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PAL 포항가속기연구소 POHANG ACCELERATOR LABORATORY

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

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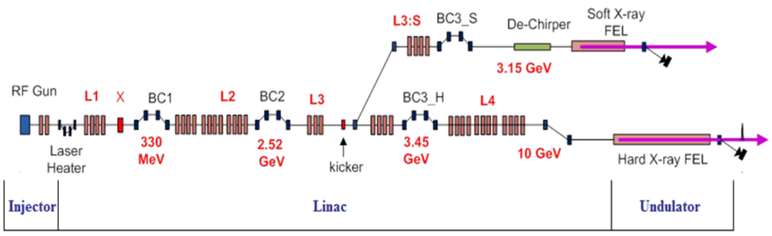
Linac Lattice of PAL-XFEL



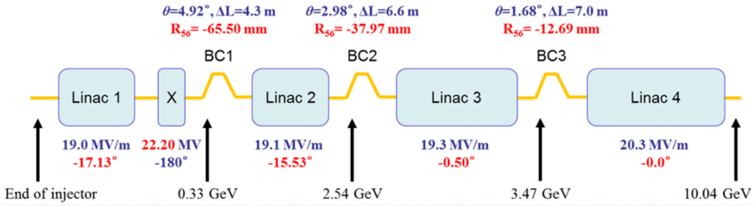
Linac Parameter for HX FEL

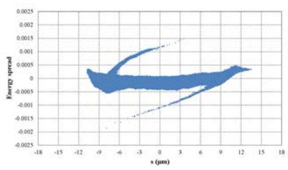
Beam energy (GeV)	10
Beam charge (nC)	0.2
Slice emittance (mm-mrad)	0.4
Injector gun	Photocathode RF-gun
Peak current at undulator (kA)	3.0
Repetition rate (Hz)	60
Linac structure	S-band

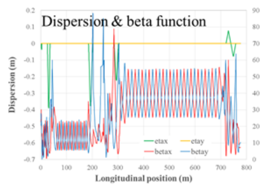
Optimized Linac Lattice

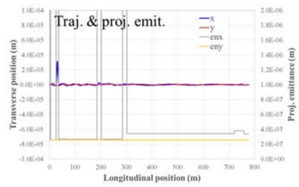
Beam parameters

Beam energy	= 10 GeV	Proj. emit. -x	= 0.337 μm
Charge	= 200 pC	Proj. emit. -y	= 0.257 μm
Current	= 2.91 kA	Sat. power	= 12.0 GW
Bunch length	= 65 fs	Sat. length	= 52.8 m









Dynamic Error Simulation

Linear Interpolation Method (ref. LCLS CDR)

$$\sqrt{\sum_{i=1}^{N}\left\{\frac{\sigma(\Delta x_i / x_{i0})}{P_{sen}}\right\}^2} < 1 \qquad P_{sen} = \frac{T}{\partial(f/f_0)/\partial(\Delta x_i/x_{i0})}$$

Target tolerances + $\left.\frac{\partial(f/f_0)}{\partial(\Delta x_i/x_{i0})}\right|_{\Delta\vec{x}=0}$ → Tolerance of variables $\sigma(\Delta x_i/x_{i0})$

Target tolerances

$|\Delta I / I_0| < 10\%$

$|\Delta E / E_0| < 0.02\%$

$|\Delta t| < 20\,fs$

$|\Delta\varepsilon_{nx}/\varepsilon_{nx0}, \Delta\varepsilon_{ny}/\varepsilon_{ny0}| < 10\%$

$\left.\frac{\partial(f/f_0)}{\partial(\Delta x_i/x_{i0})}\right|_{\Delta\vec{x}=0}$ Simulation of elegant using "vary_element" command

Tolerance Budget

[(machine *tolerance*/P_{sen})^2]

Parameter	# of klystron	symbol	$\Delta I/I_0 = \pm10\%$	$\langle\Delta E/E_0\rangle = \pm0.02\%$	$\Delta t_f = \pm20fs$	$\Delta\varepsilon_{nx}/\varepsilon_{nx0} = \pm10\%$	Tolerance (rms)	unit
Mean L1 rf phase	2	φ_1	0.0897	0.0001	0.1215	0.0840	0.03	deg.
Mean X rf phase	1	φ_X	0.3084	0.0185	0.0004	0.3637	0.07	deg.
Mean L2 rf phase	10	φ_2	0.0069	0.0050	0.0996	0.0071	0.03	deg.
Mean L3 rf phase	4	φ_3	0.0001	0.0000	0.0000	0.0001	0.1	deg.
Mean L4 rf phase	27	φ_4	0.0000	0.0000	0.0000	0.0000	0.1	deg.
Mean L1 rf voltage	2	V_1	0.0094	0.0049	0.0425	0.0055	0.01	%
Mean X rf voltage	1	V_X	0.0035	0.0020	0.0218	0.0001	0.05	%
Mean L2 rf voltage	10	V_2	0.0003	0.0053	0.1879	0.0004	0.02	%
Mean L3 rf voltage	4	V_3	0.0000	0.0135	0.0201	0.0001	0.05	%
Mean L4 rf voltage	27	V_4	0.0000	0.0994	0.0000	0.0000	0.05	%
B.C.-1 angle	-	θ_1	0.0001	0.0000	0.0000	0.0001	0.002	%
B.C.-2 angle	-	θ_2	0.0000	0.0000	0.0000	0.0000	0.002	%
B.C.-3 angle	-	θ_3	0.0000	0.0000	0.0000	0.0000	0.002	%
Sum			0.4185	0.1487	0.4937	0.4612		

*Criterion: $\sqrt{\sum_{i=1}^{N}\left\{\frac{\sigma(\Delta x_i/x_{i0})}{P_{sen}}\right\}^2} < 1$ $\sqrt{\sum(0.44 + \left(\frac{tolerance}{P_{sen}}\right)^2)} < 1$ **0.44** is portion for unconsidered variable (determined by referring LCLS CDR)

Error Study with Random Errors

Error Setting

Simulation parameter
# of prt. = 200k
csr_bin = 60
lsc_bin = 60
cutoff = 0.2
n_kicks = 20
LH power = 60 kW

error distribution: gaussian
error amplitude = σ
cutoff = 3σ
# of samples = 200

Element	rms errors (Gaussian, 3-σ cutoff)	Value #1	Value #2	Unit
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	%

Beam Jitter

	Peak Current (kA)	Beam Energy (GeV)	Arrival Time (fs)	Nor. Emit. -x (μm)	Nor. Emit. -y (μm)	Saturation Power (GW)	Saturation Length (m)
Reference	2949.45 (charge/3.6*St)	10.04	2619845660	0.488	0.257	12.063	52.123
Target	10%	0.02%	20 fs	10%			
(with 200 samples)	$\Delta I/I_0$	$\Delta E/E_0$	Δt_f	$\Delta\varepsilon_{nx}/\varepsilon_{nx0}$	$\Delta\varepsilon_{ny}/\varepsilon_{ny0}$	$\Delta P/P_0$	$\Delta L/L_0$
Jitter - #1 (STD)	8.74%	0.009%	14.01 fs	6.49%	0.007%	8.60%	1.36%
Jitter - #2 (STD)	10.14%	0.015%	19.07 fs	8.07%	0.008%	9.97%	1.52%

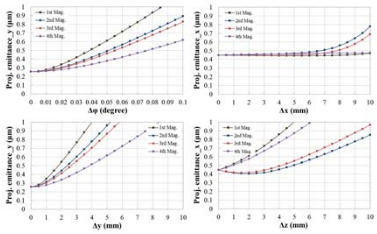
Simulation with Misalignment

Alignment Tolerance of BC

HOM of Bending Magnets

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

Emittance vs. BC1 misalignment



Error Setting

Element	parameters	Value	Unit
Bends (dipole magnets)	Δφ (tilt)	0 ~ 0.1	degree
	Δx	0 ~ 10	mm
	Δy	0 ~ 10	mm
	Δz	0 ~ 10	mm

Tolerance of BC magnets

BC1 (2% emit. growth)

	Unit	M1	M2	M3	M4
Δφ	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

Compensate with field correction by trim coil

BC2

	Unit	M1	M2	M3	M4
Δφ	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	M1	M2	M3	M4
Δφ	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

Emittance Dilution by Misalignments & Compensation with Beam Correction

Simulation Setting

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

# of samples = 50

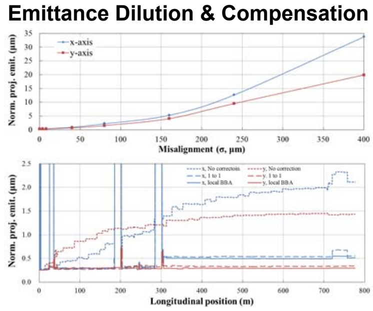
Error factor: 0.05~ 2.5

Element	rms errors (Gaussian, 3-σ cutoff)	Value	Unit
Quads	misalignment	100 (dX, dY) 1 (dZ)	μm mm
	tilt	0.5	mrad.
Bends	tilt	0.5	mrad.
RF struc.	misalignment	100 (dX, dY)	μm

Correction

- Correctors and BPMs: 98 sets
- σ = 80-μm misalignment
  σ = 50-μm relative misalignment (quads & BPM)
- BPM resolution = 5 μm
- One-to-one correction & local BBA

Emittance Dilution & Compensation



Summary

- **Machine tolerances were determined**
  - Linear interpolation method & confirmed with random dynamic error simulation
  - Machine tolerances are reasonable with $\Delta I / I_0 < 10\%$, $\Delta E / E_0 < 0.02\%$, $\Delta t < 20\,fs$, $\Delta\varepsilon_{nx}/\varepsilon_{nx0} < 10\%$
  - Significant parameters for the beam stability: φ_1, φ_2, V_1, V_2, φ_x
- **Emittance dilution by misalignments**
  - Alignment tolerance of BCs were calculated by 2% of emittance dilutions
  - 500% emittance dilution is arisen by 80-μm misalignments of all elements in the linac lattice
  - Compensated by beam correction: **60%** / **30%** by 1-to-1 correction, **50%** / **15%** by local BBA