# DEVELOPMENT OF A HIGHLY EFFICIENT ENERGY KICKER FOR LONGITUDINAL BUNCH-BY-BUNCH FEEDBACK

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## Abstract

Highly efficient new energy kicker has been originally designed and developed at SPring-8 for longitudinal bunch-by-bunch feedback (LBBF). The kicker consists of three cells with each cavity length of 96 mm, its resonant frequency of 1.65 GHz, which is 3.25 times of RF reference frequency of the storage ring, and low Q-factor of 4.2. In beam kick test, the synchrotron oscillation amplitude of 0.64 ps was excited by kick voltage with continuous amplitude modulation at synchrotron frequency when the RF input power was 132 W/3cells. The kick voltage evaluated from the experimental result is 920 V/3cells, and shunt impedance of 1.1 kΩ per each kicker cell is obtained. As we intended, the shunt impedance per length is about three times higher than those of waveguide overloaded cavity (WOC) type kickers [1-3] widely used for LBBF.

## INTRODUCTION

In the SPring-8 storage ring, the hybrid filling composed of a high-current singlet bunch and a bunch train with low bunch current has been applied to user operation. Bunch current of the singlet is 5 mA/bunch in the present operation, but we have a plan to increase the bunch current up to 10 mA/bunch. The LBBF could be useful to suppress the synchrotron oscillation observed with increasing the bunch current. And in a future upgrade plan of SPring-8, if lower electron beam energy is to be adopted for emittance reduction and electric power saving, the LBBF system will be indispensable to have a higher threshold current for longitudinal multi-bunch instability, which leads to increase of the total stored beam current.

Through the performance test using a prototype kicker [4], a new water-cooled copper kicker was fabricated and has been installed in the storage ring after tests of high-frequency characteristics with high power. The new kicker performance is reported with the results of response to a single bunch beam and beam kick test.

## HIGHLY EFFICIENT ENERGY KICKER

The longitudinal energy kicker (see Fig.1) installed in the storage ring is made some improvements in the prototype kicker design. The kicker body which is made of copper with large thermal conductivity and power feed-through ports are water-cooled to remove the heat from electron beams and input RF signals with high power. The vacuum chamber contains three kicker cells.

Figure 2 shows the inner structure of one cell with symmetric structure about the beam axis. Each cavity length is 96 mm and kicker driving frequency is $(3+1/4)f_{RF} = 1.65$ GHz, where $f_{RF}$ is frequency (508.58 MHz) of RF reference signal of the storage ring. The electron bunch is longitudinally kicked by a single resonant mode excited at the driving frequency. The mode is required to have low Q-factor, i.e. fast damping time of several nanoseconds for bunch-by-bunch control of the kick voltage. The Q-factor of 4.2 is obtained by Lorentzian fitting of calculated broad longitudinal wake impedance as shown in Fig.3. The driving power signals are fed to symmetrically attached two ports (I-port) at the same timing. Two pairs of other ports (H-port and V-port) are also attached symmetrically to remove unwanted higher order modes inside kicker cavity.
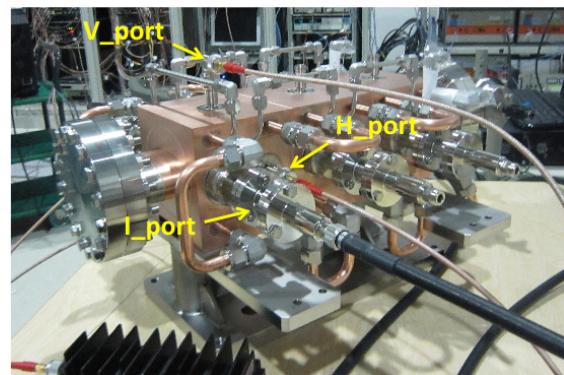


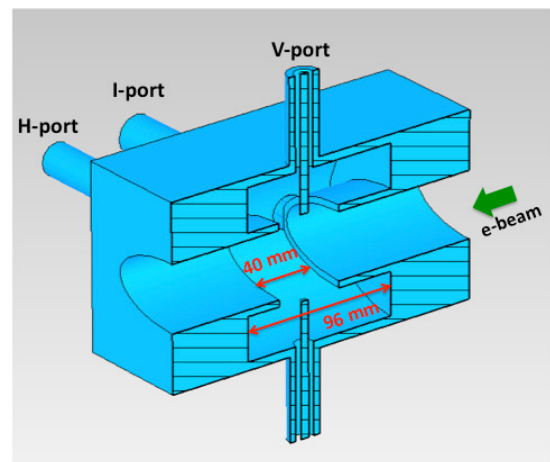Figure 1: Longitudinal energy kicker installed in the SPring-8 storage ring.



Figure 2: Inner structure of a kicker cell. One-half part is shown in figure.
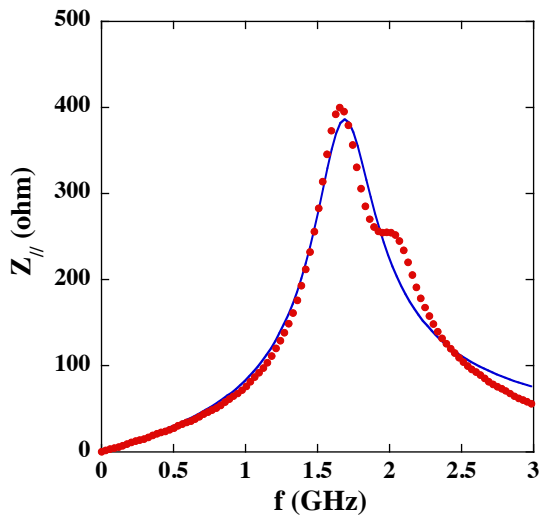
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Figure 3: Calculated longitudinal wake impedance of one kicker cell (red dots). Q-factor of 4.2 is obtained by Lorentzian fitting process (blue line).
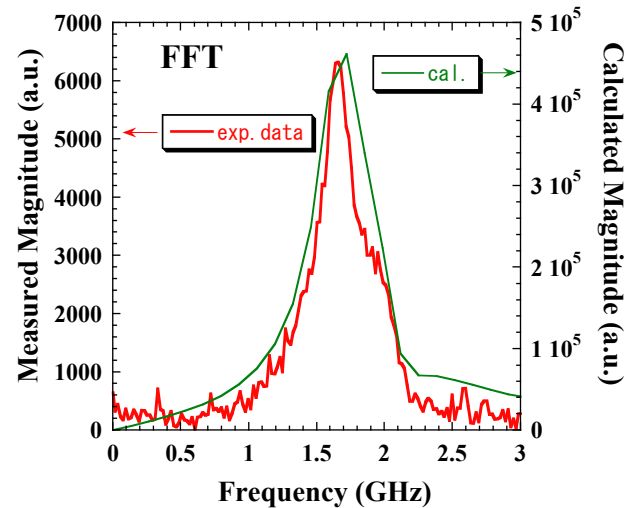


Figure 5: FFT analysis of the beam signal from the I-port shown in Fig. 4. Red and green curves show the measured and calculated data, respectively.

## RESPONSE TO A SINGLE BUNCH BEAM

We checked the beam response characteristics of the installed energy kicker by observing signals from a single bunch beam of 1mA. The signal waveforms observed at each port (I-port, H-port and V-port) have similar shapes to simulation results. Here, the measured I-port signal and its FFT analysis are shown with the simulation results in Fig.4 and Fig.5, respectively. The observed signal has the main frequency component of 1.65 GHz and fast damping time of several nanoseconds. The simulated signal has larger amplitude and higher frequency components than the measured signal. This is because the high frequency components of the observed signal are filtered out by the effect of frequency characteristics of a circulator inserted in the input power line (see Fig.6).
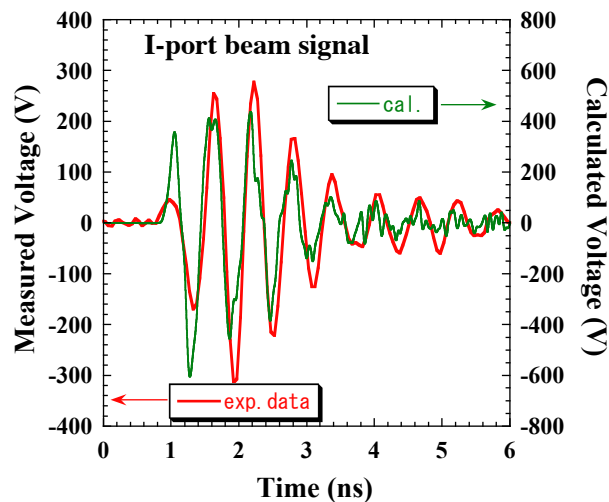


Figure 4: Response to a single bunch beam. The beam signal from the input port. Red and green curves show the measured and calculated data, respectively.

## BEAM KICK TEST AND KICKER PERFORMANCE

### Kicker Drive Circuit

The performance of the longitudinal energy kicker was experimentally evaluated by beam kick test. The kicker drive signal, which is a three-wave pulse of frequency $(3+1/4)f_{RF}$ = 1.65 GHz, is generated by a drive circuit assembled as shown in Fig.6. A rectangular pulse of duration about 200 ps synchronized with the RF reference signal is output from a fast pulse generator (Agilent: 81134A). The pulse is differentiated by an impulse forming network (IFN) to convert to a bipolar pulse. After the IFN, the bipolar pulse is divided into three pulses. Each pulse passes cable delay to make time lag corresponding to one wavelength of 1.65 GHz. The three-wave pulse is generated by combining these pulses after the cable delays. The three-wave pulse is amplified and divided into three sets of two I-ports signals to input into three kicker cells. The phase shifters enable us to tune the input timing of these signals. The circulators are inserted in the input signal line because the most power reflects back to the I-ports.

The kicker drive signal is amplitude-modulated with a function generator by a mixer (see Fig.6) to kick the electron bunch longitudinally using resonance of the synchrotron oscillation. The equilibrium beam amplitude between the oscillation excitation and radiation damping can be controlled by the amplitude and frequency of the sinusoidal modulation signal from the function generator. In the beam kick test, 84 electron bunches were filled with equal spacing, i.e. bunch interval of 57 ns. All bunches were kicked by the driving signals with repetition rate of 17.5 MHz (1/57 ns). The amplitude modulation frequency was $f_{rev}+f_s$, where $f_{rev}$ and $f_s$ are frequencies of the beam revolution and synchrotron oscillation, respectively. The excited temporal oscillation

was measured by a spectrum analyzer using the sum of signals from four electrodes of a button-type beam position monitor (BPM) installed near the kicker. As shown in Fig.7, we can see a sharp peak at frequency $2f_{RF}+f_{rev}+f_s$ when the RF power was fed into the kicker. The kick timing was tuned to maximize this spectrum peak corresponding to the excited synchrotron oscillation. The temporal amplitude can be evaluated from the ratio of the peak value to that of a carrier spectrum at frequency $2f_{RF}$.

## Residual Kicks to Adjacent Electron Bunches

After the tuning of kick timing, to estimate residual kicks to other electron bunches in RF buckets adjacent to the target bunch to be kicked, we measured the synchrotron oscillation excited while shifting the kick timing in steps of 1 bucket (1.966 ns). The residual kicks to the electron bunches of bucket numbers from -3 to +3 are less than one-tenth of the kick to the target bunch in bucket of number 0 (see Fig.8). We think that these residual kicks have little effect on practical performance as the LBBF kicker.
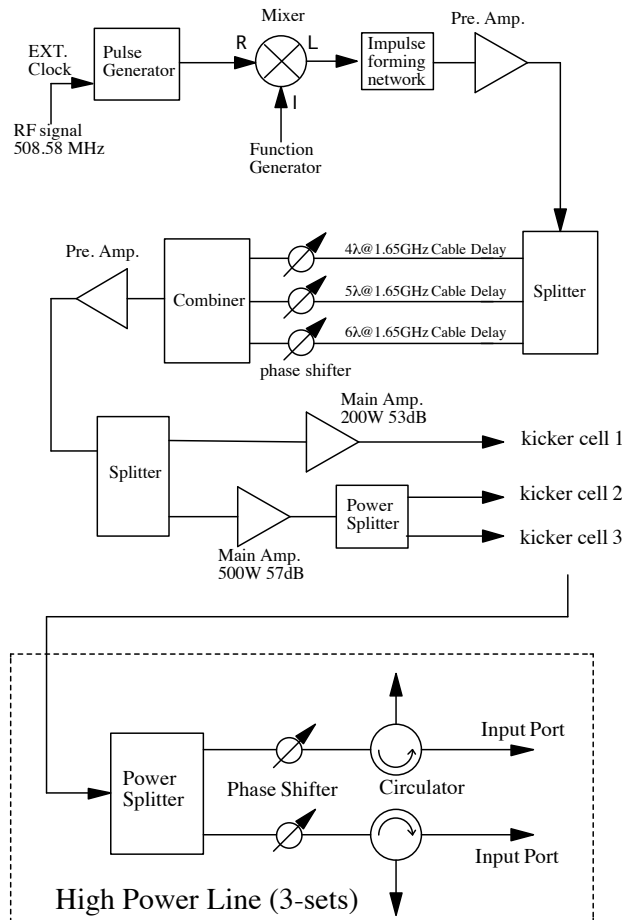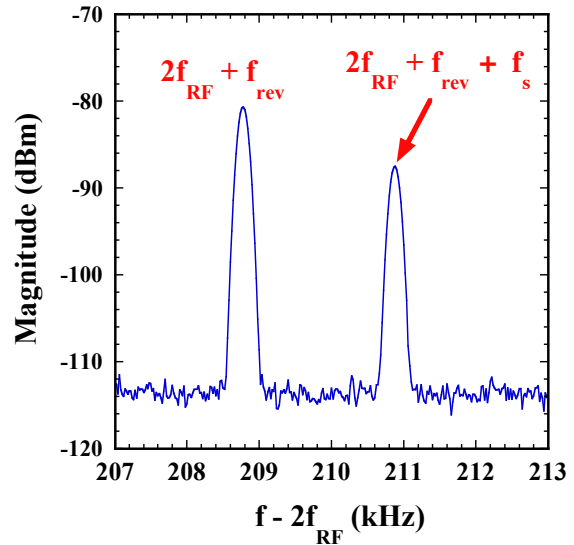


Figure 6: Diagram of kicker driving circuit.



Figure 7: Spectrum of synchrotron oscillation observed at frequency of $2f_{RF}+f_{rev}+f_s$.
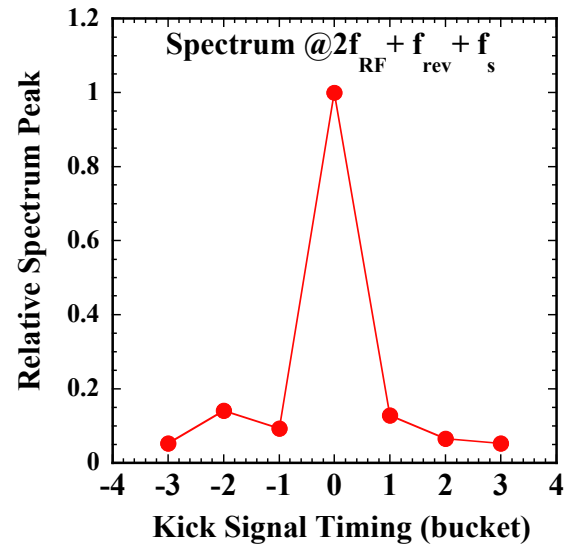


Figure 8: Residual kicks to electron bunches adjacent to the target bunch in bucket 0, measured by shifting the kick timing in steps of 1 bucket (1.966 ns).

## Resonance Curve Measurement

We obtained a resonance curve of the synchrotron oscillation by measuring the excited temporal amplitude as a function of the modulation frequency applied to the kick voltage (see Fig.9). The excitation amplitude $\tau_s$ is related with the modulation frequency $\omega = 2\pi f$ as a following Lorentzian formula,

$$\tau_s = \frac{\dfrac{\alpha_c}{T_0}\dfrac{eV_{kick}}{E_0}}{\sqrt{\left(\omega^2 - \omega_s^2\right)^2 + \dfrac{4}{\tau_d^2}\omega^2}} \quad (1)$$

where parameters $V_{kick}$, $\alpha_c$, $T_0$, $E_0$, $\tau_d$ are the total kick voltage of three kicker cells, momentum compaction factor, beam revolution time, electron beam energy, longitudinal radiation damping time, respectively. And parameter $\omega_s$ is equal to $2\pi f_s$. The kick voltage $V_{kick}$ was 920 V/3cells, evaluated by fitting the equation (1) to the measured resonance curve. The input power $P_w$ per each kicker cell was 44 W/cell, which was obtained from the power signals measured at each I-port (see Fig.10). The shunt impedance $R_s = (V_{kick}/3)^2/P_w/2$ which is a main parameter to describe the efficiency of the longitudinal kicker is 1.1 kΩ per one cell, calculated by using the measured kick voltage and input power. Since the length per cell is shorter than half that of the widely used WOC type [1-3] for this purpose, our kicker has about three times shunt impedance per unit length.
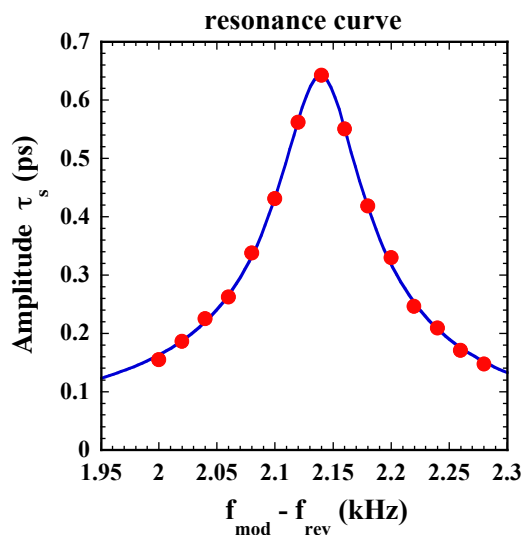


Figure 9: Resonance curve measured by scanning the modulation frequency of the kick voltage. Red dots and blue line show the experimental data and fitted curve by the equation (1), respectively.
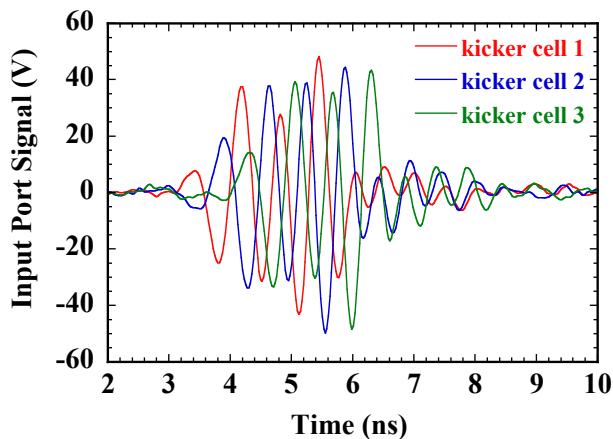


Figure 10: High power signals driving the kickers measured at each input port of the three kicker cells. The peak voltages were about 47 V and the input powers were 44 W per cell.

## SUMMARY

We have developed the highly efficient energy kicker for the longitudinal bunch-by-bunch feedback and installed it in the SPring-8 storage ring. The shunt impedance, just as we designed, was experimentally evaluated by the beam kick test. Our kicker is very useful when installation space is limited and high kick voltage is required in large storage rings of high energy, because of about three times kick efficiency per length compared with the conventional WOC type. We are planning to complete the LBBF system by combining with a signal processing circuit [5] developed at SPring-8 for the bunch-by-bunch feedback.

## REFERENCES

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