Study of superradiance based on a low-voltage backward wave oscillator *

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Abstract: According to the small size requirement for wide-band high-power microwave radiation, a superradiance backward wave oscillator (BWO) is proposed to generate such high-power microwave radiation with a low voltage (∼20 kV) pulse power supply and low guiding magnet field (∼0.1 T). In order to get a high-efficiency C-band superradiance BWO with a low beam voltage and a low guiding magnet field, the mechanism of superradiance in a BWO is explored in particle-in-cell simulation. With the oversized structure, the simulation shows that a microwave power of 405 kW with a frequency of 5.6 GHz and a spectrum width of 500 MHz can be obtained with a voltage of 23 kV and magnetic field of 0.1 T.

Key words: superradiance, backward wave oscillator, particle-in-cell simulation

PACS: 41.60.Bq **DOI:** 10.1088/1674-1137/37/4/047002

1 Introduction

In a backward wave oscillator (BWO), if the electron pulse duration is comparable with the cooperation time between the beam and microwave, it is possible to find superradiance [1–6]. Superradiance (SR) is an intensive coherent radiation characterized by high peak-value power and an ultra-short pulse width. The typical SR microwave pulse length is at the subnanosecond level, and its rise time is also short, so it is a potential candidate for a high-power wide-band radiation source.

In addition, high-power wide-band radiation sources based on superradiance backward wave oscillators (SR-BWOs) can be small because the electron pulse duration they use is several nanoseconds. Nowadays, many SR-BWOs work at high voltage (230–500 kV), and the corresponding dimensions are quite large because of the power supply and the guiding magnet. So beam voltage and guiding magnetic field strength are critical factors for developing small-sized and high-power wide-band radiation sources based on SR-BWOs.

Theoretical and simulation studies on such devices are carried out in this paper. A low-voltage SR-BWO is proposed and simulated, and particle-in-cell (PIC) simulation shows that a peak power of 405 kW with a frequency of 5.6 GHz and spectrum width of 500 MHz can be obtained with a voltage of 23 kV and magnet field of 0.1 T.

2 Physics model

Superradiance is the result of joint action when different parts of short pulse electron beams are coupled with a microwave field in a BWO device, as shown in Fig. 1 [7]. The length of the BWO device is rather long compared with the electron beam width.

2.1 Device structure

A thermal cathode electron gun is used to produce an annular electron beam. The cathode material is lanthanum hexaboride. The radius of the cathode is 26 mm, and its thickness is 2 mm.

According to the Richardson formula,

$$J=AT^2\mathrm{e}^{-e\varphi/kT}. \tag{1}$$

When $T=1900$ ℃, $e\varphi$=2.9 eV, the current density can reach J=22 A/cm^2, so in the simulation the input current is initialized to ∼80 A. A uniform corrugated waveguide is also used as the slow wave structure (SWS) for the beam wave interaction, as shown in Fig. 1. The number of periods is 34 and the period is 1 cm.

The structure of the SR-BWO is shown in Fig. 1.

Received 19 March 2012

∗ Supported by National Natural Science Foundation of China (61271109)

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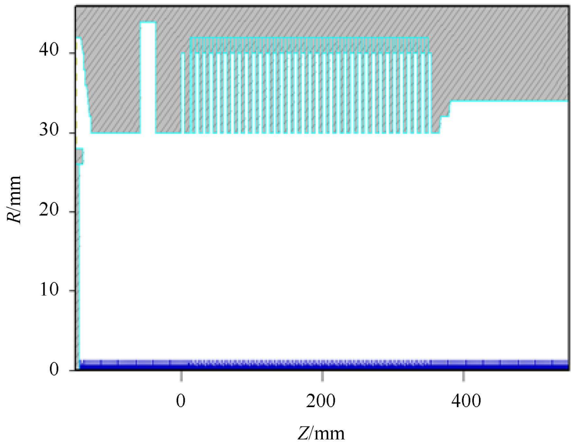

Fig. 1. (color online) A schematic drawing of the SR-BWO.

2.2 Analysis

In the linear region, the coupling impedance will be increased if we reduce the distance between the electron beam and the wall of the slow-wave structure. The output power of the superradiance could also be improved when the coupling impedance is increased, and at the same time the SR pulse length is decreased [8, 9].

3 Simulation and discussion

3.1 Electron phase space

The voltage and current waveforms are shown in Figs. 2 and 3, and the phase space plots of electrons are shown in Fig. 4.

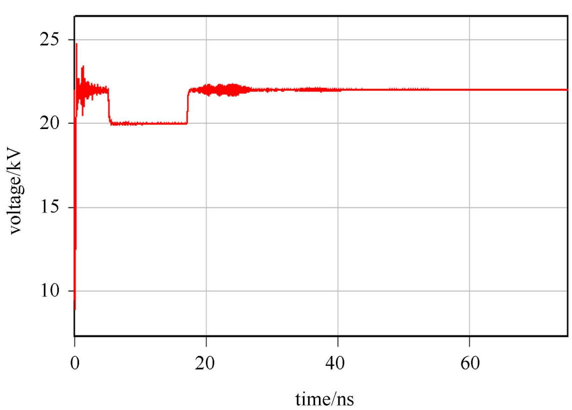

Fig. 2. (color online) The voltage waveform.

As shown in Fig. 4, the electron beam begins to bunch at about 15 ns, and subsequently the modulation depth of the electron beam increases rapidly. At about 21 ns, the modulation depth reaches its maximum, and then the superradiance is generated.

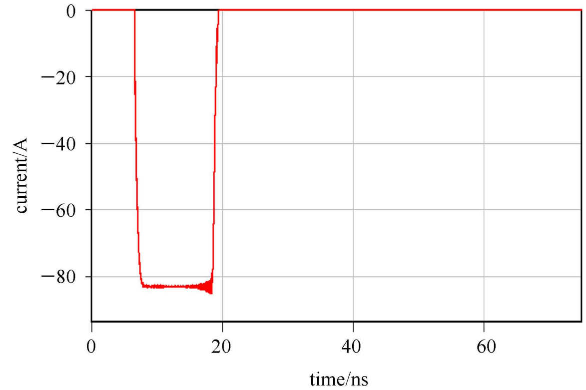

Fig. 3. (color online) The current waveform.

After 21 ns, the electron beam is debunched and collected by the collector. Then the microwave and the electron beam are separated from each other, and effective collective coherent radiation occurs.

3.2 Output microwave pulse characteristics

A temporal plot of the electric field is shown in Fig. 5, and evolution of the axial electric field through the superradiance mechanism is observed. The spectrum of the electric field in SWS is shown in Fig. 6, and the radiation frequency is 5.6 GHz. The output microwave power spectrum is shown in Fig. 7. It can be seen that the peak power is ∼405 kW, the corresponding efficiency reaches 22%, and the pulse duration is about 700 ps.

3.3 Influence of voltage on output power

The influence of the voltage on the output power is investigated on the condition that other parameters are kept constant. As shown in Fig. 8, the output power reaches the first maximum at a voltage of about 21 kV. The reason for this is that the electron at a voltage of 21 kV can keep an effective resonance relationship with the −1 harmonic wave in the slow wave structure. The best match occurs at a voltage of 23 kV, so we can set the operating voltage between 21–24 kV.

There are two other peaks of output power shown in Fig. 9 because electrons at a voltage of 25 kV and 27 kV can keep effective resonance with the second and third harmonic waves in the slow wave structure, respectively. The match between the electron and the RF field in the slow wave structure could not be kept when the voltage was above 28 kV, so the RF field cannot be built when the voltage is too high.

3.4 Influence of current on output power

The influence of the current on the output power is also investigated on the condition that the other parameters are kept constant. As shown in Fig. 9, we can see that the output power of superradiance could be improved in the superradiation region by increasing the beam current.

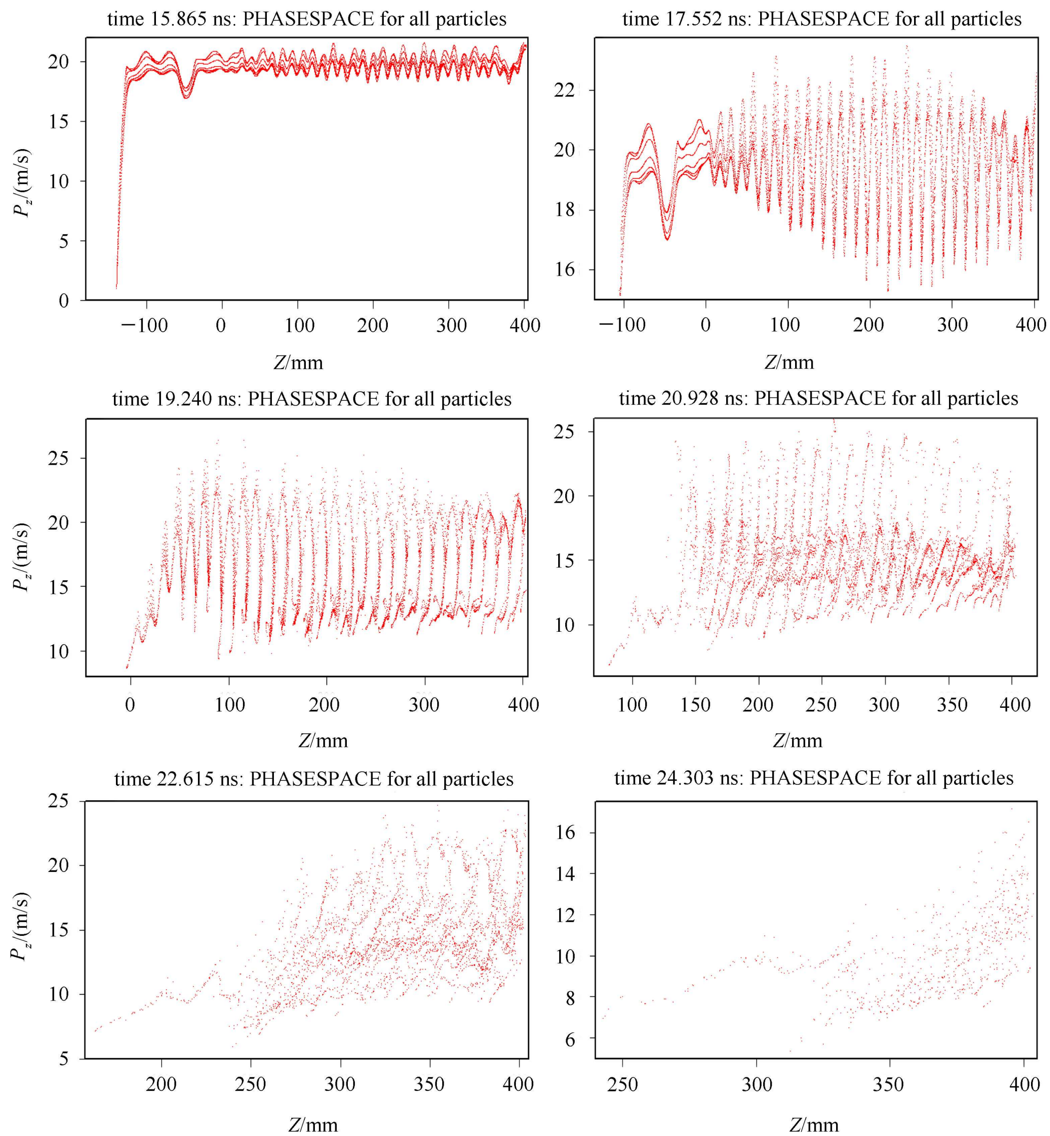

Fig. 4. (color online) The phase space plots of electrons.

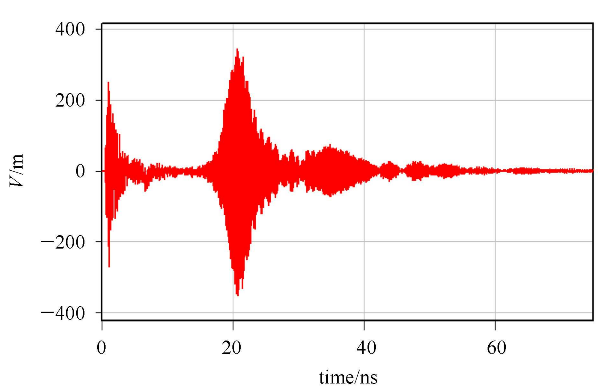

Fig. 5. (color online) The curve of electric field versus time.

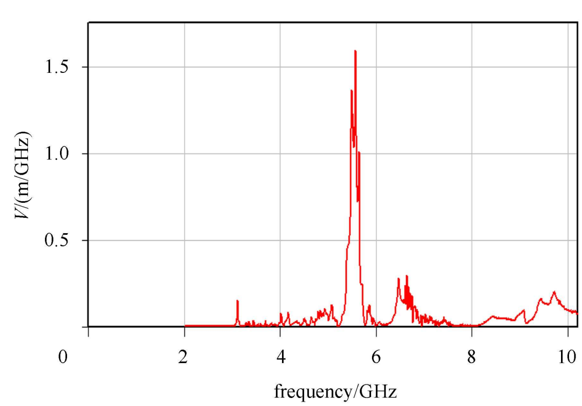

Fig. 6. (color online) The spectrum of the electric field in the device.

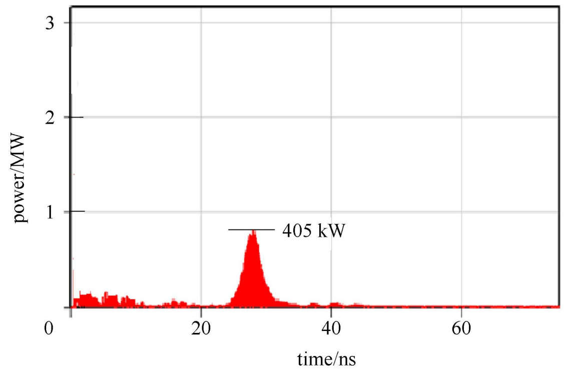

Fig. 7. (color online) The output microwave power.

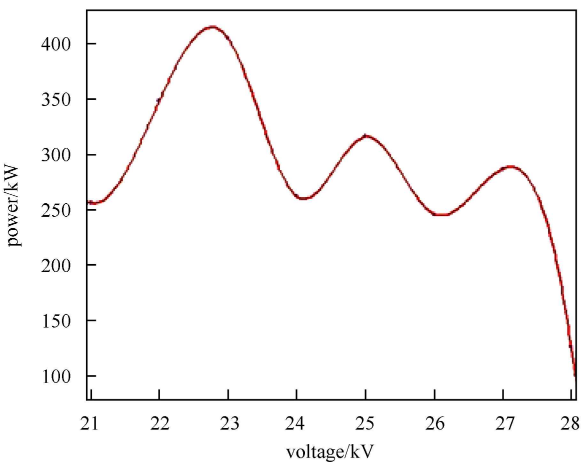

Fig. 8. (color online) The relationship between voltage and output power.

As the beam current increases further, the output power of supperradiance tends to saturate because of space charge effects.

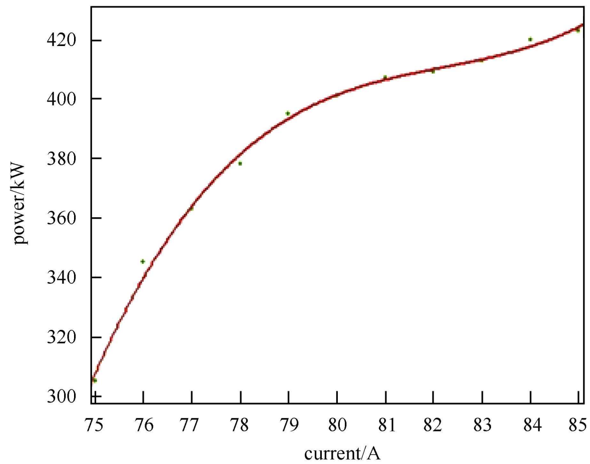

Fig. 9. (color online) The relationship between current and output power.

4 Conclusion

With the given beam parameters of a voltage of 23 kV and a current of 80 A, an overmoded BWO structure is taken to produce an SR pulse. An SR pulse with 405 kW of power and a 700 ps pulse duration is obtained using PIC simulation. The guiding magnetic field is only 0.1 T, so in future a permanent magnet can be used. This technical route therefore has an obvious advantage in developing a compact high-power wide-band radiation source at high-frequency bands such as the C and X band.

References

1 Dicke R H. Phys. Rev. E, 1954, **93**: 99–110
2 Ginzburg N S, Novozhiova N Y, Zotova I V et al. Phys. Rev. E, 1999, **60**(3): 3297–3304
3 Eltchaninov A A, Korovin S D, Pegel I V et al. IEEE Trans. Plasma Sci, 2004, **32**(3): 1093–1099
4 Klimov A I, Korovin S D, Rostov V et al. IEEE Trans. Plasma Sci., 2002, **30**(3): 1120–1125
5 Ginzburg N S. Pis'ma Zh. Tekh. Fiz. 1988, **14**(5): 197–200
6 HU Lin-Lin, MENG Fan-Bao, CHEN Hong-Bin et al. High Energy Physics and Nuclear Physics, 2006, **30**(11): 1096–1099 (in Chinese)
7 DONG Ye, DONG Zhi-Wei, ZHOU Hai-Jing. High Power Laser and Particle Beams, 2007, **19**(4): 671–676 (in Chinese)
8 DONG Ye, DONG Zhi-Wei, YANG Wen-Yuan et al. High Power Laser and Particle Beams, 2008, **20**(7): 1167–1172 (in Chinese)
9 YANG Wen-Yuan, DONG Ye, Dong Zhi-Wei. High Power Laser and Particle Beams, 2010, **22**(3): 630–634 (in Chinese)