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LONGITUDINAL BEAM MANIPULATION BY RF PHASE MODULATION AT THE KARLSRUHE RESEARCH ACCELERATOR

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Abstract

In electron storage rings, it is possible to manipulate the stored beams longitudinally by applying a phase modulation to the accelerating RF voltage. By choosing a proper modulation frequency, the electron bunch can be lengthened and the Touschek beam lifetime can be improved accordingly. To understand the effect of such modulations on the beam from the beam dynamics point of view, we have performed simulations for the beams under the RF phase modulation. The simulations were conducted for the Karlsruhe Research Accelerator (KARA) storage ring. In KARA, we have installed the function of the RF phase modulation into the low level RF system. The experimental results of the phase modulation indicate the agreement with the simulation results.

RF PHASE MODULATION

In the RF phase modulation scheme, the modulation frequency is normally chosen as a harmonic of the synchrotron frequency. For example, the quadrupole oscillation on the longitudinal phase space can be excited if the modulation frequency is settled as the second harmonic of the synchrotron frequency, and the bunch length can be increased because of the quadrupole oscillation mode. Several preceding studies for the phase modulation have been reported so far. Sakanaka *et al*. [1] reported that the RF phase modulation improved the beam lifetime and suppressed the longitudinal coupled bunch instability in KEK Photon Factory. In the reference [1], they also discussed the beam loading effect which can change the effect on the phase modulation on the beam. Abreu *et al*. [2] discussed a theoretical model for the phase modulation and Landau damping effect which is accompanied by the modulation effect. In the reference [2], they also discussed the change in the longitudinal Hamiltonian due to the modulation frequency. By considering the results in these preceding studies, we mainly investigated the dependence of the bunch lengthening on the modulation frequency and the beam loading.

SIMULATION

To consider the effect of the phase modulation on the beam, we have performed simulations based on the macro-particle tracking method. In the simulation, we have assumed the machine parameters of the KARA storage ring at 2.5 GeV. Table 1 shows the machine parameters used in the simulations.

Table 1: Machine Parameters of KARA 2.5 GeV

Parameters	Values	Units
RF frequency	499.72	MHz
Harmonic number	184	
Circumference	110.38	m
RF Voltage	1.4	MV
Synchrotron frequency	30.89	kHz
Number of RF sectors	2	
Number of cavities per 1 sector	2	
Momentum compaction factor	8.67×10^{-3}	
Natural energy spread	9.08×10^{-4}	

To consider the beam loading which occurs inside the RF cavities, we have included the beam-cavity interaction for each cavity. In the simulation, we have used the measured values of the quality factors and the shunt impedances for each cavity, and to include the beam loading effect we have applied a similar method as discussed in [1]. In the calculation of the beam loading, we have treated the transient beam loading effect which depends on the bunch filling pattern. In the following simulation results, we have used the bunch filling pattern which is similar to the normal multibunch operation at KARA; the filling pattern with 3 bunch trains and 4 vacant-gap trains. The beam loading effect depends on the tuning condition of the cavity, therefore we have settled and kept the tuning condition of all cavities under the optimum tuning; that is, the loading angles of all cavities have been always kept at zero. We have prepared 10000 macro-particles for 1 bunch and settled them on the longitudinal phase space with the equilibrium distribution initially. The tracking calculations have taken place for twice the longitudinal damping time period. In the simulation, we have mainly 3 tuning knobs to change the condition of the modulation; the modulation frequency, the modulation amplitude and the beam current. In the following sections, we discuss the simulation results when we changed these parameters.

MODULATION FREQUENCY

We have swept the modulation frequency, which is around the second harmonic of the synchrotron frequency f_s of single particle, and analyzed the dependence of the rms bunch length on the modulation frequency. In the longitudinal phase space the bunch follows the quadrupole oscillation mode due to the $2f_s$ modulation and the bunch length oscillates accordingly. We have estimated the effective rms bunch length by taking the time-average of the bunch length oscil-

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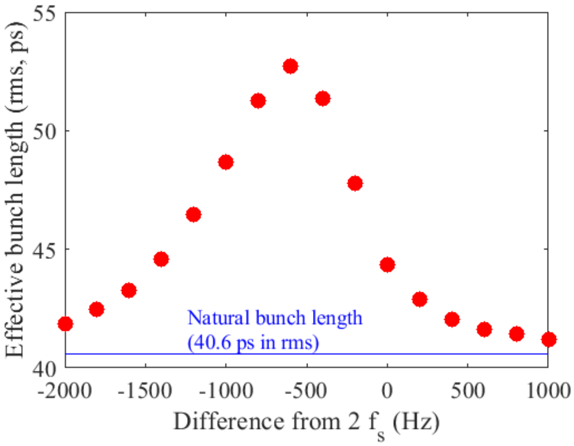

Figure 1: Detuning curve of the effective rms bunch length under the RF phase modulation. A beam current of 150 mA and a modulation amplitude of 50 mrad are assumed. The horizontal blue line corresponds to the natural rms bunch length.

lation. Figure 1 shows the "detuning curve" of the bunch lengthening under the $2 f_s$ RF phase modulation. Here we have assumed a beam current of 150 mA which is a typical operation beam current at KARA and the modulation amplitude of 50 mrad for each RF sector. The phase difference of the modulation at each sector has been adjusted so that the beam has continuous modulation without any phase jump. As seen in Fig.1, the curve has its peak at a negative frequency detuning condition. The negative detuning peak implies that the RF potential well could be deformed effectively due to the phase modulation. Due to the deformation, the effective RF voltage could decrease and the synchrotron frequency also could decrease, accordingly.

MODULATION AMPLITUDE

We have performed the same simulation as for the case shown in Fig. 1 but by changing the modulation amplitude from 50 to 200 mrad. Figure 2 shows the detuning curves for the modulation amplitudes of 50, 100 and 200 mrad. As seen in the figure, the maximum rms bunch length increases when the amplitude becomes larger, and additionally the peak frequency of the detuning curve tends to move to negative direction. This enhancement of the negative detuning could come from the deformation of the RF potential well. Figure 3 shows the time-averaged longitudinal bunch profiles for each condition of the modulation amplitudes. Here we have picked up the bunch profiles at the maximum bunch length conditions in Fig. 2, and taken the time-average for a $25/f_s$ period with 100 sampling points. This figure clearly shows that the bunch length becomes longer when the amplitude is larger. The longitudinal profile keeps the original symmetrical Gaussian at smaller modulation amplitude condition, but it changes to non-Gaussian and asymmetric at larger amplitude conditions.

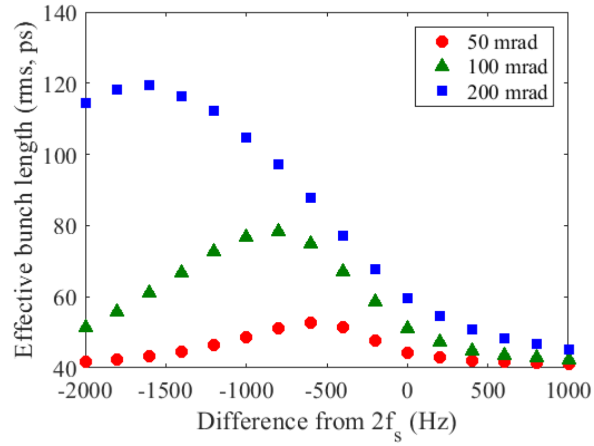

Figure 2: Detuning curves of the effective rms bunch length under the RF phase modulation with different modulation amplitude of 200, 100 and 50 mrad. A beam current of 150 mA is assumed in these simulations.

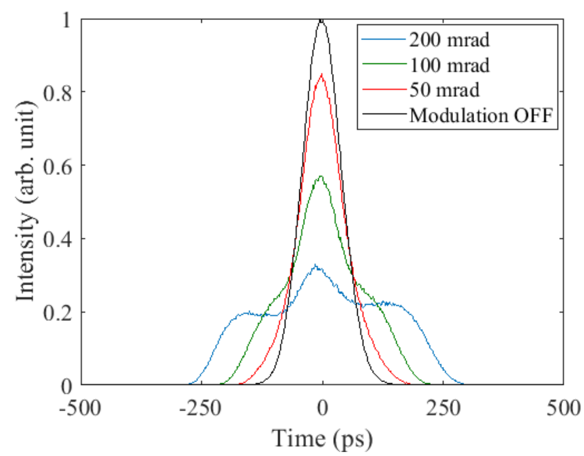

Figure 3: Time-averaged longitudinal bunch profiles for each condition of the modulation amplitudes shown in Fig. 2.

BEAM CURRENT

To discuss the influence of the beam loading on the effect of the phase modulation, we have repeated the same simulations in Fig.1 but varied the beam current. Figure 4 shows the detuning curves for the beam current of 150, 100 and 50 mA while keeping the other parameters fixed. As seen in the figure, the bunch lengthening effect tends to be enhanced at higher beam currents. This tendency implies that the beam loading effect which occurs in the RF cavities could play an important role for the beam dynamics under RF phase modulation.

EXPERIMENTS

In September 2018, we have installed the function of the RF phase modulation into our low-level RF system (LLRF, DIMTEL LLRF9/500). As KARA has 2 RF sectors and each sector has its own low level RF system module, it is possible to perform the RF phase modulation with different setups for

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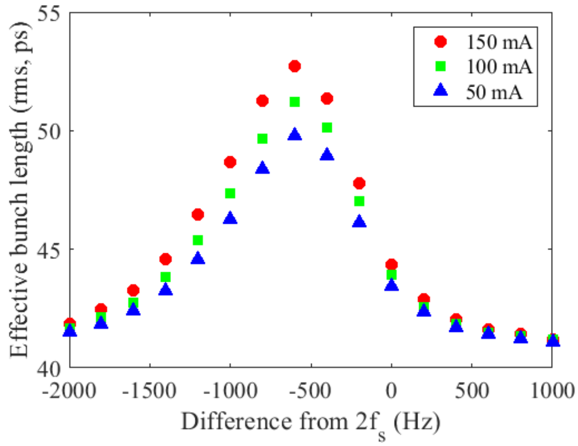

Figure 4: Detuning curves of the effective rms bunch length under the RF phase modulation in different beam current conditions of 150, 100 and 50 mA. The conditions are identical to those in Fig. 1, except for the beam curerent.

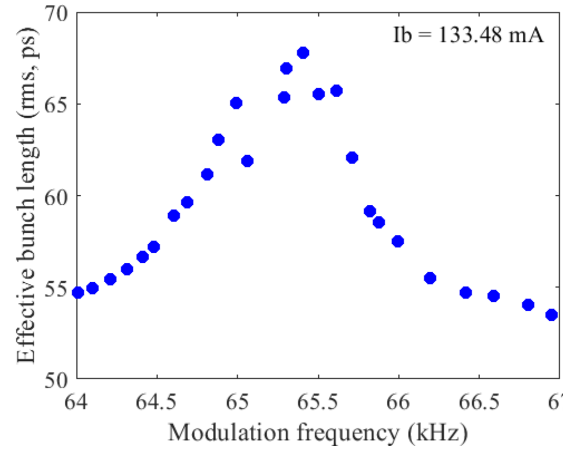

Figure 5: The experimental result of the detuning curve of the effective rms bunch length under the RF phase modulation. The error bars for the measured bunch length are inside the plotted circles. The synchrotron frequency from the bunch length measurement and calculated momentum compaction factor is 30.47 kHz in this experiment.

each RF sector. In the experiment, we have performed the RF phase modulation by using only one RF sector. From the signal of the master oscillator, the LLRF generates the RF signal for the pre-amplifier. The output of the pre-amplifier goes to a 250 kW klystron which drives the two RF cavities in each RF sector. By using the LLRF system, we can settle the phase modulation frequency and amplitude for each RF sector. The pattern of the phase modulation is a continuous sinusoidal wave. When the RF phase modulation is on, the backward power from the cavities tends to increase. Because of the device interlock, the backward power practically limits the maximum modulation amplitude. At the moment we have performed the experiment with fixed modulation amplitude of 3 degree (52 mrad).

The experiments took place with the normal multibunch filling pattern which is similar to that used in the simulations. To measure the bunch length we used a visible light streak camera (Hamamatsu, C5680). By performing the dual sweeping mode, we measured both the bunch length and its change due to the phase modulation. On the streak camera image, it was clearly visible that the longitudinal bunch structure changed because of the phase modulation. To observe the change clearly, we set the time range of the slow sweeping axis (horizontal axis) to 100~200 µs to cover several dozens of synchrotron oscillation periods. From one streak camera image taken by single shot measurement, we analyzed the effective rms bunch length by dividing the image into horizontal segments which have 5 pixel width for each and analysing the bunch length for each segment. After the analysis of the segmentation, we evaluated the bunch length statistically. To get better quality of the statistics, we took 100 single shot data for each experimental condition. Figure 5 shows the detuning curve of the effective rms bunch length under the $2f_s$ phase modulation. As seen in the figure, the width and the shape of the peak of the detuning curve seems to be quite similar to the peak from the simulation. In the experiment, we have also measured the bunch length without the RF phase modulation to get the information about the synchrotron frequency. From the bunch length measurement, the calculated value of the momentum compaction factor and the energy spread, we have estimated a synchrotron frequency of 30.47 kHz for the condition of Fig. 5. This means that the detuning curve from the experiment does have the positive detuning peak from the $2f_s$ frequency. The reason of the discrepancy between the simulation and the experiment is not yet clear. One possibility would be an underestimation of the f_s value. Because the bunch length measurement took place during the RF phase modulation experiment, the beam had a high beam current in a multibunch filling. Such a condition could lead to the bunch lengthening because of the ring impedance, and the lengthened bunch can cause the underestimation of the synchrotron frequency. A precise measurement of the synchrotron frequency, such as a measurement in single bunch mode, would be the next subject to be done.

Outlook

Now we continue to do the experiment to understand the beam dynamics of this modulation scheme in-depth. In parallel, we investigate the practical effects on the beam by the modulation to make use of this scheme for the accelerator operation; improvement of the beam lifetime and suppression of beam instabilities.

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