THREE BUNCH COMPRESSOR SCHEME FOR SASE FEL*

H.S. Kang†, S.H. Nam, and I.S. Ko
Pohang Accelerator Laboratory, POSTECH, Pohang 790-784, Korea
Changho Yi, M.H. Cho
Physics Department, POSTECH, Pohang 790-784, Korea

Abstract

The bend angle of dipoles in bunch compressor needs to be small enough to reduce the emittance increase due to CSR, which requires a larger energy chirp at the preceding RF linac to get the required bunch length. In that case, correlated energy spread cannot be reduced below FEL parameter at the following RF linac because of the small number of accelerating sections as the PAL XFEL design. Three bunch compressor scheme is introduced to make it possible to minimize the CSR induced emittnace growth as well as reduce the correlated energy spread below FEL parameter.

INTRODUCTION

Pohang Accelerator Laboratory (PAL) is constructing an X-ray free-electron laser facility that is designed to generate 0.1 nm wavelength coherent X-ray by using self-amplified spontaneous emission mechanism from a 10-GeV electron linear accelerator. One of the photon beam requirements from users is photon flux of higher than 1×10^{12} photons / pulse at the wavelength of 0.1 nm. That photon flux corresponds to the FEL power of 29 GW with the radiation pulse length of 60 fs in FWHM. To reach that goal, as many electrons in a pulse as possible should contribute to the SASE FEL interaction. So we have to care about the quality of all electrons rather than slice parameters. The projected emittance of electron beam should be well controlled like slice emittance to be below 0.5 mm-mrad for 0.2 nC beam as well as the correlated energy spread is smaller than the FEL parameter.

Bunch length after a chicane type bunch compressor is given by $\sigma_z \approx |1 + hR_{56}|\,\sigma_{zi}$, where h is energy chirp and R_{56} is the momentum compaction factor of the chicane [1]. Since σ_z and σ_{zi} are given variables, $h \times R_{56} = constant$ holds. So, the energy chirp and R_{56} are to be carefully chosen considering emittance growth and correlated energy spread.

Wake in accelerating structures cancels the energy chirp after compression [2]. As the bunch current after bunch compression is given, for example 3 kA, the length of the accelerating sections following the bunch compressor determines the required energy chirp. The beam energy of PAL XFEL is 10 GeV so that the length of linac is shorter than LCLS and it is also designed so as to reduce the length of linac to reduce the construction cost. A short linac requires a smaller energy chirp than a long linac like LCLS, which means a short linac like PAL XFEL requires a larger R_{56} than a long linac. A large R_{56} may give birth to large emittance increase at the bunch compressor due to coherent synchrotron radiation (CSR) and incoherent synchrotron radiation (ISR).

CSR generates energy spread in bends and causes bend-plane emittance growth, which is worse in short bunch. A large bend angle gives birth to a large emittance increase. A higher beam energy is preferred at the bunch compressor in case of CSR. Incoherent synchrotron radiation (ISR) in chicane bends also generates uncorrelated energy spread, diluting phase space in horizontal plane to dilute slice emittance [3] . To reduce ISR effect, chicane bends should be weak and long, and beam energy should be as low as possible.

The typical bunch compressor layout of SASE FEL facility using photocathode RF-gun as an electron beam source is to use two bunch compressors as seen in LCLS and SwissFEL. As discussed previously, a short linac requires a small energy chirp to cause a big R_{56} and a big bend angle in chicane resulting in large emittance growth due to CSR and ISR. To overcome this problem a simple method is introduced to split the 2-nd BC of the two BC Scheme into two to make one more bunch compressor. The 3rd BC has a small R_{56} to minimize the CSR effect in final bunch compression.

LATTICE DESIGN FOR THREE BUNCH COMPRESSORS

A SASE FEL layout using three bunch compressor scheme is designed for PAL XFEL (see Fig. 1). PAL XFEL will be a 10-GeV S-band linac consisting of a 135 MeV injector with 6-MeV photo-cathode RF-gun, three chicane-type bunch compressors (BC1, BC2, and BC3), and 100-m long out-vacuum undulator. The locations of BC1, BC2, and BC3 are at 314 MeV, 2.64 GeV, and 4.0 GeV, respectively. The energy chirp is given at Linac-1 and Linac-2, and the beam is accelerated on crest at Linac-3 and Linac-4. R_{56} of BC3 is as small as 7.4 mm and the bend angle of dipoles is 1.8 degrees. A 0.6-m long X-band cavity with the accelerating voltage of 21.5 MV is used to linearize the non-linear longitudinal phase-space.

Dispersion function of the lattice using three bunch compressor scheme is shown in Fig 2. The parameters of PAL

* Work supported by Korean Ministry of Science and Technology
† hskang@postech.ac.kr

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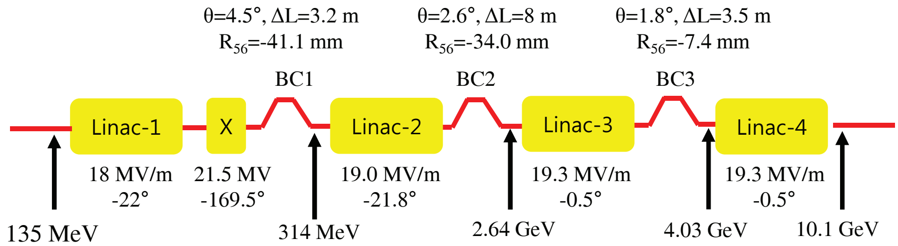

Figure 1: Three bunch compressor lattice for PAL XFEL. BC1, BC2, and BC3 represent the four-dipole chicane-type bunch compressors. ΔL represents the distance between the first and the second dipoles of chicane.

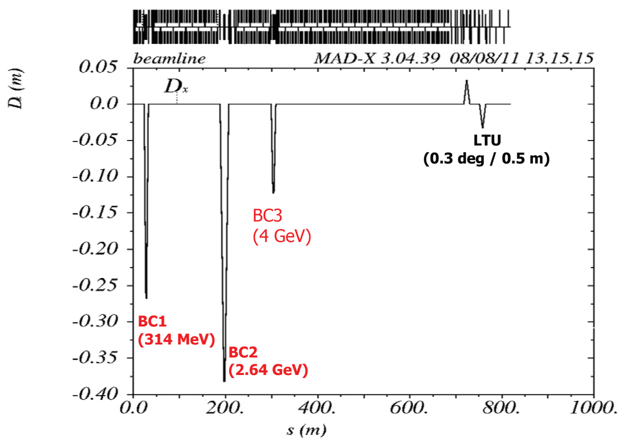

Figure 2: Dispersion function of the lattice. LTU represents the linac to undulator line consisting of four dipoles with the bend angle of 0.3 degrees.

XFEL are listed in Table 1. The beam charge is 0.2 nC, the normalized emittance is 0.5 mm-mrad, the peak current is 3.0 kA, and the FEL parameter for 0.1 nm radiation is 4.9 $\times 10^{-4}$.

Table 1: Parameters of PAL XFEL

Parameter	Value
FEL radiation wavelength	0.1 nm
Electron energy, E	10 GeV
Beam charge	0.2 nC
Normalized beam emittance	0.5 mm-mrad
Peak current at undulator	3.0 kA
FEL parameter	4.9 $\times 10^{-4}$
Undulator period	2.46 cm
Undulator gap for 0.1 nm	6.8 mm
Undulator type	out-vacuum

START-TO-END SIMULATION

Start-to-end simulation was done by using Elegant code [4]. A simulation of Coherent Synchrotron radiation is incorporated in CSRCSBEND element for dipoles and CSRDRIFT element for drifts.

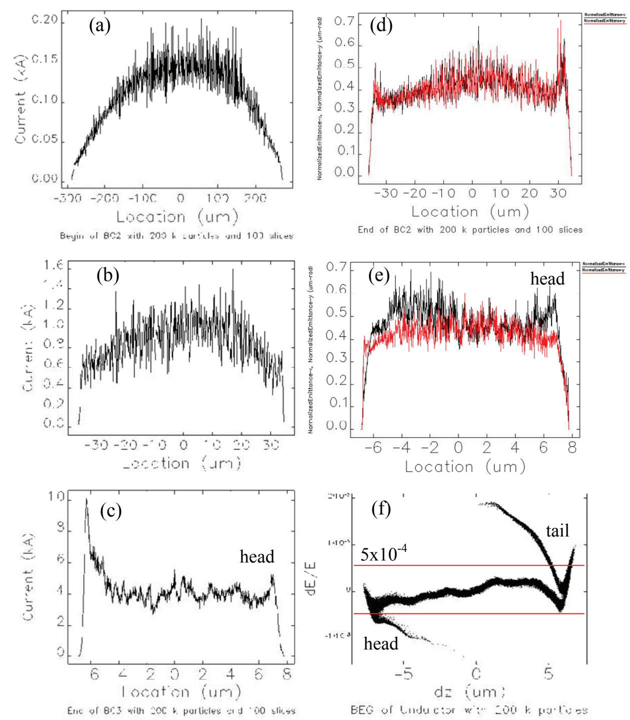

Figure 3: Start-to-End simulation result of the lattice: current profile (a) downstream BC1 and (b) downstream BC2, and (c) downstream BC3, and normalized emittance (d) downstream BC2 and (e) downstream BC3, and (f) longitudinal phase space before undulator. In (d) and (e), the black and red lines represent the horizontal and vertical emittances, respectively

Figure 3 shows the start-to-end simulation result of the lattice: the current profiles downstream of BC1 and downstream of BC2, and downstream of BC3, and the normalized emittance downstream of BC2 and downstream of BC3, and longitudinal phase space before undulator. The bunch current after BC2 is 1.0 kA, small enough not to induce emittance growth by CSR (see Fig.3(d)), and after BC3, the bunch length is reduced to below 60 fs to get the bunch current of 3 kA or higher, and emittance growth due to CSR is so small that slice amittance and even the projected emittance in both horizontal and vertical directions seems to be smaller than 0.55 mm-mrad (see

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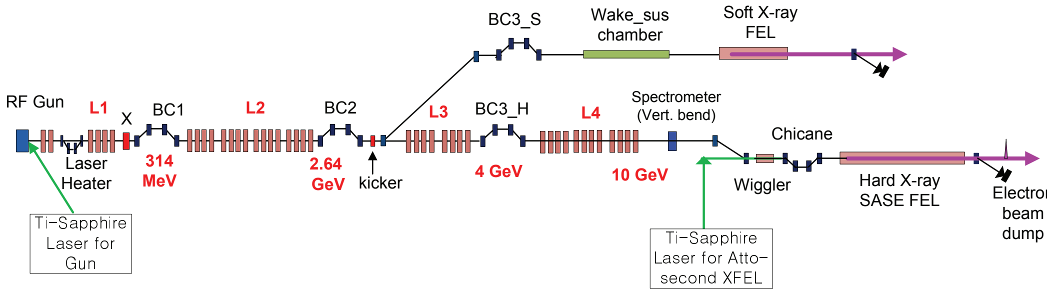

Figure 4: Layout of PAL XFEL. L1, L2, L3, and L4 represents S-band accelerating sections, BC3-S and BC3-H represent the 3rd bunch compressor for soft and hard X-ray beam line, respectively. Wake-sus-chamber represents a sus pipe chamber to introduce resistive wall wakefield.

Fig.3(e)). Beam Current profile has a shape without horn at the head (see Fig.3(c)), which can help reduce the resistive wall wake effect in small gap undulator. The coherent energy spread is much smaller than the FEL parameter of 4.9×10^{-4} as shown in Fig.3(f).

The electron beam properties at the entrance of undulator calculated by the Elegant code show that the beam emittance is well preserved along the Linac and LTU by reducing CSR effect, and the correlated energy spread is controlled well below the FEL parameter.

RMS sensitivities of linac RF parameters causing a +10% peak current change or +0.1% electron energy change at 10 GeV, and +5% emittance increase were calculated by start-to-end simulation using Elegant code. All sensitivity data are used to calculate the tolerance budget of linac RF parameters (see Table 2). The most strict requirement is 0.05 deg in rms for L1 rf phase and X rf phase, which is achievable in the current RF technology.

Table 2: Tolerance Budget

Parameter	Value
L1 rf phase	0.05 deg
X rf phase	0.05 deg
L2 rf phase	0.1 deg
L3 rf phase	0.1 deg
L4 rf phase	0.1 deg
L1 rf voltage	0.05 %
L2 rf voltage	0.05 %
L3 rf voltage	0.1 %
L4 rf voltage	0.1 %

START-TO-END SIMULATION FOR SOFT X-RAY LINE

PAL XFEL is designed to have a branch line for soft X-ray FEL line at downstream of BC2 (2.64 GeV), which consists of a kicker, a septum, and a dogleg transport line with four dipoles of 3-degree bend angle (see Fig. 4). L1, X, BC1, L2, and BC2 has the same operating parameters as hard X-ray FEL line so that two XFEL lines can operate independently. There is a 3-rd bunch compressor (BC3-s) in the soft X-ray FEL beamline as BC3-H in the hard X-ray FEL beamline. By changing the bend angle of BC3-S, the bunch current can be adjusted independent from the hard X-ray FEL line (see Fig. 5). The normalized emittances corresponding to each current profile shows an increase up to 1.2 mm-mrad at the tail of bunch, which seems to be acceptable for soft X-ray SASE FEL from 1 to 10 nm. Large correlated energy spread after compression can be reduced at the subsequent stainless steel vacuum pipes (Wake-sus-chamber in Fig. 4) by incorporating resistive wall wakefield.

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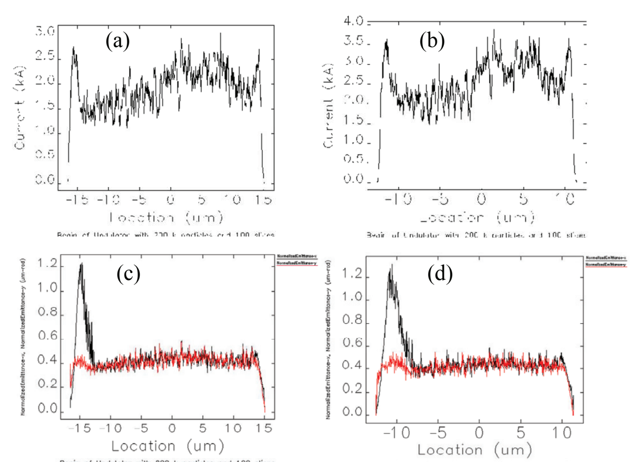

Figure 5: 2.64-GeV / 0.2 nC electron beam properties at the entrance of undulator for soft X-ray beamline: (a) and (b) bunch currents at different bend angles of BC3-S, and (c) and (d) are the corresponding normalized emittances to (a) and (b).

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