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# STUDY OF FEL OPERATION USING COLLIMATOR WITHOUT X-BAND LINEARIZER IN HX LINE AT PAL-XFEL*

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## *Abstract*

A Hard X-ray (HX) line in PAL-XFEL consists of an e-gun, a Laser Heater (LH), S-band accelerators, an X-band LINearizer (XLIN), three bunch compressors (BC), a dog-leg, and an undulator line. It generates 2.5 - 15-keV FEL with over than 1-mJ pulse energy. The XLIN before BC1 is used for linearizing the energy chirp in the longitudinal phase space and provides the flexibility for FEL optimization and operation. However, it causes the instability of FEL by large jitters and drift because of higher frequency. We study the FEL operation without XLIN. The collimator in the center of BC1 is used removing the slices to cause nonlinear compression. We optimize the FEL by short electron bunch with under 30 fs. In this paper, we present details of the optimizing sequence and performance for the FEL operation without XLIN.


## INTRODUCTION

A high harmonic cavity is used in all hard x-ray FEL machine in the world [1-5]. Since a cosine-like RF electric field is used to accelerate the electron bunch, there is a curvature in an energy chirp of a longitudinal phase space of e-bunch. The overall field of the fundamental and the high harmonic frequency linearizes the curvature in the energy chirp (Fig. 1). We call this high harmonic RF system 'linearizer'. PAL-XFEL use the X-band LINearizer (XLIN) which is the $4^{th}$ harmonic RF of S-band. It is installed before the first Bunch Compressor (BC) and used for suppressing the nonlinear e-bunch compression in next bunch compressors. It provides the flexibility of FEL operations and optimization. However, the RF phase and amplitude jitter of XLIN which cause the unstable operation are larger than S-band RF system because of the higher frequency and the limitation of RF technology. Also, there is a difficulty of the FEL operation by the RF phase drift of XLIN from the reference phase drift. The RF phase of XLIN drifts about 10° during linac RF phases drift about 2° for 12-hours operation. Since the XLIN system costs about 4M $, the scheme of FEL generation except XLIN makes big advantage of the operation stability and budget.

We study the FEL operation mode without XLIN in the Hard X-ray (HX) line of PAL-XFEL. A collimator at the BC1 is used to collimate the head and tail slices in the e-bunch which cause the micro bunching instability and nonlinear compression at the next bunch compressor. The ELEGANT simulations are conducted to verify the effect of collimator. The accelerating phase and amplitude are adjusted to compensate the exception of XLIN. The FEL operation mode without XLIN is optimized with the same sequence of the nominal operation mode. 9.7 keV FEL is generated, and e-bunch and FEL parameters are measured for all modes. In this paper, we present the FEL operation without XLIN compare to the nominal operation. Also, we present details of e-bunch and FEL performance for these operation modes.

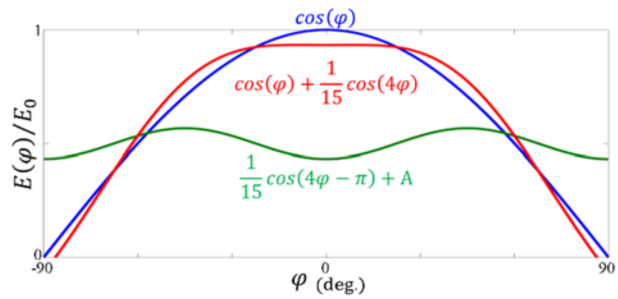


Figure 1: Linearization of the RF electric field curvature with a high harmonic cavity.

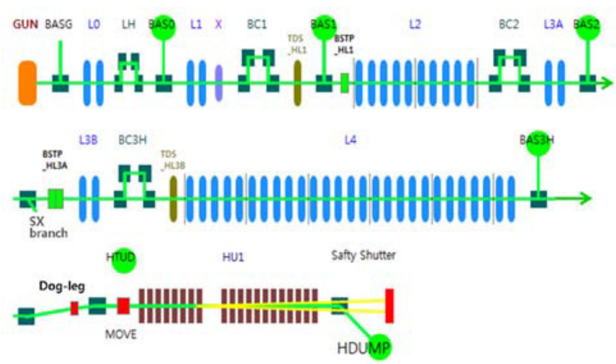


Figure 2: Schematic diagram of HX line at PAL-XFEL.

## NOMINAL FEL OPERATION

The HX line of PAL-XFEL consists of an INJector (INJ), Laser Heater (LH), 4 Linac region (L1 ~ L4), 3 BCs, a dog-leg, an undulator line, and the XLIN (Fig. 2.). An electron bunch with 250-pC charge and 0.5-μm transverse emittance is emitted from the photo-cathode RF gun, and accelerated to about 140 MeV in the INJ. The slices of e-bunch are heated at the LH, but we don't use the LH nowadays because of its little effect for the FEL performance. The improvement of the FEL pulse energy and stability by the LH is weaken in the FEL operation with shorter e-bunch length. The XLIN is operated with 20.5 MV accelerating gradient and -180° phase from on-crest phase. The e-bunch energy at the XLIN is about 350 MeV. There is a collimator on the center of each BC, and we use the collimator at BC1 for operation. Slices of in the head and tail of e-bunch are collimated in BC1, and the charge is reduced to about 200 pC. Finally, the e-bunch is compressed about 3.5 kA and accelerated to 8.54 GeV which generate 9.7 keV FEL with 1.87 K-value undulators.

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Table 1: Parameters for Operation Modes with XLIN

| Parameters | Nominal operation | Highest pulse energy |
|---|---|---|
| BC angles (°) | 4.97, 3.3, 1.6 | 4.97, 3.3, 1.6 |
| Linac RF phase (°) | -10.7, -19.0, -5.0, -2.0 | -10.5, -19.2, -5.0, -2.0 |
| XLIN RF phase (°) | -179.5 | -180.5 |
| Charge (pC) | 200/250 | 210/250 |
| COL gap (mm) | 5.5 | 5.9 |
| Bunch length (fs) | rms 14.3 | rms 17.8 |
| Photon energy (keV) | 9.7 | 9.7 |
| Pulse energy (mJ) | 1.33 | 2.08 |
| Spectral bandwidth (eV) | rms 10.9 | rms 13.5 |
| FEL pulse duration (fs) | 17.5 (FWHM) | 25.9 (FWHM) |
| FEL power stability | ~ 10% | ~ 10% |

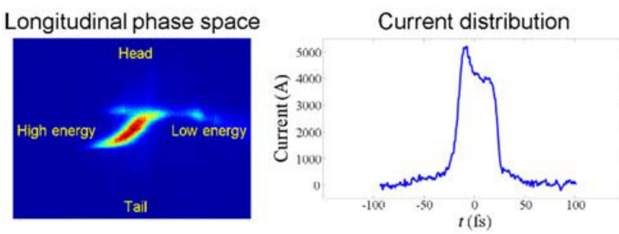


Figure 3: Longitudinal phase space and current distribution of electron bunch at the end of linac section for nominal operation. These results are measured in the BAS3H.

We achieved over 2-mJ pulse energy with rms 13.5-eV spectral bandwidth for 9.7 keV FEL. The e-bunch parameters for this are rms 18-fs e-bunch length, 210-pC charge, 0.5-µm emittance for both transverse axes. However, since some user wants the FEL with short pulse length under 20 fs and narrow spectral bandwidth near 10 eV, we decided the nominal condition for 9.7 keV FEL to reflect the users' requirement. The detail parameters of nominal operation are in Table 1. The bunch charge of 250 pC is collimated to 200 pC at BC1 collimator, and the final bunch current is over 4 kA for core slices (Fig 3). This e-bunch generates 1.33 mJ FEL with 17.5 fs (FWHM). The spectral bandwidth of FEL is 10.9 eV (rms). The FEL pulse energy was measured by the energy-loss scanning method with the beam position monitor in the HX dump [6]. The FEL spectrum was measured by scanning the double crystal monochrometer (DCM) with 1 eV resolution in the beamline. The longitudinal phase space, e-bunch length, and current distribution were measured in the BAS3H with the Transverse Deflecting System (TDS). The FEL pulse duration was measured by the cross-correlation method with the self-seeding system.

The FEL operation modes were optimized by the sequence as follows:

- Conduct the Beam Based Alignment (BBA) of the undulator region. The reference orbit is obtained.
- Confirm the undulator parameters of the K-value and mid-plane position.
- Adjust the RF phases and BC angles for optimizing the longitudinal parameter of e-bunch.
- Conduct the transverse size matching by adjusting quads with screens and wire-scanners
- Re-optimize the longitudinal parameter of e-bunch
- Apply the tapering in undulators.
- Optimize the phase shifter for maximizing the FEL pulse energy.

## FEL OPERATION WITHOUT XLIN

If there is no XLIN and no collimation for e-bunch in linac sections, the nonlinear bunch compression is occurred. Figure 4 shows the "banana"-shaped electron distribution in the longitudinal phase space and about 10 kA peak current in the bunch head caused by electrons driven into head slices. It was simulated by ELEGANT in the same condition of nominal operation except XLIN and collimators. The FEL is not generated in this condition because of diluted slice emittances and large slice energy spread. We expect that the nonlinear compression is suppressed by elimination of the head slices which are the main cause of the nonlinear compression before bunch compressing. Then, we conduct e-bunch simulations by changing the gap of the BC1 collimator with ELEGANT.

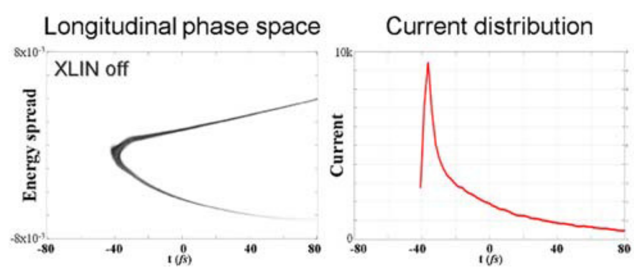


Figure 4: Longitudinal phase space and current distribution of electron bunch at the end of linac section for the operation without XLIN and collimators. These are the results of ELEGANT simulations.

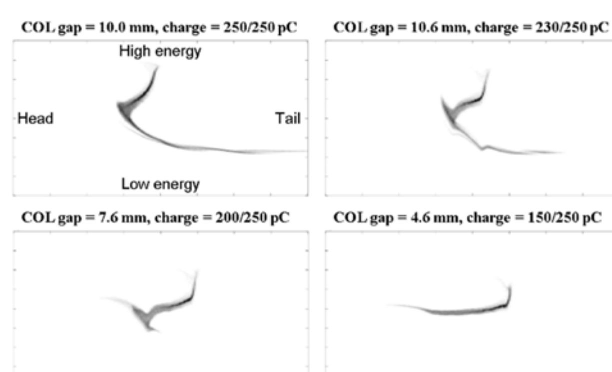


Figure 5: Variation of the longitudinal phase space by the gap of BC1 collimator. These are the results of ELEGANT simulations.

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Table 2: Parameters for Operation Modes without XLIN

| Parameters | No XLIN Mode1 | No XLIN Mode2 |
|---|---|---|
| BC angles (°) | 4.97, 3.3, 1.6 | 4.97, 3.3, 1.6 |
| Linac RF phase (°) | -14.8, -18.55, -10.0, -2.0 | -15.0, -18.55, -5.0, -2.0 |
| Charge (pC) | 150/250 | 185/250 |
| COL gap (mm) | 3.7 | 5.2 |
| Bunch length (fs) | rms 24.6 fwhm 53.9 | rms 27.8 fwhm 76.1 |
| Photon energy (keV) | 9.7 | 9.7 |
| Pulse energy (mJ) | 1.10 | 1.31 |
| Spectral BW (eV) | rms 11.2 | rms 16.5 |
| FEL pulse duration (fs) | 19.1 (FWHM) | 26.5 (FWHM) |
| FEL power stability | ~ 4% | ~ 4% |

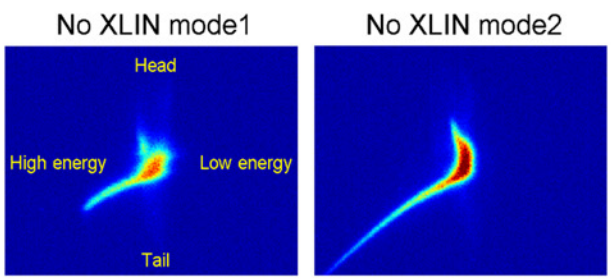


Figure 6: Longitudinal phase spaces of two FEL operation modes without XLIN.

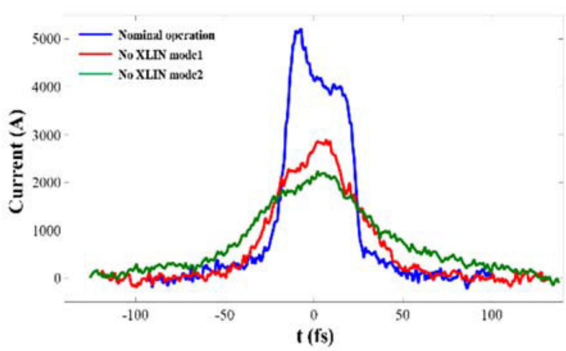


Figure 7: Current distributions for operation modes.

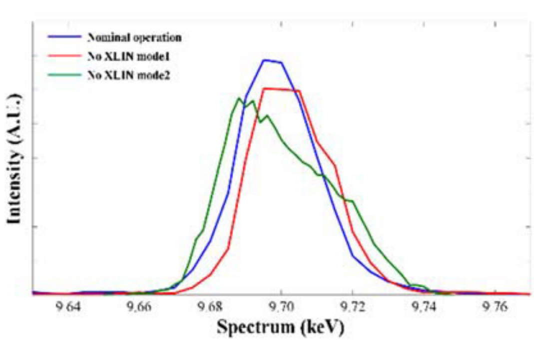


Figure 8: FEL spectrums for operation modes.

Figure 5 shows the variation of the longitudinal phase space by the gap of BC1 collimator. If 50-100 pC electrons are collimated in the BC1, the longitudinal phase space are similar to that of the nominal operation (Fig. 3, 5). We were optimize the FEL operation modes with the XLIN based on these simulation results. Mode1 were optimized for the FEL spectral bandwidth and pulse duration, and mode2 were optimized to maximize the FEL pulse energy. We generated the FEL pulse with 1.1-mJ energy, 19.1-fs (FWHM) duration, and 11.2 eV (rms) bandwidth in mode1, and 1.3-mJ energy, 26.5-fs (FWHM) duration, and 16.5 eV (rms) bandwidth in mode2. In modes of no XLIN, the head slices are in the relatively high energy region on the core slices unlike the nominal mode (Fig. 3, 6). Also, the e-bunch lengths are larger and the current shape are more Gaussian-shape comparing to the nominal mode (Fig. 7). The details of device, e-bunch, and FEL parameters of two modes in Table 2. In mode1, the spectral bandwidth is almost the same and the pulse energy is 17% lower comparing to the nominal mode (Table 2, Fig. 8). In mode2, the pulse energy is almost the same and the spectral bandwidth is 51% larger comparing to the nominal mode (Table 2, Fig. 8). The FEL power stability is improved from 10% to 4% in no XLIN modes (Table 2). We expect that there are weakness in modes of no XLIN comparing to the nominal mode, these shows good FEL performance for user services.

## SUMMARY

We implemented the operation mode without the XLIN which costs about 4M$ for the production and installation. We decided the nominal operation with the XLIN which generates the FEL with 1.3-mJ pulse energy, 10.9-eV (rms) spectral bandwidth, and 17.5 fs (FWHM) pulse duration. Two operation mode without the XLIN were optimized. The pulse energy is 17% lower in mode1 and the spectral bandwidth is 51% larger in mode2 comparing to the nominal operation, but the power jitter is improved from 10% to 4% in both modes. The performances of all operation modes are good enough to satisfy user experiments.

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