

VECTOR-SUM CONTROL OF SUPERCONDUCTING RF CAVITIES AT STF

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Abstract

Vector-sum control of 4 superconducting cavities in STF-1 at KEK is examined. Digital LLRF (low-level rf) control is carried out and the stabilities of the rf fields are measured. The stabilities were found to improve upon the addition of suitable feed-forward, and they satisfied the requirements of the ILC (International Linear Collider). Performance degradation due to the elimination of circulators is also studied from the viewpoint of an LLRF system.

INTRODUCTION

STF is a superconducting rf test facility at KEK. A digital feedback system has been adopted for the LLRF control of the rf system using a cPCI state, in a manner similar to the J-PARC linac LLRF system [1].

STF-1 comprises one cryomodule having 4 superconducting rf cavities. This is the first time that these cavities have been operated by vector sum control [2]. Thus far, various studies concerning LLRF have been conducted. We are particularly interested by the rf stabilities. With regard to the operation of STF-1, we first aim to satisfy the requirements of the ILC (amplitude: 0.07%, phase: 0.24°) [3]. However, the instabilities caused by the $8/9\pi$ mode appear to be a serious problem in the case of vector-sum control [4]. Although STF-1 has no beam source, we investigated the beam effects using a simulation experiment [4]. A promising finding is the IF mixture [5]. This method enables us to reduce the number of ADCs to 25%. Rf (1.3 GHz) cavity signals are directly detected using a fast ADC with high bandwidth [6]. Since this procedure does not require a downconverter, it can eliminate the harmonics created by a mixer.

In this report, the LLRF performance and circulator effects are mainly discussed. All the other topics are described in other papers being presented at these proceedings [4–6].

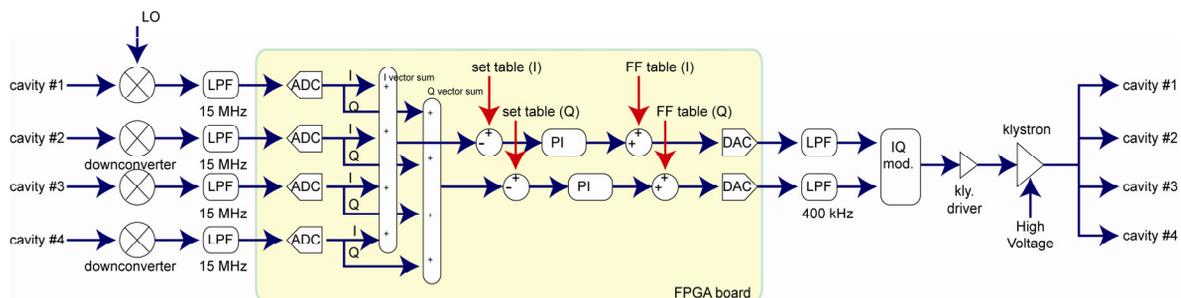


Figure 1: Schematic drawing of cavity feedback system

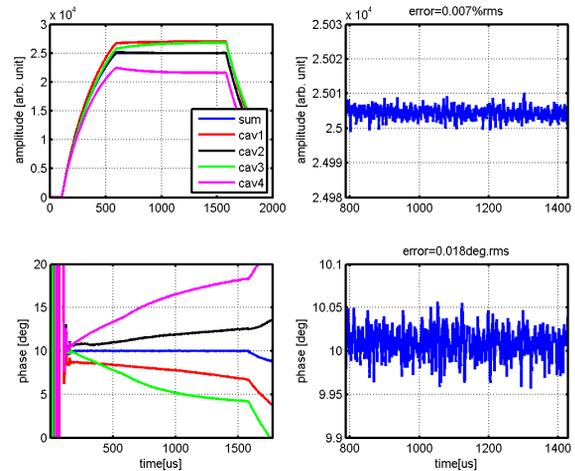


Figure 2: Vector-sum control of 4 superconducting cavities. Amplitude (upper left), phase (lower right), vector-sum amplitude during flat top (upper right), and vector-sum phase at flat top (lower right).

VECTOR-SUM FEEDBACK

An FPGA feedback controller having ten 16-bit ADCs and two 14-bit DACs is a daughter card of the commercial DSP board “Barcelona.” The FPGA board handles the fast feedback and the DSP board handles the data transfer between the FPGA board and the CPU motherboard. Figure 1 shows a schematic drawing of the system configuration. The I/Q-modulated rf signal drives a klystron and 4 cavity pick-up signals are downconverted to an intermediate frequency (IF: 10 MHz). The ADCs are sampled at 40 MHz and vector-sum feedback is carried out in the FPGA [7].

The rf stabilities during vector-sum operation are shown in Fig.2. The field stabilities are 0.007% rms in amplitude and 0.018° rms in phase. The obtained stabilities satisfy the rf requirements of the ILC. The

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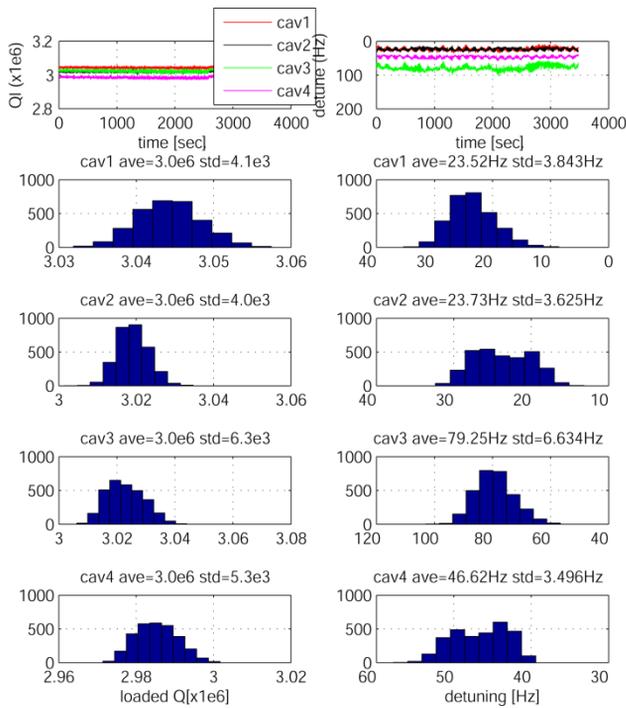


Figure 3: Loaded Q values (left) and cavity detunings (right) during operation for 1 h at an average gradient of 17 MV/m.

addition of a suitable feed-forward to the feedback algorithm is quite effective for good rf regulation during flatness.

The decay time and phase change after the rf power is switched off are used to calculate the loaded Q value and the detuning of the cavity. The loaded Q values and detuning frequencies during operation for 1 hour at an average gradient of 17 MV/m are shown in Fig.3. The rms detuning frequency corresponding to the microphonics is around 4 Hz, which agrees well with the data obtained at DESY.

CALIBRATION OF RF SIGNALS

The cavity input signal and reflected rf signal are related to the rf field within the cavity.

$$V_c = V_f + V_b \tag{1}$$

Here, V_c , V_f , and V_b denote the cavity voltage, cavity input voltage, and reflected voltage, respectively.

The raw data of the ADC input signal is a 16-bit integer. Each cavity pickup signal was calibrated to the cavity voltage using an rf power meter (e.g., 18 MV corresponds to 25,000 in a digital system). Other signals can also be calibrated using equation (1).

The calibrated sum of these signals is in good agreement with the cavity voltage. These calibrated signals are useful for the calculation of the (1) cavity detuning and (2) isolation of the rf distribution system. In the future, they will also be used for the estimation of beam loading and for the self-diagnosis of the cavity pickup signal. These calibrated signals can be used for the calculation of detuning during an rf pulse [8].

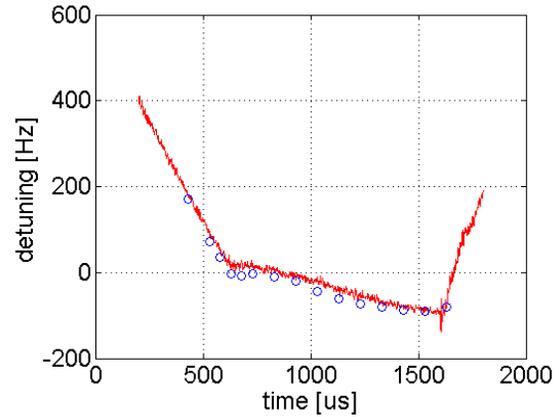


Figure 4: Cavity detuning calculated from equation (1) along with pulse-cut measurements (circle).

$$r\rho - r\Delta\omega = \omega_{1/2}\rho \sin(\theta - \varphi) \tag{2}$$

where r and ρ denote the cavity and cavity input amplitude; φ and θ , the cavity phase and cavity input phase; and $\Delta\omega$ and $\omega_{1/2}$, the cavity detuning and half-bandwidth of the cavity, respectively.

Figure 4 shows the detuning of a cavity. Due to the detuning of the Lorentz force, a dynamic change in detuning is observed and the calculated detuning agrees well with the detuning obtained from the rf decay time, where the pulse width is changed to obtain a detuning [9].

CIRCULATOR ELIMINATION

Cost reduction of the rf system is one of the most important developments at the ILC. The elimination of the circulators located in front of the cavities will be favorable from the viewpoint of cost reduction. However, this will cause difficulties in cavity control because of the crosstalk between cavities. In order to evaluate the advantages of the circulators, we compared the performance before and after their removal. The rf distribution system in STF-1 is shown in Fig.5. Tunable hybrids are installed in order to optimize the cavity input power. The improved tunability was offset by poorer isolation and self-reflection of the hybrid. Each cavity has a circulator for suppressing crosstalk with other cavities.

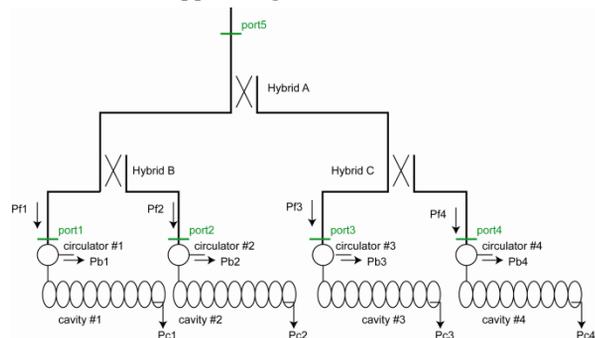


Figure 5: Layout of power distribution system.

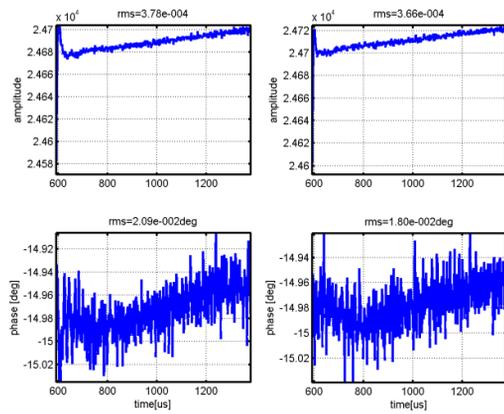


Figure 6: Vector sum amplitude (upper) and phase (lower) before (left) and after (right) circulator removal.

Figure 6 shows the cavity field before and after the removal of (all) circulators. The LLRF stabilities are both 0.04% rms in amplitude and 0.02° in phase. (Since these are acquired without feed-forward, the stabilities were worse than the best record.) Figure 7 shows the cavity input signals. After the elimination of the circulator, the cavity input signals are found to differ in each cavity. The bottom figures show the ratio normalized with the klystron output signals. The rf amplitude ratio between filling time and flat-top differs in each cavity after the removal of the circulators. In addition, cavity input signals are observed even after the rf signal is switched off. These observations are attributable to the fact that the emission from one cavity affects that from other cavities. It is difficult to obtain the precise value of the loaded Q after circulator elimination, where the decay times of the rf fields are used for calculation. Low-power measurements are also carried out after the high-power rf tests. Table 1 summarizes the results obtained in the high-power tests, where only one circulator was eliminated, and in the low-power tests. The names of the ports are shown in Fig.6. The isolation in the high-power test is calculated by the calibrated reflected amplitude and

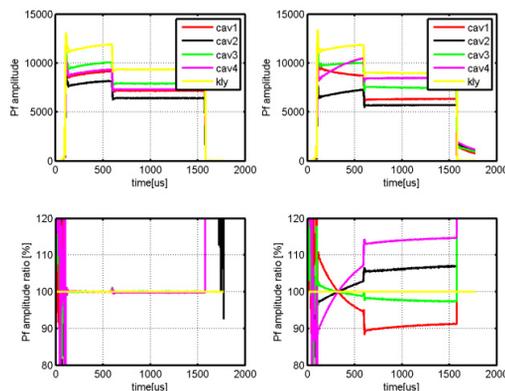


Figure 7: Cavity input amplitude before (left) and after (right) circulator removal.

forward amplitude after the rf signal is switched off. Two combinations of power split ratios of the three hybrids are selected for the measurements. One is the standard operational condition while the other has poor isolation. In the case of poor isolation, the results are in very good agreement. The disagreement at self-reflection (port 1) in the standard operating condition can be attributed to some type of high-power effect such as poor VSWR at the dummy load during high-power operation, etc. Further analysis is required to determine the exact causes.

Table 1: Low- and high-power tests.

	Standard operation		Poor isolation	
	Low power	High power	Low power	High power
Port 1	-44 dB	-29 dB	-22 dB	-20 dB
Port 1-2	-29 dB	-30dB	-27 dB	-26 dB
Port 1-3	-34 dB	-31dB	-34 dB	-31 dB
Port 1-4	-35 dB	-34 dB	-33 dB	-34 dB
Port 1-5	-6 dB		-6 dB	

SUMMARY

The measured stabilities for the vector-sum control of 4 superconducting cavities are 0.007% rms in amplitude and 0.018° in phase. These results satisfy the LLRF requirements of the ILC. Circulator removal was carried out from the viewpoint of cost reduction. Although the LLRF performance itself did not appear to be affected, interactions were observed between the cavities and, in particular, the isolation of the hybrid was poor.

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