SUPPRESSION OF LONGITUDINAL COUPLED-BUNCH INSTABILITIES AT THE KEK-PF

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Abstract

A bunch-by-bunch feedback system has been developed to suppress longitudinal coupled-bunch instabilities at the KEK-PF. A longitudinal kicker based on a DAFNE-type overdamped cavity has been designed and installed in the ring, and a general purpose signal processor, called iGp, has been developed by the collaboration of the KEK, SLAC, and INFN-LNF. The entire feedback loop has been closed by the end of June 2007, and the feedback system has successfully suppressed the longitudinal dipole-mode instabilities up to 430 mA.

INTRODUCTION

The Photon Factory electron storage ring at the KEK is a dedicated synchrotron radiation (SR) source with an energy of 2.5 GeV. The ring is operated in both single- and multibunch modes. In both cases, longitudinal oscillations starting from very low currents are observed. In the single-bunch operation, the phase noise of a low-level RF circuit excites synchrotron oscillations of the bunch. In the multibunch operation, several coupled-bunch modes of instabilities are observed above 50 mA. Cavity-like structures in the storage ring are suspected to be the source of the instabilities, although the sources have not been determined thus far.

Phase modulation of the RF acceleration frequency at twice the synchrotron frequency ($2f_s$) can suppress the longitudinal instabilities considerably [1]. This easy and inexpensive technique has been utilized during SR user operation for years because this method is very effective not only in suppressing the instabilities, but also for increasing the beam lifetime, approximately by a factor of 1.5. The enhancement of the beam lifetime is desirable for many users. However, phase modulation increases the energy spread of the bunch. The effect is apparently observed in some insertion device beamlines at the dispersive section of the storage ring. In these beamlines, the intensity of the input SR fluctuates depending on the status of the RF phase modulation. In order to stabilize these fluctuations, a longitudinal feedback system has been developed and a feasibility study on top-up injection, which is indispensable for the compensation of a short beam lifetime, has been carried out.

The main parameters of the PF-Ring and the bunch-by-bunch feedback system are listed in Table 1.

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Table 1: Main parameters of PF-Ring.

RF frequency [f_{RF}]	500.1	MHz
Harmonic number	312	
Revolution frequency [f_{rev}]	1.6029	MHz
Synchrotron tune [ν_s]	0.014	
Longitudinal damping rate	0.256	ms^{-1}
Beam current (single/ multi)	70 / 450	mA

FEEDBACK SYSTEM

The feedback system is composed of a front-end detection unit, a signal processing unit, and a corrector unit. The block diagram of the feedback system is shown in Fig. 1.

Front-end Detection Circuit

The output signals from two button-type pickup electrodes are summed by a hybrid (M/A-COM, model H-8) to cancel the transverse beam position dependence. A low-noise amplifier (LNA) is connected to a band-pass filter (BPF), which consists of three delay cables and a power combiner/splitter. The longitudinal position is detected with respect to the RF acceleration signal by synchronous detection at three times the RF frequency. The highest detection frequency is limited by the cutoff frequency of the vacuum chamber, approximately 1.8 GHz.

Though it is possible to change the RF detection phase (indicated as $\Delta\phi$ in the figure) along the bunch train, a constant phase is maintained (DC) because the difference in the synchronous phase between the head and the tail of the bunch train is not large even at 450 mA. A trombone delay adjusts the timing of the input signal and the clock of the ADC.

Digital Signal Processor

A general purpose signal processor, called the iGp, has been developed by a collaboration of the KEK, SLAC, and INFN-LNF [2,3]. iGp provides real-time baseband signal processing at an RF frequency of 500 MHz for 312 bunches at the PF. The longitudinal position of each bunch is digitized by an 8-bit ADC, processed by a 16-tap finite impulse response (FIR) filter, and transmitted to a DAC after an appropriate delay is introduced. The complete signal processing is sufficiently fast compared to the revolution time of the PF-Ring. A digital filter is implemented by using a field-programmable gate array (FPGA). The FPGA also provides a number of other

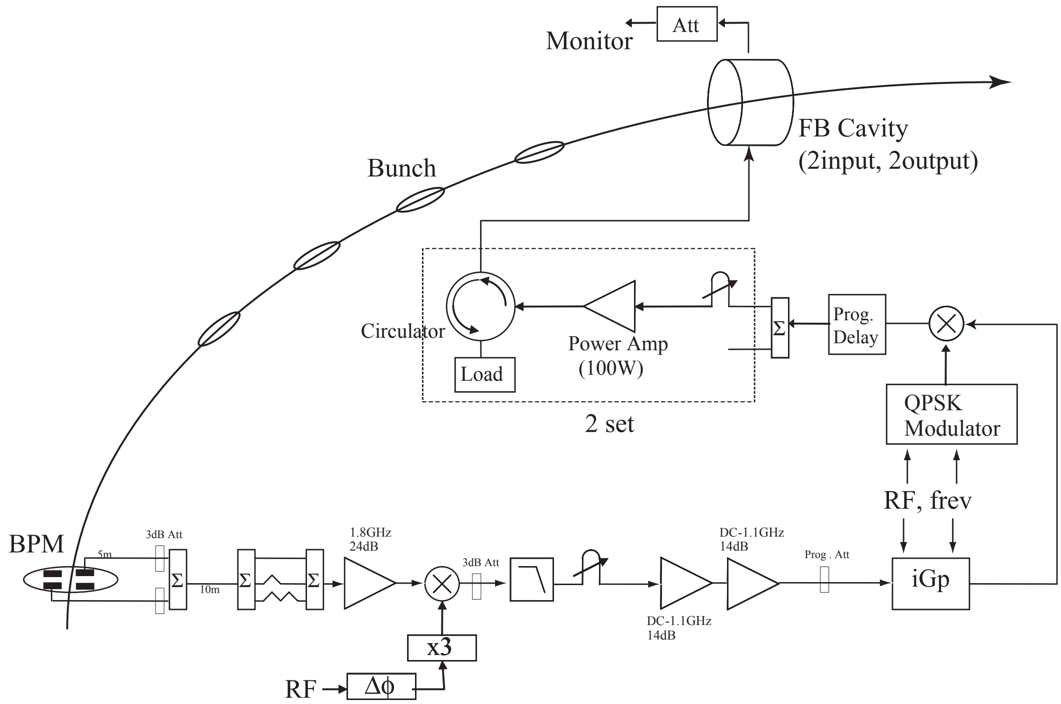

Figure 1: Block diagram of longitudinal feedback system. iGp is a fast real-time digital signal processor using FPGA. QPSK modulator has a carrier frequency that is 2.25 times the RF frequency.

interface features such as high-speed data acquisition memory (Static Random Access Memory, SRAM), slow analog and digital input/output, temperature monitoring, and power supply voltage monitoring. A USB interface in an embedded computer is used to program the FPGA. All the devices, including the signal processing unit, embedded computer, and power supply, are placed in a 19-in 2U-high chassis.

The embedded computer functions as an input/output controller (IOC) of the Experimental Physics and Industrial Control System (EPICS) [4], which is the standard control framework at the PF. The IOC runs on a customized Linux operating system and is connected to the control network. Many easy-to-use graphical user interface (GUI) panels are also provided for tuning and analysis. The FIR coefficients can be easily changed through the GUI.

High-power Component

The output of the iGp is a baseband signal. A QPSK modulator with a carrier frequency equal to the center frequency of the feedback cavity, converts the baseband signal to order to apply the energy kick to each bunch.

The feedback cavity has two input ports driven by a 100-W class-A amplifier (R&K, model A1012BW250). Two output ports are connected to a high-power attenuator (Bird, model 8327-300) to observe the beam-induced signal and output signal from the power amplifiers. In order to protect the amplifiers from the beam-induced signal from the cavity, two 10-kW wideband circulators (AFT Microwave) are installed.

Feedback Kicker Cavity

A longitudinal kicker based on the DAFNE-type overdamped cavity has been installed in the ring. Details of the cavity design and the calculated impedance are reported in ref. [5]. After mounting the cavity, the performance of the cavity is confirmed by using a mode-feedback system. Before the completion of high-speed signal processor, which can handle bunches with a 2-ns bunch spacing, an FPGA evaluation board was used to carry out 52-bunch feedback experiments. The details have already been reported in a previous paper [6]. In both the cases, the coupled-bunch instabilities up to 70 mA have been successfully suppressed.

Filter Design

A FIR filter for the feedback must have a 90° phase shift at a synchrotron frequency of 22 kHz. The impulse response of the FIR filter must be almost equal to the synchrotron period of 45 μs, which corresponds to 72 turns in the PF. Instead of using a 72-tap filter, the iGp has a 16-tap FIR filter and a downsampling feature. We selected different downsampling factors, *Nds*=4, 5 and 6; the total filter length is equivalent to 64, 80, and 96 turns, respectively. Figure 2 shows the two filter designs used in the experiment. The blue line labelled as "coef 1" is the original filter design. Since the quadrupole-mode oscillations of the beam become severe in a high beam current region, the filter with the design "coef 2" is designed to decrease the effects of the quadrupole-mode oscillations, which will be described in detail later.

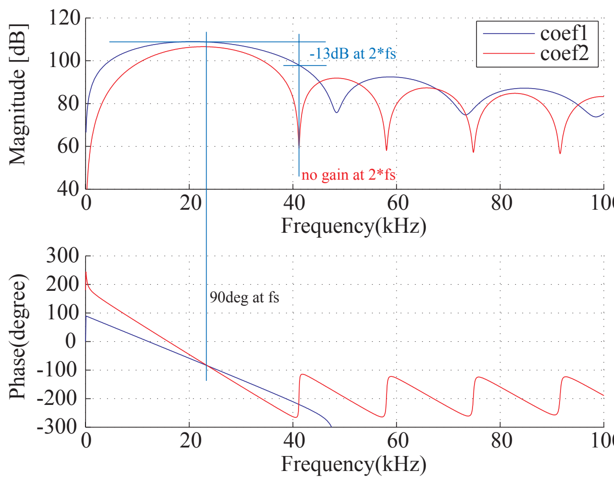

Figure 2: Gain and phase of two 16-tap FIR filter. Blue line (coef 1) corresponds to original filter design with *Nds* = 4. Red line (coef 2) corresponds to filter design with *Nds*=6; it shows almost no response to quadrupole-mode oscillations.

RESULTS

Timing Adjustment Using Single Bunch

The analog and digital delay time is adjusted precisely using a single bunch in the ring. As mentioned before, strong synchrotron oscillations caused by the main RF system are observed in the single-bunch operation. It is very difficult to completely suppress the single-bunch instabilities by using the bunch-by-bunch feedback system because the shunt impedance of the feedback cavity is considerably lower than that of the main RF system. However, it is possible to excite or suppress instabilities of approximately 3 dB in amplitude. This amplitude is sufficiently large for the timing adjustment of the feedback system. A wideband programmable delay unit (Colby Instruments, HPDL-100A-10.23NS) is in introduced between the iGp and the power amplifiers to adjust precisely the timing for the kicker.

Feedback and Phase Modulation

Out of 312 buckets, 280 bunches are stored to prevent the onset of the transverse ion-trapping instabilities. The bunch spacing is 2 ns. In order to observe a difference from the present SR user's operation, we tested the four patterns of operation listed below. 'PM' indicates the RF phase modulation, and 'FB' indicates the bunch-by-bunch feedback system hereafter.

(A) FB OFF, PM ON : same as present user's operation
(B) FB ON, PM ON : both are turned ON
(C) FB ON, PM OFF: only feedback system; ideal case.
(D) FB OFF, PM OFF: no beam stabilization

The beam current is selected to be 430 mA. The beam spectra of the button type pickup electrode under the feedback conditions (A)–(D) are shown in Figs. 3 (A)–(D), respectively. The frequency range is from DC to 3 GHz. In Fig, 3(A), harmonics of the RF frequency is observed at 500 MHz, 1 GHz, 1.5 GHz, … Some spectral lines corresponding to the longitudinal coupled-bunch mode instabilities of mode number 276 (or mode –36) are also observed. In some cases, mode 276 disappears and another mode, mode 195 (–117), is observed (not shown in the figure).

When both PM and FB are turned ON, as shown in Fig. 3(B), all the instability lines disappeared and only the RF harmonics are observed. Beam stabilization appears to be successful, although the energy spread of the bunch is still large; hence this condition is not advantageous for SR experiments.

Without any stabilization, as shown in Fig. 3(D), several instability modes are observed. The strength of each mode is not constant and the peak height varies. The baseline of the spectra is raised because many modes exist within the resolution bandwidth (RBW) of the spectrum analyzer.

Figure 3(C) shows the beam spectrum without PM and with FB. This operation pattern is the ideal case for feedback system development. In the low-frequency region below 1 GHz, there is no peak due to the instabilities. On the other hand, a small peak corresponding to mode 276 exists in the high-frequency region above 2 GHz. Expanding the frequency range around the modes reveals that the peak is located at a distance of $2f_s$ away from the revolution harmonics, and there are no peaks around f_s. The dipole motion has been successfully suppressed by the feedback system and only the quadrupole-mode oscillations remain. A streak camera is used to directly observe the bunch shape as shown in Fig. 4. The top figure shows the longitudinal bunch shape without FB nor PM (case (D)), and the bottom figure shows case (C). It is apparent that the feedback system suppresses the dipole motion, and the bunch length varies along the bunch train. It should be noted that the adjacent bunches in the Fig.4 are actually 8 ns apart since the frequency of the fast-sweep signal of the streak camera is

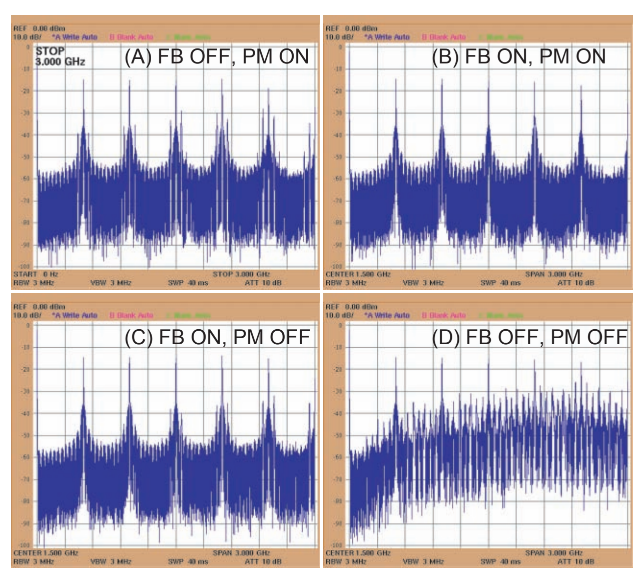

Figure 3: Beam spectra of button-type pickup electrode. FB indicates feedback, and PM indicates phase modulation of acceleration RF signal.

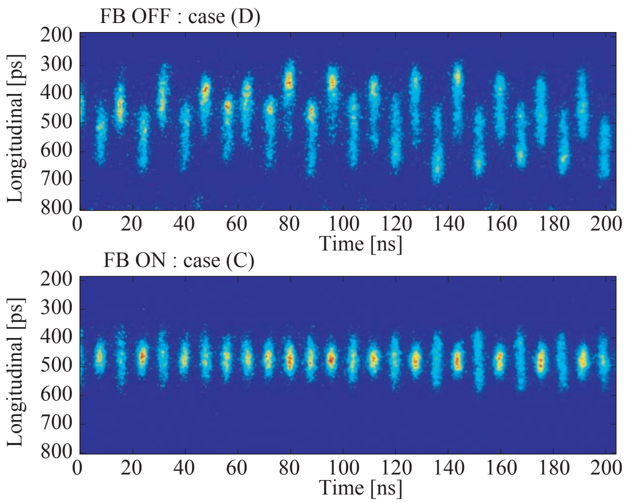

Figure 4: Longitudinal bunch shape measured by a streak camera. Top figure shows the profile without the feedback (case(D)), and bottom figure shows with the feedback (case (C)).

a quarter of the RF frequency. The bunch length is not constant. As time advances, the longer bunches become shorter, and vice versa. When a bunch arrives in the shortest time interval, the bunch length is shorter than the natural bunch length.

Figure 5 shows the transverse beam profile with and without FB (case (A) and (C)). Since the SR monitor is located in a non-zero dispersion region, the horizontal beam size includes the effects of energy spread of the bunches. By closing the feedback loop, the horizontal beam size decreases and the relative peak intensity increases by approximately 8%–9%.

It is possible to suppress the dipole motion of the beam above 430 mA, although the system sometimes goes out of the capture range of the feedback system, and the beam becomes unstable. In contrast to the transverse case, the longitudinal instabilities are difficult to be suppressed by just turning on the FB. In this case, to suppress the instabilities, the PM is turned on at first, then the FB is turned on, then finally the PM is turned off.

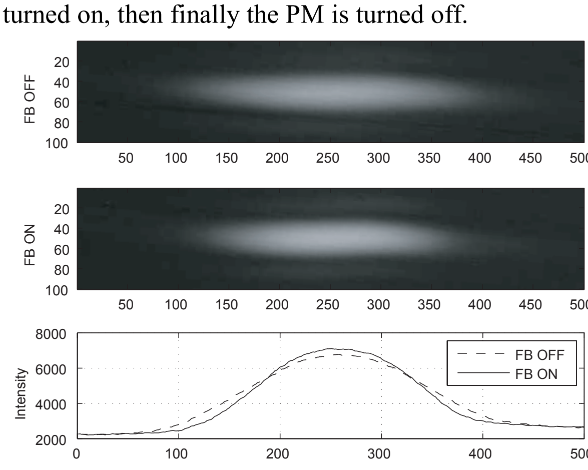

Figure 5: Transverse beam profile measured by a CCD camera in cases (A) and (C). The peak intensity increases with the feedback.

Mode Analysis of Instabilities

The iGp is equiped with two types data acquisition memories for beam diagnostics. One is the internal RAM of the FPGA, and the other is the external SRAM. They can store individual bunch positions up to 128 ksamples and 8 Msamples, respectively. The SRAM data for the mode analysis can be downloaded to the IOC through the USB, and transferred to other machines for analysis using high-level application tools such as MATLAB.

A grow/damp measurement at a beam current of 200 mA is shown in the left-hand-side figure of Fig. 6. There exist large zero-mode oscillations which are assumed to be driven by the main RF system. The growing and damping parts of mode 276 (–36) are fitted by exponential functions. The fitted growth and damping rates are obtained to be 1.1 and 0.8 ms^{-1}, respectively.

In the high beam current region, it is sometimes difficult to recapture the beam. The right-hand-side figure of Fig. 6 shows an example when the instabilities grow faster than the feedback damping time. Several modes are observed in the figure. The strongest mode has changed to mode 275 (–37) at 400 mA. Further investigations are required to identify the behavior of this variation, and the relationship between other parameters such as RF cavity temperature.

Effects of Longitudinal Feedback on SR Users

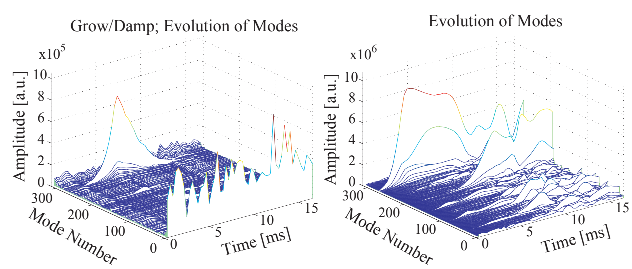

Figure 6: Evolution of modes during the grow/damp measurement. Left-hand-side figure shows the recaptured beam at a beam current of 200 mA, and right-hand-figure shows an example that the feedback cannot be recaptured at a beam current of 400 mA.

The effects of the longitudinal feedback on SR users were examined. The beamline users measured the intensity and stability of the SR while the machine was operated with pattern (A) through (D), approximately 2 h each. The initial beam current is selected to be 430 mA. The beam current and lifetime are plotted in Fig. 7. The difference in the lifetime between cases (C) and (D) indicates that the averaged bunch volume is increased by the quadrupole mode oscillation of the bunch. This is consistent with the beam spectrum or the streak camera measurement.

Figure 8 shows the intensity of the SR at beamline BL-17, which is a short-period small-gap undulator (SGU), in an in-vacuum configuration. Due to limitations of the lattice and available space, this undulator is installed at a non-zero dispersion region. In cases (A) and (B), the energy spread due to RF phase modulation causes

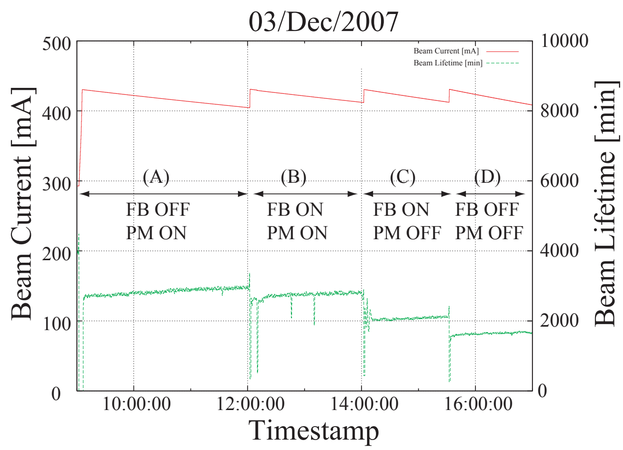

Figure 7: Beam current and the lifetime during the machine development period.

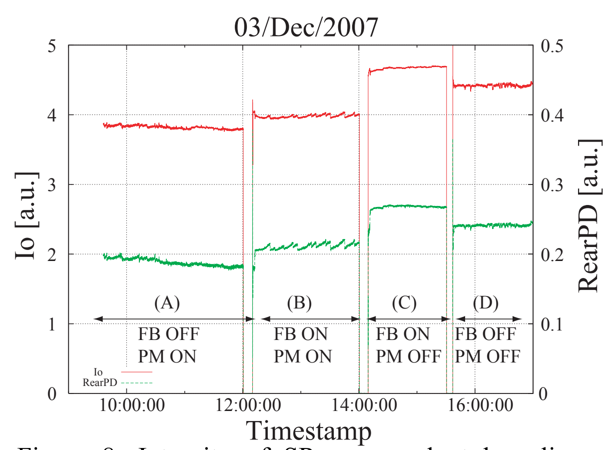

Figure 8: Intensity of SR measured at beamline BL17. Io indicates the intensity of the input light measured by an ion chamber, and RearPD indicates the output voltage of a photo detector placed after an X-ray diffractometer. Both scales are plotted in arbitrary units.

fluctuations and drifts in the intensity. On the other hand, when the feedback loop is closed, the intensity increases to approximately 30% in case (C). Further, the fluctuations and drifts are almost negligible in this case.

At beamline BL-5, an increase in the intensity of approximately 50%, and a decrease in the fluctuations from 5% to 3% with the feedback are observed. At other beamlines, the effects of longitudinal feedback are not significant, and the beam quality is not degraded by the feedback. The feedback system has been confirmed to be very effective.

Feedback Stability for Long-term Operation

The stability of the feedback system has been checked in operation for one week. Another purpose of this period was to check the effects of the short lifetime on SR users. The feedback system worked well during the week without any trouble.

When the beam current is lower than approximately 240 mA, the lifetime suddenly drops as shown in Fig. 9. There are no instability lines in the beam spectrum below this current. Further, in some beamlines, the SR intensity increases simultaneously with the drop in lifetime. There is a clear threshold and hysteresis phenomenon present in the quadrupole-mode instability. If the feedback loop is kept closed during the beam injection, the quadrupole-mode instability again appears above 300 mA. We continue to investigate the details of the hysteresis phenomenon along with the development of a quadrupole-mode suppression system.

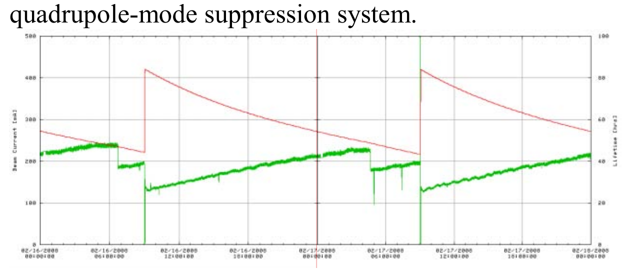

Figure 9: Beam current and lifetime for 2 days with the longitudinal feedback system in continuous operation.

SUMMARY AND FUTURE PLAN

A bunch-by-bunch feedback system has been developed to suppress the longitudinal coupled-bunch instabilities at the KEK-PF. The system can suppress the longitudinal dipole-mode instabilities up to 430 mA. The long-term stability of the system has been proven by operation of the feedback system for one week.

A regular SR operation starts at 450 mA in the multibunch mode. In order to improve the highest beam current for the dipole-mode suppression, two 500-W power amplifiers are ready to be installed in place of the present two 100-W amplifiers.

It is also important to suppress the quadrupole-mode instabilities to maximize the intensity of the insertion device beamlines with a non-zero dispersion. We are planning to develop another feedback system for the quadrupole-mode. One idea is to adjust the phase of the carrier signal to work on both the dipole and quadrupole components and design a new filter to suppress both of them [7]. The other idea is to develop another set of feedback processor and a cavity dedicated for the quadrupole mode. In both cases, it is not easy to develop a good detection circuit because button-type electrodes are less sensitive to the quadrupole motion. We continue to develop the feedback system along with the investigation on the sources of the dipole- and quadrupole-mode instabilities.

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