MEASUREMENT OF LONGITUDINAL DYNAMICS OF INJECTED BEAM IN A STORAGE RING

T. Watanabe*, T. Fujita, M. Masaki, K. Soutome, S. Takano, M. Takao and K. Tamura
JASRI/SPring-8, Hyogo 679-5198, Japan

Abstract

An observation of longitudinal dynamics of injected beams in a storage ring has been demonstrated at the SPring-8. The observation helps make sure no significant injection loss occurs from a viewpoint of the longitudinal acceptance. More importantly, the scheme is expected to enable us to observe non-linear longitudinal dynamics of ultra-short bunches injected from the XFEL linac; the bunches are in the future going to be transferred from the XFEL linac to the storage ring, where strong coherent synchrotron radiation and other high peak current effects will not be ignorable. Experimental results obtained by a dual-scan streak camera as well as numerical simulations are presented.

INTRODUCTION

At SPring-8, a dual-scan streak camera (Hamamatsu Photonics, C5680) has been used for observing stored electron beams in the SPring-8 storage ring [1]. The device has enabled a measurement of equilibrium bunch lengths in normal operations and also in specific modes such as a low momentum compaction factor operation. It has also given information on perturbed bunch distributions affected by an external kicker [2], etc. The time resolution of our streak camera is 2 ps [3]. Faster streak cameras without a function of dual-scan (as far as the author TW knows) are also available from the vendor and others, which have mainly been used for linacs and other advanced accelerators that generate shorter bunch lengths [4, 5].

In the paper, we report the observation of injection beams in a storage ring by making use of the dual-scan streak camera. The measurement gives a projected image of the longitudinal bunch distribution in a time domain. Since the streak camera is able to be synchronized with the revolution frequency of the circulating bunches, one can capture the projected image of the bunches turn by turn. The SPring-8 has improved the injection efficiency from a booster ring to the storage ring by optimizing transverse beam optics, a beam injection timing, etc. The new observation further helps to make sure no unexpected longitudinal beam dynamics has occurred. In fact, the bunch length at the injection point of the storage ring has not been directly measured, thus the measurement will tell us whether there is a disagreement in longitudinal beam optics from the end of the booster ring to the storage ring between the model and the practical lattice. More importantly, it will be necessary to observe electron beams at a transient state at the injection until it reaches an equilibrium state, since ultra-short bunches are planned to be injected from the XFEL linac (SACLA) to the storage ring in the future. Since the SACLA linac generates ultra-short electron bunches with the peak current of ∼kA, the bunch distribution is affected by coherent synchrotron radiation (CSR), and other wakefields when it passes through a 600 m beam transport. The proposed scheme enables such a diagnostic of the non-linear beam dynamics.

SIMULATION

According to the lattice design of the booster ring, the natural bunch length of the booster is 62 ps at rms. By using the value, we have run the tracking code, elegant, developed by Borland and colleagues [6]. The simulation starts at the end of the booster, and the beam is transported through the beam transport between the booster to the storage ring, then is injected to the storage ring. Due to the non-isochronous lattice of the beam transport, the beam slightly gets energy-chirped when it comes out of the beam transport. Then the beam starts synchrotron oscillation in the storage ring. Typical numerical results are shown in Fig. 1, where longitudinal bunch distributions at 1st, 15th, 25th, and 40th turns are compared.

The simulation result is compared with experimental results in the following.

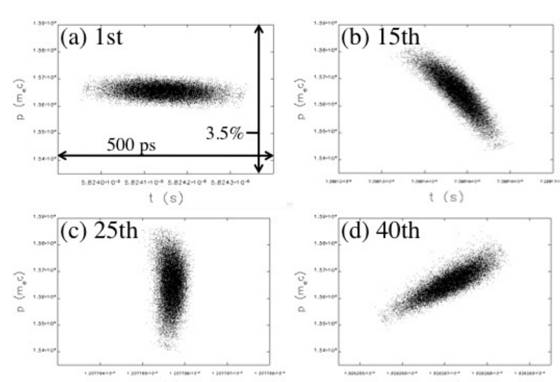

Figure 1: Longitudinal beam distributions at (a) 1st, (b) 15th, (c) 25th, and (d) 40th turns. Horizontal axis is time and vertical axis is momentum deviations. Full scales of each axis correspond to $\Delta t = 500$ ps horizontally and $\Delta E/E = 3.5$ % vertically.

* twatanabe@spring8.or.jp

EXPERIMENT

Setup

The measurement was implemented under the same condition as the normal user operation except for an injection optics (see below in detail). The major parameters of the current SPring-8 are summarized in Table 1. As one can see in the table, there are differences in the bunch length and the energy spread between the injected and stored beams, which is a source of the oscillation of longitudinal phase space distribution observed throughout the report. The revolution time is 4.79 μs, so the streak camera is synchronized to the corresponding frequency.

The streak camera is located at so-called BL-38B2, a beam line for beam diagnostics where synchrotron radiation emitted from a bending magnet is supplied. The synchrotron radiation in an optical regime is sent to the streak camera through band-pass and neutral density filters.

Table 1: Major parameters of SPring-8

Electron energy	8 GeV
Stored current	100 mA
Injection current	0.1 - 0.3 mA
Natural emittance	3.4 nm.rad
Injection emittance	~200 nm.rad
Natural bunch length	13 ps (rms)
Injection bunch length	62 ps (rms)
Natural energy spread	0.00109
Injection energy spread	0.00126
Momentum compaction factor	1.68e-4
Revolution time	4.79 μs
Synchrotron oscillation period	460 μs

The only difference of setup between the normal user operation and that employed for the measurement of the longitudinal dynamics is the injection optics. The SPring-8 is normally operated at the top-up mode with a help of an off-axis injection scheme. Since the interval between the stored beam and injected beam is set to be around 10 mm at a septum, the injected beam has to undergo the betatron oscillation with an initial amplitude of 10 mm in horizontal axis. In order to avoid the oscillation of light intensity detected by the streak camera due to the betatron oscillation at the bending magnet, we changed the injection optics so that the beam is injected on the axis. The two injection setups are compared in Fig. 2. For the on-axis injection, the stored beam experiences the DC bump of 8 mm, and the pulsed bump of 16.5 mm is applied at the injection timing.

The measurement procedure is as follows. First, no beam is stored. Then the beam is injected on the axis, and starts the synchrotron oscillation. Just before the injection, the streak camera starts the measurement to capture turn-by-turn beam distributions at the timing of injection. Note that the difference of the injection setup should not affect the measurement of the longitudinal dynamics.

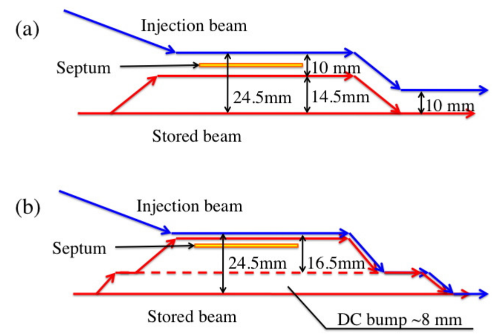

Figure 2: (a) Off- and (b) on-axis injection setups.

Results and Discussion

Figure 3 (a) represents the output image of the streak camera. The horizontal axis corresponds to turn by turn bunches, and the vertical axis indicates longitudinal bunch distributions for each turn. One can see that the injected beam is getting shorter as the beam evolves. By applying Gaussian fitting to each longitudinal distribution, the bunch length at each turn is plotted in Fig. 3 (b). Red dots are experimental data, while black solid line is that obtained by the elegant simulation. The two results reasonably agree with each other from the first to 16th turn, although there is slightly a difference between the two; (i) simulation result is constantly a bit longer than the experimental result. (ii) The bunch duration in the simulation constantly becomes shorter turn by turn as expected by theory, while in the experimental result there are several turns that are longer than the previous ones, such as 5th and 8th turns. Followings are further discussion on the two disagreements.

(i) It is known that the streak camera can conclude longer bunch duration than it really is [4, 5]. One of the reasons is that the optical light has wide spectrum that can lengthen the light pulse in dispersive media like a lens. Our optics is also composed of lenses. Therefore, we have inserted

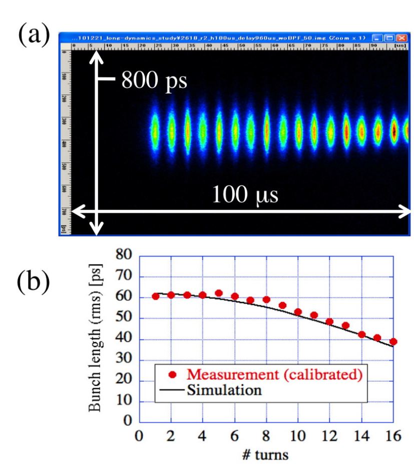

Figure 3: (a) Streak image and (b) bunch distributions turn by turn.

band-pass filters of which band width is 10 nm to see if we can suppress the chromatic effect. According to the result in Fig. 4, we may attribute the discrepancies of the bunch durations between the experiment and the simulation to the chromatic effect. However, since the band-pass filters deteriorates the signal-to-noise ratio, especially when the bunch length is long, we decided not to user the band-pass filter. The chromatic effect can be numerically calibrated after the measurement.

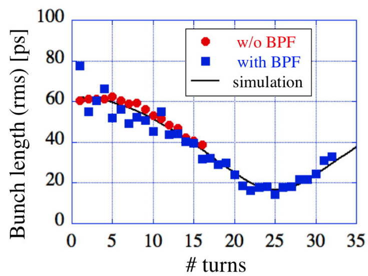

Figure 4: Bunch distributions measured (blue) with and (red) without band-pass filters. Solid curve is the simulation result.

(ii) In order to figure out the source of the fluctuation of the measured bunch duration, the light intensity distribution of the streak image in Fig. 3 (a) is plotted in Fig. 5. It turns out that the turn-by-turn intensity is not constant, although the flux of synchrotron radiation should be constant every turn. In fact, the integrated intensity for each turn in Fig. 3 is reasonably constant. As seen in Fig. 3 (a), the shots with higher intensity has narrower horizontal width in the image. Since the horizontal width in the image corresponds to a horizontal e-beam size in the bending magnet, it turns out that when the horizontal e-beam size somehow becomes smaller, the size of the light pulse at the streak camera becomes smaller, which enhances the space charge effect in a streak tube. Such a fluctuation of e-beam size does not exist after the beam gets damped, which is consistent with the fact that the streak camera measurement of stored beams does not show such a fluctuation. Therefore, we attribute it to the mismatch of betatron function between injection beam and the storage ring. Further study is necessary, though.

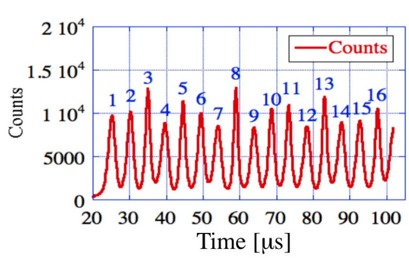

Figure 5: Intensity distribution of Fig.3 (a). The numbers are that of turns.

Next, we have changed the time scale of the streak camera (horizontal axis in Fig. 3) from 100 μs to 1 ms to observe the synchrotron oscillation in a longer period. The result is presented in Fig. 6. Since the horizontal time scale is quite long compared with the revolution time, 4.79 μs, bunches at each turn are no more separated with each other in Fig. 6 (a). In Fig. 6 (a), the image is waving in a vertical axis, which follows that the center of mass of the electron bunch oscillates in time. In order to look it more carefully, the vertical peak position of the waving is plotted by red dots in Fig. 6 (b). The solid curve is fitted under assumption that the waving forms a sinusoidal function. The period of the fitted sinusoidal function is estimated to be 0.462 ms, which is consistent with the nominal value shown in Table 1. The amplitude of the sinusoidal curve is estimated to be 14 ps, which indicates that the injection timing is off by 14 ps. Prior to the measurement, we intentionally did not optimize the injection timing.

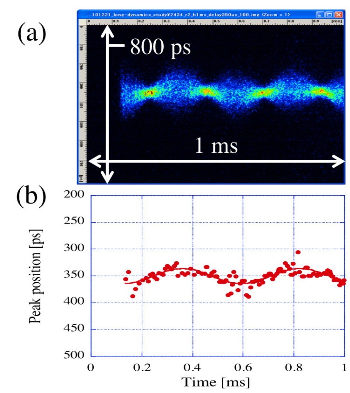

Figure 6: Oscillation of center of mass.

SUMMARY

The longitudinal dynamics of injected beam in the SPring-8 storage ring was observed by using a dual-scan streak camera. The result agrees well with tracking simulations except for a couple of details. For more precise measurement, the effect of betatron oscillation on the measurement needs to be figured out. It is expected that the scheme enables future diagnostics of the ultra-short bunch injections. The oscillation of center of mass was also observed, and was consistent with the independent measurement. The turn-by-turn measurement of the energy spread has also been prepared and will be tested.

REFERENCES

[1] S. Takano, et al., Proc. of SRI2009, 1234 (2010) 399.
[2] C. Mitsuda, et al., Proc. of SRI2009, 1234 (2010) 197.
[3] `http://jp.hamamatsu.com/en/index.html`
[4] M. Uesaka et al., PRE 50 (1994) 3068.
[5] T. Watanabe et al., NIM A 480 (2002) 315.
[6] M. Borland, APS LS-287, Sept. 2000.