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Abstract

Precise measurements of the cavity forward (Vf) and reflected signals (Vr) are essential for characterizing other key parameters such as the cavity detuning and forward power. In practice, it is challenging to measure Vf and Vr precisely because of crosstalk between the forward and reflected channels (e.g., coupling between the cavity reflected and forward signals in a directional coupler with limited directivity). For DESY, a method based on the cavity differential equation was proposed to precisely calibrate the actual Vf and Vr. In this study, we verified the validity and practicability of this approach for the Chinese ADS front-end demo superconducting linac (CAFe) facility at the Institute of Modern Physics and a compact energy recovery linac (cERL) test ma#2;chine at KEK. At the CAFe facility, we successfully calibrated the actual Vf signal using this method. The result demonstrated that the directivity of directional couplers might seriously affect the accuracy of Vf measurement. At the cERL facility, we calibrated the Lorentz force detuning (LFD) using the actual Vf. Our study confirmed that the precise calibration of Vf significantly improves the accuracy of the cavity LFD measurement.

Full Text

Preamble

Precise Calibration of Cavity Forward and Reflected Signals Using Low-Level Radio-Frequency System

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Precise measurements of cavity forward (Vf) and reflected signals (Vr) are essential for characterizing key parameters such as cavity detuning and forward power. In practice, measuring Vf and Vr precisely is challenging due to crosstalk between forward and reflected channels (e.g., coupling between cavity reflected and forward signals in a directional coupler with limited directivity). For DESY, a method based on the cavity differential equation was proposed to precisely calibrate the actual Vf and Vr. In this study, we verified the validity and practicability of this approach for the Chinese ADS front-end demo superconducting linac (CAFe) facility at the Institute of Modern Physics and a compact energy recovery linac (cERL) test machine at KEK. At the CAFe facility, we successfully calibrated the actual Vf signal using this method. The results demonstrated that the directivity of directional couplers can seriously affect Vf measurement accuracy.

At the cERL facility, we calibrated the Lorentz force detuning (LFD) using the actual Vf. Our study confirmed that precise calibration of Vf significantly improves the accuracy of cavity LFD measurement.

Keywords: Forward and reflected signals, Measurement, Calibration

Introduction

The Chinese ADS front-end demo superconducting linac (CAFe) was constructed at the Institute of Modern Physics to develop key technologies for a superconducting (SC) front-end linac. It was used to demonstrate the feasibility of a 10 mA high-power continuous-wave (CW) proton beam for the China Initiative Accelerator-Driven System project [1-3].

The CAFe facility is a 162.5 MHz SC radio frequency (RF) facility operating in CW mode, consisting of a normal conducting section and an SC section. As shown in Fig. 1, the normal conducting section comprises an ion source, low-energy beam transport line (LEBT), RF quadrupole accelerator, and medium-energy beam transport line (MEBT). The SC section comprises SC accelerating units, which consist of 23 SC half-wave resonator cavities assembled in four cryomodules (CM1 to CM4).

Cavity forward and reflected signals (Vf and Vr) are typically used to control key parameters such as the cavity voltage signal (Vc), cavity detuning (Δf), and forward power. For example, at the SC test facility (STF) at KEK [4], because there is no pickup antenna in the STF RF gun cavity, Vc is reconstructed by computing the superposition of Vf and Vr ($Vc = Vf + Vr$) [5]. Note that in this paper, Vc, Vf, and Vr refer to baseband signals, which can be represented by their amplitude and phase (e.g., $Vc = |Vc|e^{\{j\}Vc\}}$). The cavity pickup signal

at the Paul Scherrer Institute was found to be corrupted by noise [6]. Therefore, V_c was recalculated using the actual V_f and V_r , successfully removing the noise.

Furthermore, V_f measurement can affect the accuracy of cavity dynamical detuning. For instance, at the compact energy recovery linac (cERL) test facility at KEK, we compared the cavity Lorentz force detuning (LFD, Δf_{LFD}) calculated using the cavity differential equation with that calibrated using the square of the accelerating gradient. We found that these two methods disagree at the beginning of cavity filling. This discrepancy was attributed to inaccurate V_f measurement caused by the limited directivity of the RF directional coupler [7].

At CAFE, we measured the V_c , V_f , and V_r signals and the low-level RF (LLRF) output in cavity CM3-5 (see Fig. 2). The location of the LLRF output signal is marked in Fig. 3. The cavity amplitude loop was operated in closed-loop mode, whereas the phase loop was operated in open-loop mode. As shown in Fig. 2, the cavity amplitude error was well compensated by the feedback loop. In contrast, because the phase loop was open, the cavity phase fluctuated greatly due to perturbations such as microphonics and Δf_{LFD} . Moreover, Fig. 2 shows a significant difference between the V_f phase and LLRF output phase. One possible reason for this phase difference is the nonlinearity of the solid-state amplifier (SSA). Another possible reason involves inaccurate V_f measurement due to crosstalk between forward and reflected channels, such as coupling between cavity reflected and forward signals in the directional coupler. Later sections demonstrate that SSA nonlinearity is not the primary reason for this phase difference.

Because of crosstalk between measurement channels, the measured V_f signal is mixed with the V_r signal, resulting in inaccurate V_f measurement. To address this problem, Brandt proposed a method to eliminate the effect of V_r on the V_f signal [8]. We calibrated the actual value of V_f in CM3-5 at CAFE and in an SC cavity at KEK-cERL using this method. The measurement results confirmed that this method is effective.

The remainder of this paper is organized as follows. Section II briefly describes the CAFE LLRF system. Section III reviews the algorithms used to calibrate the actual values of V_f and V_r and estimates the actual V_f and V_r values with higher precision. Section IV demonstrates the validity of the method using experimental results from CAFE and cERL. Section V discusses future work. Finally, we summarize our study in Section VI.

LLRF System

At CAFE, the LLRF data acquisition system measures amplitude, phase, and frequency and employs various signal processing methods to monitor and control RF fields. Figure 3 shows a simplified illustration of the digital LLRF system layout at CAFE. The frequencies of the RF signals and intermediate frequency (IF) signal are 162.5 MHz and 25 MHz, respectively. A field-programmable gate array (FPGA) module performs real-time signal processing and high-speed data

acquisition. RF signals such as V_c , V_f , and V_r are first converted to IF signals. The IF signals are sampled at 100 MHz via a 16-bit analog-to-digital converter (ADC) and fed to the FPGA. The amplitude and phase of V_c are extracted from the IF signals. Subsequently, these signals are compared with their setpoints, and errors are calculated. These error signals are controlled by a proportional-integral (PI) controller. The controlled amplitude and phase signals are used to rebuild the IF signal. Next, the IF signal is up-converted, and the up-converted signal drives the SSA to power the cavity.

An ARM chip is integrated into the FPGA. An experimental physics and industrial control system (EPICS) is installed on the ARM chip as an embedded Linux system for data acquisition. The amplitude and phase waveforms of V_c , V_f , and V_r are saved to the CPU controller's hard drive during measurement, and the measurement data are analyzed offline.

Calibration of Real Cavity Forward Signal

To calibrate the real V_f and V_r signals (see Fig. 2), we review Brandt's method and present an example for cavity CM3-5 at CAFe. CM3-5 is mounted in the third cryomodule (CM3). It is the fifth cavity in CM3, with a loaded quality factor of 3.8×10^5 , as illustrated in Fig. 1.

Figure 4 shows the V_c , V_f , and V_r signals measured by the LLRF system during pulse conditioning of cavity CM3-5. According to these results, the cavity signal cannot be obtained by computing the measured signal between the V_f and V_r vectors if the two signals are uncalibrated. The actual cavity signal V_c is a superposition of the actual V_f and V_r signals, and it can be reconstructed using the formula [8-10]:

$$V_c = V_f + V_r.$$

The actual V_f and V_r signals can be calibrated using the measured cavity forward and reflected signals according to [5, 8]:

$$\begin{pmatrix} V_f \\ V_r \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} V_f^* \\ V_r^* \end{pmatrix}$$

where V_f and V_r are the measured values. In this equation, a , b , c , and d are complex constants relating actual and measured values. Then, Eq. (1) can be written as:

$$V_c = X V_f^* + Y V_r^*$$

where $X = a + c$ and $Y = b + d$. The complex constants X and Y can be estimated by multiple linear regression. The specific calculation methods are as follows.

The complex signals V, X, and Y can be written as $V = R(V) + jI(V)$, $X = C_1 + jC_2$, and $Y = C_3 + jC_4$, respectively. $R(V)$, C_1 , and C_3 represent the real parts, whereas $I(V)$, C_2 , and C_4 represent the imaginary parts. Then, Eq. (3) can be written as:

$$R(V_c) + jI(V_c) = (C_1 + jC_2)[R(V_f^*) + jI(V_f^*)] + (C_3 + jC_4)[R(V_r^*) + jI(V_r^*)].$$

For a single pulse with sampled data points $V_{\{ck\}}$, $V_{\{fk\}}$, and $V_{\{rk\}}$, where k runs from 1 to n, this method can be used to obtain a linear, over-determined system of equations. Let V_c be the response variable; then:

$$y = [R(V_{c1}) \cdots R(V_{cn}) \ I(V_{c1}) \cdots I(V_{cn})]^T.$$

In addition, let the measured values V_{f^*} and V_{r^*} form the regressor matrix:

$$A = \begin{pmatrix} R(V_{f1}^*) & -I(V_{f1}^*) & R(V_{r1}^*) & -I(V_{r1}^*) \\ R(V_{f2}^*) & -I(V_{f2}^*) & R(V_{r2}^*) & -I(V_{r2}^*) \\ \vdots & \vdots & \vdots & \vdots \\ R(V_{fn}^*) & -I(V_{fn}^*) & R(V_{rn}^*) & -I(V_{rn}^*) \\ I(V_{f1}^*) & R(V_{f1}^*) & I(V_{r1}^*) & R(V_{r1}^*) \\ I(V_{f2}^*) & R(V_{f2}^*) & I(V_{r2}^*) & R(V_{r2}^*) \\ \vdots & \vdots & \vdots & \vdots \\ I(V_{fn}^*) & R(V_{fn}^*) & I(V_{rn}^*) & R(V_{rn}^*) \end{pmatrix}.$$

Then the relation $y = AC$ is approximately satisfied for some parameter vector:

$$C = [C_1 \ C_2 \ C_3 \ C_4]^T$$

where C represents the values of interest. The best estimates of C_1 , C_2 , C_3 , and C_4 can be determined using multiple linear regression. The complex constants X and Y can be obtained using these C values.

The crosstalk elements b and c can be taken into account using information from the RF decay time (after 3.5 ms in Fig. 4). During decay, the actual V_f should be 0, and the factors a and b are then limited by another complex factor Z as:

$$Z = a/b = -V_r^*/V_f^* \quad (t > 3.5\text{ms}).$$

Then the complex factors can be expressed in terms of X, Y, and Z according to:

$$a = X/(1 + Z), \quad b = a/Z, \quad c = X - a, \quad d = Y - a/Z.$$

The final unknown complex factor a can be extracted numerically from the cavity differential equation assuming a constant cavity half-bandwidth $\omega_{0.5}$, which can be estimated from the field decay curve ($t > 3.5$ ms).

The cavity equation can be written in polar coordinates as:

$$\frac{d|V_c|}{dt} + |V_c|\omega_{0.5} = \omega_{0.5} \cdot (2|V_f|) \cos(\theta - \phi).$$

Consequently, the differential of $|V_c|$ can be computed using the formula:

$$y(a, t_k) = \omega_{0.5}[(2|V_f|) \cos(\theta - \phi) - |V_c|],$$

where θ and ϕ represent the phases of V_c and V_f , respectively. The variable $y(a)$ represents the calibrated $d|V_c|/dt$ as a function of factor a according to Eq. (13). By contrast, $d|V_c|/dt$ can be directly calibrated from the amplitude of V_c , which is independent of a . The difference between these two calculations should be minimized by optimizing a . Therefore, we denote the difference as $\lambda^2(a)$:

$$\lambda^2(a) = \sum \left(\frac{d|V_c|}{dt} - y(a) \right)^2.$$

Note that a is a complex number with two components. A two-dimensional map can be obtained by sweeping the real and imaginary components of a , as shown in Fig. 5. Here, the color axis represents the value of $\lambda^2(a)$. The X and Y axes represent the real and imaginary components of (a/X) , respectively. The optimal value of (a/X) is clearly $0.99 + 0.07i$. To better illustrate this result, Figs. 6 and 7 compare the waveforms of V_f and $y(a)$, respectively, for $a/X = 1$ and $a/X = 0.99 + 0.07i$. The difference between $d|V_c|/dt$ and y is minimized when the optimal value of a is used.

Experimental Verification

To demonstrate the method described in the previous section, V_f measurement data were processed and analyzed at the CAFé and cERL facilities.

A. Experimental Result at CAFé

During RF commissioning at CAFé, the LLRF output, SSA output, and V_f^* and V_r^* signals of CM3-5 were down-converted and sent to the ADCs of the LLRF system. The positions of the four signals (points A, B, C, and D, respectively) are shown in Fig. 8. As mentioned in Section I, the phase of

V_f^* differs from the LLRF output phase according to measurement (see Figs. 2 and 9). In theory, the LLRF output phase and V_f phase should agree, whereas the phases at points A and C differ greatly, according to Fig. 9.

As shown in Fig. 8, in the ideal case, the phases of the LLRF output (point A) and V_f (point C) should be in agreement. The discrepancy has two possible causes: SSA nonlinearity and crosstalk between measurement channels (i.e., unwanted coupling of some V_r components with V_f). We analyze these two causes as follows.

To eliminate the impact of SSA nonlinearity, we measured the output characteristics of the SSA, as shown in Fig. 10. The amplitude and phase characteristics of the SSA output were measured using a network analyzer. The operating point for Fig. 2 (and Fig. 9) is marked on Fig. 10 as $P(x, y)$. The amplitude nonlinearity curve can be fitted using the polynomial formula [11]:

$$f_A(x) = h_{nx}^n + h_{n-1}x^{n-1} + \cdots + h_{1x} + h_0.$$

The phase characteristic curves can be fitted by:

$$f_\theta(x) = q_{mx}^m + q_{m-1}x^{m-1} + \cdots + q_{1x} + q_0.$$

The amplitude ($f_A(|V_{\text{LLRF}}|)$) and phase ($f_\theta(|V_{\text{LLRF}}|)$) of the SSA output can be calibrated using Eqs. (14) and (15), as shown in Fig. 9.

Furthermore, $f_A(|V_{\text{LLRF}}|)$ and $f_\theta(|V_{\text{LLRF}}|)$ can also be estimated using the differential near the operating point. If the SSA is linear, its output amplitude increases linearly with input amplitude, and the linear gain is $K = y/x$. In fact, the SSA output amplitude is often nonlinear with respect to input amplitude; thus, the differential at point P is approximately $G = \Delta y/\Delta x$, as illustrated in Fig. 9 [11-13]. The amplitude variation of the SSA output signal depends on the value of G/K . For $G/K > 1$, the amplitude fluctuation of the LLRF output will be G/K times larger than that of the SSA. By contrast, for $G/K < 1$, the amplitude fluctuation of the LLRF output will be G/K times smaller than that of the SSA. We can see from Fig. 10 that the value of G/K is approximately 1.8; thus, a 1% fluctuation in LLRF output amplitude near the operating point corresponds to a 1.8% fluctuation in SSA output amplitude. It is easy to see that the ratio of LLRF output amplitude and f_A is in good agreement with the value of G/K in Fig. 9. In addition, a 1% fluctuation in LLRF output amplitude near the operating point will result in an error of 0.015° in SSA output phase, according to the phase curves in Fig. 9. Noise from various sources also contributes to the error, which is difficult to determine from the LLRF output phase, as shown in Fig. 9.

Thus far, we have successfully estimated the amplitude and phase at point B (f_A and f_θ). Figure 9 shows that f_A and f_θ differ greatly in amplitude and phase (especially in phase) from f . Thus, we deduce that SSA nonlinearity is

not the main reason for the phase discrepancy by comparing the phase curves of $f_{\perp}(|V_{\text{LLRF}}|)$ and $f_{\perp A}$.

To determine whether the V_r signal is coupled with the V_f signal, it is necessary to calculate the actual V_f value of CM3-5. The values of complex constants a and b must be known before this calculation. The exact value of a for CM3-5 was obtained by theoretical analysis and derivation in Section III. The exact value of b can then be calculated using Eq. (9). From the known a and b values, the actual cavity forward signal can be calibrated using the measured signals V_f^* and V_r^* . Figure 11 shows the actual V_f signal, measured V_f signal, and SSA output signal considering SSA nonlinearity effects. Panels (a), (b), and (c) represent measurement results using the same calibration factors (i.e., a and b) but for different dates. The red lines represent the amplitude and phase of the SSA output signal considering SSA nonlinearity effects. The blue lines show the calibrated actual forward signal, representing $V_{\{f2\}}$ in the figure. The aqua lines represent the measured forward signal, as in the previous section, representing $V_{\{f1\}}$. Figure 11(a) shows good phase agreement between the blue and red lines. The LLRF output phase is in agreement with the V_f phase in theory. This result confirms that the V_r signal is coupled with the V_f signal in signal measurement. It is demonstrated that crosstalk in measurement channels (e.g., crosstalk caused by limited directivity of the directional coupler) is the major reason for inaccurate V_f measurement and thus the phase discrepancy.

To further confirm the V_f signal calibration results, we used the same calibration array (i.e., the same values of a , b , c , and d) to calibrate measurement results for other cases. In these cases, the working point of the SSA is the same as in Fig. 10. The blue and red lines show good agreement [see Figs. 11(b) and 11(c)] in all cases, indicating that the calibration array has high universality.

B. Experimental Result at KEK-cERL

The cERL facility was constructed at KEK to accommodate industrial applications of SC technology. It is a 1.3 GHz SC machine operated in CW mode [14-16]. At cERL, two nine-cell cavities (ML1 and ML2) with high Q_L values up to 1×10^7 were installed in the main linac.

At cERL, we observed that the LFD calculated using V_f differs from the theoretical value at the beginning of cavity filling in ML2. The discrepancy was assumed to be related to inaccurate V_f measurement due to signal crosstalk between measurement channels. To verify this assumption, the experimental data were re-analyzed.

The cavity detuning ($\Delta\omega$) during the RF pulse without beam can be estimated using the cavity differential equation [7, 8, 12]:

$$\Delta\omega = \omega_{0.5} \frac{(|2V_f|) \sin(\theta - \phi)}{|V_c|},$$

where ϕ and ψ represent the phases of V_c and V_f , respectively. The quantity $\omega_{0.5}$ represents the cavity half-bandwidth. The detuning calculated using Eq. (16) includes sources other than LFD, although LFD plays a major role in overall detuning when the SC cavity is operated in pulse mode.

Moreover, for a given pulse pattern, the LFD can be calibrated using the LFD transfer function model $K(s)$ [7, 17-19] as:

$$\Delta\omega_{LFD} = -2\pi K(s) E_{acc}^2,$$

where $K(s)$ is the LFD transfer function and E_{acc} is the accelerating gradient. The detuning at the beginning of filling time can be estimated using the above equation [see Δf_{model} in Fig. 12(b)].

According to Eq. (16), the amplitude and phase ($|V_f|$ and ψ) of V_f are required to calculate cavity detuning $\Delta\omega$. When crosstalk components b and c are not considered, the calibrated cavity forward signal V_f equals V_f^* [Cali1 in Fig. 12(a)]. Under this assumption, the detuning Δf_{Cali1} is calibrated as shown in Fig. 12(b). Note that in Fig. 12(a), the amplitude of the Cali1 curve does not decrease to zero immediately when RF power is switched off. As shown in Fig. 12(b), the waveforms of Δf_{Cali1} and Δf_{model} (red curve) are slightly different at the beginning of filling time.

Next, crosstalk coefficients b and c in Eq. (2) are considered, and coefficients a , b , c , and d are recalculated using the method described in Section III. Then, the actual cavity forward signal V_f is calibrated by $V_f = aV_f^* + bV_r^*$ [Cali2 in Fig. 12(a)]. As shown in Fig. 12(a), the amplitude of the Cali2 curve decreases to zero immediately when RF power is turned off. Using the V_f waveform in the Cali2 curve, the LFD (Δf_{Cali2}) is obtained, as shown in Fig. 12(b). As expected, the trends of Δf_{Cali2} and Δf_{model} are in good agreement at the beginning of filling time.

From the analysis above, we conclude that inaccurate V_f measurement can result in miscalculation of LFD. In addition, the analysis demonstrates the validity of Brandt's method.

Future Work

In the future, after estimating values of a , b , c , and d in the offline state, we will implement Eq. (2) in the FPGA. The actual cavity forward signal V_f and actual reflected signal V_r are expected to be calibrated in real time. In the next stage, the calibrated V_f can be used to calibrate other parameters such as cavity detuning and beam current.

In addition, the directivity of the directional coupler is related to its input power (the output of the RF source); therefore, the value of a/X may also depend on the location of the nonlinear operating point of the SSA. In the next step, we will attempt to determine the dependence of parameter a/X on the operation

point of the RF source. This research will be based on many measurements and calculations at CAFE at various SSA powers according to the research purpose.

Finally, this paper assumes that crosstalk exists only between measured forward and reflected waves. However, RF components could also contribute to crosstalk signals. We will study these crosstalk relationships further in future work.

Summary

In this study, the actual V_f was successfully calibrated using the method proposed by Brandt. We verified the validity of this method for the CAFE and cERL facilities. The study at CAFE indicated that inaccurate V_f measurement is caused mainly by coupler directivity. We confirmed that at cERL, calibration accuracy of cavity detuning can be significantly improved by considering crosstalk components resulting from, for example, limited directivity of the directional coupler.

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Author Contributions

All authors contributed to study conception and design. Material preparation, data collection, and analysis were performed by Feng Qiu, Jin-Ying Ma, and Gui-Rong Huang. The first draft of the manuscript was written by Jin-Ying Ma, and all authors commented on previous versions. All authors read and approved the final manuscript.

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