ERROR ANALYSIS FOR LINAC LATTICE OF HARD X-RAY FEL LINE IN PAL-XFEL*

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Abstract

PAL-XFEL consists of the hard x-ray line for 0.06 – 1-nm FEL and the soft x-ray line for 1 – 10-nm FEL. The linac of hard x-ray line is designed to generate 10-GeV, 200-pC, and 3-kA electron beam. It consists of S-band accelerating columns, an X-band linearizer, three bunch compressors (BC). We conduct error simulation in order to evaluate the tolerances of machine parameters and alignments. First, the machine tolerances and beam jitter levels are calculated in the simulations with dynamic errors and we find out the optimized lattice to satisfy the target tolerance of machine. Second, we conduct simulations with misalignment. We quantify the emittance dilution by misalignments, especially those of BCs. In order to compensate the misalignments, the methods of beam correction like Beam Based Alignment (BBA) are presented and the effects of emittance improvements are calculated.

INTRODUCTION

PAL-XFEL is designed to provide the hard x-ray (HX) FEL and the soft x-ray (SX) FEL with the branch line on the middle of the linac lattice, as shown in Fig. 1 [1]. The linac for HX generates 10-GeV, 200-pC, and 3-kA electron beam for 0.06 – 1-nm FEL, as shown in Table 1. The HX linac lattice consists of four sections of accelerating columns, three bunch compressors (BC), an X-band linearizer, and dog-leg line, as shown in Fig. 1. The linac lattice is optimized by the Multi-Objective Genetic Algorithm (MOGA) optimizer whose objectives are the FEL saturation power and length [2]. The parameters of optimized linac lattice are presented in Fig. 2 and the optimized beam parameters are summarized in Table 2. The performance of FEL deteriorates by the dynamic and static errors of the system. The instability of FEL operation is arisen by the dynamic errors of machine like the jitter of the RF phase and voltage. Also, the emittance dilution by static errors should be compensated to achieve the target of FEL performance.

We conducted error simulations for dynamic and static errors with ELEGANT. Two methods were used in the dynamic error simulations, which are the linear interpolation method and the random error simulation with machine parameters. In the first method, not only the machine tolerances were calculated, but also the significant parameters for the stable operation were identified. In the random error simulations, machine tolerances obtained by the previous method were confirmed and beam jittering levels were calculated. The misalignments were applied in the linac lattice for the static error simulations. First, the emittance dilution by the misalignments of bending magnets in BCs was obtained and alignment tolerances of these magnets were calculated. Second, we obtained the emittance dilution by misalignments of all elements in the linac lattice. It was identified that the emittance with best alignment by the developed technology is not enough for FEL operation. In order to suppress the emittance dilution, we conducted two types of the beam correction which are the one-to-one beam correction and the local Beam Based Alignment (BBA) in simulations. In this paper, we present the details of the setting and results in error simulations. Also, we discuss the improvement of the emittance with various beam correction methods.

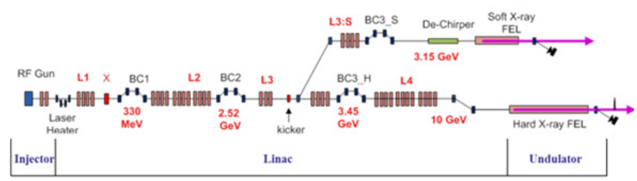

Figure 1: Schematic diagram of PAL-XFEL. The SX branch line is on the middle of the linac lattice.

Table 1: Parameters for HX FEL

Parameters (unit)	Values
Beam energy (GeV)	10
Beam charge (nC)	0.2
Slice emittance (mm-mrad)	0.4
Injector gun	Photocathode RF-gun
Peak current at undulator (kA)	3.0
Repetition rate (Hz)	60
Linac structure	S-band
Hard x-ray wavelength (nm)	0.06 ~ 1

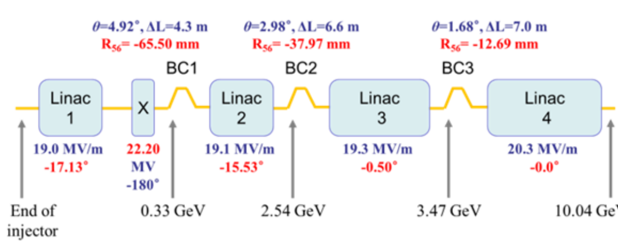

Figure 2: The optimized parameters of the linac lattice for HX line.

*Work supported by MSIP, Korea.
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ISBN 978-3-95450-133-5

Table 2: The Optimized Beam Parameters of HX Line

Parameters (unit)	**Values**
Beam energy (GeV)	10.04
Beam charge (pC)	200
Peak beam current (kA)	2.91
Bunch length (fs)	65
Normalized projected emittance_H (μm)	0.337
Normalized projected emittance_V (μm)	0.257
Saturation power (GW)	12.0
Saturation length (m)	52.8

DYNAMIC ERROR SIMULATION

We conducted the linear interpolation method to calculate the machine tolerance and find out significant machine parameters for the beam stability. Then, simulations of random machine errors were conducted in order to verify previous results.

Linear Interpolation Method

The target beam tolerances (*T*) were determined under ±10% of the current variation, ±0.02% of the energy variation, ±20 fs of the arrival time variation, and 10% of the horizontal normalized projected emittance variation [2]. The machine tolerances (*M*) were calculated with the beam tolerances and the equation which is represented by [3]

$$\sqrt{\sum_{i=1}^{N}\left\{\frac{\sigma(\Delta x_i/x_{i0})}{P_{sen}}\right\}^2} < 1\,, \qquad (1)$$

where, $P_{sen} = T/[\partial(f/f_0)/\partial(\Delta x_i/x_{i0})]$, x is machine parameter, f is beam parameter. The machine parameters used in simulations are summarized in Table 3. $\partial(f/f_0)/\partial(\Delta x_i/x_{i0})$ were obtained by the linear interpolation of simulation results.

The machine tolerances were determined by the criterion of $\sum[M/P_{sen}]^2 < 0.56$, as shown in Table 3. 0.44 remained for other variables in the injector and $\sigma(x_i) = \sqrt{N}\sigma(x)$ (*N*: number of klystrons) was applied for multi-klystron in this calculation [3]. It was verified that the RF phase and voltage of the L1 and L2, and the RF phase of the linearizer are significant parameters for the beam stability.

Random Error Simulation

We conducted the simulations with random machine errors about 2 cases. The machine tolerances obtained by the previous method were applied in Case 1 and the relatively loosened tolerances than the previous results were applied in Case 2, as shown in Table 4. As a result, both of cases were verified to satisfy target beam tolerances, as shown in Table 5.

Table 3: Machine Tolerances of HX Linac Lattice

Parameter	# of kly.	sym bol	[(*machine tolerance* / P_{sen})^2]				Tolerance (rms)	unit
			$\Delta I/I_0$ = ±10%	$<\Delta E/E_0>$ = ±0.02%	Δt_f = ±20fs	$\Delta\varepsilon_{nx}/\varepsilon_{nx0}$ = ±10%		
Mean L1 rf phase	2	φ_1	0.090	0.000	0.122	0.084	**0.03**	deg.
Mean X rf phase	1	φ_X	0.308	0.019	0.000	0.364	**0.07**	deg.
Mean L2 rf phase	10	φ_2	0.007	0.005	0.100	0.007	**0.03**	deg.
Mean L3 rf phase	4	φ_3	0.000	0.000	0.000	0.000	**0.1**	deg.
Mean L4 rf phase	27	φ_4	0.000	0.000	0.000	0.000	**0.1**	deg.
Mean L1 rf voltage	2	V_1	0.009	0.005	0.043	0.006	**0.01**	%
Mean X rf voltage	1	V_X	0.004	0.002	0.022	0.000	**0.05**	%
Mean L2 rf voltage	10	V_2	0.000	0.005	0.188	0.000	**0.02**	%
Mean L3 rf voltage	4	V_3	0.000	0.014	0.020	0.000	**0.05**	%
Mean L4 rf voltage	27	V_4	0.000	0.099	0.000	0.000	**0.05**	%
B.C.-1 angle	-	θ_1	0.000	0.000	0.000	0.000	**0.002**	%
B.C.-2 angle	-	θ_2	0.000	0.000	0.000	0.000	**0.002**	%
B.C.-3 angle	-	θ_3	0.000	0.000	0.000	0.000	**0.002**	%
Sum			**0.418**	**0.149**	**0.495**	**0.461**		

Table 4: Error Setting of Random Error Simulations

Element	**Errors (Gaussian, 3-σ cutoff)**	**Value**		**Unit**
		Case 1	**Case 2**	
RF strucs.	phase errors	0.03 (L1) 0.07 (X) 0.03 (L2) 0.1 (L3~4)	0.05 (L1) 0.1 (X) 0.05 (L2) 0.1 (L3~4)	deg.
	relative voltage errors	100 (L1) 400 (X) 200 (L2) 500 (L3~4)	200 (L1) 400 (X) 200 (L2) 1000 (L3~4)	ppm
Bends	bending angle errors	20	20	ppm
Drift	length errors (→ timing errors)	10 (66)	10 (66)	μm (*fs*)
e^- beam	random charge error	1	1	%

Table 5: Beam Jitters by Random Machine Errors

Beam jitter (standard deviatioin)	**$\Delta I/I_0$**	**$\Delta E/E_0$**	**Δt_f**	**$\Delta\varepsilon_{nx}/\varepsilon_{nx0}$**
Target	**10%**	**0.02%**	**20 *fs***	**10%**
Case 1	8.7%	0.009%	14.0 *fs*	6.5%
Case 2	10.1%	0.015%	19.1 *fs*	8.1%

ISBN 978-3-95450-133-5

SIMULATION WITH MISALIGNMENTS

Alignment Tolerance of BC

The dispersive emittance dilution is arisen by the misalignments of magnets and beam position monitors (BPM) [4]. Since the main source of the dispersion is the errors in BCs, we calculated the alignment tolerances of bending magnets in BCs. In this calculation, we applied multipole components to the sixth order in the magnetic field, as shown in Table 6 [5]. The tolerances for horizontal (x), vertical (y), longitudinal (z) distance, and azimuthal (φ) tilt were obtained.

The transverse emittance dilution by magnets of BC1 is presented in Fig. 3. These components are dominant for the whole of the emittance dilution. The alignment tolerances of bending magnets in BCs were determined by the limitation of 2% emittance growth, as shown in Table 7. The values are achievable except the longitudinal alignment tolerances (Δz) of BC1, but it is able to be compensated by the trim coil in each bending magnet whose maximum magnetic field is 10% of the main field.

Emittance Dilution by Misalignments and Compensation with Beam Correction

In order to quantify the emittance dilution by the misalignment, it was applied to all elements of magnets, RF structures, and diagnostics in the linac lattice. It distributes Gaussian distribution which σ is 0 – 400 μm for offsets and 0 – 2.5-mradian for tilt, as shown in Table 8. Figure 4 is the result of 50 random seeds. Since the target alignment tolerance of the linac lattice is σ = 70 – 80 μm, the horizontal normalized projected emittance is about 2.1 μm and the vertical one is about 1.5 μm, as shown in Fig. 4. These are about 500% of emittance dilutions from the ideal values in Table 2.

In order to compensate it, the beam corrections with 98 sets of correctors and BPMs in the HX linac lattice were applied. It was applied that σ = 80-μm misalignments of quadrupoles and RF structures, the BPM resolution of 5 μm, and the BPM misalignment of σ = 50 μm relative to the quadrupole because the quadrupole and BPM are in the same structure.

Table 6: Multipole Strengths of Bending Magnets in BC

HOM	BC1	BC2	BC3
b_1/b_0	-	-1.60 x 10^{-16}	-1.60 x 10^{-16}
b_2/b_0	-0.93 x 10^{-4}	-0.80 x 10^{-4}	-0.80 x 10^{-4}
b_3/b_0	-	-	-
b_4/b_0	3.68 x 10^{-4}	-0.57 x 10^{-4}	-0.57 x 10^{-4}
b_5/b_0	-	-	-
b_6/b_0	2.57 x 10^{-4}	0.58 x 10^{-4}	0.58 x 10^{-4}

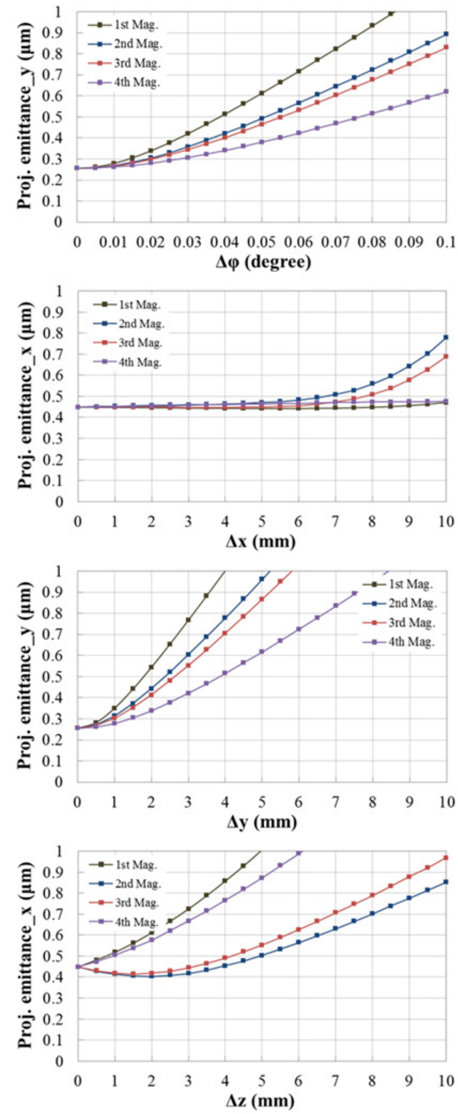

Figure 3: The emittance dilution by misalignments of bending magnets of BC1.

Table 7: Alignment Tolerances of BC Magnets

BC1	Unit	1st Mag.	2nd Mag.	3rd Mag.	4th Mag.
$\Delta\varphi$	deg.	0.005	0.005	0.005	0.010
Δx	mm	9.0	2.5	6.0	3.0
Δy	mm	0.20	0.30	0.35	0.50
Δz	mm	0.1	4.0	3.0	0.2
BC2	**Unit**	**1st Mag.**	**2nd Mag.**	**3rd Mag.**	**4th Mag.**
$\Delta\varphi$	deg.	0.010	0.015	0.020	0.020
Δx	mm	10	7.5	6.0	10
Δy	mm	2.5	4.0	4.5	6.0
Δz	mm	7.5	1.5	2.0	6.0
BC3	**Unit**	**1st Mag.**	**2nd Mag.**	**3rd Mag.**	**4th Mag.**
$\Delta\varphi$	deg.	0.030	0.040	0.045	0.060
Δx	mm	10	10	10	10
Δy	mm	10	10	10	10
Δz	mm	10	8.5	9.5	10

ISBN 978-3-95450-133-5

The one-to-one correction and local BBA were conducted in simulations. The one-to-one correction is to correct the beam passing though the BPM center. The misalignments of BPMs are not considered in this correction. The local BBA is conducted by scanning of a quadrupole magnet and a corrector before a BPM. It takes much time, but the BPM position which beams pass through the quadrupole center is found out by this sequence. The emittance improvement by beam corrections is presented in Fig. 5, which each plot is average of 200 random seeds. The normalized projected emittances are 0.55 of x-axis and 0.34 of y-axis by the one-to-one correction and 0.51 of x-axis and 0.30 of y-axis by the local BBA at the end of the linac. In the other word, the emittance dilution is suppressed to 60% for x-axis and 30% for y-axis by the one-to-one correction, and 50% for x-axis and 15% for y-axis by the local BBA. For more emittance improvement and less time of the beam correction, it is required to apply other correction methods like dispersion-free steering (DFS) and wakefield-free steering (WFS) [6, 7].

Table 8: The Misalignment Setting of All Elements

error distribution: gaussian
error amplitude = σ
cutoff = 3σ

# of samples = 50
Error factor: 0.05 ~ 5

Element	rms errors (Gaussian, 3-σ cutoff)	Value	Unit
Quads	misalignment	**80 (dx, dy)** **1 (dz)**	µm mm
	tilt	**0.5**	mrad.
Bends	tilt	**0.5**	mrad.
RF struc.	misalignment	**80 (dx, dy)**	µm

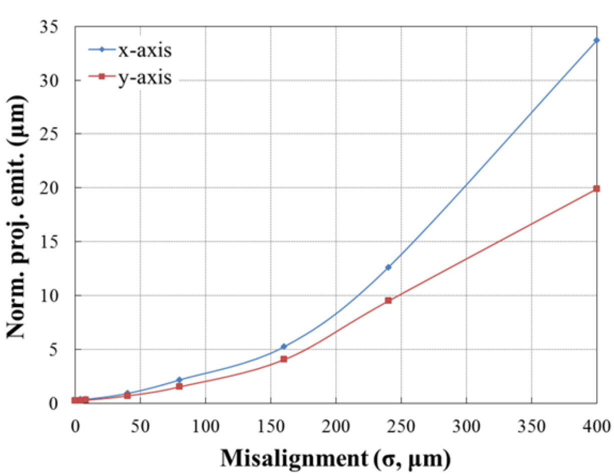

Figure 4: The emittance dilution by misalignments of all elements in the linac lattice.

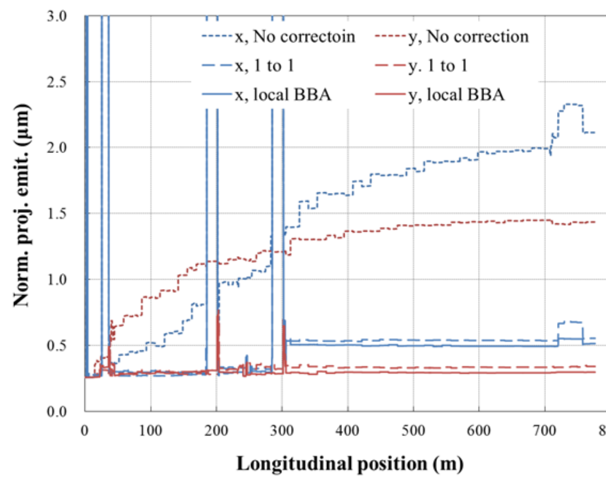

Figure 5: Emittance improvements by beam corrections.

SUMMARY

We conducted the error analysis of HX linac lattice in PAL-XFEL. Machine tolerances and beam jittering level were obtained by dynamic error simulations, which are achieved the beam tolerances under ±10% of the current variation, ±0.02% of the energy variation, ±20 fs of the arrival time variation, and 10% of the projected emittance variation. It was found out that the significant machine parameters for the beam stability are the RF phase and voltage of the L1 and L2, and the RF phase of the linearizer. Alignment tolerances of bending magnets of BCs were calculated and verified to be achievable. The emittance dilution was 500% from the ideal emittance in σ = 80-µm misalignments of all elements in the linac lattice. It was suppressed to 60% for x-axis and 30% for y-axis by the one-to-one correction, and 50% for x-axis and 15% for y-axis by the local BBA.

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ISBN 978-3-95450-133-5