BUNCH BY BUNCH ENERGY PROFILE MONITOR OF LINAC BEAM USING STREAK CAMERA AT THE STORAGE RING

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Abstract

We developed a new method to measure the energy profile of a linear accelerator beam using a streak camera in a storage ring. We observed a change in the timing profiles of the injected beam, which synchrotron oscillates in a storage ring. From these profiles, we reconstructed a high-resolution energy profile. We also successfully separated the profiles from different linear accelerator bunches, which enabled a bunch-by-bunch energy profile measurement.

1 INTRODUCTION

Typically, an energy spread of a linear accelerator beam is obtained by following ways.

(1) Measuring a profile using screen monitors in a dispersion section of a beam transport line.
(2) Observation of OTR (Optical Transition Radiation) light using a fast gated CCD camera[1].
(3) Using multi-strip-line beam energy monitor[2].

Method (1) is easy, but has poor time resolution and the contribution from the η function must be corrected. Methods (2) and (3) have sufficient time resolution to separate linac bunches. However, these methods do not provide information on the structure of the energy distribution. One good method is to measure a time profile after magnetic chicanes which rotate the phase space by almost 90 degrees[3]. Our idea is to use a storage ring as a phase rotator.

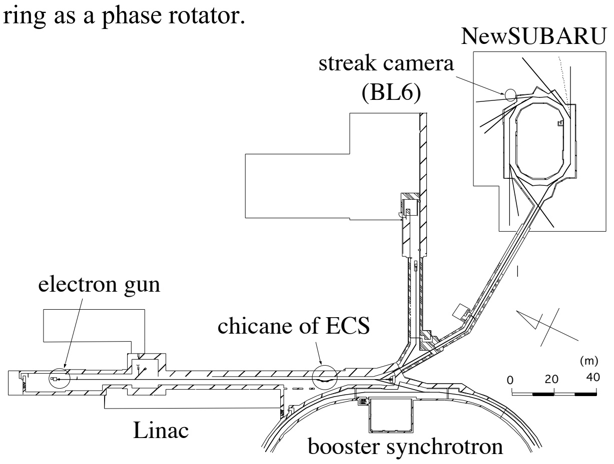

Figure 1: SPring-8 Linac , SY and NewSUBARU

In this paper, we demonstrate our new method by measuring the energy profile of SPring-8 linear accelerator (Linac) using a streak camera in the storage ring, NewSUBARU[4]. We obtained energy profiles of each micro bunch in the Linac's macro pulse. The streak camera has sufficient time resolution to observe bunch-by -bunch profiles of Linac. Since we only observe the energy oscillation of the beam, we don't have to consider the contribution of η function. Furthermore, using the streak camera in the storage ring, we can get a sufficient intensity to measure a detailed energy profile of the Linac beam.

2 EXPERIMENTAL SET-UP

Tables I and II list the main parameters for each of Linac and NewSUBARU. Fig. 1 shows the layout of the SPring-8 Linac, 8 GeV booster synchrotron (SY) and NewSUBARU. Linac supplies a 1 GeV electron beam to SY and NewSUBARU. The macro pulse width of Linac is determined by the pulse width of the grid-cathode voltage of the electron gun. We chose 1 ns for a double top-up mode. In order to stabilize the beam energy and reduce the energy spread, Linac has an energy compression system (ECS)[5]. We have previously used the streak camera (C6860 SYNCHRO FESCA, Hamamatsu Photonics) to monitor the Linac beam. The camera was set up in one of bending magnet beam lines (BL6) of NewSUBARU and operated in the double-sweep mode. The fast-sweep frequency is 83.3 MHz, 1/6 of the RF clock signal. The injection timing signal, with a variable delay, is used as a slow-sweep trigger. Fig. 2 shows the layout of the optical equipment from the light source point to the camera.

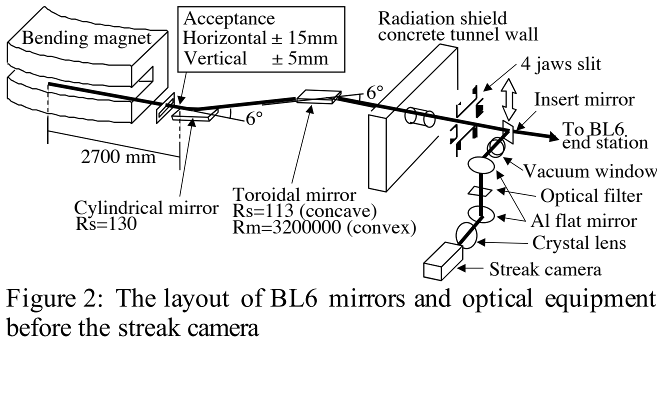

Figure 2: The layout of BL6 mirrors and optical equipment before the streak camera

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Table Ⅰ: Main parameters of SPring-8 Linac

Parameters	Without ECS	With ECS
RF frequency	2856 MHz	
Emittance	50π nmrad	
Macro bunch length	1 ns (0.25 ns, 40 ns is possible)	
Micro bunch length (FWHM)	10 ps	20 ps
Energy spread (full width)	1.0 %	0.6 %
Energy stability (rms)	0.06 %	0.01 %

TableⅡ: Main parameters of NewSUBARU

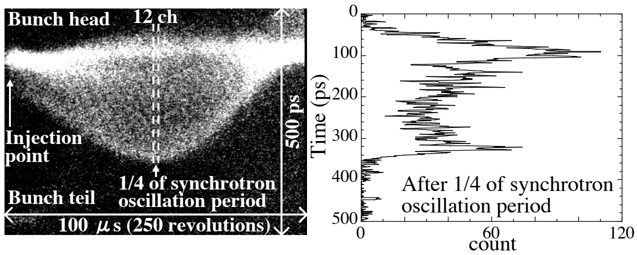
Parameters	Value (at 1.0GeV)
RF frequency	499.955 MHz
Synchrotron oscillation freq.	6 kHz at V_{RF} = 130kV
	10 kHz at V_{RF} = 400kV
Synchrotron oscillation Damping time	12 ms
Harmonic number	198
Momentum compaction factor	0.0013

3 MEASUREMENT

3.1 Measurement of single bunch beam

We selected the 0.25 ns macro pulse width since it only has one bunch. Fig. 3 (a) is the streak camera image and (b) is the intensity profile at the timing of 1/4 synchrotron oscillation period after the injection. The timing width of the intensity profile, which has a horizontal slice width in Fig. 3 (a), is about 1.9 ms (12 channel, 5 revolutions). The fluctuation of the injection time is very small with the synchronization circuit, but the fluctuation does not influence the energy profile measurements. The camera observed synchrotron light for 100 ms along the slow-sweep axis, which is equal to a half of the synchrotron oscillation period. The full scale of the fast-sweep axis is selected to 500 ps, which is 1/4 of RF period.

Herein, we refer to the slow-seep time of 1/4 synchrotron oscillation period after the injection as 'the 1/4 point'. At this time, the energy profile of the beam at the injection point converts to a fast-sweep timing profile, which the streak camera can measure. The synchrotron oscillation damping time is about 12 ms, which is much longer than the oscillation period. The contribution of the transverse emittance to the timing spread is about 0.6 ps[6], which is negligible. In this experiment, we used multi-shot images to improve clarity, but the profile from a single shot can also produce an image. When we convert the timing profile (Fig. 3 (b)) to an energy profile, we corrected for the effect of non-linearity in the RF bucket. Fig. 4 is a model of a non-linear RF bucket used for the correction and Fig. 5 shows the energy profile. The effect of the correction was very small. Hence, a simple, re-scaled profile from the timing to the energy displacement is sufficient. The energy resolution, which is a conversion from time resolution of the streak camera, is about 0.08 %. The energy spread (full width) of the measured beam is 0.92% and the center energy is 0.32 %



(a) (b)

Figure 3: (a) is a steak camera image of the synchrotron oscillation of the injected beam in the storage ring. (b) is an intensity profile of the slice. The images are accumulations of 50 injection images and we set V_{RF} = 130kV.

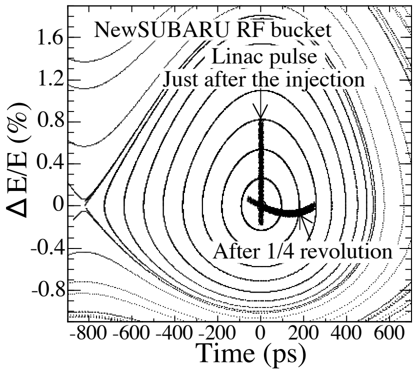


Figure 4: Non-linear RF bucket of NewSUBARU at V_{RF} = 130 kV and the ring energy of 1 GeV. The bucket is calculated from the measurement results of f_s at various energy displacements[7]. We simulated the movement of the injected beam with a 20 ps bunch length, 1.0 % energy spread (full width), and 0.32 % center energy displacement.

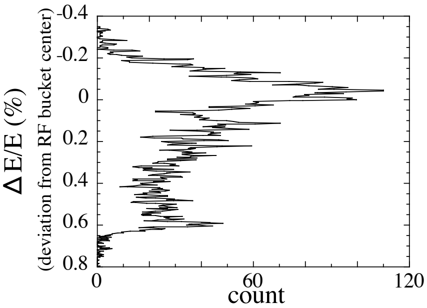


Figure 5: The energy profile of the Linac beam with the correction of non-linearity of the RF bucket.

3.2 Measurement multi-bunch beam

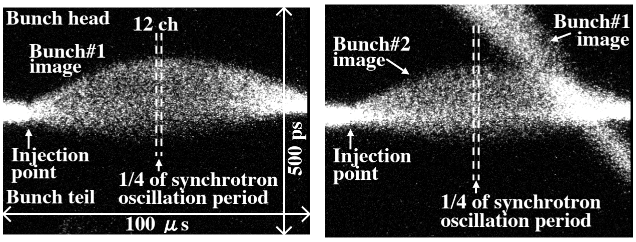
We selected a macro pulse width of 1 ns. The pulse contains two or three bunches since the actual width is shorter than 1.0 ns. In our measurements, one macro pulse contains two micro bunches. We selected the target bunch by changing the injection phase of the storage ring RF. The bunch injected at the synchronous phase is the one that was measured.

When the macro pulse contains some micro bunches, synchrotron oscillation images of different micro bunches overlap at the 1/4 point. To solve this problem, we set the V_{RF} as high as possible. The higher V_{RF} gives a larger energy displacement for the off-timing injected bunches at the 1/4 point. It is effective to separate the different bunches through the following processes.

(1) The larger energy displacement enlarges the radial displacement of the beam center of the off-timing injected bunches at the 1/4 point. The displacement is caused by dispersing the light source point. We can stop the light from the off-timing injected bunches by setting appropriately the 4 jaws slit at the beam line.

(2) The larger energy displacement enlarges the non-linear shift of the synchrotron oscillation period. It shifts the timing of overlap from the 1/4 point.

Fig. 6 shows the streak camera images of different micro bunches. Process (1) is effective for bunches injected later than the target (Fig.6 (a) bunch#2) and process (2) are effective for bunches injected earlier than the target bunch (Fig. 6 (b) bunch#1). The higher V_{RF} reduces the bunch length at the 1/4 point, which makes it easier to separate the bunches. However, changing the fast-sweep range of the camera kept the energy resolution at the same level. The effect of the non-linearity increased, but remained small.



(a) (b)

Figure 6: Obtained synchrotron oscillation image for each Linac micro bunch. The images are accumulations of 80 injection images and we set V_{RF} =400kV. (a) is when the front bunch (bunch#1) is the target bunch and is injected at the synchronous phase of the ring RF. (b) is when the rear bunch (bunch#2) is the target bunch.

3.3 Example application – Effect of ECS

We measured the energy profiles with different ECS parameters. The compression force was changed by the RF power and the center energy remained roughly the same by adjusting the RF phase. Fig. 7 shows the energy profiles of the front (bunch #1) and the rear (bunch #2) bunches. Differences between the profiles of the two bunches are observed. Table Ⅲ lists the full energy spreads and energy centers (middle of the highest and the lowest energy) obtained from the profiles. The energy spread measured by a screen monitor is listed in the same table. The results are roughly consistent with those from a screen monitor. The results demonstrate that the optimum RF power is higher for a longer macro pulse width. The RF power in daily operation is 6.5 MV/m since the power is optimized before beginning the double top-up operation for the 40 ns macro pulse[5].

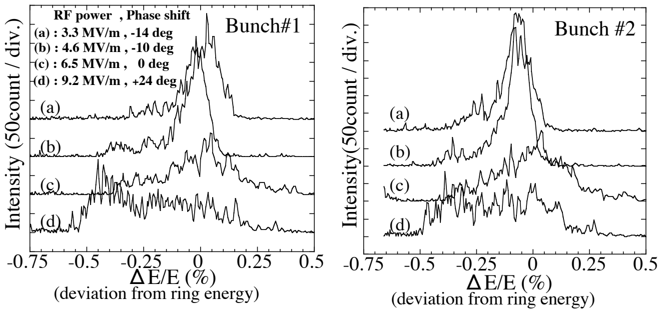


Figure 7: The energy profiles of the front bunch and the rear bunch with various ECS parameters.

4 SUMMARY AND DISCUSSION

We have demonstrated that our method using a streak camera in the storage ring provides a high resolution, bunch-by-bunch energy profile for a linear accelerator beam and the betatron oscillation with the β function does not need to be corrected. We could correct the non-linear effect of the RF bucket, but the effect of it is very small and not always necessary. The measurements are highly sensitive to the structure of the energy profile for each bunch. This method can be used in any electron synchrotron, which has a streak camera and uses a linear accelerator as an injector.

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Table Ⅲ: The results of the measurements of the Linac beam by the present method and by the screen monitor.

ECS parameter RF power / Phase shift	Bunch number	Center energy (%) (from ring energy)	Energy spread (%) (full width)	Energy spread (%) (screen monitor)
9.2 MV/m / +24 deg	1	-0.13	0.83	0.87
	2	-0.12	0.70	
6.5 MV/m / 0 deg.	1	0.01	0.70	0.82
	2	0.03	0.71	
4.6 MV/m / -10 deg.	1	-0.16	0.42	0.56
	2	-0.18	0.41	
3.3 MV/m / -14 deg.	1	-0.09	0.37	0.45
	2	-0.14	0.34	