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Novel transit-time oscillator (TTO) combining advantages of radial-line and axial TTO*

Wei-Li Xu(徐伟力), Jun-Tao He(贺军涛)†, Jun-Pu Ling(令钧溥), Li-Li Song(宋莉莉), Bing-Fang Deng(邓秉方), Ouzhixiong Dai(戴欧志雄), and Xing-Jun Ge(葛行军)

College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha 410073, *China*

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A novel transit-time oscillator (TTO) is proposed in this paper. An axial cathode which has been widely used in high power microwave (HPM) source and an extractor with radial feature are adopted. In this way, the inherent advantages of axial and radial TTO, both of which can be utilized as high-quality intense relativistic electron beam (IREB), can be generated and the power capacity is also increased. The working mode is π /2 mode of TM_{01} based on small-signal theory, and under the same energy storage, the maximum electric field in extractor decreases 16.3%. Besides, by utilizing the natural bending of the solenoid, this TTO saves over 60% of the length required by the uniform magnetic field, and consequently reduces the energy consumed by solenoid. The PIC simulation shows that by using 1.0-T decreasing magnetic field generated by the shorter solenoid, 3.37-GW microwave at 12.43 GHz is generated with 620-kV and 13.27-kA input, and the overall conversion efficiency is 41%.

Keywords: axial TTO, radial-feature extractor, larger power capacity, shorter uniform magnetic field

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1. Introduction

Transit-time oscillator (TTO) has many advantages in generating high power microwave (HPM). Compared with other O-type HPM sources, TTO needs a low magnetic field and uses body wave to interact with beams,[1] so generally its size is smaller and thus reduces the possibility of electron bombardment on wall, which is beneficial to obtaining the repeated and long-pulse operation.

A lot of researches have been done on TTO and many valuable results have been achieved.[2,3] What is worth noticing is that inside the axial TTO, the maximum electric field often occurs in the extractor,[3,4] which limited the output microwave power. As frequency goes higher, this problem will become more serious.

To solve the above power handling problem, radial-line microwave devices were proposed and have aroused much interest in HPM generation due to their inherent advantages in increasing power capacity,[5–7] especially in extractor area. Researches have obtained very good results.[6] However, to generate uniform and high-quality intense relativistic electron beam(IREB) experimentally is difficult. It was found that in experiment the radially radiated electron imprint seems dispersive and asymmetric, indicating non-uniform electron emission.[8] Some electrons also did not enter into the slow wave structure (SWS).[8]

Based on the researches above, a novel TTO is proposed in this paper, which combines the advantages of the radial-line and axial TTO. As shown in Fig. 1, adopting the mature technique of generating IREB in axial dimension, we make electrons interact with wave in a partially radial extractor. In this way, higher-quality IREB than that by using those radially radiated TTOs is guaranteed, and in the beam–wave interaction region a weakening space-charge effect and larger power capacity will lead to high efficiency and long-pulse operation.[6]

The rest of this article is organized as follows. in Section 2, the model structure is illustrated. In Section 3 the physics analysis and magnetic field design are demonstrated. The simulation results and analysis are shown in Section 4, and some conclusions are drawn from the present study in Section 5.

2. Model description

The novel TTO is schematically illustrated in Fig. 1. In this TTO, a widely used axial cathode (where the IREB is explosively emitted) is used, in addition, a reflector, a three-cavity buncher and a partly-upward extractor are also adopted. Although this structure is different from axial or radial TTO, the mechanism of microwave generation is very similar. Reflector reflects transverse electric and magnetic field (TEM) mode electronic wave and pre-modulates IREB so that the saturation time is reduced. The three-cavity buncher generates a standing wave to well modulate the IREB, and after passing through the curved drift tube, electrons lose their energy to microwave in extractor. Finally microwave is output through the coaxial waveguide.

As the extractor has a larger radius, it generally has larger

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†Corresponding author. E-mail: hejuntao12@163.com

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power handling. The electron beam density becomes also more and more small during the motion, so the space charge effect continuously decreases and this leads to smaller magnetic field and higher conversion efficiency.

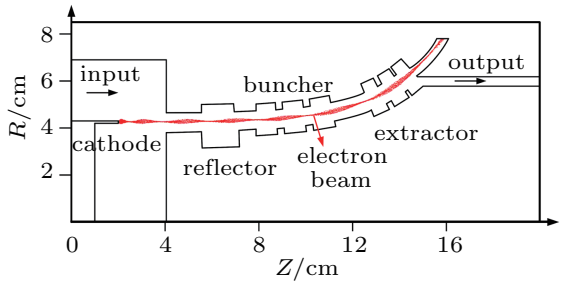


Fig. 1. Model structure and electron trajectories.

3. Physics analysis and solenoid design

3.1. Physical analysis

Electrons passing through the TTO buncher feels a force from the standing wave formed in the buncher. Some electrons gain energy and accelerate while the others behave in the opposite way. An overall energy exchange between beam and wave can be obtained by calculating the electron conductance G_e/G_0. In axial or radial TTO, only one dimension of the electric field should be considered based on small-signal theory.[9] However, in this novel TTO, as the buncher and extractor are curved, electric field along the electron trajectory direction should be taken into consideration.

Electron orbits in Fig. 1 can be fitted by the following polynomial equation:

$$R(z) \approx 2.908 + 0.867z - 0.164z^2 + 0.010z^3. \tag{1}$$

Using Superfish, we obtain the electric field distribution inside the buncher, As shown in Figs. 2(a)–2(c), where 0 mode, $\pi/2$ mode, and π mode standing wave is formed.

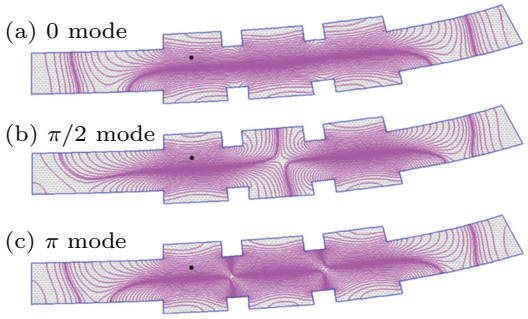


Fig. 2. Field distributions of different TM_{01} modes: (a) 0 mode, (b) $\pi/2$ mode, and (c) π mode.

When electrons pass through the three-cavity buncher and extractor, the velocity would not only be modulated in axial direction, but also radial dimension. As shown in Fig. 2, the standing wave formed in the buncher should interact with IREB along the trajectory.

For any point in the path, set θ to be the included angle between $E_{\parallel}(z,r,t)$ (it represents electric field along the beam path) and the z axis, then $R'(z) = \tan\theta$. Thus

$$E_{\parallel}(z,r,t) = E_z * \cos\theta + E_r * \sin\theta. \tag{2}$$

Electric field along the electron beam should be expressed as

$$E_{\parallel}(z,r,t) = E_{\mathrm{m}} f(z,r)\, \mathrm{e}^{\mathrm{j}\omega t}, \tag{3}$$

where E_{m} is the maximum amplitude of the electric field and $f(z,r)$ is the normalized distribution function. Therefore the gap coupling coefficient M is

$$M = \frac{1}{2L}\left|\int_{-\infty}^{\infty} f(z,r)\, \mathrm{e}^{\mathrm{j}\beta_e l}\mathrm{d}l\right|, \tag{4}$$

where L is the length of electron trajectory which is expressed in Eq. (1), and f_c the resonant frequency, c the light speed, V_0 the beam voltage, $\mathrm{d}l = \sqrt{(\mathrm{d}z)^2 + (\mathrm{d}r)^2}$, and β_e the electron phase constant and could be written as

$$\beta_e = \frac{2\pi f_c}{v_e} = \frac{2\pi f_c}{c\sqrt{1-(1+V_0(kV)/511)^{-2}}}. \tag{5}$$

Electron conductance subsequently can be expressed as

$$\frac{G_e}{G_0} = -\frac{1}{4}\beta_e \frac{\partial M^2}{\partial \beta_e}. \tag{6}$$

The electron conductance ratio between different modes is illustrated in Fig. 3. For the beam voltage in a range between 400 kV and 800 kV. Table 1 gives the figure for G_e/G_0. It is noticed that G_e/G_0 is negative in this voltage range and $\pi/2$ mode of TM_{01} microwave can thus be stimulated effectively.

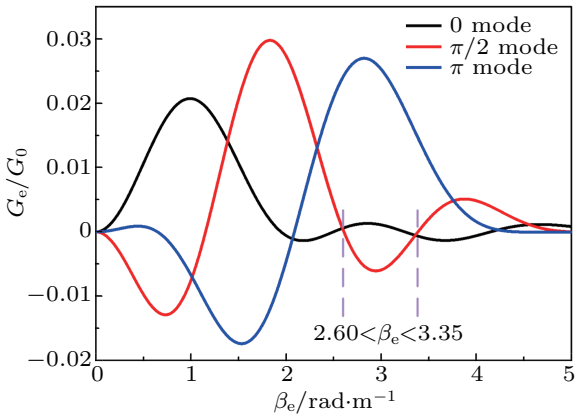


Fig. 3. Plots of electron conductance G_e/G_0 *versus* phase constant for different modes

Table 1. Electron conductance ratios of different modes for 400 kV< V_0 < 800 kV.

Mode (f_c/GHz)	Mode (12.07)	$\pi/2$ mode (12.55)	π mode (13.12)
β_e/cm^{-1}	$2.75 < \beta_e < 3.5$	$2.85 < \beta_e < 3.17$	$2.98 < \beta_e < 3.32$
G_e/G_0	> 0 (No)	< 0 (Yes)	> 0 (No)

Comparison of power capacity (cold test) at extractor between this novel TTO and axial TTO (where extractor has the same radius as the cathode) is demonstrated in Figs. 4(a) and 4(b). With the same cavity structural parameters, the maximum electric field decreases from 1.23 MV/cm to 1.03 MV/cm, specifically 16.3%, under the same storage and resonant frequency. Hence, the extractor in this proposed TTO can sustain larger power than the traditional axial extractor.

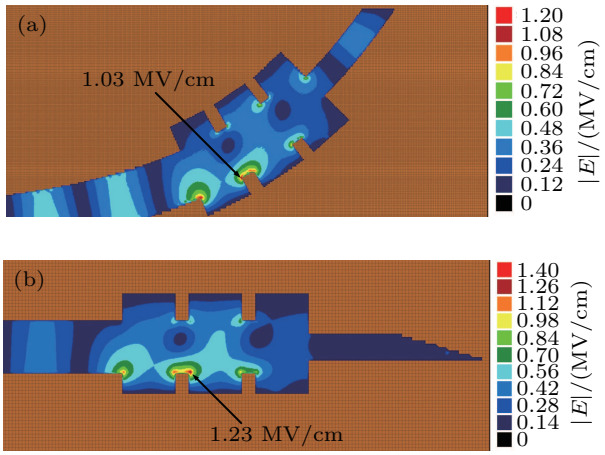


Fig. 4. Electric field $|E|$ distribution in extractor of (a) novel TTO and (b) traditional TTO.

Furthermore, it can also be reasonably deduced that if the extractor has larger radius, more and more power could be sustained.

3.2. Solenoid design

In most of TTOs, a uniform magnetic field is necessary to guide IREB through the anode–cathode gap, which also plays an important role in guaranteeing good beam–wave interaction. As electrons enter into the extractor, the density of which and the space charge effect are reduced, and thus lower magnetic field is needed. The three-dimensional map of magnetic field is shown in Fig. 5. In this novel TTO, a 1.0-T uniform magnetic field is only required in the cathode area and it gradually decreases after electrons have entered into the reflector.

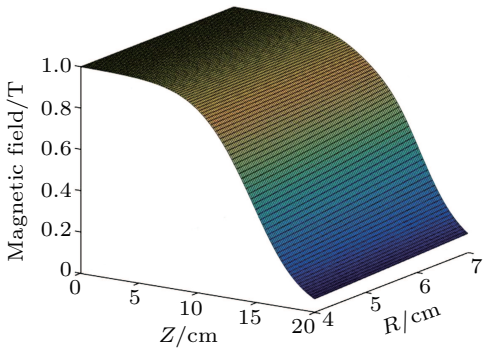


Fig. 5. Three-dimensional map of magnetic field.

It could be found in Fig. 6 that the uniform magnetic field used to guide IREB through the cathode area is very short (less than 6.0 cm), while in most of the other O-type sources, uniform magnetic field should cover at least the area of electron trajectory (both in the axial source and in the radial source). In this novel TTO, the natural bending of the solenoid is utilized, after cavities have been well designed to match the beam motion. Considering that the buncher, extractor and collector have a length of around 16.0 cm, the length of solenoid is thus saved more than 60%.

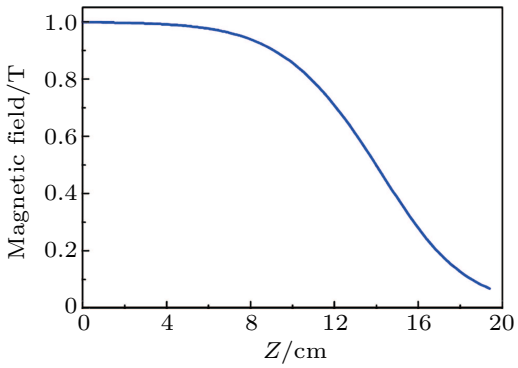


Fig. 6. Magnetic field B at 4.3-cm radius (cathode radius).

Shorter solenoid has lighter weight and smaller volume, and it typically needs less energy to generate a certain magnetic field intensity. Therefore, this shorter solenoid is of importance for HPM sources which need to be smaller and highly repetitive, since smaller ones can be used in more conditions and repeated sources normally require a large amount of energy.

4. Simulation results

Under a 620-kV cathode voltage, 13.27-kA current input and 1.0-T decreasing magnetic field, the PIC simulation (CHIPIC) results are shown in the following.

Figure 7 shows that the output power reaches its peak at 3.37 GW with an efficiency of 41%. It could also be seen that the starting oscillation time is 10 ns and the saturation time is around 25 ns. The frequency also remains stable at 12.43 GHz after 10 ns.

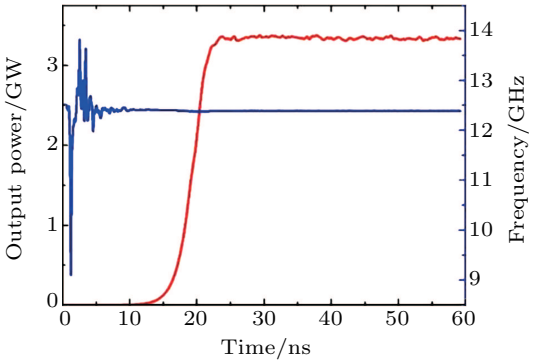


Fig. 7. Output power and frequency *versus* time.

The phase space plot in the axial and radial direction are demonstrated in Fig. 8. Obviously, the reflector at first only modulates the axial velocity, and the buncher also mainly influences the axial motion. After reaching the three-cavity buncher, electrons gradually have a radial velocity due to the action of guiding magnetic field. Therefore, they interact with eigenmode microwave in both axial and radial dimension as shown in Fig. 8(b).

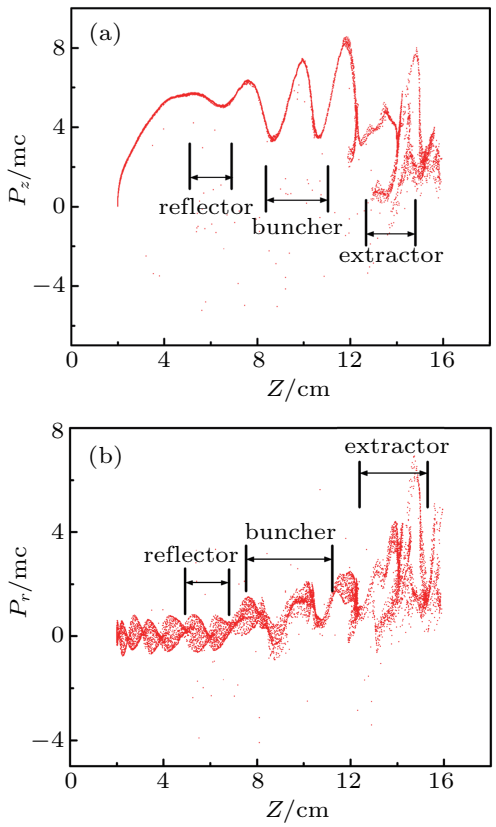


Fig. 8. (a) Axial phase space plot and (b) radial phase space plot of HPM source after saturation.

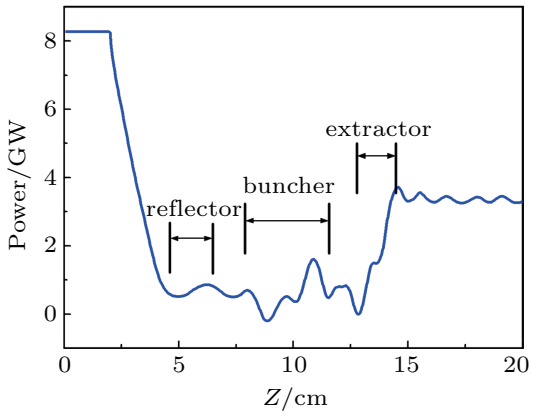


Fig. 9. Total Poynting flux power distributions in source.

Although the structure has the radial feature, it has no overlap in the axial dimension, so it is reasonable to analyze the simulation results by only monitoring the axial dimension. The total pointing flux power in the source is illustrated in Fig. 9. It could be found that the reflector, which premodulates electrons, has less influence on modulation while the buncher modulates the electron velocity intensely and these electrons finally give energy to the microwave in the extractor.

The TTO uses standing wave but not travelling wave to modulate electron velocity as shown in Fig. 10. As this novel TTO has an equal-width electron transporting tube which cuts off the TM_{01} mode microwave, the cavities will generate similar standing waves along the electron trajectory to those produced by the cavities with the same shape parameters in the axial direction.

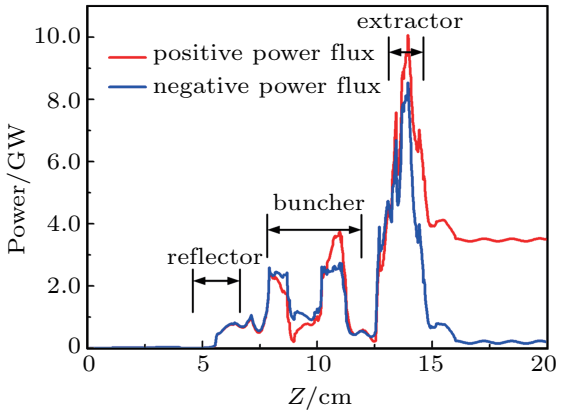


Fig. 10. Positive and negative power flux in axial direction.

The fundamental harmonic current peak in Fig. 11 occurs right in front of the extractor at 19.5 kA, which means that the maximum modulation coefficient is 141%. This indicates that the beam has a good interaction with microwave and reasonably explains the high efficiency output.

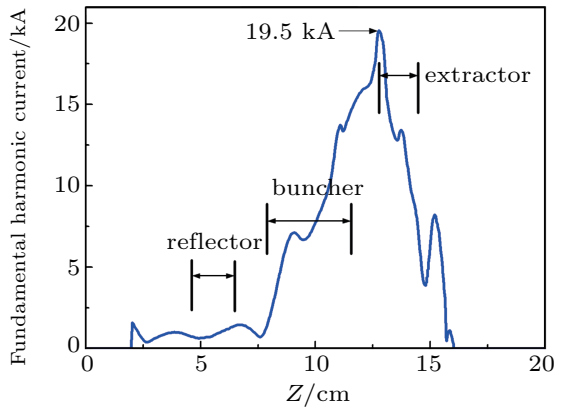


Fig. 11. Fundamental harmonic current *versus* axial dimension.

5. Conclusions

In the novel TTO proposed in this article, the mature technique of axial cathode and inherent advantages of radial

sources are utilized. Electrons are guided by the natural bending of the magnetic field and interact with both the axial electric field and the radial electric field. Mode analysis shows that it works well with $\pi/2$ mode of TM_{01} microwave. This novel TTO also has larger power capacity in the extractor and csn be further improved by increasing the extractor radius. Besides, over 60% of the uniform magnetic field is saved. The PIC simulation shows that when 620-kV diode voltage and 13.27-kA current input into the device, it could output 3.37-GW microwave at 12.43 GHz, with 41% efficiency.

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