BUNCH SHAPING BY RF VOLTAGE MODULATION WITH A BAND-LIMITED WHITE SIGNAL - APPLICATION TO THE KEK-PS

T. Toyama, D. Arakawa, S. Igarashi, J. Kishiro, E. Nakamura, H. Someya, K. Takayama
KEK, 1-1 Oho, Tsukuba-shi, Ibaraki, 305-0801, Japan
Y. Shimosaki, Kyushu Univ.
6-4-1 Hakozaki, Fukuoka-shi, Fukuoka, 812-8581, Japan

Abstract

In the 12-GeV synchrotron of the KEK PS, beam losses during the injection flat bottom and at the transition energy were serious and final obstacles to beam intensity upgrade for the long-baseline neutrino-oscillation experiment. To supplement existing schemes to cope with the losses, an additional method was proposed: bunch shaping by modulating acceleration rf voltage with a band-limited white signal. A unique feature of this method is to increase the bunching factor without the longitudinal emittance blow-up, in principle. The temporal evolution of the beam distribution and the time constant was evaluated through computer simulations and analytic considerations. This method has been successfully applied to the KEK-PS. The system of bunch shaping has been working very stably more than a year and keeps the beam intensity more than 7×10^{12} protons per pulse at the top energy.

1 INTRODUCTION

The beam loss during the injection flat bottom resulted from space charge force related phenomena[1] and the other loss at the transition energy (γ_t) resulted from a temporal defect in the current low-level rf feedback system or a microwave instability remain until recently, in spite of all our efforts [2][3]. Because of these losses, we could not reach the intensity goal of 6×10^{12} protons per pulse (ppp) at the beginning stage of the commissioning in 1999.

On the other hand, it has been well known that mitigation of the local beam density is quite effective to avoid any collective instabilities [4][5]. In the Main Ring a method so called "$2f_s$ anti-damping" was used [6], in which the quadrupole oscillation mode in the longitudinal motion is enhanced by feeding the bunch signal onto the accelerating voltage. This method was effective to some extent. However the performance was not very reliable because it resorts to positive feedback. In this context bunch shaping by rf voltage modulation with a band-limited white signal has been proposed [7].

We applied this method to the moving buckets in the 500 MeV fast-cycling synchrotron (Booster) and the 12 GeV synchrotron (Main Ring), and successfully achieved the intensity goal of 6×10^{12} ppp.

In this paper we describe the theory of the method and report the experimental results applied for stationary buckets and moving buckets in the Booster and Main Ring.

2 THEORY

The bunch shaping is performed by rf voltage modulation with a band-limited white signal.

The particles trapped in the rf bucket oscillate with different synchrotron frequencies, because of the rf potential nonlinearity. Suppose that we apply the rf voltage modulation with a band-limited white signal: the frequency band extends from $2\omega_0 - \Delta\omega$ to $2\omega_0$ (ω_0: synchrotron angular frequency of zero synchrotron amplitude and $\Delta\omega$: bandwidth). The particle located within the frequency spectrum, resonates in one of the band of the frequency spectrum and changes its amplitude. Then, the particle changes in synchrotron frequency due to a nonlinear rf potential, resonates at another frequency and continues a random walk in the longitudinal phase space. However, this continues only until reaching the edge of the band of the frequency spectrum. The amplitude cannot increase any further because there is no driving force of the resonance. Consequently, particles diffuse in a bounded region and form a uniform distribution in the longitudinal phase space.

The temporal evolution of the distribution was analytically derived for a stationary bucket by using the diffusion equation in which the lowest order term of J is taken[7]:

$$\frac{\partial\rho(J,t)}{\partial t} = \frac{\partial}{\partial J}\left(\frac{A_2}{2}\frac{\partial\rho(J,t)}{\partial J}\right), \qquad (1)$$

with

$$\begin{aligned} A_2 &\approx \begin{cases} \pi\omega_0^2\Lambda_0 J^2, & if \quad 0 \le J \le J_1, \\ 0, & if \quad J_1 < J, \end{cases} \\ J_1 &\approx 8\pi\Delta\omega, \end{aligned} \qquad (2)$$

where J is the action variable, $\rho(J,t)\Delta J$ is the number of particles found between J and $J+\Delta J$, $A_2/2$ is a diffusion constant which is determined by the modulation dynamics and spectrum, and Λ_0 is the power spectrum density of the amplitude modulation $\xi(t)$. The condition of limited frequency band width is included in the definition of A_2.

The temporal evolution of the distribution $\rho(J,t)$ was derived and then the time constants τ of $\sqrt{<\phi^2>}$ and $\sqrt{<(\Delta p/p)^2>}$ was roughly estimated as

$$\tau \sim \frac{4\Delta\omega}{\pi\omega_0^2\xi_{rms}^2},$$

where $\xi_{\rm rms}$ is the root mean square of $\xi(t)$.

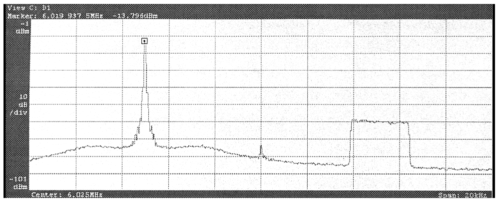

Figure 1: Frequency spectrum of the rf voltage.

The numerical simulation was also performed using 100 equally spaced spectral lines with typical parameters at the Main Ring injection energy and agreed very well with the theory[7].

3 EXPERIMENTS

3.1 Experiments at the injection flat bottom of the Main Ring

Voltage modulation has been easily implemented in the existing rf system. The pseudo band-limited white signal which consists of many spectral lines was generated by the 2 MS/s arbitrary waveform generator (Pragmatic 2711A). The twice of the synchrotron frequency is ~12 kHz and typical frequency bandwidth is 2 - 3 kHz. This signal was fed into the voltage control loop in the low-level rf feedback system, which has a frequency band width of ~30 kHz [6].

The typical frequency spectrum of the rf voltage with modulation was observed as shown in Fig. 1.

The left peak corresponds to the rf frequency, the flat-topped spectrum on the right side is the side-band due to the rf voltage modulation, the band width of which is ~2.7 kHz, and the small peak at the center is just the marker. For the degree of modulation of ~5.1%, a pseudo-uniform distribution was successfully obtained.

The bunch shapes without/with modulation at 48 ms after modulation start are shown in Figs 2 and 3. The density, i.e. the number of particles between J and $J + \Delta J$, are plotted as a function of J in Fig. 4. The improvement of uniformity is obvious. The peak line density can be reduced without emittance blow-up in this method.

The time constant was also measured with various modulation degree and the band width of 1.9 kHz. The envelope of the bunch signal begins to decay just after the modulation initiated. The decay time constant of different modulation degree ξ_{rms} is derived from the data during 50 ms. The result is plotted with the theoretical prediction in Fig. 5, where the time constant for the peak current is assumed to be equal to those of $\sqrt{<\phi^2>}$ and $\sqrt{<(\Delta p/p)^2>}$. They agree well each other where ξ_{rms} is below 5 %. At larger modulation degree, the picture of diffusion and/or the approximation in the theory may not be correct, which may be the reason of the discrepancy between the measurement and the theory.

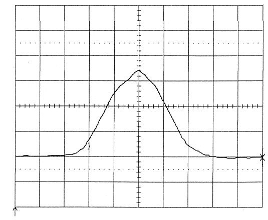

Figure 2: Bunch profiles without rf voltage modulation; abscissa: 20 ns/div.

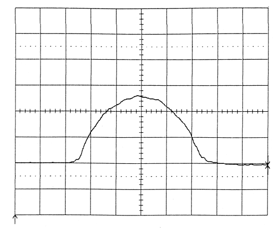

Figure 3: Bunch profiles with rf voltage modulation. $\xi_{rms} \approx 5.1\%$, abscissa: 20 ns/div.

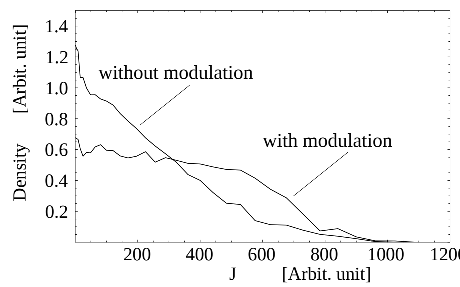

Figure 4: Phase space densities with/without rf voltage modulation.

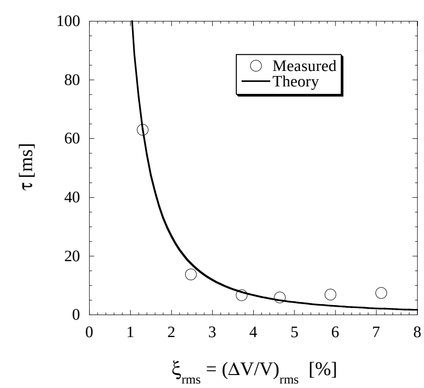

Figure 5: Time constant as a function of the degree of modulation.

3.2 Operation during acceleration in the Booster and the Main Ring

A pseudo-uniform distribution has been also obtained by modulating the moving buckets in both the Booster and the Main Ring. For the moving buckets we have to track the synchrotron frequency. The tracking was realized by frequency-modulating the clock of the arbitrary waveform

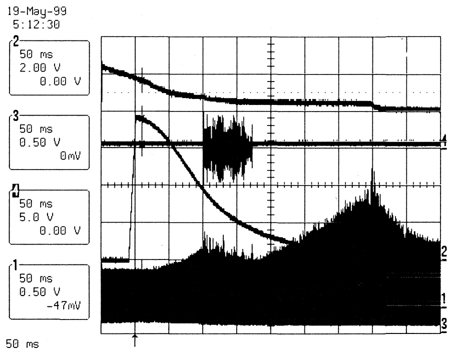

Figure 6: Bunch shaping in the Main Ring. Upper to lower traces; trace 3: beam intensity, trace 4: modulation signal, trace 2: voltage pattern proportional to the synchrotron frequency, trace 1: bunch signal.

generator, which was accomplished by using another pair of arbitrary waveform generators, one was for generating the voltage proportional to $2f_0$ and the other was used as a voltage controlled oscillator. The beam intensity, the modulation signal, the voltage pattern signal proportional to the synchrotron frequency and the bunch signal are shown in Fig. 6.

The timing and the degree of modulation were adjusted so as to minimize the beam loss at γ_t, typically starting 100 ms after the beginning of acceleration, continuing ~80 ms and modulating 5.6%. Figures 7 and 8 show the bunch shapes without/with band-limited white signals that were observed ~15 ms before transition energy. The bunching factor is increased by ~80%.

The same system has been applied to the Booster. It is more difficult to manipulate the bunch because the acceleration period is only 25 ms. The synchrotron frequency changes from ~14 kHz to ~5 kHz. The parameter optimization which includes the start timing, amplitude of modulation shows that applying the modulation at the beginning part of acceleration gives the best result. One of the reason may be that higher synchrotron frequency is preferable for faster diffusion. The beam loss at the injection flat bottom in the Main Ring is reduced ~10 % due to larger bunching factor, although a little beam loss is inevitable during the Booster acceleration cycle.

In consequence an beam intensity increased about 24% comparing with the previous method. More than the intensity goal of 6×10^{12} ppp has been achieved at the Main Ring flat top and kept since May, 1999, although increase in the longitudinal emittance before γ_t was inevitable for stability at the transition energy. In this achievement additional machine tunings, especially fine tuning of the octupole magnetic fields to compromise Landau damping for head-tail instability[8] and dynamic aperture, have been indispensable.

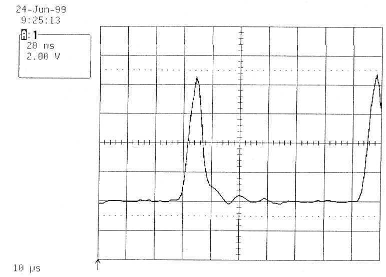

Figure 7: Bunch profiles without rf voltage modulation; abscissa: 20 ns/div.

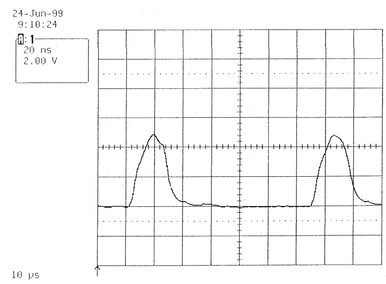

Figure 8: Bunch profiles with rf voltage modulation. $\xi_{rms} \approx 5.6\%$, abscissa: 20 ns/div.

4 CONCLUSION

By applying rf voltage modulation with a band-limited white signal, diffusion occurs in a bounded area of the longitudinal phase space defined by the frequency band width.

Demonstration at the Main Ring flat bottom showed that peak line density can be reduced without emittance blow-up as theoretically expected. The measured time constant also agrees with the theory.

This method has been successfully applied to the moving rf buckets of the KEK PS, which contributes to achieving the intensity goal of 6×10^{12} protons per pulse.

Introducing a 2nd harmonic rf cavity in the Booster is now considered to get much more intensity without beam loss.

5 REFERENCES

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