Feedback experiments in TRISTAN-AR and the bunch by bunch feedback systems for KEKB

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Abstract. Beam tests of the KEKB bunch by bunch feedback system prototypes have been performed in the TRISTAN-AR in both longitudinal and transverse planes. A two-tap FIR filter system, consisting of hardware logic's, realized the function of the phase shift by 90 degrees, the suppression of the static component and the delay of up to a few tens of turns in longitudinal plane with 508 MHz of system clock. The transverse systems were purely analog systems without any digital signal processing part. More than 100 bunches with maximum current of 376 mA have been accumulated successfully with the bunch spacing of 2 ns. The growth time and the growing modes of the transverse instabilities has also been measured with the memory function of the two-tap FIR filter. It suggests that the bunch-by-bunch feedback system is a powerful tool to explore the source of the instabilities. Based on the results of the AR experiments, the design and the expected performances of the feedback systems for KEKB rings are presented.

I INTRODUCTION

The KEKB rings are designed to accumulate huge beam current with many bunches. Even with the great care on the reduction of the possible impedance sources around a beam, unexpected impedance may remain high and it can cause strong coupled bunch instabilities. The method to analyze and suppress the instabilities has the key to achieve the expected quality of the rings. A straightforward and the only realistic method is to apply bunch by bunch feedbacks based on very fast digital technology with the wide bandwidth up to 255 MHz and large power to supply enough negative impedance. The target of the KEKB bunch feedback systems has been set to achieve the damping time of about 1 ms both on the transverse and the longitudinal planes for the minimum bunch spacing of 2 ns.

The feedback system consists of three major parts: a front-end circuit to detect the bunch positions, a signal processing system, and kickers and wideband amplifiers with large power. The front-end circuit need to detect the individual bunch positions without disturbed by the signals from the preceding bunches with enough resolution. The signal processing system is a simple digital filter with the function of signal delay which corresponds to phase rotation thorough 90°, and the noise elimination, if necessary. The kickers should have enough shunt impedance over the necessary bandwidth without HOM's.

We have examined the feasibility of our feedback systems during the high-beam-current experiment of TRISTAN-AR [1]. The prototype systems have been installed in the south experimental section of the AR. We will show the results in the first half of this report. In the latter half, we show the present status of the feedback systems for KEKB rings.

II AR HIGH BEAM CURRENT EXPERIMENT

As the KEKB needs to store huge current with the enormous number of bunches, it is necessary to establish the method to accumulate the unusually high-beam-currents against several obstacles. One of the major limitations will come from coupled bunch instabilities arising from the higher order modes or the fundamental mode of the accelerating cavities. We have developed two new types of RF cavities; the ARES cavity [2] and the damped superconducting cavity [3], to escape from the instabilities. We have installed the new cavities in TRISTAN Accumulation Ring (TRISTAN-AR). The main purpose of the high-beam-current experiment is to investigate whether these RF systems do work well under a high-beam-current condition.

In parallel with the cavities experiment, we also carried out machine studies on the fast ion instability and other coupled bunch instabilities.

We have also installed prototype beam feedback systems in AR and examined the feasibility of the systems during the high-beam-current accumulation study. Related parameters of the TRISTAN-AR for the high-current study are listed in Table 1.

TABLE 1. Main parameters of TRISTAN-AR.

Circumference	377.26	m
RF Frequency f_{RF}	508.58	MHz
Harmonic number	640	
Tune ν_x, ν_y	10.16, 10.23	
Beam Energy E	2.5	GeV
Typical RF voltage	1	MV
Typical Synchrotron tune ν_s	0.22	
Longitudinal damping time τ_ϵ	21.6	ms
Transverse damping time τ_x, y	43.1	ms
Natural bunch length σ_z	2	cm

III EXPERIMENTAL SETUP

A Transverse system

A block diagram of the transverse feedback system prototype at TRISTAN-AR is shown in Fig. 1. Signals

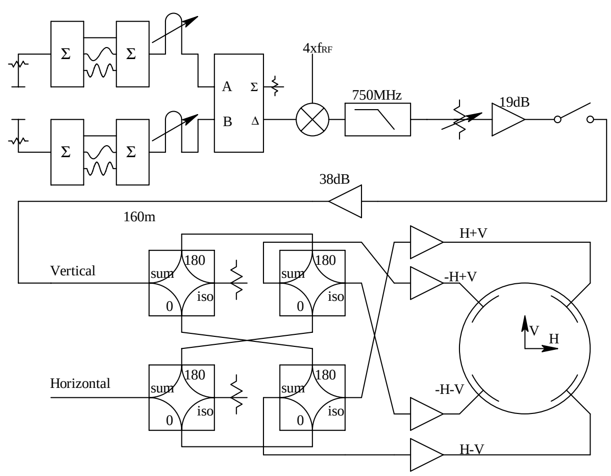

FIGURE 1. Block diagram of the transverse feedback system prototype installed in AR.

from a button electrode is divided into three branches by a power combiner and summed up again by another power combiner. As the lengths of the delay cables which connect the two combiners are chosen to be of α + nλ (n=0,1,2), where α is constant and λ is the wavelength of the detection frequency, this system works as an FIR bandpass filter with the first center frequency of nλ/c. The detection frequency is chosen to be the 4-th harmonic of the RF frequency. The differential of the two sine-like burst signal by a 180°-hybrid is multiplied by the reference signal which is quadruple of the RF signal with a double balanced mixer (DBM). Higher-frequency components are rejected by a low pass filter (LPF) of which cutoff frequency is 750 MHz.

The stripline kicker has four electrodes with the length of 30 cm and the opening angle of 60° rotated 45° from horizontal plane. As it was impossible to prepare amplifiers which have bandwidth from 95 kHz to 255 MHz, we divided the required band to two sub-bands; from 95 kHz to 25 MHz (lower-band) and from 20 MHz to 255 MHz (higher-band) and used two stripline kickers for each amplifier-set. Totally, four lower-band amplifiers and four higher-band amplifiers were used. The maximum power output for each amplifiers was 200 W.

The damping times for the bunch current of 4 mA are estimated to be about 400 μs for the horizontal plane and about 800 μs for the vertical plane.

B Longitudinal system

Figure 2 shows a block diagram of the longitudinal feedback system prototype. The longitudinal position

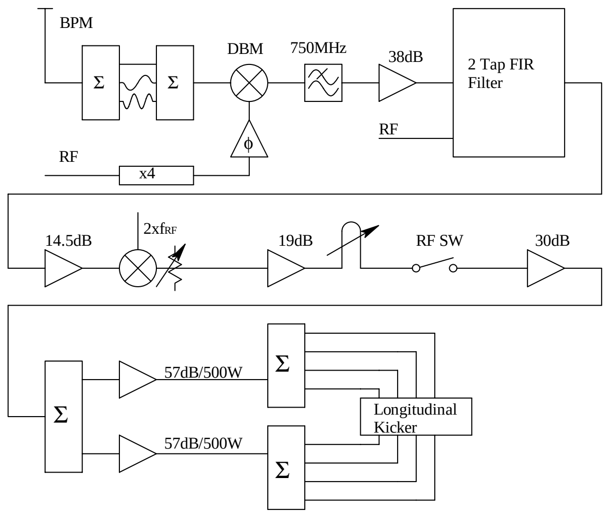

FIGURE 2. Block diagram of the longitudinal feedback system prototype installed in AR.

of a bunch is measured with a wideband phase detection system. Using the same BPF and the DBM as the transverse system, the sine-like burst signal from a bunch is multiplied by the quadruple of the RF signal. This time the nominal phase is adjusted to be 90° shifted from that of the bunch. By rejecting the higher-frequency component with the LPF, baseband signal of synchrotron oscillation is detected as the form of $\sim I_b \Phi \sin(\omega_s t)$ if the amplitude Φ is small.

The signal process is performed with a two-tap FIR filter realized by a simple hardware system. Detailed description of the filter system is written in the reference [4]. We have used a four cells of series-drift-tube type longitudinal kicker just same structure as used in ALS at LBNL [5]. Total shunt impedance was about 1.6 kΩ and the maximum feedback voltage was 1.7 kV/turn.

IV BEAM TEST OF THE FEEDBACK SYSTEMS

General information of the high-beam-current study of AR is written elsewhere [1]. We therefore describe only the subjects concerning the feedback experiments here.

A Transverse feedback experiment

We have encountered heavy coupled bunch instabilities both in horizontal and longitudinal planes and could not accumulate bunch train without the transverse feedback systems. Maximum number of stored bunches was less than 25 bunches with no feedbacks.

With the transverse feedback system on, we successfully accumulated more than 300 bunches with the bunch spacing of 2 ns and the bunch current of 1 mA. Table 2 shows the maximum number of accumulated bunches on the bunch-train mode with the bunch spacing of 2 ns together with the state of each feedback system. The maximum stored beam current of 376 mA with the transverse feedback system on was achieved with the bunch-train mode of 4 mA per bunches. We also applied the feedback system to the equally-filled mode such as 8 ns or 10 ns spacing mode and succeeded to suppress the instabilities.

TABLE 2. The maximum number of stored bunches with the bunch-train mode. H means horizontal system and V means vertical system.

Bunch current	H: off V: off	H: On V: off	H: off V: On	H: On V: On
1 mA	18	20	—	> 300
2 mA	20	70	20	> 170
4 mA	25	25	65	> 100

The memory function of the two-tap FIR filter complex enables us to observe the growth and damp of the instabilities in time domain. As the filter has 1 Mb of memory, we have recorded the oscillation of all the bunches over about 1600 turns. The growth time of the instabilities just after turning off the feedback system was about 2 $\sim$ 3 ms for both horizontal and vertical planes, much faster then the radiation damping time. The damping time just after turning on the feedback was less than 1 ms for horizontal plane, about 2 ms for vertical plane, which are consistent with the rough estimates of the damping times. By arranging the data in a two dimensional array of bunch number vs. time and making the Fourier transform of each rows, we get the change of the modes of the oscillation of the bunches in time domain. Figure 3 shows an example of the growing modes of horizontal and vertical instabilities starting 13ms and 3 ms after turning off the feedback system, respectively. The filling pattern was equally spaced mode with 5 bunch spacing, 2 mA/bunch. In the vertical plane, clearly only one mode corresponding to 10.2 MHz is growing rapidly. This frequency is consistent with the simulation using the normal ion trapping [7]. In the horizontal plane,

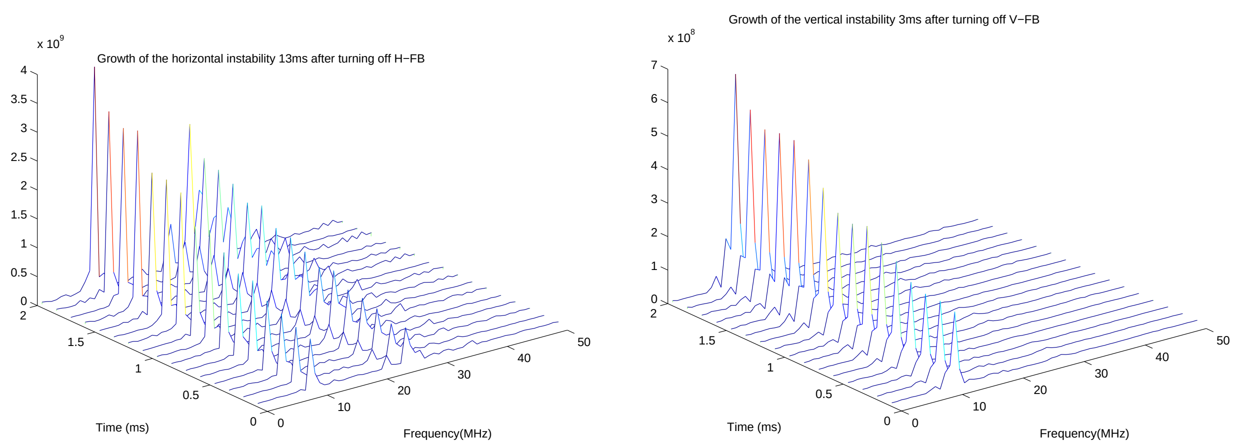

FIGURE 3. Growth of the horizontal and vertical coupled bunch oscillation recorded in the two-tap FIR filter.

three modes corresponding to 9.4 MHz, 22.2 MHz and 25 MHz were growing rapidly. In the same method, we observed the damping of the oscillations as shown in Fig. 4.

B Longitudinal feedback experiment

As it was impossible to accumulate the multi-bunched beam without transverse feedback system, we always turned on the transverse systems with the maximum gain during the longitudinal feedback experiments. We have at first tuned the tap positions of the two-tap filter to have the maximum gain with the positive feedback loop. Also the phase of the kicker was adjusted under the same conditions.

In the bunch-train mode with the bunch spacing of 4 ns and the bunch current of 2 mA, the synchrotron oscillation was successfully damped up to 6 bunches. However, when we injected the 7-th bunch, strong quadrupole oscillation in the 7-th bunch occurred and the second sidebands has appeared. It was impossible to damp the oscillation, though the first sideband was fairly suppressed. It obviously shows there is huge longitudinal impedance in the ring.

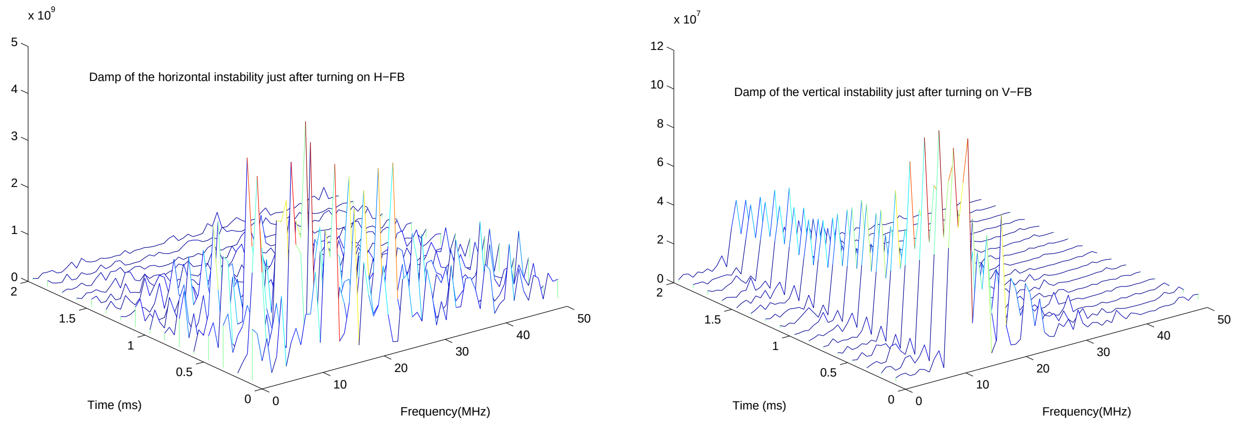

FIGURE 4. Damp of the horizontal and vertical coupled bunch oscillation observed with the two-tap FIR filter.

In the equally-spaced-bunched mode with 10-RF bucket spaces and 2 mA/bunch, we successfully suppressed the longitudinal oscillation. However, if we once turned off the feedback system, we were not able to re-capture the oscillation when turning on the feedback until the total current got down from 120 mA to 90 mA. This shows that the maximum feedback voltage was insufficient. With the equally-spaced-mode with 5 bunch space and 1 mA/bunch, we also successfully suppressed the oscillation. In this case we easily re-captured the oscillation after turning off the feedback system. Figure 5 shows the beam spectra with the longitudinal feedback off and on.

During the high-current study in AR, we have been monitoring temperatures of the vacuum components and the high power components of the feedback systems. No fatal troubles has occurred during the experiment. We also checked the status of the components after the experiment and got no damage at all except the final power combiner to the longitudinal kickers.

V SUMMARY FOR THE FEEDBACK EXPERIMENTS ON TRISTAN-AR

We have installed the transverse and longitudinal feedback systems which are prototypes for KEKB rings in the TRISTAN-AR and examined the feasibility in the high-beam-current study. As the instabilities were fairly stronger than expected, we should say that it was unexpectedly heavy examination for our feedback systems.

The analog transverse feedback systems worked very well. With the two-tap FIR filter as the memory board, we observed the growth and damp of the modes of the oscillation. Also our system worked as the instrumentation tool for other experiments, such as the first ion trapping experiment [6]. They clearly observed the individual oscillation of bunches in the bunch-train with 2 ns spacing.

The longitudinal system worked, though it also showed the insufficient feedback voltage for the oscillation with large amplitude. For the KEKB rings, it should be necessary to invest much more power in the final amplifier and to use kickers with larger shunt impedance.

VI FEEDBACK SYSTEMS FOR KEKB

KEKB rings are about 8 times larger than the AR. We need the feedback voltage of 8 times larger than that of AR to get the same damping time for the same oscillation amplitude. However, the shunt impedance of the kickers and the maximum power of the amplifiers, and also the budgets are limited. It means that we must control the instability at the very small oscillation. Table 3 shows the related parameters of the KEKB rings.

The expected sources of the instabilities and estimates of the growth time are given below:

- Transverse planes ($\tau_{rad} \sim 46$ ms for HER, 86 ms for LER)

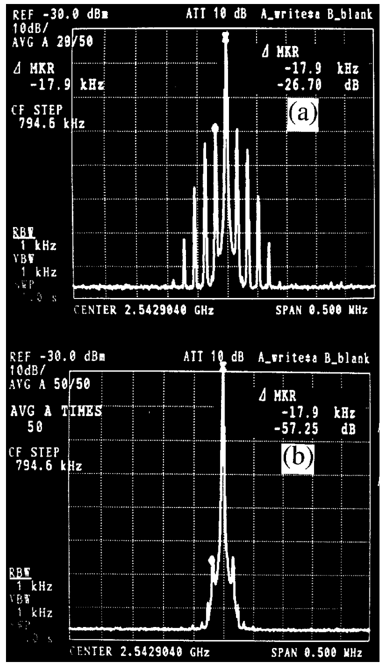

FIGURE 5. Beam spectra, (a) with longitudinal feedback off (b) with longitudinal feedback on. Without the feedback, there appeared many synchrotron sidebands corresponding to the strong longitudinal oscillations. The amplitude of the first sideband has reduced down to -30dB with the longitudinal feedback on. The total beam current was about 120 mA.

- Fast beam-ion instability in HER
  $\tau \sim 1$ ms with modes ~ 80.
- Photo-electron instability in LER
  $\tau \sim 0.5$ ms with modes < 2560.
- HOMs of the RF cavities for both rings
  $\tau > 10$ ms.
- Resistive wall instability for LER
  $\tau \sim 1$ ms with very low modes.

• Longitudinal plane ($\tau_{rad} \sim 23$ ms for HER, 43 ms for LER)

- HOMs of RF cavities
  $\tau >30$ ms

TABLE 3. Main parameters of KEKB.

Ring	LER	HER	
Energy	3.5	8.0	GeV
Circumference	3016.26		m
Luminosity	1×10^{34}		$cm^{-2}s^{-1}$
Beam current	2.6	1.1	A
Natural bunch length	0.4		cm
Particles/bunch	3.3×10^{10}	1.4×10^{10}	
Synchrotron tune	$0.01 \sim 0.02$		
Betatron tune	45.52/45.08	47.52/43.08	
RF voltage	$5 \sim 10$	$10 \sim 20$	MV
RF Frequency	508.887		MHz
Harmonic number	5120		
Longitudinal damping time	43	23	ms

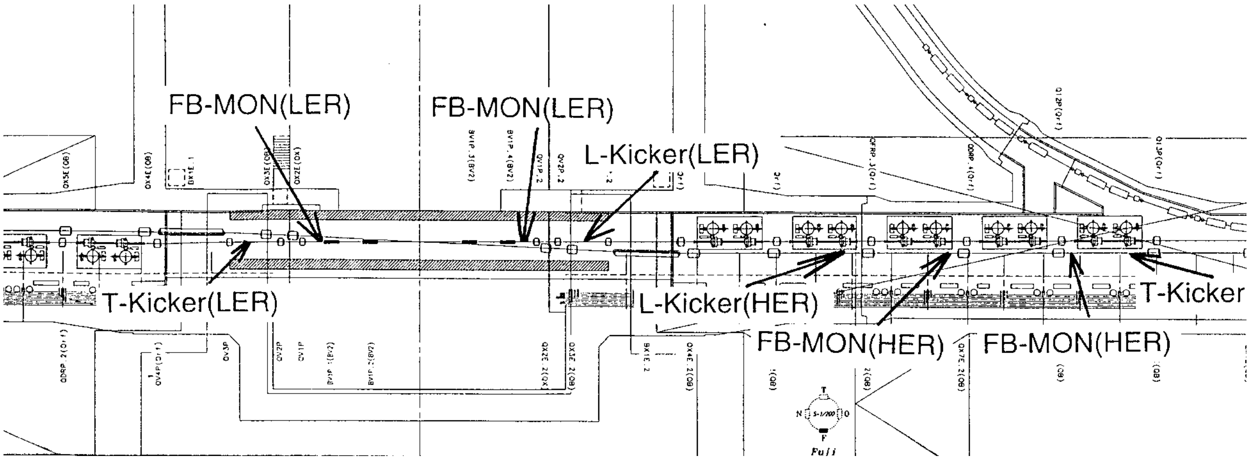

FIGURE 6. Arrangements of the feedback components in the Fuji experimental hall.

TABLE 4. Maximum amplitude for exponential damping region of the feedback system.

Ring	40 cm kicker	1.2 m kicker
LER	0.2 mm	0.7 mm
HER	0.09 mm	0.3 mm

– Fundamental mode
$\tau \sim 20$ ms

We have designed the system under the condition of expected damping time of about 0.5 ms for the transverse planes and 5 ms for the longitudinal plane. All the monitors and kickers will be installed in one of the four long straight sections, "Fuji". This is just at the opposite position of the interaction region. Figure 6 shows the plan of the arrangement of the feedback components in the rings. In each ring, two sections of monitor-electrodes will be prepared. Distance between these sections is chosen to be roughly 90° in the betatron phase for both horizontal and vertical planes. For the transverse feedback detection, the signals from the two sections vectorially combined to make the phase advance from the monitor to the kicker to be $\pi/2($ mod $2\pi)$. One monitor section have about 16 pickup electrodes that will be used for transverse and longitudinal feedback systems, bunch oscillation monitors, spectrum monitors, a bunch current monitor, and so forth. The pickup electrodes have the SMA type connectors with a disc of 6 mm diameter. The inner radius of the detection chamber is 64 mm.

A Transverse systems

We will use two types of stripline kickers: a 40 cm wide-band kicker for 50 kHz to 255 MHz and a 1.2 m lowest band kicker (the long kicker) for 5 kHz to 400 kHz. Expected shunt impedance is about 8 kΩ at 100 MHz for the wide-band kicker, and about 120 kΩ for the long kicker. The maximum power of the feedback amplifier for the wide-band kicker is 250 W per each stripline, and 200 W for the long kicker. The maximum amplitudes at the saturation of the amplifier with the damping time of 0.5 ms are listed in Table 4. Above the value, the feedback system works in the bang-bang damping mode.

B Longitudinal systems

We are now developing the waveguide-overloaded cavity (DAΦNE type kicker [8]) for the longitudinal kicker with 4-input ports and 4-output ports. By using the codes HFSS[1] and MAFIA[2], we optimized the geometry of the kicker to get reasonable shunt impedance and the quality factor. Figure 7 shows the HFSS model and the calculated shunt impedance. The shunt impedance of about 800 Ω with the quality factor

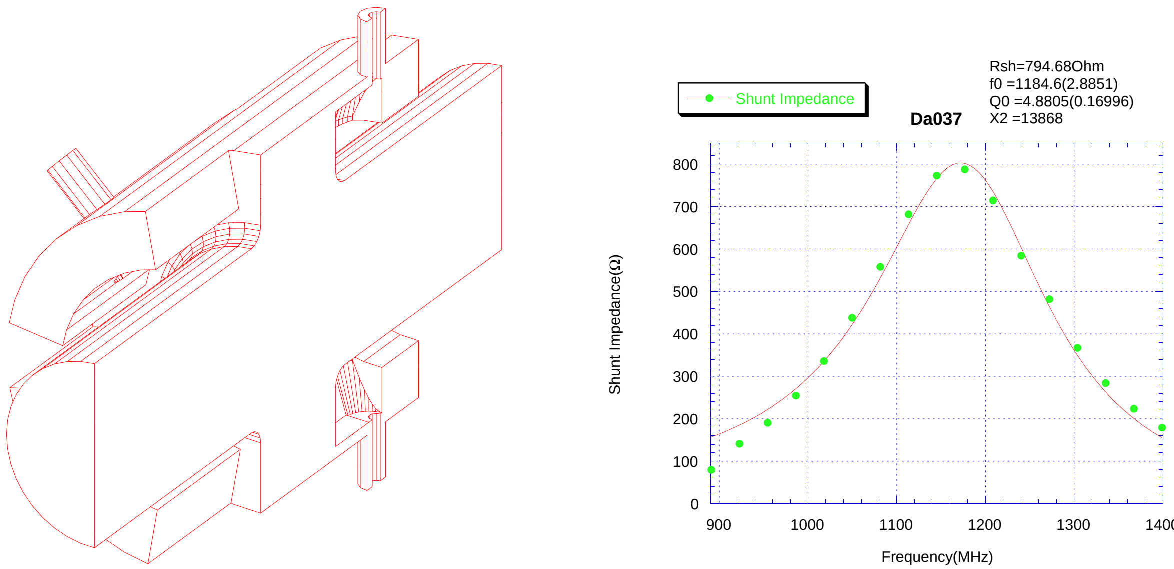

FIGURE 7. HFSS model of the wageguide overloaded cavity as the longitudinal kicker and the calculated shunt impedance. The value includes the transit time factor.

of about 4.8 has been obtained. The calculation using MAFIA shows the longitudinal loss factor of about 0.3 V/pc, and the peak output voltage of about 280 V_{p-0} with the bunch current of 0.5 mA. As we will use the circulators with the power capacity of 6 kW, the operation with the bunch current larger than 2 mA will be dangerous.

The transverse impedance of the cavity has also calculated with MAFIA. The result shows the transverse impedance of about 5 kΩ at the frequency around 1.6 GHz. This value is comparable of residual HOM of the ARES cavity.

We plan to install two kickers only in LER at the commissioning stage. With two 500 W amplifiers, that is 8×125 W amplifiers, we will have the effective damping time of about 10 ms with the bang-band damping scheme for the phase amplitude about 2 °.

VII COMMISSIONING SCHEDULE

Both rings of KEKB will start commissioning on October, 1998. Most of the vacuum components, such as the monitor chambers or the kickers, will be prepared within the fiscal year of 1997. The control system or the software will be left untouched until the next year. As we have terribly limited man power, indeed only two staffs, and the budget of this year is also very limited, we will construct the parts of the systems considering the priority or necessity for the commissioning of the rings. Together with the progress of the operation of the rings and the feedback systems, we will improve the systems to have sufficient performance.

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1) HP High-Frequency Structure Simulator, HP 85180A.
2) MAFIA Manual Version 4.00, CST, Gesellschaft für Computer-Simulationstechnik.

VIII ACKNOWLEDGMENTS

The authors would like to express their sincere appreciation to Prof. T. Kasuga and Dr. T. Obina of KEK-PF for numerous thoughtful discussions. We thank Dr. Y. Funakoshi who made efforts to operate the accelerator smoothly during our experiments. The discussions with the people who are developing the same kind of feedback systems at SLAC and DAΦNE are very fruitful. Especially, we thank Dr. J. D. Fox of SLAC with his sincerely advises to our systems. All the discussion during the workshop were fairly impressive and we want to thank all the participants of the workshop.

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