The 9th Symposium on Accelerator Science and Technology, Tsukuba, Japan 1993

A Longitudinal Feedback System used under Low-Energy 4-Bunch Operation of the Photon Factory Storage Ring

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Abstract

This paper describes a longitudinal feedback system used to cure longitudinal coupled-bunch instabilities under low-energy operation of the Photon Factory storage ring (PF ring) at KEK. A bunch-by-bunch feedback system which operates on up to four equally spaced bunches was constructed using conventional analog circuits and a simple feedback cavity. The system worked well, and the longitudinal coupled-bunch instabilities were largely suppressed under low-energy operation.

I. INTRODUCTION

Research on a free electron laser (FEL) for the short-wavelength region is under way [1] at the PF ring. For this purpose, an optical klystron has been installed in the ring, and a measurement of the FEL gain is being prepared. The FEL experiments require high-quality positron beams at a low beam-energy (0.75 GeV). Although the gain measurement will be carried out with a single bunch, further experiments concerning FEL oscillation call for four bunches in the ring. At the low beam-energy, problems due to beam instabilities are serious because the radiation damping time is long. Therefore, cures for the instabilities are particularly important to obtain stable beams. (Some of the ring parameters are given in Table 1 for beam energies of 2.5 and 0.75 GeV.)

Studies on low-energy operation of the PF ring have been carried out since November, 1989 [2]. Positron beams were injected at a beam energy of 2.5 GeV (the nominal energy of the PF ring), and were then slowly deccelerated to 0.75 GeV. Beam currents of up to 40 mA in a single bunch have been successfully stored at 0.75 GeV. However, the beam currents and beam quality were largely limited by longitudinal coupled-bunch instabilities under four-bunch operation. In order to suppress these instabilities, a longitudinal feedback system was developed. Among several feedback schemes that have been either constructed or proposed [3-7], we built a system similar to that for UVSOR [6] and for the proposed PEP SR project [7].

Table 1. Parameters of the PF ring at 2.5 and 0.75 GeV.

Beam energy	E (GeV)	2.5	0.75
Longitudinal damping time	τ_ε (msec)	3.9	145
Cavity gap voltage*	V_c (MV)	1.7	0.85
Synchrotron frequency	f_s (kHz)	35.6	46.6
rf frequency for acceleration	f_{rf} (MHz)	500.1	
Revolution frequency	f_r (MHz)	1.603	

* used under present operations.

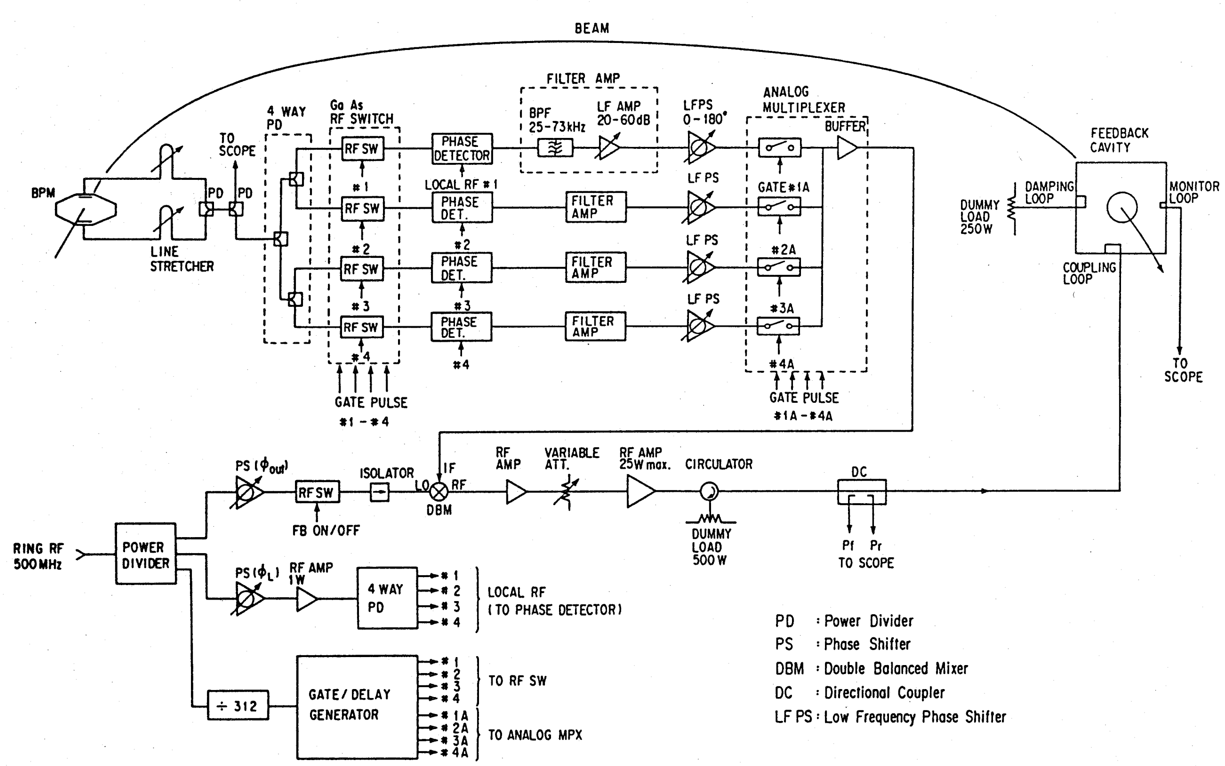


Fig. 1. Longitudinal feedback system for the PF ring.

II. FEEDBACK ELECTRONICS

A block diagram of the feedback system is shown in Fig. 1. Pulses induced by bunches in the upper and lower button-type electrodes of a beam position monitor (BPM) are combined into one signal, which gives an amplitude that is nearly independent of the beam position. The signal is distributed to four separate channels which correspond to four bunches. In each channel, the signal from the corresponding bunch is gated with a GaAs rf switch; the phase of the bunch is then detected by means of a phase detector. The output signal is filtered by a bandpass filter (BPF) which has a center frequency at around the synchrotron frequency; it is amplified by 40-60 dB, resulting in a signal that represents the phase oscillation of the bunch. The phase of this signal is shifted by 90° in order to obtain a signal that represents the energy deviation. The output signals from four channels are gated again, summed up, and used to modulate an rf of 500.1 MHz (which is locked to the ring rf). The modulated rf signal is amplified with a power amplifier (25 W max.), and is then fed into a feedback cavity, which provides a correction voltage to each bunch.

The following is an additional description of some of the components: a) The switching times of the rf switch and the analog multiplexer are less than ~10 nsec, which is much shorter than the bunch spacing, 156 nsec. b) A block diagram of the phase detector is shown in Fig. 2. A direct phase comparison between the 312th harmonic of the beam and the ring rf is made with a double-balanced mixer (DBM). The use of a BPF (center frequency is 500 MHz) and an rf amplifier before the DBM improves the signal-to-noise ratio of the input signal to the DBM.

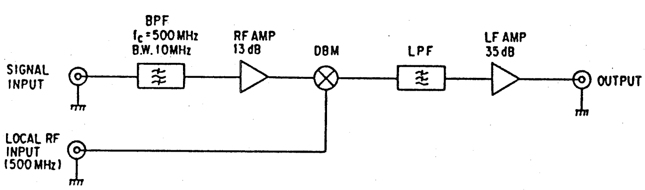


Fig. 2. Block diagram of the phase detector.

III. FEEDBACK CAVITY

A choice for the energy feedback device must be made while considering required feedback voltage and bandwidth. The maximum voltage required for the feedback cavity is given by [4]

$$V_{FB} = \frac{2E}{e\tau f_r} \cdot \frac{\Delta E}{E},$$

where $\Delta E/E$ is the relative energy error and τ is the damping time required for the feedback system. In our case, it is reasonable to set τ to be 4 msec, which is of the same order as the radiation damping time at 2.5 GeV, since we can avoid the instabilities at that energy, at least up to 100 mA (the present target current). Assuming the energy error to be $\sim 3\times10^{-3}$, which is a fraction of the rf bucket height, the required voltage becomes ~700 V. The filling time of the cavity should be less than about one third of the bunch spacing [4], which imposes the filling time to be less than ~50 nsec.

For our system, a feedback cavity with a ceramic gap was adopted, since it is easy to fabricate and is economical. This is because there is no need to develop an in-vacuum tuner or an input window. A cross-sectional view and a photograph of the feedback cavity are shown in Figs. 3 and 4. The cavity body has a rectangular shape (inner dimensions of 247×247× 180 in mm), and is made of stainless-steel plates. A ceramic gap (120 mm in length) breaks the ring vacuum from the air. The left and right side walls of the cavity are movable within ±30 mm, thus providing a wide tuning range of more than ±20 MHz. This tuning range covers anticipated frequency errors due to mechanical tolerances of the ceramic gap, while allowing one to sufficiently detune the cavity when desired.

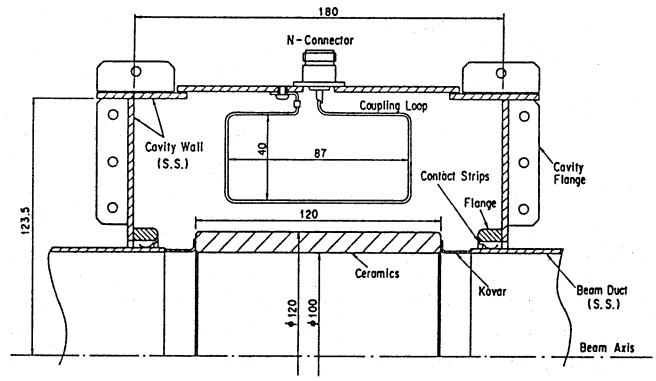


Fig. 3. Cross-sectional view of the feedback cavity.

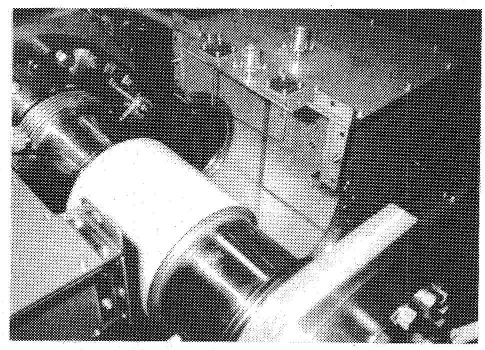


Fig. 4. Photograph of the feedback cavity.

The basic dimensions of the cavity were determined using the MAFIA 3D code. The resonant frequency is 500.1 MHz, which is the same as the ring rf frequency. The measured unloaded-Q (Q_0) is 710, 44% of the calculated value. The main contribution to this degradation is possibly due to imperfect electric contacts used at the cavity noses and the tuner walls. With the measured Q_0 and a calculated R_{sh}/Q of 179 Ω, the shunt impedance was estimated to be 127 kΩ.

The cavity has a large input loop at the top wall, and a damping loop at the side wall. By adjusting these loops, a loaded-Q of 72 was obtained for the fundamental mode, which corresponds to a filling time of 46 nsec. The input power required to produce the feedback voltage (V_{FB}) is given by

$$P_g = \frac{(1+\beta_1+\beta_2)^2}{4\beta_1} \cdot \frac{V_{FB}^2}{R_{sh}},$$

where β_1 and β_2 are the coupling factors of the input and damping loops, respectively. A feedback voltage of 630 V is available with an input power of 16 W, using the measured factors of β_1=4.8 and β_2=4.1. Both loops also damp some harmful HOMs (higher-order-modes). For example, for TM110-like modes (two quasi-degenerated modes), which have an R_T/Q of 1820 (Ω/m), the loaded-Q's were lowered to ~300.

The parasitic mode loss for the fundamental mode of the cavity was estimated to be ~240 W at a stored current of 100 mA in 4 bunches. Since only 10% of the loss is dissipated in the cavity, the cavity can be easily cooled down by forced air flow. On the other hand, under routine operations of up to 360 mA in 312 bunches, and under single-bunch operations at high currents, the cavity body is removed from the ring in order to avoid any problems due to the parasitic mode loss or beam instabilities. For this purpose, the cavity body can be split into two parts, thus allowing quick removal and re-installation. After the cavity body is removed, the ceramic gap is electrically shielded by a cover made of aluminum alloy.

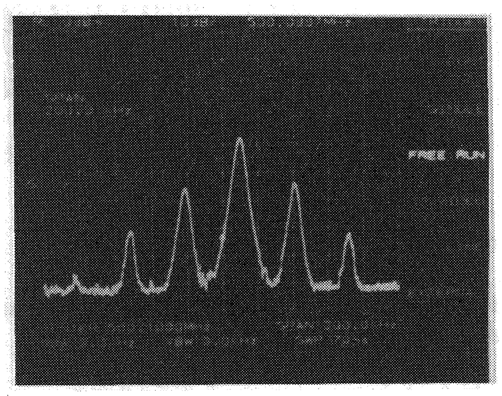
IV. Operation Results

The feedback system was initially tested under single-bunch operation at 2.5 GeV. A strong coherent oscillation of a bunch was deliberately excited by tuning one of the main accelerating cavities (which was not powered) to a frequency of about ($f_{rf} + f_s$). By adjusting the electronics, this oscillation was successfully damped by the feedback. Figures 5(a) and 5(b) show the spectra of a BPM signal without and with the feedback, respectively.

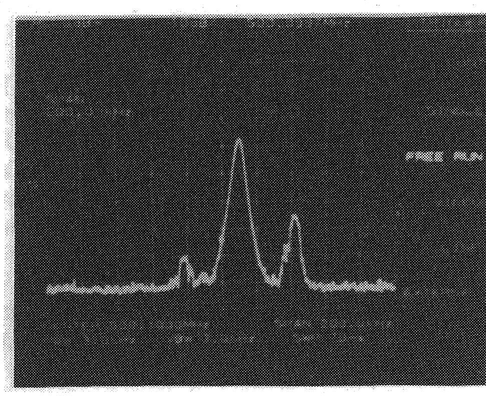
As the next step, a single-bunch beam was deccelerated to 0.75 GeV. Due to the change of the synchrotron frequency during the decceleration, additional phase shifts of the synchrotron oscillation signal arose in the filter amp and the low-frequency phase shifter (LFPS). Thus, the LFPS was re-adjusted so as to retain the total phase shift of 90° with canceling these additional phase shifts. Then, a longitudinal oscillation, which was observed at 0.75 GeV, was successfully damped.

Finally, the system was tested under four-bunch operation. The gate timings of the analog multiplexer were adjusted so that each bunch felt the corresponding feedback voltage when it crossed the cavity. The stored beam was then deccelerated to 0.75 GeV. The longitudinal coupled-bunch instabilities were largely suppressed by the feedback during decceleration. As a result, a maximum beam current of 40 mA in 4 bunches was achieved at 0.75 GeV. The spectrum of a BPM signal under that condition showed small synchrotron sidebands about 37 dB below from the main peak at the rf frequency. A future subject is to reduce this residual oscillation.

During other studies under single-bunch operation at high currents, heating-up was observed in the ceramics shielded by the cover. The temperature of the ceramics was raised up to 100°C at ~70 mA/bunch. This was attributed to a large loss parameter of the structure, which was found to be ~0.20 V/pC from a calculation using the T2 code in MAFIA. At present, the maximum beam current under single-bunch operation is limited to 70 mA due to this problem. No problems were observed during routine multibunch runs of up to 360 mA.



(a) Feedback off.



(b) Feedback on.

Fig. 5. Spectra of a BPM signal without and with the feedback. 10 dB/division. Center frequency: 500.1 MHz, span: 200 kHz. Beam energy: 2.5 GeV, beam current: 8.6 mA (in single bunch).

V. Conclusion

The constructed feedback system is capable of controlling longitudinal coupled-bunch instabilities on up to 4 bunches. The system is now routinely used under low-energy operations for FEL experiments. The heating-up problem in the ceramic duct under single-bunch operation still calls for future improvements.

Acknowledgments

The authors wish to thank M. Izawa and S. Tokumoto for useful discussions in designing the system as well as M. Katoh for low-energy operation during the studies.

VI. References

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