MEASUREMENTS OF FEEDBACK-INSTABILITY DUE TO 8/9π AND 7/9π MODES AT KEK-STF

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Abstract

At the superconducting RF test facility (STF) at KEK, high-power tests of the superconducting nine-cell cavity for the International Linear Collider (ILC) have been performed. The cavity was driven by an RF of 1.3GHz which corresponds to the π mode with zero beam acceleration. Feedback instabilities due to the 8/9π and 7/9π modes were observed when the other modes were not filtered. The intensities of the 8/9π and 7/9π modes were measured by varying the feedback loop delay, and the stable/unstable regions appeared at regular intervals as expected.

INTRODUCTION

The superconducting RF test facility (STF) at KEK is the research and development facility of the International Linear Collider (ILC). At the STF, high-power tests of the superconducting nine-cell cavity have been performed. The cavity is driven by an RF of 1.3 GHz with a pulse duration of 1.5 ms and a repetition rate of 5 Hz. A stability of 0.3% amplitude and 0.3° phase is required at the flat-top region where beam acceleration is performed. To achieve this stability, we adopt a high-speed digital feedback control system using a field programmable gate array (FPGA) in the low-level RF (LLRF) system [1,2]. The cavity is operated in the π mode which has the highest efficiency for beam acceleration. However, Vogel [3] has pointed out the occurrence of the feedback control instability due to the passband of TM_{010} mode except for the π mode. Therefore, we measured the instability in the STF.

MODE FREQUENCIES

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

	cav#1@2K f-f_π (MHz)	cav#2@2K f-f_π (MHz)	cav#3@2K f-f_π (MHz)	cav#4@RT* f-f_π (MHz)
8/9π	−0.70	−1.11	−0.88	−0.83
7/9π	−3.53	−3.45	−3.39	−3.04
6/9π	−7.31	−6.98	−7.08	−6.27
5/9π	−11.69	−11.62	−11.50	−10.00
4/9π	−16.47	−16.37	−16.31	−14.05
3/9π	−20.83	−20.94	−20.63	−17.86
2/9π	−24.54	−24.52	−24.20	−21.14
1/9π	−27.25	−26.68	−26.64	no-data

*RT: Room Temperature

Table 1 shows the frequency differences between the π mode and other modes for each cavity in the STF. For a given mode, the frequency is different for different cavities due to fabrication error. When performing vector-sum control, we have to pay attention to many frequency components in comparison with the control for only one cavity. Figure 1 shows the band-pass characteristics of a TH2104A klystron used at the STF. The peak is observed at 1294 MHz. Therefore, it is easier for frequencies of modes in the range 6/9π - 8/9π to pass through the klystron as compared to π mode.

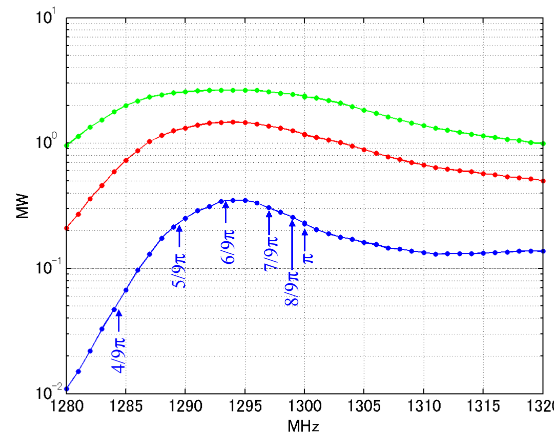

Figure 1: Band-pass characteristics of klystron (TH2104A).

ESTIMATION OF GAIN MARGIN

In order to estimate the feedback instability, the gain margin of each mode, except the π mode, was calculated. A more detailed description of the calculation is presented by Vogel [3]. The open-loop transfer function (TF) of the system is represented as follows:

$$H(s) = Gp\, H_{delay}(s)\, H_{cav}(s)\, H_{kly}(s), \quad (1)$$

where Gp is the proportional gain of the feedback, $H_{delay}(s)$ is the TF of the feedback loop delay, $H_{cav}(s)$ is the TF of the cavity, and $H_{kly}(s)$ is the TF of the klystron. In this calculation, $H_{kly}(s)$ is approximated by a low-pass filter with a 3 dB bandwidth of 3 MHz in a manner similar to that employed by Vogel [3]. $H(s)$ is converted to a discrete system of 40 MHz, which is the sampling frequency in analog-to-digital converter (ADC), and the gain margin is calculated from the Nyquist stability criterion. The gain margins for different feedback loop delays are shown in Fig. 2. In the figure, the area shaded grey indicates a stable region, while that shaded white denotes an unstable region. Even when Gp is small, the feedback system becomes unstable for modes in the range of 8/9π – 5/9π. The stable and unstable regions appear at regular intervals with the intervals depending on the difference between their frequencies and the frequency of the π mode. On the other hand, low-order modes such as the 2/9π and 1/9π modes are stable for large values of Gp.

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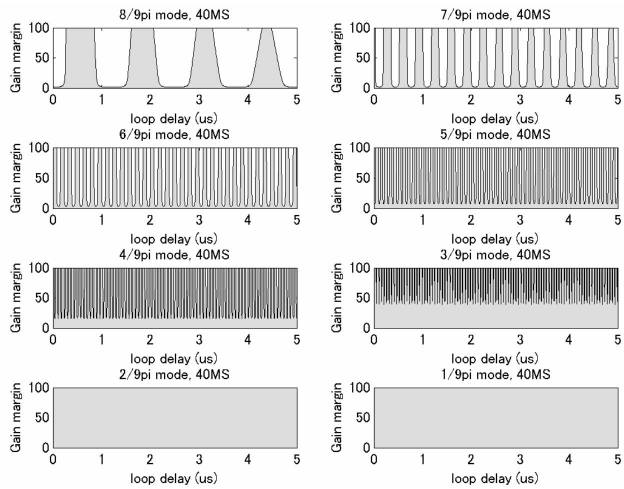

Figure 2: Calculation of gain margins for feedback loop delay (grey : stable; white : unstable).

MEASUREMENT

Figure 3 shows the LLRF control system in the STF. The pick-up signal (1.3 GHz) from the cavity is down-converted to an intermediate frequency (IF) of 10.156 (1300/128=10.156) MHz. The IF signal is sampled by a 16-bit ADC whose sampling rate is four times the IF (40.625 MHz). Separation of I/Q components and feedback calculation using proportional control are performed in the FPGA. The calculation yields baseband I/Q signals as an output from the 14-bit digital-to-analog converter (DAC). In the IQ modulator, these baseband signals are modulated using an RF of 1.3GHz generated by the master oscillator. In our typical LLRF system, a 0.4-MHz low-pass filter (LPF) is installed between the DAC and the IQ modulator in order to reject the signals corresponding to modes other than the π mode. In this study, the LPF was removed in order to measure the raw intensities of the signals of the other modes. A digital delay system (0.0246 μs/tap) was introduced in the FPGA in order to observe the relation between feedback loop delay and instability. The digital delay was varied between 1 tap and 200 tap at each step. In this study, the cavity that is labelled #4 in Table 1 was employed and *Gp* was set to 11.5. The power was set at a low level, so that it did not quench even when the feedback became unstable condition due to large oscillations.

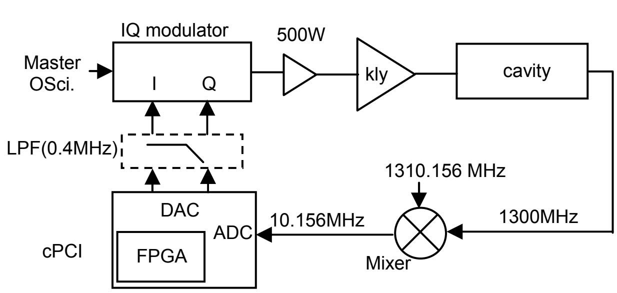

Figure 3: Schematic view of the LLRF system.

IF signal of the electric field in the cavity was sampled at 40.625 MHz. The frequency spectra of the klystron and the cavity were calculated by using Fourier transform algorithm using 2048 data points obtained from the region of the flat-top. The frequency resolution was 0.02 MHz.

RESULTS

Results of Waveform Spectrum

The feedback became stable or unstable depending on the duration of the digital delay, and the shape of the spectrum for the electric field in the cavity also varied. Figure 4 shows an example of variations in the intensity of the electric field in the cavity and the frequency spectra of the klystron and the cavity. In the case of stable feedback, only one IF (π mode) was observed; this is shown in Fig. 4 (a). Figure 4 (b) shows the instance when the feedback just turns unstable due to the 8/9π mode.

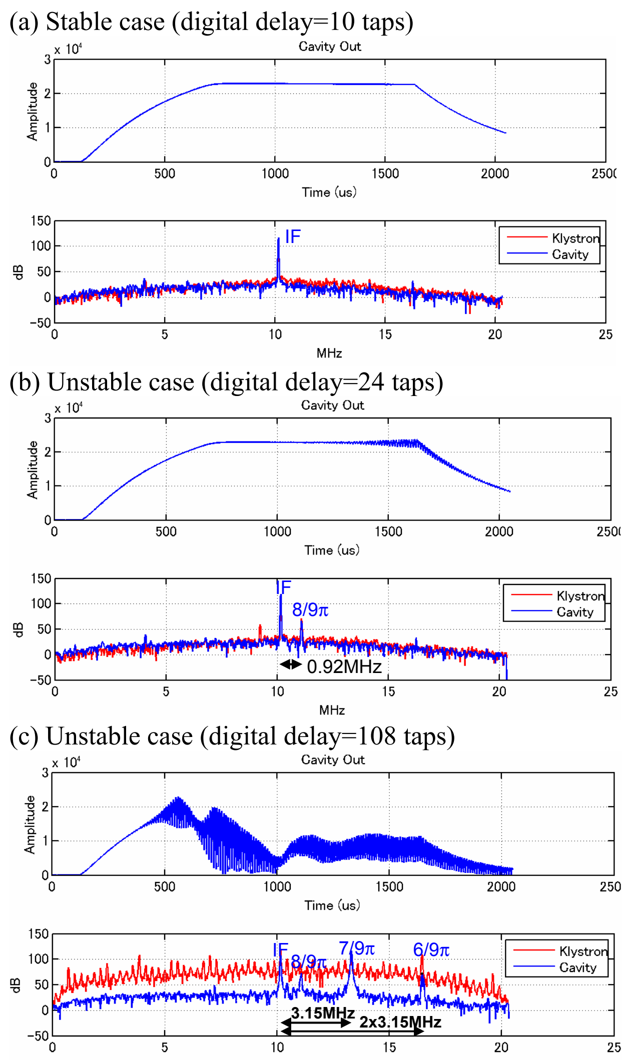

Figure 4: Electric field in the cavity (up) and frequency spectra of the klystron and cavity in the flat-top region (down).

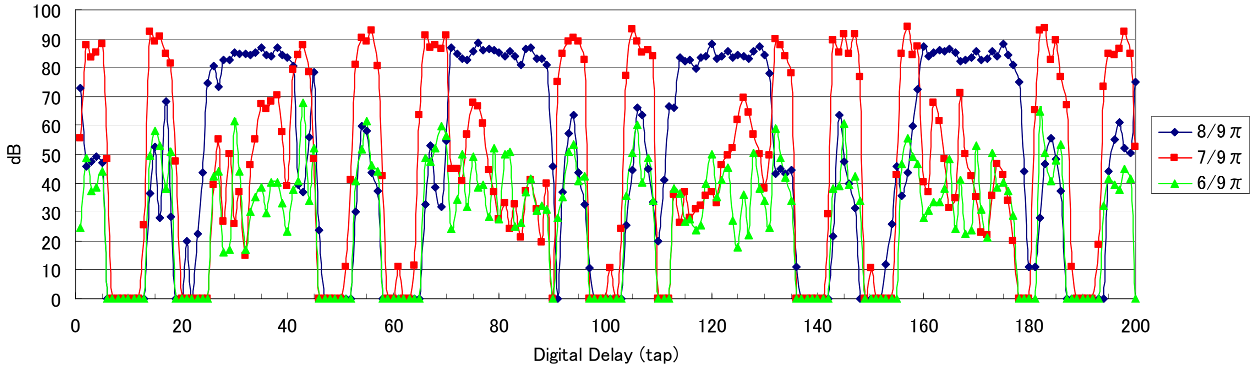

Figure 5: Intensities of the 8/9π, 7/9π, and 6/9π modes for each digital delay.

Incrementing the digital delay by a few more taps led to an increase in the instability. Figure 4 (c) shows a large oscillation due to the 7/9π mode. In this case, several frequencies were output from the klystron and the 8/9π and 6/9π modes were also excited in the cavity. Frequency differences (Δf) between the π mode and the 8/9π and 7/9π modes are 0.92 MHz and 3.15 MHz, respectively. Further, Δf between the π mode and the 6/9π mode was 6.35 MHz ($\Delta f_{(8/9\pi)} \times 7$) or 6.29 MHz ($\Delta f_{(7/9\pi)} \times 2$) depending on whether the 8/9π mode or the 7/9π mode excited to a greater extent.

Results of Digital Delay Scan

Figure 5 shows the intensities of the 8/9π, 7/9π and 6/9π modes with digital delays introduced in the feedback loop. For a digital delay in the range 0 – 200 taps (4.9μs), the stable region is extremely narrow: the unstable region extends across a large part of the plot. Severe instabilities are produced mainly by the 8/9π and 7/9π modes, while the 6/9π mode does not induce instability by itself. Therefore, we suggest that occurrence of the 6/9π mode is associated with the large instabilities caused by the 8/9π or 7/9π mode. The periodicity of stability for feedback loop delays for the 8/9π and 7/9π modes is determined by using points that do not overlap the 8/9π and the 7/9π modes. The resulting periodicities are 44 taps (1.08 μs) for the 8/9π mode and 13 taps (0.32 μs) for the 7/9π mode, respectively. These values are approximately equal to those calculated from the expression $1/(f_\pi - f_{n/9\pi})$.

Estimation of Feedback Loop-Delay

If the feedback loop delay is 0, the feedback control is unstable for the 8/9π mode and stable for the 7/9π mode (see Fig. 2); this is because the initial stability condition of each mode is based on the direction of the electric-field vector at the end cell of the cavity. The original feedback loop delay of this system was evaluated by comparing the patterns in Fig. 2 and Fig. 5. For the 8/9π mode in Fig. 5, the 25^{th} tap, where the leading edge of 8/9π mode occurs, is used as the reference point. The point of zero digital delay is obtained by subtracting the half period, which is 22 taps, from the reference point. Since the 25th tap was designated as the reference point, the point with zero digital delay would be the 3^{rd} tap from the end of unstable region. By comparing this delay with that obtained from Fig. 2, the feedback loop delay is estimated as 1.22 μs or 2.3 μs (1.22μs + 1 cycle). In addition, integration in order to obtain the delay of each component, DAC (~10ns) + IQ modulator (~160ns) + wave guide · coaxial cable of 100m (~500ns) + Mixer (130 ns) + ADC (6 clock, 150 ns) + FPGA (16 clock, 400 ns), was also estimated. This integration yielded a value of ~1.35 μs. Therefore, a feedback loop delay of ~1.22 μs would be reasonable for this system.

SUMMARY

In the STF at KEK, the feedback instability due to TM_{010} passband modes, except for the π mode, was measured under the conditions of low *Gp* and zero beam acceleration. The RF was predominantly destabilized by the 8/9π and 7/9π modes. A component of the 6/9π mode also appeared; however, it did not destabilized the system by itself. By varying the feedback loop delay through the introduction of a digital delay in the FPGA, the stable/unstable regions appeared at regular intervals. The period for each mode was almost equal to that obtained from the expression $1/(f_\pi - f_{n/9\pi})$. The original feedback loop delay was also estimated by using the periodic pattern. If feedback is employed by using a large *Gp*, the 6/9π mode or 5/9π mode will destabilize the system, and the stable region will shrink further. Therefore, a filter is required for stable operation. In our typical LLRF system, a 0.4 MHz LPF inserted between the DAC and the IQ modulator would ensure the stable operation of the RF system.

REFERENCES

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