# Advance of Research on Coaxial Relativistic Backward Wave Oscillator

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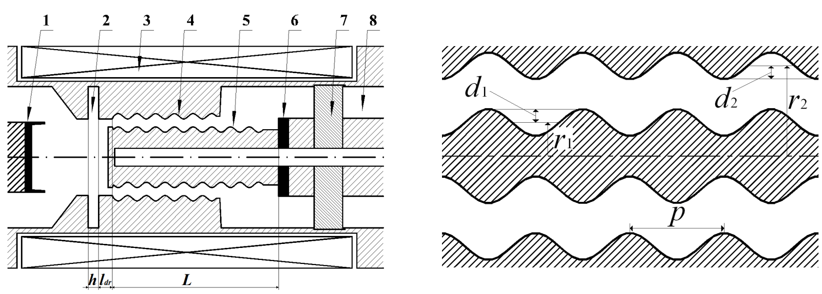
**Abstract—** Coaxial relativistic backward wave oscillator (CRBWO) is a new type of high power microwave (HPM) generator remarked by the conversion efficiency higher than 35%. It is found that in CRBWO the promotion of the beam quality, the synchronous harmonic distribution, and the collection of the spent electron on the inner conductor of the coaxial slow wave structure (SWS) accounts for the high efficiency which is confirmed by experiments. According to the special structure and distinguishing physical mechanism, a series of important improvements of the coaxial reflector and the structure with coaxial dual annular cathodes has been developed to enhance both the output power and the conversion efficiency up to 3.63 GW and 45%. And making full use of the both rippled conductors of CRBWO by installing an additional set of SWS into the inner conductor results in the generation of the beating wave with the average output power 5.88 GW and conversion efficiency 41.5%.

## 1. INTRODUCTION

As high power microwave (HPM) technology matures gradually, relativistic backward wave oscillator (RBWO) attracts more and more attention due to its compact structure and the capacity of repetitive operation [1–4]. The conversion efficiency has been considered to be very important [5]. The coaxial relativistic backward wave oscillator (CRBWO) as shown in Figure 1 developed in recent years presents a practical approach to achieve high output efficiency [6–9]. The numerical simulation [6] and the theoretical calculation [7] on CRBWO predicted its output efficiency up to 35%, which is validated by experiment [8, 9].




(a) (b)

Figure 1: (a) Structure of coaxial RBWO. 1-annular cathode; 2-resonant reflector; 3-guide magnet solenoid; 4-outer SWS; 5-inner SWS; 6-fluting electron collector; 7-equipotential support; 8-output waveguide. (b) Coaxial SWS.

Compared with the hollow slow wave structure (SWS), coaxial SWS reduces the space-charge effect, which makes the electron beam more energetic to amplify the microwave [7]. The synchronous harmonic distribution in coaxial SWS benefits the wave-beam interaction [10]. And the electron dump on the inner conductor ensures the wave-beam interaction efficiently till the electron is collected by the inner conductor [11]. These distinguishing physical characteristics result in the high conversion efficiency.

In recent year, much progress has been made on the development of CRBWO. This paper summarizes the present advance of research on CRBWO and provides suggestion for the development and practical application of this new type of HPM generator.

## 2. ANALYSIS ON PHYSICAL MODEL

The dispersion with consideration of annular electron beam of CRBWO is demonstrated in Figure 2. The fast space charge wave interacts with the electron beam without energy exchange, while the slower space charge wave and the structure wave merge into a complex conjugate pair with the

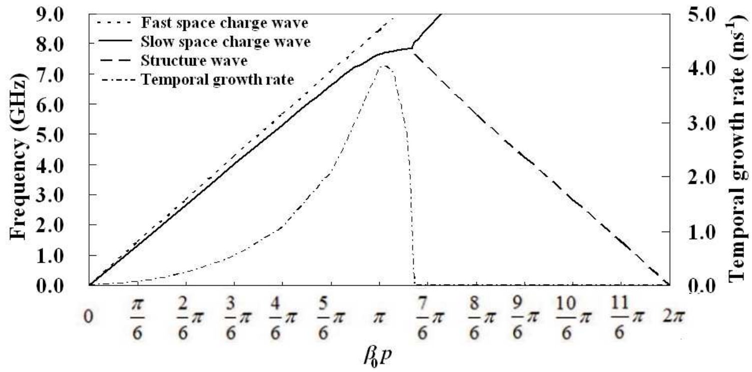
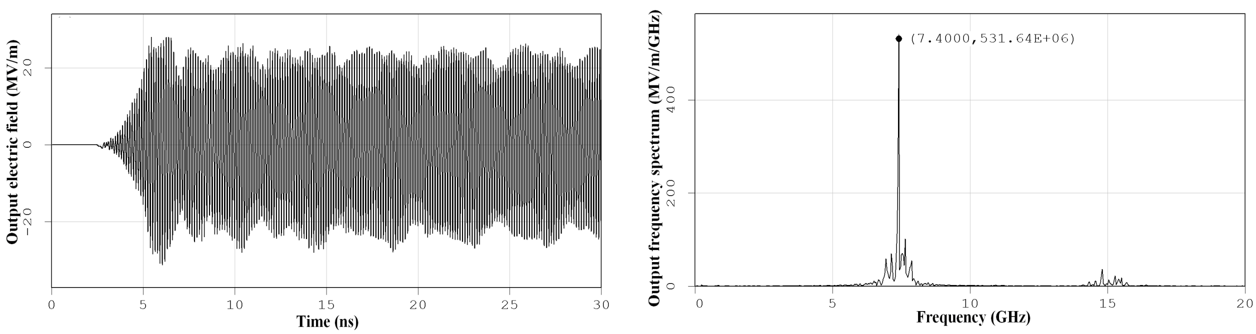



Figure 2: Dispersion of coaxial SWS with the consideration of annular electron beam with energy of 500 keV and current of 400 kA.




(a) (b)

Figure 3: Numerical simulation of CRBWO. (a) Output electric field. (b) Output frequency.

nontrivial temporal growth rate from $\beta_0 p = 0$ to $\pi$. The largest temporal growth rate occurs on the branch of the fundamental harmonics.

The starting current of CRBWO as shown in Figure 1(a) is analytically expressed as

$$I_{st} = \frac{\varepsilon_0 \omega_s m_0 \gamma_0^3 v_0^3 \sqrt{\left[(\omega_s^2 - \omega^2)/\omega\omega_s\right]^2 + Q^{-2}}}{e\omega E_h hl \left[\sin\left(\omega h/2v_0\right)/\left(\omega h/2v_0\right)\right] \left|\int_L e^{-j\omega z/v_0} E_{sz}\left(r_b, z\right) dz\right|}, \tag{1}$$

where $\varepsilon_0$ and $\mu_0$ are the vacuum permittivity and permeability, $\omega_s$ is the eigen frequency of the finitely long coaxial SWS, $m_0$ is the electron rest mass, $\gamma_0$ is the electron relativistic factor, $v_0$ is the electron velocity, $\omega$ is the operation frequency, $Q$ is the external quality factor of finitely long coaxial SWS, $e$ is the electron charge, $E_h$ is the average modulating electric field in the resonant cavity, $E_{sz}\left(r_b, z\right)$ is the normalized electric field in the coaxial SWS, $r_b$ is the radius of the annular beam, $l = -h/2 - l_{dr}$. The result calculated from (1) is in good agreement with those obtained by numerical simulation. It is found that during the startup of oscillation CRBWO is suffering from mode competition, which will be more severely when the electron kinetic energy becomes higher. Therefore, CRBWO should be driven by electron beam of the medium kinetic energy about 400 keV–500 keV [12].

The physical model of the wave-beam interaction in CRBWO, which is described by the self-consistent equations of the electromagnetic field and the electron movement equation, is established for the conversion efficiency prediction [13]. The electron relativistic factors at both ends of SWS are $\gamma_0 = 1.92$ and $\gamma_L = 1.57$ at the stable state, which indicates the conversion efficiency is $(\gamma_0 - \gamma_L)/(\gamma_0 - 1) = 0.38$ [14]. In numerical simulation, the microwave pulse of 754 MW at 7.33 GHz is generated under 508 kV and 3.97 kA with the conversion efficiency 36% as shown in Figure 3.

## 3. EXPERIMENTAL RESEARCH

In experiments, some important technical improvement has been made. First, the components of CRBWO are surface-treated shown in Figure 4(a), because the problem of the power capacity became more serious due to the introduction of the inner conductor [7]. Second, the equipotential

(a)

(b)

Figure 4: Important technical improvement in experiments. (a) Outer and inner ripples coated with the TiN film. (b) Close-up view of equipotential support in Figure 1.

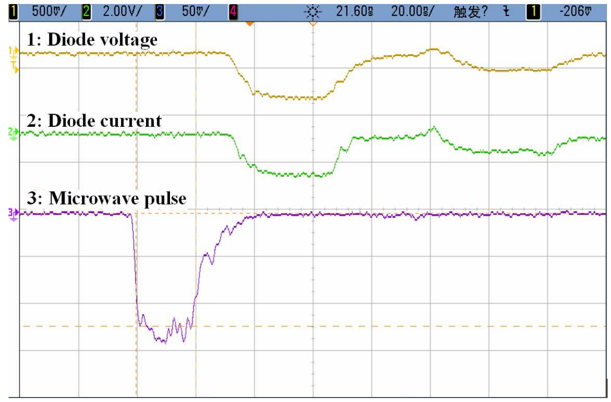



Figure 5: Typical experiment results of CRBWO. Resolution is 20 ns/div on horizontal axis. 1: diode voltage, 505 kV; 2: diode current, 4.26 kA; 3: microwave pulse, 733 MW.

support in Figure 1(a) has been developed as shown in Figure 4(b) to make sure the inner and outer conductors are well coaxial. The equipotential support is carefully designed and optimized for the maximum microwave transmission coefficient so that the electromagnetic wave can propagate through with little reflection.

With these improvements, the output power higher than 730 MW and the pulse duration 20 ns were obtained in the experiment under the diode voltage 500 kV and current 4.3 kA as shown in Figure 5. The conversion efficiency is about 34%, and the output frequency measured by the heterodyne method is 7.4 GHz close to the simulation prediction. This is the first experimental research on CRBWO which has confirmed its high efficiency close up to 35% as the theoretical and numerical expectation. When the diode voltage was up to 560 kV, the output power and efficiency increase 1.01 GW and 36%, but the pulse duration fell to 16 ns. It can be tentatively indicated that beyond the limitation of the power capacity, the output power and the conversion efficiency of CRBWO can be enhanced further [9].

## 4. FURTHER ENHANCEMENT OF OUTPUT POWER AND CONVERSION EFFICIENCY

### 4.1. New Type of Coaxial Reflector

The coaxial reflector, which is different from the traditional reflector in Figure 1(a), is developed specialized for CRBWO. Two types of resonant reflector are illustrated in Figure 6, and bunches of the electron beams are compared in Figure 7. It can be concluded that the ratio of the difference between the maximum and minimum modulated velocities to the initial one is 0.13 in the resonant reflector in Figure 1(a), while that is 0.17 in the coaxial reflector [15]. The improvement of the electron modulation results in increasing of the conversion efficiency. In numerical simulation, the conversion efficiency 43% and output power 1.0 GW at 7.3 GHz are obtained under the diode voltage 530 kV and current 4.4 kA [15].

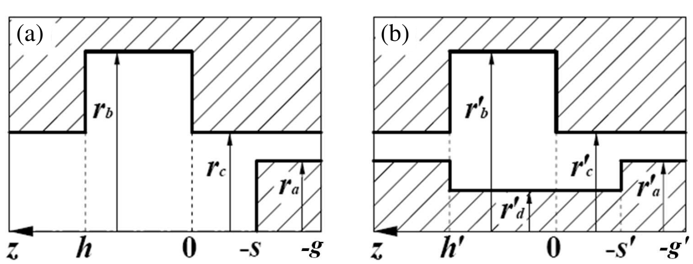



Figure 6: (a) Traditional and (b) improved resonant reflector for CRBWO.

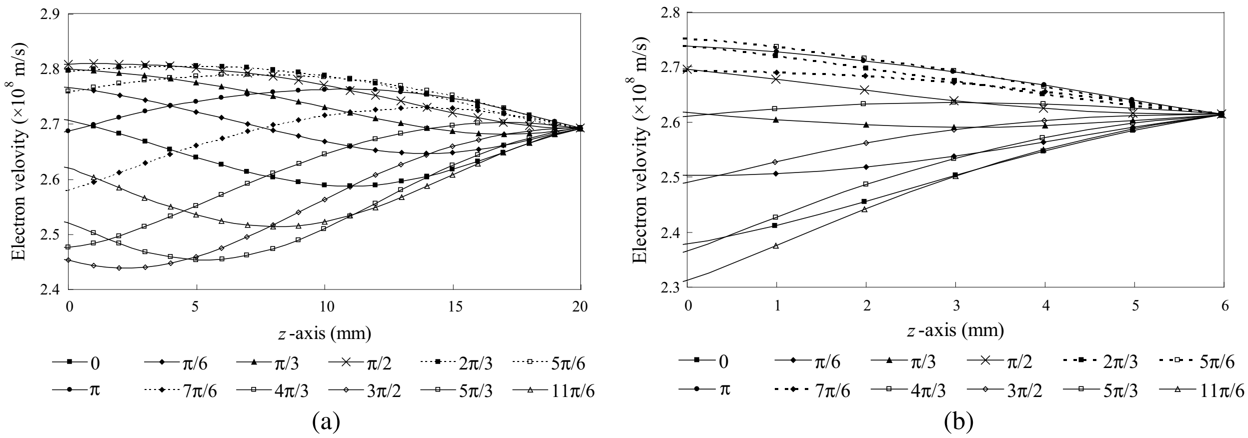



Figure 7: Bunches of electron beam in (a) traditional reflector and (b) coaxial reflector.

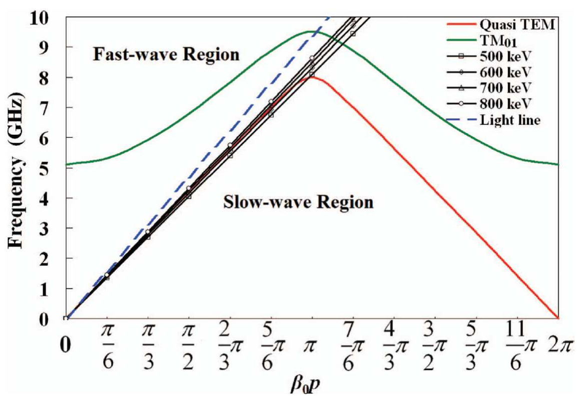



Figure 8: Dispersion of quasi-TEM mode in coaxial SWS and $TM_{01}$ mode in traditional hollow SWS with the same outer average radius, the same ripple depth and the same ripple period.

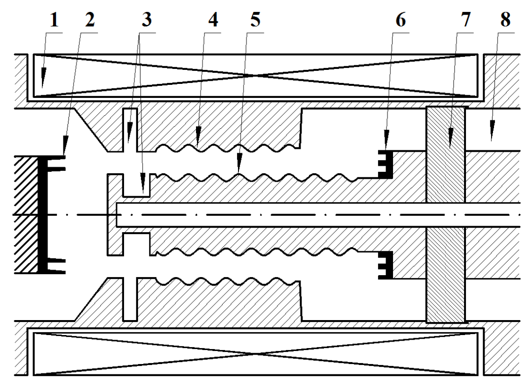



Figure 9: CRBWO with coaxial dual annular cathodes. 1-guide magnet solenoid; 2-coaxial annular cathodes; 3-coaxial reflector; 4-outer SWS; 5-inner SWS; 6-fluting electron collector; 7-coaxial transmission supporter; 8-cylindrical waveguide.

### 4.2. CRBWO with Coaxial Dual Annular Cathodes

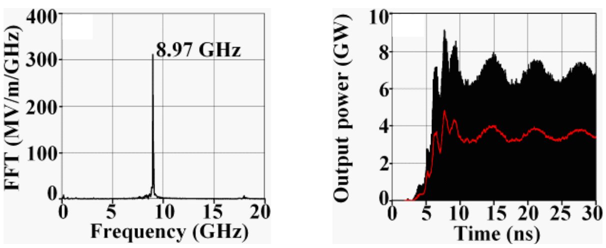
It is found that raising the diode voltage can hardly increase the output power with high conversion efficiency [7]. This can be qualitatively explained by the comparison of dispersion between the coaxial and traditional hollow SWSs as shown in Figure 8, which is divided into fast-wave and slow-wave regions by the light line. The fundamental harmonic branch of the $TM_{01}$ mode in the traditional hollow SWS is located in the fast-wave region and the $-1$st harmonic branch is located in the slow-wave region. The beam lines are under the light line in any case. Therefore, the operating point determined approximately by the intersection of the wave structure with the beam lines can be found obviously, no matter how high the diode voltage becomes. However, in the coaxial SWS, both the fundamental and the $-1$st harmonic branches of the quasi-TEM mode in the coaxial SWS lie in the slow-wave region [12]. Thus an electron beam with too large kinetic energy will deviate seriously from the $\pi$ point of the quasi-TEM mode as shown in Figure 8. This deviation may result in inefficient wave-beam interactions with low conversion efficiency in the coaxial SWS.

However, the double rippled conductors of the coaxial SWS provide a feasible way to increase the output power with high conversion efficiency by the interaction with coaxial dual annular beams. Thus CRBWO with coaxial dual annular cathodes is devised as illustrated in Figure 9. In numerical simulation, the microwave generation is up to 3.63 GW with the conversion efficiency 45% under a diode voltage 659 kV and current 12.27 kA at 8.97 GHz as shown in Figure 10. The currents of the inner and outer annular beams with the same kinetic energies are $I_i = 3.72$ kA and $I_o = 8.55$ kA, respectively.

### 4.3. HPM Beating Wave Generator

Owing to the special structure and physical characteristics CRBWO also offers the efficient approach to compactly generate the beating-wave HPM pulse, which is proved to be able to decrease the injury threshold of the electronic devices and cause more serious damage [16]. In order to make full use of the inner conductor, the multi-coaxial relativistic backward wave oscillator (M-CRBWO) which produces HPM beating wave is developed as shown in Figure 11, in which one inner cathode feeds the annular beam into the inner RBWO while the two outer cathodes feed the outer CRBWO. The coaxial transmission supporter as illustrated in Figure 12(a) fixes the inner RBWO into the outer CRBWO. It also converts TEM mode in the coaxial waveguide into $TM_{01}$ mode in the cylindrical one with little reflection as shown in Figure 12(b) for the sake of the incoherent combination of the generations of the inner RBWO and outer CRBWO.

In numerical simulation M-CRBWO generates HPM beating wave with the average power 5.88 GW under the diode voltage 724 kV and current 19.57 kA with the conversion efficiency 41.5%.




(a) (b)

Figure 10: (a) Output spectrum. (b) Instantaneous waveform and envelope of output power.

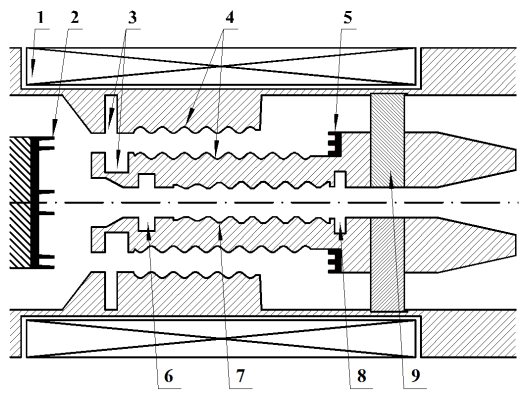
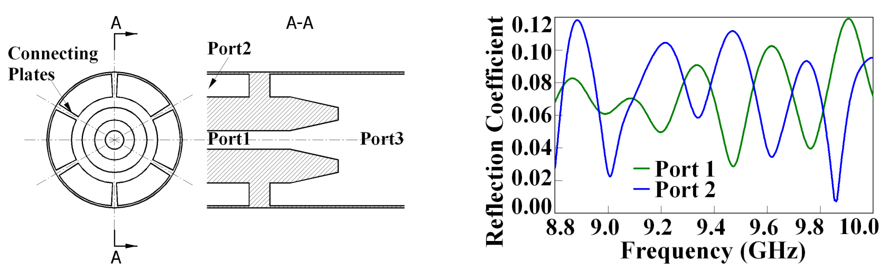
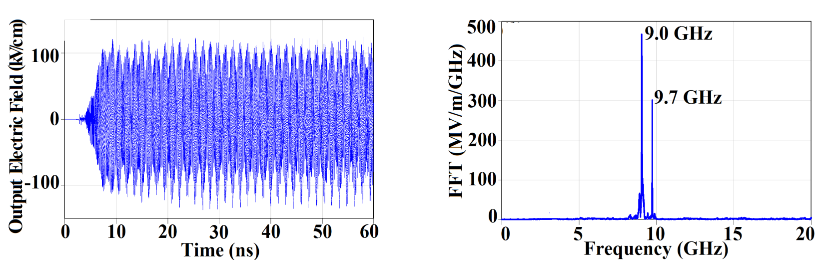



Figure 11: Configuration of M-CRBWO. 1-guide magnet solenoid; 2-coaxial annular cathodes; 3-coaxial reflector; 4-coaxial SWS; 5-fluting electron collector; 6-inner reflector; 7-inner SWS; 8-abstracting cavity; 9-coaxial transmission supporter.




(a) (b)

Figure 12: (a) Schematic of coaxial transmission supporter in Figure 11. (b) Reflection coefficients of electric field.




(a) (b)

Figure 13: Beating wave of HPM pulse generated by M-CRBWO. (a) Instantaneous waveform of electric field. (b) Spectrum of electric field.

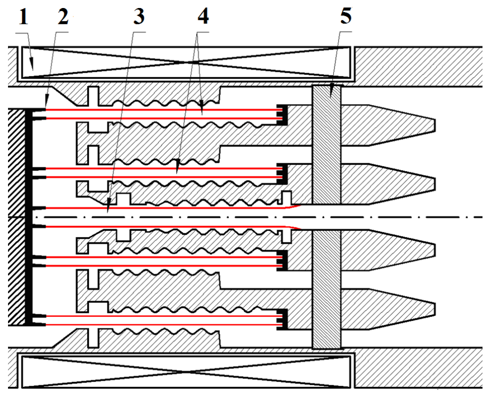



Figure 14: Expanded M-CRBWO. 1-guide magnet solenoid; 2-coaxial annular cathodes; 3-inner RBWO; 4-middle CRBWO and outer CRBWO; 5-coaxial transmission supporter.

The HPM pulse consists of two frequency components 9.0 GHz and 9.7 GHz as shown in Figure 13, corresponding to 2.23 GW and 3.65 GW, respectively [17].

The proposal of M-CRBWO not only puts up a compact generator of HPM beating wave, but also provides a practical method and platform of organizing multiple source devices to realize the synchronous composite HPM output of several narrow-band pulses at one shot. Therefore, M-CRBWO can be expanded into the configuration as shown in Figure 14. As a result, HPM generation combining different frequency components, or different output powers, or different pulse widths, will be obtained.

## 5. SUMMARY AND CONCLUSION

Since CRBWO with two rippled conductors was put forward in 2002, its notable merit of high efficiency is validated primarily through experiments and the reasons accounting for its high conversion efficiency has been investigated and analyzed. Moreover, a series of important improvements including the coaxial reflector, the coaxial dual annular cathodes, and the beating wave generator, has been made in order based on the special structure and the physical characteristics. However, the further study indicates two key points which are important for the development of CRBWO. First, the physical mechanism of the wave-beam interaction in CRBWO which is remarkably distinguished from that in the traditional hollow RBWO should be researched totally to make full use of its potential of the high efficiency. Second, the technological problems especially such as coaxiality and power capacity should be well considered and optimized delicately to make sure the experimental structure is identical to the physical model.

## ACKNOWLEDGMENT

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