DEVELOPMENT AND APPLICATION OF A FREQUENCY SCAN-BASED AND A BEAM-BASED CALIBRATION METHOD FOR THE LLRF SYSTEMS AT KEK STF

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Abstract

In order to calibrate the ratio of the forward and reflected signal in the waveguide system of the Superconducting RF Test Facility (STF) RF gun a technique based on a frequency scan was developed. The application allowed the reconstruction of the cavity pick-up signal and therewith a stable feedback operation in absence of an actual pick-up antenna.

For the determination of the RF phase for on-crest beam acceleration by superconducting 9-cell L band cavities as well as for the calibration of the cavity gradient a method using beam loading effects during an RF phase scan was developed. The optimal RF phase for on-crest beam acceleration was found with an accuracy of 3°. A stable feedback operation was established. The cavity gradient was calibrated with an error due to the calibration method of less than 5%.

INTRODUCTION

In preparation for the International Linear Collider (ILC) [1] STF is operated at the High Energy Accelerator Research Organization (KEK) in Tsukuba. In the current configuration for the quantum beam project [2] the linear accelerator for electrons consists beside others of a 1.3 GHz normal conducting photo-cathode RF gun as well as two superconducting (SC) 9-cell TESLA type L band cavities, which are driven by one klystron in the Distributed RF Scheme (DRFS) [3]. Both systems are operated using digital Low Level RF (LLRF) control techniques [4, 5].

Due to the absence of a pickup antenna in the STF RF gun cavity a calibration method for the forward and the reflected signal in the waveguide had to be developed in order to reconstruct the cavity signal, which is the requirement for the feedback operation.

For the on-crest acceleration using the SC cavities and the feedback operation of the DRFS a method for the determination of an appropriate RF phase as well as for setting the loop phase to 0° had to be developed. Furthermore the beam-based calibration of the cavity gradient was intended.

RF GUN CALIBRATION AND FEEDBACK OPERATION

Since the actual cavity signal is a superposition of the actual forward and reflected signal [6], it can be reconstructed by

$$U_{\mathrm{cav}} = U_{\mathrm{for}} + U_{\mathrm{ref}} \ . \tag{1}$$

The calibration of U_{for} and U_{ref} corresponds to finding the complex matrix elements of

$$\begin{pmatrix} U_{\mathrm{for}} \\ U_{\mathrm{ref}} \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} U^*_{\mathrm{for}} \\ U^*_{\mathrm{ref}} \end{pmatrix} \ , \tag{2}$$

where $\mathrm{U}^*_{\mathrm{for}}$ and $\mathrm{U}^*_{\mathrm{ref}}$ are measured values. It was shown that the cross talk is negligible small so that b and c can be considered as zero. There with equation (2) can be rewritten as

$$\begin{pmatrix} U_{\mathrm{for}} \\ U_{\mathrm{ref}} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & d/a \end{pmatrix} \begin{pmatrix} U^*_{\mathrm{for}} \\ U^*_{\mathrm{ref}} \end{pmatrix} \ . \tag{3}$$

This means d/a has to be determined, which can be archived by using the reflection coefficient

$$\Gamma = \frac{U_{\mathrm{ref}}}{U_{\mathrm{for}}} = \frac{d}{a}\frac{U^*_{\mathrm{ref}}}{U^*_{\mathrm{for}}} = \frac{d}{a}\Gamma^* \ . \tag{4}$$

Performing an RF frequency scan (typical range of ±100 kHz) by changing the phase constantly over time during the second flattop of the pulse, which corresponds to a value different from zero for y3 of the phase as shown in Figure 1, and plotting $\mathrm{Im}(\Gamma^*)$ versus $\mathrm{Re}(\Gamma^*)$ results in a resonance circle as shown in Figures 2 and 3 (blue). The point of full reflection can be identified as

$$\Gamma^*_\infty = (|c| + r)\frac{c}{|c|} \ , \tag{5}$$

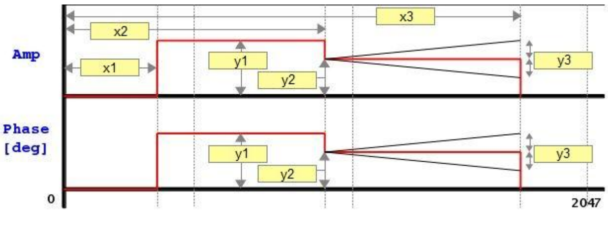

Figure 1: RF pulse shape properties for amplitude (top) and phase (bottom).

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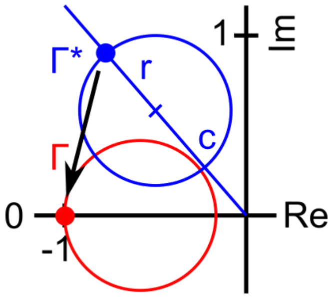

Figure 2: Imaginary part versus real part of Γ^* (blue) and Γ (red).

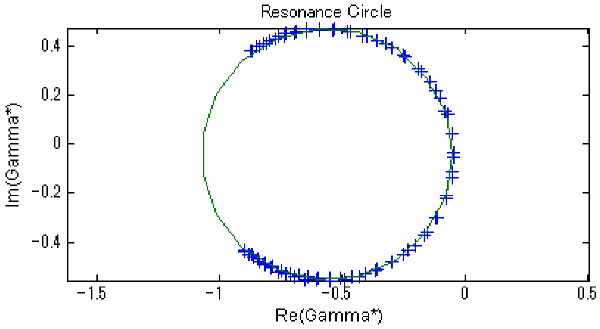

Figure 3: Imaginary part versus real part of Γ^*: Measured data (blue) and fit (green).

where c and r result from a fit of a circle to the measured data (see Figure 3). The point Γ_∞^* corresponds to $(-1{,}0)^{\mathrm{T}}$ in reality, which allows the normalization

$$\frac{d}{a} = -\frac{1}{\Gamma_\infty^*} \ . \tag{6}$$

Insertion of this in equation (3) and in equation (1) yields the reconstructed cavity signal.

Once the calibration factor d/a is determined and set to the system, U_{cav} is calculated in real-time. Thereby a stable feedback operation was established yielding a longtime stability of $\Delta A/A_{\mathrm{RMS}} = 0.094\%$ in amplitude and $\Delta\phi_{\mathrm{RMS}} = 0.056°$ in phase, respectively. Figures 4 and 5 are showing amplitude and phase of the respective pulse.

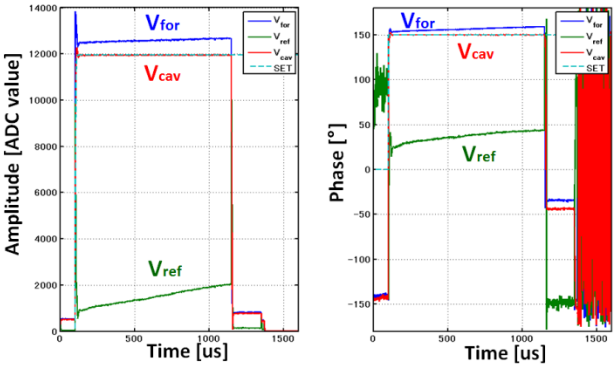

Figure 4: Amplitude (left) and phase (right) versus time of the forward signal (blue), the reflected signal (green), the reconstructed cavity signal (red), and the set point (light blue) of an RF pulse while feedback operation.

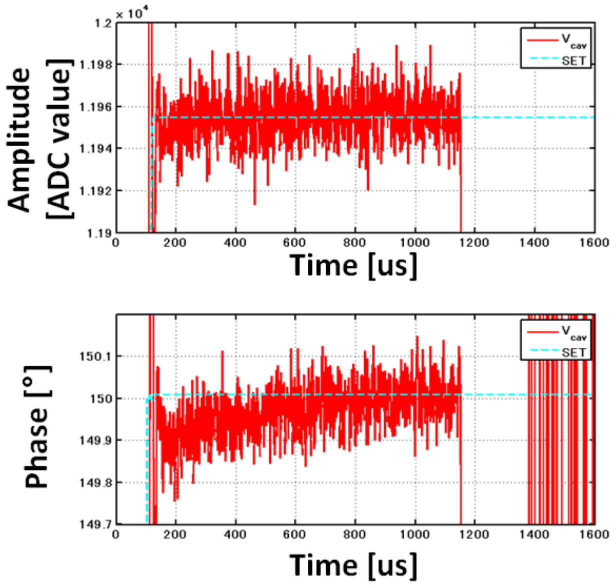

Figure 5: Zoomed in region of amplitude (top) and phase (bottom) at first flattop versus time of reconstructed cavity signal (red) and set point (light blue) during feedback operation.

Beside this the calibration method allows to obtain the coupling coefficient β by

$$\beta = \frac{1+\Gamma_0}{1-\Gamma_0} \ . \tag{7}$$

BEAM-BASED CALIBRATION OF SUPERCONDUCING CAVITIES

As shown in Figure 6 the DRFS waveguide system consists beside others of several waveguide phase shifters (WPS) and waveguide reflectors (WR). Thereby the combination of WR 1 and WPS 3 as well as WR 2 and WPS 4 are used to set the Q_L values of cavity 1 (MHI 12) and cavity 2 (MHI 13), respectively [7].

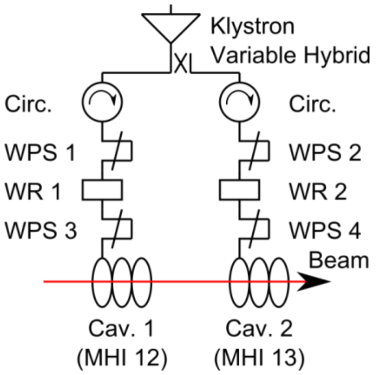

Figure 6: Schematic of the DRFS waveguide system: Klystron, variable hybrid, circulators, waveguide phase shifters (WPS 1 and WPS 2), waveguide reflectors (WR 1 and WR 2), waveguide phase shifters (WPS 3 and WPS 4), and superconducting cavities (MHI 12 and MHI 13).

By scanning the RF phase using WPS 1 and WPS 2 consecutively while observing the beam induced change in amplitude ΔA at the flattop of the pulses [8] as shown in Figure 7 for each cavity the RF phases for on-crest beam acceleration were determined.

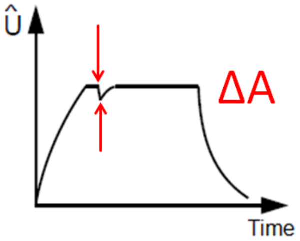

Figure 7: Amplitude versus time of an RF pulse including a beam induced drop-off during the flat top.

Those correspond to the maximal negative ΔA and are identified by a fitting procedure. By taking the charge per bunch into account as well as averaging over ten pulses per step motor position, the calibration method was improved so that the fluctuation due to the change of the charge per bunch over time could be smoothed out. Figure 8 shows a respective phase scan. Besides determining the RF phases the loop phase for the feedback loop was set to zero and a reference table was created, which allowed a stable feedback operation.

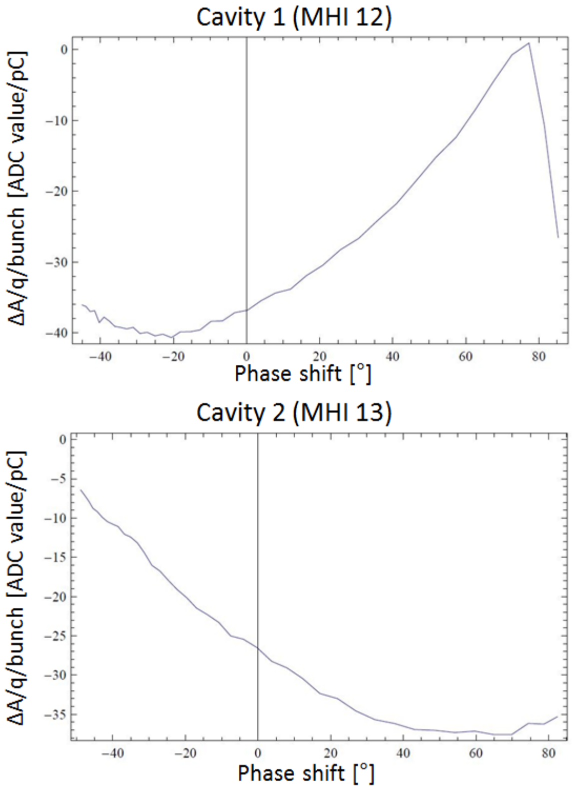

Figure 8: Beam induced amplitude ΔA/charge per bunch versus RF phase shift for cavity 1 (top) and cavity 2 (bottom). The drop at cavity 1 above 77° of RF phase shift originates from effects of far off-crest beam operation.

In a low power measurement of the two paths between the klystron and the two cavities in the DRFS waveguide system (see Figure 6) after a RF phase shift calibration it was shown that the phase difference between the two cavities is $\measuredangle_{\text{cav1cav2}} = 93°$. Since the cavities are mounted in $\lambda/4$ distance the measured value is in good agreement with the expected and required value of 90°, showing that the developed and applied method is effective.

The beam induced voltage, which causes to a drop in amplitude as shown in Figure 9 for five different step motor positions of WPS 1, can be calculated by

$$\Delta V_{\text{ind}} = I_{\text{b}} \cdot \Delta t \cdot \frac{r}{Q} \cdot \pi \cdot f_0 \quad . \tag{8}$$

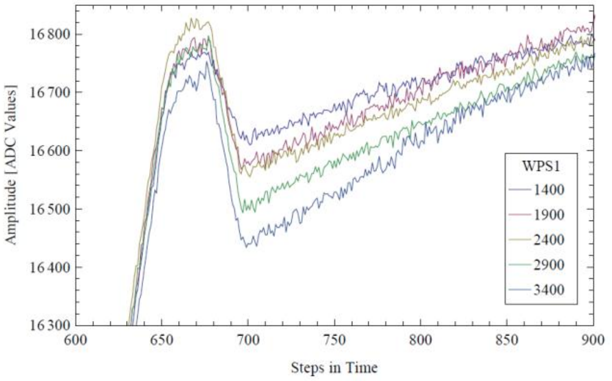

Figure 9: Zoomed in region of amplitude versus steps in time of flattop including beam for five different WPS 1 step motor positions.

Comparing this value with the ADC values allows a calibration of those. Taking the length of the cavities into account yielded cavity gradients of $V_{\text{cav1}} = 18.7$ MV/m and $V_{\text{cav2}} = 19.2$ MV/m. The errors for these values due to the calibration method are $\Delta V_{\text{cav1}} = 4.8\%$ and $\Delta V_{\text{cav2}} = 4.9\%$. In respect of the estimated errors, these cavity gradients are in good agreement with the measured beam energy of 40 MeV.

SUMMARY

By developing and applying a calibration method for the forward and reflected signal in the waveguide of the STF RF gun, the cavity signal could be reconstructed, which allowed a stable feedback operation even in absence of an actual pick-up antenna with a longtime stability of $\Delta A/A_{\text{RMS}} = 0.094\%$ in amplitude and $\Delta\phi_{\text{RMS}} = 0.056°$ in phase, respectively.

A beam-based calibration method for the RF phase for on-crest acceleration as well as for the cavity gradients was developed and successfully applied. The determined cavity gradients were $V_{\text{cav1}} = 18.7$ MV/m and $V_{\text{cav2}} = 19.2$ MV/m with an error of $\Delta V_{\text{cav1}} = 4.8\%$ and $\Delta V_{\text{cav1}} = 4.9\%$ due to the calibration method. Furthermore the stable feedback operation of the DRFS system was achieved.

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