DEVELOPMENT AND TEST OF A FULLY AUTOMATED P_kQ CONTROL PROCEDURE AT KEK STF

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Abstract

In order to operate the superconducting cavities at the International Linear Collider (ILC) [1] near their maximum gradients, cavity input (P_k) and cavity loaded Q (Q_L) have to be controlled individually (P_kQ_L control [2]). In this scope a fully automated P_kQ_L operation procedure was developed and demonstrated at cavity gradients of 16 MV/m and 24 MV/m with Q_L values of 9e6 and 3e6. During a long-time operation with beam (6.4 mA, 615 µs) the vector sum gradient and phase stabilities during the beam transient were $\Delta A/A_{RMS} = 0.009\%$ and $\Delta\phi_{RMS} = 0.009°$ with cavity gradient stabilities of $\Delta A/A_{cav1,RMS} = 0.041\%$ and $\Delta A/A_{cav2,RMS} = 0.031\%$.

INTRODUCTION

In preparation of ILC, the Superconducting RF Test Facility (STF) is operated at the High Energy Accelerator Research Organization (KEK). In the configuration for the quantum beam project [3], the linear electron accelerator consists beside others of two superconducting 9-cell TESLA type L band cavities driven by a single klystron in the Distributed RF Scheme (DRFS) [4] and operated using digital Low Level RF (LLRF) control techniques [5, 6]. A simplified schematic of the feedback loop is shown in Figure 1.

The down converted and filtered cavity signals are digitized by ADCs on the µTCA board. After a signal rotation and computation of the vector sum (select) the signal is filtered and subtracted from the set table. In the following the gain is applied and the base and the beam feedforward (FF) tables are added. The rotated and to analog converted signal is filtered by an analog 400 kHz low pass filter in order to suppress the excitation of 8/9π-modes and sent to the klystron, which drives both superconducting cavities. Therefor the power is divided by a variable hybrid (range from 0 dB to -6 dB for the through port). The cavity phases are optimized individually by waveguide phase shifters. Since no remote control for the coupler position is available the Q_L values (possible range from 2.5e6 to 5e7) are controlled by waveguide reflectors.

In ILC the nominal design gradient is 31.5 MV/m for a 9.0 mA beam. A cavity gradient spread of ±20% around the average gradient is planned as well as the operation of all cavities with flat gradients at 5% below their respective quench limits, which must never be exceeded. In order to fulfill these requirements an automated beam compensation as well as a fully automated setting procedure for P_kQ_L operation had to be established.

BEAM LOADING

Beam loading induces a drop ΔV_{ind} in the cavity gradient. An example for a 31 µs beam pulse is shown in Figure 2. The beam induced voltage can be derived from the cavity differential equation

$$\frac{dV}{dt} = -\omega_{1/2}V + R_L\omega_{1/2}(I_g - I_b) \ . \qquad (1)$$

Considering only the contribution of the beam, solving for ΔV_{ind}, and substituting R_L and $\omega_{1/2}$ yields

$$\Delta V_{\text{ind}} = \pi \frac{r}{Q} f_0 I_b \Delta t \ . \qquad (2)$$

In the example shown in Figure 2, the average beam

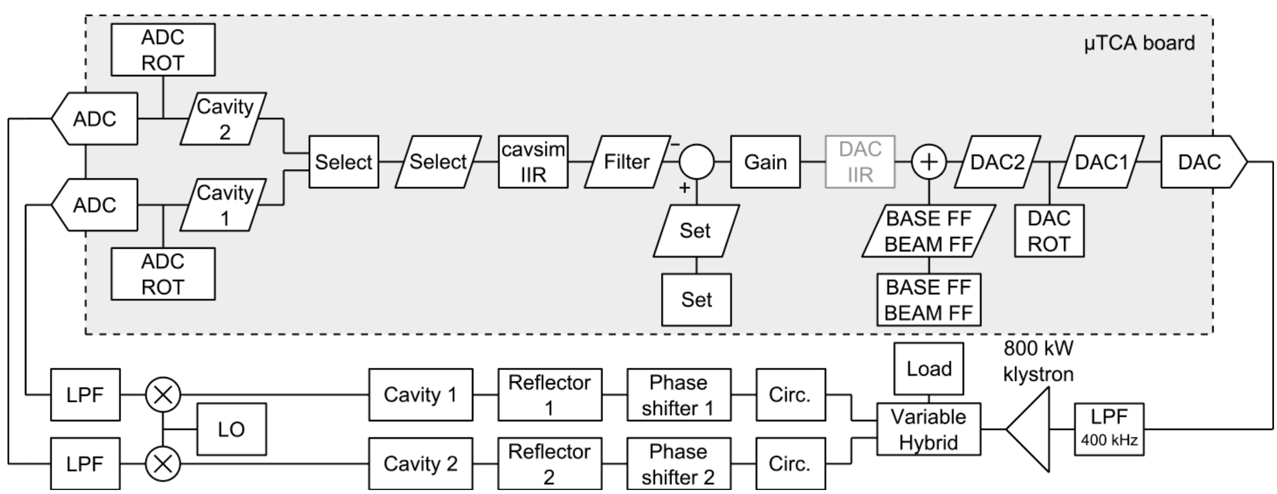

Figure 1: Schematic of the digital LLRF feedback loop controlling two superconducting cavities at STF. Hardware and software components are represented by squares, data channels accessible on the µTCA board via EPICS by rhombi.

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current has been 9.9 mA (corrected ICT value), which corresponds to a calculated beam induced drop of 1.31 MV/m. The actual drop is 1.26 MV/m, which agrees with an error of 3.8% well with the estimated value.

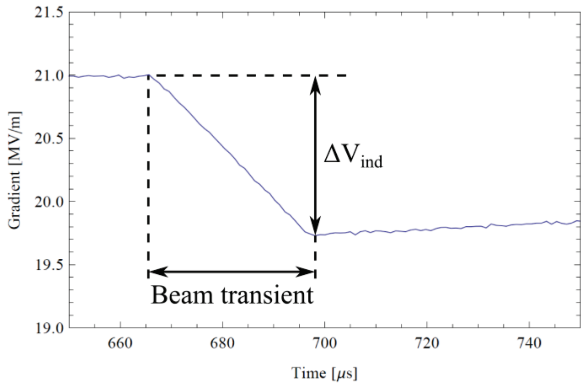

Figure 2: Cavity 1 gradient [MV/m] versus time [μs] during the flattop covering the beam transient, during which beam loading induces the gradient drop ΔV_{ind}.

AUTOMATED BEAM COMPENSATION

Since cavity gradient tilts and RF fluctuations induce transverse beam orbit changes [7], a stable beam acceleration requires flat cavity gradients during the beam transient. For compensation of the beam induced gradient drop, additional driving power has to be supplied during beam transient, which is achieved by the addition of a beam FF table to the base FF table as shown in Figure 3.

Since the beam has a non-constant structure over the whole pulse a fully automated beam FF amplitude shape generation was established. Figure 4 shows an example of an automatically generated beam FF table for a 5.5 mA beam with a pulse width of 308 μs. Due to beam current fluctuations during the generation procedure, the beam FF amplitude table is not smooth. Since the cavity itself acts like a low pass filter this structure is no issue. Figure 5 shows the corresponding vector sum gradient. The stabilities are same to nominal operation (see below).

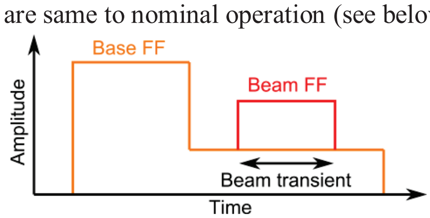

Figure 3: Schematic of the amplitude versus time for a base FF table (orange) and a beam FF table (red).

NOMINAL OPERATION

The nominal operation parameters at STF in scope of the quantum beam project are $V_{cav1} = 16$ MV/m and $V_{cav2} = 24$ MV/m with $Q_{L1} = Q_{L2} = 3e6$ and a filling time of 540 μs. In two long-time runs of up to 1 hour the vector sum stabilities have been evaluated with (6.6 mA, 615 μs) and without beam. The beam FF table was established as described above. The vector sum gradient and phase stabilities were $\Delta A/A_{RMS} = 0.009\%$ and $\Delta\phi_{RMS} = 0.009°$ with and $\Delta A/A_{RMS} = 0.008\%$ and $\Delta\phi_{RMS} = 0.008°$ without beam.

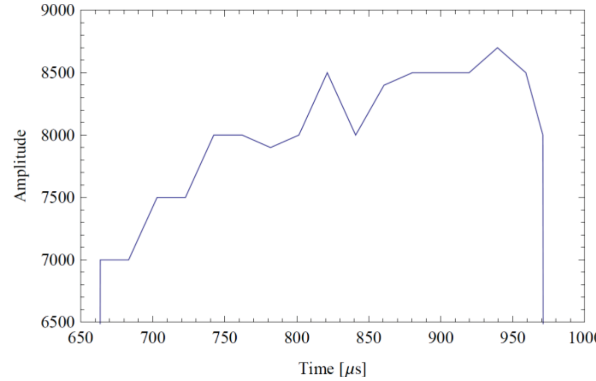

Figure 4: Amplitude versus time [μs] of automatically generated beam FF table.

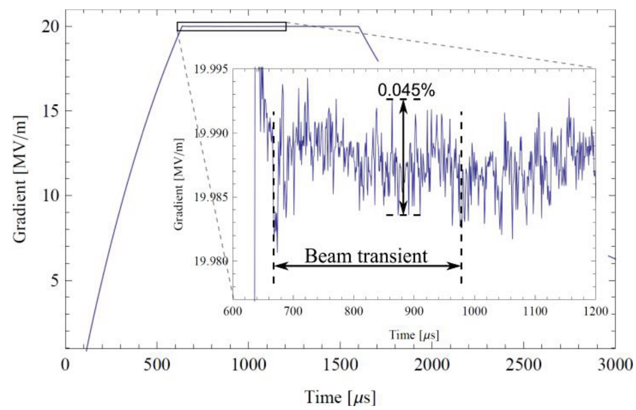

Figure 5: Vector sum gradient [MV/m] versus time [μs] after automated generation of beam FF table.

FULLY AUTOMATED PKQL CONTROL

The essentials for LLRF cavity control are to operate at flat gradients during beam transient with a constant RF output over filling and flattop time in order to operate the klystron near to saturation. In nominal operation only the second requirement can be fulfilled as illustrated in Figure 6. Solely by adjusting the driving power P_k and the Q_L values of each cavity individually (P_kQ_L operation) both requirements can be fulfilled.

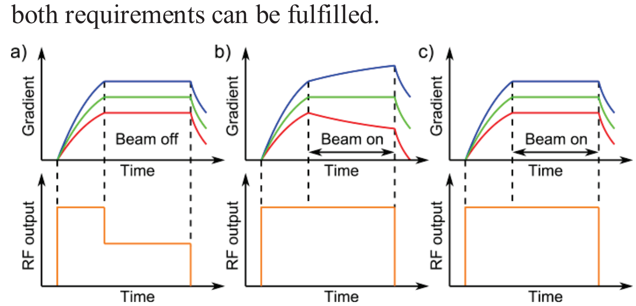

Figure 6: Schematic of cavity 1 (red), cavity 2 (blue), and vector sum (green) gradients with corresponding RF output for a) nominal operation without beam, b) nominal operation with beam, and c) P_kQ_L operation with beam.

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Determination of the Working Point

In order to meet the ILC gradient spread requirements, the cavity gradients were chosen to be $V_{cav1} = 16$ MV/m and $V_{cav2} = 24$ MV/m with a filling time of 410 µs and a beam current of 6.4 mA. Solving the cavity differential equation [8] yields the required power values during filling and the flattop as shown in equations (4) and (5)

$$P_{\mathrm{fill}} = \frac{V_{\mathrm{cav}}^2}{4\frac{r}{Q}Q_{\mathrm{L}}\left(1+\mathrm{Exp}\left(\frac{-\omega_0 t_{\mathrm{fill}}}{Q_{\mathrm{L}}}\right)-2\mathrm{Exp}\left(\frac{-\omega_0 t_{\mathrm{fill}}}{2Q_{\mathrm{L}}}\right)\right)} \qquad (4)$$

$$P_{\mathrm{flat}} = \frac{V_{\mathrm{cav}}}{4\frac{r}{Q}Q_{\mathrm{L}}}\left(1+\frac{\frac{r}{Q}Q_{\mathrm{L}}I_{\mathrm{b0}}}{V_{\mathrm{cav}}}\right)^2 , \qquad (5)$$

which hold for the constraint of flat flattops ($\frac{dV}{dt} = 0$) and the on resonance case ($\Delta\omega = 0$). Since both cavities are driven by a single klystron the power ratio for filling and flattop is the same. By this the $P_k Q_L$ working points for both cavities are determined as shown in Figure 7 ($Q_{L1} = 9.0e6$ and $Q_{L2} = 3.0e6$).

Automated Setting Procedure

The initial system parameters for the fully automated $P_k Q_L$ setting procedure are gradients of 10 MV/m with Q_L values of 3e6 for each cavity and no beam. The procedure covers automated adjustments of Q_L values and cavity gradients as well as an automated detune and phase compensation. After the manual activation of the feedback, the beam (98 µs, 6.4 mA), and the beam FF table the flattop (finally 617 µs) and the beam pulse lengths (finally 615 µs) are simultaneously extended in an automated way. The resulting cavity and vector sum gradients are shown in Figure 8. During the whole procedure the virtual quench limits of 16.8 MV/m and 25.2 MV/m were never exceeded. Both cavities are operated with 16 MV/m and 24 MV/m within 5% below their respective virtual quench limits. The gradient setting precision was 0.31% for cavity 1 and 0.004% for cavity 2.

Long-time Operation

During a long-time operation of 1 hour the vector sum gradient and phase stabilities during the beam transient were $\Delta A/A_{RMS} = 0.009\%$ and $\Delta\phi_{RMS} = 0.009°$, with cavity gradient stabilities of $\Delta A/A_{cav1,RMS} = 0.041\%$ and $\Delta A/A_{cav2,RMS} = 0.031\%$.

SUMMARY

By performing an automated beam compensation and a fully automated $P_k Q_L$ setting procedure all introduced requirements for ILC like operation were fulfilled. The vector sum gradient and phase stabilities for the long-time $P_k Q_L$ operation during the beam transient were $\Delta A/A_{RMS} = 0.009\%$ and $\Delta\phi_{RMS} = 0.009°$, which are comparable to those under nominal operation of $\Delta A/A_{RMS} = 0.009\%$ and $\Delta\phi_{RMS} = 0.009°$.

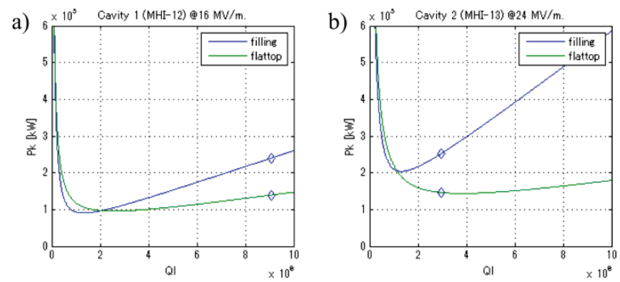

Figure 7: Power [kW] versus Q_L for a) cavity 1 and b) cavity 2. Working points are marked by blue diamonds.

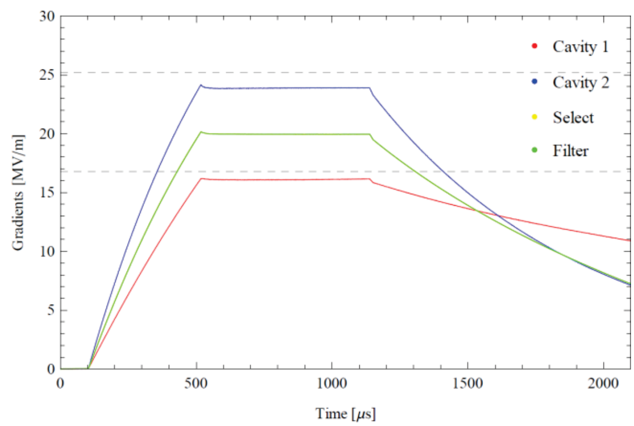

Figure 8: Gradients [MV/m] versus time [µs] during $P_k Q_L$ operation. The dashed lines indicate the virtual quench limits.

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