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CORRECTION OF CROSSTALK EFFECT IN THE LEReC BOOSTER CAVITY*

Binping Xiao†, K. Mernick, F. Severino, K. Smith, T. Xin, Wencan Xu
Brookhaven National Laboratory, Upton, New York 11973-5000, USA

Abstract

The Linac of Low Energy RHIC electron Cooler (LEReC) is designed to deliver a 1.6 MeV to 2.6 MeV electron beam, with peak-to-peak dp/p less than 7e-4. The booster cavity is the major accelerating component in LEReC, which is a 0.4 cell cavity operating at 2 K, with a maximum energy gain of 2.2 MeV. It is modified from the Energy Recovery Linac (ERL) photocathode gun, with fundamental power coupler (FPC), pickup coupler (PU) and higher order mode (HOM) coupler close to each other. The direct coupling between FPC and PU induced crosstalk effect in this cavity. This effect is simulated and measured, and it is further corrected using low level RF (LLRF) to meet the energy spread requirement.

INTRODUCTION

The LEReC design has a tight energy spread requirement [1, 2]. In the electron linac of LEReC, the 704 MHz superconducting radio frequency (SRF) booster cavity is the major accelerating cavity that accelerates 400 keV bunches from the DC gun near the top of the RF wave, with an accelerating voltage up to 2.2 MV [3]. In a typical SRF cavity, the FPC and the PU are positioned on different sides of the cavity. In the booster cavity, however, since it is modified from an SRF photocathode gun, one side is reserved for photocathode insertion, and the FPC and PU are installed on the same side of the cavity that is opposite to the photocathode. In this case there is a direct coupling between them, that causes distortion of the RF response. During the operation of this cavity, we noticed this phenomenon, named crosstalk effect, that produces around 1 kV voltage fluctuation while combining with fast and slow variation on the cavity resonant frequency. This effect was introduced and simulated without electron beam previously [4]. In this paper, this effect with beam is further modelled, measured, and corrected using LLRF to meet the energy spread requirement.

BOOSTER CAVITY AND CIRCUIT MODEL

As described in [4], the SRF booster cavity is modified from the ERL photocathode gun. It has two FPCs, two PUs, and one HOM coupler, with a PU (HOMPU) on the HOM coupler to monitor the RF leakage of the fundamental mode to the HOM damper. All couplers are on the same side of the cavity, shown in Figure 1. Please note the second PU is opposite to the one shown in the Figure. With FPC and PU on the same side of the cavity, the direct coupling between FPC and PU causes distortion of the RF response, so called crosstalk effect. With this effect, the voltage on the PU, which is regulated by LLRF, is not strictly proportional to the cavity accelerating voltage, and thus introduce an energy spread that is with the same order of the budget.

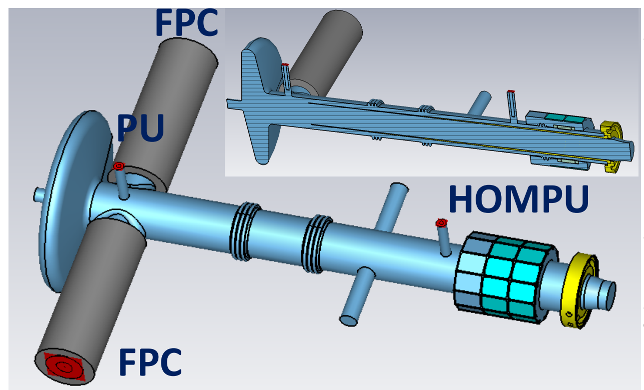

Figure 1: LEReC booster cavity with cross-section view (top-left).

In order to understand this effect, a circuit model similar to [5] is used to model the crosstalk effect. In this model, we analyse only one FPC (with admittance $B_1=j\omega C_1$) and one PU ($B_2=j\omega C_2$). The crosstalk (direct capacitive coupling between FPC and PU) is represented by $B_{12}=j\omega C_{12}$. In this plot, $G_S(=1/Z_S)$ and $G_L(=1/Z_L)$ are the admittance of source and load. $Y_c=(1+jQ2\Delta\omega/\omega_0)/R$ the admittance of cavity, with R the shunt impedance of the cavity. A term I_b is further added to model the cavity with beam. Coupling coefficients of FPC and PU are $\beta_1=-B_1^2R/G_S$ and $\beta_2=-B_2^2R/G_L$, respectively. We have the loaded quality factor, as well as the loaded shunt impedance: $Q_L=Q/(1+\beta_1+\beta_2)$ and $R_L=(R/Q)*Q_L$. These two numbers are temperature dependent.

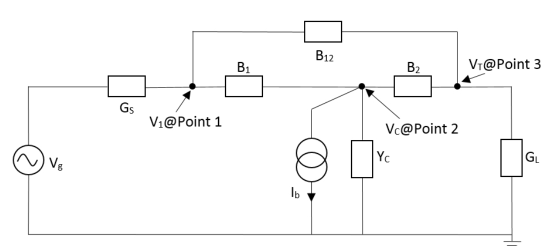

Figure 2: Circuit model of the cavity with crosstalk.

We define $Y_0=Y_C+B_1+B_2$, $Y_1=G_S+B_1+B_{12}$ and $Y_2=G_L+B_2+B_{12}$. Applying Kirchhoff law, one obtains the following equations:

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† binping@bnl.gov

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$Y_1V_1-B_{12}V_T-B_1V_c=G_SV_g$ at point 1
$I_b-B_1V_1-B_2V_T+Y_0V_c=0$ at point 2
$-B_{12}V_1+Y_2V_T-B_2V_c=0$ at point 3

CROSSTALK WITHOUT BEAM

In Figure 2, $V_1=V_F+V_R$, $I_1=(V_F-V_R)/Z_S$, $I_T=V_T/Z_L$, with I_1 and I_T the current through Z_S and Z_L, respectively, and V_F, V_R, V_T the forward, reflected and transmitted voltage on the tips of FPC and PU. The S parameter measured between point 1 and point 3 is $S_{21}=V_T/V_F$, $V_g=V_1+I_1Z_S=2V_F$ we have $V_T/V_g=S_{21}/2$. And $V_T/V_1=V_T/(V_F+V_R)=S_{21}/(1+S_{11})$.

Without beam, the S parameter is:
$S_{21}/2=(B_{12}Y_C+B_1B_2)/[Y_CG_L+(\beta_1+\beta_2)G_L/R]$

The term that contains B_{12} comes from the crosstalk effect, and the term that does not comes from the cavity resonance. Please note both terms are $\Delta\omega$ dependent. This expression can be further noted as:
$S_{21}/2=B_{12}/G_L+[B_{12}/G_L(Q_L/Q-1)+B_1B_2R_L/G_L]/(1+jQ_L2\Delta\omega/\omega_0)$.

This equation is similar to the equation shown in [6]. The first term is a vector independent of $\Delta\omega$, in polar chart it is a translation, it is from crosstalk. The second term in this expression is a Lorentz distribution, in polar chart it is a circle with origin point corresponding to $\Delta\omega\rightarrow\pm\infty$. In the second term, the portion that does not contain B_{12} represents the cavity resonance without crosstalk effect, and the portion that contains represents a rotation and enlarging around the origin point due to crosstalk. We use coefficient k to represent the ratio between the amplitude of the first term and the diameter of the circle.

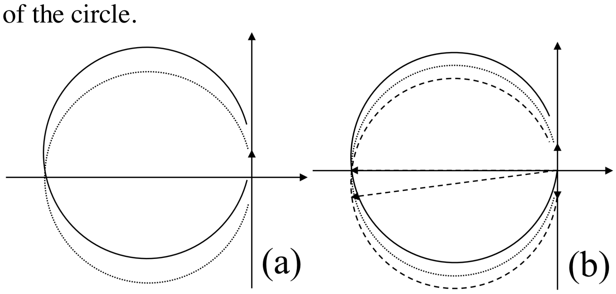

Figure 3: Polar chart of the S_{21} (a) at room temperature (b) at cryogenic temperature. With dotted circle the cavity resonance without crosstalk, and the solid circle with. The dashed circle in (b) represents the rotation and enlarging of the circle.

Network analyzer measurement was done both at room temperature and at 2K to retrieve the k value. First the S-parameter should be measured to get the resonant frequency f_0. Then the complex S-parameter between $f_0-\Delta f$ and $f_0+\Delta f$ should be measured, with the selection of Δf big enough so that the in polar chart, these two points are close enough while comparing with the origin point. During this measurement fine IF bandwidth should be used to resolve the small signals.

This measurement was first done at room temperature. The measured Re-Im chart is shown in Figure 4(a). Distortions appeared at the frequencies away from resonance. This is because of the coaxial/waveguide cables that cannot be included in the cable calibration. The phase change in these cables are different at different frequencies, shown in Figure 4(c). This phase change information can be retrieved from the S11 and S22 parameters. After taking this into account, a "calibrated" Re-Im chart is shown in Figure 4(b). At room temperature, $Q_L=Q=5600$, $k=B_{12}/(B_1B_2R_{L\text{-}RT})$. k is measured to be 0.18 for the LEReC booster cavity.

At 2K, $\beta_1=Q/Q_L>>1$, $k=B_{12}/[B_{12}(1/\beta_1-1)+B_1B_2R_L]\approx B_{12}/(-B_{12}+B_1B_2R_{L\text{-}2K})$. With FPC Q_{ext}=1.5e5, $R_{L\text{-}2K}/R_{L\text{-}RT}=26.8$. In this case the k value is predicted to be 0.0067 from the room temperature measurement, and it is measured to be 0.0069.

For both temperatures, the phase of $B_{12}/(B_1B_2R_L)$ is always $-\pi/2$.

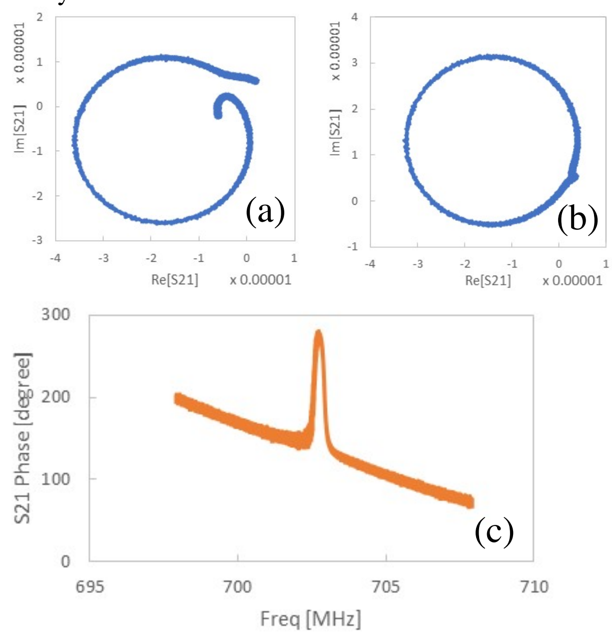

Figure 4: (a) Measured Re-Im chart of the S21; (b) Re-Im chart after considering phase on coaxial/waveguide cables; (c)Measured S21 that shows the phase versus frequency.

CROSSTALK WITH BEAM

With beam current I_b, the cavity accelerating voltage can be calculated based on the measured V_F, V_R and V_T:
$V_C=(Y_2/B_2)V_T-(B_{12}/B_2)(V_F+V_R)$

The first term is the term we normally use (without crosstalk), the second term is an additional term, it represents the RF leakage from the tip of the FPC to the PU. The value of B_{12}/B_2 can be evaluated from the k value that we measured previously. Beam current I_b did not appear in this term, since it could be determined from V_F, V_R and V_T. The cavity voltage without applying the above crosstalk correction is the first term only, $V_{C\_old}=(Y_2/B_2)V_T$, it does not represent the actual accelerating voltage of the booster cavity.

There is a 180-degree bending magnet in the LEReC electron Linac, so that it can cool both yellow and blue

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ion beams. This bending magnet provides a way to measure the electron beam energy. Without applying crosstalk correction, the cavity resonance frequency was intentionally detuned using the cavity tuner, the electron beam energy was measured, shown in the top of Figure 5 with time <400s. The energy versus phase error is also plotted, shown as green star in the bottom of Figure 5. After applying the crosstalk correction, the cavity resonance frequency was detuned, and the electron beam energy was measured, shown in the top of Figure 5 with time >400s. The energy versus phase error is also plotted, shown as black dot in the bottom of Figure 5. From the top plot of Figure 5, one can clearly see that the electron beam energy varies with cavity detuning phase error without crosstalk correction, and after applying the correction, it does not change any more. Linear fitting on the bottom plot of Figure 5 suggests that without correction, energy change is about 46.5 eV per degree of detuning, and with correction, it changes to ~2.5 eV per degree of detuning. This is a reduction by a factor of about 20. Note that this is the average beam energy after the various RF gymnastics, the energy change of the beam immediately after the booster cavity is about 2-3 times larger.

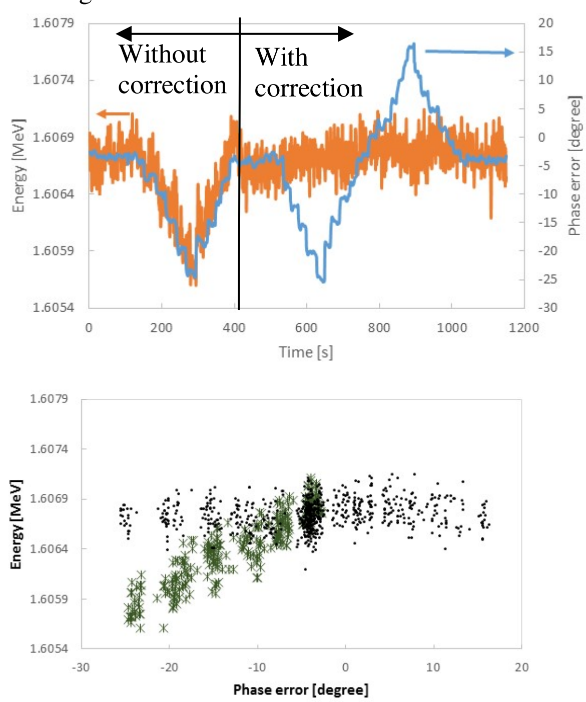

Figure 5: (top) Measured beam energy without (<400s) and with (>400s) crosstalk correction, while intentionally detuning the cavity resonance frequency. (bottom) Energy versus phase error without (green star) and with (black dot) crosstalk correction.

CONCLUSIONS

In this paper, a phenomenon called crosstalk effect is studied. Crosstalk is a direct coupling between FPC and PU that causes RF power leakage between them. While combining with the microphonics, cryogenic temperature/pressure drifting, and ±20 degree "dead-band" on the phase error to reduce the movement of the tuner, the crosstalk effect is found to cause cavity accelerating voltage fluctuation with a magnitude equivalent to the LEReC longitudinal energy spread budget if not properly corrected. Previous study revealed that this fluctuation can be explained by the distortion of S parameter simulated via CST [4] while there is no electron beam. To include electron beam into crosstalk effect, we started from a circuit model based on reference [5]. Based on the circuit model without beam, a method was proposed to measure the strength of crosstalk using the S parameter of the cavity at room temperature without beam. The same S parameter at cryogenic temperature was predicted and the prediction matched measurement results. In the case while electron beam presents, the cavity accelerating voltage can be determined by a new equation that is related to the measured V_F, V_R and V_T (in real time), R/Q and PU Q_{ext}, and the strength of crosstalk. For comparison, without crosstalk, one needs measured V_T (in real time), R/Q and PU Q_{ext} to determine cavity accelerating voltage. This method is applied into the LLRF of booster cavity and is verified using a bending magnet to measure the electron beam energy. The energy fluctuation is measured to be suppressed by a factor of 20.

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