ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPRB049

MODELING AND SIMULATION FOR MULTI-FEEDING CAVITY WITHOUT BEAM LOADING

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Abstract

The Multi-feeding cavity can be applied in superconducting and normal conducting RF cavity. The differences between input couplers in coupler coefficient, incident power and phase will cause the cavity field stabilities can't meet the requirements. For explore the influences of these differences and develop equations for measurement, a multi-feeding LCR transient model was developed. As dual-feeding cavity, the VHF photocathode electron gun was model and simulated in this paper.

INTRODUCTION

Shanghai HIgh repetition rate XFEL aNd Extreme light facility (SHINE) will be the first high repetition hard x-ray free electron laser. As the source of the whole facility, the electron gun requires critically for beam quality, especially in terms of current, emittance and longitudinal stability [1]. To consider the advantages of low frequency, good vacuum conditions and small dark current load [2], Single-cell 162.5MHz CW Very High Frequency (VHF) photocathode gun was chosen as the electron source.

However, RF cavity needs very high microwave power (~100kW) under high average current intensity and CW operation mode. To reduce the power handling capacity of the coaxial waveguide and compensate coupler kick, RF cavity usually is designed to feed power by two power couplers [3]. Developing multi-feeding cavity's model is necessary to research and analyse the influences in cavity amplitude stability and phase stability which can caused difference of coupler coefficient, incident power and phase.

In this paper, multi-feeding cavity mathematic model was set up. As a special case, a two-feeding VHF cavity model without beam loading was built and simulated in Simulink.

MULTI-FEEDING CAVITY MODEL

Assuming RF power in multi-feeding cavity is fed by n RF sources through n transmission lines. If we consider external m port which are field probe couplers or Higher Order Mode couplers (HOMs), it will be an n + m ports cavity. The RF power source model can see as voltage source $E(\omega,t)=\hat{E}e^{j\omega t}$. Assuming the impedance of transmission line and load are real, the impedances of the i-th transmission line and the k-th load severally are Z_i and R_{p_j} (i=1~n, k=1~m). The equivalent LCR circuit model shows in Figure 1. The R_0, L, C are the resistance, inductance and capacitance of the multi-feeding cavity. The influence of electron beam is saw as the current source I_B. The coupler coefficient of the i-th input coupler and the k-th probe coupler β_i are and β_{P_j} (i=1~n, k=1~m). The equivalent transfer rates of the i-th input coupler, the k-th probe coupler are N_i and M_k (i=1~n, k=1~m).

$$\begin{cases} N_i=\sqrt{R_0/(\beta_i Z_i)} & (i=1,2\cdots n) \\ M_k=\sqrt{R_0/(\beta_{P_k} R_{P_k})} & (k=1,2\cdots m) \end{cases} \tag{1}$$

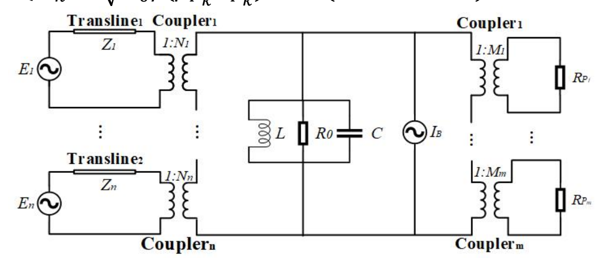

Figure 1: Equivalent circuit LCR model of multi-feeding cavity with beam loading.

For simplicity, the voltage sources and the right part of the cavity are transformed to the side of the cavity, and shows in Figure 2. The voltage sources are equivalent to current sources.

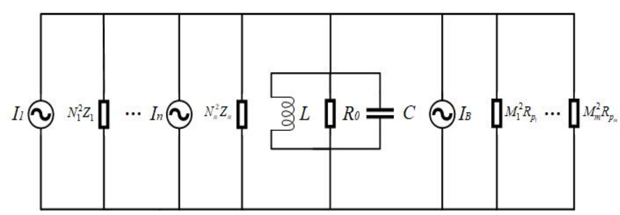

Figure 2: Equivalent parallel LCR circuit of multi-feeding cavity with beam loading at cavity side.

Steady State Equations

T. Schilcher [4] obtained the cavity voltage at the side of the transmission line is

$$\vec{V}'_c=\frac{2Z'_c}{Z'_c+Z_0}\vec{V}'_{for} \tag{2}$$

The Z'_c, Z_0 severally are impedances of the cavity and the transmission line at the side of the transmission line. The $\vec{V}'_{for}$ is forward voltage on the transmission line.

Assuming only the i-th RF power source turns on, the impedance of the cavity at the side of the i-th transline is

$$Z'_{c_i}=\frac{1}{N_i^2}\left(\frac{R_0}{1+jR_0(\omega C-1/(\omega L))}||Z'_i||R'_P\right) \tag{3}$$

Here, $Z'_i=N_1^2Z_1||\cdots||N_{i-1}^2Z_{i-1}||N_{i-1}^2Z_{i-1}||\cdots||N_n^2Z_n$, $R'_P=M_1^2R_{P_1}||\cdots||M_m^2R_{P_m}$

Under $\omega=\omega_0$, based on equation (2), cavity voltage $\vec{V}'_{c_i}$ is

$$\vec{V}_c^i=\frac{2\beta_i}{1+\beta_T}\vec{V}_{for_i} \tag{4}$$

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Where $\beta_T = \sum_{i=1}^{n} \beta_i + \sum_{k=1}^{m} \beta_{P_k}$, $\vec{V}'_{for_i}$ is forward voltage on the i-th transmission line.

Meanwhile, on the j-th transmission line, there is transmitted voltage $\vec{V}_{t_j}$ which comes from the i-th power source. Assuming the impedances of transmission lines are the same, $\vec{V}_{t_j}$ can be inferred base on equation (1)(4)

$$\vec{V}_{t_j} = (-1)^u \frac{2\beta_i}{1+\beta_T} \vec{V}_{for_i} \frac{N_i}{N_j} = (-1)^u \frac{2\sqrt{\beta_i \beta_j}}{1+\beta_T} \vec{V}_{for_i} \quad (5)$$

Here, the u is the number of cavity cell. So, when all power source is working, the cavity field voltage $\vec{V}_c$ is

$$\vec{V}_c = \sum_{i=1}^{n} \frac{2\beta_i}{1+\beta_T} N_i \vec{V}_{for_i} \quad (6)$$

The reflect voltage on the i-th transmission line is,

$$\vec{V}_{ref_i} = \vec{V}'_{c_i} - \vec{V}_{for_i} - \vec{V}_{t_i}$$
$$= \left(\frac{2\beta_i}{1+\beta_T} - 1\right) \vec{V}_{for_i} - (-1)^u \frac{2\sqrt{\beta_i \beta_j}}{1+\beta_T} \vec{V}_{for_i} \quad (j \neq i) \quad (7)$$

The detecting voltage at the k-th coupler is,

$$\vec{V}_{P_k} = \frac{\vec{V}_c}{M_k} = \sum_{i=1}^{n} \frac{2\sqrt{\beta_i \beta_j}}{1+\beta_T} \vec{V}_{for_i} \quad (8)$$

Transient State Equations

Base on the transient model that comes from [4],

$$\frac{d\tilde{V}_c}{dt} + (\omega_{1/2} - j\Delta\omega)\tilde{V}_c = R_T \omega_{1/2} \tilde{I}_T \quad (9)$$

Here $R_T = \frac{R_0}{1+jR_0(\omega C - 1/(\omega L))} \| N_1^2 Z_1 \| \cdots \| N_n^2 Z_n \| R'_P$; $\tilde{I}_T(\omega, t) = \sum_{i=1}^{n} \tilde{I}_1(t) + \tilde{I}_B(t)$;$\omega_{1/2} = \frac{\omega_0}{2Q_L}$.

Let equation (9) has a Laplace Transform, we can obtain a transfer function of the cavity model at the baseband.

$$\tilde{V}_c(s) = \frac{\omega_{1/2}}{s + \omega_{1/2} - j\Delta\omega} \quad (10)$$

So, the reflect voltage $\tilde{V}_{ref_i}$ $(j \neq i)$and detector voltage $\tilde{V}_{P_k}$ can be written as below

$$\tilde{V}_{ref_i} = \left(\left(\frac{2\beta_i}{1+\beta_T} - 1\right) \tilde{V}_{for_i} - (-1)^u \frac{2\sqrt{\beta_i \beta_j}}{1+\beta_T} \tilde{V}_{for_i}\right) \tilde{V}_c(s) \quad (11)$$

$$\tilde{V}_{P_k} = \sum_{i=1}^{n} \frac{2\sqrt{\beta_i \beta_j}}{1+\beta_T} \tilde{V}_c(s) \tilde{V}_{for_i} \quad (12)$$

VHF CAVITY SIMULATION

VHF cavity transient model can be built base on multi-cavity model and the parameters which are budgeted in table 1. Among this parameter, the β_{P_1} is the coupler coefficient of cavity field detector. The Z_0 is the impedance of transmission line and is assumed as 50 Ω. The two constant normalized square waves as stimulation source are severally input to the VHF model, then observing the change of cavity field voltage by change the power coupler factor and the amplitude or phase of square wave.

Table 1: VHF Electron Gun Cavity Parameters

Parameters	Value	Units
f_0	162.5	MHz
Q_0	34193	-
β_{P_1}	1E-4	-
R_s	7.06	MΩ
Z_0	50	Ω
$\Delta\omega_{bandwidth}$	5.85	Rad/s
Δf	0	Hz

Optimal Input Coupler Coefficient

When we fix on the amplitude and phase of forward voltage at 1V and 45°. The coefficients of two input couplers only changed. The signals are the same on the transmission line 1 and 2. Figure 3 shows, $\beta_1 = \beta_2 > 0.5$,the change tendency of reflect voltage amplitude has a reversal at about 0.05ms, which are caused by reflect voltage phase jump 180°. It can be explained by equation (7), the phase of reflect voltage is easy to jump 180° due to tiny change of forward voltage when β_1 , β_2 are equal to 0.5, and lead to the control loop is unstable. So, the coupler coefficient generally is overcoupling. Meanwhile, the amplitude of the field detector voltage is the biggest under $\beta_1 = \beta_2 = 0.5$.

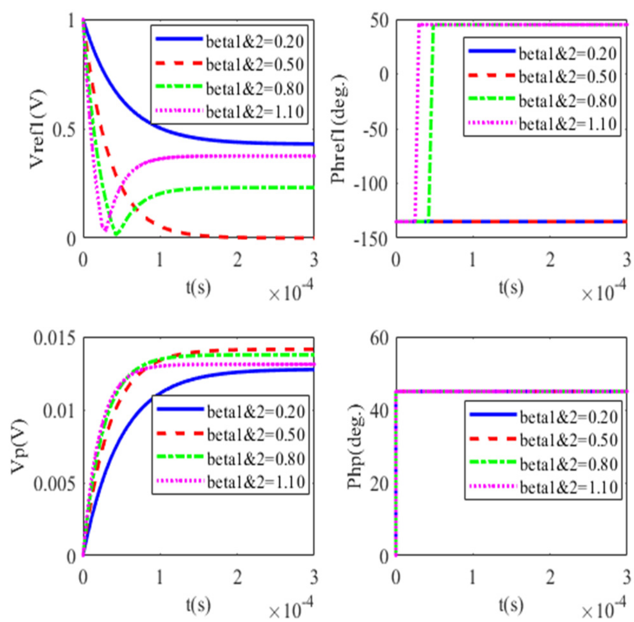

Figure 3: The amplitude and phase of $\tilde{V}_{ref_1}$, $\tilde{V}_{ref_2}$ and $\tilde{V}_P$ in different β_1 and β_2.

Influence of Forward Power Difference

The forward power is proportional to the square of the forward voltage amplitude of the power source, so we can change the amplitude of forward voltage to substitute change forward power.

Only the amplitude of forward voltage on the transmission line 1 change. The simulation result shows in Figure

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4. The amplitude of reflect voltage on the transmission line 2 is easier to has a reversal, on account of transmitted voltage which comes from input coupler 1. The amplitude of field voltage is certainly bigger and bigger with input coupler 1's incident power increase. For the reflect voltage which has a reversal in amplitude at steady state (blue line), its phase is 180°. larger than the phase whose amplitude of reflect voltage without reversal.

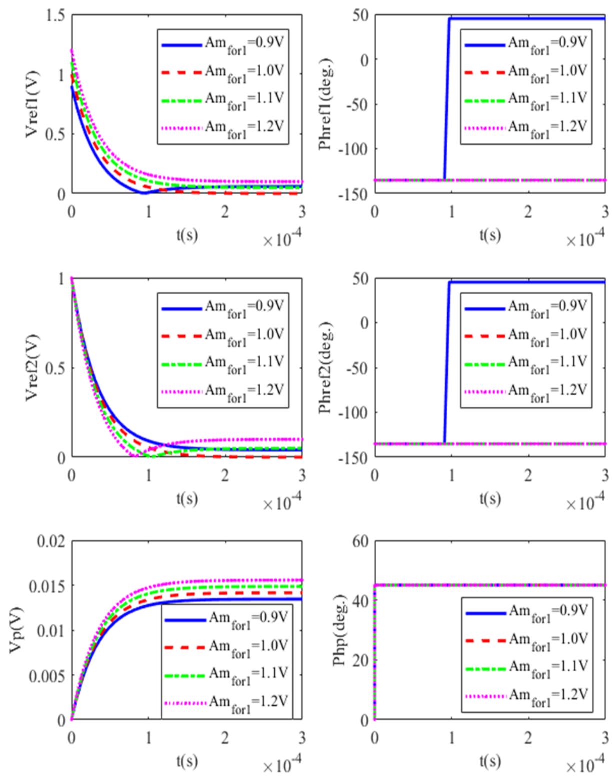

Figure 4: The amplitude and phase of $\tilde{V}_{ref_1}$, $\tilde{V}_{ref_2}$ and $\tilde{V}_P$ in the different amplitudes of $\vec{V}_{for_1}$.

Influence of Forward Voltage Difference in Phase

For research the influence of forward voltage difference in phase, the phase of the forward voltage 1 is fixed on different values. Figure 5 shows, the amplitude of the reflect voltage 1 is the same as the amplitude of the reflect voltage 2 under different situation. But, the absolute value of the difference between the phase of reflect voltage 1 and reflect voltage 2 is 180°. So the amplitudes of reflect voltage 1 and reflect voltage 2 are the same, but they have an opposite direction. The amplitude of the field voltage is maximum when the phase of the forward voltage 1 is the same as the phase forward voltage 2. The phase of the field voltage is the same as the phase of the forward voltage 1.

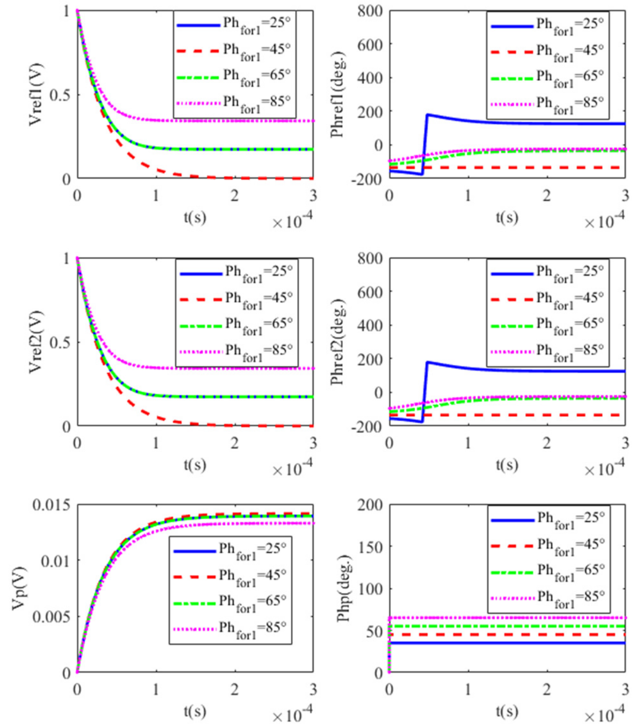

Figure 5: The amplitude and phase of $\tilde{V}_{ref_1}$, $\tilde{V}_{ref_2}$ and $\tilde{V}_P$ in different phases of $\vec{V}_{for_1}$.

CONCLUSION

The multi-feeding cavity model has been inferred and built for simulation and measurement. Base on the model, a Matlab Simulink model of the VHF cavity also has been developed and analyzed. It will help us to understand and measure the performance of the VHF cavity in low power and high power.

In addition, the characterization and stability analysis can be a reference to determine the criterion and requirement in the future FPGA firmware developing.

REFERENCES

[1] https://www.researchgate.net/publication/266282966

[2] S. John, F. Sannibale, and S. Virostek. "VHF-band Photoinjector", CBP Tech Note 366, Oct. 2006.

[3] S. Noguchi *et al.*, "Development of 2-Cell SC Cavity System for ERL Injector Linac at KEK", in *Proc. 23rd Particle Accelerator Conf. (PAC'09)*, Vancouver, Canada, May 2009, paper TU5PFP071, pp. 987-989.

[4] T. Schilcher, Ph.D. thesis, "Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities", University of Hamburg, 1998; (TESLA Report No. TESLA 1998-20,1998).