Optics Correction Strategy for KOREA-4GSR

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- Summary

Overview

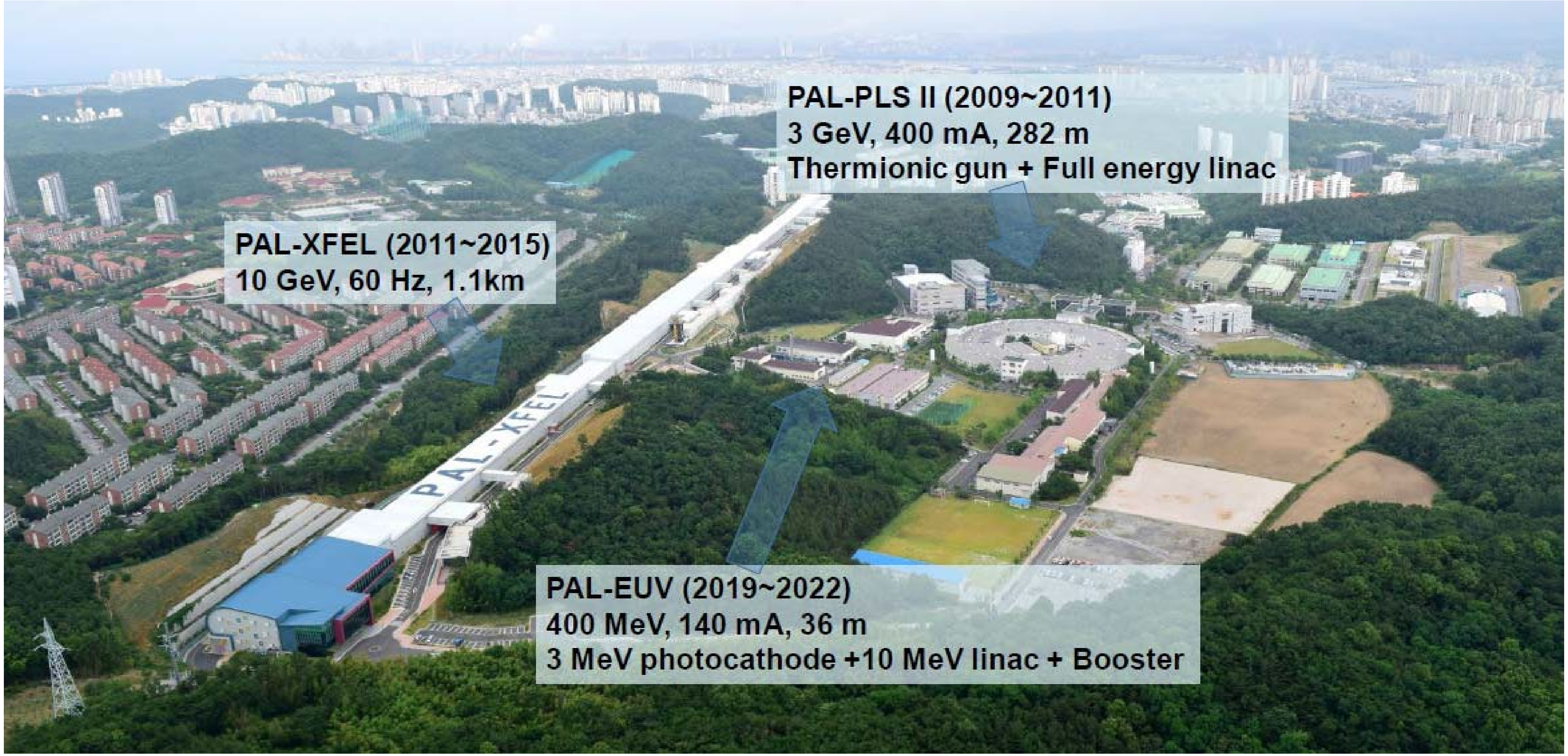
❖ **Multipurpose Synchrotron Radiation Construction Project**

- Period : from July 2021 to June 2027 (6yrs)
- Budget : 1.0454 Trillion KRW (≈ USD 750 M)
- Land : 540,000 m^2 / Building : 69,400 m^2
- Location : Ochang, Chungcheongbuk-do

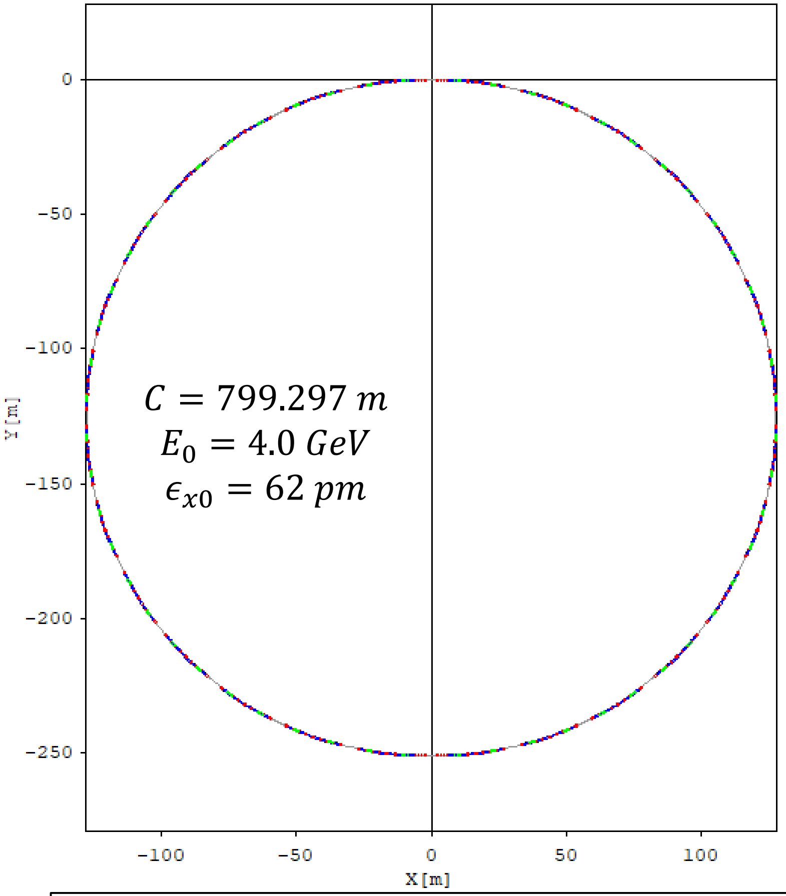
❖ **KOREA-4GSR specifications**

- Beam energy : 4 GeV
- Beam emittance : less than 100 pm·rad (62 pm · rad)
- Circumference : 800 m
- Beamlines : more than 40
- Accelerator : Gun, 200 MeV Injector LINAC, 4 GeV Booster and Storage Ring
- Lattice : H7BA

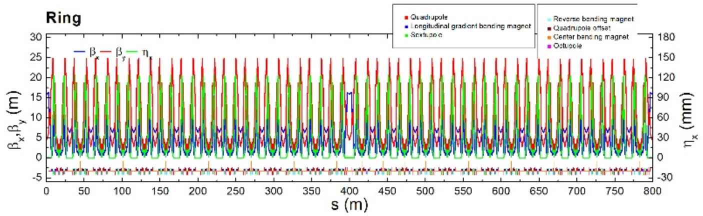
Accelerators in Pohang Accelerator Laboratory



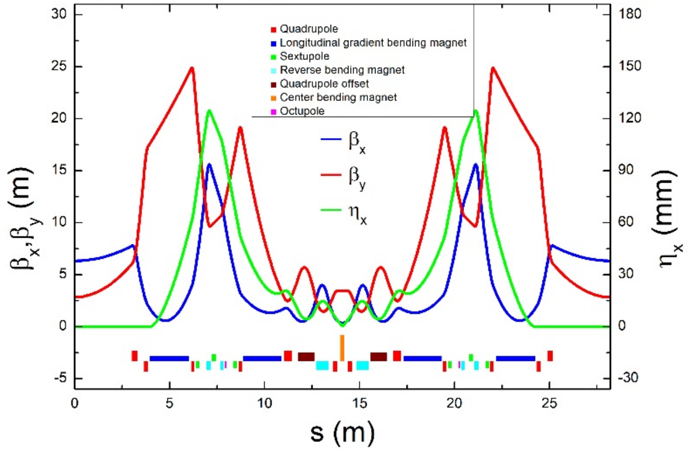
Linear Optics of the Storage Ring



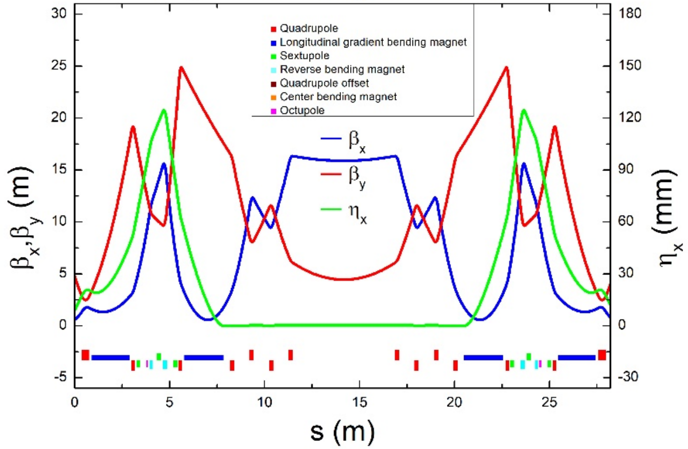
- The ring is composed of 28 cells
(28 identical arcs, 26 ID SS + 2 high-beta SS)
- **It has 2-fold geometric symmetry**



Arc + ID straight section

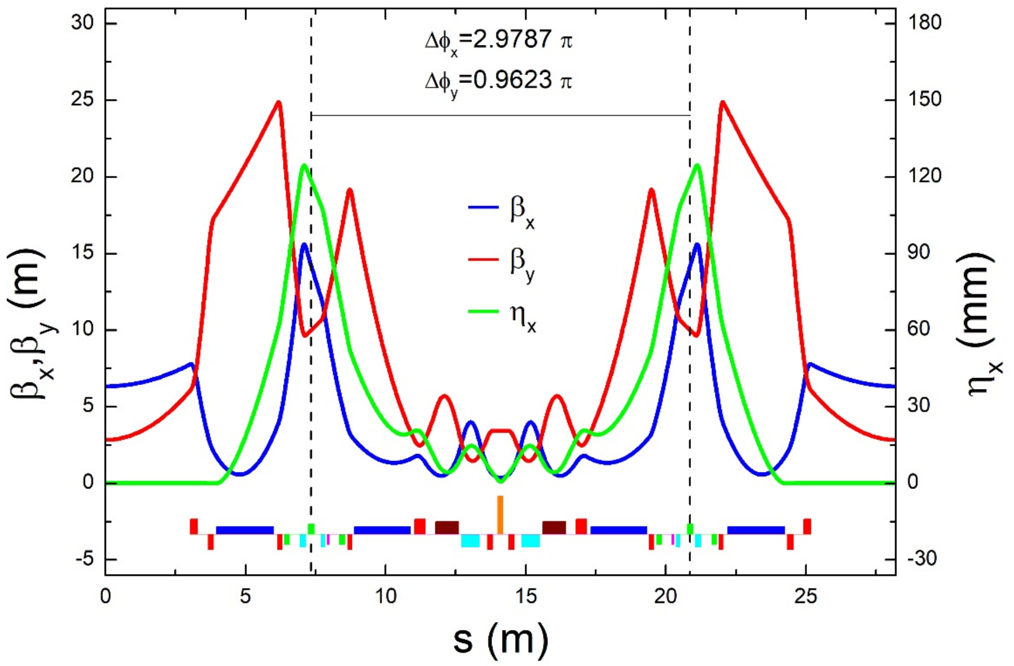


Arc + High-beta straight section



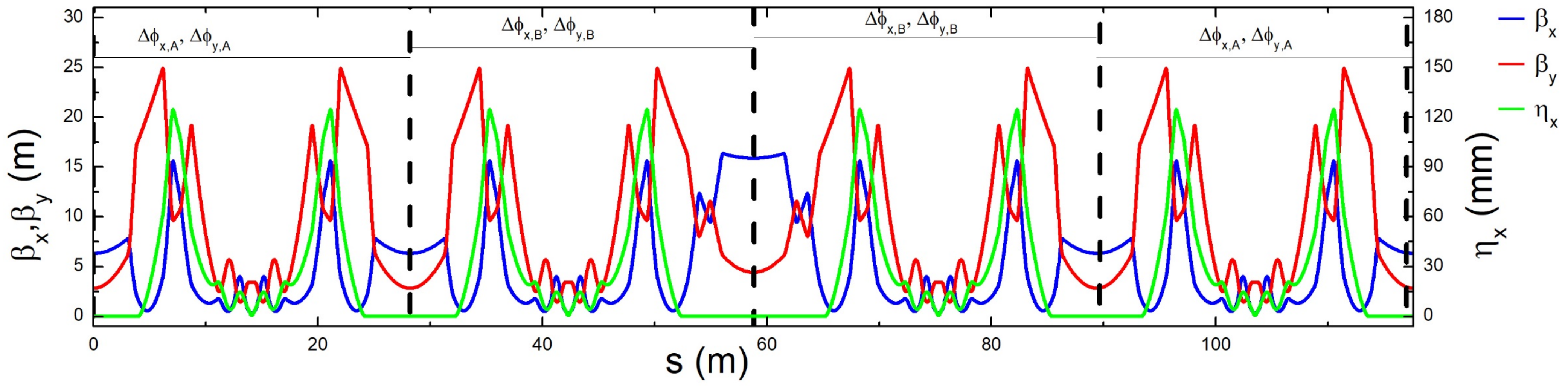
Parameters	Value
Energy (GeV)	**4.0**
Circumference (m)	**799.297**
Emittance (pm)	**62**
Tunes (H,V)	**68.18, 23.26**
Natural chromaticity (H,V)	**-112.2, -85.3**
Chromaticity (corrected) (H,V)	**5.8 , 3.5**
Hor. Damping partition	**1.84**
Momentum compaction	$\mathbf{7.8 \times 10^{-5}}$
Energy spread (σ_δ)	$\mathbf{1.26 \times 10^{-3}}$
Energy loss per turn (MeV)	**1.098**
Beam current (mA)	**400**
Bunch length (σ_z) (mm)	**3.66 / 14.66**

Linear Optics of the Storage Ring



- Each arc has a 2-T bending source.
- Phase advance between dispersion bumps nearly satisfy –I transform which help to cancel out nonlinear driving terms within a cell.
- Length of ID SS is 6.06 m.
- β_x at the middle of SS is 6.33 m which is higher than the known optimal β_x for best matching between photon beam and electron beam ($\beta_{x,\,optimal}$ = $\frac{L}{2\pi}$ = 1 m).
- We realized that further reducing β_x from current value highly compromises with high-order chromaticity which result in poor Touschek lifetime.

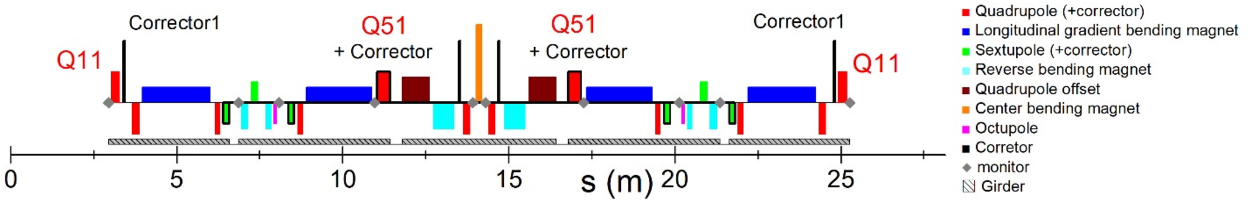
Linear Optics of the Storage Ring



- The ring is composed of 28 cells (28 identical arcs, 26 ID SS + 2 high-beta SS).
- Phase advance is matched to have identical phase advance ($\Delta\phi_{x,A} = \Delta\phi_{x,B}$ and $\Delta\phi_{y,A} = \Delta\phi_{y,B}$).
- Though the ring has 2-fold geometric symmetry, it has 28-cell symmetry in terms of phase advance (on-momentum).
- High-beta straight section provides larger DA than ID SS as much as $\sqrt{\frac{15.90}{6.33}} = 1.58$.
- One high-beta straight section is dedicated for off-axis injection and the other one will be occupied by RF cavities.

Amplification factor and Corrector Deployment

Magnet diagram : ID cell



❖ The amplification factor is defined as $x_{COD,rms}^2 = \beta(z)A_{\Delta x}^2\sigma_{\Delta x}^2 + \beta(z)A_{\Delta B/B}^2\sigma_{\Delta B/B}^2 + \beta(z)A_{\Delta\theta}^2\sigma_{\Delta\theta}^2$

Amplification factor type	Magnet name	A_x	A_y	$A = \sqrt{A_x^2 + A_y^2}$
Quadrupole $A_{\Delta x}$ $\sigma_{\Delta x}^2$ = 100 μm	QH1	0.12	0.05	0.13
	QH2	0.15	0.12	0.20
	QH3	0.27	0.17	0.32
	QH4	0.06	0.10	0.11
	Q11	**1.09**	**0.76**	**1.33**
	Q12	0.42	0.81	0.91
	Q31	0.56	1.00	1.14
	Q32	0.49	0.88	1.01
	Q51	**0.93**	**0.80**	**1.22**
	Q52	0.34	0.52	0.62
Dipole $A_{\Delta B/B}$ $\sigma_{\Delta B/B}^2 = 0.1\%$	LGBM1	0.16	0.68	0.70
	LGBM2	0.20	0.35	0.40
	DQ51	0.20	0.25	0.32
	CENT	0.06	0.13	0.14

❖ $A_{\Delta x}^2$ shows the effect on the closed orbit distortion from the quadrupole misalignment error and $A_{\Delta B/B}^2$ from the dipole field strength error.

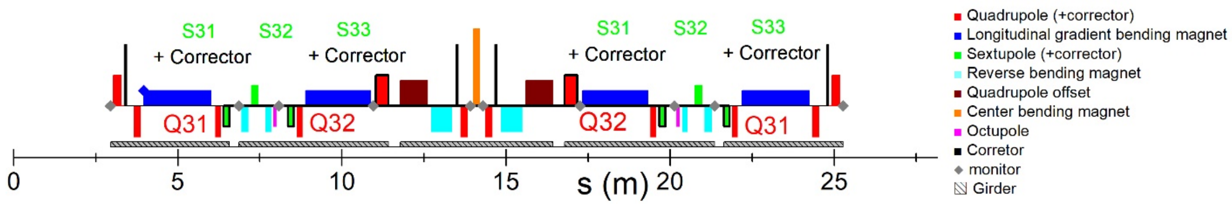
❖ Most powerful sources are Q11 and Q51.

❖ The correctors are required to correct them.

❖ For Q11, independent corrector "corrector1" is employed close to the quadrupole.

❖ For Q51, the magnet design is revised to have the corrector field by adding the auxiliary coil.

Magnet diagram : ID cell



Amplification factor and Corrector Deployment

❖ The amplification factor is defined as $x^2_{COD,rms} = \beta(z)A^2_{\Delta x}\sigma^2_{\Delta x} + \beta(z)A^2_{\Delta B/B}\sigma^2_{\Delta B/B} + \beta(z)A^2_{\Delta\theta}\sigma^2_{\Delta\theta}$

Amplification factor type	Magnet name	A_x	A_y	$A = \sqrt{A_x^2 + A_y^2}$
Embedded corrector $A_{\Delta\theta}$ $\sigma^2_{\Delta\theta}$=500 μrad	QH1	27.54	11.46	29.83
	QH2	20.03	16.35	25.85
	QH3	22.34	13.73	26.22
	QH4	12.29	19.39	22.95
	Q11	64.88	45.15	79.04
	Q12	37.18	70.92	80.07
	Q31	**50.39**	**89.75**	**102.93**
	Q32	**44.04**	**79.20**	**90.62**
	Q51	33.02	28.58	43.67
	Q52	21.88	33.16	39.73
	S31	**64.50**	**79.82**	**102.62**
	S32	**91.70**	**57.17**	**108.06**
	S33	**54.82**	**74.02**	**92.11**
Independent corrector $A_{\Delta\theta}$ $\sigma^2_{\Delta\theta}$=500 μrad	Corrector1	54.11	55.38	77.43
	Corrector2	33.81	27.69	43.71

❖ $A^2_{\Delta\theta}$ shows the effectiveness of the corrector on the closed orbit.

❖ To select the embedded corrector, the amplification factor of quadrupole and sextupole is calculated.

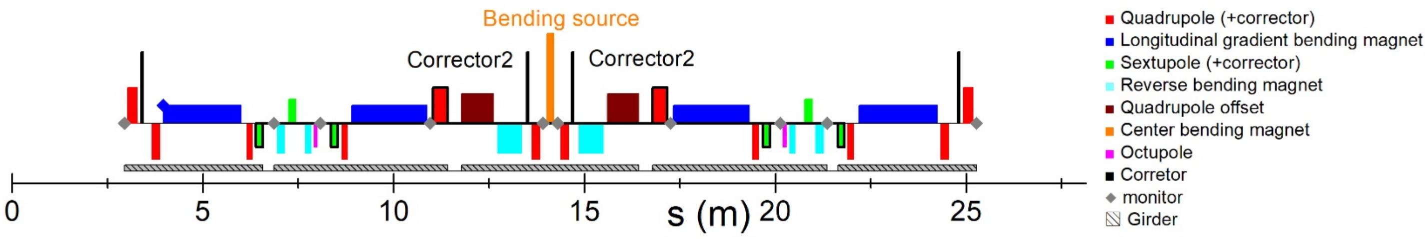
❖ Most effective magnets are Q31, Q32 and sextupoles.

❖ Q31, S31 and Q32, S33 are close, so two of one is selected as embedded corrector and because sextupoles are slightly more effective, sextupoles are selected.

❖ Because the phase advance between three sextupole are too small, all three sextupole are not required. Considering the easiness of magnet manufacturing, S31 and S33 are selected as embedded corrector finally.

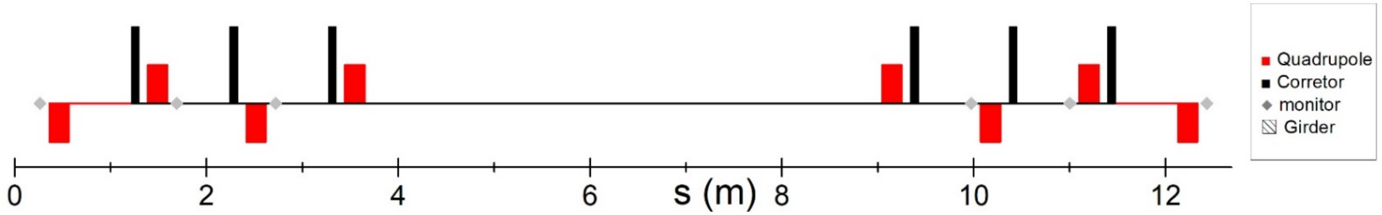
Amplification factor and Corrector Deployment

Magnet diagram : ID cell



❖ "Corrector2" is also employed for the bending beamline alignment.

Magnet diagram : high beta straight section



❖ For the injection at the commissioning stage, more correctors are employed in high beta straight section.

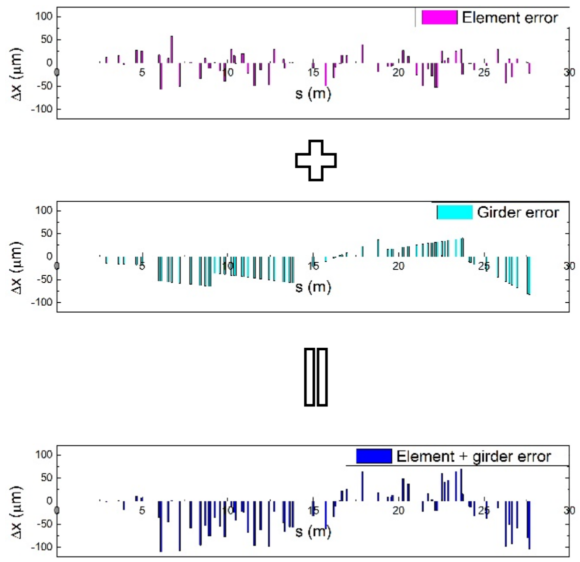
	Number in a cell	Number in a ring
Monitor	10 / 12	288
Corrector	10 / 12	288

❖ As a pair of corrector, monitors are employed, so the number of monitor and the number of the corrector is the same.
❖ The monitor is located as close as possible to corrector.
❖ The number of corrector(monitor) in a cell is 10.
❖ The total number of corrector(monitor) in a ring is 288.

Error Tolerance

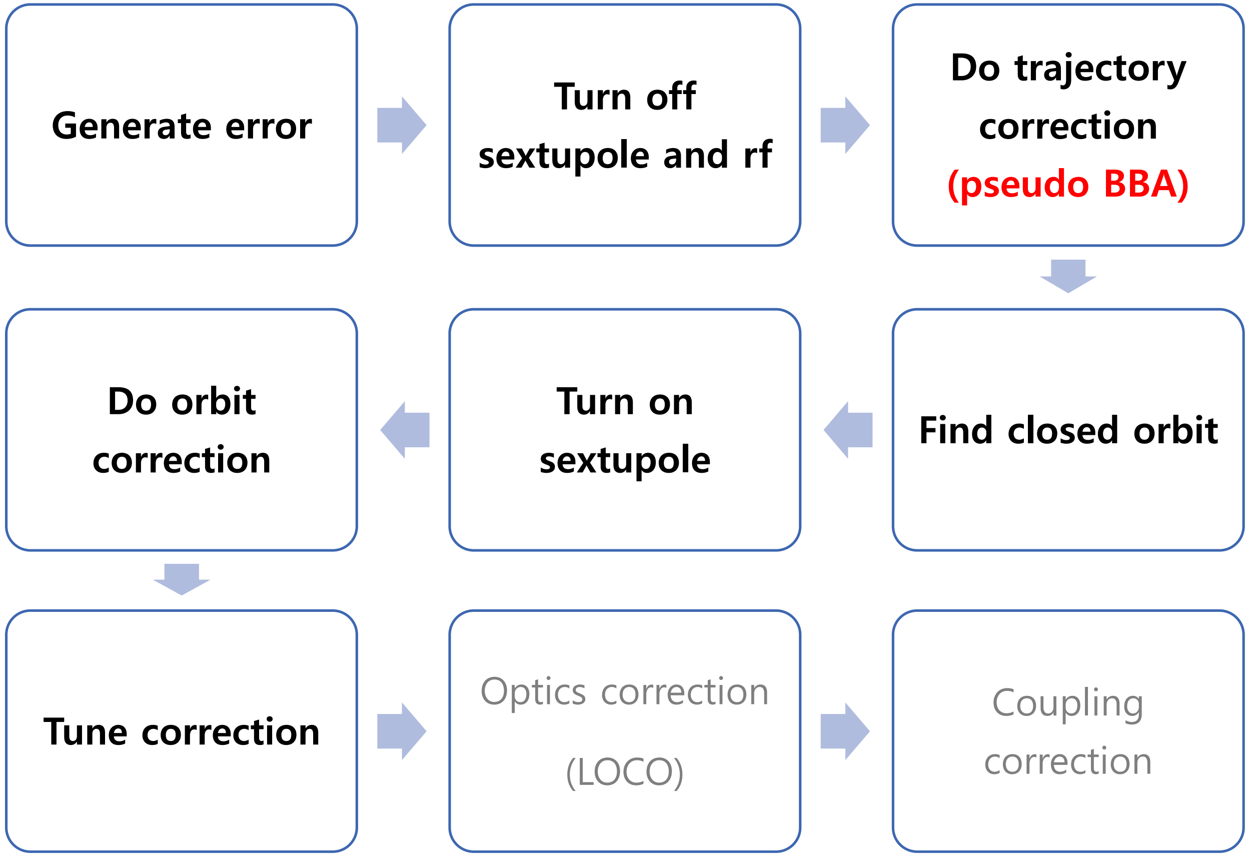
Gaussian error cut off : 2σ	Horizontal misalignment error	Vertical misalignment error	Longitudinal misalignment error	Rotation error tilt / pitch / yaw	Relative strength error
Longitudinal gradient bend magnet	30 μm	30 μm	250 μm	400/100/100 μrad	0.05 %
Combined magnet (Quadrupole offset)	30 μm	30 μm	250 μm	400/700/700 μrad	0.05 %
Quadrupole	30 μm	30 μm	250 μm	400/700/700 μrad	0.05 %
Center bend magnet	30 μm	30 μm	250 μm	400/100/100 μrad	0.05 %
Sextupole	30 μm	30 μm	250 μm	400/700/700 μrad	0.05 %
Octupole	30 μm	30 μm	250 μm	400/700/700 μrad	0.05 %
Girder (1σ cut off)	100 μm	100 μm	100 μm	-	-
BPM	600 μm	600 μm	-	1 mrad	-
Corrector	-	-	250 μm	1 mrad	5.0 %

Misalignment error



- ❖ For the correction simulation, realistic error tolerance is determined which is comparable to other 4GSR error tolerance.
- ❖ Element misalignment error is a relative displacement between the elements within the same girder, the girder misalignment error is relative displacement between the girders (figure).
- ❖ Our alignment team has investigated this tolerance data and in the process of confirming it.
- ❖ Multipole errors for quadrupoles and sextupoles are included in the correction simulation.
- ❖ Injection error at the commissioning stage, is contained.
- ❖ Aperture information is included.

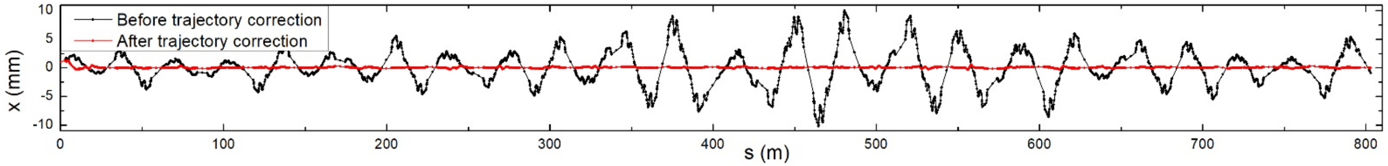
Correction Simulation Process



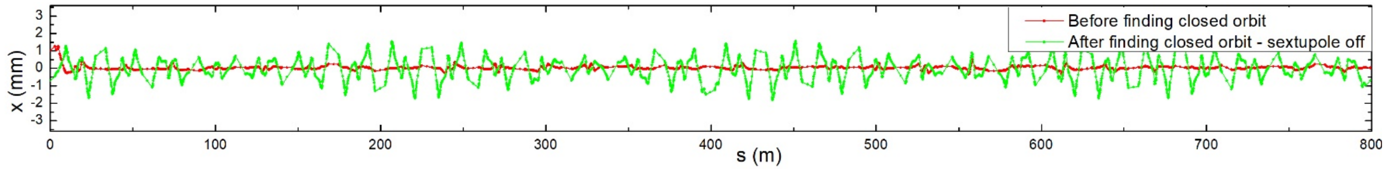
- ❖ 20 error ensembles are used for the simulation.
- ❖ To reduce the nonlinear effect, sextupoles are turned off during the trajectory correction.
- ❖ Without trajectory correction, most of the error seed can't find a closed orbit.
- ❖ Pseudo beam based alignment is assumed (next page).
- ❖ SVD method is used for the trajectory correction and orbit correction. The number of singular value for the correction is optimized for each seed.
- ❖ The closed orbit is found under the trajectory correction setting.
- ❖ After finding closed orbit, sextupole are turned on.
- ❖ Linear optics correction has not been conducted completely.
- ❖ In the whole process, the corrector strength is limited to 600 μrad.

Correction Simulation Process

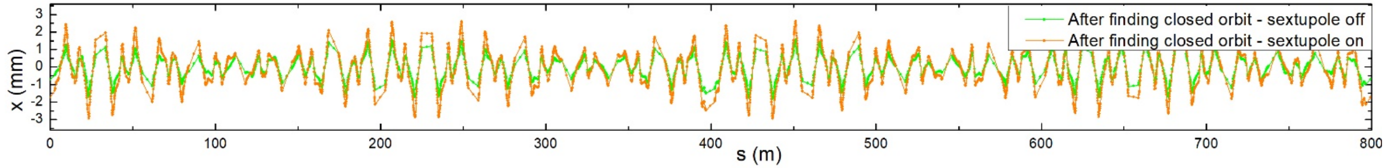
1 Trajectory correction



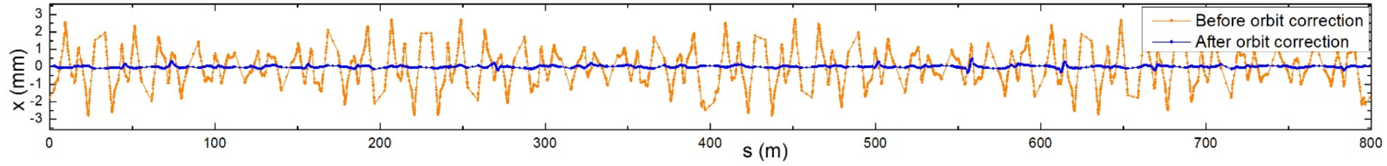
2 Finding closed orbit



3 Sextupole turned on



4 Orbit correction



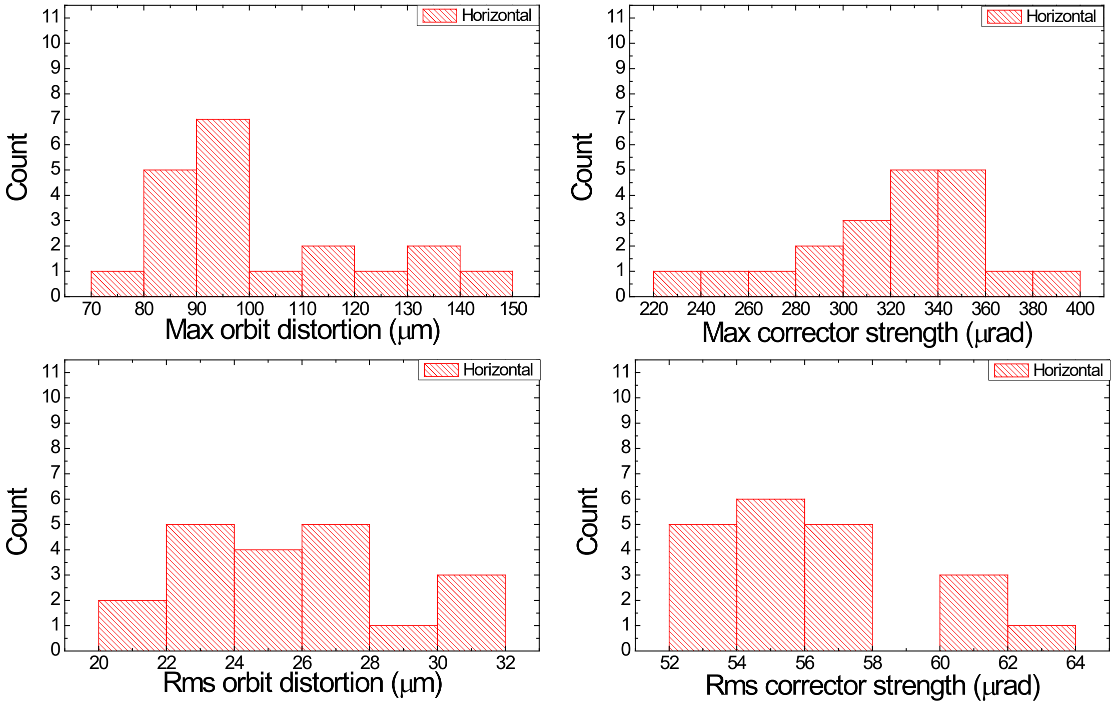
1.5 Pseudo beam based alignment

- ❖ Beam based alignment technic is used to align the quadrupole and bpm.
- ❖ In the trajectory correction process, we assumed the beam based alignment is conducted.
- ❖ With this assumption the bpm misalignment error reduces from 600 μm to 30 μm related to the neighborhood quadrupole.

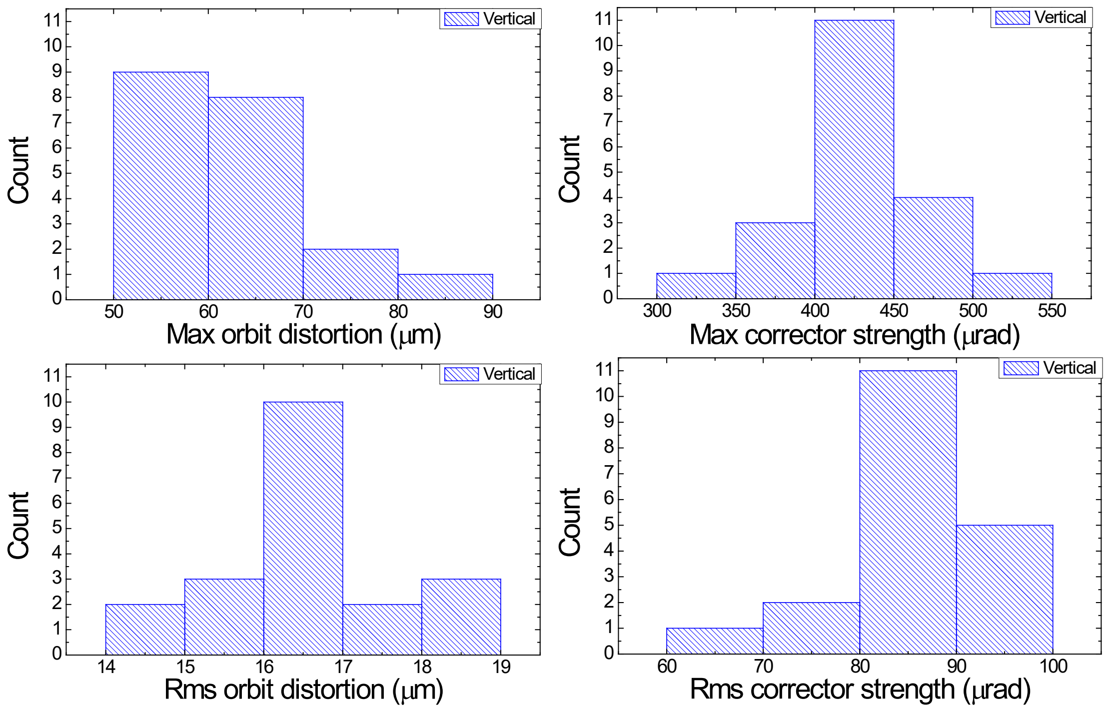
Correction Result

Closed orbit distortion

Horizontal plane

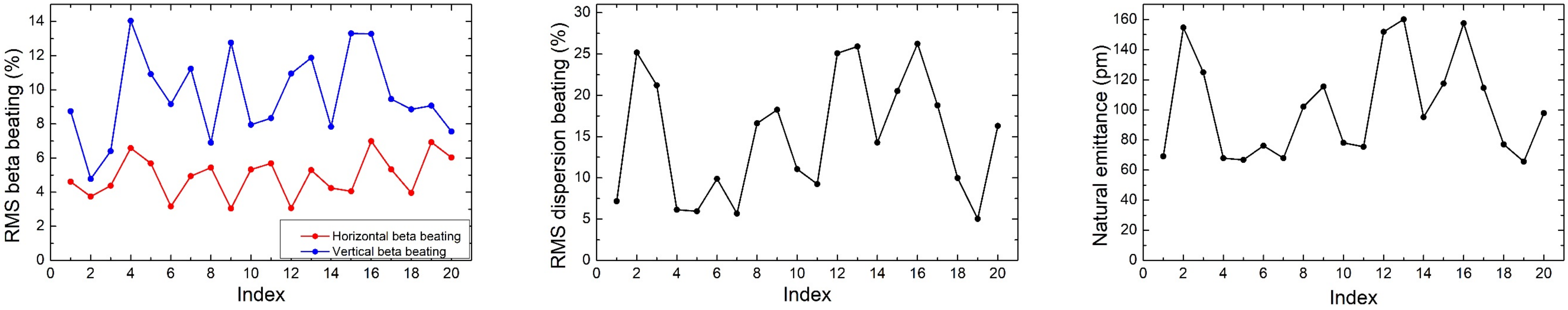


Vertical plane



- ❖ For all error sets, maximum orbit is below than 150 μm in horizontal plane and below than 90 μm in vertical plane.
- ❖ For the correction the maximum corrector strength is 550 μrad. Mechanical limit of the corrector is 600 μrad.
- ❖ For all seed, rms orbit is less than 32 μm in both planes.

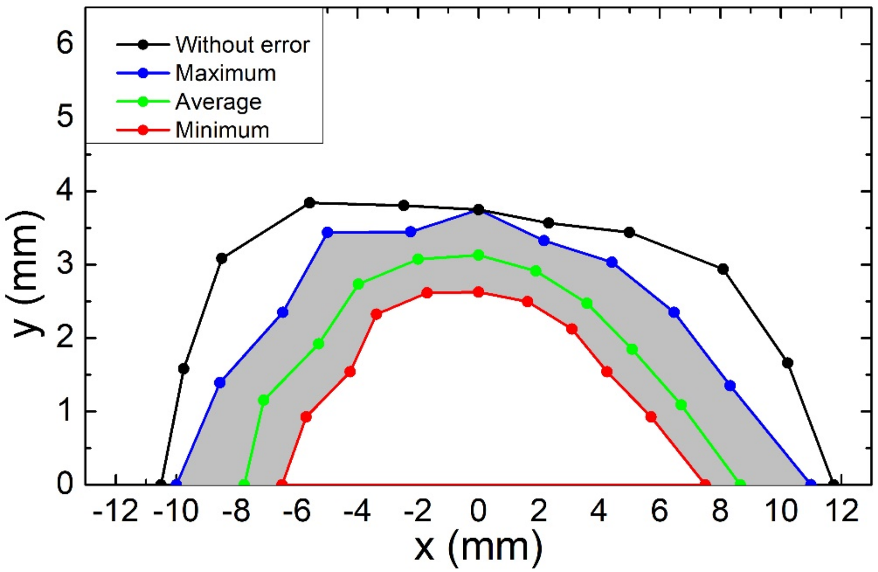
Correction Result



- The beta beating is about 3-14 %.
- Vertical beta beating is bigger than horizontal beta beating.
- The vertical beta function is larger than the horizontal beta function and that results in larger vertical beta beating.
- Our beta beating target is about 1 % and to reach the target, optics correction study is in progress.
- The shape of dispersion beating graph and emittance graph seem similar. The dominant factor of emittance increase is the dispersion distortion.

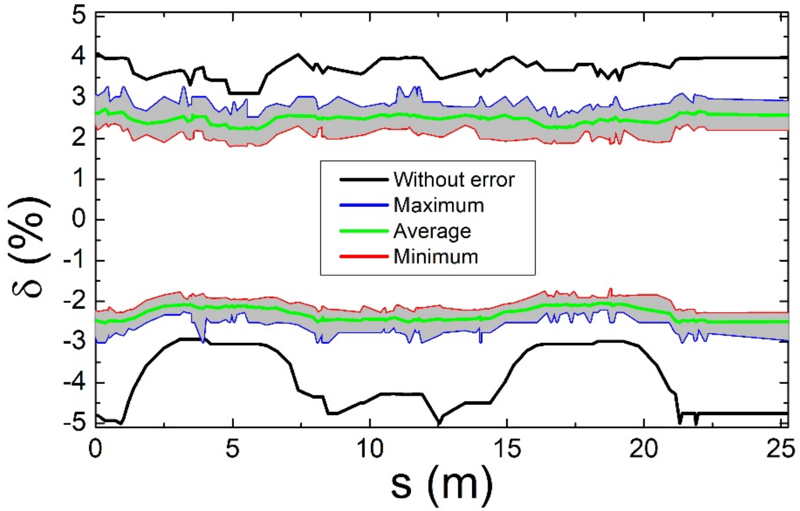
Correction Result

Dynamic aperture



- Even before the linear lattice correction, at least 6.5 mm dynamic aperture is obtained.
- The injection scheme of the storage ring is four kicker off-axis injection with 5 mm oscillation amplitude.
- Even for the worst case, the promising injection is expected.

Momentum aperture and Touschek lifetime



Bunch charge [nC]	1.0	
With/without error	Without error	With error average
Touschek lifetime [h]	5.26	1.47

- The bunch charge is 1.0 nC for the multi-bunch operation mode (1065/1332) with 400 mA.
- Active third harmonic cavity will be installed to increase the Touschek lifetime.
- The study of using harmonic cavity is conducted and the result shows that the three times longer Touchek lifetime can be obtained.
- Improvement of local momentum acceptance expected by running MOGA or MOPSO with increased number of sextupole/octupole families.

Summary

- ❖ The 800 m – 4 GeV – 28-cell ring with 62 pm natural emittance is under construction at Ochang.
- ❖ Two high-beta straight sections are used for off-axis injection and RF installation respectively.
- ❖ From the error study, the tolerance and the corrector requirement are determined.
- ❖ After the correction, max orbit is less than 150 μm, and rms orbit is less than 32 μm.
- ❖ Even before the linear lattice correction, at least 6.5 mm dynamic aperture is obtained which is promising result for the off-axis injection.

Thank you!

Amplification factor and Corrector Deployment

Closed orbit distortion from perturbation $p_0(\varsigma)$ is

$$u_c = \frac{\sqrt{\beta(z)}}{2\sin\pi\nu}\oint_z^{z+C} d\varsigma \left(p_0(\varsigma)\sqrt{\beta(\varsigma)}\cos[\nu\varphi(z) - \nu\varphi(\varsigma) + \nu\pi]\right)$$

. The rms orbit distortion is

$$\langle u_c^2(z)\rangle = \frac{\beta(z)}{8\sin^2\pi\nu}\sum_i \langle p_0^2 \beta l_i^2\rangle$$

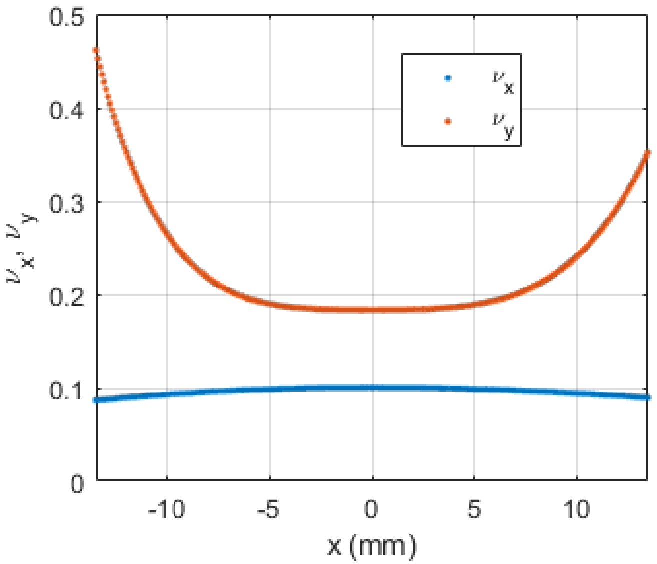
. The definition of amplification factor is

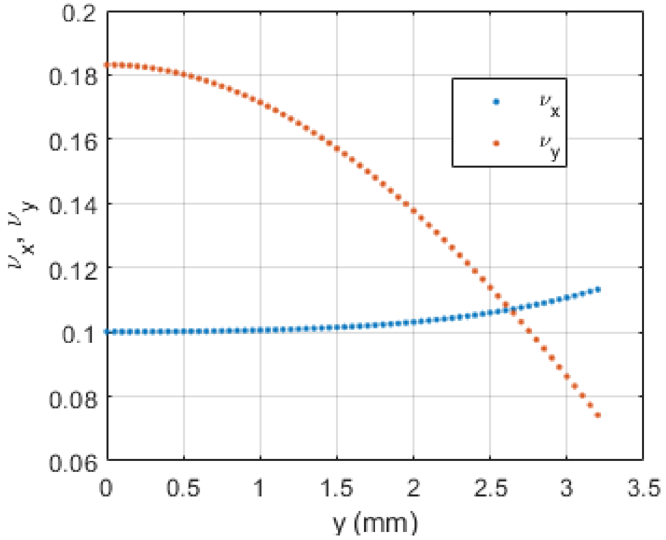
$$\langle u_c^2(z)\rangle = x_{COD,rms}^2 = \beta(z)A_{\Delta x}^2\sigma_{\Delta x}^2 + \beta(z)A_{\Delta B/B}^2\sigma_{\Delta B/B}^2 + \beta(z)A_{\Delta\theta}^2\sigma_{\Delta\theta}^2$$

$$A_{\Delta x}^2 = \frac{N\beta_i}{8\sin^2\pi\nu}(k_i \cdot L_i)^2, \qquad A_{\Delta\theta}^2 = \frac{N\beta_i}{8\sin^2\pi\nu}, \qquad A_{\Delta B/B}^2 = \frac{N\beta_i}{8\sin^2\pi\nu}{\theta_i}^2$$

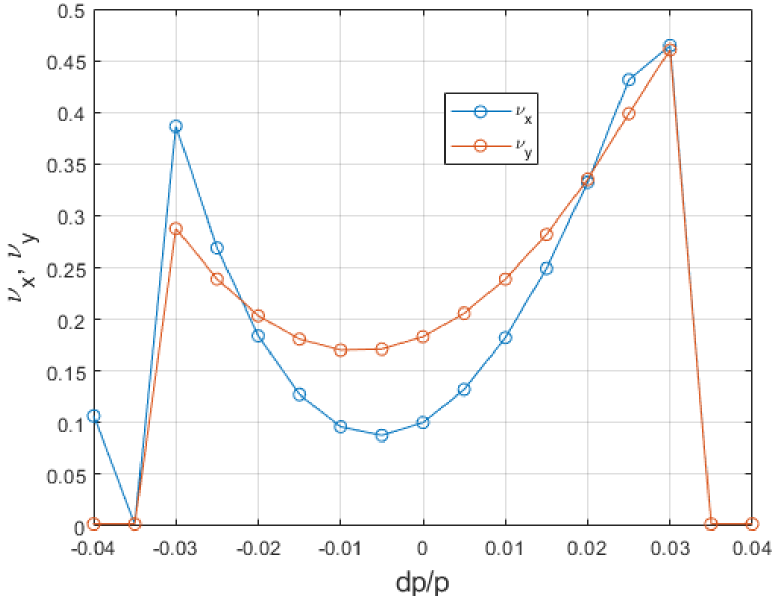
Nonlinear Optimization

Amplitude dependent tune shift (ADTS)





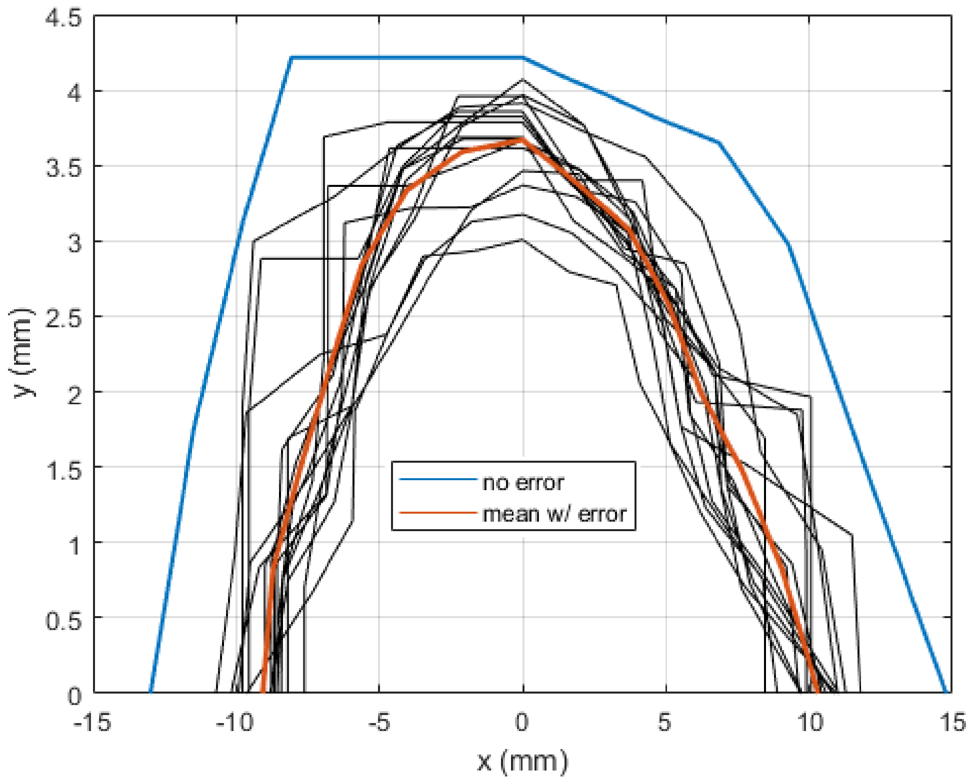
Momentum dependent tune shift (MDTS)



- ❖ Phase advance between dispersion bumps (fine-tuning around $\Delta\phi_x \sim 3\pi$ / $\Delta\phi_y \sim \pi$) and strengths of 3 sextupole families and 1 octupole family are iteratively scanned to suppress ADTS and MDTS.
- ❖ ADTS looks safe from critical resonances (integer/half-integer).
- ❖ Further suppression on MDTS is expected by running MOGA or MOPSO with increased number of sextupole/octupole families.

Nonlinear Performance

Dynamic aperture



❖ Field strength error and tilt error are assigned to selected quads and sexts to generate lattice ensembles of ~1 % beta-beat and ~10 % coupling.

❖ Realistic correction routines (orbit correction, optics correction, …) are omitted.

❖ Single particle tracking for 2048 turns w/RF cav, w/Synch Rad.

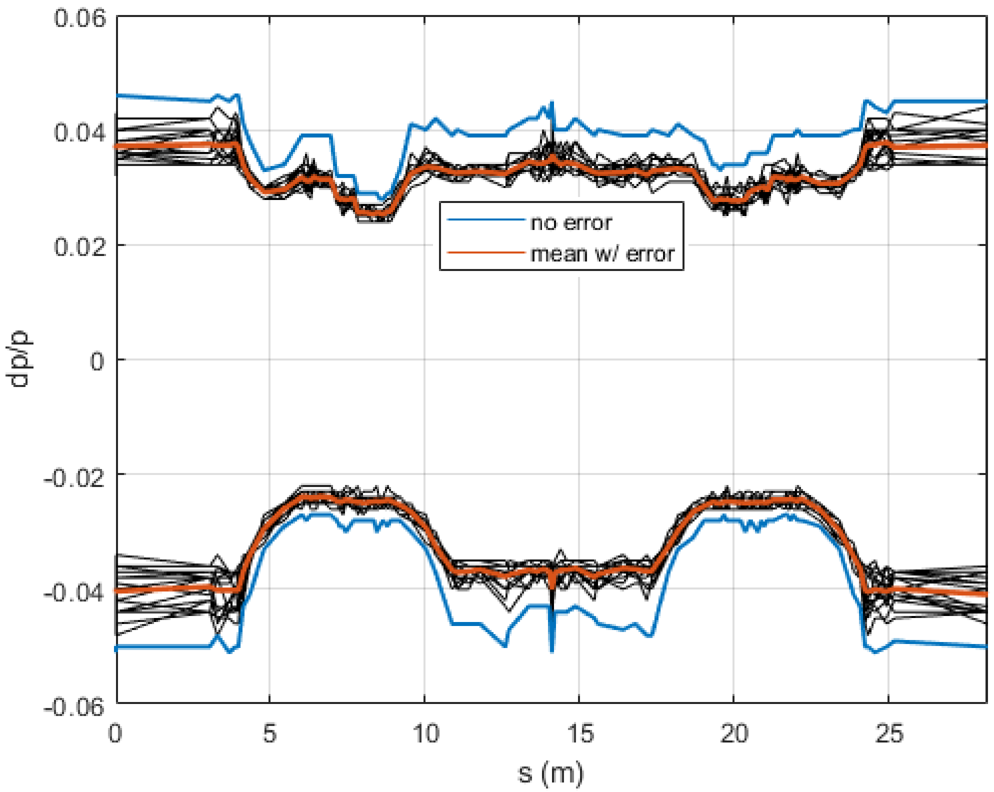
❖ **Dynamic aperture**

Beam will be injected at -x direction.
-13.0 mm (no error)
-9.1 mm (mean w/error)

❖ Realistic aperture information is not included.

Nonlinear Performance

Momentum aperture and Touschek lifetime



- ❖ Lattice ensembles of ~1 % beta-beat and ~10 % coupling are used (see previous slide).
- ❖ Single particle tracking for 2048 turns w/RF cav, w/Synch Rad.
- ❖ **Touschek lifetime (w/o 3HC)**

7.46 h (no error)
3.65 h (mean w/ error)
(for a single bunch of 1 nC (or 0.375 mA), 400 mA = 1067×0.375 mA)

- ❖ It can exceeds ~11 h when 3HC is included active 3HC will be installed for Korea-4GSR.