Mode control in a high-gain relativistic klystron amplifier*

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Abstract Middle cavities between the input and output cavity can be used to decrease the required input RF power for the relativistic klystron amplifier. Meanwhile higher modes, which affect the working mode, are also easy to excite in a device with more middle cavities. In order for the positive feedback process for higher modes to be excited, a special measure is taken to increase the threshold current for such modes. Higher modes' excitation will be avoided when the threshold current is significantly larger than the beam current. So a high-gain S-band relativistic klystron amplifier is designed for the beam of current 5 kA and beam voltage 600 kV. Particle in cell simulations show that the gain is 1.6×10^5 with the input RF power of 6.8 kW, and that the output RF power reaches 1.1 GW.

Key words high power, microwave, mode control, microwave device

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1 Introduction

There are several kinds of microwave devices for high power microwave (HPM) generators: relativistic klystron amplifier (RKA) [1, 2], magnetron, backward wave oscillator (BWO) [3], traveling wave tube (TWT) [4], gyrotron, vircator [5], and transit tube oscillator [6]. Some of them are oscillators, others are amplifiers. Amplifiers become increasingly important in HPM developments because power limitation becomes obvious in a single device for recent years, and the power adder with amplifiers is a better way to exceed the limitation. RKA is a typical device among HPM amplifiers [1, 7]. Compared with the conventional klystron amplifier with driven current of several amperes, the driving current for RKA is several kA, which is significantly more than that for the conventional klystron amplifier. So higher mode excitation is very serious in RKA, especially for the high-gain amplifier, pulse shortening [8, 9] will occur. Special methods to increase the threshold current for higher modes in the device are very important for RKA, and higher modes must be avoided. A high gain RKA with a gain of 1.6×10^5 and RF output power of 1.1 GW is designed for a driving beam of 600 kV voltage and 5 kA current. In Sec. 2, a brief description of RKA is given. A high gain RKA structure and its simulation result are presented in Sec. 3. In Sec. 4, higher mode's excitation and methods to increase the corresponding threshold current are discussed. Finally, a summary is given in Sec. 5.

2 Principle

The structure for a two cavity relativistic klystron is shown in Fig. 1. The electron beam is modulated when it passes the modulation cavity, and becomes intensely bunched as shown in Fig. 2. Fig. 2 shows the first harmonic bunching current along the beam path for the structure shown in Fig. 1. The bunched beam excites the rf field in the output cavity, the beam energy is converted into the RF field, and the high power microwave is generated. Under certain conditions, the output power can be approximately

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expressed by [10, 11]

$$P=\frac{1}{2}I_1V_0 \quad , \tag{1}$$

here I_1 is the first harmonic bunching current when the beam enters the output cavity and V_0 the beam voltage respectively.

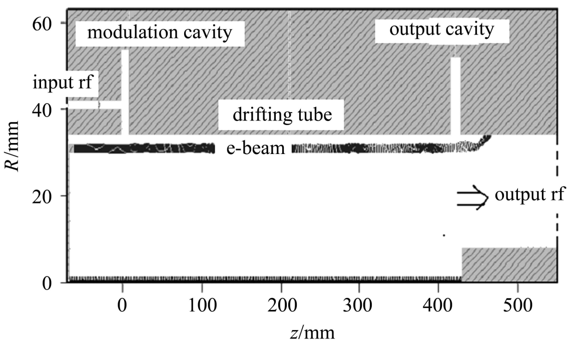

Fig. 1. Structures for a two cavity relativistic klystron amplifier.

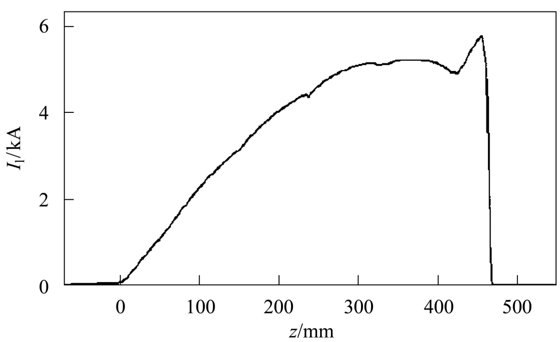

Fig. 2. Curve of the first harmonic bunching current along a beam path.

The electron movement in the drifting tube (shown in Fig. 1) can be expressed by the RF phase φ as follows

$$\frac{\mathrm{d}}{\mathrm{d}z}\varphi=\frac{\omega}{v}. \tag{2}$$

The approximate solution of Eq. (2) is given by:

$$\varphi\approx\varphi_0+\frac{\omega}{v_0}z-\frac{\omega}{v_0}k_1z\sin\left(\varphi_0+\frac{\theta_0}{2}\right), \tag{3}$$

here $k_1\approx\frac{V_1}{2V_0}M_1(\theta_0)$, V_1 is the RF voltage in the modulation cavity ($V_1\propto\sqrt{P_{\rm in}}$, $P_{\rm in}$ denotes the input RF power), $M_1(\theta_0)$ stands for the couple between the beam and the modulation cavity. And the first harmonic bunching current can be given by [12]

$$I_1(z)=2I_0J_1\left(\frac{\omega}{v_0}k_1z\right). \tag{4}$$

When beam enters the output cavity ($z=L_1$), the first harmonic bunching current can be given by

$$I_1=2I_0J_1\left(\frac{\omega}{v_0}k_1L\right). \tag{5}$$

The first harmonic current bunching factor $i(i=I_1/I_0)$ reaches the maximum ($i_1=1.164$) when $\frac{\omega}{v_0}k_1L$ =1.8. With the input power of $P_{\rm in}$=68.3 MW in Fig. 1, the first harmonic bunching current reaches the maximum after the beam drifts 30 cm in the drifting tube as shown in Fig. 2. The RF voltage in the modulation cavity is: V_1=90 kV. The out power is 1.1 GW with the beam of 5 kA and 600 kV, and the corresponding gain is only 16. With the lower input power, a longer drifting tube is needed because the RF voltage in the modulation cavity decreases, for example, the drifting tube needs to be 300 cm long for the first harmonic bunching current to reach the maximum when $P_{\rm in}$=683 kW. Such structure is very difficult to be realized in the experiment. So, middle cavities are necessary. The stationary RF field in a middle cavity, when a weak modulation beam passes, is given by [8]

$$A=\frac{QI_0}{\varepsilon_0}id-\frac{QI_0}{\varepsilon_0}\int_0^d J_1\left(\frac{\omega}{v_0}\frac{1}{\sqrt{(\gamma_0^2-1)^3}}\frac{eAE_0}{m_0c^2}\frac{z^2}{2}\right)\mathrm{d}z, \tag{6}$$

here the RF voltage in the middle cavity is $V_2=AE_0d$ and the first harmonic bunching current after the middle cavity can be given by

$$I_1(z,t)=2I_0J_1\left(\frac{\omega}{v_0}k_2z\right)\sin\left(\varphi_0+\frac{\omega}{v_0}z+\frac{\theta_0}{2}+\frac{\omega}{v_0}L_1\right), \tag{7}$$

here $k_2\approx\frac{eV_2}{mv_0^2}M_2(\theta_0)$ ($M_2(\theta_0)$ stands for the couple between the beam and the 2nd modulation cavity). Curves of the induced RF voltage versus the interaction length d in the middle cavity are shown in Fig. 3. It is shown that the RF field is approximately proportional to the first harmonic bunching current when beam enters the middle cavity, and the optimum

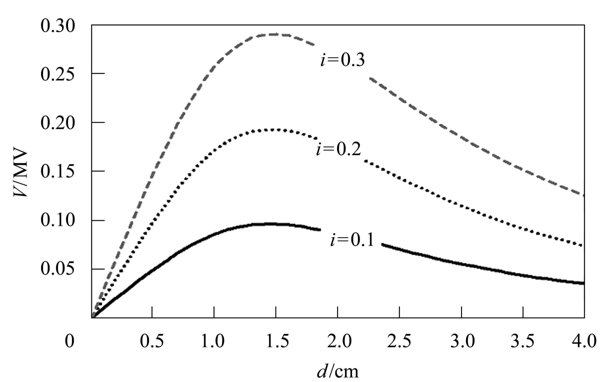

Fig. 3. Curves of the induced RF voltage in the middle cavity versus its interaction length d with different first harmonic current bunching factors.

interaction length is about 1.5 cm. The RF voltage of V_2=90 kV in the middle cavity can be excited when $i=0.1$ shown in Fig. 3.

3 High gain RKA structure

With the input power P_{in}=6.83 kW in Fig. 1 and the RF voltage V_1=0.9 kV in the modulation cavity, the first harmonic current bunching factor is only ∼1.1% after beam drifts 30 cm in the drifting tube, and the RF voltage up to V_2=9 kV is excited in the first middle cavity as shown in Fig. 4. The first harmonic current bunching factor reaches ∼11% after another 30 cm drifting. Then the RF voltage can reach V_3=90 kV in the second middle cavity as shown Fig. 4. Shown in Fig. 4 is a high-gain RKA structure, and Fig. 5 is the envelope curve of the RF output power versus time for the structure. The beam is intensively bunched before it enters the output cavity, and the output power is 1.1 GW as shown in Fig. 5 with the corresponding gain of 1.6×10^5.

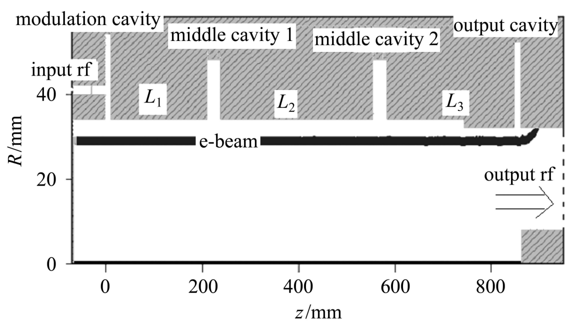

Fig. 4. A high gain RKA structure.

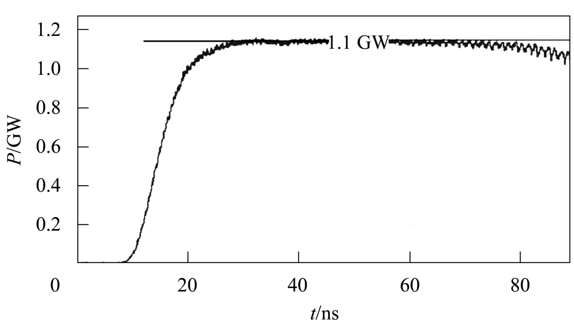

Fig. 5. Envelope of the rf power versus time.

4 Mode control

Theoretically middle cavities can decrease the required RF input power and increase the gain of RKA, meanwhile higher modes can also be excited because of middle cavities. The working mode will be seriously disturbed because of the excitation of these higher modes, and then the pulse shortening occurs. The threshold current for higher modes' excitation is inversely proportional to the number of middle cavities, so it is easy for higher modes to excite with several middle cavities. A special measure to avoid higher mode excitation is important for high gain klystron amplifiers, especially for HPM-typed klystron amplifiers, whose driven current is several kA.

Because of the guiding magnet field, electron beam moves very close to the tube wall as shown in Fig. 1 and 4. The axial electric field is very small along the beam path in the drifting tube, so interaction between beam and the rf field in the drifting tube is negligible. It can be explained that no higher modes' excitation in the structure of Fig. 1 is observed in PIC simulations. But strong axial electric field can be induced along the beam path with middle cavities when the RF wave passes them as shown in Fig. 4, 7 and 12. And higher modes will be excited due to the interaction between these kinds of axial electric fields and beam.

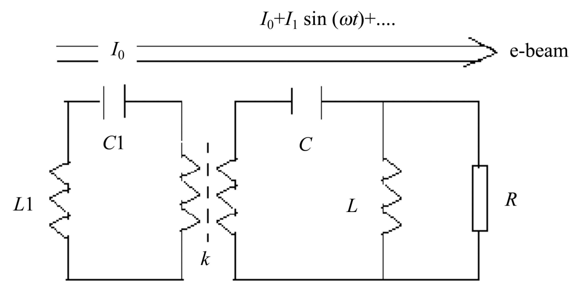

Fig. 6. Circuit model of positive feedback process for higher modes' excitation.

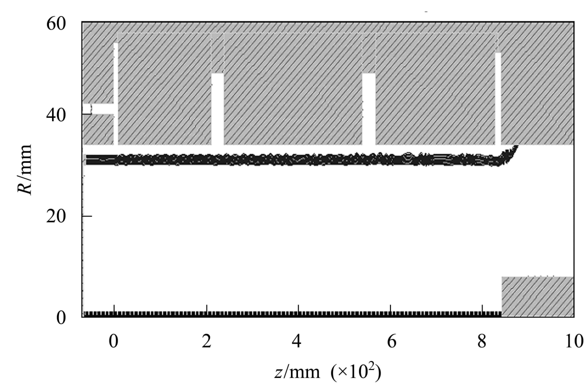

Fig. 7. A high gain RKA structure without special measures to avoid higher modes' excitation.

Higher mode excitation is a kind of self-excitation. The RF field is produced when the beam interacts with one cavity and some of its RF field energy is fed back to another cavity to further modulate the beam as shown in Fig. 6. Fig. 6 is the positive feedback circuit model for higher mode excitation where R denotes the RF power dissipated in the device. This feed back process is very important for higher modes to be excited. With frequency of the higher mode less than the cut-off frequency of the drifting tube, the feed back process is realized by backward electrons reflected from the output cavity. The threshold current for such higher mode' excitation can be significantly increased by adjusting Q-factor of the output cavity.

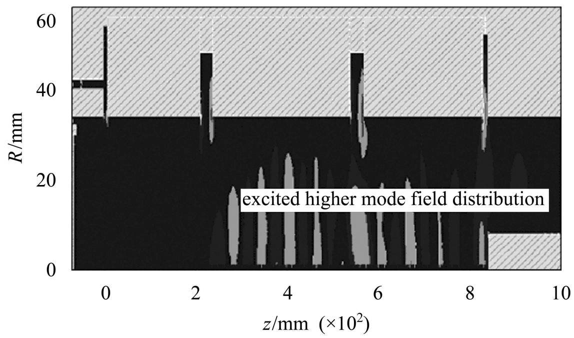

Fig. 8. Excited higher modes' field distribution in the device.

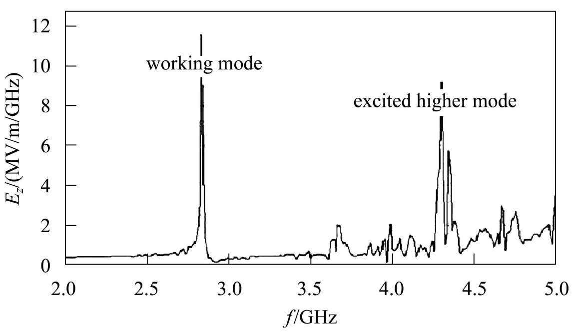

Fig. 9. Spectrum of the RF field in the first middle cavity.

With the frequency of higher modes larger than the cut-off frequency of the drifting tube, it is difficult to avoid the feed back process because the RF field in one cavity can easily be coupled to another. Higher mode excitation depends on two factors: the feed back process and interaction between the beam and the RF field shown in Fig. 6. The threshold current for higher mode can be increased by decreasing the couple between beam and some cavities in the structure shown in Fig. 4. The threshold of the structure shown in Fig. 4 is 8 kA, and its driving current is 5 kA. Fig. 7 is a high gain RKA structure without special measures to avoid higher modes' excitation, and its threshold is only 3 kA. Higher modes are excited as

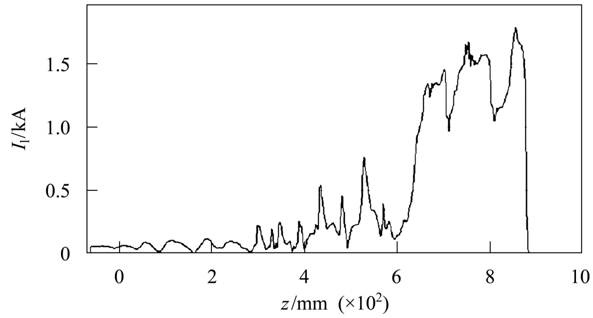

Fig. 10. Curve of first harmonic bunching current along the beam path with higher modes excited in the device.

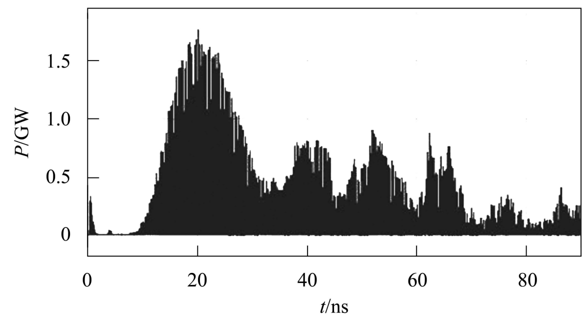

Fig. 11. Curve of the RF output power versus time with higher modes excited in the device.

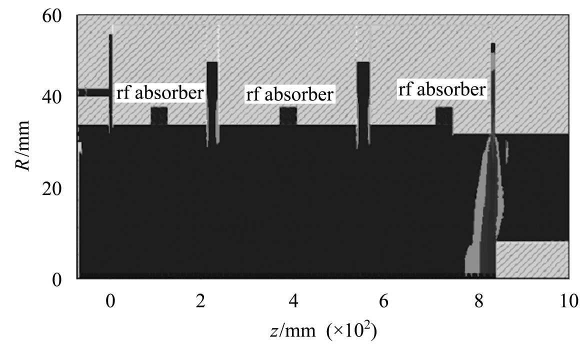

Fig. 12. A high gain RKA structure with RF absorbers to avoid higher modes' excitation.

shown in Fig. 8 when beam current is 5 kA. Fig. 8 is the higher mode field distribution when it excites in the device. Fig. 9 is the spectrum of the RF field along the beam path in the first middle cavity shown in Fig. 6. It is shown that the working mode with frequency of 2.85 GHz and higher modes with frequency of 4.3 GHz and 4.4 GHz are simultaneously excited in the first middle cavity. Fig. 10 shows the first harmonic bunching current along the beam path, and that the bunching process for the working mode is seriously disturbed. Fig. 11 is the RF output power versus time for the structure shown in Fig. 7, and pulse shortening occurs shown in Fig. 11. Because the frequency of the working mode is less than the cut-off frequency of the drifting tube, the threshold current for higher modes excitation can be further increased by putting the RF absorbers in the drifting tube as Fig. 12, and the working mode will not be affected. Fig. 12 is the high gain RKA structure with the RF absorbers put in the drifting tube to further avoid higher mode excitation. The threshold for the structure shown in Fig. 12 is 11 kA, which is significantly more than the driving current, and the output RF power also reaches 1.1 GW.

5 Conclusion

According to the positive feedback process for higher mode excitation, a special measure is taken in the high gain RKA, and higher modes' excitation is avoided when the threshold current for higher modes' excitation is significantly larger than the driving current. And a high gain RKA with gain of 1.6×10^5 and the RF output power of 1.1 GW is realized without higher modes' excitation in PIC simulations.

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