ANALYTICAL AND EXPERIMENTAL STUDY OF CROSSTALK IN THE SUPERCONDUCTING CAVITY*

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Abstract

The 3.5-cell cavity for the PKU DCSC photoinjector requires the main coupler and the pickup be on the same side of the cavity, which will cause crosstalk between them. At room temperature, serious distortion of the RF response is caused. This paper applies a clear understanding of the RF signal; numerical and experimental study shows that the crosstalk will be negligible in superconducting (SC) status. Furthermore, a method to calculater resonant frequency and loaded quality factor from the crosstalk signal is provided.

A

B

C

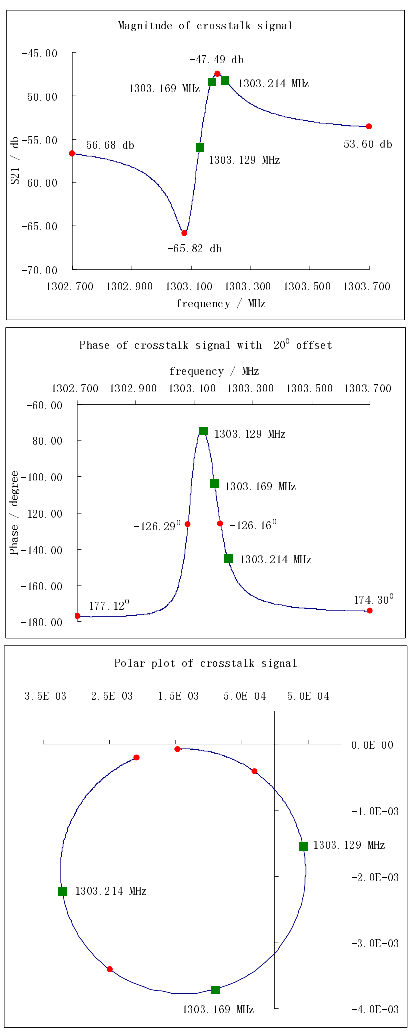

Figure 1: Typical crosstalk signals measured at room temperature. A, B, and C are the magnitude, phase, and polar plot, respectively.

INTRODUCTION

The DCSC photoinjector under construction at Peking University uses a 3.5-cell SC cavity. As the cathode is on one side of the cavity, the main coupler and pickup have to be located on the other side, which will cause direct coupling between them. Some typical measured signals at room temperature of a 2-cell copper cavity which has an are shown in Fig. 1. This phenomena can be described using an equivalent circuit model [1][2], but the calculation is complicated. We found a way to explain it clearly, and showed the relationship between the geometry of antennae and the characteristics of RF signal numerically and experimentally. Furthermore, a method to calibrate the distorted signal is provided.

SUPERPOSITION OF SIGNALS

As the beam tube of the cavity has a cut-off frequency of higher than 2GHz, the field around the antenna area is weak, and we can treat the antennae as perturbation. Thus we can analyse respectively: the signal from the cavity without crosstalk, and the signal of direct coupling through a circular waveguide between the coupler and pickup ports; and then add the two vectors together with both magnitude and phase information to get the distorted crosstalk signal.

Signal from the Cavity

The cavity could be modeled as a lossy oscillator with external excitation, and the homogeneous differential equation for the electrical field Ec in the cavity is [3]:

$$\frac{\partial^2 Ec}{\partial t^2} + \omega_0^2 Ec + \frac{\omega_0}{Q_L}\frac{\partial Ec}{\partial t} = Ee \quad (1)$$

where $Ee = Ce^{i\omega t}$ is the excitation field; ω_0 is resonant frequency; and Q_L is the loaded Q factor. We are concerned about the ratio of pickup signal and source signal, and the pickup signal $Ae^{i\omega t} = K \bullet Ec$, where K is a constant. So the solution of Eq. 1 is:

$$\frac{A}{C} = \frac{K}{\left(f_0^2 - f^2\right) + i\dfrac{f_0 f}{Q_L}} \quad (2)$$

*Work supported by National Basic Research Program(No. 2002CB713600) and NSFC(No. 10775010).
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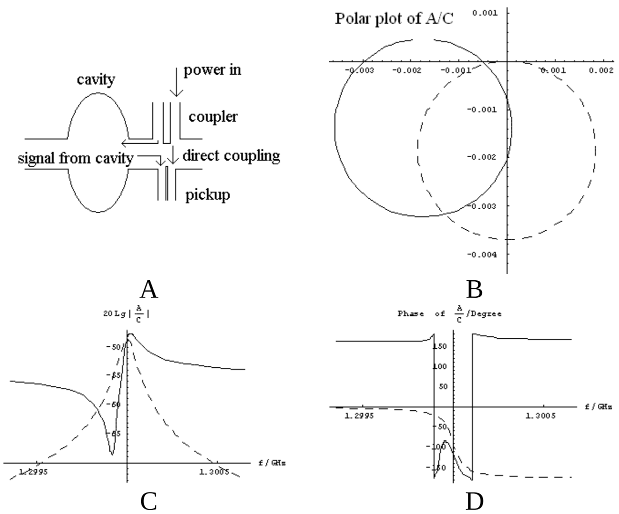

Figure 2: Calculated signal, where dashed curves indicate signal from the cavity, and solid curves indicate the superposition of cavity signal and direct coupling signal.

The dashed curves in Fig. 2 show the calculated A/C signal using Eq. 2, where we set f_0=1.3GHz, Q_L=1.6×10^4, and K=3.9×10^{11} to match the experiment. Note that the phase in Fig. 1B has an offset of -20 degrees. In the polar plot, the distance to the origin gives the magnitude, and the angle to x-axis gives the phase. We can see that: if f-f_0<<f_0, then the response curve in polar plot can be described as a circle in good accuracy; turning clockwise corresponds with the increase of frequency, and it approaches the origin when f get far from f_0.

Direct Coupling Signal

As the direct coupling signal transmits in circular waveguide, its magnitude and phase are not sensitive to frequency, so we could set them as constant: $Md \times e^{iPd}$.

Crosstalk Signal

The whole crosstalk signal is the superposition of cavity signal and direct coupling signal:

$$Signal_{whole} = \frac{K}{\left(f_0^2 - f^2\right) + i\frac{f_0 f}{Q_L}} + Md \times e^{iPd} \qquad (3)$$

To match the experiment, we set Md=1.8×10^{-3} and Pd=11π/12. The calculation results of Eq. 3 are shown by the solid curves in Fig. 2. We can find that: the circle in the polar plot is translated by the vector $\overline{Md}$; the magnitude maximum and minimum should be in the line which passes both the origin and the centre of the circle.

IMPACT OF CROSSTALK IN SC STATUS

We are concerned about whether crosstalk may cause distortion in SC status, and here we will analyse it. The intrinsic difference between normal and SC status is the change of Q factor of the cavity (including beam load), thus the length of the antenna should change correspondingly to keep matched. So we only need to study how $(A/C)_{max}$ and Md change when Q_0 and length of antenna vary, where $(A/C)_{max}$ is at resonant frequency.

From an equivalent circuit model we can get [4]:

$$\left(\frac{A}{C}\right)_{max} = \sqrt{\frac{4\beta_t\beta_e}{\left(1+\beta_e\right)^2}} \qquad (4)$$

when $\beta_t \ll \beta_e$, where $\beta_t = Q_0/Q_t$ and $\beta_e = Q_0/Q_e$ are the coupling coefficient of the pickup and coupler, while Qt and Qe are external Q factor, respectively.

The resonant frequency is under the cut off frequency of the beam tube, so the electric field should decrease exponentially along the axial direction, and the voltage signal that antenna picks should be proportional to the electrical field at the terminal of the antenna. As a consequence, we can get $Q_e \propto e^{-2\alpha_e d_e}$ and $Q_t \propto e^{-2\alpha_t d_t}$, where d_e and d_t are the length of coupler and pickup antenna respectively, α_e and α_t are constants. So we have $(A/C)_{max} \propto e^{\alpha_e d_e + \alpha_t d_t}$; similarly, $Md \propto e^{\alpha_1 d_e + \alpha_2 d_t}$.

Furthermore, we could estimate that $\alpha_1/\alpha_e \sim 1$ and $\alpha_2/\alpha_t \sim 1$, because the excitation and pickup of both cavity signal and direct coupling signal are achieved by same structure. Simulation from CST 2008 Microwave Studio shows that $\alpha_1/\alpha_e \sim 1.01$ and $\alpha_2/\alpha_t \sim 0.87$, while experiments show that $\alpha_1/\alpha_e \sim 0.70$ and $\alpha_2/\alpha_t \sim 0.95$. So when the length of the antenna changes, $(A/C)_{max}$ and Md will change by a same order.

Normal Status

We carried out the measurement at under coupling condition of $\beta_e \sim 0.48$, as shown in Fig. 1. As $(A/C)_{max} \sim 3.7\times10^{-3}$, from Eq. 4 we can get that $\beta_t \sim 1.6\times10^{-5}$; measured $Q_0 \sim 2.3\times10^4$, so $Q_e \sim 4.8\times10^4$ and $Q_t \sim 1.4\times10^9$.

On the other hand, $Md \sim 1.8\times10^{-3}$, so we get that $Md/(A/C)_{max} \sim 0.49$ at room temperature.

SC Status with Beam Load

To match power to the beam, Qe is designed to be 10^7, while Qt should be 10^{12}; so the effective $\beta_e \sim 1$, and $\beta_t \sim 10^{-5}$, as a result $(A/C)_{max} \sim 3.2\times10^{-3}$.

Md also changes as the antennae get shorter: $Md \sim 4.7\times10^{-6}$. So $Md/(A/C)_{max} \sim 1.5\times10^{-3}$, and it will not cause any detectable phenomena.

SC Status without Beam Load

Here Qe, Qt, and Md are the same as the situation of SC status with beam load, but Q_0 becomes 10^{10}, so $\beta_e \sim 10^3$, $\beta_t \sim 10^{-2}$, and $(A/C)_{\max} \sim 6.3\times10^{-3}$, therefore $Md/(A/C)_{\max} \sim 7.4\times10^{-4}$.

In all, crosstalk can safely be ignored in SC status.

CALIBRATION OF THE SIGNAL

As part of the quality control of cavities, the 3.5-cell cavity need to be tested frequently at room temperature, so it makes sense to develop a method to calibrate the distorted signal. The parameters we want to know are resonant frequency f_0, loaded Q, βe and βt, so we need to calculate the magnitude of cavity signal at f_0 and the frequency of half-maximum. From the view of superposition of vectors, an simple method is provided below.

First, as the direct coupling is much smaller than the reflection at the coupler port, the S_{11} signal is not affected, and thus we can get βe directly.

Then we only need to calibrate the S_{21} signal. See Fig. 3 for details: the dashed circle represent the cavity response, and it passes the origin; the arrow is the direct coupling vector; while the circle with solid line is the overall crosstalk signal, and we can see that it is translated from the dashed circle.

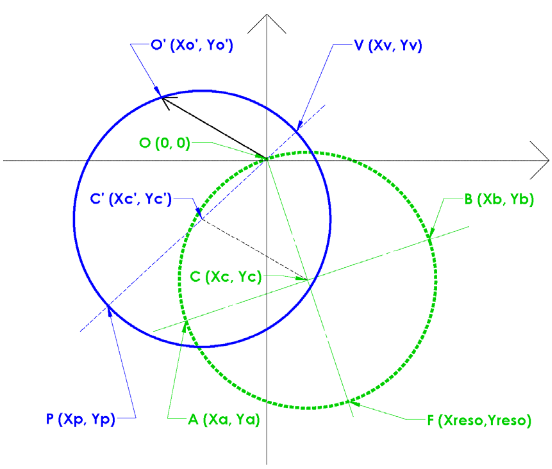

Figure 3: Schematic diagram of the calibration.

The point P is the magnitude peak in crosstalk curve, while point V is the valley, and Point O' is for frequency far from resonance. It is easy to pick up the point P, V, and O' from the magnitude and phase of S_{21} measured, as shown in Fig. 1A and Fig. 1B; the coordinates of them in polar plot can then be calculated (note that O' is estimated by the average of data from the start and stop frequency).

Once we get (Xp, Yp), (Xv, Yv), and (Xo', Yo'), all the parameters we need could be calculated: set F as the resonance point, A and B as half-maximum point, C as the centre of the dashed circle. Then we find that: line AB is perpendicular to line OF; line PV pass both C' and the origin. So:

- The direct coupling vector is:

$$\overline{OO'} = \sqrt{Xo'^2 + Yo'^2}\, e^{i\arctan(Yo'/Xo')};$$

- $(Xc', Yc') = (\frac{Xp + Xv}{2}, \frac{Yp + Yv}{2})$;
- $(Xc, Yc) = (Xc' - Xo', Yc' - Yo')$;
- $(Xreso, Yreso) = (2Xc, 2Yc)$, so we can read out the resonant frequency from curves measured by checking the point $F' = F + \overline{OO'}$;
- By translate the dashed circle by a vector of $\overline{CO}$, in other words, to move C to the origin, we can find that $(Xa - Xc, Ya - Yc) = (Yc, -Xc)$, and $(Xb - Xc, Yb - Yc) = (-Yc, Xc)$. So we can check out the full width at half-maximum (FWHM) by: $A' = (Xc + Yc + Xo', Yc - Xc + Yo')$, and $B' = (Xc - Yc + Xo', Yc + Xc + Yo')$;

We calibrated the data in Fig. 1 by this method, and get that $f_0 = 1303.1688MHz$, and $Q_0 = 22755$. In contrast to the measurement that exciting from the other side of the 2-cell cavity (thus no crosstalk at all): $f_0 = 1303.1652MHz$, and $Q_0 = 23481$. The results coincide with each other very well and thus justify the method.

SUMMARY

The crosstalk phenomenon has been explained via the view of superposition of vectors. Numerical and experimental study illustrated the relationship between the geometry of antenna and the characteristics of RF signal, and showed that the crosstalk will be negligible in SC status. Furthermore, a method to calibrate the distorted signal is provided.

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