Mode control in a high gain relativistic klystron amplifier with 3 GW output power*

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Abstract: Higher mode excitation is very serious in the relativistic klystron amplifier, especially for the high gain relativistic amplifier working at tens of kilo-amperes. The mechanism of higher mode excitation is explored in the PIC simulation and it is shown that insufficient separation of adjacent cavities is the main cause of higher mode excitation. So RF lossy material mounted on the drift tube wall is adopted to suppress higher mode excitation. A high gain S-band relativistic klystron amplifier is designed for the beam current of 13 kA and the voltage of 1 MV. PIC simulation shows that the output power is 3.2 GW when the input power is only 2.8 kW.

Key words: high power microwave, relativistic klystron amplifier, high gain, mode control

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1 Introduction

Increasing effective radiation power of high power microwave (HPM) sources is one of the most important considerations of the HPM technologies [1]. It is clear that the peak power of a single HPM source is limited by plasma formation and breakdown inside the source. The most straightforward solution to overcome single source limitation is to generate the HPM from multiple power amplifiers driven by a relatively lower power master oscillator and combine their outputs through phased-array techniques. The relativistic klystron amplifier (RKA) is a potential HPM source to realize power combination as it has some significant advantages [2]. The key issue in the power combination is designing high power, high gain RKA while controlling the tendency to break into self-oscillation. Compared with the conventional klystron amplifier, whose driving current is several amperes, the driving current for RKA is several kilo-amperes, so higher mode excitation is very serious in RKA, especially for the high gain RKA. There are many possible causes to drive tube oscillation, such as retrograde electrons returning from the output cavity due to excessive output cavity voltage [3], monotron oscillation [4] and mode coupling [5, 6].

The high gain RKA, with a gain of 60.6 dB and an output power of 3.2 GW, is designed to produce an S-band high power microwave radiation. In Section 2, a high gain RKA structure is presented; the mechanism of higher mode excitation is explored in the PIC simulation. In Section 3, RF lossy material is introduced to suppress higher mode excitation; mode control is realized in the simulation with an RF output power of 3.2 GW. Finally, some conclusions are given in Section 4.

2 Physics model and higher mode excitation

The structure of the high gain RKA is shown in Fig. 1. An annular electron beam with a voltage of 1 MV and current of 13 kA is injected into a drift tube from an explosive emission cathode. The beam is modulated by a modulating cavity driven by an external RF source and bunched in the drift tube. Two middle cavities are mounted on the drift tube to further increase current modulation. The beam is intensively bunched when it enters the output cavity and slowed down by the RF field in the output cavity, then the kinetic energy of the beam is converted into RF radiation.

Theoretically including more middle cavities can increase the gain of RKA, whereas higher modes can also be excited because of middle cavities. If no measure is taken to avoid higher modes excitation, the working mode is disturbed, as shown in Fig. 2. From the electric field distribution in Fig. 1, it can be observed that the higher mode is mainly located between two middle cavities. Fig. 3 is the spectrum of the electric field in

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the second middle cavity. Besides the working frequency and its second harmonic, there are two other tips in the curve, whose frequencies are 4.25 GHz and 4.72 GHz, respectively. The higher modes in the middle cavities are proved to be TM02 modes, which are converted into TM01 modes in the drift tube.

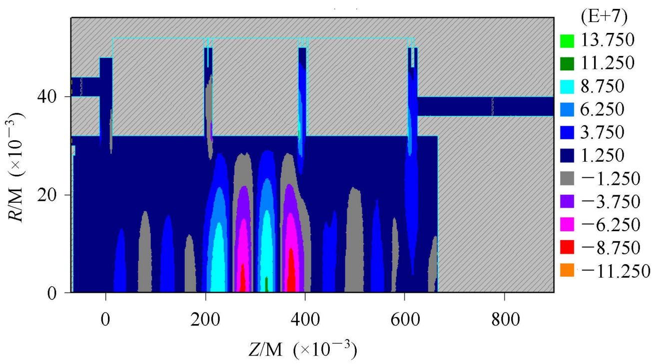

Fig. 1. High gain RKA structure and its electric field distribution.

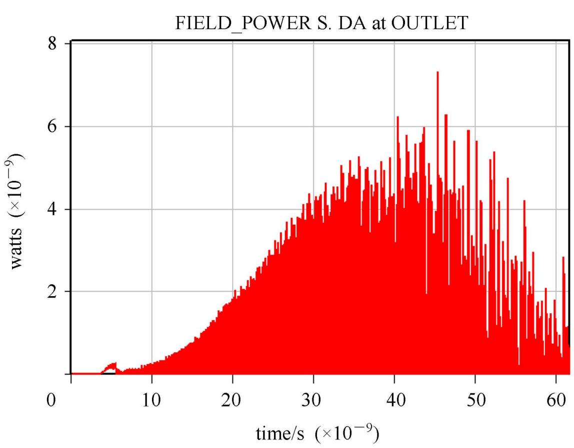

Fig. 2. RF output power in the RKA without mode control.

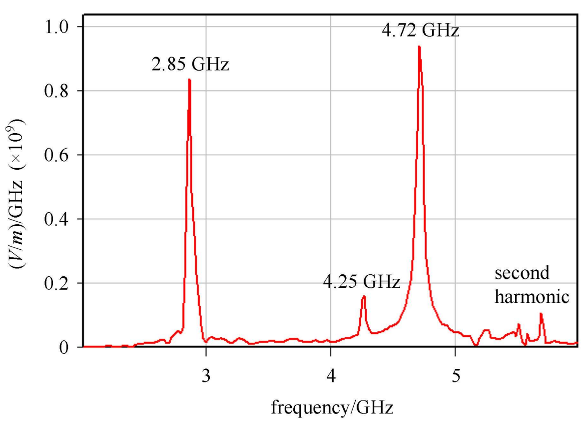

Fig. 3. Spectrum of the electric field in the middle cavity 2.

The RF field leaked from the second middle cavity to the first middle cavity forms a positive feedback loop for the higher mode to be excited. Similar to the Bitron [7], the beam is modulated by the first cavity and excites a strong RF field in the second cavity. Some of its RF field energy in the second cavity is fed back to the first cavity to further modulate the beam. The circuit model is shown in Fig. 4.

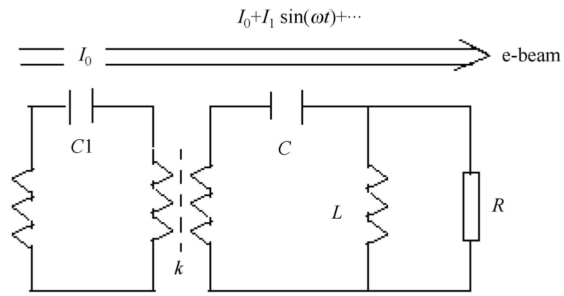

Fig. 4. Circuit model of the positive feedback process for higher mode excitation.

The formula for the startup current of the higher mode deduced from this circuit model is given by [8],

$$I_{\text{startup}}=-\frac{I_{\text{A}}}{4\pi}\frac{\beta^3\gamma^3}{\omega\varepsilon_0\rho\cdot Q}\frac{1}{L_{\text{d}}\sin\left(\dfrac{\omega}{v_0}L_{\text{d}}+\varphi_{\text{c}}\right)},\tag{1}$$

where $I_{\text{A}}=4\pi\varepsilon_0 m_0 c^3/e=17.1$ kA is the Alfven current, ρ is the characteristic impedance of the middle cavity, L_{d} is the drift tube length between the two middle cavities and φ_{c} is a phase term depending on the excited higher mode. It is shown that when $\dfrac{\omega}{v_0}L_{\text{d}}=\left(n+\dfrac{1}{2}\right)\pi$ (n is even), the higher modes which have the opposite direction of the electric field in the cavity gap are easy to be excited. Moreover, when $\dfrac{\omega}{v_0}L_{\text{d}}=\left(n+\dfrac{1}{2}\right)\pi$ (n is odd), the higher modes which have the same direction of the electric field in the cavity gap are easy to be excited.

3 Mode control

Equation (1) reveals that the startup current of the higher mode is inversely proportional to the Q-factor, so we can decrease the Q-factor of the higher modes to increase the threshold current. Because the frequency of the working mode is less than the cut-off frequency of the drift tube, the threshold current for higher modes excitation can be increased by putting the RF lossy material on the drift tube wall, as shown in Fig. 5, then the working mode will not be affected [9]. As shown in Fig. 3, the higher mode of a frequency of 4.72 GHz is the dominant parasitic mode in the amplifier. So we need to find the lossy material which has the maximum attenuation of the mode with the frequency of 4.72 GHz in the simulation.

The schematic diagram of the drift tube with a lossy layer is shown in Fig. 5. The outer and inner radius of the lossy layer are labeled as b and a, respectively. Moreover, the thickness of the lossy layer is labeled as t. For sinusoidal traveling waves propagating along the longitudinal axis z of the cylindrical coordinate system, the field distribution can be written as $e^{(j\omega t-\gamma z)}$, where γ is the propagation constant. Here we introduce a quantity α, equal to the real part of γ. This quantity is the so-called attenuation constant.

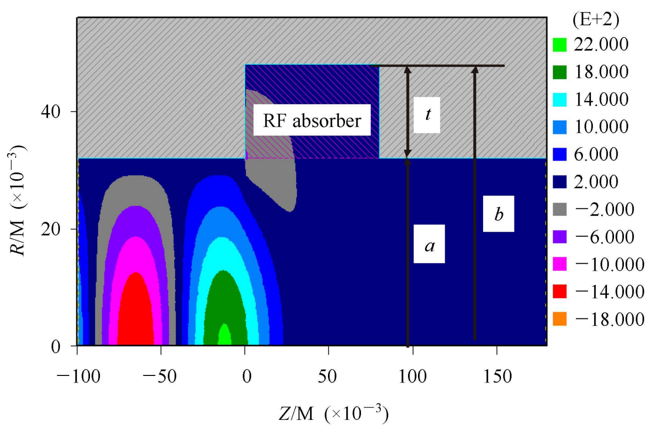

Fig. 5. Higher mode field distribution in the drift tube with lossy material.

The dispersion relation of a circular waveguide with a lossy layer is given by [10],

$$\left(\frac{\varepsilon_r}{k_{c2}}\frac{Q'(k_{c2}a)}{Q(k_{c2}a)}-\frac{1}{k_{c1}}\frac{J_n'(k_{c1}a)}{J_n(k_{c1}a)}\right)$$
$$\times\left(\frac{1}{k_{c2}}\frac{P'(k_{c2}a)}{P(k_{c2}a)}-\frac{1}{k_{c1}}\frac{J_n'(k_{c1}a)}{J_n(k_{c1}a)}\right)$$
$$+\left(\frac{1}{k_{c1}^2}-\frac{1}{k_{c2}^2}\right)\frac{\gamma^2n^2}{k^2a^2}=0, \tag{2}$$

where n is the angular mode number, $J_n(x)$ is the Bessel function of the first kind with n order, $N_n(x)$ is the Bessel function of the second kind with n order and ε_r is the relative permittivity of the material, defined as $\varepsilon_r=1-\dfrac{j\sigma}{\omega\varepsilon_0}$. Moreover, the functions $Q(x)$ and $P(x)$ in Eq. (2) are defined as,

$$Q(x) = J_n(x)N_n(k_{c2}b)-N_n(x)J_n(k_{c2}b),$$
$$P(x) = J_n(x)N_n'(k_{c2}b)-N_n(x)J_n'(k_{c2}b), \tag{3}$$

where $k_{c1}^2=\omega^2\mu_0\varepsilon_0+\gamma^2$, $k_{c2}^2=\omega^2\mu_0\varepsilon_0\varepsilon_r+\gamma^2$.

Figure 6 is the attenuation constant versus the thickness of the lossy layer with a different electric conductivity. It is shown that when t/δ equals 1.6, the attenuation constant reaches the maximum (δ is called the skin depth). Fig. 7 is the attenuation constant versus the electric conductivity of the lossy layer with t/δ=1.6. In order to have the maximum attenuation, we select the electric conductivity of 0.5 as our RF lossy material with attenuation constant of 30 Np·m^{-1}. For the higher mode of frequency of 4.72 GHz, the skin depth is 1 cm. Then the thickness of the lossy layer is t=1.6 δ=1.6 cm.

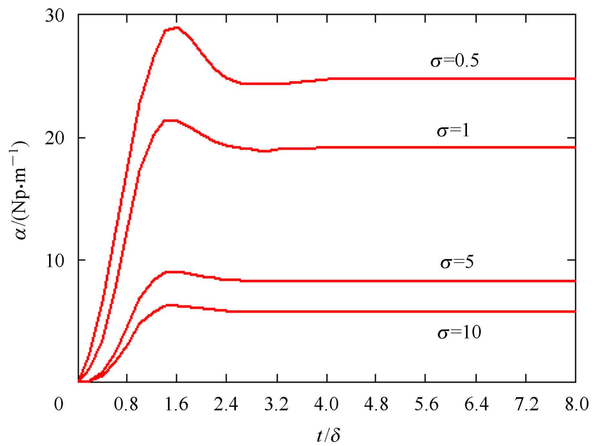

Fig. 6. Attenuation constant vs. the thickness of the lossy layer.

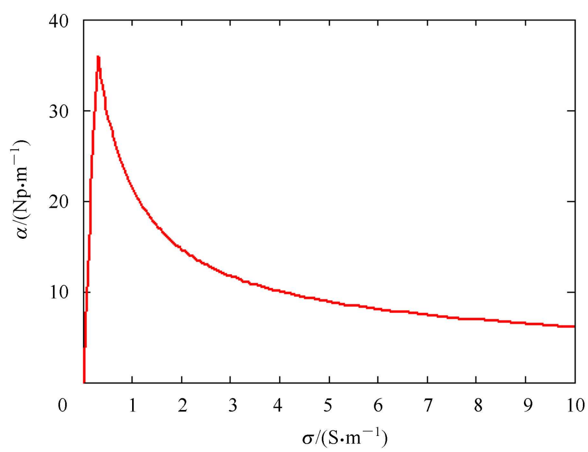

Fig. 7. Attenuation constant vs. the electric conductivity of the lossy layer.

The length of the lossy layer is determined by the PIC code, as shown in Fig. 8. When the length is 8 cm, the Q-factor of the parasitic mode is 50. Compared with the state without lossy material, the Q-factor is decreased by 2.6 times. So the startup current can be significantly increased and the higher mode excitation can be suppressed.

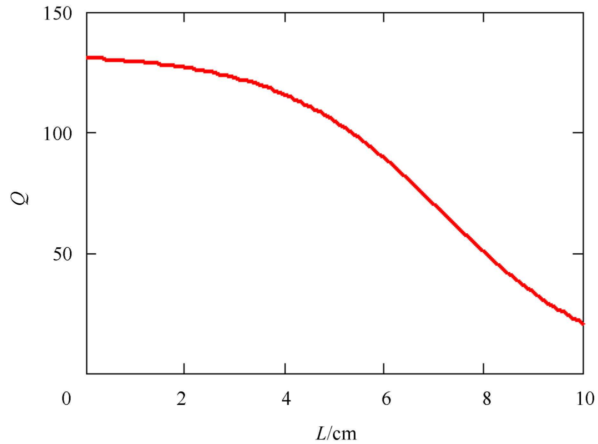

Fig. 8. Q-factor of the dominant higher mode vs. the length of the lossy layer.

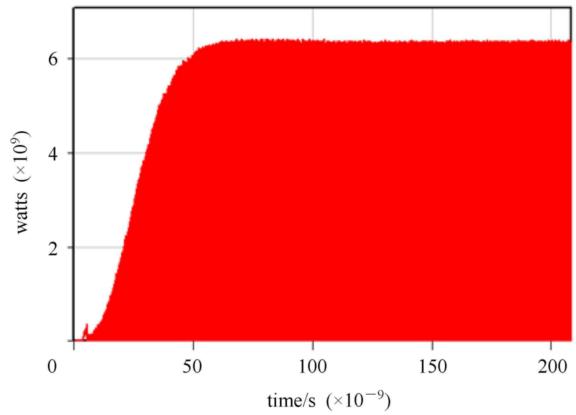

Fig. 10. RF output power versus time.

A new high gain RKA is designed with RF lossy material as shown in Fig. 9. Fig. 10 is the RF output power versus the time. It is shown that the RF output power is 3.2 GW and the corresponding gain of the device reaches 60.6 dB. Fig. 11 is the spectrum of the electric field in the second middle cavity. It is clearly shown that higher mode excitation is suppressed in the spectrum.

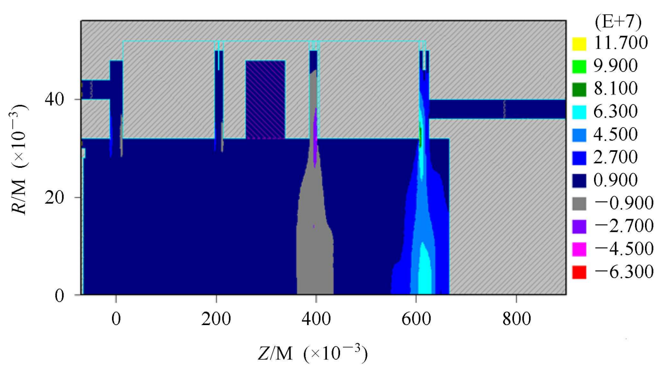

Fig. 9. Electric field distribution in the high gain RKA with mode control.

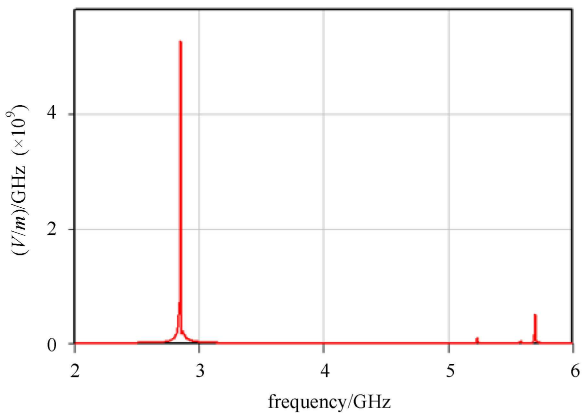

Fig. 11. Spectrum of the electric field in the middle cavity 2.

4 Conclusions

RF field leakage and insufficient separation of adjacent cavities are confirmed as the main causes of higher mode self-excitation in the high gain relativistic klystron amplifier. The RF lossy material is introduced to suppress the higher mode excitation. The relations of the attenuation characteristics with thickness, electric conductivity and length of the lossy layer are studied. An output power of 3.2 GW with the efficiency of 24.6% and a gain of 60.6 dB is obtained in the simulation. The corresponding experiment will be carried out in the near future.

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