START TO END SIMULATION OF THREE BUNCH COMPRESSOR LATTICE FOR PAL XFEL*

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Abstract

The PAL XFEL lattice is three bunch compressor lattice (3-BC lattice) with a hard x-ray FEL line at the end of 10-GeV linac and a switch line at 3-GeV point for soft X-ray FEL line. The 3-BC lattice is chosen to minimize emittance growth due to CSR and mitigate the microbunching instability. Start to end simulation of the 3-BC lattice is done for hard x-ay FEL line and soft x-ay FEL line as well to emphasize superiority over the 2-BC lattice. De-chirper using corrugated pipe is included in the simulation of soft x-ray FEL line.

OUTLINE OF PAL XFEL

The PAL XFEL is a 0.1-nm hard X-ray FEL project starting from 2011, which aims at providing higher photon flux than 10^{12} photons/pulse at 0.1 nm using a 0.2 nC / 10 GeV electron linac. The photon flux of 10^{12} corresponds to the FEL power of 29 GW at 0.1 nm with the pulse length of 60 fs in FWHM. As many electrons in a pulse as possible should contribute to SASE FEL lasing to realize this flux goal.

Three bunch compressor lattice (3-BC lattice) is chosen so as to make more electrons in a bunch meet the requirements of emittance and correlated energy spread for SASE FEL [1]. The 3-BC lattice can minimize emittance growth due to CSR and mitigate the microbunching instability as well.

In the 2-BC lattice using S-band accelerating structure, small wake of the structure requires an energy chirp for bunch compression to be small if the available linac length is limited. Then, R_{56} needs to be big to get the target bunch length after bunch compression. Thus, the large bend angle of chicane in the Two-BC lattice causes a large emittance growth due to CSR and ISR. To reduce this effect, the 2-nd BC in the Two BC lattice is splitted to have additional 3-rd BC with a small bend angle.

Figure 1 shows the schematic layout of the 3-BC lattice of PAL XFEL. BC1 and BC2 are located at 330 MeV and 2.52 GeV, respectively. A switch line for soft x-ay FEL is located at 3 GeV point with a kicker and a Lamberston type septum. The switch line is so called dog-leg type consisting of two double bend achromat with a bend angle of 3 degree for one dipole. The 3-rd bunch compressor for hard X-ray FEL line is located at 3.93 GeV, while the soft X-ray FEL line has its own third bunch compressor (BC3-S). A de-chirper system using corrugated pipe is to reduce the correlated energy spread below the requirement of soft X-ray FEL. A laser heater just after the 139 MeV injector is to mitigate microbunching instability.

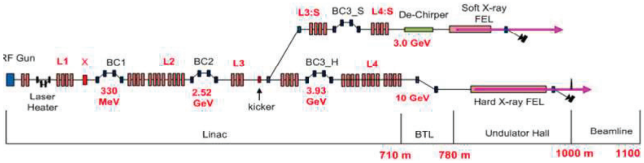

Figure 1: Schematic Layout of the PAL XFEL 3-BC lattice.

The PAL XFEL lattice has a flexibility of beam control for soft X-ray and hard X-ray FEL line. Switching by a kicker and a septum magnet is used for soft X-ray FEL beamline. Simultaneous operation is feasible for soft X-ray and hard X-ray FEL with a flexibility in control of bunch current and bunch length by changing the BC3 bend angle of each FEL Line. The number of bunch is single or two. In case of single bunch, pulse by pulse switching is feasible to soft X-ray FEL line, while for two bunches with 20-ns separation, a bunch by bunch switching is feasible to soft X-ray FEL line. Table 1 lists the parameters of PAL XFEL. The shortest wavelength of PAL XFEL is extendable to 0.06 nm by changing the undulator gap.

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
Pulse repetition rate	60 Hz
Number of bunch	single or two
Linac structure	S-band
FEL parameter	4.9×10^{-4}
Undulator period	2.44 cm
Undulator gap for 0.1 nm	7.2 mm
Undulator type	out-vacuum

START TO END SIMULATION OF HARD X-RAY FEL LINE

Start-to-end particle tracking with Elegant code [2] is done with micro-bunching instability excluded and/or included. Lattice design is so as to meet the requirement

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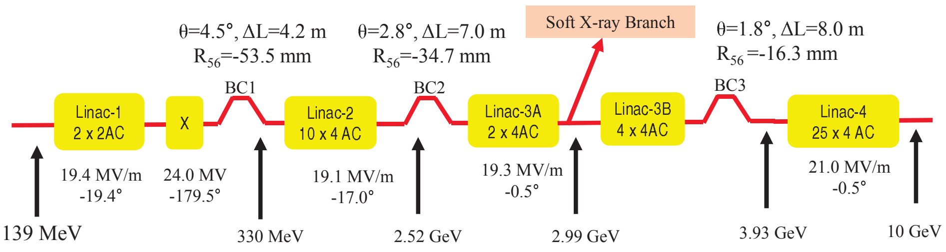

Figure 2: Parameters of bunch compressors and linac section L1, L2, L3, and L4.

of emittance and energy spread and to mitigate the microbunching instability due to linac wake, CSR, and LSC. Figure 2 shows the parameters of bunch compressors and linac section L1, L2, L3, and L4, which were determined through the comparison study for the CSR induced emittance growth and micro-bunching instability to emphasize the better performance of the 3-BC over the 2-BC lattice. The peak current of bunch is 25A at the exit of the 139 MeV injector, 125A after BC1, 530A after BC2, and 3.5 kA after BC3.

Comparison of 3-BC and 2-BC Lattice

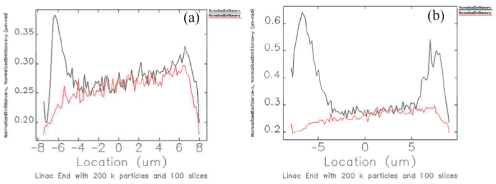

Figure 3: Slice emittance at the end of linac: a) three BC lattice and b) two BC lattice.

Figure 3 shows the slice emittance at the end of linac for the 3-BC lattice and the 2-BC lattice. Large emittance growth appears at the head and tail of bunch in the 2-BC lattice, while it is quite small in the 3-BC lattice. Figure 4 shows the projected emittance along the linac for the 3-BC and the 2-BC lattice. The growth of the projected emittance is as small as 0.5 mm-mrad after bunch compression for the 3-BC lattice while it is over 1.2 mm-mrad for the 2-BC lattice. Growth of the projected emittance is negligibly small at the BC1 and BC2 in the 3-BC lattice. It is confirmed that the CSR-induced emittance growth is much bigger in the 2-BC lattice than the 3-BC lattice. The CSR-induced emittance growth in the 2-BC lattice can be reduced a little by changing the BC2 angle from 2.8 degree to 2.2 degree and increasing the bunch compression at BC1. But, the current profile after BC2 becomes very bad, spiky, which seems like that the micro-bunching instability goes high. So, the 3-BC lattice is better in terms of the CSR-induced emittance and micro-bunching instability gain.

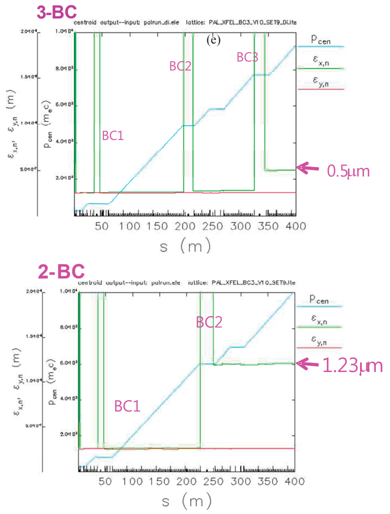

Figure 4: Projected emittance along the linac: a) three BC lattice and b) two BC lattice.

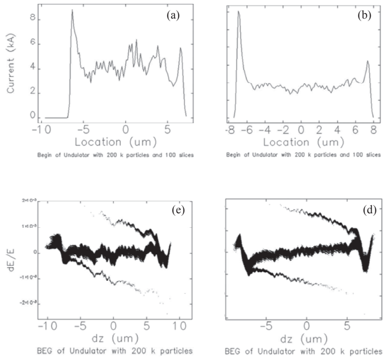

Figure 5: Slice current and energy profile before undulator for two different beam energies at BC2 in the 3-BC lattice: a) and c) for 1.84 GeV, b) and d) for 2.52 GeV.

Microbunching Instability

To check the dependence of microbunching instability on the beam energy of the bunch compressor, we did the elegant simulation of microbunching instability with two different beam energies at BC2 in the 3-BC lattice. Figure 5 shows the slice current and energy profile before undulator for 1.84 GeV and 2.52 GeV, respectively, at BC2. The current profile and the energy profile of the 2.52 GeV case look fine. But, the current profile of the 1.84 GeV case look very bad, spiky, which seems like that the micro-bunching instability goes high. The current profiles in Fig. 5 is at the condition of low cutoff frequency to exclude microbunching instability effect in the simulation by setting Nbins=60 and laser heater turned OFF and using 200 k particles. The energy profiles in Fig. 5 is at the condition of high cut-off frequency to include microbunching instability effect in the simulation by setting Nbins=500 and with laser heater turned ON and 1-million particles. At this high cutoff frequency condition the shortest modulation wavelength amplified in the instability would be $6\mu m$.

With the BC2 energy of 1.84 GeV, the current profile is too spiky even with low frequency cut-off. But, higher BC2 energy (2.52 GeV) shows a better profile, damping of microbunching instability. Even with laser heater turned ON, the instability is not suppressed well in the case of 1.84 GeV as shown in Fig. 5(c).

In general, microbunching instability is amplified at the bunch compressor through converting the energy modulation to density modulation. To reduce this microbunching instability gain in the 3-BC lattice, PAL XFEL adopts two ideas:

- Increase the beam energy at the bunch compressor as $0.33 \rightarrow 0.41$ GeV at BC1 and $1.84 \rightarrow 2.52$ GeV at BC2
- Lower the peak current at the BC1 and BC2 as 100 A at BC1 and 500A at BC2. The peak current at BC2 is 1 kA in the old design.

START TO END SIMULATION OF SOFT X-RAY FEL LINE

The same lattice up to the kicker for switching to soft x-ray line in Fig. 2 are used in the start to end simulation of soft X-ray FEL line. Figure 6 shows the projected emittance along the soft x-ray line. Growth of the projected emittance is negligibly small along the 3-degree dog-leg switch line, which results mainly from the small peak current of 500A along the switch line. And the projected emittance growth is as small as up to 0.48 mm-mrad after the bunch compression at the BC3-S to 2.5 kA.

De-chirper for Soft X-ray Branch Line

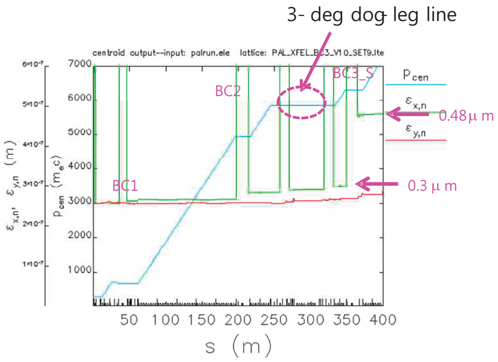

Figure 6: Projected emittance along the soft x-ray line.

Large correlated energy spread still remains after BC3-S as shown in Fig. 7(a) because there is no accelerating structures like L4 in the hard X-ray line. The energy spread needs to be reduced below FEL parameter. If we use S-band accelerating structure like L4 in the hard X-ray line, the total length required is approximately 285 m, which corresponds to 95 S-band structures. So, we decided to use resistive wall wake structure with smaller diameter than the S-band structure as a de-chirper to reduce the length. Figure 7 shows the simulation result of de-chirping in the soft X-ray line for two different type resistive wake structures: smooth, resistive pipe with radius of 3mm and corrugated pipe with radius of 3 mm. The corrugated pipe gives a linear de-chirping to have flat energy profile while non-linear energy profile is shown in smooth, resistive pipe because the first zero crossing of the smooth pipe is as small as 32 μm while it is as high as 900 μm for corrugated pipe [3].

As the required chirp is different for a different bunch length and charge, a circular shape of de-chirper lacks controllability. So adjustable gap type using parallel plate with corrugations provides better controllability. But the wake reduces to a factor of $\pi^2/16$ from circular type. The proposed design is a movable gap of 6 to 12 mm full distance with remote control. And one unit length is 3 m. A total of 6 units is necessary for soft X-ray FEL line.

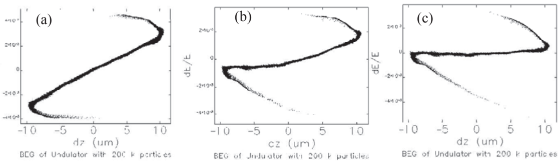

Figure 7: Longitudinal phase spaces of the electron bunch in the soft X-ray line: a) after BC3-S, b) after an smooth, resistive pipe with radius of 3mm and length of 15 m, c) after a corrugated pipe with radius of 3 mm and length of 15 m.

SUMMARY

Three bunch compressor lattice for PAL XFEL is designed so as to minimize emittance growth due to CSR and mitigate microbunching instability. Start-to-end simulation result of the lattice shows that the electron beam at the entrance of undulator satisfies the requirement of emittance and energy spread for SASE FEL in pursuit of the idea that as many electrons in a pulse as possible should contribute to SASE FEL lasing to realize the target photon flux. Corrugated plate is a good choice as a De-chirper for soft X-ray FEL line.

REFERENCES

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[2] M. Borland, ”Elegant: A Flexible SSD-Compliant Code for Accelerator Simulation,”

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