MULTI-STAGE BUNCH COMPRESSION AT THE JAPANESE X-RAY FREE ELECTRON LASER SACLA

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Abstract

The Japanese x-ray free electron laser facility, named as SACLA (**SP**ring-8 **A**ngstrom **C**ompact free electron **LA**ser), was constructed at the SPring-8 site. After finishing installation of all accelerator components, beam commissioning started on February 21, 2011, and the first lasing was achieved on June 7, 2011. In order to produce a high-quality electron beam with extremely low-emittance and high-peak current, SACLA adopts a multi-stage bunch compression scheme that uses an injector velocity bunching system and three magnetic bunch compressors. A design bunch compression factor reaches to 3000, namely the peak current of 1 A at the CeB_6 thermionic gun increases up to 3 kA at the exit of the final bunch compressor at 1.4 GeV. A longitudinal bunch profile was measured using a transverse beam deflector cavity that was located at the exit of the final bunch compressor. After step-by-step beam commissioning from the injector, we have accomplished a peak current of a few kA and a short bunch length less than 50 fs. In this paper, we report on present status of the multi-stage bunch compression system at SACLA.

INTRODUCTION

The Japanese x-ray free electron laser (XFEL) facility was constructed at SPring-8 [1-2]. It was named as SACLA (**SP**ring-8 **A**ngstrom **C**ompact free electron **LA**ser) to describe the distinctive features of this facility. After finishing the construction, beam commissioning started on February 21, 2011. By performing step-by-step beam tuning from a gun to an undulator line, we have succeeded in lasing at a wavelength of 0.12 nm on June 7, 2011 [3-6].

In order to produce a stable XFEL light, extremely high-quality electron beam with low-emittance and high-peak current must be injected into the long undulator line. To make such an electron beam, SACLA adopts a multi-stage bunch compression scheme [7-8]. Here, we report on some detail of the multi-stage bunch compression system and preliminary results of longitudinal bunch profile measurements, and finally discuss some problems to be solved at an early date.

MUNTI-STAGE BUNCH COMPRESSION AT SACLA

A schematic layout of the bunch compression system, which consists of all accelerator components upstream of SACLA, is shown in Figure 1.

A CeB_6 gun generates a low-emittance electron beam with a 1-A peak current and a micro-second pulse width. A beam chopper cut out a central 1-ns part from the long beam, and this short bunch is injected into the buncher section. Three rf cavities: a 238 MHz buncher cavity, a 476 MHz booster cavity, and an L-band correction cavity are used for velocity bunching process, which is a first stage of the multi-stage bunch compression. A peak current of the beam increases to ~20 A in this section.

Next, the beam is accelerated to ~40 MeV in an L-band linac. An energy chirp is also supplied for a following bunch compression process using a magnetic chicane. A C-band correction cavity is used to linearize the energy chirp of the beam. This cavity supplies a second-order positive energy chirp to cancel out a second-order negative chirps generated not only at the L-band linac but also at the following all linacs and bunch compressors. The first bunch compressor (BC#1) compresses the bunch by a factor of ~3.

At an S-band linac, the beam is accelerated to ~400 MeV off crest, and is compressed by a factor of ~10 at the second bunch compressor (BC#2). At a C-band linac, the

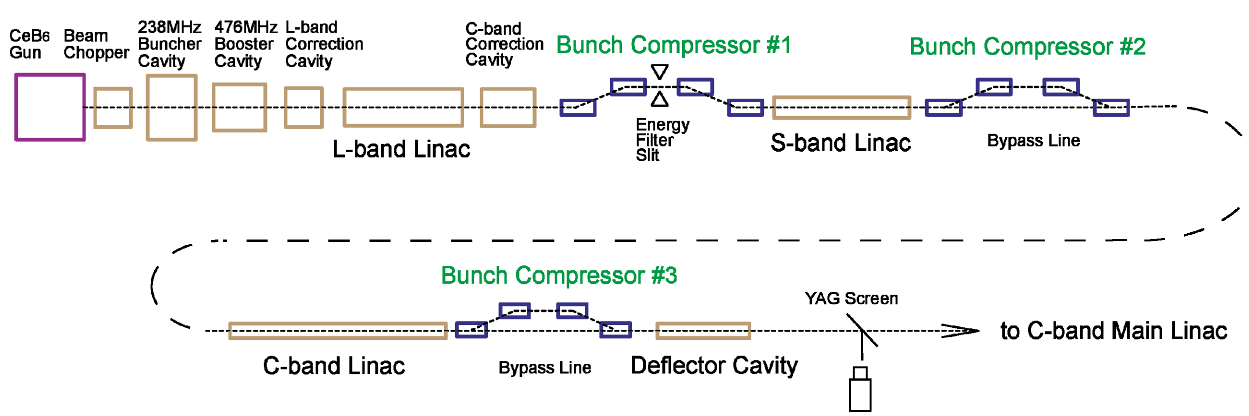

Figure 1: Schematic layout of the multi-stage bunch compression system at SACLA.

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beam is accelerated to ~1.4 GeV off crest, and is compressed by a factor of ~5 at the last bunch compressor (BC#3). Finally, the peak current reaches to 3 kA level.

An example of the rf parameter set when laser amplification was achieved and parameters of the magnetic bunch compressors are shown in Table 1 and Table 2, respectively.

Table 1: Example of the rf parameter set in lasing condition.

Gun Voltage	500 kV
238 MHz Buncher Cavity Amplitude	200 kV
238 MHz Buncher Cavity Phase	-121 deg.
476 MHz Booster Cavity Amplitude	800 kV
476 MHz Booster Cavity Phase	-8 deg.
L-band Correction Cavity Amplitude	140 kV
L-band Correction Cavity Phase	-174 deg.
L-band APS Accelerator Amplitude	40 MV
L-band APS Accelerator Phase	-15 deg.
C-band Correction Cavity Amplitude	4.3 MV
C-band Correction Cavity Phase	-152 deg.
S-band Accelerator Amplitude	417 MV
S-band Accelerator Phase	-22 deg.
C-band Accelerator Amplitude	1385 MV
C-band Accelerator Phase	-49 deg.

Table 2: Parameters of the magnetic bunch compressors.

	Momentum Compaction (R_{56})	Dispersion (η)
BC#1	-41 mm	170 mm
BC#2	-37 mm	345 mm
BC#3	-7.5 mm	155 mm

MEASUREMENT OF LONGITUDINAL BUNCH PROFILES

Injector

A longitudinal bunch profile at the end of the injector was measured at a dispersive point of BC#1. Since almost linear energy chirp is supplied at the L-band linac and the C-band correction cavity, an energy profile at the injector end represents a temporal profile of the beam indirectly.

Relationship between a horizontal coordinate at the dispersive point (center of BC#1) (Δx) and a time coordinate (Δt) is given as follows,

$$\Delta t = \frac{E}{c \cdot \eta \cdot dE/dz} \Delta x ,$$

where E is a beam energy, dE/dz is a first-order energy chirp, η is a dispersion of BC#1, and c is a light velocity. Since the beam energy and the chirp were almost determined by the L-band linac and the C-band correction cavity, these were estimated using the rf parameters that were listed in Table 1, where it was assumed that an energy at the entrance of the L-band linac was 1 MeV and an energy chirp was too small so that it could be ignored.

Figure 2 shows a longitudinal bunch profile at the injector end. The left side is the head of bunch and the right side is the tail of bunch. The solid line is a data that was taken when an energy filter slit at the center of BC#1 was fully opened, that is, it shows a temporal beam profile at the end of the injector. A single peak generated at the velocity bunching process was seen in the figure. The head and tail components of the beam can be beam halos that give a bad influence to precise measurements of beam positions at the long undulator line. In order to obtain a clear transverse profile, the head and tail components were cut out by reducing an opening width of the energy filter slit to ~5 mm (ΔE~1 MeV). The dotted line shows the data in the condition of narrowed slit. This is an effective temporal profile of the injector beam. The total charge was 0.1 nC/bunch.

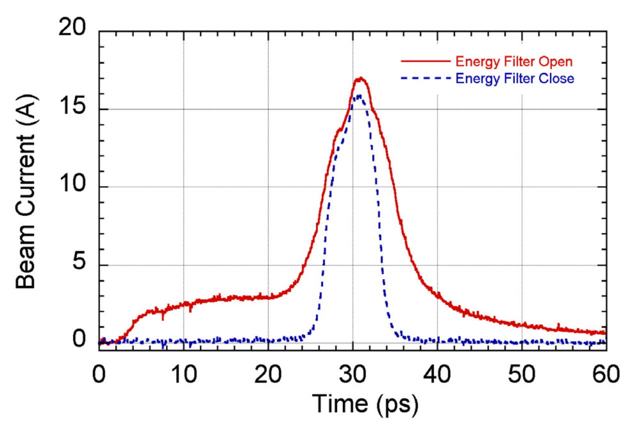

Figure 1: Longitudinal bunch profile at the injector.

Magnetic Bunch Compressors

Longitudinal bunch profiles after magnetic compression processes were measured by means of a transverse beam deflector (rf deflector) that was located just after BC#3. Since an electron beam is streaked in the vertical direction by a time-depending rf kick, a longitudinal bunch structure can be observed directly at a screen monitor.

The rf deflector that operates at a C-band frequency was newly developed at SPring-8 [9]. Since a coherent optical transition radiation (OTR) light generates after BC#3, a proper beam profile cannot be observed by a standard OTR light. Therefore, we exchanged the stainless steel screen to a YAG screen [10].

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Relationship between a vertical coordinate of the streaked beam (Δy) and a time coordinate (Δt) is given as follows,

$$\Delta t = \frac{P_z}{e \cdot k_c \cdot V_y \cdot L} \Delta y ,$$

where P_z is the longitudinal momentum of the beam, k_c is the wave number of the rf deflector, V_y is the transverse rf voltage of the rf deflector, and L is the distance between the rf deflector and the screen monitor.

A longitudinal profile after BC#1 was measured by passing the beam through two straight bypass lines prepared at BC#2 and BC#3. Since the bunch length after BC#1 is on the order of picoseconds, a time range of the measurement must be broadened. A kick angle at the rf deflector was reduced by setting a smaller V_y, and a full streaked profile was measured by dividing into two screen shots. A longitudinal profile after BC#2 was also measured by passing the beam through the straight bypass line of BC#3.

Examples of the longitudinal bunch profiles at every bunch compressors are shown in Figures 3-5.

DISCUSSION

By the success of x-ray lasing at SACLA, it was confirmed that the multi-stage bunch compression system is available to generate a low-emittance and high-peak current beam. However, some problems to be solved appeared in the series of the longitudinal bunch profile measurements.

In the bunch profiles after BC#1 and BC#2, these structures are not composed of a single peak. Especially, the latter shows a fairly complicated structure. It is supposed that the energy chirp did not become linear all over the bunch. Nonlinear components of the energy chirp seem to make over-bunching portions locally. Since the over-bunching can cause emittance growth in general, we must avoid this situation. Apparatuses for controlling the nonlinearity of the energy chirp are the L-band correction cavity and the C-band correction cavity that are located in the injector section. There is a possibility that these rf parameters were not set to proper values in this first beam commissioning. We need to perform further fine tuning of the longitudinal beam structure.

From the measurement of the bunch profile after the final bunch compressor, it was found that a peak current was approximately 2 kA, which was somewhat lower than the design value of 3 kA. It is possible to increase the peak current up to the design value or more, however, decrease of a laser power has been observed in such conditions. Over-bunching due to hard compression seems to become a cause of emittance degradation. In order to confirm that a proper bunching condition is realized inside the bunch, a finer bunch structure should be monitored by the rf deflector. A time resolution is currently limited to ~10 fs due to the finite vertical beam size. The resolution must be improved by optimizing beam focusing optics around the bunch profile measurement section.

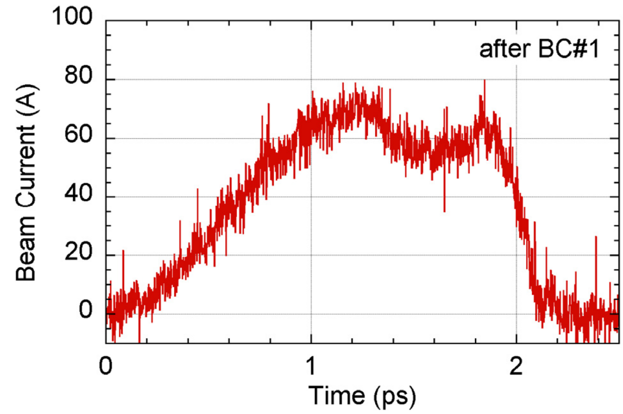

Figure 3: Longitudinal bunch profile at the exit of BC#1.

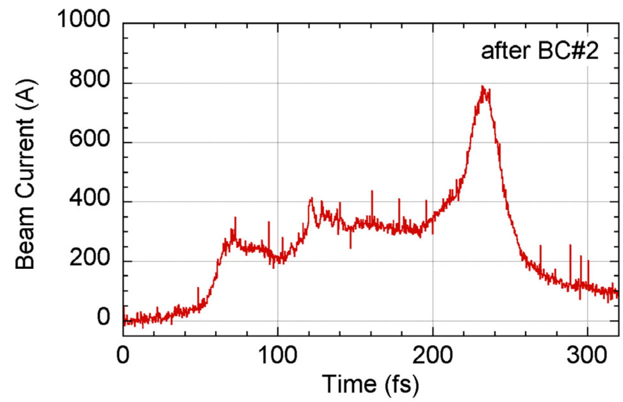

Figure 4: Longitudinal bunch profile at the exit of BC#2.

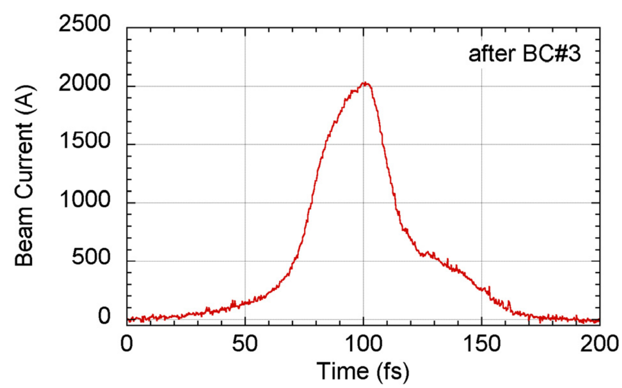

Figure 5: Longitudinal bunch profile at the exit of BC#3.

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