Design of a C-band relativistic extended interaction klystron with coaxial output cavity

WU Yang(吴洋)[1,2] ZHAO De-Kui(赵德奎)[3] CHEN Yong-Dong(陈永东)[3]

[1] Institute of Applied Electronics, China Academy of Engineering Physics, Mianyang 621900, China
[2] Science and Technology on High Power Microwave Laboratory, Mianyang 621900, China
[3]Sichuan University of Science and Engineering, Zigong 643000, China

Abstract: In order to overcome the disadvantages of conventional high frequency relativistic klystron amplifiers in power capability and RF conversion efficiency, a C-band relativistic extended interaction klystron amplifier with coaxial output cavity is designed with the aid of PIC code MAGIC. In the device, disk-loaded cavities are introduced in the input and intermediate cavity to increase the beam modulation depth, and a coaxial disk-loaded cavity is employed in the output cavity to enhance the RF conversion efficiency. In PIC simulation, when the beam voltage is 680 kV and current is 4 kA, the device can generate 1.11 GW output power at 5.64 GHz with an efficiency of 40.8%.

Key words: high power microwave, C-band, relativistic extended interaction klystron, PIC simulation

PACS: 41.20.-q, 41.20.Jb, 41.60.Dk **DOI:** 10.1088/1674-1137/39/7/077005

1 Introduction

Combining the output powers from multiple phase locked high power amplifiers or oscillators is considered an effective way to increase the radiation power of high power microwave (HPM) systems [1]. High power amplifiers, especially the relativistic klystron amplifier (RKA) driven by intense electron beams, are among the most promising HPM sources to realize coherent power combining, due to their good performance in frequency and phase control [2–5]. Although the RKA has many advantages, it also suffers from quite severe limitations such as low RF conversion efficiency and low power handling capability [6]. These limitations become more severe in the high frequency regime because the size of the RKA is inversely proportional to the working frequency. As the frequency increases, the radius of the drift tube decreases while the current density increases. This leads to potential energy increase and conversion efficiency degradation. Moreover, the gap length of the resonant cavity also decreases with the increase of the frequency, and the probability of RF breakdown increases. In order to overcome these disadvantages of the conventional RKA, a C band relativistic extended interaction klystron (REIK) with a coaxial output cavity is designed in this paper with the aid of PIC code MAGIC [7]. An output power of 1.11 GW with an efficiency of 40.8% is obtained in the simulation. The remainder of the paper is organized as follows. In Section 2, we present the REIK structure and a detailed description of the simulation results. In Section 3, a comparison between the single gap output cavity, the disk-loaded cavity and the coaxial disk-loaded cavity is given, and a method to enhance the efficiency is also investigated. Finally, some conclusions are given in Section 4.

2 Physics model and simulation results

The structure of the C-band REIK is shown in Fig. 1. An annular electron beam with a voltage of 680 kV and a current of 4 kA is used in the simulation. The beam is modulated by a modulating cavity and further modulated by an intermediate cavity. When the beam enters the output cavity, it is intensively bunched with a modulation depth of 100%. Then the beam gives out kinetic energy to the RF field. The biggest difference compared with conventional RKA is that the reentrant pillbox cavity is replaced by a disk-loaded slow wave structure to enhance the modulation depth and reduce the electric field [8, 9]. Another difference is that a coaxial disk-loaded cavity is employed in the output cavity to decrease the potential energy and enhance the conversion efficiency [10, 11]. The geometrical parameters of the structure are listed in Table 1.

Table 1. Geometrical parameters of C-band REIK.

	$r_{\rm in}$/cm	$r_{\rm out}$/cm	d/cm	p/cm
input cavity	2.0	3.0	0.3	0.9
intermediate cavity	1.7	2.4	0.3	0.9
output cavity	2.1	2.9	0.3	0.8

Received 28 September 2014, Revised 18 January 2015

When the input power is 320 kW, the RF output power reaches 1.11 GW with an efficiency of 40.8% and frequency of 5.64 GHz. The corresponding gain is 35.4 dB. Fig. 2 is the RF output power versus time. Fig. 3 is the spectrum of the output electric field.

The modulating efficiency of a single gap cavity and disk-loaded cavity are compared as shown in Fig. 4. With the same input RF power of 320 kW, the fundamental harmonic current reaches about 500 A at a distance of 40 cm when the input cavity employs the disk-loaded cavity, while in the other case the fundamental harmonic current is only about 200 A.

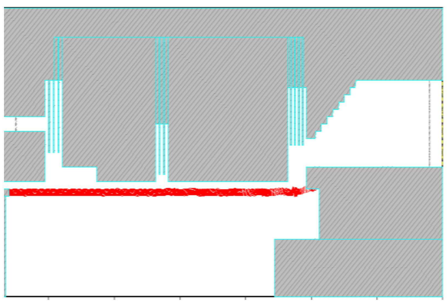

Fig. 1. (color online) Model of C-band REIK.

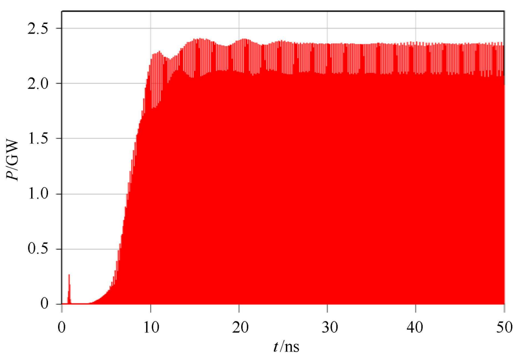

Fig. 2. (color online) RF output power versus time.

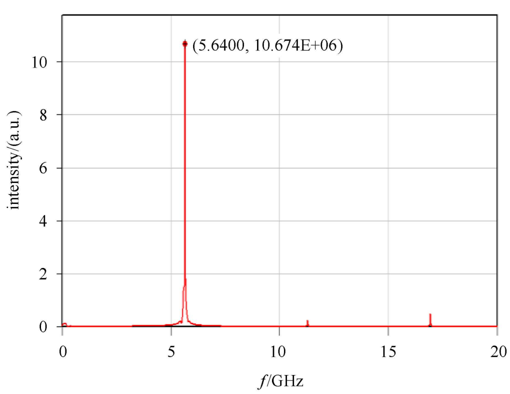

Fig. 3. (color online) Spectrum of the output electric field.

Figure 5 is the axial electric field distribution in the device with the output cavity employing the single gap cavity and the coaxial disk loaded cavity. Since the geometrical parameters of the modulating cavity and the intermediate cavity are exactly the same in the two structures, the axial electric field is almost the same in these cavities in the two structures naturally. But the electric field in the output cavity has a significant difference. It can be found that the structure with the coaxial disk-loaded cavity has a lower electric field than the structure with the single gap cavity.

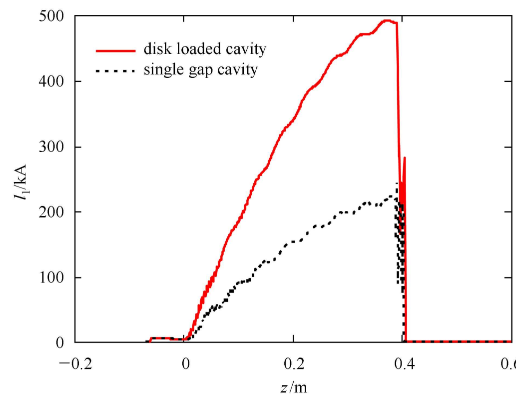

Fig. 4. (color online) Fundamental harmonic current modulated by single gap cavity and disk-loaded cavity.

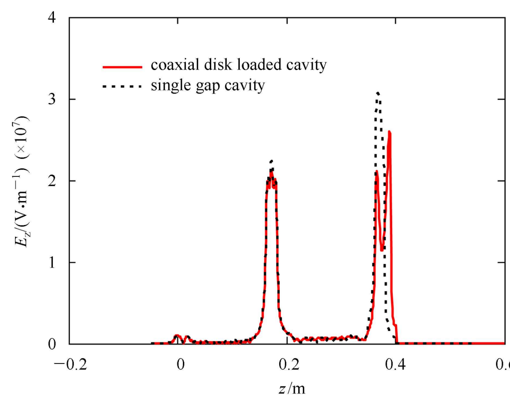

Fig. 5. (color online) Axial electric field amplitude with single gap output cavity and coaxial disk-loaded output cavity.

3 Comparative study of three types of output structures

Output cavities are the most important parts of the RKA, as they take full responsibility for converting the kinetic energy of the electron beam to RF power. It is clear that when the electrons propagate through the output cavity gap, a part of their kinetic energy will convert to potential energy. In an intense electron beam regime, the potential energy is comparable in size to the kinetic energy. Since the conversion efficiency of the device depends on the amount of kinetic energy that we can extract from the electron beam, a potential depression of

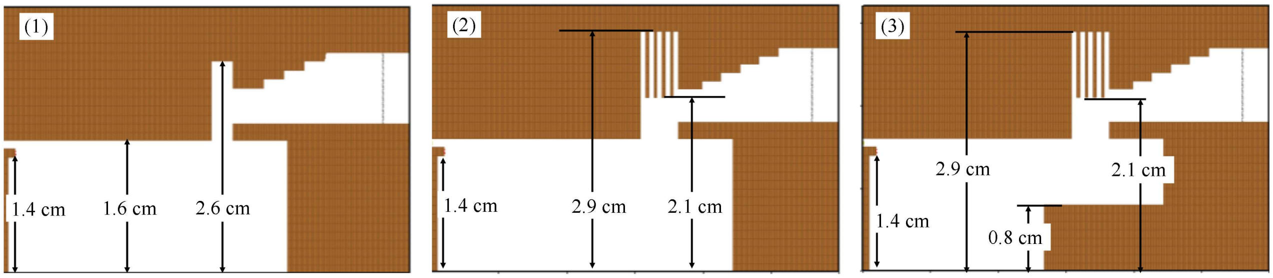

Fig. 6. (color online) Models of three types of output structures: (1) single gap cavity; (2) disk-loaded cavity; (3) coaxial disk-loaded cavity.

the beam would significantly degrade the conversion efficiency. In this section, we present a detailed comparative study on three types of output structure: (1) single gap cavity, (2) disk-loaded cavity and (3) coaxial disk-loaded cavity, to examine techniques to eliminate or mitigate potential depression of the beam. The models of the three types of output structures are shown in Fig. 6. In order to have the maximum extraction efficiency, each structure's dimensional parameters have been optimized in the PIC simulation. The radial dimensions of the structures are labeled in the figure.

Firstly, we examine the kinetic energy distribution with the DC current injection in three types of structures. The radius of the annular electron beam is 1.4 cm. The injection voltage is 680 kV, and the current is 4 kA. The kinetic energy distributions are shown in Fig. 7. As shown in the figure, due to the wall discontinuity, an electron beam passing through the output cavity gap requires a larger amount of potential energy than that passing through the drift pipe. So there is a trough in the kinetic energy distribution curve in each case. However, owing to the different radial boundary conditions, the drop in kinetic energy is different in each case. It can be found that the electron beam passing through the hollow cavity requires the largest potential energy, and the coaxial disk-loaded cavity requires the least, while the requirement in the disk-loaded cavity is moderate. Although the disk-loaded cavity has a larger radius of outer wall than the hollow cavity, the disk period is very short compared with the space charge wavelength. The disks operate as a conducting plane to short out the potential difference between the outer wall and the beam. Therefore, the potential depression depends on the inner radius of the disks rather than the outer wall radius. So the beam in the disk-loaded cavity requires less potential energy than that in the hollow cavity. By the aid of an inner conductor, the potential depression is further suppressed.

These simulated results can be explained in theory [12]. The potential of an annular beam injected at a radius $r_{\rm b}$ with initial gamma $\gamma_{\rm inj}$ into a hollow pipe of radius r_2 and into a coaxial pipe of outer radius r_2 and inner radius r_1 are given below, respectively.

$$\varphi(r_{\rm b})=\begin{cases}\dfrac{I_0}{2\pi\varepsilon_0 v_{\rm b}}\ln\left(\dfrac{r_2}{r_{\rm b}}\right) & \text{(hollow pipe)}\\[2ex] \dfrac{I_0}{2\pi\varepsilon_0 v_{\rm b}}\ln\left(\dfrac{r_2}{r_{\rm b}}\right)\cdot\dfrac{\ln\left(\dfrac{r_{\rm b}}{r_1}\right)}{\ln\left(\dfrac{r_2}{r_1}\right)} & \text{(coaxial pipe)}\end{cases}. \tag{1}$$

Here I_0 is the beam current, ε_0 is the vacuum permittivity, and $v_{\rm b}$ is the beam velocity in the pipe, which can be solved from the energy partition equation.

$$\gamma_{\rm inj}=\gamma_0+\frac{I_0}{I_{\rm s}\beta_0}. \tag{2}$$

Here γ_0 is the Lorentz factor of the beam, and $I_{\rm s}$ is a normalized threshold current defined as,

$$I_{\rm s}=\begin{cases}\dfrac{2\pi\varepsilon_0 m_0 c^3}{e\ln\left(\dfrac{r_2}{r_{\rm b}}\right)} & \text{(hollow pipe)}\\[2ex] \dfrac{2\pi\varepsilon_0 m_0 c^3}{e\ln\left(\dfrac{r_2}{r_{\rm b}}\right)\cdot\dfrac{\ln\left(\dfrac{r_{\rm b}}{r_1}\right)}{\ln\left(\dfrac{r_2}{r_1}\right)}} & \text{(coaxial pipe)}\end{cases}. \tag{3}$$

Thus, integrating Eq. (1) and Eq. (2), the potential energy in the hollow pipe and in the coaxial pipe with different injection radii can be obtained as shown in Fig. 8. There are three curves in the figure: the dotted line is the potential energy in the hollow pipe with a radius of 2.6 cm, the dashed line is the same case with a radius of 2.1 cm, and the solid line is the potential energy in the coaxial pipe with an outer and inner radius of 2.1 cm and 0.8 cm, respectively. As shown in the figure, in the hollow pipe the potential energy increases monotonically with the increase of distance between beam and outer wall, while the case with the coaxial pipe is significantly different. The potential energy vanishes when the beam is close to the outer or inner wall, and it has a maximum when the beam radius is selected to an in-between value. Particularly, when the beam radius is 1.4 cm, the potential energy in the coaxial pipe is about 63 keV, the potential in the hollow pipe of radius 2.1 cm is about 110 keV, and that in the hollow pipe of radius 2.6 cm is about 170 keV. The results agree well with the kinetic energy drop in Fig. 7.

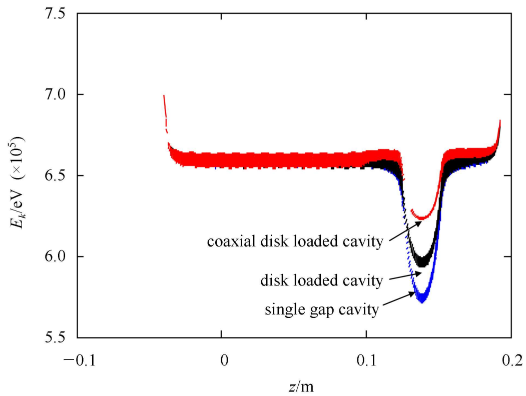

Fig. 7. (color online) Kinetic energy distribution in three types of output structures.

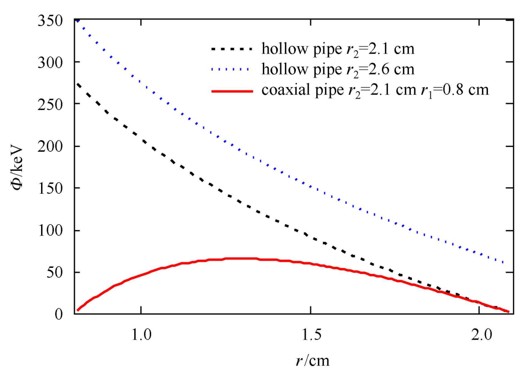

Fig. 8. (color online) Potential energy in hollow pipe and in coaxial pipe with different injected radius.

Since the maximum available kinetic energy in the three types of structures is different, we can expect that the output characteristics of the RKA employing these structures would behave differently. Fig. 9 shows the output powers of three types of output cavities with the same input and modulating structure. As the Q-factors of the three structures differs a little, the saturation times of the output power are very close to each other, but the output power differs significantly. The coaxial disk-loaded cavity has the maximum output power as it has the maximum kinetic energy that can be extracted. The simulation results are generally consistent with the potential analysis, although the exact difference of output power in numbers is not equal to the difference in available kinetic energy.

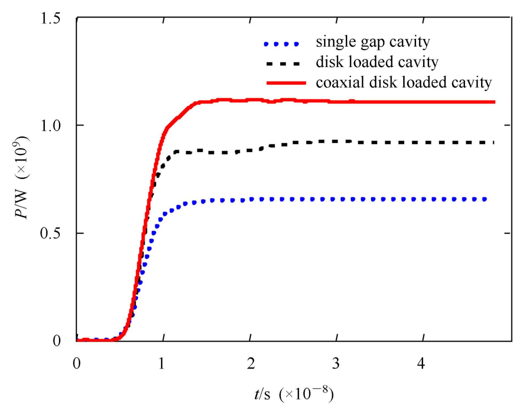

Fig. 9. (color online) Output RF power of three types of output structures.

4 Conclusions

In this paper, a C-band REIK is proposed and investigated in theoretical analysis and PIC simulation. Under conditions of a beam voltage of 680 kV and a current of 4 kA, a microwave power of 1.11 GW with an efficiency of 40.8% is obtained in the simulation. Moreover, the potential depression and the RF conversion efficiency of three types of output structures are compared and studied. It is proved that the coaxial disk-loaded output cavity has the highest conversion efficiency of 40.8% among the three, due to DC space charge potential energy suppression at the gap with the aid of disks and inner conductors.

References

1 Friedman M, Krall J, Lau Y Y et al. J. Appl. Phys., 1988, **64**: 3353
2 Caryotakis G. Phys. Plasmas, 1998, **5**: 1590
3 WU Yang, XIE Hong-Quan, LI Zheng-Hong et al. Phys. Plasmas, 2013, **20**: 113102
4 LI Zheng-Hong, ZHANG Hong, JU Bing-Quan et al. Chinese Physics C, 2010, **34**(5): 598
5 CHEN Yong-Dong, JIN Xiao, LI Zheng-Hong et al. High Power Laser and Particle Beams, 2012, **24**(9): 2151 (in Chinese)
6 Carlsten B E, Faehl R J, Fazio M V et al. IEEE Trans. Plasma Sci., 1996, **22**: 719
7 Goplen B, Ludeking L, Smithe D. MAGIC User's Manual. Newington, VA: Mission Research Corp., 1996
8 WU Yang, LI Zheng-Hong, HUANG Hua et al. High Power Laser and Particle Beams, 2010, **22**(3): 625 (in Chinese)
9 WU Yang, XU Zhou, ZHOU Lin et al. Acta Phys. Sin., 2012, **61**(22): 224101 (in Chinese)
10 Friedman M, Serlin V, Lampe M et al. Phys. Rev. Lett., 1995, **74**: 322
11 HUANG Hua, MENG Fan-B, FAN Zhi-Kai et al. Acta Phys. Sin., 2006, **55**(10): 5344 (in Chinese)
12 Carlsten B E, Faehl R J, Fazio M V et al. IEEE Trans. Plasma Sci., 1994, **22**: 730