# CIRCULATION OF A SHORT, INTENSE ELECTRON BUNCH IN THE NEWSUBARU STORAGE RING

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*Abstract*

We have demonstrated the idea of circulating a short, intense linac bunch for some tens of turns in an isochronous ring. We compressed a bunch from the SPring-8 linac to a few picoseconds rms by means of an energy compression system and a beam transport line from the linac to NewSUBARU. The NewSUBARU storage ring was set to a quasi-isochronous condition and the bunch circulated for some tens of turns after injection while maintaining the short bunch length.

## INTRODUCTION

The production of short bunches is an important technique, since bunches on a millimeter scale are necessary for time-resolved experiments and for stable production of coherent synchrotron radiation (CSR). Some methods have been proposed for producing a short electron bunch in a storage ring, and two of them are in operation for synchrotron radiation users. One is the laser-slicing method [1], where a high-power femto-second laser slices out part of the stored electron bunch. The length of the sliced bunch can be as short as 100 fs. The other is the quasi-isochronous (QI) operation of a storage ring [2]. The ring stores electron bunches as short as a few pico-seconds in a stationary state. These two methods produce more stable radiation than that produced by a linear accelerator (linac). However, the beam charge in a short bunch is much smaller than in a bunch produced by a linac.

This paper reports a demonstration of another method, which is based on a combination of a linac and a storage ring. A short, high-current bunch is produced with a linac and a bunch compression system. The short bunch is injected into an isochronous ring, in which the time structure of the bunch is almost frozen, and circulates for many turns. The bunch length becomes longer even in an ideal isochronous ring because of the longitudinal radiation excitation, but this takes many turns [3]. This method has several merits: (1) a bunch with higher charge is possible in a storage ring than with the existing two methods; (2) one short bunch produced by the linac is reused at every turn of the ring that it makes; (3) the repetition rate of the radiation pulse can be very stable in an isochronous ring; (4) pulsed light is obtained in every beam line of the storage ring; (5) a few pico-seconds long pulse is possible with no special expense; and (6) future improvements of the linac beam quality would give better performance of this method.

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The aims of this report are (a) to demonstrate the method, (b) to investigate the problems associated with it, and (c) to clarify the limitations of the present hardware, the SPring-8 linac, and the NewSUBARU storage ring. The results of our experiment provide suggestions for future light source projects with an energy recovery linac and a more sophisticated short-bunch circulator [4].

## EXPERIMENTS AND MEASUREMENTS

### *Bunch Compression of Linac Beam*

Figure 1 shows the layout of the SPring-8 linac [5], the energy compression system (ECS) [6], the booster synchrotron, and the NewSUBARU storage ring [7]. Tables 1 and 2 show the main parameters of the linac and the NewSUBARU ring. In normal operation, the typical bunch length of the linac bunch was about 20 ps (full width), and the energy spread was 0.7% (full width) [5] at 1 GeV. However, in the experiment described here, the chicane of the ECS was bypassed and the acceleration cavities of the ECS were used to compress the bunch as it passed through the transport line to the NewSUBARU ring. Figure 2 shows the time profile and the energy distribution of the compressed linac bunch, measured by a streak camera in beamline 6 (BL6) of the NewSUBARU ring using the bunch rotation technique [8]. Stronger compression was in principle possible but the transport line would not accept the larger energy spread of such a compressed bunch. The observed energy spread was smaller than expected, probably because of optimization of the parameters of the bunching section. The time profile was fitted to a Gaussian distribution for the subsequent analysis, although the fitting was not good.

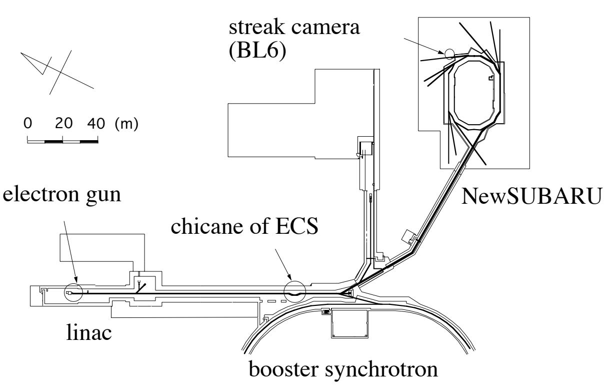


Figure 1: Layout of the SPring-8 linear accelerator, the energy compression system (ECS), the booster synchrotron, and the NewSUBARU storage ring. The streak camera is placed in beamline 6 (BL6) of NewSUBARU.

Table 1: Main parameters of the linac with the ECS.

| | |
|---|---|
| RF frequency | 2856 MHz |
| Transverse emittance at 1GeV | 71 πnm |
| Micro bunch length (FWHM) | 20 ps |
| Energy spread (full width) | 0.6 % |
| Micro bunch charge | 0.03-0.3 nC |

Table 2: Main parameters of NewSUBARU at 1 GeV.

| | |
|---|---|
| RF frequency | 500 MHz |
| Harmonic number | 198 |
| Linear momentum compaction factor | 0.0013 |
| Natural energy spread ($\sigma$) | 0.047 % |

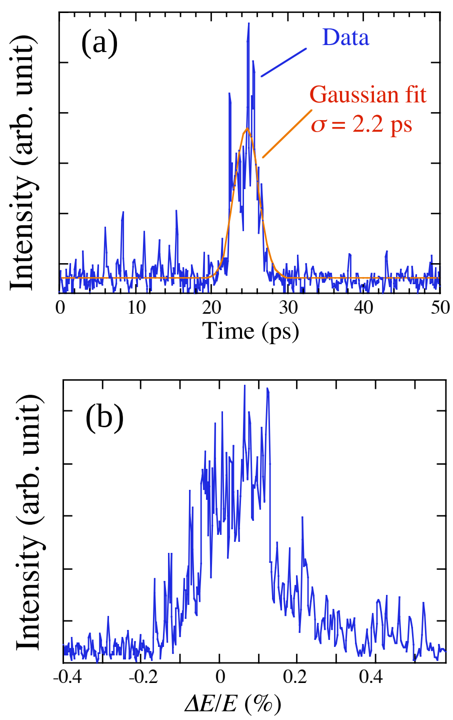


Figure 2: Time profile (a) and energy distribution (b) of the compressed linac bunch measured at BL6.

## Bunch Length Measurement

The NewSUBARU ring has six modified double bend achromat (DBA) cells with an 8° inverted bending magnet between two 34° normal bending magnets. These special cells facilitate control of the linear momentum compaction factor $\alpha_1$ while maintaining the achromatic condition. The $n$th momentum compaction factor, $\alpha_n$, is defined by

$$\Delta L / L_0 = \alpha_1 \delta + \alpha_2 \delta^2 + \alpha_3 \delta^3 + \ldots . \tag{1}$$

Here $L_0$ is the circumference, $\Delta L$ is the change of the path length for one revolution, respectively, and $\delta$ is the relative energy displacement. At the NewSUBARU ring, $\alpha_1$ and $\alpha_2$ are adjustable but $\alpha_3$ is not ($\alpha_3 \approx 0.5$).

Figure 3 shows the bunch length in the ring after injection for different values of $\alpha_1$. A small negative value of $\alpha_1$ is better for maintaining a short bunch because it reduces the spread caused by $\alpha_3$. Figure 4 shows the evolution of the time profile in a quasi-isochronous ring for the best condition ($\alpha_1 = -6 \times 10^{-5}$). The injected beam charge was 24 pC/bunch in this case. The bunch length ($\sigma$ of the fitted Gaussian) was still less than 3 ps after 50 turns (20 ps).

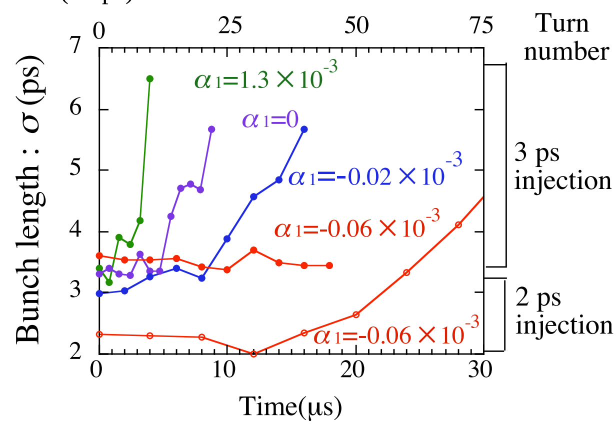


Figure 3: The elongation of the bunch length after injection for different values of $\alpha_1$. The initial length was not the shortest, because the buncher phase of the linac was not optimized at that time.

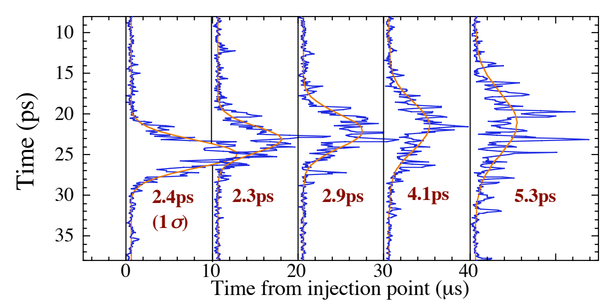


Figure 4: Evolution of the time profile of the bunch after injection, for $\alpha_1 = -6\times10^{-5}$.

## CSR Power Measurement

The radiation power $P_{tot}(\omega)$ from a short bunched beam containing $N$ electrons is given by [9, 10]

$$P_{tot}(\omega) = p(\omega)[N + (N^2 - N)|f(\omega)|^2], \tag{2}$$

where $p(\omega)$ is the power at a frequency $\omega$ radiated from one electron, and $f(\omega)$ is the form factor calculated from the azimuthal charge distribution $\rho(z)$ using

$$f(\omega) = \int \rho(z) \exp(i\omega z / c) dz . \tag{3}$$

The relative CSR power was measured by a Schottky diode detector, which was sensitive to radiation in the frequency range 90–140 GHz. The turn-by-turn change of the CSR power is shown in Fig. 5. The reduction of the CSR power was due to a reduction of $f(\omega)$. In the frequency range of the detector, $f$ is sensitive to small changes in the length and shape of the bunch; the shape may be angular or a smooth Gaussian shape.

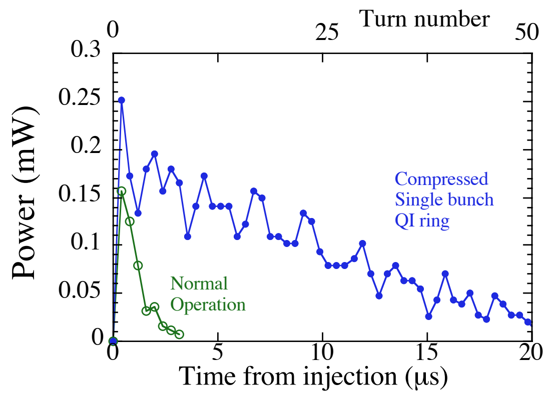


Figure 5: The turn-by-turn CSR power after injection. The line with open circles shows the power obtained with the parameters of normal operation, where there were three bunches in a pulse. The line with filled circles shows the power obtained from one compressed bunch in a QI ring. The bunch charge was about 20 pC/bunch in both cases.

## DISCUSSIONS

We have demonstrated that the NewSUBARU ring could keep a bunch as short as 3 ps and with a charge of about 20 nC for 50 turns. Here we mention some additional results and problems encountered in the experiments:

(1) Adjustment of the higher-order $\alpha$'s was essential for keeping a short bunch in the storage ring. With a small value of $\alpha_2$, we observed a considerable increase in the bunch length. Fig.6 shows the double-sweep streak camera image after the injection with $\alpha_2$ =-0.005. The measured $\alpha_4$ was about –20, then the optimum $\alpha_2$ was less than 0.002.

(2) The optimized value of $\alpha_1$ was not reasonable for the energy spread shown in Fig. 2(b). One possible explanation was the setting error of $\alpha_2$. The optimum sextupole configuration depends on $\alpha_1$ but it was not optimized at each $\alpha_1$. The small elongation in Fig. 4 could be produced by an error in $\alpha_2$.

(3) We observed a coherent timing oscillation, probably produced by betatron motion [11]. This oscillation was reduced by adjusting the injection orbit. On the other hand it is impossible to avoid the elongation by an finite horizontal emittance. The estimated elongation was 0.6 ps rms at BL6.

(4) The RF of the linac is not a multiple of that of the storage ring. Then a special synchronization system is used to make an rf synchronization between the linac and the ring [12]. It produced a timing jitter of 2 ps.

(5) The shot-by-shot fluctuation of the shape and charge of the injected bunch was also considerable.

(6) The CSR power from a short bunch comparable in length to the wavelength depends strongly on the form factor. This means that the bunch should be much shorter than the wavelength to obtain stable CSR.

The beam performance at present does not reach that achieved by the existing methods mentioned earlier. However the improvement of the bunch charge would not be difficult and more careful adjustment of the linear and higher order momentum compaction factor would keep the short bunch longer in the ring. In order to achieve much shorter pulses, we need to upgrade the hardware. In particular, the linac and the transport line were not originally designed for short-pulse injection and leave much room for improvement.

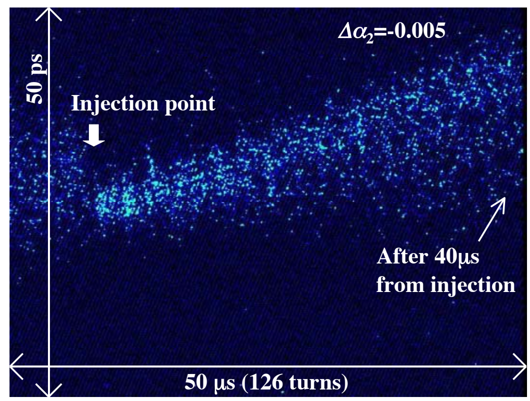


Figure 6: Double-sweep streak camera image with improper $\alpha_2$. The vertical axis is the rf phase of the ring and the horizontal axis is the revolution.

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