DEMONSTRATION OF RF STABILITIES IN STF 9-CELL CAVITIES AIMING FOR THE NEAR QUENCH LIMIT OPERATION

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Abstract

The achieved long-time vector sum (VS) stabilities of two superconducting cavities controlled by digital Low Level Radio Frequency (LLRF) techniques under nominal operation in the scope of the quantum beam project [1] with an about 6 mA beam were ΔA/A = 0.009% rms and $\Delta\phi$=0.009° rms. Since in the International Linear Collider (ILC) [2] the cavity gradient spread will be large (31.5 MV/m ± 20%) the required range of loaded Q values will be 3E6 to 1E7. A high loaded Q operation at 2E7 with beam was demonstrated at STF. The beam transient VS stabilities were ΔA/A = 0.011% rms and $\Delta\phi$=0.015° rms. Furthermore in preparation of ILC an operation at different gradients (V_{Cav1}=16 MV/m, V_{Cav2}=24 MV/m) with flat flattops and beam was demonstrated, which is only possible by PkQL control (individual settings of driving power and loaded Q per cavity) [3, 4]. The beam transient VS stabilities were ΔA/A=0.009% rms and $\Delta\phi$=0.009° rms.

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, 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) [5] and operated using LLRF control techniques [6, 7] in a 5 Hz pulsed mode. A simplified schematic of the feedback loop is shown in Figure 1. Lorentz force detuning in the cavities is dynamically compensated by piezo tuners driven by a sine function.

LONG-TIME NOMINAL OPERATION

In scope of the quantum beam project the nominal operation parameters were V_{Cav1} = 16 MV/m and V_{Cav2} = 24 MV/m, with $Q_{L,Cav1}$ = $Q_{L,Cav2}$ = 3E6 and a filling time of 540 μs. The beam compensation was automatically matched to the beam pulse profile [4]. The vector sum stabilities during beam transient achieved in a long-time run with and without a 6.6 mA beam with a pulse length of 615 μs are listed in Table 1. A snapshot of the vector sum gradient is shown in Figure 2.

Table 1: Vector sum amplitude and phase stabilities under long-time nominal operation (rms values)

Beam	6.6 mA (60 mins)	Off (20 mins)
ΔA/A Vector sum	0.009%	0.008%
$\Delta\phi$ Vector sum	0.009°	0.008°

HIGH QL OPERATION

The operational cavity gradients at ILC will be (31.5 ± 20%) MV/m due to quench limits different from cavity to cavity. This leads to the requirement of a Q_L range from 3E6 to 10E6. Since $\omega_{1/2} = \omega_0/2Q_L$ the cavity bandwidth becomes narrow at high Q_L values (e.g. $\omega_{1/2}$ = 32 Hz at Q_L = 2e7 and f_0 = 1.3 GHz). Due to this cavity detune induced e.g. by microphonics is expected to become severe.

At KEK STF the range of Q_L values of both superconducting cavities is 2e6 to 5e7. For the demonstration of high Q_L operation the Q_L values were set to 2e7. Due to this the filling time was extended to 800 μs. Both cavity

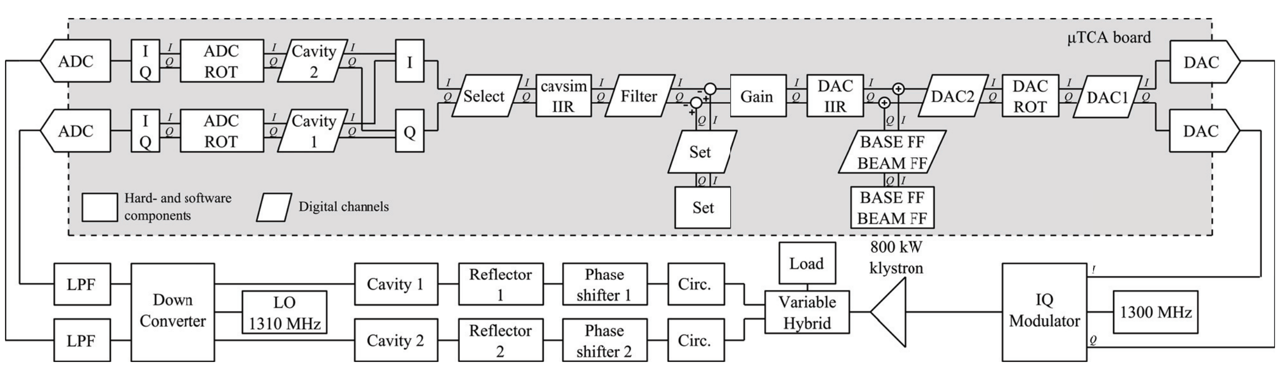

Figure 1: Schematic of the digital LLRF feedback loop controlling two superconducting cavities at STF.

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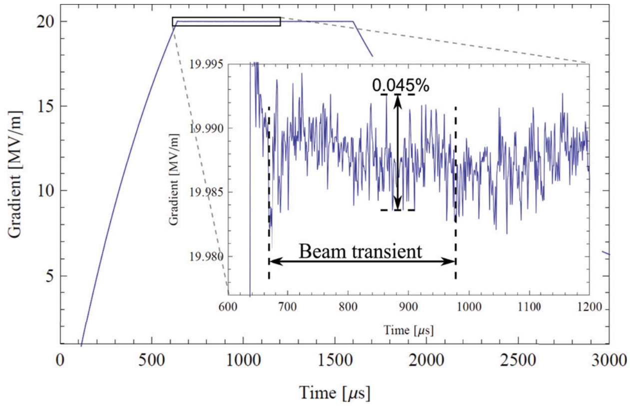

Figure 2: Vector sum gradient [MV/m] versus time [s] during nominal operation.

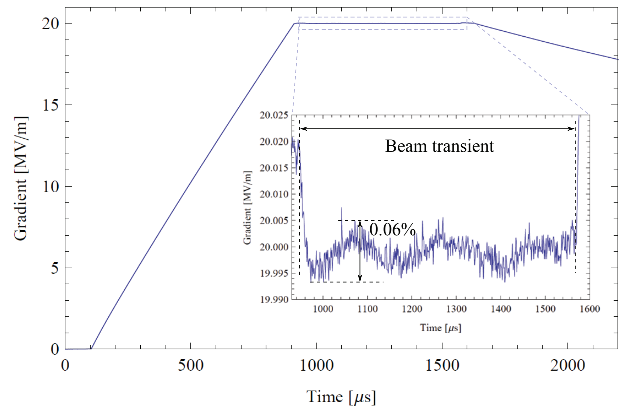

Figure 3: Vector sum gradient [MV/m] versus time [s] during high Q_L operation.

gradients were set to 20 MV/m. In an 1 hour long-time run with a 6.1 mA beam with a pulse length of 615 μs as well as beam compensation and feedback (FB) turned on the amplitude and phase stabilities as listed in Table 2 were achieved. Figure 3 shows a snapshot of the vector sum gradient. Beside this a run of 20 minutes without beam at the same condition was performed. The corresponding stabilities are also listed in Table 2.

Table 2: Vector sum amplitude and phase stabilities under high Q_L operation (rms values)

Beam	6.1 mA (60 mins)	Off (20 mins)
ΔA/A Cavity 1	0.12%	0.03%
ΔA/A Cavity 2	0.16%	0.03%
ΔA/A Vector sum	0.011%	0.008%
$\Delta\phi$ Cavity 1	0.03°	0.03°
$\Delta\phi$ Cavity 2	0.03°	0.03°
$\Delta\phi$ Vector sum	0.015°	0.014°

The measured Q_L values of both cavities during beam operation, which were determined by the evaluation of the cavity gradient decays, were in average $Q_{L,\mathrm{Cav1}} = 21E6$ rms and $Q_{L,\mathrm{Cav2}} = 22E6$ rms. Figure 4 a) shows the detune for both cavities versus the 1 hour time span. The corresponding histograms are shown in Figure 4 b). The standard deviations are $\sigma_{\Delta f,\mathrm{Cav1}} = 10.1$ Hz and $\sigma_{\Delta f,\mathrm{Cav2}} = 4.7$ Hz. An average detuning of both cavities lower than the cavities bandwidths allowed the demonstration of a very stable high Q_L operation with stabilities comparable to nominal operation.

PKQL OPERATION

It is essential to operate multiple cavities driven by a single klystron near their respective quench limits over the whole pulse length. This is only possible by adjusting the driving power P_k and the Q_L values individually. At KEK STF an automated procedure to engage in P_kQ_L operation as well as a subsequently long-time P_kQ_L operation

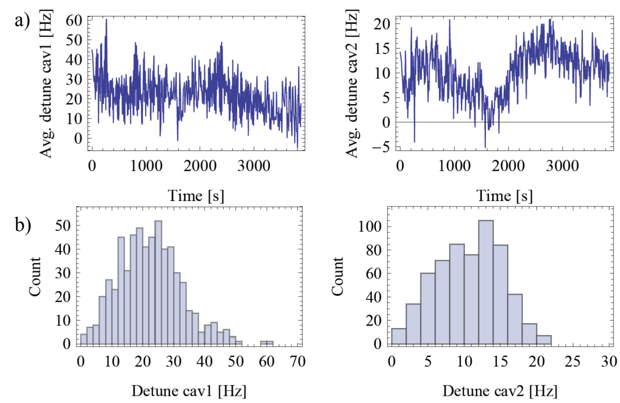

Figure 4: a) Detune [Hz] of both cavities versus time [s] and b) detune histogram for both cavities during high Q_L operation.

have been successfully demonstrated [4]. The final operation parameters were V_{Cav1}=16 MV/m, V_{Cav2}=24 MV/m, $Q_{L,\mathrm{Cav1}}$ = 9E6, $Q_{L,\mathrm{Cav2}}$ = 3E6, a filling time of 410 μs, an average beam current of 6.4 mA, and a beam pulse length of 615 μs. Virtual quench limits were defined to be 16.8 MV/m and 25.2 MV/m and were never exceeded. A snapshot of the cavity 1, cavity 2, and vector sum gradients is shown in Figure 5. The procedure to engage in P_kQ_L operation covers the following steps:

- Setting Q_L values using waveguide reflectors (automated)
- Detune compensation using piezo tuners (automated)
- Setting of cavity gradients by adjustment of the ratio of the variable hybrid and the feedforward amplitude (automated)
- Phase compensation using waveguide phase shifters (automated)
- Turning on feedback (manually)
- Turning on beam (manually)
- Turning on beam compensation (manually)
- Simultaneous extension of beam pulse and cavity gradient flattop lengths (automated)

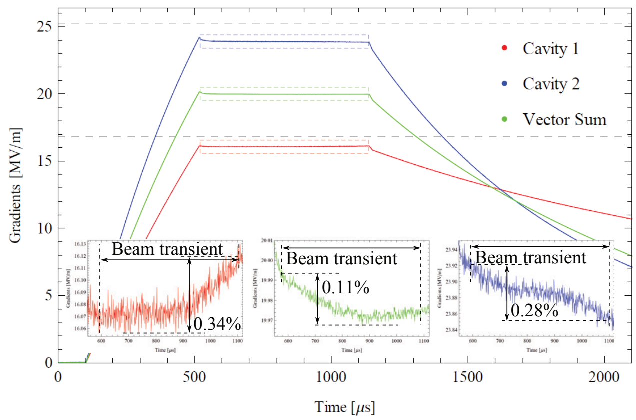

Figure 5: Cavity 1, cavity 2, and vector sum gradients [MV/m] versus time [s] during $P_k Q_L$ operation. The dashed lines indicate virtual quench limits of 16.8 MV/m and 25.2 MV/m.

The manual steps were not automated due to machine protection reasons. Figure 6 shows the gradient stabilities for both cavities versus time for a 800 second sample time span of the subsequently performed 1 hour long-time operation with beam. The mean vector sum stabilities were $\Delta A/A_{Cav1,mean}$=0.211% and $\Delta A/A_{Cav2,mean}$=0.132% and the best $\Delta A/A_{Cav1,best}$=0.041% and $\Delta A/A_{Cav2,best}$= 0.031%.

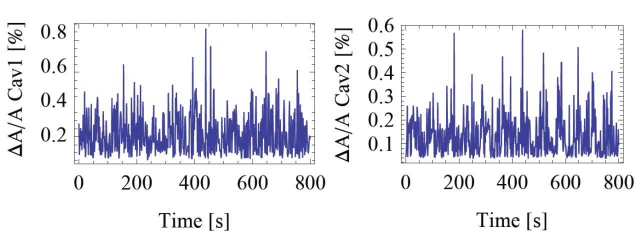

Figure 6: Cavity 1 (left) and cavity 2 (right) gradient stabilities during beam transient versus time [s] in $P_k Q_L$ operation.

Figure 7 shows the vector sum gradient and phase stabilities during the beam transient versus time for the same 800 second sample time span. The performances of the vector sum stabilities are listed in Table 3. These are comparable to the stabilities during nominal operation and allow with this a very stable first actual $P_k Q_L$ operation.

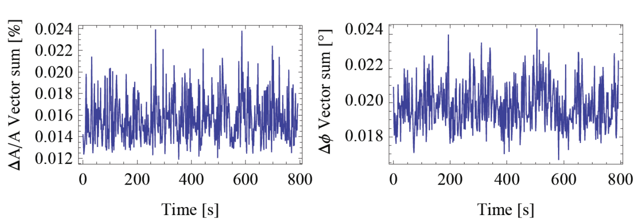

Figure 7: Vector sum gradient and phase stabilities during beam transient versus time [s].

Table 3: Vector sum amplitude and phase stabilities under $P_k Q_L$ operation (rms values).

Beam	6.1 mA (60 mins)
Best vector sum $\Delta A/A$	0.009%
Mean vector sum $\Delta A/A$	0.016%
Best vector sum $\Delta\phi$	0.009°
Mean vector sum $\Delta\phi$	0.019°

The dominant source for the cavity as well as vector sum stability fluctuations has been a beam current fluctuation of about 20%. Even under this condition average vector sum stabilities indicated as mean in Table 3 were maintained. If the beam current could be controlled precisely and the matched condition could be kept up the vector sum stabilities would be as good as indicated as best in Table 3 over the whole time.

SUMMARY

At KEK STF demonstrations of RF stabilities using two superconducting 9-cell cavities driven by a single klystron aiming for the near quench limit operation were performed successfully. Those cover a high Q_L operation ($Q_{L,Cav1}$=$Q_{L,Cav2}$=2E7, V_{Cav1}= V_{Cav2}=20 MV/m) with beam (6.1 mA) with resulting vector sum stabilities of $\Delta A/A$ = 0.011% rms and $\Delta\phi$ = 0.015° rms as well as a $P_k Q_L$ operation (V_{Cav1} = 16 MV/m, V_{Cav2} = 24 MV/m (both 5% below their respective virtual quench limits), $Q_{L,Cav1}$ = 9E6, $Q_{L,Cav2}$ = 3E6) with beam (6.4 mA) with resulting vector sum stabilities of $\Delta A/A$ = 0.009% rms and $\Delta\phi$ = 0.009° rms. These stabilities are comparable to those under nominal long-time beam operation (V_{Cav1} = 16 MV/m, V_{Cav2} = 24 MV/m, $Q_{L,Cav1}$ = $Q_{L,Cav2}$ =3E6, I_0=6.6 mA) of $\Delta A/A$ = 0.009% rms and $\Delta\phi$ = 0.009° rms.

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