# The Beam-wave Interaction for Different Modes in Three-gap Coupled Cavity Output Circuit

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**Abstract**— An analytic theory describing the conversion efficiency of the electron beam in multi-gap coupled cavity is developed. Through calculating the electronic conversion efficiencies in three-gap coupled cavity for modes $2\pi$, $\pi$ and $\pi/2$ respectively, the mechanism of the beam-wave interaction in output circuit is discussed in this paper.

## 1. INTRODUCTION

Extended-interaction klystron (EIK) is invented to achieve a large power, wide frequency bandwidth and high gain in the millimeter/sub-millimeter wave length range [1–3]. Multi-gap coupled cavity in it is a key technique for enhancing the gain-bandwidth product and power capability.

Based on kinematics theory, by calculating the conversion efficiency of the electron beam in single gap, the beam-wave interaction was analyzed in paper [4]. On this basis, the effects of the distance of gap-gap, R.F. gap voltage on the conversion efficiency were discussed in paper [5]. But the analysis was carried out under the assumption of narrow gaps separated by drift tubes and neglected the beam-wave interaction of other modes in the multi-gap cavity. Because of strong electromagnetic coupling between the adjacent cavities, there are multiple resonant modes which have a very great difference of the electric field intensity on the gap. The mechanism of the beam-wave synchronization and coupling for these modes is the key technology investigation of multi-gap coupled cavity chain. Based on kinematics theory, this paper will present the simulation results of the conversion efficiencies in three-gap coupled cavity and discuss the effect of drift tube length on beam-wave interaction for modes $2\pi$, $\pi$ and $\pi/2$.

## 2. MODEL AND FORMULA

Assume that the model is one-dimensional and the effect of space charge is neglected. Hence, the equation of motion an electron moving under the assumption is given by

$$\frac{d^2z}{dt^2} = -\left|\frac{e}{m}\right| E_c(z)\sin(\omega t + \varphi_0) \tag{1}$$

where $z$ is the axial distance, $e$ and $m$ are the electronic charge and mass respectively, $E_c(z)$ denotes the axial electric filed intensity at a distance $z$, $\omega$ denotes the angular frequency, $\varphi_0$ specifies the electron entrance phase.

An electron entering the interaction region with a velocity $u_0$ at the phase $\varphi_0$ leaves the region with a velocity $u$ which is obtained by successive use of Equation (1). With a pulse width $\theta_e$ of the electron beam, the conversion efficiency $\eta$ is then given by

$$\eta = 1 - \frac{1}{\theta_e}\int_{\varphi_0}^{\varphi_0+\theta_e}\left(\frac{u}{u_0}\right)^2 d\theta \tag{2}$$

If a resulting efficiency is positive, the kinetic energy of the electron beam will be converted to electromagnetic energy.

Taking three-gap coupled cavity as the output circuit, there are three eigen modes with different filed distributions. Assume that the axial RF standing electric fields are constant on the gaps and vanish on the drift tubes as shown in Figure 1. Where $E_c = \alpha V_0/d$, $\theta_d = \omega d/v_0 \theta_{12} = \omega l_{12}/v_0$, $\theta_{23} = \omega l_{23}/v_0$, $\alpha$ is the modulation index of the gap voltage, $v_0$ is the longitudinal velocity of the electron under the accelerating voltage $V_0$, $\omega$ is the angular frequency of the mode, $d$ is the width of the gap, $l_{12}$ and $l_{23}$ are the lengths of the first and the second drift tube respectively. For $2\pi$ mode, the RF fields on gaps are the same both in amplitude and direction; For $\pi$ mode, the adjacent RF fields on gaps are the same in amplitude and the opposite in direction; For $\pi/2$ mode, the RF fields vanish in middle gap and exist on the other two gaps with the same amplitude and the opposite direction.

## 3. RESULTS AND DISCUSSION

Taking for example $\theta_e = 0.5\pi$, $\theta_d = 0.5\pi$, $|\alpha| = 0.4$, $\varphi_0 = 0$ and $v_0 = u_0$, the efficiencies as function of $\theta_{12}$ and $\theta_{23}$ for $2\pi$ mode, $\pi$ mode and $\pi/2$ mode are displayed in Figure 2.

The analytic result of $2\pi$ mode shows that the high efficiency region appears on the right of the bisector and the maximum efficiency $\eta = 80\%$ is obtained upon selecting the parameters $\theta_{12} = 1.26\pi$ and $\theta_{23} = 0.66\pi$. This can be explained that average speed of the electronic beam is reduced ceaselessly after passing a gap, and in view of transit time effect, the corresponding $\theta_{12}$ and $\theta_{23}$ decrease in order to make the electronic beam at the optimal phase in next gap.

Compared with $2\pi$ mode, there are four high efficiency regions with different distribution for $\pi$ mode. However, when the efficiency $\eta$ is over 80%, the corresponding parameter $\theta_{23}$ is too small to realize in structure. Therefore, it is practical to choose $\theta_{12} = 0.42\pi$ and $\theta_{23} = 1.32\pi$ in the upper left region with maximum efficiency $\eta = 78.48\%$.

Because the beam-wave interaction occurs on the two gaps, $\pi/2$ mode can be regarded as a kind of special $\pi$ mode of double-gap cavity with a longer drift distance (Figure 1). In this case, the maximum efficiency $\eta$ is only 60% with a fixed value of $\theta_{12} + \theta_{23} = 1.47\pi$.

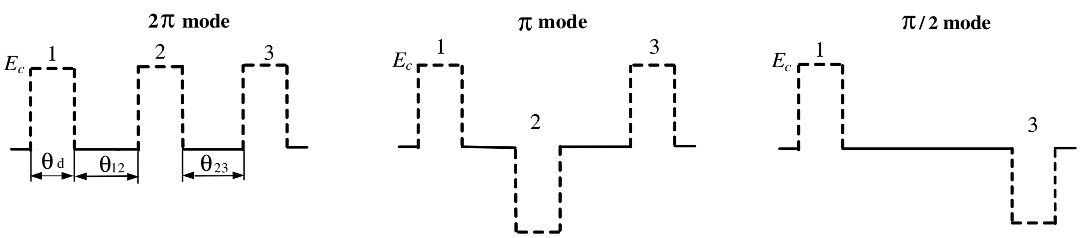


Figure 1: The electric field distribution for modes $2\pi$, $\pi$ and $\pi/2$.

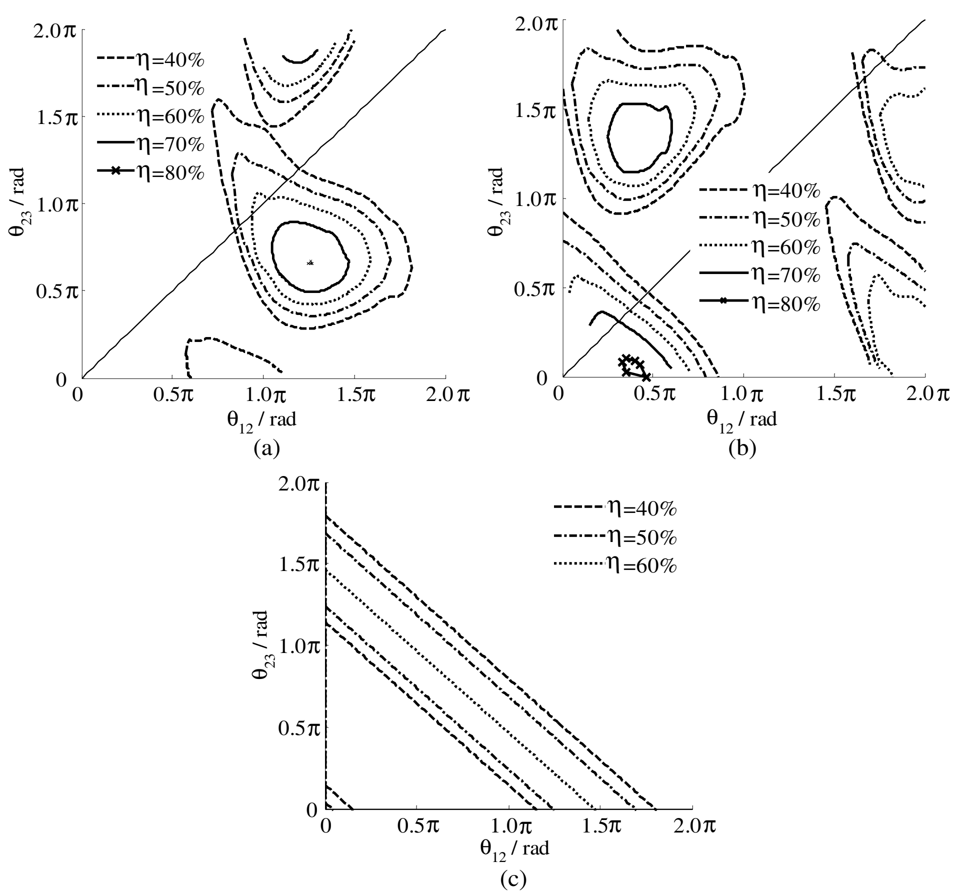


Figure 2: The electronic conversion efficiencies for (a) $2\pi$ mode, (b) $\pi$ mode, (c) $\pi/2$ mode.

## 4. CONCLUSION

In this paper, an analytic theory describing the conversion efficiency of the electron beam in Multi-gap coupled cavity with different mode is developed. The conversion efficiencies of the electron beam in three-gap coupled cavity for modes $2\pi$, $\pi$ and $\pi/2$ have been obtained. The results show that the maximum efficiency depends on the optimal combination of $\theta_{12}$ and $\theta_{23}$, which have a great difference for these modes. Considering the beam-wave interaction on two gaps for $\pi/2$ mode, the maximum efficiency $\eta$ is only 60% less than that of $2\pi$ mode and $\pi$ mode.

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