X-BAND KLYSTRON OUTPUT CAVITY SIMULATION

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Abstract

Two-dimensional modeling of klystron output cavity coupler is presented. The coupler is considered to be the mode converter between TE10 mode of the rectangular waveguide and TM0*0 mode of the cavity cell. The components of the scattering matrix are calculated using MAFIA eigenmode solver. For the simulation by MAGIC2D 2.5 dimensional particle-in-cell code, finite-conducting material is set in the coupler region to match S11. Output powers, which are calculated from the Poynting vector, are compared with the measured values of KEK XB72K#9 and SLAC XL-4 klystrons.

1 INTRODUCTION

Development of X-band (11.424GHz) klystrons capable of 120MW(XB72K series) is undergoing at KEK [1-3]. To reduce the maximum electric field in the output cavity, traveling wave type structures are used. Output structures of XB72K#8 and #9 were designed at BINP using one dimensional simulation code DISKLY [4]. Due to the limitation of one-dimensional design, not enough powers were extracted with these output structures. MAGIC2D [5], a 2.5 dimensional particle-in-cell code, was introduced in KEK in 1997 for the design of the next klystron XB72K#10 with a 4-cell traveling wave type output cavity. Since the coupler of the output cavity is not axisymmetrical, the structure cannot be simulated directly by 2 dimensional codes. To make it possible, the notion of scattering matrix is introduced, and is calculated using the eigenvalue solver of MAFIA [6] codes. Output powers calculated by MAGIC2D are compared with the measured values of KEK XB72K#9 and SLAC XL-4 [7] klystrons. In section 2, calculation of scattering matrix is shown. In section 3, output cavity simulation by MAGIC2D is presented. Design of XB72K#10 klystron output structure is briefly discussed in section 4.

2 SCATTERING MATRIX

Though there are many modes around operating frequency with the multi cell output structure, the field pattern around the output cell of these modes are similar to TM0*0 mode. The phasor of the electric field in the region can be approximated as the following,

$$E_{CAV} = a_{1in}H_0^{(1)}(kr) + a_{1out}H_0^{(2)}(kr), \qquad (1)$$

where H is the Hankel function, $k=\omega/c$ is the wave number. Time dependence of the electric field is assumed to be $\exp(-i\omega t)$. The electric field in the waveguide can be described as,

$$E_{WG} = a_{2in}\exp(-ik_g y) + a_{2out}\exp(ik_g y),$$
$$k_g = \sqrt{(\omega/c)^2 - (\pi/a)^2}, \qquad (2)$$

where a is the width of the rectangular waveguide, y is the distance from the center of the coupler. If the output coupler is considered as the mode converter between TM0*0 of the cavity cell and TE10 mode of the rectangular wave guide, the scattering matrix can be defined as follows,

$$a_{1out} = S_{11}a_{1in} + S_{12}a_{2in},$$
$$a_{2out} = S_{21}a_{1in} + S_{22}a_{2in.} \qquad (3)$$

The variables ξ_1 and ξ_2 are defined as the ratio between the amplitudes of the incoming and outgoing waves,

$$\xi_1 = a_{1out}/a_{1in}, \quad \xi_2 = a_{2out}/a_{2in}. \qquad (4)$$

Using (4), (3) becomes

$$(S_{11} - \xi_1)(S_{22} - \xi_2) = S_{12}S_{21} \qquad (5)$$

If the values of three (ξ_1,ξ_2) pairs are known, S_{11}, S_{22} and $S_{12}S_{21}$ can be calculated.
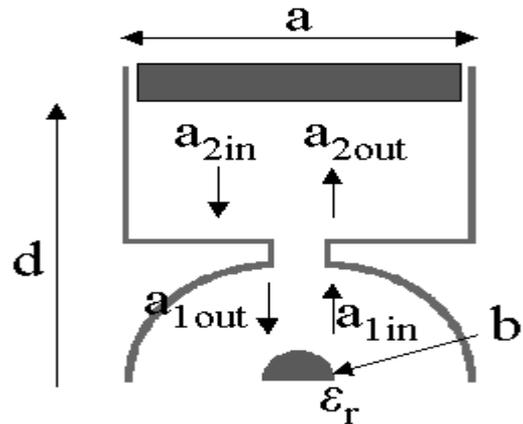
Figure 1: Configuration for MAFIA calculation.

MAFIA eigenmode solver is used to calculate three (ξ_1,ξ_2) pairs. As shown in figure 1, the waveguide is short at distance d, and the dielectric material is set at the center of the cavity cell. Since the electric field on the plane y=d is zero, ξ_2 is,

$$\xi_2 = -\exp(-2ik_g d). \qquad (6)$$

By putting dielectric material at the center of the coupler cell, the parameter ξ_1 can be varied as,

$$\xi_1 = \frac{kJ_0(k'b)H_1^{(1)}(kb) - k'J_1(k'b)H_0^{(1)}(kb)}{k'J_1(k'b)H_0^{(2)}(kb) - kJ_0(k'b)H_1^{(2)}(kb)},\qquad(7)$$

$$k' = \sqrt{\varepsilon_r}\,\omega/c,$$

where b is the radius of the dielectric material, ε_r is the relative dielectric constant, J is Bessel function.

From the energy conservation, the following equations

$$|S_{11}| = |S_{22}|, \; S_{11}S_{22} - S_{12}S_{21} = S_{22}/S_{11}^*,\qquad(8)$$

are obtained. These are used to check the calculation of scattering matrix.
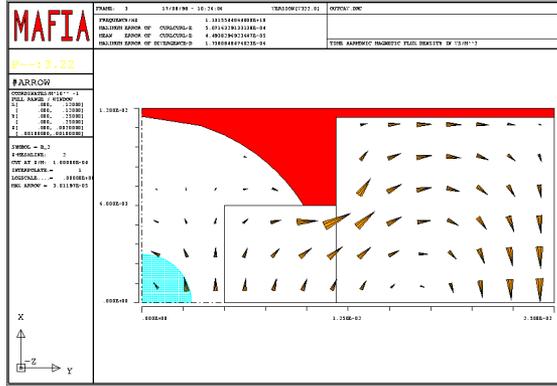
Figure 2: An example of MAFIA calculation.

Figure 2 shows the example of eigenmode solver calculation using MAFIA. The structure is from KEK XB72K#9. Three relative dielectric constants ε_r=1,3,5 are used to obtain three different ξ_1. The distance d is changed to find the frequency dependence of the scattering matrix. Reflection coefficient S_{11} for XB72K#9 output cavity coupler is shown in figure 3.
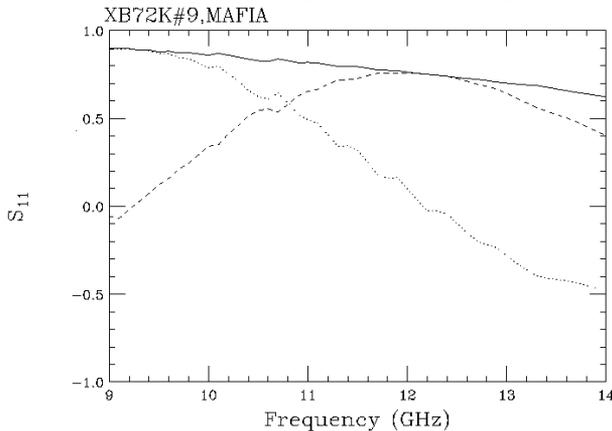
Figure 3: Reflection coefficient S_{11} as a function of frequency. Dotted and broken lines are real and imaginary parts, respectively.

3 MAGIC2D SIMULATION

Since the reflection coefficient r at the rectangular waveguide looked from the center of the cell is usually designed to be zero, the reflection coefficient at the coupler looked from the center of the cell can be assumed to be S_{11}. If the reflection coefficient r is not negligible, S_{11} should be replaced by the parameter S, which is defined by,

$$S = S_{11} + S_{12}(r + r^2S_{22} + r^3S_{22}^2 + \cdots)S_{21}$$
$$= S_{11} + rS_{12}S_{21}/(1 - rS_{22}).\qquad(9)$$

In order to realize the reflection coefficient S_{11} in the MAGIC2D simulation, a finite conducting material is set in the coupler region as shown in figure 4.
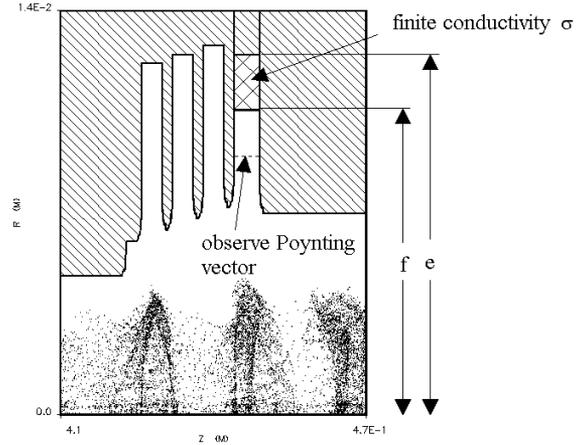
Figure 4: An example of MAGIC2D simulation. A finite conducting material is set in the coupler region to match S_{11}. Output power is calculated by time average of the area integral of Poynting vector. This structure is KEK XB72K#9 output cavity.

With this configuration, S_{11} is,

$$S_{11} = \frac{k\alpha H_1^{(1)}(kf) - k''\beta H_0^{(1)}(kf)}{k''\beta H_0^{(2)}(kf) - k\alpha H_1^{(2)}(kf)},$$

$$\alpha \equiv H_0^{(1)}(k''e)H_0^{(2)}(k''f) - H_0^{(2)}(k''e)H_0^{(1)}(k''f),$$

$$\beta \equiv H_0^{(1)}(k''e)H_1^{(2)}(k''f) - H_0^{(2)}(k''e)H_1^{(1)}(k''f),$$

$$k'' = \sqrt{(\omega/c)^2 + i\mu_0\sigma\omega},$$
(10)

where e is the outer radius, f is the inner radius, σ is the electric conductivity, of the material. The reflection coefficient S_{11} in (10) is fitted to the value calculated from (5) at operating frequency 11.424GHz by changing three parameters (σ, e, f) with the aid of Mathematica [8]. Since number of unknown parameters (σ, e, f) are three, and number of known parameters (Real(S_{11}), Imag(S_{11})) are two, one parameter is free. In many cases, the outer radius e is fixed to one of the outer radii of the upstream cells in order that Courant stability criterion,

$$\sum_i \frac{\beta c \Delta t}{\Delta x_i} < 1,\qquad(11)$$

is satisfied in the MAGIC simulation. In this equation, βc is the velocity of the particle, Δt is the time step, Δx_i is the grid size of i-th coordinate. For XB72K#9, the parameter e is fixed to the outer radius of the second cell, as can be seen in figure 4. The conductivity σ should be small so that the skin depth

$$\delta = \sqrt{2/\mu\sigma\omega} \qquad (12)$$

is larger than the grid size. Since the conductivity is chosen to be 2.5/Ωm in case of XB72K#9, skin depth is 3mm, which is larger than the grid size of 0.2mm. Figure 5 shows the frequency dependence of S_{11}, which is calculated from (10).
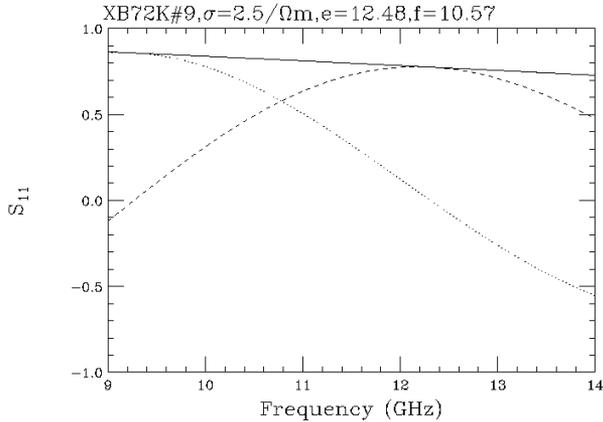
Figure 5: Frequency dependence of the S_{11} calculated from (10). Parameters of the conductor are obtained by fitting S_{11} at the operating frequency of 11.424GHz.

Output cavity simulations are done with imported bunches and space-charge waves, which are created by buncher section simulation [3]. Output power is calculated from time average of Poynting vector just below the finite conductor, as shown in figure 4. Saturated output powers of XB72K#9,10 and SLAC XL-4 are shown in figure 6. For SLAC XL-4, simulation results and measured values are consistent within a few percent. For XB72K#9, simulation results are about 10 percent lower than measurements. We think that accuracy of the measured cathode voltage is not good due to the capacitance in gun region. We have a plan to test XB72K#9 again with longer pulse.
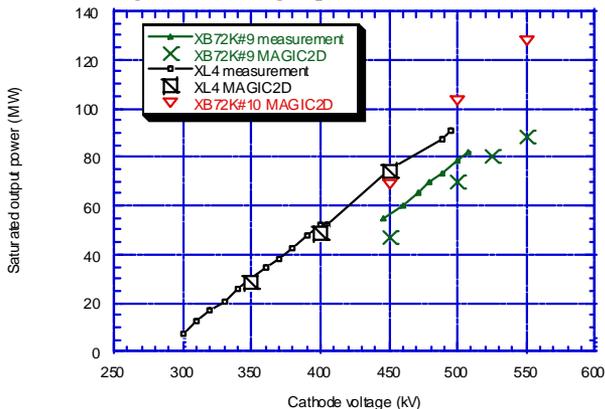
Figure 6: Saturated output power as a function of cathode voltage for XB72K#9,10 and SLAC XL-4.

4 DESIGN OF XB72K#10 OUTPUT STRUCTURE

How to reduce the maximum electric field in 120MW output structure design is the problem. By choosing 2π/3-

like mode instead of π/2, we can make the width of the cells wider than that of SLAC XL-4. Since the electric field was high at the disk between third and fourth cell, we increased the width of the disk. After hundreds of simulations, we decided the approximate structure, which has the maximum electric field less than that of SLAC XL-4. The structure was slightly changed in order to separate the resonant frequencies of transverse deflecting modes from the operating frequency. Figure 7 shows one example of the MAGIC2D simulations of XB72K#10 output structure. Saturated output powers by MAGIC2D simulation are plotted in figure 6. XB72K#10 is being manufactured at TOSHIBA. We will test it in November this year.
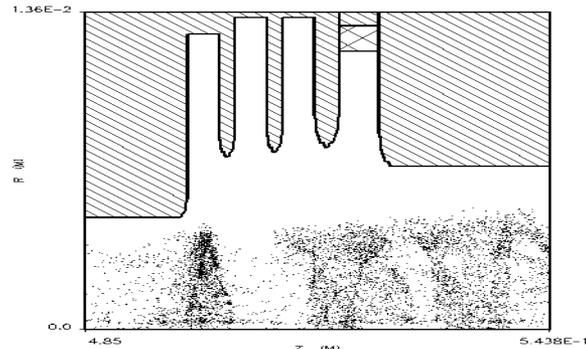
Figure 7: An example of MAGIC2D simulation of XB72K#10 output structure.

5 REFERENCES

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