XFEL AS A LOW-EMITTANCE INJECTOR FOR A 4TH-GENERATION SYNCHROTRON RADIATION SOURCE

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Abstract

Low-emittance beam injection is required for the future SPring-8-II due to its small injection beam aperture. To meet this requirement, the SACLA linear accelerator has started to be used as a low-emittance injector of the present SPring-8 storage ring. In order to perform beam injection in parallel with XFEL operation, three accelerators are virtually constructed in a control system for two XFEL beamlines and beam injection, and thus the parameters of accelerator can be independently tuned. Although the reference clock frequencies of SACLA and SPring-8 are not related by an integer multiple, the developed timing system achieves 3.8 ps (rms) synchronization between the two accelerators. To maintain bunch purity of 10^{-8}~10^{-10}, which is routinely requested at SPring-8, an electron sweeper and an RF knock-out system are introduced for the SACLA injector section and the SPring-8 storage ring. Although 0.1 nm-rad emittance of SACLA is increased by an order of magnitude at a transport line mainly due to quantum excitation of synchrotron radiation, it is still small enough for SPring-8-II. By shutting down an old dedicated injector accelerators, energy consumption has been significantly reduced and it contributes to create a low-carbon society.

INTRODUCTION

SPring-8-II is an upgrade project of the SPring-8 storage ring [1]. As a part of SPring-8-II, the linear accelerator of SACLA has been used as a low-emittance full-energy injector since 2020 [2]. To pursue low emittance, SPring-8-II employs a multi-bend optics design, which increases nonlinearity due to strong focusing magnets [3]. As a result, a small dynamic aperture for an injected beam becomes an issue, which is common to all recent low-emittance storage rings [4-6]. In SPring-8-II, traditional off-axis beam injection is planned using an in-vacuum septum magnet in combination with a low-emittance injection beam [7].

Figure 1 is a schematic layout of SACLA [8]. There are three FEL beamlines (BL1, BL2 and BL3), in which BL2 and BL3 are XFELs and BL1 is a soft x-ray FEL. BL1 is equipped with a dedicated 800 MeV linear accelerator, which was originally constructed as a proto-type accelerator called SCSS, and BL1 operates independently from the SACLA main linear accelerator [9, 10]. For the beam injection, the electron beam accelerated up to 8 GeV is delivered through a transport line named XSBT (XFEL to Storage ring Beam Transport). A beam repetition rate of SACLA is 60 Hz and the electron bunches are distributed pulse by pulse between BL2, BL3 and XSBT at a switchyard installed at the end of the linear accelerator [11, 12].

The beam injection from SACLA not only improves the emittance of the injection beam, but also saves electricity consumption and facility related costs. Dedicated injector accelerators of SPring-8 consisting of a 1 GeV linear accelerator and an 8 GeV synchrotron are more than twenty-year old and major renewal of their high-voltage power station was needed. By using a small portion of the SACLA electron beam, these renewal and operation costs of the old injector accelerators are no more necessary.

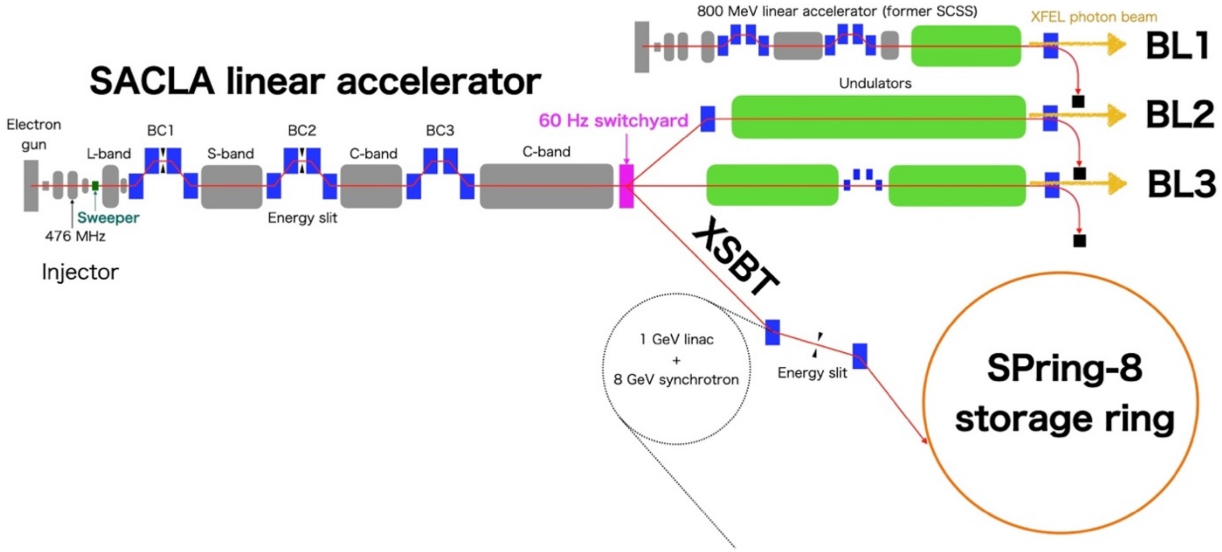

Figure 1: Schematic layout of the SACLA facility.

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There is a VUV storage ring called NewSUBARU run by the Hyogo prefectural government in the SPring-8 campus, and the electron beam of the 1 GeV linear accelerator had been used for beam injection. To shut down the old injector, a compact linear accelerator based on high-gradient C-band structures was newly built for the NewSUBARU storage ring [13].

ELECTRON BEAM CONTROL

Figure 2 shows the beam switchyard. The accelerated electron bunches are distributed to three destinations, which are the two XFEL beamlines (BL2 and BL3) and the beam transport to the storage ring (XSBT), using a kicker magnet. The accelerator parameters, such as RF phases, are controlled bunch by bunch depending on the destination. For example, the electron beam energy is fixed at 8 GeV for SPring-8, while the energy and bunch length are adjusted and optimized for the XFEL beamlines [14].

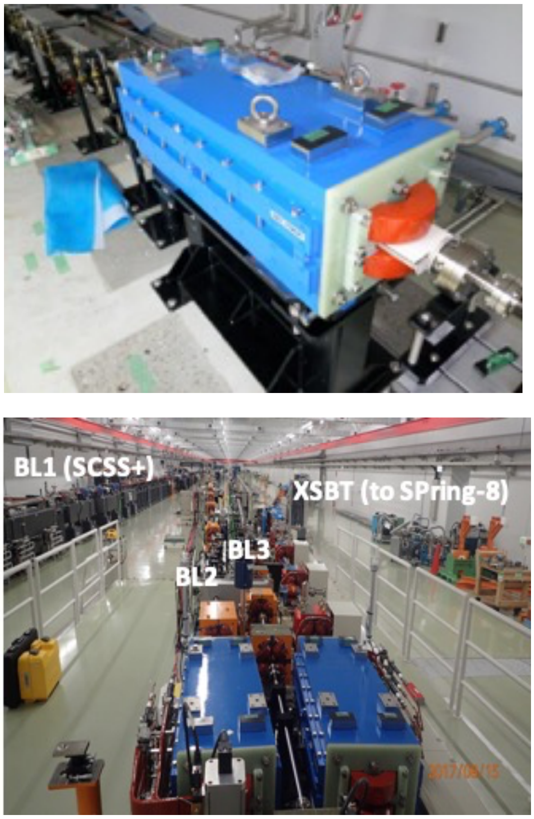

Figure 2: Beam switchyard. A 60 Hz kicker magnet (upper) and a view downstream (lower).

To achieve bunch-by-bunch control of the beam destination and the accelerator parameters, several beam distribution patterns for a period of 1 second (60 bunches) are prepared and stored in a master controller [15, 16]. According to a pattern, the master controller sends a 16-bit bunch tag to the accelerator components through a reflective memory network. The tag contains the information of the bunch destination. Once the component receives the tag, it operates with prestored parameters defined for each destination, such as the RF phase, RF timing and direction of deflection at the switchyard. When the beam injection is requested from SPring-8, a pattern including the destination of XSBT is loaded to the master controller and the beam is injected in the next second.

Regarding diagnostics, measured data are saved in a database with the bunch tag. Therefore, beam energy feedback can be applied and the accelerator can be tuned independently for each destination using tagged data. Figure 3 shows three beam orbits displayed separately by destinations.

Different beam energies result in different focusing strengths, and consequently transverse beam envelop mismatch occurs. The transverse envelops of the three destinations are currently re-matched downstream the switchyard. In order to facilitate the envelop matching, replacement of some quadrupoles with pulsed ones is underway.

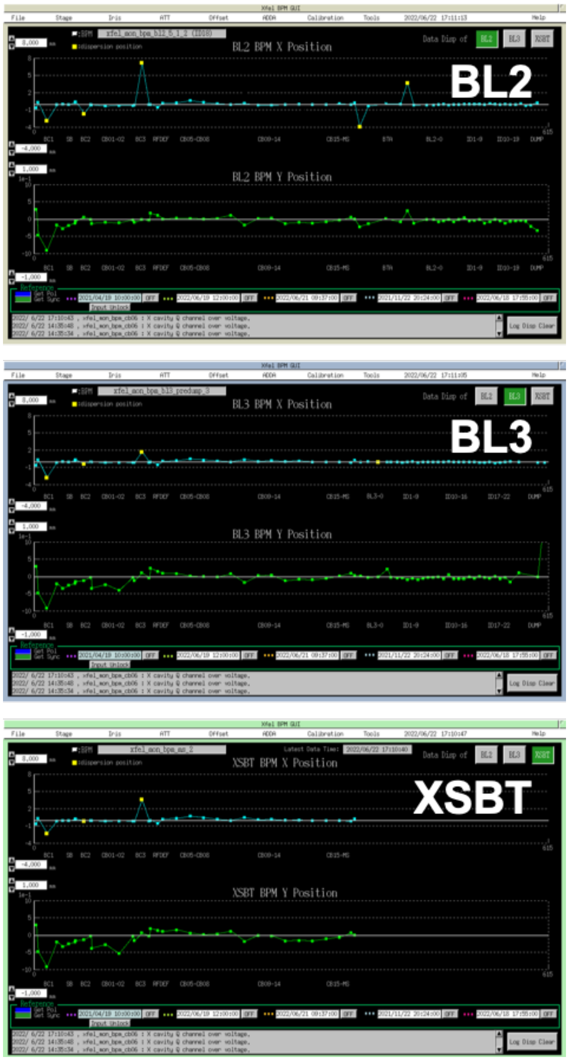

Figure 3: Electron beam orbits measured and displayed by destinations. Top blue lines and bottom green lines show horizontal and vertical orbits respectively in each window.

SYNCHRONIZATION

Since the reference clock frequencies of SACLA (238 MHz) and SPring-8 (508 MHz) are not related by an integer multiple, the beam injection timing naturally goes off with respect to the target RF bucket of SPring-8 by maximum 4.2 ns (one period of 238 MHz). In order to synchronize the two accelerators, two steps are taken [17]. When the beam injection is requested from SPring-8, the best injection timing is searched first. By waiting for up to 40 revolution periods (~197 μs), there should be a point where the timing difference takes its minimum (< 105 ps). As a second step, slight frequency modulation is applied to the reference clock of SACLA to finely synchronize the two accelerators. The developed timing system achieves final synchronization of the two accelerators within 3.8 ps (rms).

BEAM INJECTION

For the beam accumulation from 0 mA, SACLA injects the beam at 10 Hz. The electron bunch charge is about 200 pC and it takes about 10 minutes to reach 100 mA, which is a nominal stored current of SPring-8. XFEL operation is suspended during the 10 Hz injection. Once SPring-8 is filled up, the stored current is maintained by top-up injection performed in parallel with XFEL operation. Figure 4 shows the stored current of SPring-8 during the beam injection from SACLA. The frequency of the top-up injection is typically 2 or 3 times every minute.

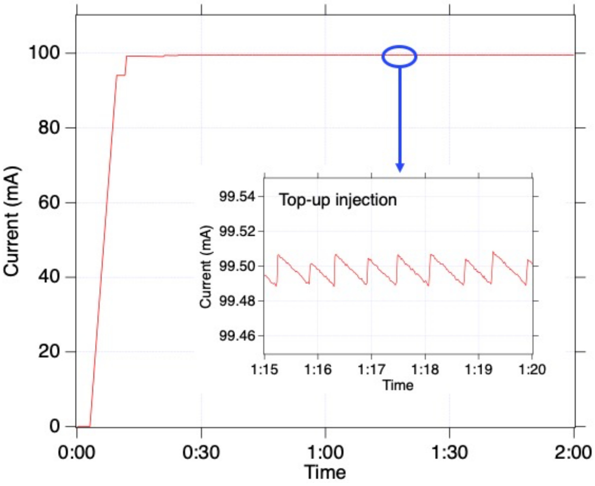

Figure 4: Stored current of SPring-8 during the beam injection followed by the top-up injection.

Figure 5 compares the electron beam sizes observed on a screen close to the injection point of SPring-8 [18]. The injection beam from SACLA is obviously much smaller than that from the old injector synchrotron. The projected emittance of the SACLA linear accelerator is typically 0.15 nm-rad, but it increases to around 1 nm-rad at the injection point due to quantum excitation of synchrotron radiation along XSBT [2].

The emittance growth ($\Delta\varepsilon_{x,y}$) caused by quantum excitation can be expressed as

$$\Delta\varepsilon_{x,y} = \frac{55 r_e \hbar \gamma^5}{48\sqrt{3} m_e c} \int \frac{\mathcal{H}_{x,y}(z)}{\rho^3_{x,y}(z)} dz \tag{1}$$

where r_e, $\hbar$, γ, m_e and c are the classical electron radius, Dirac's constant, Lorentz factor, electron rest mass and speed of light in vacuum. $\mathcal{H}_{x,y}$ is defined as $\mathcal{H}_{x,y} = \beta_{x,y}\eta'^2_{x,y} + 2\alpha_{x,y}\eta_{x,y}\eta'_{x,y} + \gamma_{x,y}\eta^2_{x,y}$ with Twiss parameters (α, β, γ), a linear dispersion function and its derivative (η, η'). ρ is a bending radius and the integration is taken along a beam trajectory (z) [19, 20]. While at the same time, the emittance is decreased by radiation damping given by

$$\Delta\varepsilon_{x,y} \approx -\frac{2 r_e \gamma^3}{3} \int \frac{\varepsilon_{x,y}(z)}{\rho^2_{x,y}(z)} dz. \tag{2}$$

In a storage ring, quantum excitation, Eq. (1), and radiation damping, Eq. (2), are balanced at ring emittance after many turns around the ring, whereas the electron beam passes only once at the beam transport. From Eq. (2), we see that the emittance reduction is proportional to a value of emittance. In the case of the small emittance beam of SACLA (0.15 nm-rad) passing through XSBT, it found that radiation damping of Eq. (2) is much smaller than quantum excitation of Eq. (1) by roughly three orders of magnitude and almost negligible.

Another possibility of emittance growth at the beam transport is CSR (Coherent Synchrotron Radiation) effects. But the electron bunch immediately lengthens to longer than 100 fs at the first bending magnet of XSBT, and the emittance growth caused by CSR effects is limited.

The expected emittance at the end of XSBT is about 1 nm-rad calculated with ELEGANT [21]. Although the emittance is increased by one order at XSBT, it is still sufficiently smaller than the requirement for SPring-8-II, that is around 10 nm-rad.

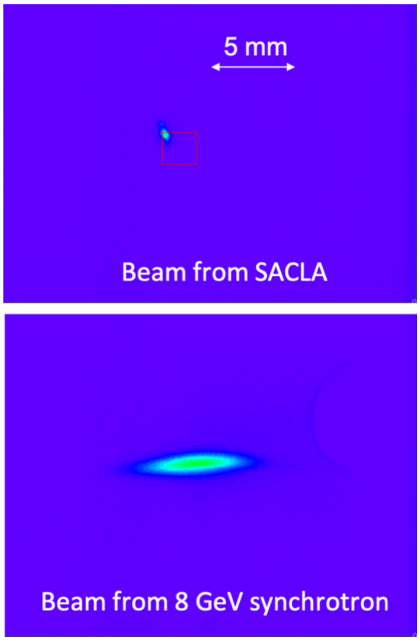

Figure 5: Transverse beam sizes of the electron beam from SACLA and the 8 GeV synchrotron.

BUNCH PURITY AND HYSTERESIS CORRECTION

When the injector was switched to the SACLA linear accelerator, we encountered two issues, which are bunch purity and magnetic hysteresis of the switchyard.

The bunch purity, which represents a ratio of bunch charges between beam injected RF buckets and empty buckets, is an important factor for some time-resolved experiments, such as nuclear resonance scattering, to obtain low background noise. The bunch purity of 10^{-8}~10^{-10} is routinely requested at SPring-8 [22].

The electron beam from SACLA has a bunch length of around 5 ps (rms) at the injection point and it is sufficiently short to be captured in a single RF bucket of SPring-8. But a small number of electrons are found to be also injected into a ninth bucket (18 ns) after the target RF bucket. SACLA employs a thermionic cathode gun with a beam chopper [23]. The electron bunch of 1 ns after the beam chopper is compressed by velocity bunching in the injector section of SACLA, but it has a long tail. Then some electrons at the tail of the bunch are decelerated in an L-band accelerator and accelerated again in a 476 MHz cavity (Fig. 1). Consequently, they make a round trip between the L-band accelerator and the 476 MHz cavity in the injector section before being accelerated to a nominal beam energy of 8 GeV. Since this round-trip time is about 18 ns, they are injected to SPring-8 with a delay of 18 ns with respect to the main bunch. Although the number of delayed electrons is not large, they have a long life time and do not decay. After one night of top-up injection, the bunch purity was worsened to 10^{-7}.

In order to remove these unwanted electrons, an electron sweeper, an energy filter and a bunch knockout system were introduced. The electron sweeper was installed between the 476 MHz cavity and the L-band accelerator to deflect decelerated electrons using pulsed electric fields (Fig. 1). The bunch knockout system, which applies rf fields and excites vertical betatron oscillations, was set up in the storage ring to remove unwanted electrons. By these remedies, a bunch purity of 10^{-10} is now maintained.

The switchyard distributes the electron bunches using a kicker magnet. The kicker magnet horizontally deflects the beam by ±1.5 degrees. For the beam injection, the kicker magnet is excited by reversed polarity and magnetic hysteresis becomes an issue. Since XFEL is very sensitive to orbit deviation inside undulators, the correction of the kicker hysteresis is indispensable. In order to erase residual magnetization of reversed fields, the kicker magnet is excited with a blank pulse after the beam injection. The kicker excitation currents of following three pulses are also finely adjusted. After taking these procedures, the beam injection has little influence on the XFEL operation.

CONCLUSION

As a part of the SPring-8 upgrade project, low-emittance beam injection from SACLA to the present SPring-8 storage ring has been started. Although quantum excitation of synchrotron radiation increases emittance at the beam transport, it still remains small enough for the future SPring-8-II. The old injector accelerators, a 1 GeV linear accelerator and an 8 GeV synchrotron booster ring, were shut down in 2021. The use of the SACLA linear accelerator as a low-emittance full-energy injector attains lower energy consumption and reduction of operation costs.

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