PIC SIMULATION OF THE COAXIAL MAGNETRON FOR LOW ENERGY X-BAND LINEAR ACCELERATORS

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Abstract

For the miniaturization of low energy linear accelerators, X-band pulsed magnetron with a stable output of 1.5 MW peak power is being developed, and this paper presents the 3D particle-in-cell (PIC) simulation of an X-band coaxial magnetron. In simulation, a pattern of N/2 spokes of the time evolved electron flow shows the generation of π-mode, and the mode competition in the startup process manifests itself in the spectra.

INTRODUCTION

Low energy electron linacs have been widely used in nondestructive testing, radiation therapy and radiation processing. Extremely small accelerator structures with high shunt impedance are needed for medical and industrial applications. X-band electron linac can meet these requirements.

The Accelerator Laboratory at Tsinghua University started R&D of X-band standing wave(SW) electron linacs since 1991, and have developed a 6 MeV X-BAND SW accelerating guide in 2004 [1]. However,the development of the X-band linac subjects to the X-band microwave power sources. In order to reduce side and weight of accelerator, magnetron is adopted as microwave power source for X-band linac, so 1.5MW X-band coaxial magnetron is being developed in the Accelerator Laboratory.

Magnetron is known as a successful device with high-efficiency in the centimeter wavelength. However the non-linear beam-wave interaction mechanism of magnetron is not well understand [2]. Recently, Simulation of magnetron has been developed by using particle-in-cell(PIC) code, such as MAGIC, 3DPIC, QUICKSILVER and so on [3, 4, 5]. Many structures such as multi-cavity system, rising-sun system, strapped system are modeled, and the 3D simulation studies were found to be in good agreement with experimental results.

In this paper, a 3D model of X-band coaxial magnetron is simulated , in which time evolved spoke formation and power extracted from the output port indicate the generation of π-mode.

SIMULATION MODEL DESCRIPTION

A coaxial magnetron is composed of an inner and an outer resonant system. The inner system includes a plurality of anode vanes mounted on a cylindrical wall member which is normally designed to operate in the π mode and around a cathode. The outer system is presented as a coaxial cavity which oscillates in the TE_{011} mode. This two systems are coupled by the means of the sew. The high Q outer cavity made the magnetron with high frequency stability, so coaxial structure was wildly used since 1960s. The two sectional views of the magnetron model are depicted in Fig.1. The microwave power is extracted from the outer cavity to the rectangular waveguide through the coupling slot and the impendence transformer. In the computer modeling, the impendence transformer and ceramic window are neglected for simplicity. Two attenuators made by microwave absorbing material are fixed to suppress spurious modes.

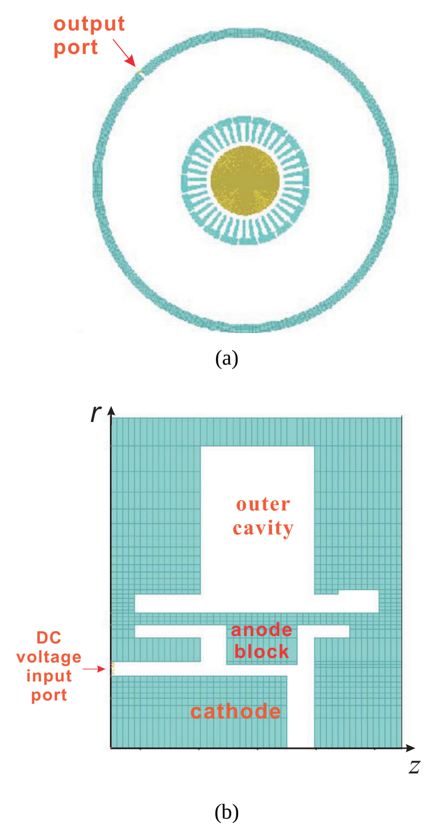

Figure 1: (a)Sectional view of the coaxial magnetron in the $r\theta$ plane. (b) Sectional view of the coaxial magnetron in the rz plane.

According to the Hull cutoff and Buneman-Hartree resonance conditions, the magnetron oscillation region is obtained, as shown in Fig.2. The upper line shows the Hull

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cutoff conditions above what there is no oscillation, because the electron will directly pass through the DC gap without interaction with the RF field. On the Buneman-Hartree line, the drift velocity of the electron is equal with the angular phase velocity of the π-mode, then an electron bunching is formed due to accelerating and decelerating phases of the electron clouds. So the magnetron must operate between this two lines [6]. In Fig.2, the operating point on which the simulations are performed is also marked as the DC voltage of 41kV and an axial magnetic field of 4800Gs.

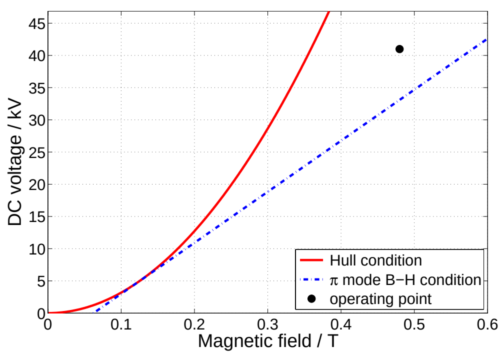

Figure 2: Hull cutoff condition and Buneman-Hartree resonance condition of the magnetron

HOT TEST SIMULATION RESULT

Fig.3 shows the applied DC voltage and the predefined emission current of the cathode.

The inner and outer conductors compose a coaxial transmission line. The DC voltage is applied as a TEM mode wave traveling through this transmission line. Because of the open end of this line, the voltage is applied as half of the required value. The rise time of the voltage is set as 2ns.

Magnetron often operates with both thermionic and secondary emission. In this paper, the current density of the emission zone is predefined as $J = 22.83\text{A}/\text{cm}^2$ and the rise time as 10ns. The total emission current from the cathode is about 140A. Secondary emission on the cathode surface is not included in the simulation.

The uniform magnetic field is applied in the axially direction.

The PIC simulation time is defined as 400nanoseconds. Time evolved electron distribution at 100, 200, 300, and 400 ns are plotted in Fig.4. At 100, 200ns, there is no oscillation in the interaction space. After the oscillation started, electron spokes formed. The number of spokes in the electron flow is determined by the operating mode. As shown in Fig.4, the 20 spokes are formed azimuthally around the cathode, so the mode is so-called the π-mode when the inner system includes 40 vanes. This proves the π-mode oscillation in the magnetron.

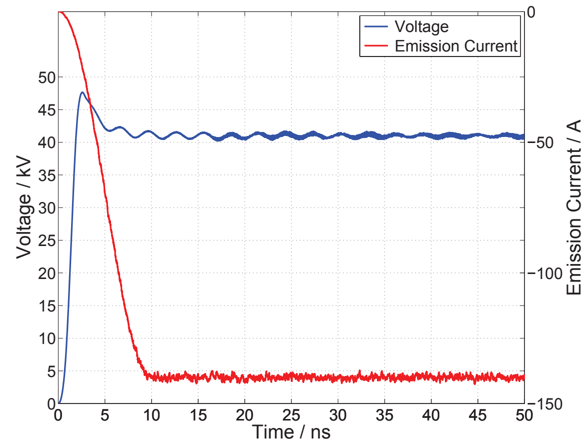

Figure 3: Applied DC voltage and emission current from the cathode

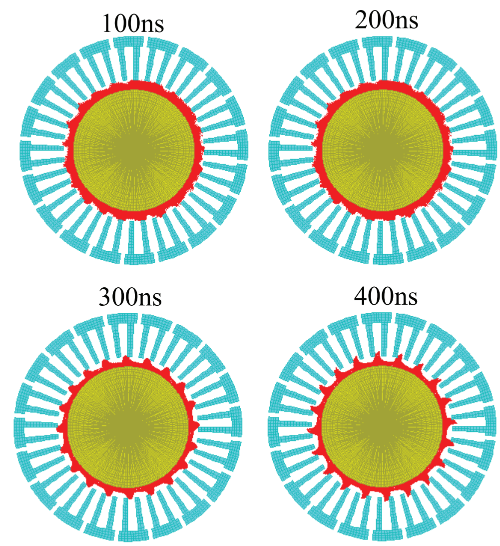

Figure 4: Time evolved electron distribution at 100ns, 200ns, 300ns, 400ns

Fig. 5 shows the azimuthal electric field at a point in the outer cavity varying with time from 0ns to 400ns. As shown in the figure, there is strong mode competition before 200ns, and the electric field get Saturation after 360ns. From the Fourier transformation of this time-varying electric fields, the frequency of π-mode oscillating is obtained as about 9.303GHz. There are also several unknown modes with frequency of 11.320GHz, 11.440GHz and 7.960GHz, which is denoted in Fig. 6. Further simulation need to been done on these modes.

The power exacted from the slot on the outer cavity wall is plotted in Fig.7. The anode current is also presented. The current reaches the steady state of about 75A at 260ns, and the output power becomes stable of 1.61MW after 360ns. As shown in the figure, the output power rises rapidly after the anode current reached steady state.

The power being dissipated on the anode and the cathode is obtained from calculating the kinetic energy of electron

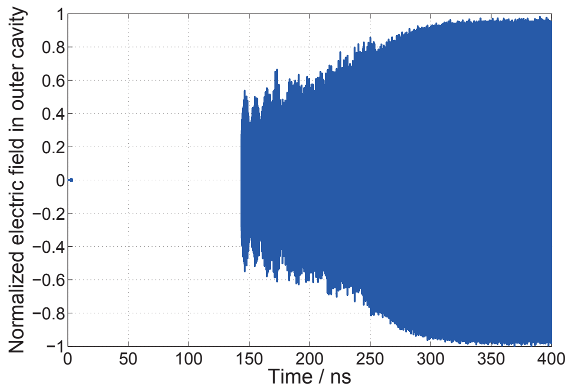

Figure 5: Temporal azimuthal electric field in the outer cavity

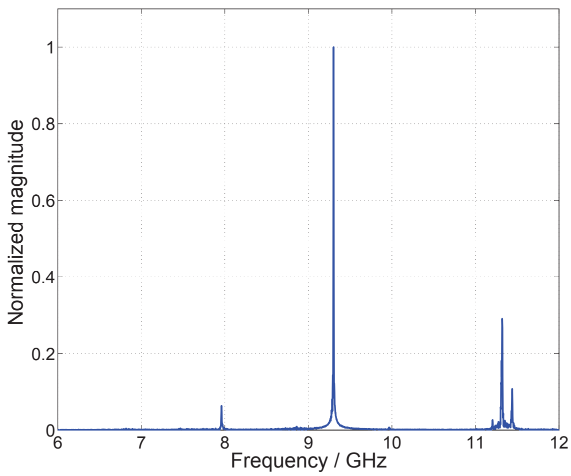

Figure 6: A frequency spectrum obtained from Fourier transformation of the time-varying electric fields

destroyed on them. Meanwhile, the microwave power dissipated on the attenuator and the copper cavity wall is also recorded. Then the efficiency is obtained. The electron efficiency is about 59.2%, and the circuit efficiency about 85.8%. The total efficiency exceeds 50%, which can meet the design requirements.

Table 1: Power distribution and efficiency

Parameters	Values
Power	
Total	3.16 MW
Dissipated on the anode	1.20 MW
Dissipated on the cathode & endcaps	0.09 MW
Absorbed by the attenuator	0.04 MW
Lost on the cavity wall	0.22 MW
Output	1.61 MW
Efficiency	
Total efficiency	50.8%
Electron efficiency	59.2%
Circuit efficiency	85.8%

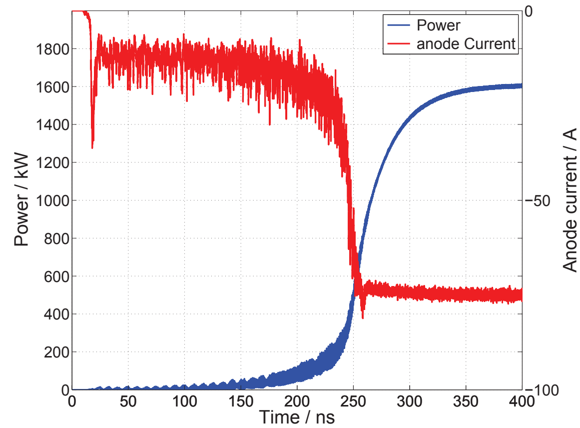

Figure 7: Temporal output power and current collected on the anode

CONCLUSION & FUTURE WORK

In this paper, an X-band coaxial magnetron is modeled by PIC simulation. Electron spoke formation is obtained in the simulation. N/2 spokes and Fourier transformation of the electric field indicate that the π-mode oscillates at 9.302GHz. Mode competition in the startup process is also observed.

In this paper, we predefine the cathode current density. But the magnetron often operate with thermionic and secondary emission, so further work should to be done to improve the model.

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