and Motivations

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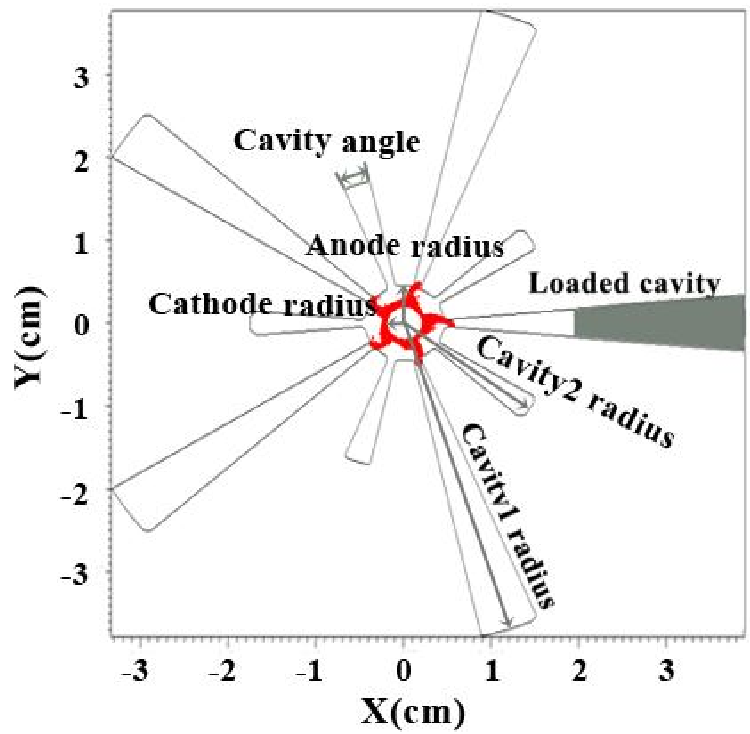
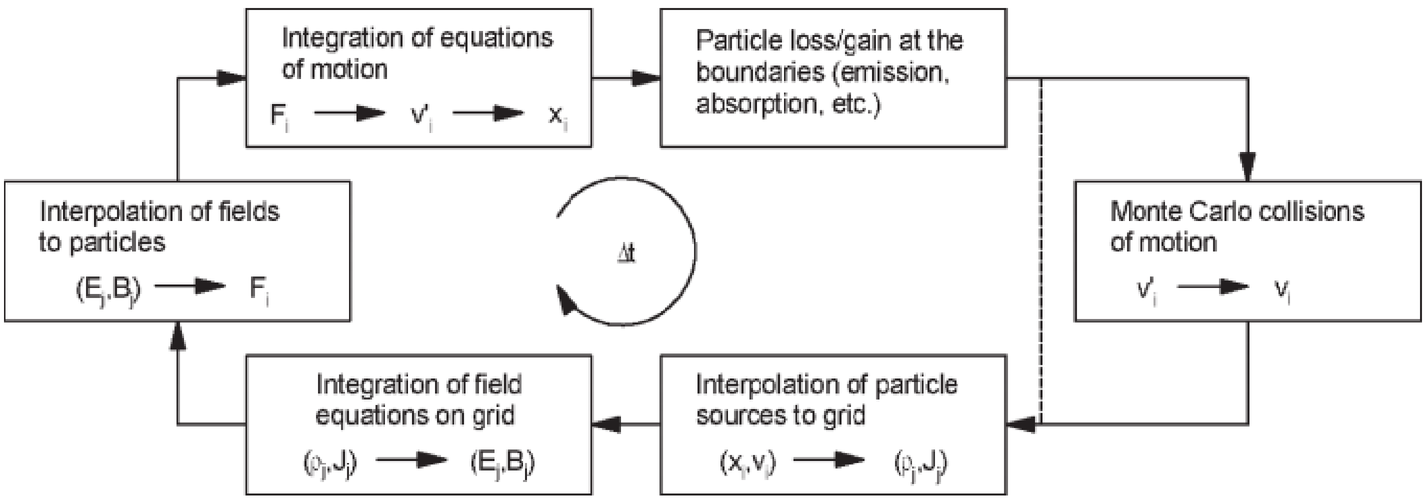
The goal of this research is to design and develop magnetrons operating at a frequency of **2.45 GHz** and at a working power of **> 3 kW** for industrial applications. A preliminary design after the optimization could achieve the required power at a high efficiency up to ~80%.



Research Methods and Simulation Model Design

FDTD PIC simulation

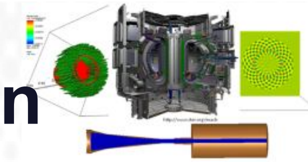


In this method, individual particles in a Lagrangian frame are tracked in continuous phase space, whereas moments of the distribution such as densities and currents are computed simultaneously on Eulerian mesh points.

The finite-difference time-domain (**FDTD**) particle-in-cell (**PIC**) applications provide the capability to model and simulate a wide variety of vacuum electronics problems and beam-wave interaction issues.

J. P. Verboncoeur, "Particle simulation of plasmas: review and advances", Plasma Phys. Control. Fusion **47**, A231–A260 (2005).

Research Methods and Simulation Model Design



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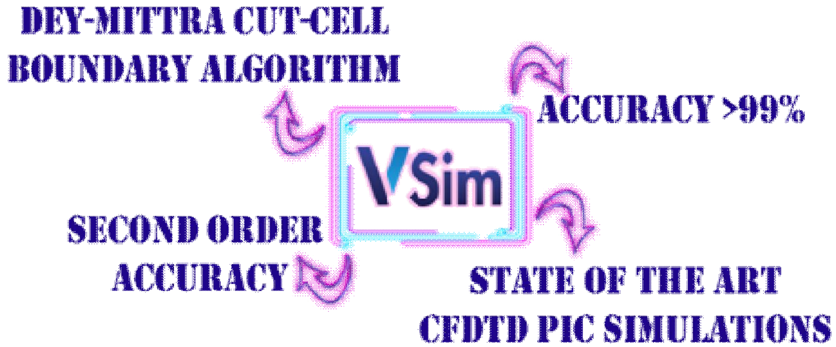

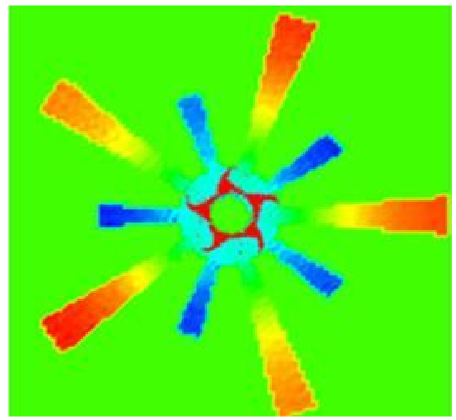

Rising-sun magnetrons employing a field emission cathode designed and developed using accurate and efficient CFDTD PIC modeling exhibit a lot of advantages compared to conventional strapped magnetron employing a thermionic cathode.

Research Methods and Simulation Model Design

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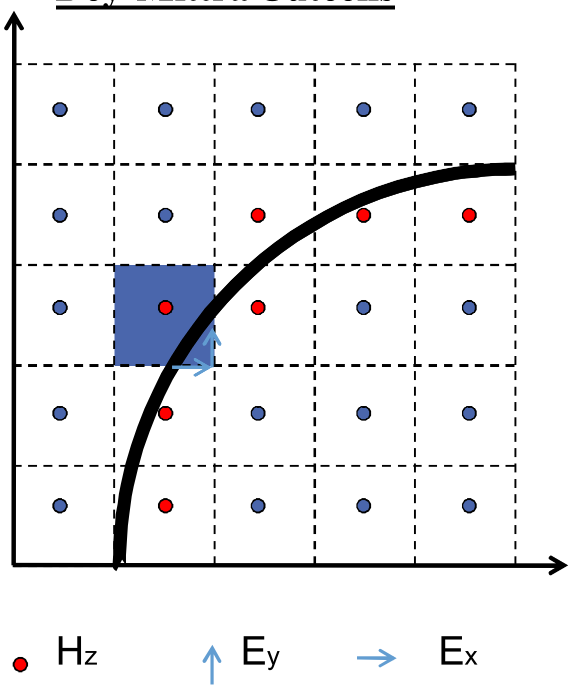
Dey-Mittra Cutcells



The Conformal FDTD Algorithm in VSim

Locally Conformal Grids

For each cell that is at least partially within the region of interest, the magnetic (H) field is assumed to be located at the center of that Cartesian cell, and is assumed to be constant over the area of the cell that is inside the cavity. The electric field values are assumed to have a constant value along the edge of a cell that resides within the cavity and are zero along the metallic surface. Note that in this scheme, the magnetic field is assumed to be located at the center of the undistorted cell for the purpose of numerical calculations, irrespective of whether this location is inside or outside the cavity.

S. Dey, R. Mittra, and S. Chebolu, Microwave and Opt. Technol. Lett. **14**, 213-215 (1997)

Research Methods and Simulation Model Design

The Conformal FDTD Algorithm in VSim

Just use the regular FDTD equation for updating the magnetic field with the use of the electric field values along the distorted contour appropriately weighted with the lengths of the contours:

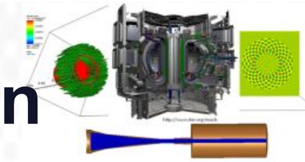
$$
\begin{aligned}
&H_z^{n+1/2}(i,j)\\
&\quad = H_z^{n-1/2}(i,j) + \frac{\Delta t}{\mu^{*}\mathrm{Area}(i,j)}\\
&\qquad \times \left\{ \begin{array}{l} E_x^n(i,j)^{*} l_x(i,j) - E_x^n(i,j-1)^{*} l_x(i,j-1) \\ -E_y^n(i,j)^{*} l_y(i,j) + E_y^n(i-1,j)^{*} l_y(i-1,j) \end{array} \right\}.
\end{aligned}
$$

Once the H fields are computed, the E fields are updated in the conventional manner with the use of the adjacent H-field values. For example,

$$
E_x^{n+1}(i,j) = E_x^n(i,j) + \frac{\Delta t}{\varepsilon^{*}\Delta y}\{H_z^{n+1/2}(i,j+1) - H_z^{n+1/2}(i,j)\}.
$$

S. Dey, R. Mittra, and S. Chebolu, Microwave and Opt. Technol. Lett. **14**, 213-215 (1997)

Research Methods and Simulation Model Design



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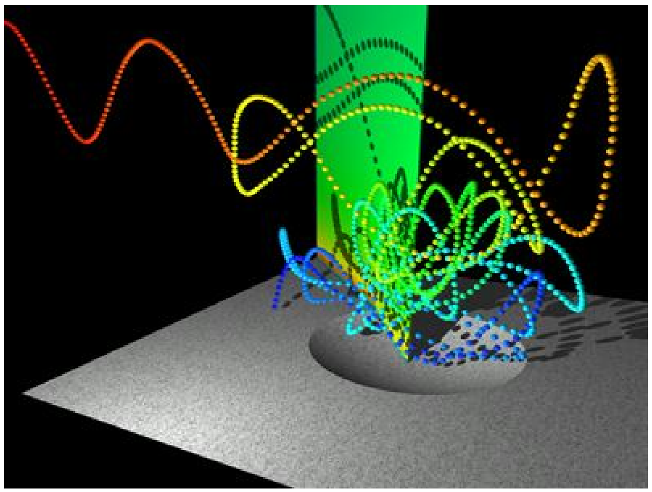
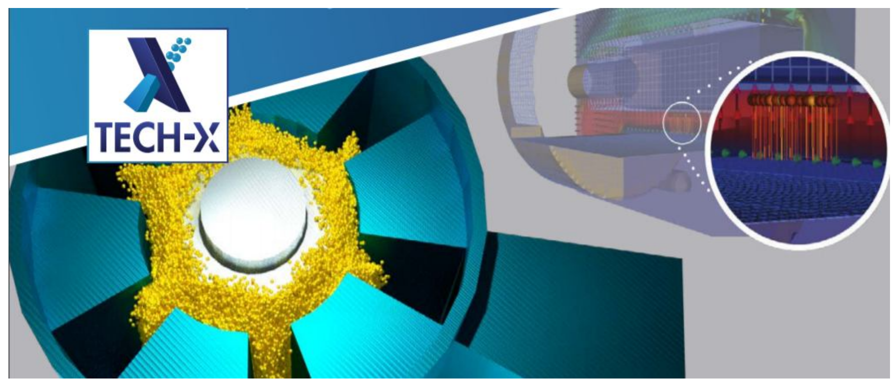


Electromagnetics and Plasma Simulation

VSim is a flexible, multiplatform, multiphysics simulation software tool. VSim is designed to run computationally intensive electromagnetic, electrostatic, and plasma simulations in the presence of complex dielectric, magnetic, and metallic shapes.



VSim

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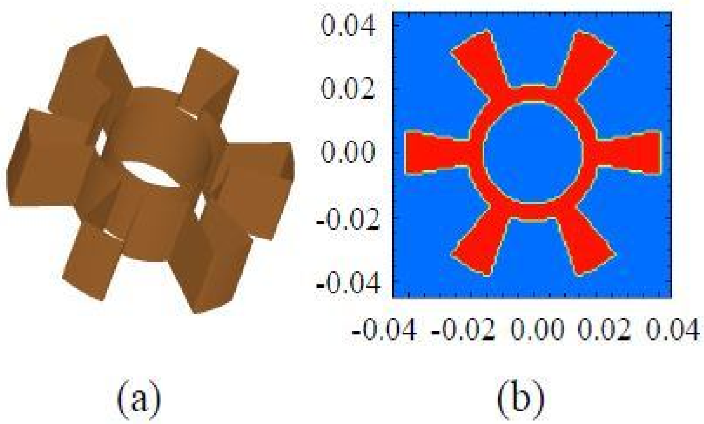
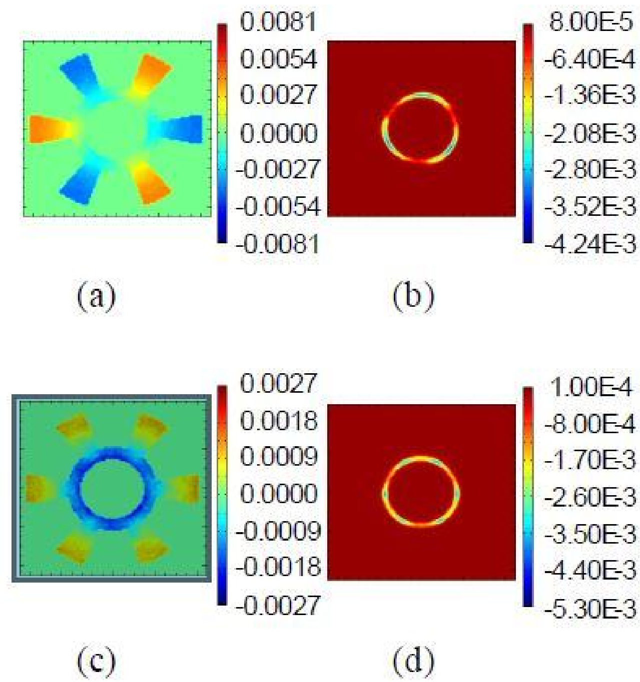


Model of the A6 relativistic magnetron constructed in VORPAL, (**a**) 3D view and (**b**) 2D cross section view.



M.C. Lin*, C. Nieter, P.H. Stoltz and D.N. Smithe, "Accurately and Efficiently Studying the RF Structures Using a Conformal Finite-Difference Time-Domain Particle-in-Cell Method", The Open Plasma Physics Journal 3, 48-52 (2010).

Research Methods and Simulation Model Design

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48 *The Open Plasma Physics Journal*, 2010, *3*, 48-52

Open Access

Accurately and Efficiently Studying the RF Structures Using a Conformal Finite-Difference Time-Domain Particle-in-Cell Method

M.C. Lin*, C. Nieter, P.H. Stoltz and D.N. Smithe

Tech-X Corporation, Boulder, Colorado, USA

Abstract: This work introduces a conformal finite difference time domain (CFDTD) particle-in-cell (PIC) method to accurately and efficiently study electromagnetic or radio frequency (RF) structures and their interactions with charged particles. For illustration, the dispersion relation of an A6 relativistic magnetron has been determined and a preliminary hot test including electrons has been done. The accuracy of the CFDTD method is measured by comparing with calculations based on the finite element method. The results show that an accuracy of 99.4% can be achieved by using only 10,000 mesh points with the Dey-Mittra algorithm as implemented in the CFDTD method. By comparison, a mesh number of 250,000 is needed to preserve 99% accuracy using a staircased FDTD method. This suggests one can more efficiently and accurately study the hot tests of microwave tubes or the interactions of charged particles and RF structures using the CFDTD PIC method than a conventional FDTD one.

Research Methods and Simulation Model Design

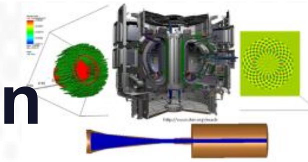

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Table 1. Accuracy of VORPAL with Dey-Mittra CFDTD by Comparing with SUPERFISH Calculations. The Total Simulation Time is 1,000 ns

A6 Relativistic Magnetron Mode Number n (Ref. [3])	f (GHz) SUPERFISH # 410,481	f (GHz) VORPAL (CFDTD) # 10,000 DM_FRAC=0.5	Relative Error	f (GHz) VORPAL (CFDTD) # 40,000 DM_FRAC=0.5	Relative Error
1	1.38443754	1.379	0.00393	1.382	0.00176
2	2.15457799	2.150	0.00212	2.156	0.00066
3	2.35399345	2.345	0.00382	2.352	0.00085
0_1	4.63362062	4.620	0.00294	4.631	0.00057
1_1	5.02876229	5.017	0.00234	5.030	0.00025
2_1	6.25401881	6.217	0.00592	6.243	0.00176
3_1	7.69109058	7.669	0.00287	7.683	0.00105

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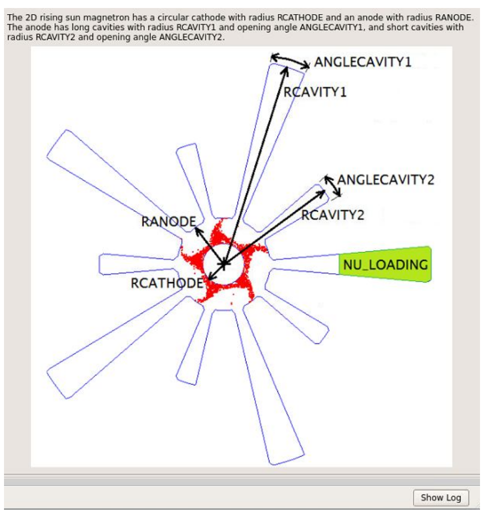
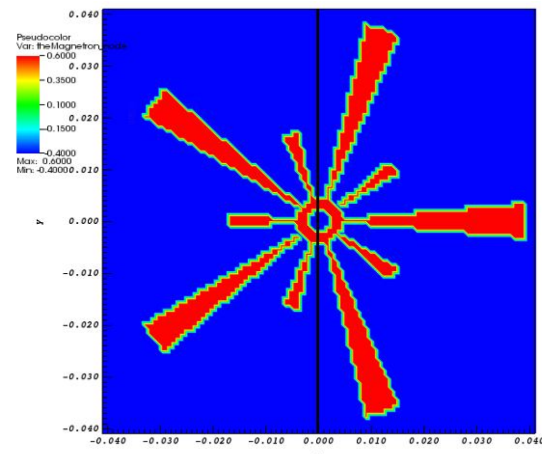
In the magnetron design, a π-mode oscillation can be stably produced and it has been confirmed with a grid **resolution of** 102×102 in the CFDTD simulation to give an accuracy > 99%, comparing with an FEM frequency domain calculation.



There is one long cavity in the horizontal x axis loaded with an absorber, in order to simulate the output power coupling and the RF power dissipation of this device. This absorber goes as a cavity loading parameter that is used to control the magnetron loaded quality factor, Q.



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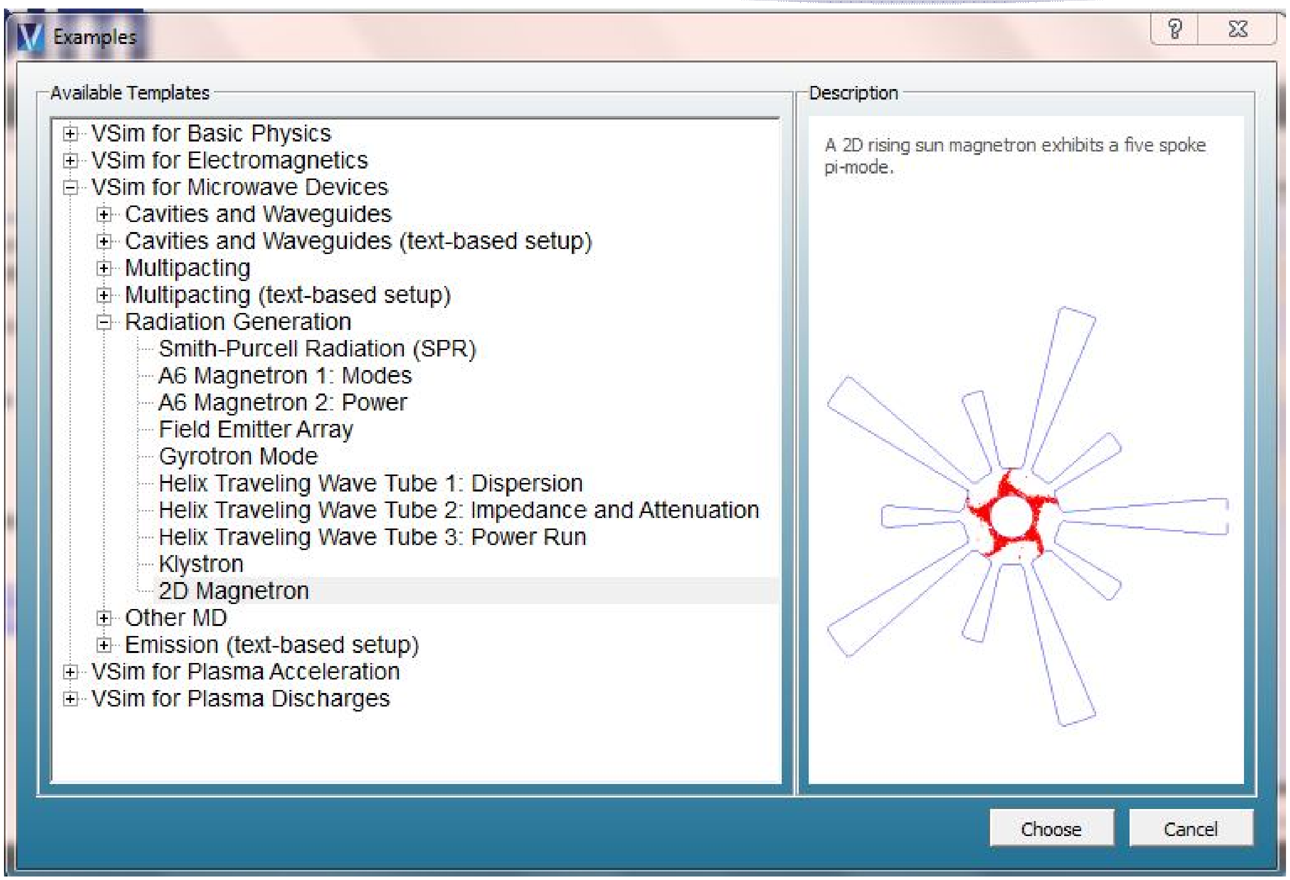

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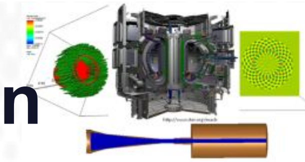

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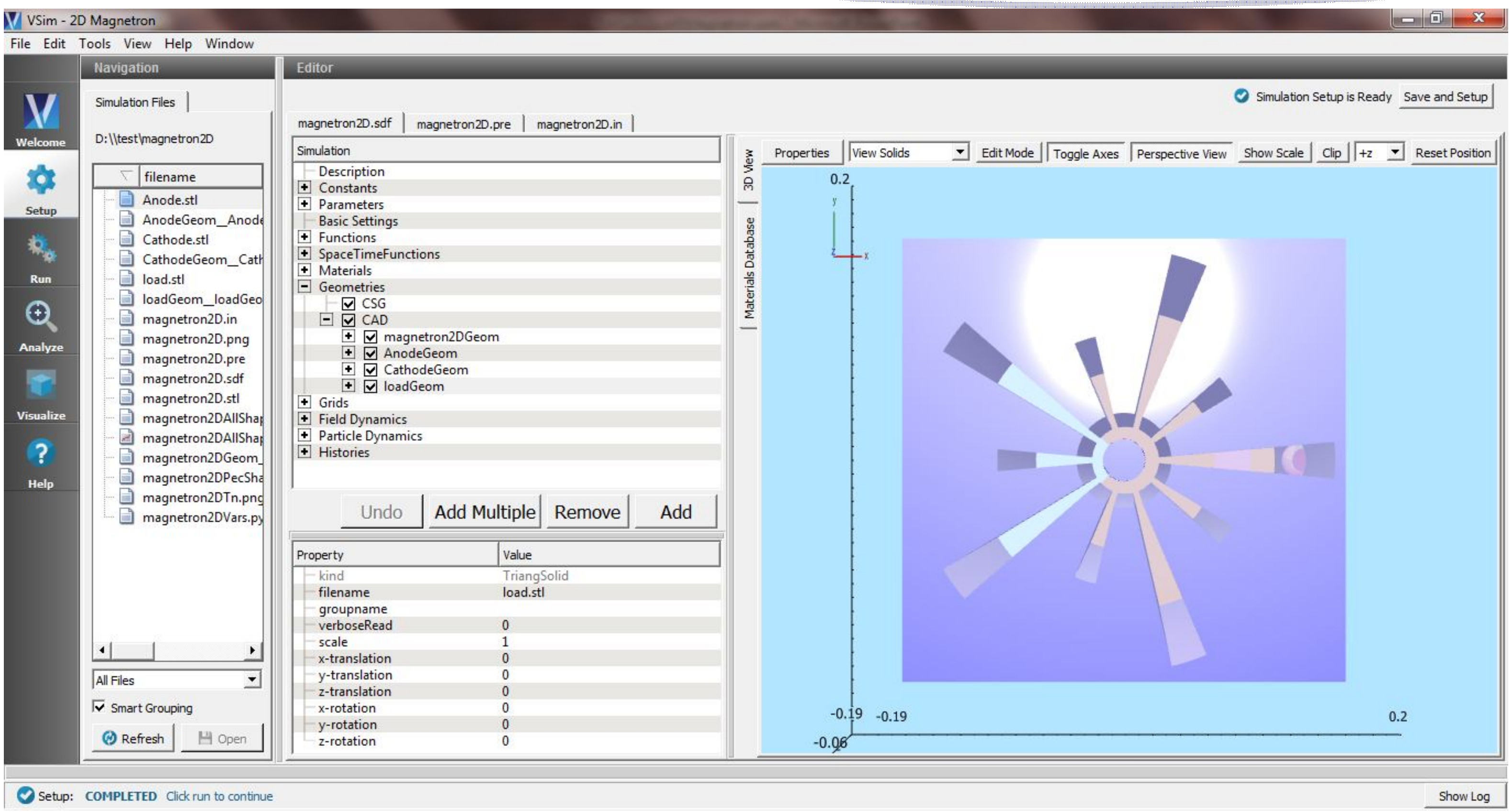

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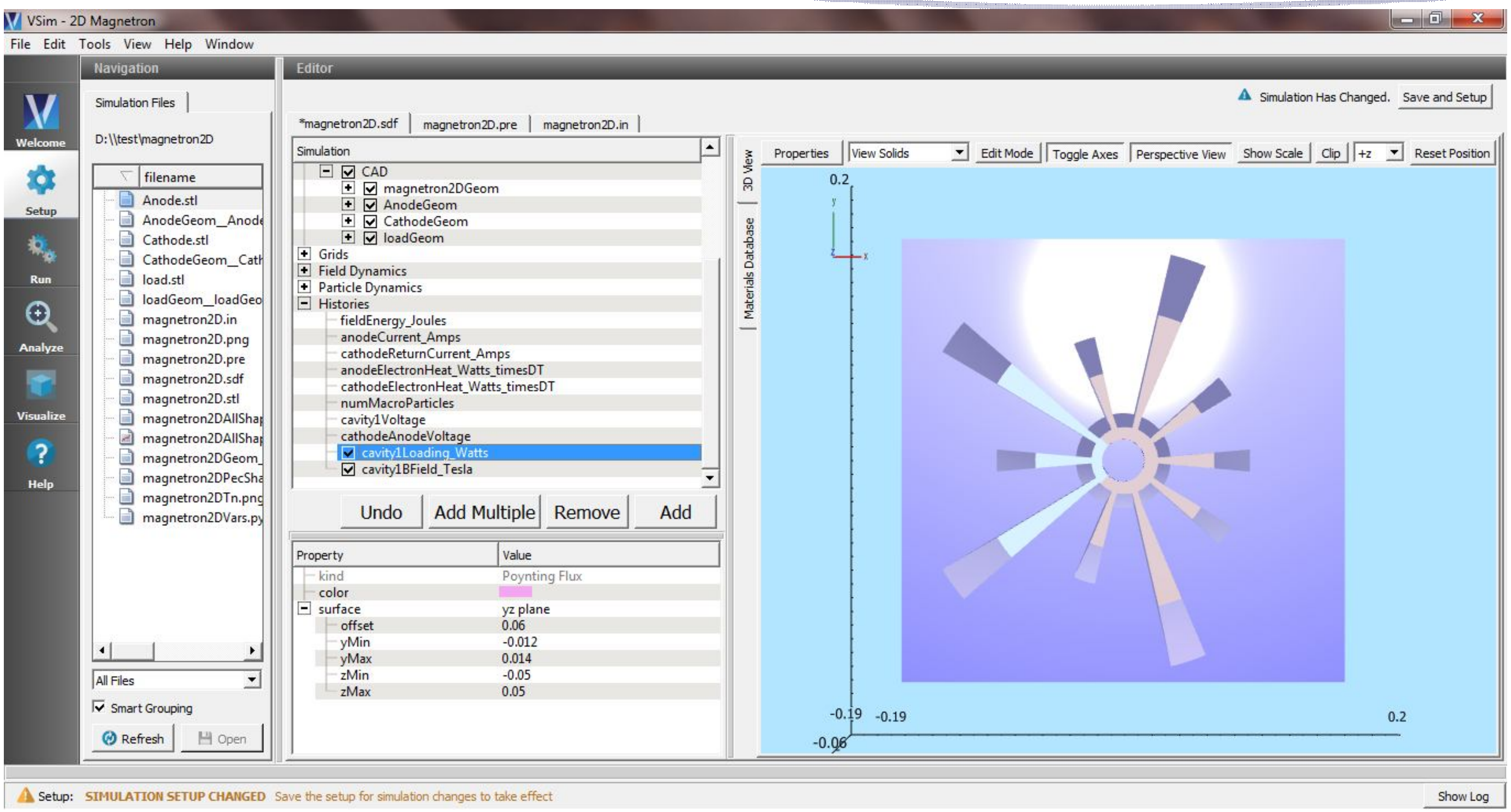

Research Methods and Simulation Model Design

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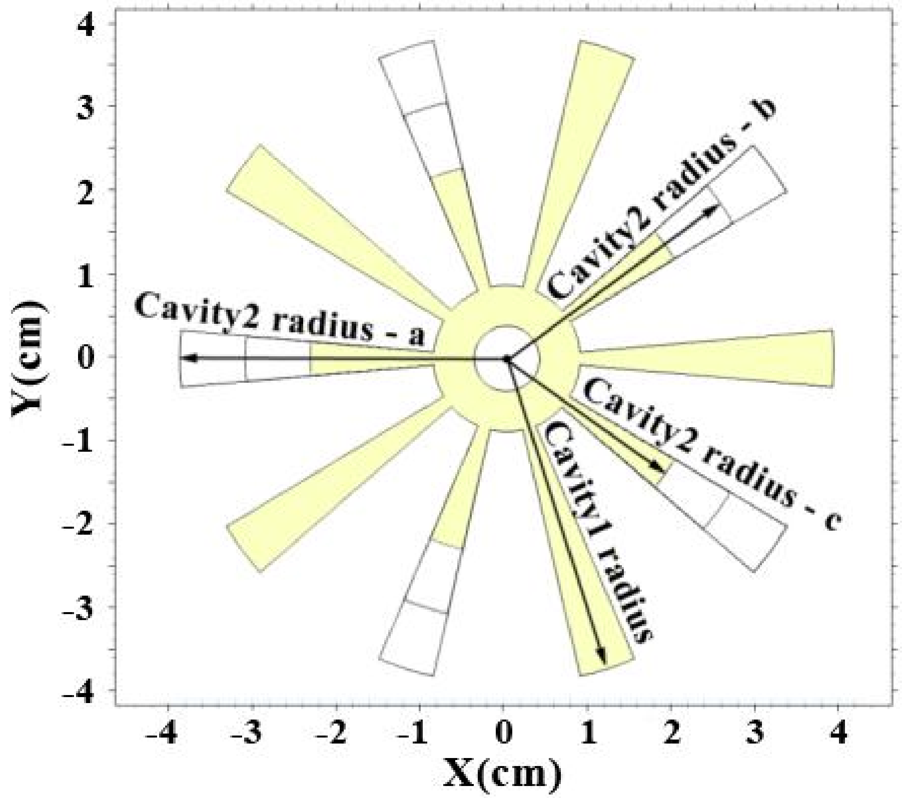

A **conventional magnetron** employs side cavities with equal radii but integrates some straps for mode separation.

Scaling of a conventional magnetron model parameters to a **2.45 GHz rising-sun magnetron model** from finite element analysis.

Simulation Results and Discussion

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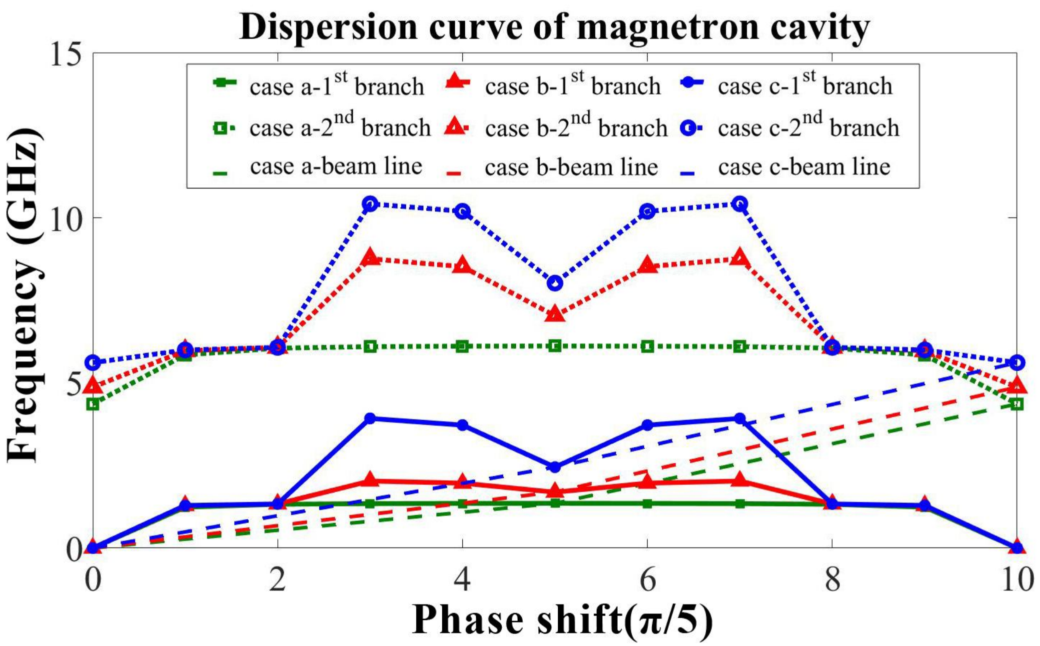
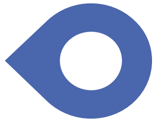




Case c:

a further reduction of the cavity2 radius to 1.76 cm.

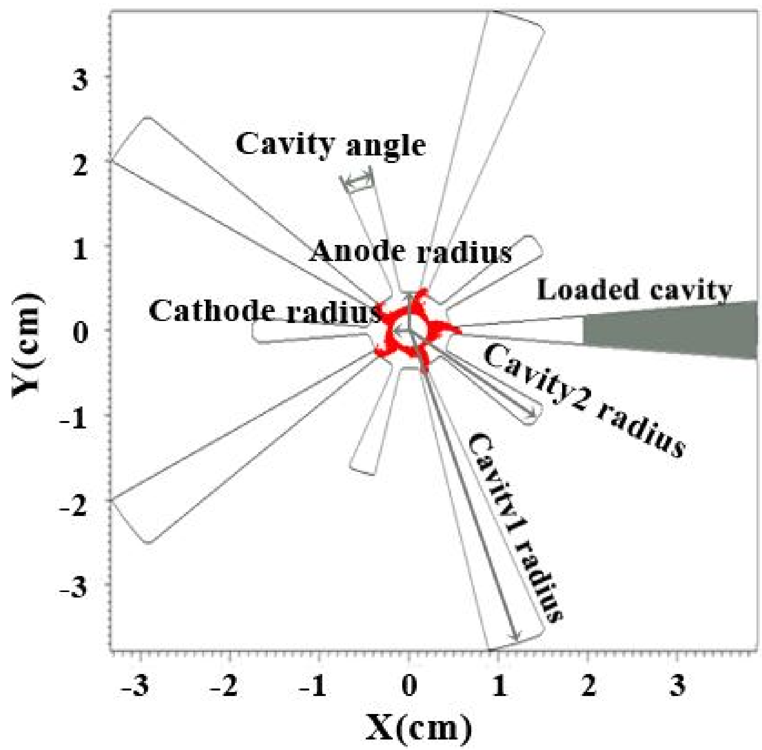
This dispersion curves of conventional magnetron and rising sun magnetron cavities shows the **rising sun configuration** can provide **enough mode separation** for a magnetron operation without losing the axial symmetry, not as in conventional magnetrons.

Simulation Results and Discussion

Schematic of a 10-vane field emission based rising sun magnetron in the VSim CFDTD PIC simulation with **indicated geometry parameters** and an **RF output loading**.

TABLE II. Rising sun magnetron dimensions in the simulation

Cathode radius (cm)	*Anode radius (cm)*	*Cavity1 radius (cm)*	*Cavity2 radius (cm)*	*Angle (degree)*
0.2	0.45	3.89	1.76	10.0



Simulation Results and Discussion

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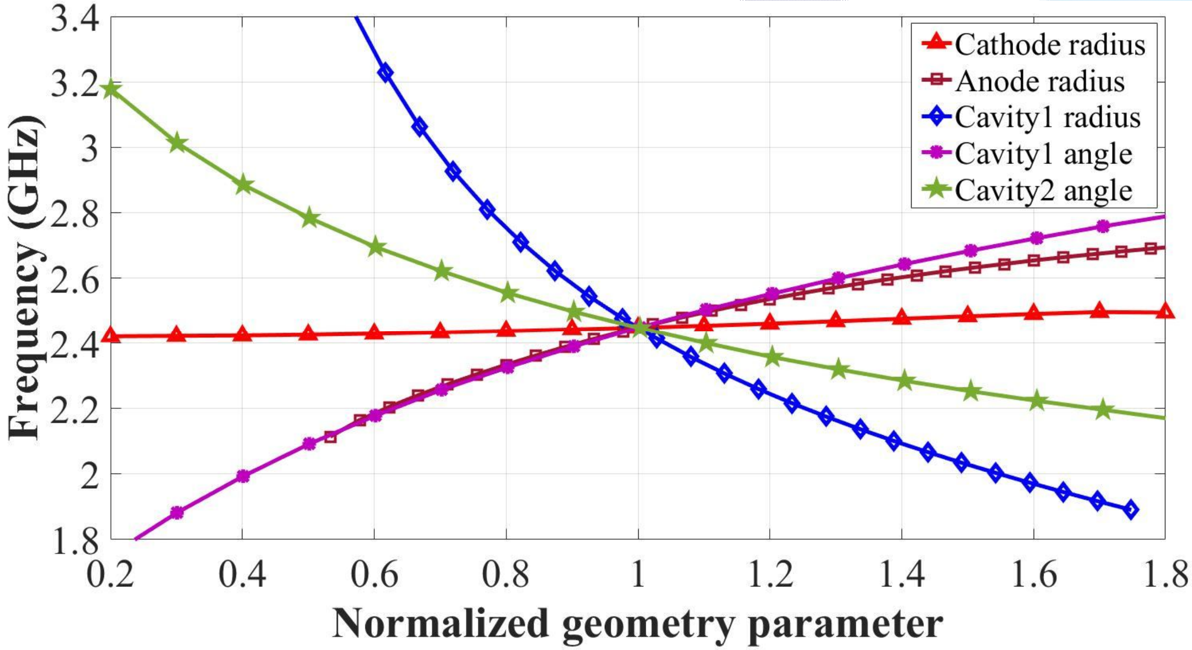

Frequencies of **π mode** have been calculated as functions of normalized geometry parameters of the rising sun magnetron model using finite element method.

The **corresponding geometry parameters** of the rising sun magnetron model in normal scale are 0.45 cm, 3.89 cm, and 0.174 radian for the anode radius, the cavity1 radius, and both angles of cavity1 and cavity2.

Simulation Results and Discussion

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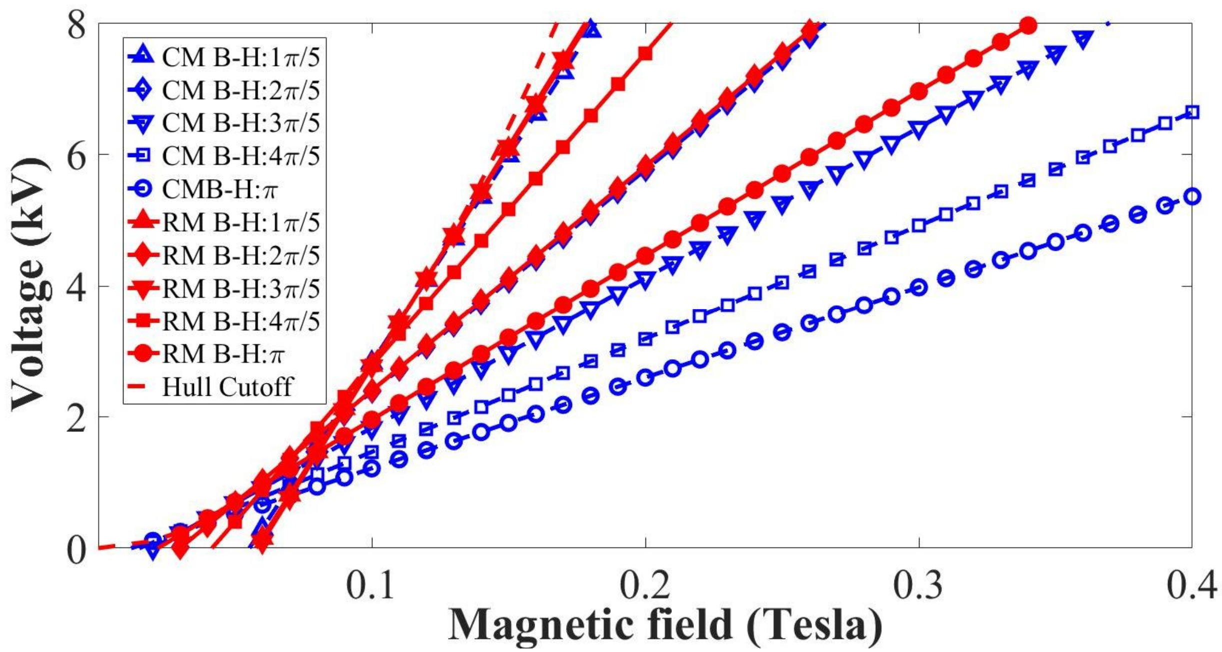

The Hull cutoff curve and Buneman-Hartree resonance curves of 1/5pi-mode, 2/5pi-mode, 3/5pi-mode, 4/5pi-mode and **pi-mode** for conventional model (CM) and rising sun model (RM).

Obviously, compared with the pi-mode of the conventional model, the **pi-mode** of the rising-sun model can be more **clearly distinguished and separated** from the other four modes.

Simulation Results and Discussion

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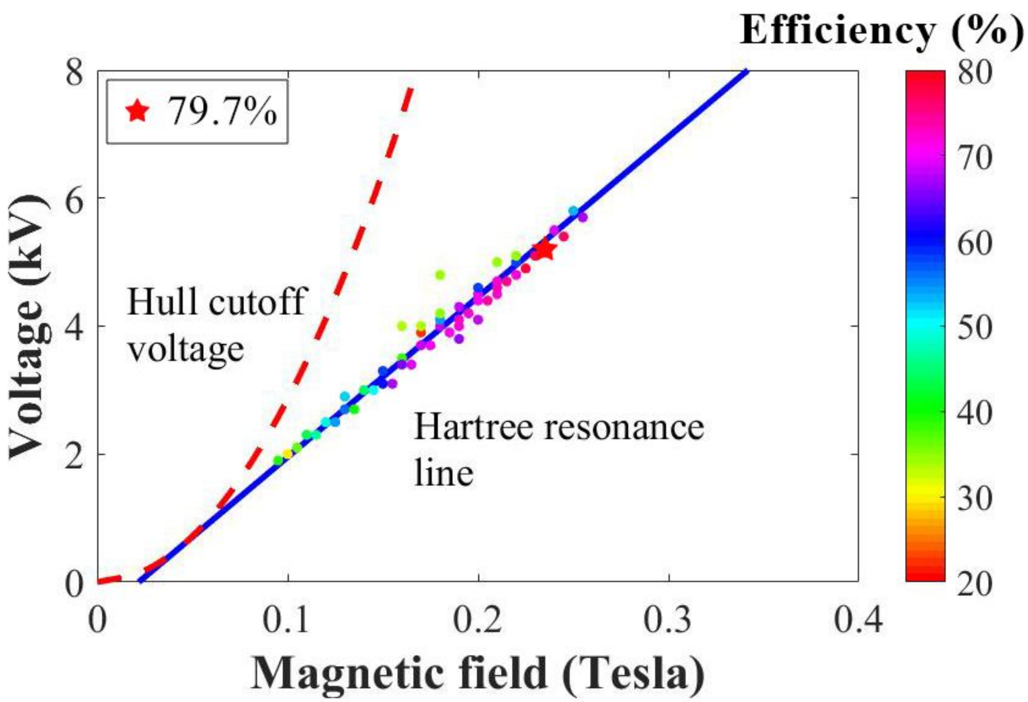


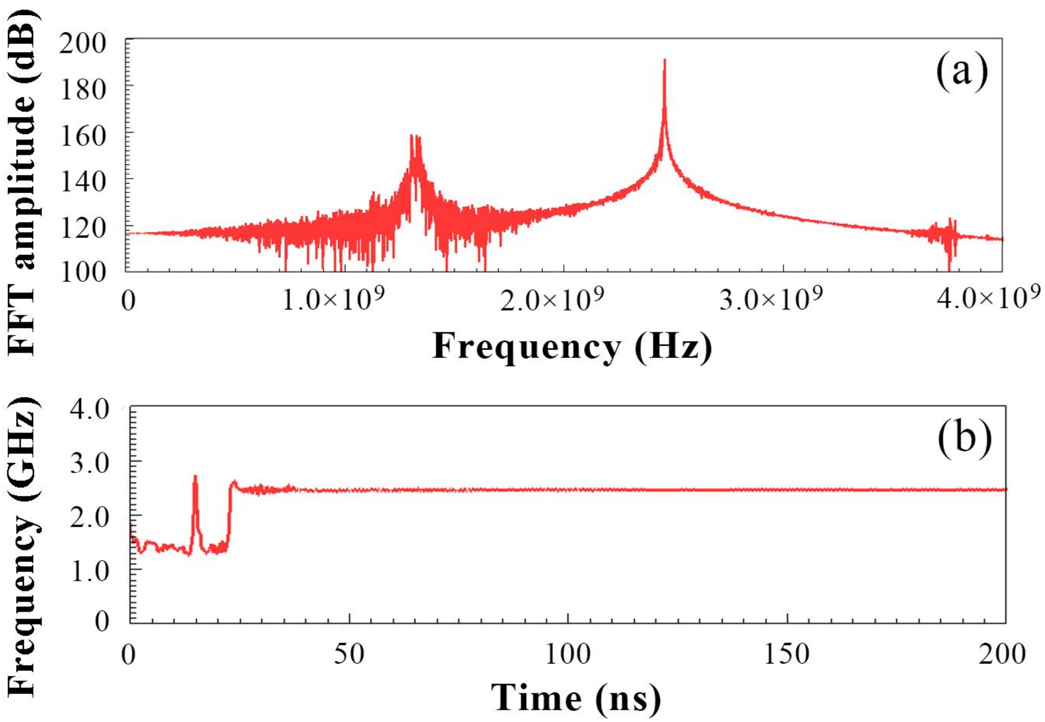
$$\bar{V} = \bar{B}\beta - (1 - \sqrt{1-\beta^2}), \quad \text{(Buneman-Hartree)}$$

$$\bar{B} = \sqrt{2\bar{V} + \bar{V}^2}, \quad \text{(Hull cutoff)},$$

A lot of simulation runs have been performed to find **a good operating point** of the rising sun magnetron for an optimization of the output power and efficiency.

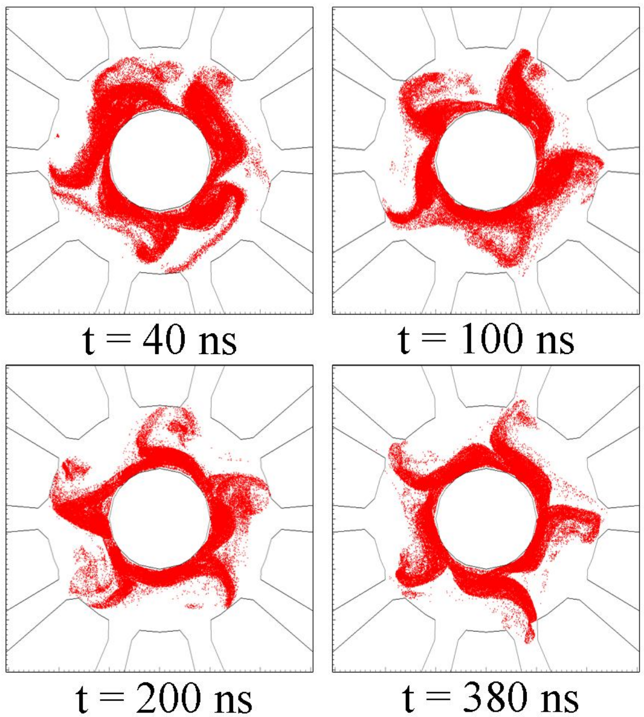
B-V map of operating conditions of the 2.45 GHz rising-sun magnetron model with the corresponding **Hull cutoff** and **Buneman-Hartree resonance** curves indicated.

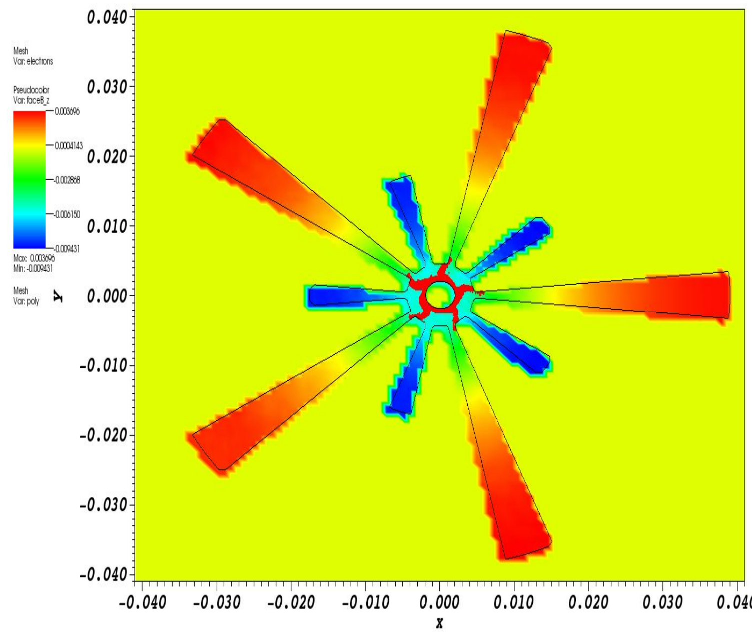
Simulation Results and Discussion



(a) FFT, over entire simulation time, of the cavity1 voltage of the field emission based rising sun magnetron and (b) resonant frequency versus time showing the start-up time at 40 ns for the device from the CFDTD PIC simulation.

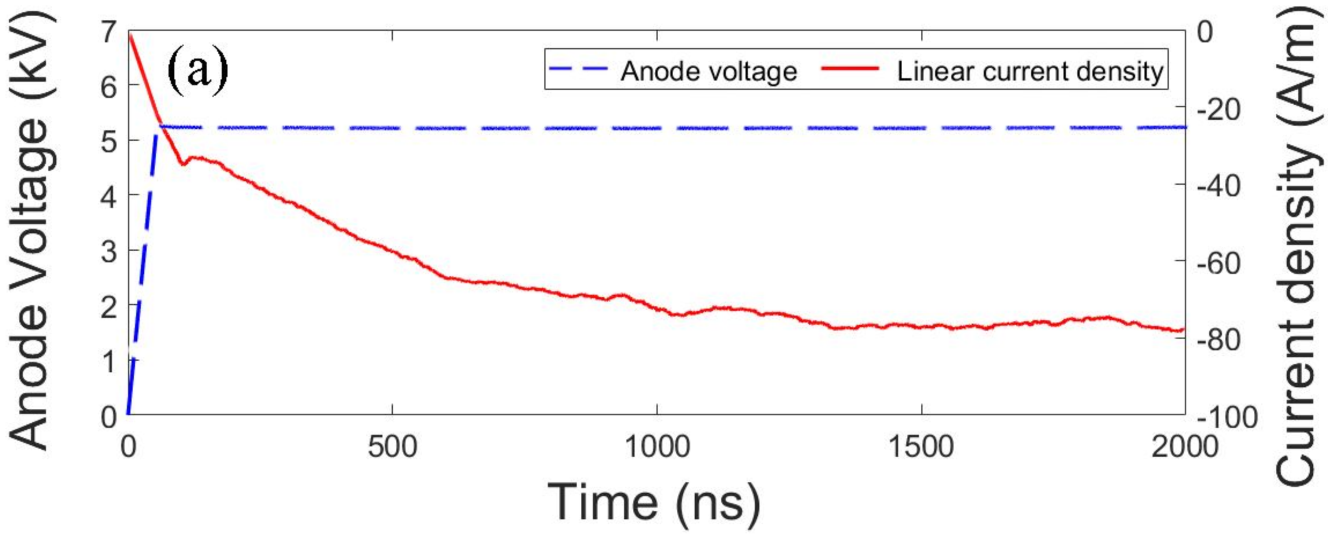
Simulation Results and Discussion





Screen shots of **electron clouds** at different time from the 2-D CFDTD PIC simulations of the rising sun magnetron at V_{ca} =5.2 kV, B= 0.235 T, and J_e= 200 A/m.

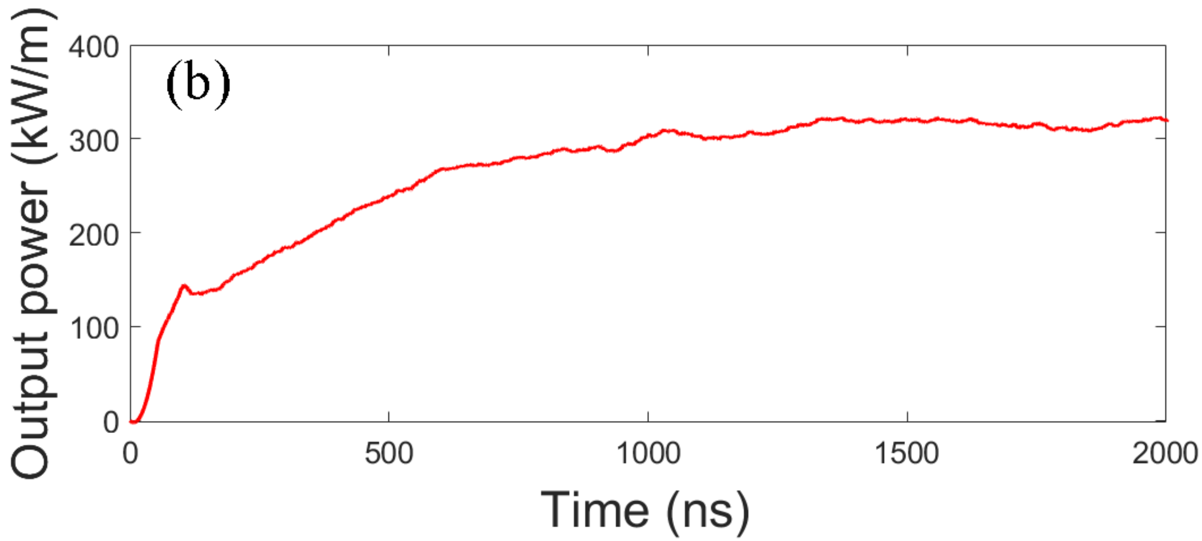
Simulation Results and Discussion



After the simulation is stable, the anode voltage value (blue dashed line) is stabilized at **5.2 kV**;

The linear anode current density (red solid line) is determined to be about **75.67 A/m** by averaging the anode current from the simulation over a period of 1,000 ns after the oscillation is stable.

Simulation Results and Discussion



Calculated by **energy conservation** from the 2-D CFDTD PIC simulation.

Linear input power density:
393.48 kW/m

Linear output power density:
313.4 kW/m

Efficiency:
79.7 %

Simulation Results and Discussion

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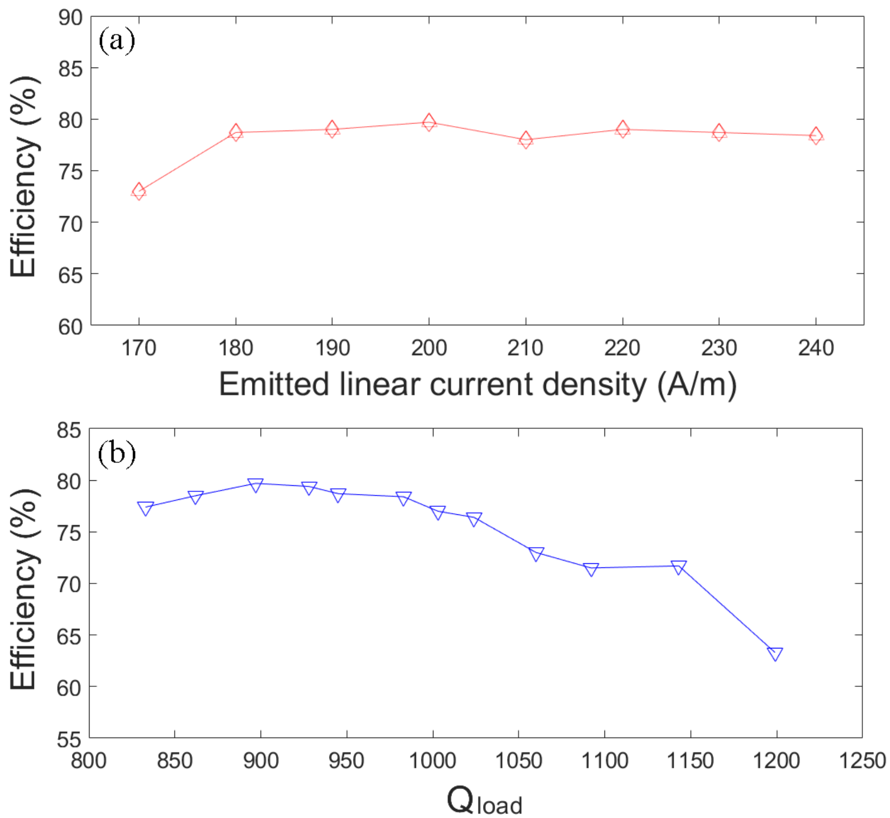

· Verify that it is optimal case

(a) By varying the emitted linear current density while keeping other values fixed, the optimal case is obtained;
(b) The efficiency as a function of the cavity loading (Q_{load}).

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3-D Design

In this design, the current density is about **0.602** A/cm^2, which is achievable with a field emission array or cold cathode under the maximally achievable current density demonstrated experimentally. In this case, the output power is estimated to be ~**3.13** kW.

A feasible design for **industrial applications**

Simulation Results and Discussion

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JVST B
Journal of Vacuum Science & Technology B
ARTICLE
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Design and development of field emission based magnetron for industrial applications using conformal finite-difference time-domain particle-in-cell simulations

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ABSTRACT

The magnetron is a high-efficiency high-power vacuum tube that generates microwaves based on the interaction of a stream of moving electrons under crossed electric and magnetic fields with a series of open coupled cavity resonators. They are widely used as a low-cost microwave source for industrial heating. Traditionally, a thermionic cathode is used as the electron source and a heater is needed to increase the temperature of the cathode up to about 1000 K. In this work, a field emission-based magnetron has been investigated for industrial applications as an easier and more robust configuration. The design and development were performed using a conformal finite-difference time-domain particle-in-cell simulation as implemented in the VSim code. A rising-sun configuration has been optimized and the corresponding operating condition has been determined to achieve an efficiency of up to ~80%. The rising-sun magnetron operating at a frequency of 2.45 GHz can give an output power of 3 kW, serving as a good replacement of existing industrial magnetrons.

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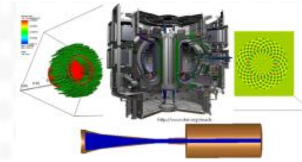
Summary



•The design and simulation study of a field emission-based rising-sun magnetron has been conducted using a 2D CFDTD PIC simulation as implemented in VSim.

•For industrial applications, the rising-sun magnetron cavity has been optimized to 2.45 GHz after considering geometry and cavity loading effects. The current density is about 0.602 A/cm^2, which is achievable with a field emission array or cold cathode under the maximally achievable current density demonstrated experimentally.

•From the hot test simulation results, it is demonstrated that a preliminary design after the optimization of an operating point would give a higher output power and achieve a high efficiency of about 80%.

•According to the achievable current density of FEAs, the field emission-based rising-sun magnetron operating at 2.45 GHz and >3 kW is determined for industrial applications. The fabrication and assembly can be greatly simplified compared to a conventional strapped magnetron with a thermionic cathode.

THANK YOU