EVALUATION OF LLRF STABILITIES AT STF

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Abstract

In STF phase-1, four-cavities are operated with vector-sum feedback (FB) control. The FB control instabilities arising from passband of TM_{010} mode other than π mode were measured. Further, a feedforward (FF) table was used in combination with FB control, which improved the flatness of the flat-top region. A method for reduction of overshoot in FB + FF operation is also proposed. By electrically developing a quasi-beam, the response for quasi-beam injection was also measured, and the correction on beam-loading was performed.

INTRODUCTION

The Superconducting RF Test Facility (STF) is the R&D facility of the International Linear Collider (ILC). In the STF phase-1, four nine-cell cavities [1] were installed in a cryomodule and operated using the vector-sum feedback (FB) control [2]. They were driven by a pulse with a width of 1.5 ms and a repetition rate of 5 Hz. The rf stability of 0.07% in amplitude and 0.24° in phase is required at the flat-top region for ILC.

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In this paper, we report the measurement of rf instabilities arising from the other mode for each cavity. The feedback became stable or unstable depending on the digital delay system with a clock of 40 MHz was implemented in the FPGA to observe the relation between feedback loop delay and the rf instability. The digital delay was varied between 1 and 120 clocks (3 μs).

FEEDBACK INSTABILITY DUE TO PASSBAND OF TM_{010} MODE

The cavity is operated in the π mode, which has the highest efficiency for beam acceleration. In the operation with FB control, rf instability can occur due to the passband of TM_{010} mode except for the π mode [3,4].

Table 1 shows the frequency difference between the π mode and the other modes measured at each cavity at the STF. For a given mode, the frequency is different for different cavities due to fabrication error.

Table 1: Frequency differences between π mode and the other mode for each cavity.

<table>
<thead>
<tr>
<th>mode</th>
<th>Cavity 1</th>
<th>Cavity 2</th>
<th>Cavity 3</th>
<th>Cavity 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/9π</td>
<td>1.1675</td>
<td>0.7223</td>
<td>1.1225</td>
<td>0.8859</td>
</tr>
<tr>
<td>7/9π</td>
<td>3.6413</td>
<td>3.5922</td>
<td>3.4742</td>
<td>3.3931</td>
</tr>
<tr>
<td>6/9π</td>
<td>6.9246</td>
<td>7.3201</td>
<td>7.0056</td>
<td>7.0822</td>
</tr>
<tr>
<td>5/9π</td>
<td>11.8131</td>
<td>11.6902</td>
<td>11.6116</td>
<td>11.5009</td>
</tr>
<tr>
<td>1/9π</td>
<td>26.4603</td>
<td>27.2074</td>
<td>26.6434</td>
<td>26.6119</td>
</tr>
</tbody>
</table>

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The feedback became stable or unstable depending on the digital delay. In the case of unstable, 8/9π, 7/9π and 6/9π modes are observed other than π modes in the frequency spectra. The rms values of amplitude indicating instability for additional loop delay is shown in Fig.2; the upper four graphs in the figure show the result of the FB at each cavity, while the lowest graph shows the result of the vector-sum FB operation. In the case of high gain, i.e., p=50, stable region is extremely narrow in individual operation because of the large excitation by the 8/9π and 7/9π modes; the position of stable region is different for each cavity, since frequencies of the 8/9π and 7/9π modes are different for
each cavity. The result of vector-sum operation, therefore, became unstable over all regions of loop delay. In the case of low gain, i.e., \( p = 5 \), the stable region became wider. In the vector-sum operation, since the intensities of the signals from each cavity become \( \sim 1/4 \), less instability is observed over almost the entire range of additional loop delay.

Figure 2: Result of rms values of amplitude indicating instability for additional loop delay. The upper four graphs are results of FB operation of the individual cavity, the lowest graph is the result the vector-sum operation.

**FEEDFORWARD TABLE**

In this section, we discuss the FB operation with the use of a FF table. The amplitude and phase of the flat-top region was measured under three operational conditions; FB, FB + FFDAC, and FB + FFSM; the measurement results are shown in Fig.4. The result under FB differs slightly from the set value, and the amplitude and phase are sensitive to the FB Gain. In contrast, in the case of the use of a FF table such as FFDAC or FFSM (see. Fig.3) in combination with FB, the results are in good agreement with the set value. The flatness observed at 700–1600 \( \mu \)s corresponds to 0.02% rms and 0.016° rms in the case of FB operation and 0.007% rms and 0.015° rms in the case of FB operation with a FF table. Figure 3 shows a comparison between the FFDAC and FFSM. FFDAC is the FF table whose output is the same as that from DAC in the FB operation. DAC output is used as the FF table to correct the nonlinearity of a klystron or the RF amplifier. Under FB + FFDAC condition, however, a large overshoot of 1% was observed at the leading-edge of the flat-top region. The overshoot is thought to be caused by the delay in the feedback. To compensate the delay, FFDAC should be shifted temporally forward the length of delay. FFSM is made by applying the smoothing procedure from each channel to the next X channel which is corresponding the twice the amount of the delay. The amount of delay for FB gain = 90 was approximately 20 \( \mu \)s for \( Q_L \) (loaded \( Q \)) = 3 \times 10^6 and \( \sim 8 \) \( \mu \)s for \( Q_L = 1.2 \times 10^6 \). These delay length are longer than the loop delay of the FB-circuit itself, which is estimated to be approximately 3.26 \( \mu \)s (LPF: 1.476 \( \mu \)s + Amp: 0.763 \( \mu \)s + klystron: 0.123 \( \mu \)s + FPGA: 0.4 \( \mu \)s + cable/waveguide: 0.5 \( \mu \)s). The FB delay depends not only on \( Q_L \) but also on the FB gain. Under FB + FFSM condition, the overshoot decreased to 0.1% and 0.1°.

Figure 3: Comparison of FFDAC with FFSM

**OPERATION WITH QUASI-BEAM**

In STF phase-1, the beam is not available. Therefore, to measure the response of a beam, a quasi-beam was electrically fabricated. For this, a square wave with an angle of \( \sim 180° \) was introduced for klystron input, as shown in Fig.5. The DAC outputs of the FB operation with and without the quasi-beam are shown in Fig.6. The amplitude of quasi-beam was adjusted such that the resultant DAC outputs in FB operation had the same amplitude between the filling time (100–600 \( \mu \)s) and the beam injection time (812–1322 \( \mu \)s).
Figure 5: Block diagram of quasi-beam introduction.

Figure 6: DAC output in FB operation with and without quasi-beam (DAC1 and DAC2, respectively) and that by subtracting (DAC1 $-$ DAC2) that is used for FF(beam).

Figure 7: Difference between normal FB operation with and without quasi-beam at the flat-top. A drop of 1.5% in amplitude and 0.2° in phase by the introduction of quasi-beam was observed.

Figure 8: Flat-top stability around quasi-beam injection in FB + FF table (including beam compensation) operation with timing adjustment.

SUMMARY

The vector-sum operation for four cavities was performed at the STF. The instability arising from the other mode except for the $\pi$ mode was measured. In high FB gain, the vector-sum operation becomes unstable over all regions of additional loop-delay. In contrast, in low FB gain, the vector-sum operation is stable over almost the entire range. In the operation of FB + FF table, 0.007% rms and 0.015° rms was achieved. Finally, tests were performed using a quasi-beam, and a FF(beam) was developed as a FF table to compensate the beam loading. By adjusting the timing of the FF(beam), the stability at beam region excluding the head and tail was achieved to be within the range required by ILC.

REFERENCES