EXPERIMENT OF THE RF FEEDBACK USING A PARALLEL COMB FILTER

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Abstract

In high beam-current storage rings like KEK B-factory (KEKB) [1], severe coupled-bunch longitudinal instability can be driven by the accelerating mode of significantly detuned RF cavities. The RF feedback with a comb filter, which can reduce the effective cavity impedance at the synchrotron sidebands of the revolution harmonics, is a possible way to damp the instability. This paper describes the results of the experimental RF feedback loop, which includes a N-path filter referred to as a parallel comb filter, a choke mode cavity, and a 1.2 MW klystron. With the feedback, the real part of the cavity impedance was reduced by 16 dB to 24 dB, at the five synchrotron sidebands 100 kHz apart each other.

I. INTRODUCTION

The cavity is detuned to a lower frequency than the RF frequency to compensate the reactive component of the heavy beam loading. This detuning causes the longitudinal coupled-bunch instability by creating the difference in the real part of the cavity impedance at upper and lower sideband of each mode. For KEKB the impedance of the accelerating mode is much higher than that of damped higher order modes (HOM's). Therefore, if the amount of detuning is comparable to or more than the revolution frequency, the accelerating mode would excite more severe instabilities than those by HOM's. For example if the KEKB low energy ring (LER) employs the normal conducting choke mode cavities [2] [3], the amount of detuning frequency is 236 kHz which is over twice as large as the revolution frequency. Figure 1 shows the growth rates of the coupled-bunch instabilities due to the accelerating mode of the choke mode cavities as a function of the beam current, together with the longitudinal radiation damping rate and the expected damping rate by the longitudinal bunch-by-bunch feedback. The first six coupled-bunch modes ($n = -1$ to -6) are so severe that these modes can not be damped by the longitudinal bunch-by-bunch feedback.

In order to cope with the difficulty, a novel three-cavity accelerating system, ARES, has been developing, which consists of an accelerating cavity coupled with a high-Q energy storage cavity through a coupling cavity [4]. Owing to its large stored energy it reduces the amount of detuning by an order of magnitude and can eliminate the coupled-bunch instability associated with the accelerating mode. Another possible means to deal with the problem is to use an RF feedback, which can reduce the cavity impedance seen by the beam at the synchrotron sidebands. As a backup scheme for ARES, we are developing an RF feedback system using a parallel comb filter. This filter enables us to adjust the feedback phase at sideband frequencies even if a frequency-dependent group delay is present around the feedback loop.

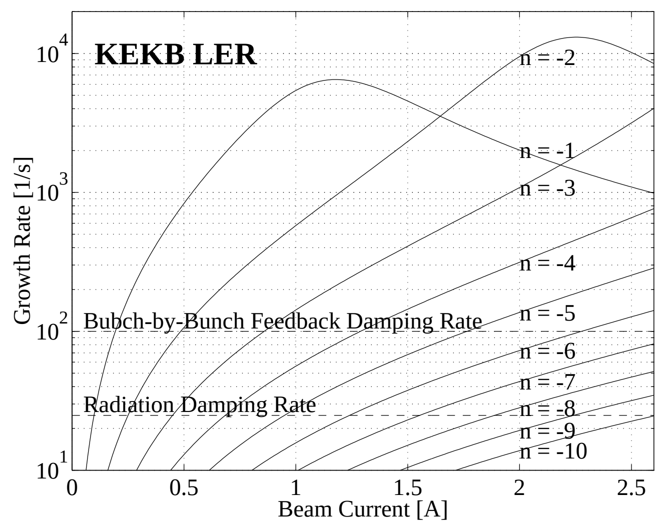

Figure 1. Estimated growth rate of longitudinal coupled-bunch instabilities due to the accelerating mode of choke mode cavities in the KEKB LER.

II. PARALLEL COMB FILTER FEEDBACK

The wide-band RF feedback is necessary to suppress several coupled-bunch modes. The maximum gain and bandwidth, however, are limited by the long group delay around the loop. To solve this problem, a feedback scheme using a comb filter combined with a one-turn delay has been proposed by D. Boussard [5]. In the KEKB RF system, the feedback loop consists of not only constant group delay elements such as coaxial cables and waveguides, but also frequency-dependent group delay elements such as klystrons and cavities. Hence the phase variation of the feedback loop can be written in the form

$$\theta(\omega) = \theta_d(\omega) + \theta_k(\omega) = -\omega\tau_d + \theta_k(\omega) \; , \qquad (1)$$

where $\theta_d(\omega)$ is due to the constant group delay τ_d, and $\theta_k(\omega)$ is due to the frequency-dependent group delay. $\theta_d(\omega)$ is compensated by the one-turn delay feedback, but $\theta_k(\omega)$ is not. One way to compensate for the delay variation is to add a phase equalizer in the feedback path [6] [7]. The other way is to adjust the phase only at the synchrotron sidebands of the revolution harmonics, because we need to reduce the impedance only at these frequencies. This is realized by a N-path filter, each path of which consists of a narrow-band bandpass filter, a phase shifter for compensating the delay variation, and an attenuator for adjusting the loop gain. For convenience this filter is called here a parallel comb filter.

In the application of the RF feedback with a parallel comb filter, the RF signal sampled from the cavity has to be transposed down to a convenient intermediate frequency before filtering, because it is difficult to realize the high-Q bandpass filter at this frequency range. For this frequency transposition, we developed a single-sideband (SSB) filter using broad-band quadrature hybrids, because the feedback is needed only in the lower side of the RF frequency. The block diagram of the RF feedback system using a parallel comb filter is shown in Figure 2.

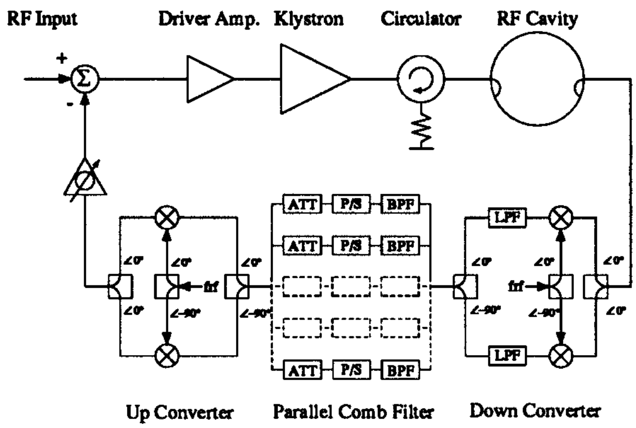

Figure 2. Block diagram of the RF feedback system using a parallel comb filter with frequency transposition by a single-sideband filter.

The transfer function of parallel comb filter can be written as

$$G(s) = \sum_{n=1}^{N} \frac{2\sigma_n s}{s^2 + 2\sigma_n s + \omega_{0n}^2} e^{j\theta_n(\omega)} \ , \qquad (2)$$

where σ_n and ω_{0n} are the half bandwidth and the center frequency of the n-th filter respectively. For the ideal feedback, the each element of a parallel comb filter is adjusted as follows

- The center frequency of each filter is adjusted to the upper synchrotron sidebands of the revolution harmonics.
- The open loop phase response of the feedback loop is adjusted to zero for each frequency by the phase shifter of each path.

Hence, the center frequency of the n-th filter ω_{0n} is

$$\omega_{0n} = (h - n + \nu_s)\omega_{rev}, \quad n = 1, 2, \cdots, N \ , \qquad (3)$$

where h is the harmonic number, ν_s is the synchrotron tune, and ω_{rev} is the angular revolution frequency. By the phase shifter, $\theta_n(\omega)$ is adjusted to

$$\theta_n(\omega) = -(\theta_d(\omega_{0n}) + \theta_k(\omega_{0n})) = \omega_{0n}\tau_d - \theta_k(\omega_{0n}) \ . \qquad (4)$$

With this feedback, the real and the imaginary part of the cavity impedance is reduced in a same ratio at ω_{0n}, because the open loop transfer function is a real number. Therefore the real part of impedance seen by the beam is reduced by a factor $(1 + G)$, where G is a loop gain.

III. RESULTS OF MEASUREMENT

We made a preliminary experiment of the RF feedback with a prototype parallel comb filter. Figure 3 shows the experimental setup which includes a parallel comb filter, a choke mode cavity, a 1.2 MW CW klystron, and the constant group delay of 1 μs mostly due to cables. This value of group delay is comparable to that of the KEKB RF system. As the first step of the experiment, we made a low power measurement. Only a small portion of the klystron output power was extracted with a 55 dB directional coupler, and was fed into the cavity. The detuning frequency and the loaded Q of the cavity were made equal to those used in the instability calculation shown in Fig. 1. The parallel comb filter was comprised of five individual LC bandpass filters arranged with 100 kHz intervals, and each filter has 2 kHz 3 dB-bandwidth. A network analyzer was used to measure the response of each component of the feedback loop to estimate the loop performance, and then the open and closed loop complex transfer responses were measured over a 1 MHz frequency bandwidth.

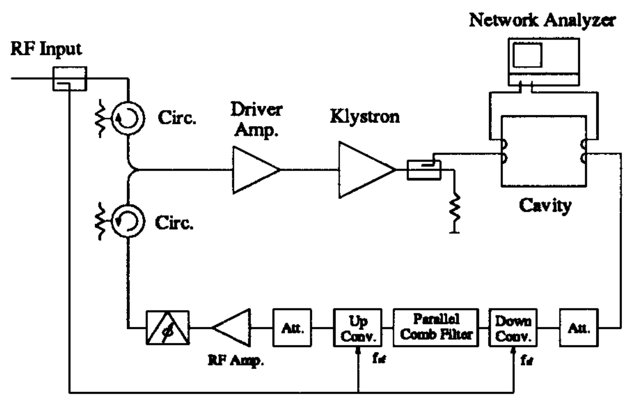

Figure 3. Block diagram of the experimental RF feedback loop which includes a parallel comb filter, a choke mode cavity and a klystron.

Figure 4(a) shows the measured open loop response of the feedback loop. The open loop phase response was adjusted to zero for each frequency by the phase shifter. The unwanted upper sideband of RF frequency was rejected by about 60 dB with the single-sideband filter. We were able to get 29.8 dB of the maximum gain and 25.2 dB of the loop gain with a phase margin $45°$ over a 1 MHz bandwidth.

The measured closed loop response is shown in Figure 4 (b). The top figure shows the normalized magnitude (broken lines) and the real part (solid lines) of the effective cavity impedance with or without feedback, as a function of normalized frequency $(f - f_{rf})/f_{rev}$. The bottom figure shows the phase response of the cavity with or without feedback. We were able to reduce the real part of the impedance by 16 dB to 24 db with feedback. Table 1 shows the coupled-bunch mode number,the measured real part of the cavity impedance at the five synchrotron sidebands and the growth time of the coupled bunch instability with or without feedback.

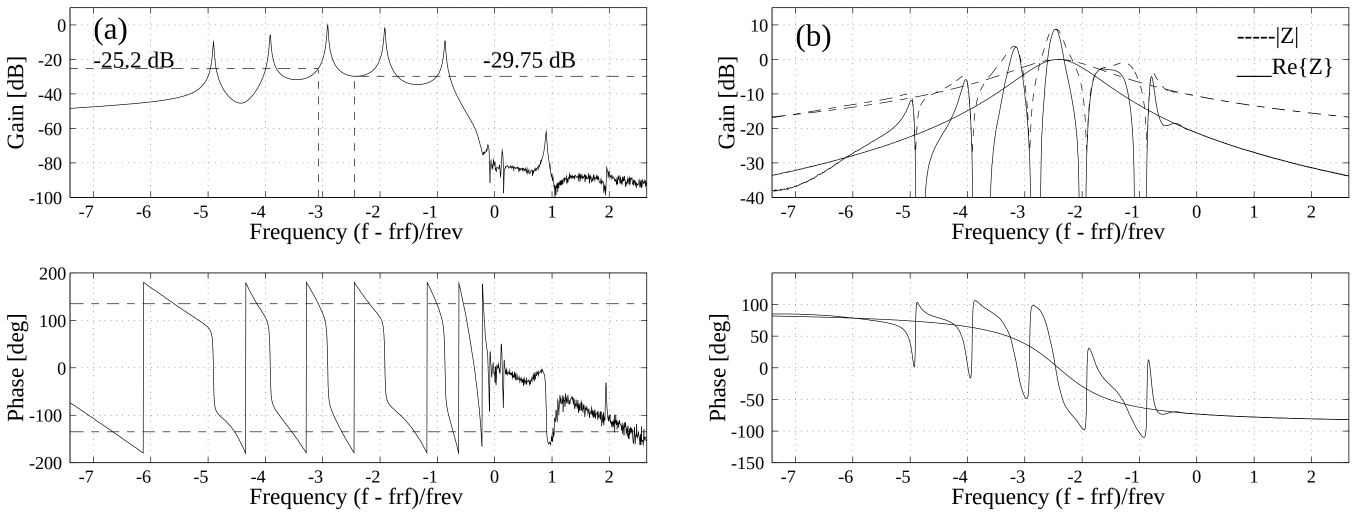

Figure 4. The measured open (a) and the closed (b) loop response as a function of normalized frequency $(f - f_{rf})/f_{rev}$.

Table I
The real part of the impedance and growth time of coupled bunch instabilities with / without parallel comb feedback

Mode	without feedback			with feedback		
	Re{Z_+} [kΩ]	Re{Z_-} [kΩ]	Growth time [ms]	Re{Z_+} [kΩ]	Re{Z_-} [kΩ]	Growth time [ms]
-1	60.36	12.76	0.63	11.27	12.76	-20.16
-2	211.46	7.73	0.15	17.23	7.73	3.15
-3	163.33	5.16	0.19	10.63	5.16	5.48
-4	48.18	3.69	0.67	6.08	3.69	12.55
-5	20.56	2.76	1.68	3.43	2.76	45.18

IV. CONCLUSIONS

We made the experiment on the RF feedback loop, which includes the parallel comb filter, the choke mode cavity and the klystron. The real part of the cavity impedance were reduced by 16 dB to 24 dB at the five synchrotron sidebands 100 kHz apart. If the choke mode cavity is employed in LER, however, the loop gain must be improved by more than 10 db in order to damp the most severe modes ($n = -2, -3$) to a level which can be damped by the bunch-by-bunch feedback system. A feedback simulation shows that 10 dB gain improvement is possible by reducing the bandwidth of the filter to 1 kHz from the present value of 2 kHz. In the next experiment we will try to increase the loop gain up to 35 dB.

V. ACKNOWLEDGEMENTS

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