A Steady-State Theoretical Model Applicable to Solving Klystron Beam-Wave Interaction

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Abstract: *This paper proposes a steady-state theoretical model for the klystron beam-wave interaction and develops the relevant code. First, the electron beam channel and the resonant cavity are expanded in a mode, and the equations satisfying the voltage and current of the electron beam channel and the resonant cavity in the steady state are derived, and then the corresponding field distribution is obtained for solving the electron motion equation. Taking an X-band klystron simulation design as an example, the calculation ability and effect of the program are tested. The results are comparable to the 3D PIC software, and the calculation efficiency is greatly improved. The preliminary design and parameter optimization of the beam-wave interaction system.*

Keywords: Klystron; steady-state; Beam-Wave

Introduction

The klystron is a vacuum device that gradually amplifies and converts weaker electronic energy into microwave energy through the process of converting speed modulation to density modulation. Due to the characteristics of each module being separated from each other, it has advantages such as high efficiency and high stability.

In order to shorten the development cycle of the device, it is particularly urgent to develop a set of short calculation time and accurate simulation results of the beam-wave interaction simulation program.

This paper attempts to propose a steady-state theoretical model for the klystron beam-wave interaction. The equations satisfying the voltage and current of the electron beam channel and the cavity using the mode expansion and the longitudinal field method are established; the coupling equation between the electron beam channel and the cavity is established using the continuity of the field at the gap; the electronic motion information is solved by the relativity Lorentz equation. Based on this, an analysis program for the klystron beam-wave interaction is written. An X-band klystron is analyzed, and the results include the electron trajectory and the electron phase.

Theoretical Model

In the cylindrical electron injection channel, the solution area is discrete, the space is evenly divided, and the space step size is as follows:

$$D_h = \left\{ z_j \mid z_j = \left(j-1\right)\Delta z \right. \\ \left. j = 1,2,\ldots J \quad J:\left(J-1\right)\Delta z = L \right\} \tag{1}$$

In the klystron simulation, generally only the TM mode is considered, and the angle-symmetric mode is taken, that is $TM_{0,k}$. In a klystron, the radius of the drift tube usually remains the same, so we ignore the coupling between the different modes and only consider the mode self-coupling. Starting from Maxwell's equations, the mode expansion is performed in the cylindrical electron beam channel, which is divided into active mode and passive mode. The equations of voltage and current under steady state conditions are derived separately and discretized by difference.

Active mode steady-state difference equation:

$$A\left(I_k\right)_{j-1} - \left(Bj + 2A\right)\left(I_k\right)_j + A\left(I_k\right)_{j+1} = dcC \tag{2}$$

where: $A = \dfrac{1}{ik_0\left(\Delta z\right)^2}$, $Bj = ik_0\left(1 - \dfrac{\left(k_{c,k}{}^2\right)_j}{k_0}\right)$, $D = \dfrac{1}{2ik_0\Delta z}$

$$\begin{aligned} dcC = &-\frac{1}{2ik_0\Delta z}\left[\left(K_{k,k}\right)_{j+1} - \left(K_{k,k}\right)_{j-1}\right]\left(I_k\right)_j \\ &-\frac{1}{2ik_0\Delta z}\left(K_{k,k}\right)_j\left[\left(I_k\right)_{j+1} - \left(I_k\right)_{j-1}\right] + \left(K_{k,k}\right)_j\left(V_k\right)_j \\ &-\frac{1}{2ik_0\Delta z}\left(\left(S_{T,k}\right)_{j+1} - \left(S_{T,k}\right)_{j-1}\right) - \left(S_{z,k}\right)_j + \sum_s K^{*res}_{s,k,j} V_s \end{aligned} \tag{3}$$

Where $k_{c,k}$ is the eigenvalue of the k mode, $k_{c,k} = \dfrac{j_{0,k}}{r_\omega\left(z\right)}$ and k represents a mode, corresponding to a set of c , k , I_k is current, V_k is voltage, and $K^{*res}_{s,k,j}$ is conjugate of the coupling term between the electron beam channel and the cavity, and $S_{z,k}$ and $S_{t,k}$ is the source term. The difference format as above is valid for all internal nodes. When $j=1$ and $j=J$, it is related to the field amplitude on the boundary. Field meets evanescent wave boundary conditions at both entrance and exit

Left border $j=1$: $$\frac{dI_k\left(z\right)}{dz} = \gamma_k I_k\left(z\right) \tag{4}$$

Right border $j=J$: $$\frac{dI_k\left(z\right)}{dz} = -\gamma_k I_k\left(z\right) \tag{5}$$

The Thomas algorithm is used to solve $\left(I_k\right)_j, j=2, J-1$, and then the I_k of the whole area can be obtained in turn. Then, $\left(V_k\right)_j=\frac{\gamma_k}{ik_0}\left(I_k\right)_j, j=1,2 \ldots \mathrm{J}$, the V_k of the whole area can be obtained from.

Passive mode steady-state difference equation:

$$\left(i_{k,s}\right)_{j-1}-[2+\Delta z^2\left(k_{c,k,j}^2-k_0^2\right)]\left(i_{k,s}\right)_j +\left(i_{k,s}\right)_{j+1}=ik_0\Delta z^2 K_{s,k,j}^{*res} \tag{6}$$

$$v_{k,s}(z)=\frac{di_{k,s}(z)}{ik_0 dz}=\frac{1}{ik_0}\frac{i_{k,s,j+1}(z)-i_{k,s,j-1}(z)}{2\Delta z} \tag{7}$$

Starting from Maxwell's equations, the equations that the voltage and current meet in the steady state of the resonator can also be obtained.

$$(1-i\omega\Delta t)V_s+\omega_s\Delta t\int_{gap}\sum_{k=1}^{k_{\max}} I_k K_{s,k}^{res} dz = V_s-\omega_s\Delta t\frac{4\pi}{c}\int_{z_{\min}}^{z_{\max}} dz\iint_{s_\perp}\vec{J}_\omega\cdot\vec{e}_s^{\,*gap}ds-i\omega_s\Delta t I_s \tag{8}$$

$$\left(1-i\omega\Delta t+\omega_s\Delta t\frac{1+i}{Q}\right)I_s+ i\omega_s\Delta t V_s=I_s-\omega_s\Delta t V_+ C_{k,s}^* \tag{9}$$

Electron beams are represented by macro particles, and the electric field force between the macro particles is solved by the plasma frequency reduction factor of the corresponding mode. In the electron beam motion, the field in the electron beam channel and the resonant cavity and the current source are substituted into the relativistic motion equation to get the particle's displacement, momentum and speed in the next step, which is used to advance the particle's next move[1].

Simulation

Based on the previous models, formulas and approximations, we have written a program for the simulation and analysis of the klystron injection wave interaction. Take an X-band klystron as an example. The working frequency of the klystron is 9.8GHz, the DC voltage of the electron beam is 17kV, the current is 0.8A, the radius of the electron beam channel is 0.6mm, and the length of the drift tube is 28mm. The magnetic field focus, the placement position of each resonant cavity and the gap width are shown in Table I.

Table Ⅰ Cavity frequency and position

Cavity	Frequency/GHz	Gap/mm	Position/mm
1	9.818	0.6	1.5
2	9.79	0.6	5.7
3	9.81	0.6	9.1
4	9.8383	0.6	12.5
5	9.8	0.6	25

In the calculation, an electron beam with an electronic wavelength is divided into an axial direction of 32 × radial of 16 × angle of 8. When the input power is 200mW, the result obtained is shown in the figure below.

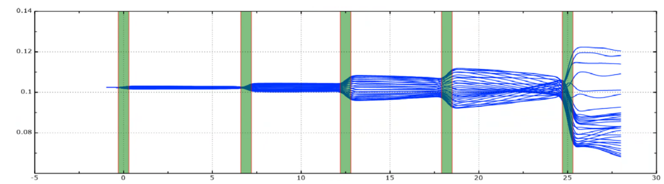

Fig. 1 Electronic axial velocity

Figure 1 shows the axial distribution of the normalized velocity of an electronic disk. It can be seen from the figure that the speed of each layer of disks just entered is the same. After the speed modulation in the interaction area, the speeds are different. After energy exchange through the position of the output cavity, the overall disk speed has decreased significantly.

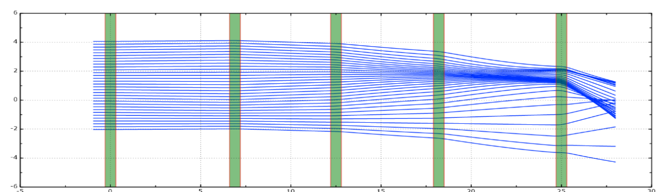

Fig. 2 Electronic phase

Figure 2 shows the phase trajectory of the electrons, which reflects the changing process of electrons gradually appearing from the uniform incidence to the modulation of the gaps in each cavity.

The X-band klystron can obtain a gain of 29.5dB. By carrying out the research work in this paper, it is of great significance to the design, simulation analysis and performance exploration of X-band klystrons, laying a foundation for the development of high-gain klystrons. For the calculation of Klystron interactions, our frequency domain steady-state program is relatively fast.

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References

[1] Scheitrum G, Caryotakis G, Burke A, et al. W-band sheet beam klystron research at SLAC[C]. IEEE 2006 international vacuum electronics conference, California, 2006, 481-482