Particle-In-Cell (PIC) Simulation of Spatial-Harmonic Magnetron (SHM)

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Abstract: *RF Vacuum Electronic Devices (RF VEDs) have been the most promising milestones for radio-wave and microwave generation at high power and high frequencies for decades. Spatial Harmonic magnetrons (SHMs) with cold secondary emission cathodes have proved to be an efficient solutions to the viability of magnetrons at high frequency. The paper presents a 3-D Particle in Cell (PIC) simulation of a D-Band (140 GHz) SHM using CST particle studio (CST-PS).*

Keywords: Spatial Harmonic Magnetrons, Compact Terahertz devices, 3D Particle-In-Cell Simulation, Beam-wave interaction, CST Particle Studio.

I. Introduction

Spatial Harmonic Magnetrons (SHMs) have been a technical breakthrough in the development of a variant of magnetron, utilizing a spatial harmonic of the RF field of a non-π (usually a π/2 mode or a neighboring one) for its operation [1]. These magnetrons have facilitated various advantages of increased dimensions of resonant system even at higher frequencies, increased mode separation, reduction of dc magnetic field, thermal and operational stability with extended lifetime using cold cathodes [2]. Vehicle guidance system, meteorological and navigational high resolution radars, environmental monitoring systems, desktop charge particle accelerators, compact terahertz (THz) devices for chemical and biological reagents are some of the possible applications for such high frequency magnetrons [3]. The paper introduces a brief review in section I. The 3-D PIC simulation details of a D-band (140 GHz) SHM is summarized in section II. Section III contains the simulation results and discussions. Section IV concludes the paper.

II. Simulation & Analysis

Single harmonic approximation approach [4] is used to find the initial geometrical parameters of a vane type anode of the designed SHM. On the finalization of the anode structure and its dimensional parameters summarized in Table.1, a simulation model is designed in CST microwave studio [5]. Later a cold secondary emission (CSE) cathode, end caps, an iris coupled $\lambda_g/4$ output section and a WR-6 waveguide is added to complete the SHM simulation model. The SHM utilizes a CSE cathode which requires the modelling of suitable secondary emission coefficient (δ) (Fig.2). This is done by coding eq.1, 2, 3 in MATLAB obtained from various secondary emission models [6]. In addition the operating voltage and the applied magnetic field deciding the operating point is obtained by solving Hull- Hartree equation (eq.4) in MATLAB (Fig.3). These inputs (simulation model, secondary emission characteristics, Operating voltage and magnetic field) are then given to the CST-PS. The nonlinear beam wave dynamics in CST particle studio reveals interesting insight into the interaction mechanism of spatial harmonic magnetrons.

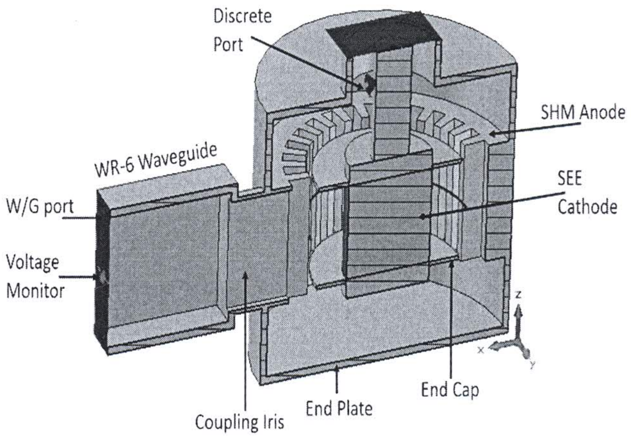


Figure 1: Simulated Model of SHM in CST-Particle Studio.

$$\delta_r = 0.47(1 - e^{-2.3\omega_o}) \quad (1)$$

$$\delta_{ts} = \begin{cases} \sqrt{5\omega_o} & , \quad \omega_o < 0.3 \\ 1.39 - 0.8(0.8 - \omega_o)^2 & , \quad 0.3 \le \omega_o < 1 \\ 1.57e^{-0.24\omega_o} & , \quad \omega_o \ge 1 \end{cases} \quad (2)$$

$$\delta = \delta_r + \delta_{ts} \quad (3)$$

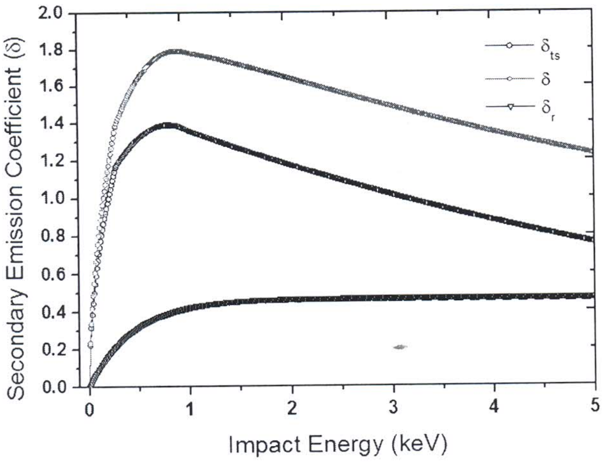


Figure 2: Secondary emission yield for platinum versus impact energy for normal incidence.

$$V_{oc} = \frac{eB_o^2 r_a^2}{8m}\left(1 - \frac{r_c^2}{r_a^2}\right)^2 \quad (4)$$

$$V_{th} = \frac{0.942 * r_a^2}{n\lambda}\left(1 - \frac{r_c^2}{r_a^2}\right) B - \left(\frac{10100 * r_a^2}{(n\lambda)^2}\right) \quad (5)$$

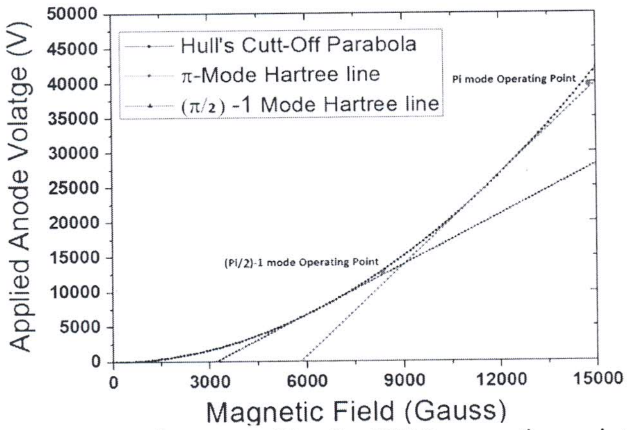


Figure 3: Hull-Hartree Plot for SHMs operating point.

Table 1: Parameters of SHM resonator block

Parameters	Value (mm)
Anode Height	1.50
Cathode Radius	0.70
Anode inner Radius	1.30
Vane depth*	1.654
Number of Resonators	28

III. Results and Discussions

The SHM dispersion profile by simulations (CST-MWS) is shown in Fig.3. The mode numbered (mode number n=22) is the first backward harmonic of $\pi/2$ mode (i.e. $(\pi/2)$ -1 mode). This is the operating mode of SHM. The mode separation between the $(\pi/2)$ +1, $(\pi/2)$, and $(\pi/2)$ -1 mode is summarized in Table.2.

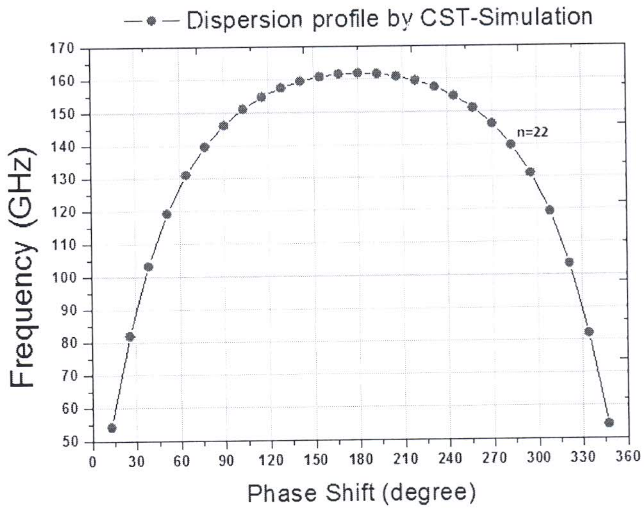


Figure 4: Hull-Hartree Plot for SHMs operating point.

Table 2: Mode separation in SHM

Mode	Frequency (GHz)	Mode separation (GHz)
$(\pi/2)$ +1	151.19	4.89
$(\pi/2)$	146.30	-
$(\pi/2)$ -1	139.78	6.52

The output Power is calculated using eq.6 where a: WR-6 waveguide width, b: WR-6 waveguide height, Z_o is wave impedance, V_{out} is voltage at output port, fc is Wr-6 cut-off frequency, and f is operating frequency.

$$P_{out} = \left(\frac{a}{4bZ_o}\right) V_{out}^2 \sqrt{1 - \left(\frac{f_c}{f}\right)^2} \quad (6)$$

Fig.5 shows the Voltage signal growth and its power spectral density which reveals the hot resonant frequency is 137.32 GHz. The temporal growth of the anode current and output power is shown in Fig.6. The anode current and output power starts to build up at around 1 ns and saturates at around 8 ns. The saturated current and power values are 5.6 A and 1.40 kW. The SHM provides an efficiency of 2.19%. The output parameters of the designed SHM are summarized in

Table.3. Fig. 7 shows the Particle view of the Spoke formation in (π/4 -1) mode and its zoomed view.

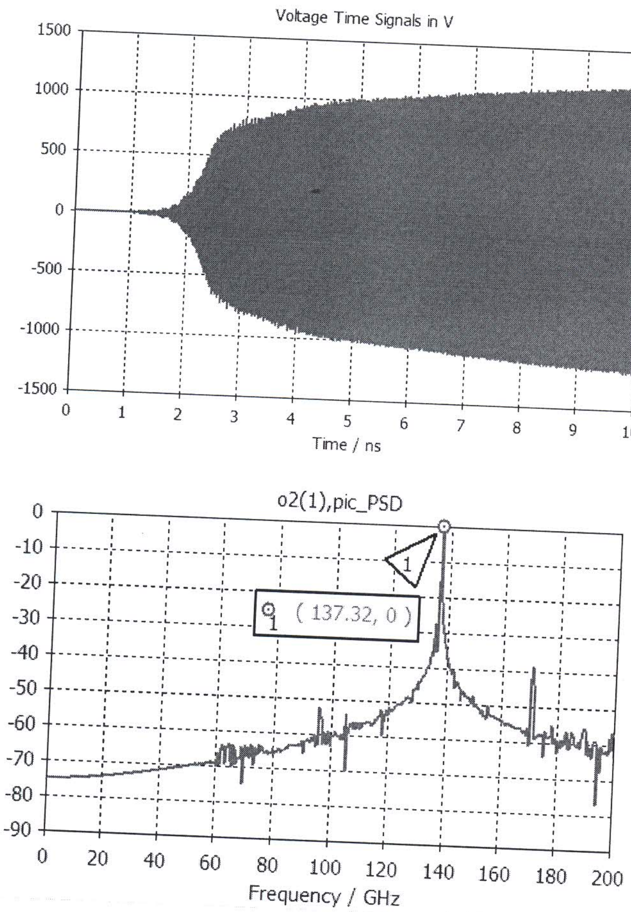
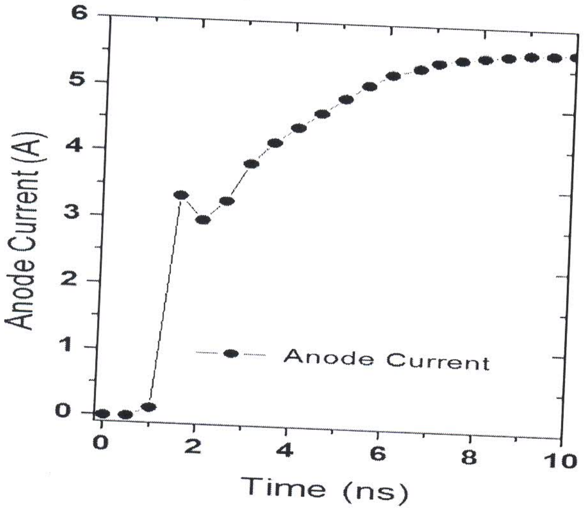


Figure 5: Voltage signal growth at output and its Power spectral density.



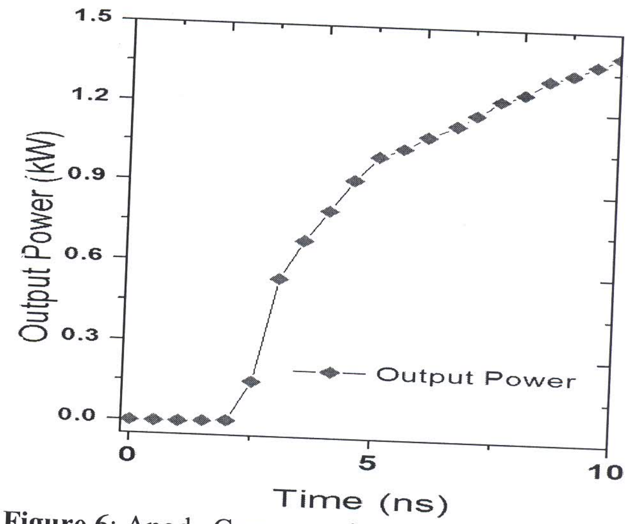


Figure 6: Anode Current and Output Power plots.

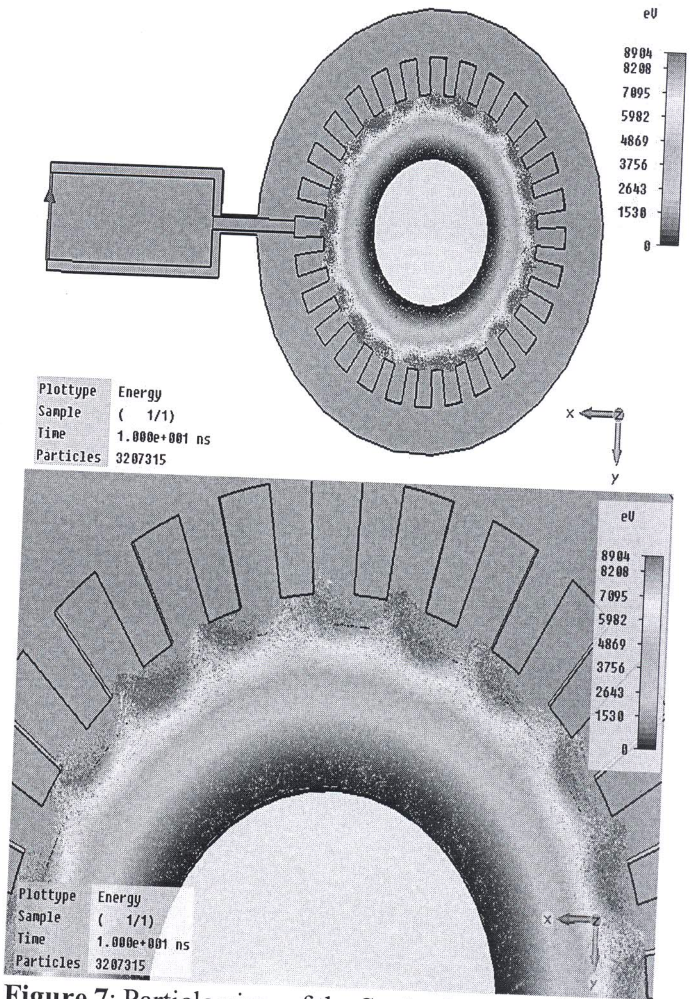


Figure 7: Particle view of the Spoke formation in (π/2 -1) mode and its zoomed view.

Table 3: Output Parameters of designed SHM.

Parameters	CSIR-CEERI SHM
Output Power (kW)	1.40
Anode Voltage (kV)	11.30
Anode Current (A)	5.6
Magnetic Field (G)	7900
Overall Efficiency (%)	2.19

Conclusions

The simulation reveals the PIC study and analysis of beam wave interaction in SHMs. The space charge cloud shows the formation of electron spokes (representing the beam wave interaction) near the anode surface. The designed SHM provides 1.40 kW power with an efficiency of 2.19% at around 140 GHz. The work will be extended to raise the power level and improve efficiency of the designed SHM.

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