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ABSTRACT
The radial transit time oscillator (RTTO) is promising to realize high power output of millimeter-waves. Although the radial structure can enhance the power capacity, less cavities and small radial dimension make it difficult to improve the power capacity in RTTOs, especially in the extraction cavity. A one-gap extraction cavity in the Ka-band RTTO is proposed in this paper to improve the power capacity. Without electrons, taking the TM_{011} cavity as an example, the radial reversal resonant electric field can intersect with radial electrons. By choosing the sizes of the cavity, the synchronization of the electrons and the electric field can be realized to achieve effective energy exchange. In particle-in-cell simulation, the RTTO with the TM_{011} extraction cavity can output 1.0 GW high power microwaves (HPMs) at 31.2 GHz, and the beam-wave conversion efficiency is 31.6%. The maximum electric field in the TM_{011} cavity is only 800 kV/cm, which is less than one third that in the TM_{010} extraction cavities. In addition, the TM_{012} extraction cavity is employed to improve the efficiency to 35.4%. At the same time, because of the increase in the output power, the maximum radial electric field in the TM_{012} cavity increases to 850 kV/cm. Therefore, the one-gap extraction cavity can realize multiple energy exchanges to get high beam-wave conversion efficiency and enhance the power capacity in the extraction cavity significantly.

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I. INTRODUCTION

As the high power microwave (HPM) technology is widely used in many fields, considering the advantages of millimeter-waves, realizing high power millimeter-wave coherent electromagnetic radiation is getting more attention. However, the low power capacity and the mode competition restrict the use of axial devices in high power millimeter-wave generation. The radial generator based on the transit-time effect was proposed by Arman. In radial lines, as electrons move along the radial direction, the number density will decrease and the space-charge effect will be weakened. As a result, the power capacity will be significantly improved. Besides, the lower diode impedance of the radial device is good for production of HPMs. Therefore, radial devices have potential to output high power millimeter-waves. In simulation, the radial transit time oscillator (RTTO) can realize Ka-band HPMs output and enhance power capacity significantly. Within a certain range, the thickness or the axial position offset of the electron beam will not influence the steady operation of Ka-band RTTOs. In addition, change of the radial guiding magnetic field has little effect on the performance, too. With these characteristics, the RTTO is promising to output high power millimeter-waves.

Unfortunately, some factors limit the power capacity in the RTTO. First, taking the ohmic loss into consideration, the radial size should be restricted within some acceptable range. Second, the number of cavities is less than that in the radial relativistic backward oscillator (RBWO), which will decrease the space of the beam-wave intersection region. According to the current research result, the maximum radial electric field usually occurs in the extraction cavity. Therefore, improving the power capacity in the extraction cavity is crucial for the application of the RTTOs. In axial devices, the TM_{021} extraction cavity was employed to improve the power capacity, which may be worth trying in the radial Ka-band oscillator.

In this paper, a one-gap extraction cavity is proposed in the giga-watt Ka-band RTTO to enhance the power capacity. This
paper is organized as follows: In Sec. II, without electrons, the characteristics of the TM$_{011}$ cavity are analyzed. The performance of the RTTO with the TM$_{011}$ cavity is discussed in Sec. III. The RTTO with the TM$_{010}$ extraction cavity is studied in Sec. IV. Finally, the research results are summarized in Sec. V.

II. CHARACTERISTICS OF THE TM$_{011}$ CAVITY

The multiple-gap extractor with the π mode of the radial TM$_{01}$ can work effectively in the Ka-band RTTO to realize the giga-watt class high efficiency output of HPMs, and this has been published in Ref. 15. Based on this result, we hope that the one-gap extraction cavity can realize the function of the multiple cavities and improve the power capacity. For simplicity, we carried out the research on the TM$_{011}$ extraction cavity first and compared it with the two TM$_{010}$ extraction cavities. Without electrons, the characteristics of the extractor are the foundation of effective beam-wave intersection, which will be analyzed in this section.

A. Distribution of the electric field in the TM$_{011}$ cavity

The distribution of the resonant electric field in the one-gap TM$_{011}$ cavity and the two TM$_{010}$ cavities is given in Fig. 1. The resonant frequency of the cavities is 31.3 GHz, and there are standing waves in both circumstances. The distribution of the electric field in the TM$_{011}$ cavity is the same as that in the two TM$_{010}$ cavities. Considering that the cavities with the radial TM$_{010}$ mode have been used to realize high power output, the one-gap TM$_{011}$ cavity can also be employed in RTTOs as the extraction cavity.

The components of the resonant electric field with the TM$_{011}$ mode along the axis centerline in the cavity are illustrated in Fig. 2. It can be seen that the axial electric field is zero, and the radial electric field reverses once. Therefore, this electric field can intersect with the radial electrons to realize energy exchange. In addition, selecting the axial size of the electron channel to be less than $\lambda_g/2$ ($\lambda_g$ is the guide wavelength of the outputted HPMs), the TM$_{011}$ mode will be cutoff, and this is also proved in Fig. 2.

Comparison of the radial electric fields in the two extractors is shown in Fig. 3, and the amplitude of the radial electric field at both ends of the cavities is normalized. The distribution of the radial electric field in the TM$_{011}$ cavity is the
same as that in the TM\(_{010}\) cavities, but the amplitude of the radial electric field in the TM\(_{011}\) cavity is smaller, which demonstrates that the beam-wave efficiency of the RTTO with the TM\(_{011}\) cavity will be a little lower and the power capacity will be higher.

B. Analysis of energy exchange

To realize effective beam-wave intersection in extractors, the speed of the electron beam \(v_e\) should be close to the phase speed of the radio frequency (RF) field \(v_p\), and \(v_e \geq v_p\). The phase speed of the RF electric field can be calculated to be

\[
v_p \approx \frac{2\pi f L_c}{c}.
\]

where \(f\) is the frequency of the guiding waves, which can be expressed as \(f = c/\lambda_g\), where \(c\) is the speed of the light in a vacuum. For the TM\(_{011}\) cavity, \(L_c\) is the radial size, and \(L_c = R_o - R_i\), where \(R_o\) is the outer radius of the cavity and \(R_i\) is the inner radius. \(\varphi\) is the phase-shift over the cavity, and \(\varphi = 2\pi\) for the TM\(_{011}\) mode. Considering that the electron beam voltage is 406 kV, the speed of electrons can be calculated to be \(v_e = 0.83c\). Therefore, we can get \(L_c = 0.83\lambda_g\). Based on the fixed value of \(L_c\), the axial size of the cavity \(D_c\) will be adjusted to make the resonant frequency of the electric field in the extraction cavity close to that of the RF electric field in the buncher. Usually, \(D_c = 0.6\lambda_g\sim 0.8\lambda_g\). Here, we choose \(L_c = 8.0\) mm and \(D_c = 6.6\) mm. Selecting sizes of the TM\(_{010}\) cavities in the same way, it can be calculated that the space of the beam-wave intersection region in the TM\(_{011}\) cavity is larger than that in the TM\(_{010}\) cavities.

The beam-loading conductance ratio \(G_e/G_0\) from small signal theory is usually employed to scale the energy transfer between electrons and electric fields. The amplitude of \(G_e/G_0\) is in direct proportion to the exchange energy. The \(G_e/G_0\) can be calculated as

\[
G_e/G_0 = -\frac{\beta_e}{4} \frac{\partial M^2}{\partial \beta_e},
\]

where \(M\) is the gap coupling coefficient, and it is decided by the distribution of the radial electric field. The electron phase shift constant \(\beta_e\) is related to the frequency of microwaves and the diode voltage.

From the distribution of the radial electric field in Fig. 3, the beam-loading conductance ratio vs the electron phase shift constant for the two extractors is given in Fig. 4. It can be seen that the sign of \(G_e/G_0\) for the TM\(_{011}\) cavity is the same as that in the TM\(_{010}\) cavities, and the amplitude of the \(G_e/G_0\) for the TM\(_{011}\) cavity is a little smaller. Therefore, the beam-wave conversion efficiency in the TM\(_{011}\) cavity will be a little lower. This may be explained that the vane between...
the TM$_{010}$ cavities can increase the radial electric field to enhance the beam-wave intersection to some extent.

III. SIMULATION RESULTS AND DISCUSSION

All above analyses need to be verified by the particle-in-cell (PIC) simulation, which has been proved to be in good agreement with the experimental results. In PIC simulation, the 2.5-D fully electromagnetic code for HPM simulation, CHIPIC, is utilized. In simulation, the RTTO with TM$_{011}$ extraction cavity and the RTTO with two TM$_{010}$ extraction cavities were analyzed.

The structural sketch of the published RTTO with the two TM$_{010}$ extraction cavities is given in Fig. 5. The whole structure is rotationally symmetric with respect to the horizontal axial $z$. There are four main parts, i.e., a foil-less diode, a four-gap buncher, a two-cavity extractor, and a coaxial output waveguide. In detail, the performance of the developed RTTO was analyzed in Ref. 15. The sketch diagram of the RTTO with the TM$_{011}$ extraction cavity is illustrated in Fig. 6, and the most obvious adjustment is that the one-gap cavity is employed to realize the beam-wave intersection. The two RTTOs are very close in output power, mesh generation, and the chamfering. The input power for the RTTO with the TM$_{011}$ extraction cavity is 3.16 GW, while the value for the RTTO with the TM$_{010}$ cavities is 2.85 GW. Except for the different extractors, sizes of some other parts have been adjusted to realize higher efficiency.

Distribution of the radial momentum of electrons can illustrate the modulation of electron beam as well as the process of energy exchange between electrons and the RF electric field. The distribution of the radial momentum in the two RTTOs is shown in Fig. 7. As illustrated in Fig. 8, the average electron power drops from 3.01 GW to 1.97 GW in the TM$_{011}$ cavity and the decline amplitude is close to the output power. Besides, the two decreases in the cavity prove the reversing electric field intersect with electrons effectively. As a contrast, the TM$_{010}$ cavities can make the electron power fall from 2.92 GW to 1.73 GW, which is larger than that of the TM$_{011}$ mode, which agrees with the above analysis. The two declines in the TM$_{010}$ cavities are realized by the electric field of $\pi$ mode in the two cavities, and the decline amplitude in the first cavity is much higher, which will result in significant enhancement of the electric field in the first cavity. This can be explained that the microwave extraction in the second cavity is appropriate to decrease the field. However, the TM$_{011}$ cavity can realize the beam-wave intersection as well as the microwave extraction in one cavity, which is beneficial to enhance the power capacity.

The average output power of the two RTTOs is shown in Fig. 9. The power is almost 1.0 GW, and the saturation time of the power is about 26 ns. The corresponding efficiency can be calculated to be 31.6%. This proves that the TM$_{011}$ cavity can realize effective beam-wave intersection. However, the conversion efficiency of the RTTO
FIG. 11. Contour of the radial electric field in the two RTTOs. (a) The RTTO with the TM$_{011}$ cavity. (b) The RTTO with the TM$_{010}$ cavities.

FIG. 12. Average output power of the RTTO with the TM$_{012}$ cavity and the RTTO with the TM$_{011}$ cavity.

FIG. 13. Distribution of the radial electric field in the RTTO with the TM$_{012}$ cavity.

with the TM$_{010}$ cavities is about 35.0%, and this result agrees with the above analysis without electrons. The frequency spectrum of the two RTTOs is given in Fig. 10. The center frequency of the two RTTOs is 31.2 GHz. Besides, the frequency spectrum is pure and there is nearly no miscellaneous frequency interference.

To research on the power capacity in the extractor of the RTTO with the TM$_{011}$ extraction cavity, the contour of the radial electric field in the beam-wave intersection region is demonstrated in Fig. 11. It can be seen that distribution of the radial electric field is the same as that without electrons, and the operating mode in the extraction cavity is the TM$_{011}$ mode. The maximum radial electric field in the TM$_{010}$ cavities is 1200 kV/cm, and the value for the TM$_{011}$ cavity is only 800 kV/cm. Since the output power is almost the same, considering that the volume of the TM$_{011}$ cavity is larger than that of the TM$_{010}$ cavities, the TM$_{011}$ extraction cavity can improve the power capacity significantly.

IV. THE RTTO WITH THE TM$_{012}$ EXTRACTION CAVITY

However, the beam-wave conversion efficiency of the above RTTO with the TM$_{011}$ cavity is a little lower. In the same way, the
TM_{012} cavity is introduced to enhance the beam-wave intersection. The sizes of the TM_{012} cavity are selected through the same method in Sec. II. The electric field of the TM_{012} mode can realize one more time energy exchange between the electron beam and the RF electric field, which will result in efficiency growth. Besides, the input power is also 3.16 GW and the sizes of some parts are adjusted to maximum the efficiency.

In PIC simulation, the output power of the RTTO with the TM_{012} extraction cavity is given in Fig. 12. The center frequency is still 31.2 GHz. By introducing the TM_{012} mode, the average power of the RTTO can be increased to 1.12 GW, and the efficiency is improved to 35.4%. However, the saturation time of the output is about 6 ns later than that of the RTTO with the TM_{031} cavity, and the reason may be ascribed to the change of Q factor. In Fig. 13, the contour of the radial electric field in this RTTO is illustrated, and it can be seen that the electric field in the extraction cavity is exactly the TM_{012} mode. In addition, the maximum radial electric field in the TM_{012} cavity is about 850 kV/cm, which results from the increased output power. Therefore, the TM_{012} cavity can improve the output power effectively.

V. CONCLUSION

A one-gap extraction cavity is proposed in this paper to enhance the power capacity. Without electrons, the distribution of the electric field in the TM_{011} cavity is the same as that for the two TM_{010} cavities. The sizes of the TM_{011} cavity can be chosen to acquire the synchronization of the electrons and the RF electric field to realize effective energy exchange. Therefore, the resonant electric field in the TM_{011} cavity can intersect with the radial electrons effectively.

In PIC simulation, the radial momentum and the average electron power in the two RTTOs at the stable stage illustrate that the RTTO with the proposed TM_{011} cavity can realize effective beam-wave interaction. The oscillator with the TM_{011} cavity can output HPMs with the power of 1.0 GW, the center frequency of 31.3 GHz, and the beam-wave conversion efficiency of 31.6%. In addition, the maximum radial electric field in this device is only 800 kV/cm, which is 33.3% smaller than that in the RTTO with two TM_{010} cavities. Considering that the volume in the TM_{011} cavity is larger, the power capacity in the TM_{011} cavity is improved significantly.

Besides, the electric field with the TM_{012} mode can realize three energy exchanges with electrons, which can increase the beam-wave conversion efficiency to 35.4%. As the output power grows to 1.12 GW, the maximum electric field will increase to 850 kV/cm. Therefore, the one-gap extraction cavity can improve the power capacity in the extractor significantly, and the effective beam-wave intersection can be realized by multiple energy exchanges at the same time.

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