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Comparative research on three types of coaxial slow wave structures

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This paper studies three types of coaxial slow wave structures (SWSs): (1) with ripples on both the inner and outer conductors; (2) with ripples on the outer conductor and smooth on the inner one; and (3) with ripples on the inner conductor and smooth on the outer one. The frequencies, coupling impedances, time growth rates and beam-wave interaction efficiencies of the three types of coaxial SWSs are obtained by theoretical analysis. Moreover, the relativistic Cerenkov generators (RCGs) with the three types of coaxial SWSs are simulated with a fully electromagnetic particle-in-cell code, and the results verify the theoretical analysis. It is proved that the RCG with double-rippled coaxial SWS has the highest conversion efficiency and the shortest starting time.

Keywords: relativistic Cerenkov generator, coaxial slow wave structure, dispersion characteristics, particle-in-cell simulation

PACC: 5235, 5240, 5265, 4110H

1. Introduction

Slow wave structures (SWSs) are the most important parts of high power microwave devices of Cerenkov-type. There are various SWSs,[1−15] and among them coaxial SWSs are widely used due to the potential of increasing the beam-to-microwave conversion efficiency.[1−10] There are several types of coaxial SWSs: (1) both the inner and outer conductor walls are varying periodically;[1−6] (2) only the outer conductor wall is varying periodically, whereas the inner one is smooth;[7,8] (3) and only the inner conductor wall is varying periodically, whereas the outer one is smooth.[9,10] However, there has not been a comparative research on the SWSs yet. Thus, we compared the three types of coaxial SWSs by means of theoretical analysis and particle-in-cell (PIC) simulation in this paper.

2. Theoretical analysis

First we consider the coaxial SWS shown in Fig.1. It consists of a coaxial cylindrical waveguide with the inner and outer wall radii $r_{\rm w1}$ and $r_{\rm w2}$ varying sinusoidally according to the relations

$$r_{\rm w1} = r_1 + r_{01}\sin(h_0 z + \theta)\,,$$

$$r_{\rm w2} = r_2 + r_{02}\sin(h_0 z)\,, \tag{1}$$

where r_1 and r_2 are the inner and outer mean radii, r_{01} and r_{02} are the inner and outer corrugation amplitudes, respectively, $z_0 = 2\pi/h_0$ is the length of the corrugation period, and θ is the relative phase between the inner and outer corrugations.

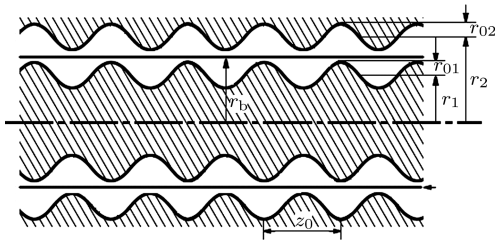


Fig.1. The coaxial SWS and beam model. An infinitely thin electron beam at $r_{\rm b}$ within a perfectly conducting corrugated-wall waveguide.

In this study, we will concentrate three types of coaxial SWSs as follows:

type I: $z_0 = 1.6\,{\rm cm}$, $r_1 = 0.75\,{\rm cm}$, $r_2 = 1.4\,{\rm cm}$, $r_{01} = r_{02} = 0.2\,{\rm cm}$,

type II: $z_0 = 1.6\,{\rm cm}$, $r_1 = 0.75\,{\rm cm}$, $r_2 = 1.4\,{\rm cm}$, $r_{01} = 0$, $r_{02} = 0.2\,{\rm cm}$,

type III: $z_0 = 1.6\,{\rm cm}$, $r_1 = 0.75\,{\rm cm}$, $r_2 = 1.4\,{\rm cm}$, $r_{01} = 0.2\,{\rm cm}$, $r_{02} = 0\,{\rm cm}$.

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The dispersion curves of above-mentioned coaxial SWSs can be obtained according to the dispersion relations derived in Ref.[6], shown in Fig.2. The lowest two modes of the dispersion curves are quasi-TEM mode and A mode, which are yielded by the coupling of two dominant terms among the Floquet spectra of TEM mode: $f = ck_0/2\pi$ and $f = -c\,(k_0 - 2\pi/z_0)/2\pi$.[16] Here we explain the second mode concisely. The cutoff frequency of the second mode is much lower than that of TM_{01} mode in the coaxial waveguide, i.e., $f_{cTM_{01}} \approx c/2\,(r_2 - r_1) = 23\,\mathrm{GHz}$. So it can not be denoted by TM_{01}, and for convenience we name it A mode, just as in Ref.[16]. From Fig.2, the dispersion curve of quasi-TEM mode for type I is between those of type II and type III, and the highest is for type II.

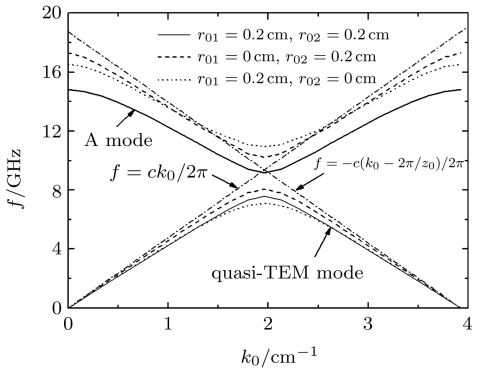


Fig.2. Dispersion curves of three types of coaxial SWSs. The lowest-frequency mode is quasi-TEM mode, and the second is A mode. Also shown are $f = ck_0/2\pi$ and $f = -c\,(k_0 - 2\pi/z_0)/2\pi$.

Since the operation mode is quasi-TEM mode and near the "π" point,[6] the coupling impedances of the -1st and 0th space harmonics R_c^{-1} and R_c^0 of the quasi-TEM mode are both calculated and displayed in Fig.3.

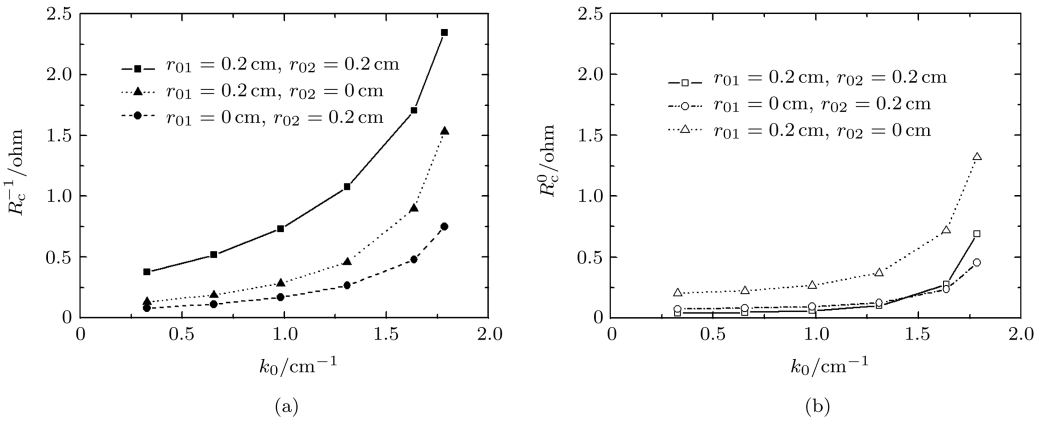


Fig.3. Coupling impedances for (a) the -1st and (b) 0th space harmonics of the quasi-TEM mode.

The impedance R_c^{-1} for the coaxial SWS of type I is the largest, and R_c^0 for type III is maximum. The frequencies and R_c^{-1} and R_c^0 for $10\pi/11$ mode of quasi-TEM mode are listed in Table 1.

Table 1. Frequencies and coupling impedances of three types of coaxial SWSs for $10\pi/11$ mode of the quasi-TEM mode.

Type of SWS	f/GHz	R_c^{-1}/Ω	R_c^0/Ω
I	7.30	2.35	0.69
II	7.78	0.75	0.45
III	6.93	1.53	1.32

The presence of a beam to the coaxial SWS provides the energy source to drive unstable interactions. When instability results ($\omega_i > 0$), the size of ω_i, i.e., the time growth rate, will provide some measure of the strength of the unstable interaction.[17] Figure 4 gives the time growth rates for various types of coaxial SWSs, and the growth rate for type I is much larger than the other two.

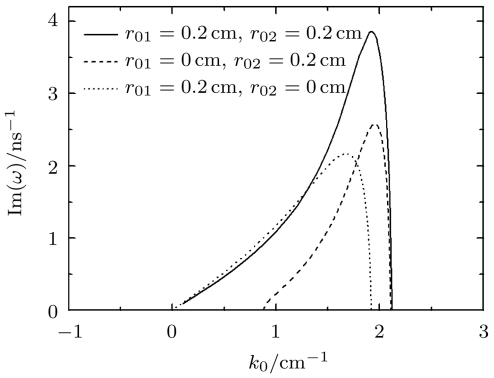


Fig.4. Time growth rates for three types of coaxial SWSs. The beam current, beam radius, and cathode potential are 5.6 kA, 1.075 cm, and 750 kV, respectively.

To obtain the conversion efficiency, we solve the

self-consistent equations of beam-wave interaction in Ref.[6]. Figures 5–7 give the numerical results for the $10\pi/11$ modes of the quasi-TEM modes for the three types of coaxial SWSs, and the efficiency is 39%, 24%, 22%, respectively. As the beam is propagating along the coaxial SWS, the energy of most electrons falls, and the corresponding synchronous wave will be changed from the 0th space harmonic to the -1st one. The SWS with ripples on both the inner and outer conductors can provide the strongest synchronous harmonic of axial electric field, since the coupling impedance of the -1st space harmonic for SWS of type I is the largest, and consequently the efficiency is the highest.

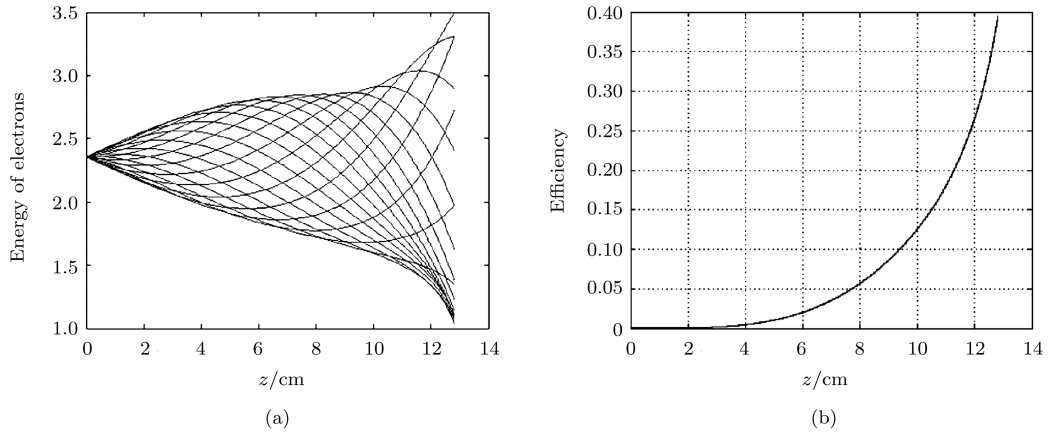


Fig.5. (a) Energy of electrons and (b) efficiency versus axial distance z for the coaxial SWS of type I.

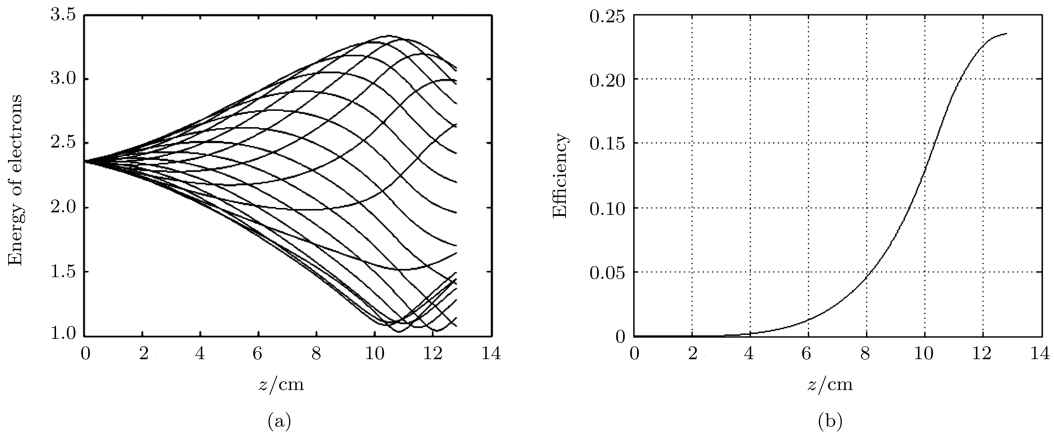


Fig.6. (a) Energy of electrons and (b) efficiency versus axial distance z for the coaxial SWS of type II.

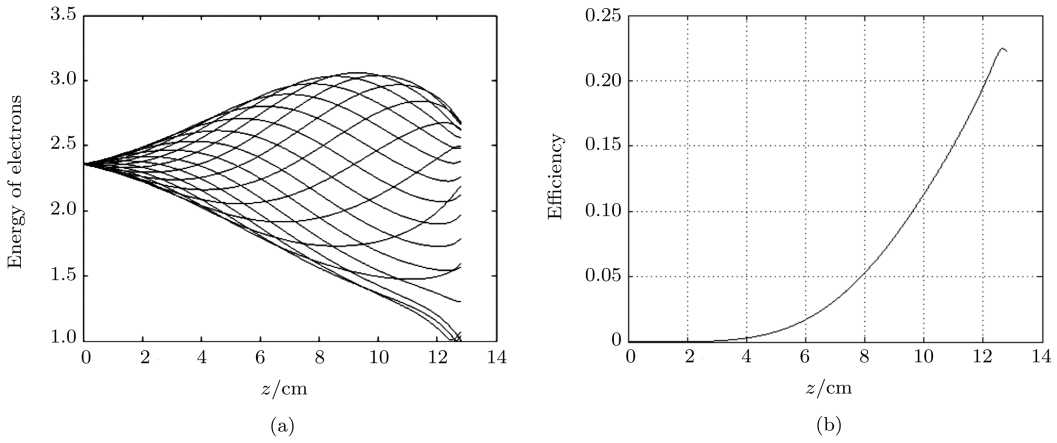


Fig.7. (a) Energy of electrons and (b) efficiency versus axial distance z for the coaxial SWS of type III.

3. PIC simulation

The relativistic Cerenkov generators (RCGs) with three types of coaxial SWS are simulated with a 2.5-D fully electromagnetic PIC code MAGIC.[18] An electron beam is emitted from the annular cathode, and is guided by a magnetic field of 2.6 T through the coaxial SWS and into the inner collector. The inner and outer conductors are connected with an anode foil at the front-end which is used as a reflector and also removes the effect of the DC power at the output port by returning the current of the collector.

Figure 8 illustrates the simulation model and results of the generator with coaxial SWS of type I. The generated microwave power is 1.48 GW, corresponding to an efficiency of 39%, which agrees with the results of theoretical analysis very well. The starting time t_s is very short, less than 4 ns. The frequency is 7.43 GHz, and the frequency spectrum illustrates a high purity.

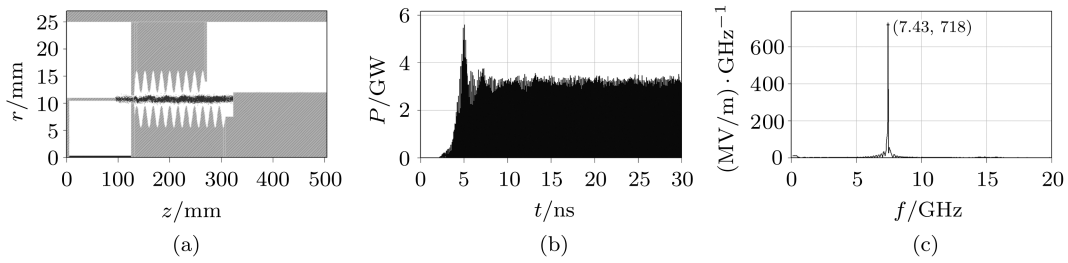


Fig.8. (a) Model of the RCG with coaxial SWS of type I; (b) evolution of power; (c) fast Fourier transform (FFT) spectrum of the radial electric field at the output port.

The Cerenkov generators with coaxial SWSs of types II and III have also been simulated. And the reflection coefficients of the SWSs are optimized by changing the drift length at both ends. The results are presented in Figs.9 and 10. Comparing with Fig.8, we find that the microwave power is much lower, and the starting time is much longer, which are basically consistent with the types dependence of the coupling impedances and the time growth rates, shown in Figs.3 and 4. The frequencies for types II and III are 7.53 GHz and 6.90 GHz, respectively, which also agree with the theoretical results listed in Table 1. The simulations are summarized in Table 2.

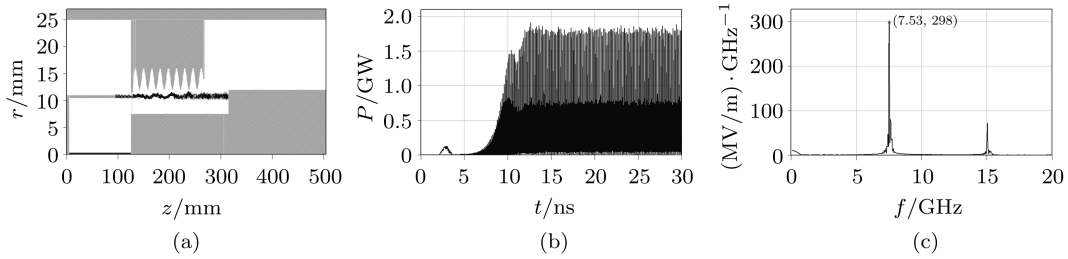


Fig.9. (a) Model of the RCG with coaxial SWS of type II; (b) evolution of power; (c) FFT spectrum of the radial electric field at the output port.

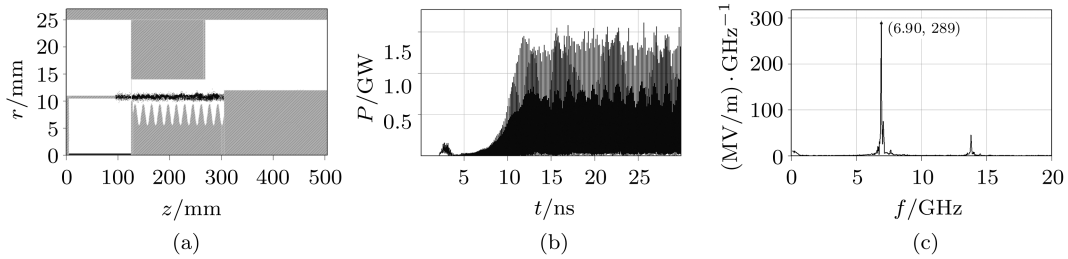


Fig.10. (a) Model of the RCG with coaxial SWS of type III; (b) evolution of power; (c) FFT spectrum of the radial electric field at the output port.

Table 2. Results of the RCGs with three types of coaxial SWSs obtained by simulation.

Type of SWS	P/GW	t_s/ns	η/%	f/GHz
I	1.48	4	39	7.43
II	0.57	10	14	7.53
III	0.48	12	13	6.90

4. Conclusions and discussions

Three types of coaxial SWSs are investigated in theoretical analysis and PIC simulation. Comparing with the coaxial SWS with ripples either on the inner or on the outer conductor wall, we find that the coupling impedance of the 1st space harmonic, the time growth rate, and the conversion efficiency of the coaxial SWS with ripples on both the inner and outer conductor walls are much larger. The particle simulations show that the RCG with double-rippled coaxial SWS has the highest efficiency and the shortest starting time, which agree with the theoretical results very well. Also, the frequencies obtained by simulation are basically consistent with the dispersion curves.

Nevertheless, we only consider the case that the operation mode is quasi-TEM mode here. In some other cases, the operation mode may be different, such as TM_{01} mode,[1] and additional careful consideration will be required.

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