Lattice design for Korea-4GSR

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POHANG ACCELERATOR LABORATORY

Outline

- Brief introduction to Korea-4GSR project
- Storage ring lattice design
- Booster ring and injection system
- Summary

Brief introduction to Korea-4GSR project

Multipurpose Synchrotron Radiation Construction Project

Period: 2021 July to 2028 Feb. (7yrs)
Budget: ~750M USD
Location: Ochang, Chungcheongbuk-do

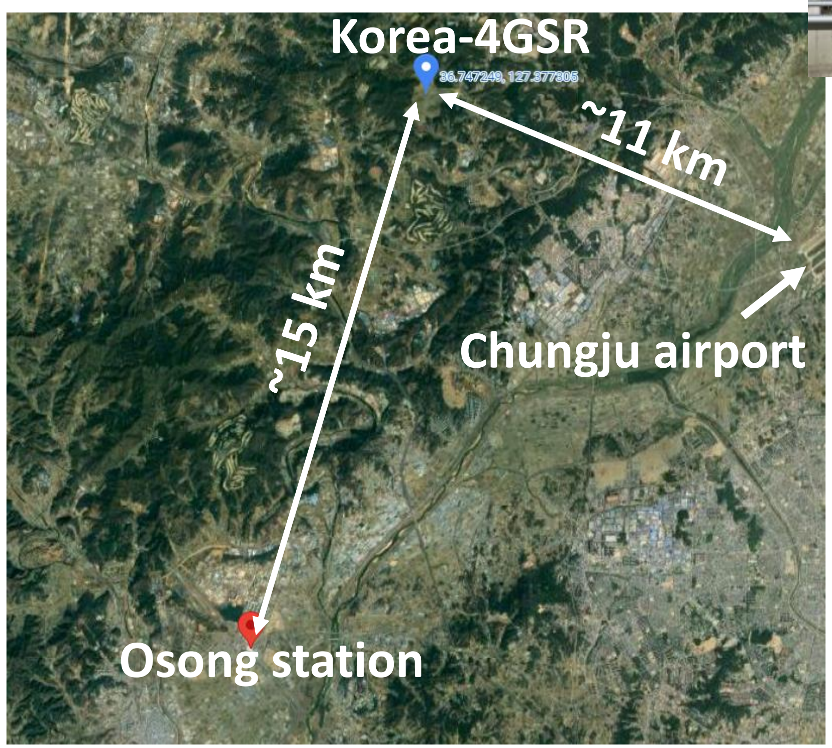
Beam energy: 4 GeV
Beam emittance: less than 100 pm
Circumference: 800 m

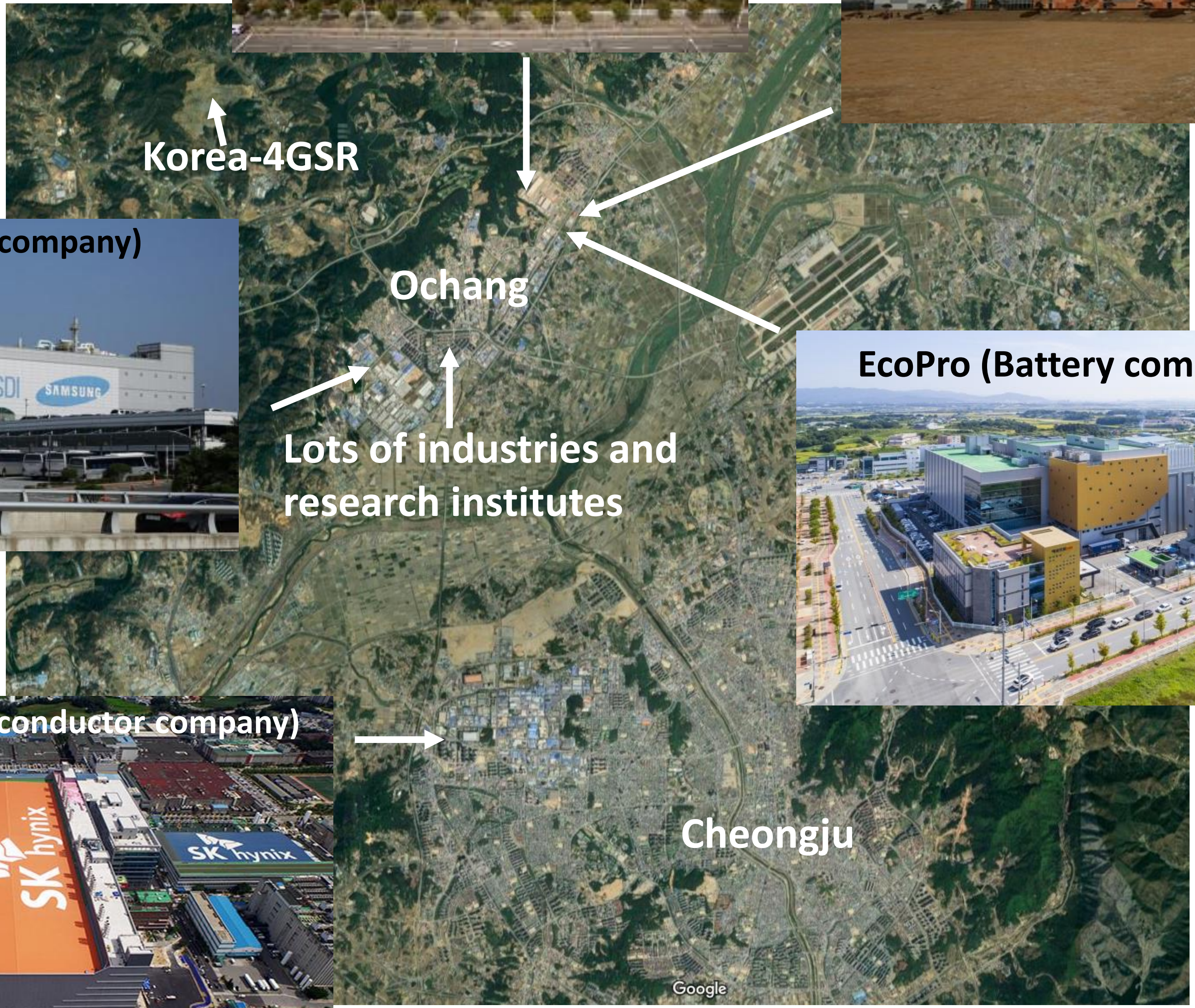
Ochang industrial complex

4GSR stands for 4th generation storage ring

Why Ochang?


Korea bullet train map
Seoul
Gangneung
Suwon
Cheonan(Asan)
Cheongju(Osong)
Andong-si
Daejeon
Gumi
Pohang
Jeonju
Daegu
Ulsan
Changwon
Jinju
Busan
Suncheon
Mokpo
Yeosu


Korea-4GSR
~11 km
~15 km
Chungju airport
Osong station


Korea-4GSR
Ochang
Lots of industries and
research institutes
Cheongju
Google
EcoPro (Battery company)

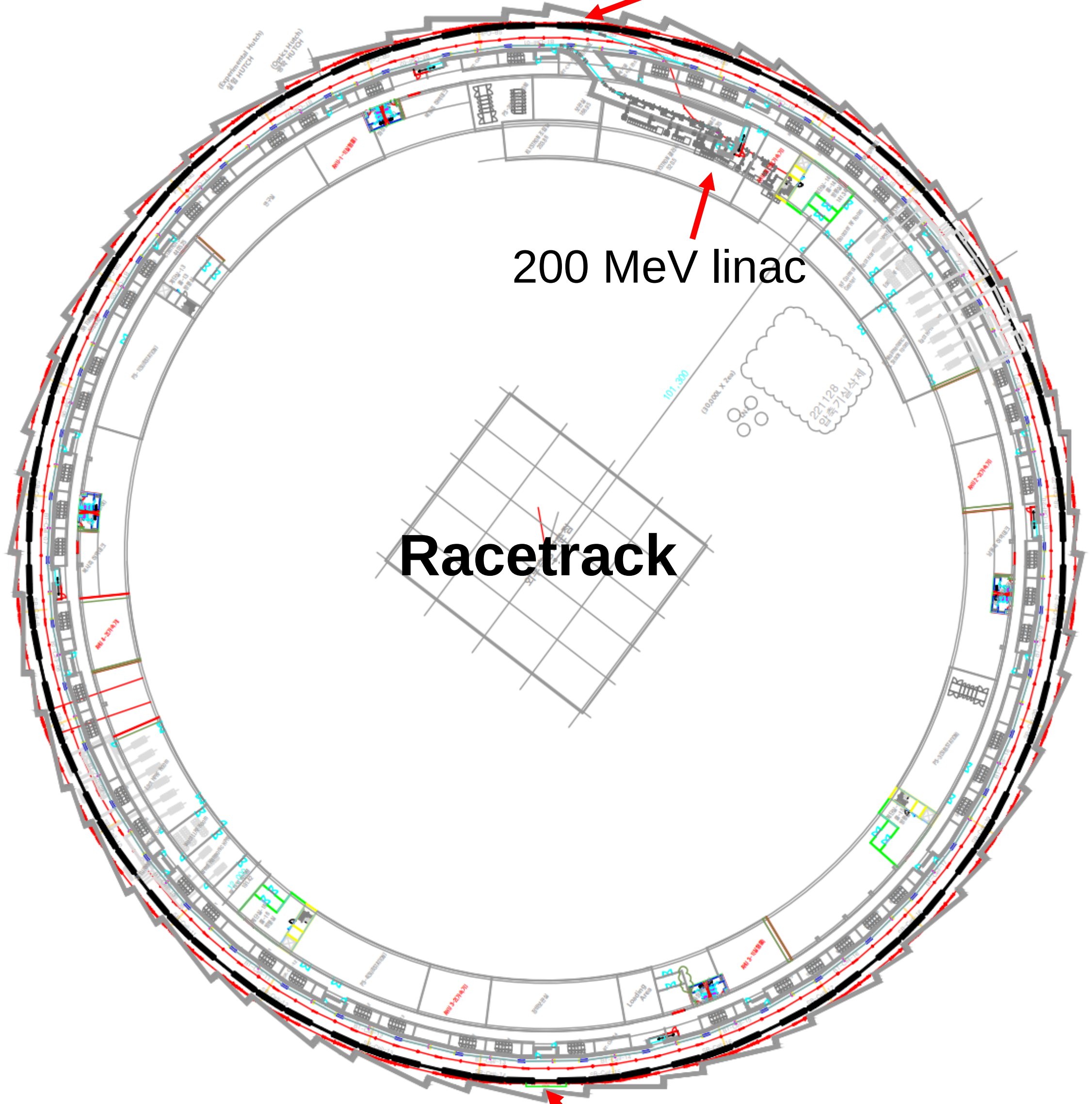

LG Energy solution (Battery company)


CELLTRION (pharmaceutical company)
CELLTRION


Samsung SDI (Battery company)
삼성SDI
SAMSUNG


SK Hynix (Semiconductor company)
SK hynix
SK hynix

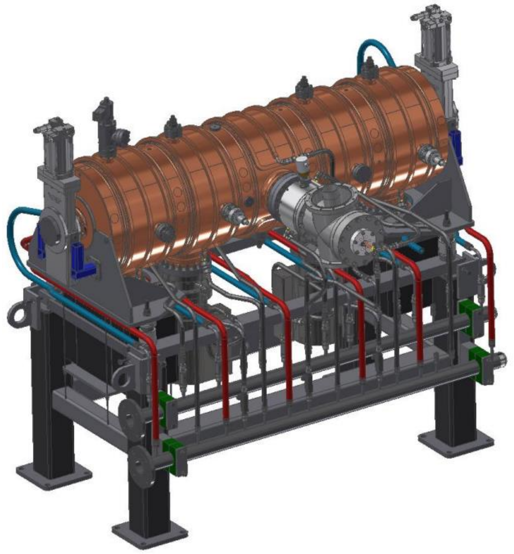
Overview of Korea-4GSR



Building cross section

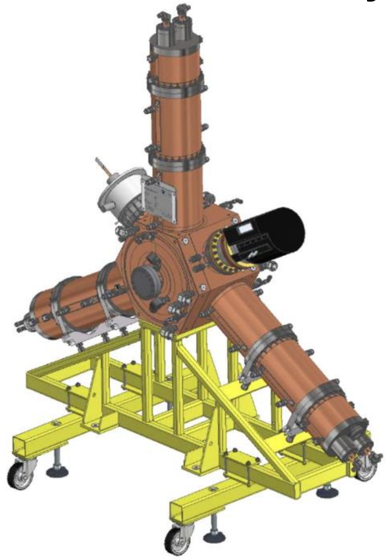
Booster and storage rings share a same tunnel

Booster RF cavity



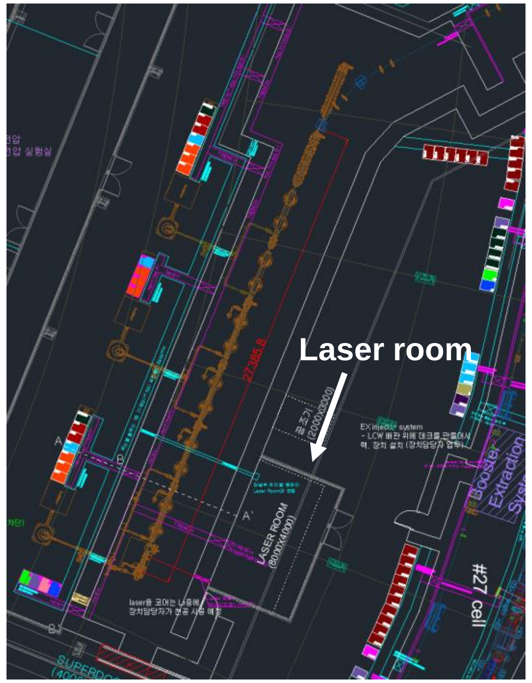
Normal conducting 5 cell cavity, 500 MHz

SR RF main RF cavity



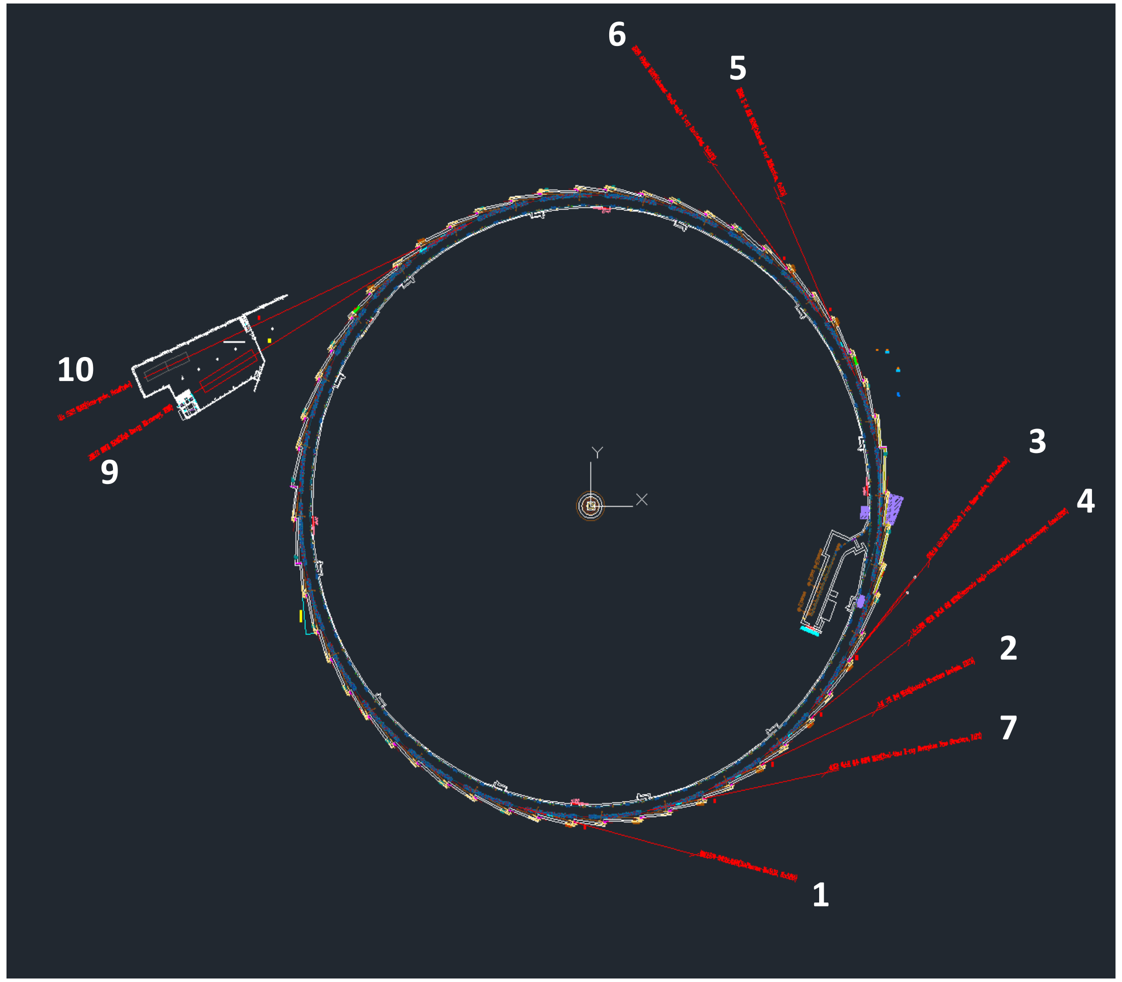
EU type normal conducting HOM damped RF cavity, 500 MHz

Photocathode gun



Initial X-ray beamlines

- 10 X-ray beamlines are planned

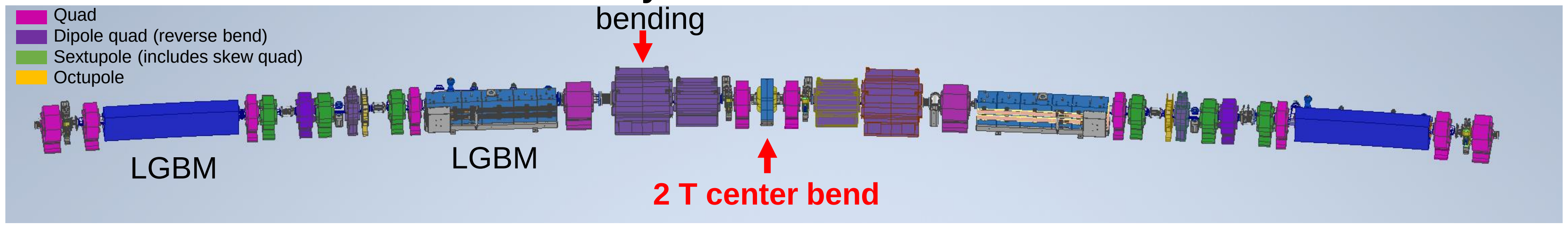


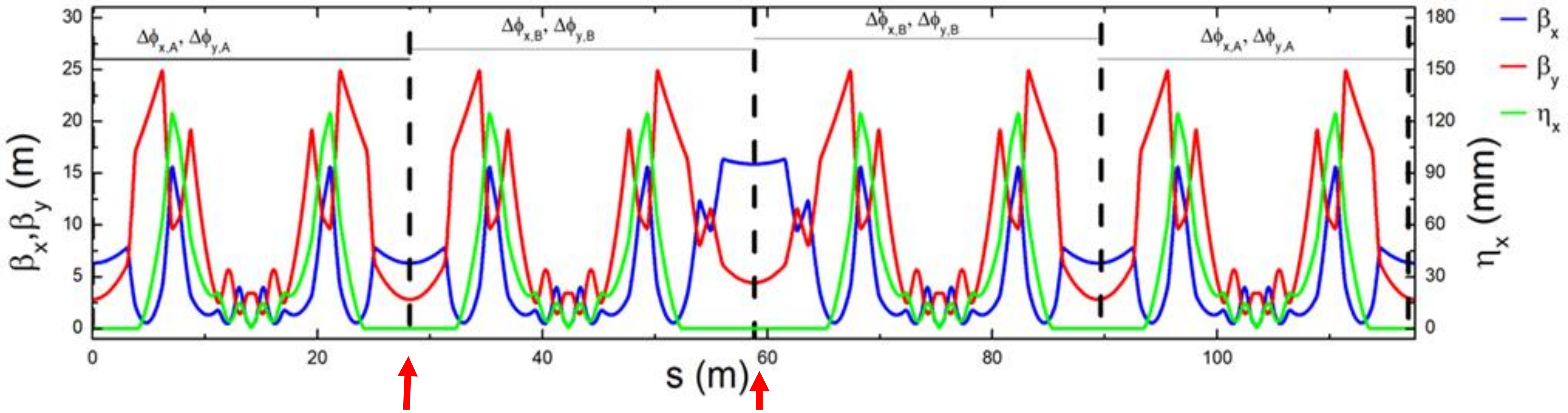
Target	Beamlines	Source	X-ray energy	Note
Industry oriented	1. BioPharma BioSAXS	IVU	5~20 keV	
	2. Material Structure Analysis	IVU	5~40 keV	
	3. Soft X-ray Nano probe	EPU+IVU	0.1~5.0 keV	
Research oriented	4. Nanoscale Angle resolved Photoemission	EPU	0.005~2 keV	
	5. Coherent X-ray Diffraction	IVU	3~30 keV	
	6. Coherent Small angle X-ray Scattering	IVU	8~30 keV	
	7. Real time X-ray Absorption Fine structure	IVU	4~40 keV	
	8. Bio Nano crystallography	IVU	5~20 keV	
	9. High Energy Microscopy	Center bend	5~100 keV	Long beamline
	10 Nano-probe	IVU	5~25 keV	Long beamline

Storage ring lattice design

Storage ring lattice design

Hybrid 7 Bend Achromat





Beta functions at the center of ID SS:
(β_x, β_y) = (6.33 m, 2.84 m)

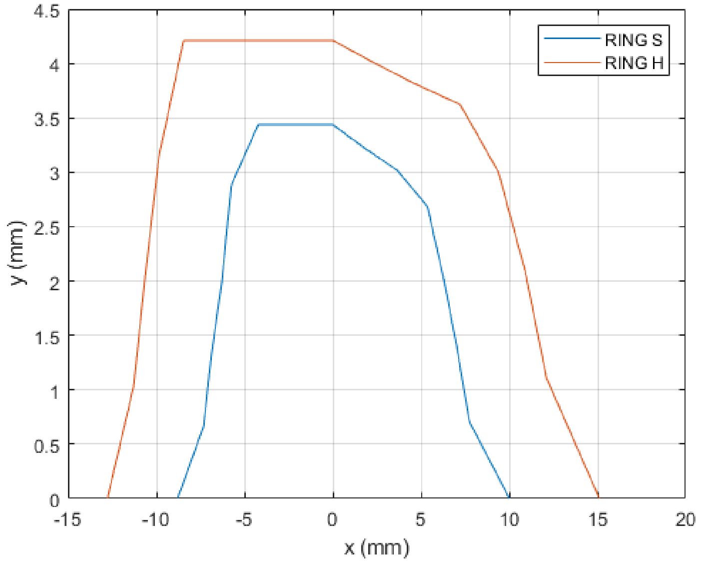
Beta functions at the center of High-beta SS:
(β_x, β_y) = (15.90 m, 4.45 m)

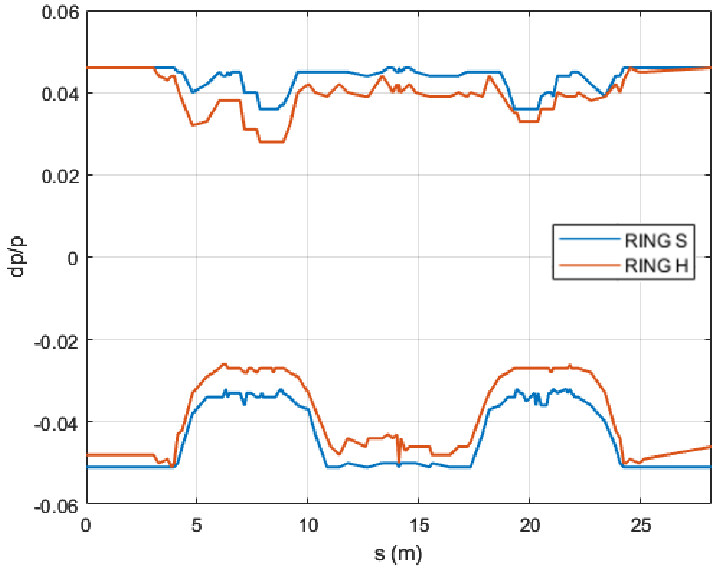
- The ring is composed of 28 H7BA cells (28 identical arcs, 26 ID SS + 2 high-beta SS)
- -I transform between dispersion bumps cancels dominant resonance driving terms within a cell
- Though the ring has 2-fold geometric symmetry, it has 28-cell symmetry in terms of on-momentum p hase advance ($\Delta\phi_{x,A} = \Delta\phi_{x,B}$ and $\Delta\phi_{y,A} = \Delta\phi_{y,B}$)

Parameters	Value
Energy (GeV)	**4.0**
Circumference (m)	**799.297**
Emittance (pm)	**62**
Tunes (H,V)	**68.18, 23.26**
Natural chromaticity (H,V)	**-112.1, -85.3**
Chromaticity (corrected) (H,V)	**5.8 , 3.5**
Hor. Damping partition	**1.84**
Momentum compaction	$\mathbf{0.78 \times 10^{-4}}$
Energy spread (σ_δ)	$\mathbf{1.26 \times 10^{-3}}$
Energy loss per turn (MeV)	**1.097**
Main RF voltage (MV)	**3.5**
Beam current (mA)	**400**
Bunch length (σ_z) (mm) (w/o HC, w/ HC)	**3.66 / 14.66**

Why we choose High-beta section

RING_S : Ring with full periodic 28-cell (no high-beta straight)
RING_H : Ring with 26 ID straights + 2 high-beta straights (28 identical arcs)



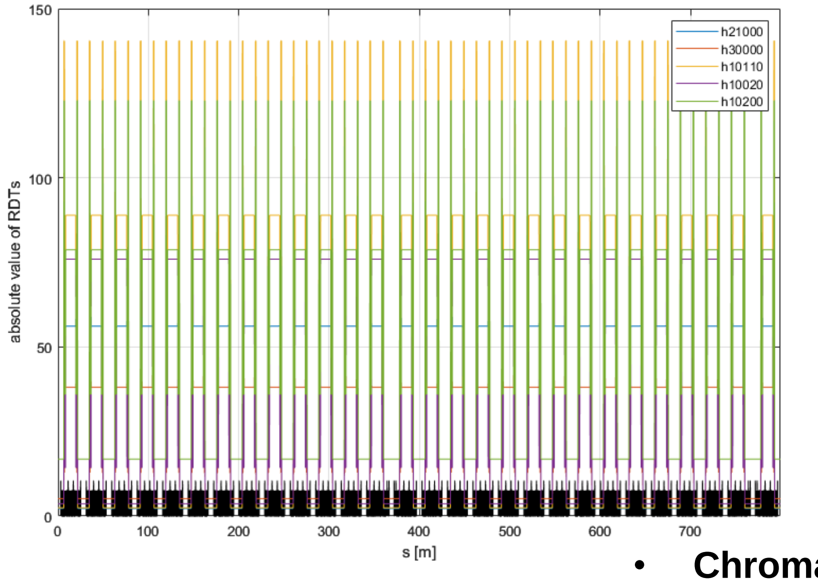


- RING_H has larger DA as much as ~ 1.45
- RING_H has smaller MA which result in 27% decrease of Touschek lifetime

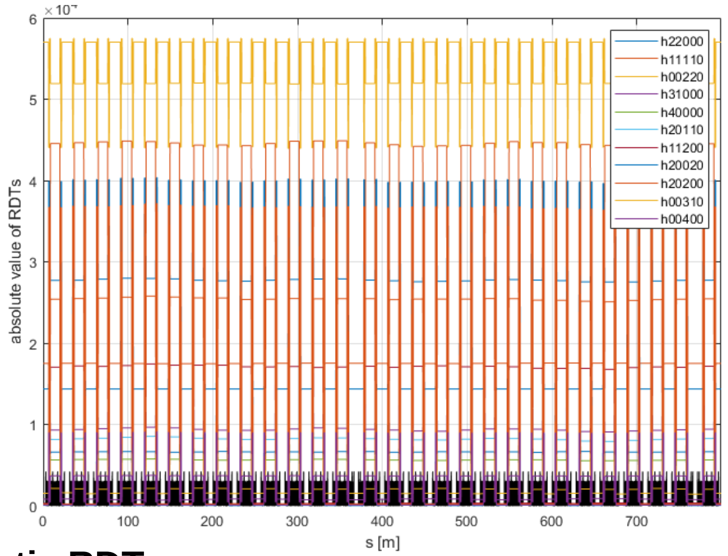
Korea-4GSR lifetime

Flat beam : coupling 10%			Round beam : coupling 100%		
Without HC	Without IBS	With IBS	Without HC	Without IBS	With IBS
Emittance (H/V)	58.40/5.84 pm	79.57/7.96 pm	Emittance (H/V)	39.91/39.91 pm	45.79/45.79 pm
Touschek lifetime	7.30 h	8.52 h	Touschek lifetime	17.04 h	17.38 h
With HC	Without IBS	With IBS	With HC	Without IBS	With IBS
Emittance (H/V)	58.40/5.84 pm	65.32/6.53 pm	Emittance (H/V)	39.91/39.91 pm	41.56/41.56 pm
Touschek lifetime	29.22 h	34.09 h	Touschek lifetime	68.18 h	66.39 h

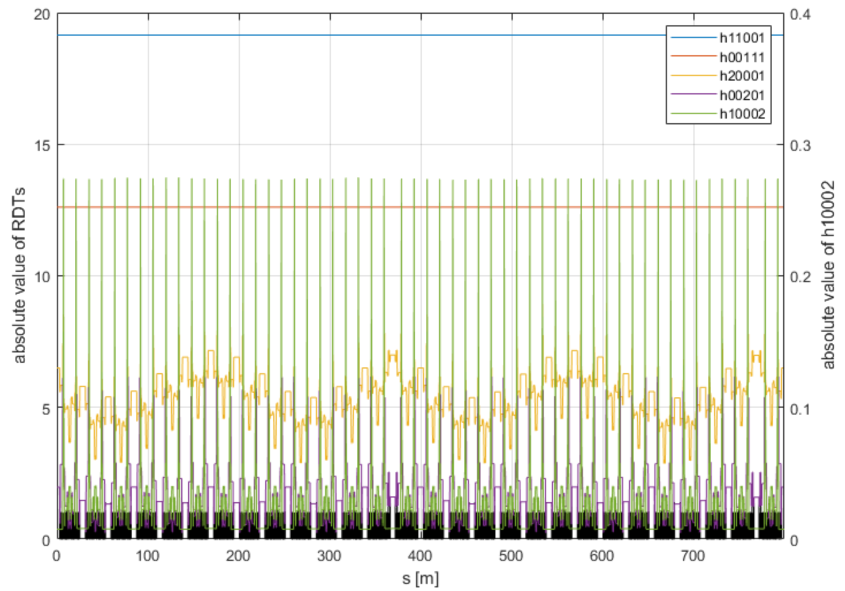
- **Geometric RDTs up to 3rd order**



- **Geometric RDTs up to 4th order**



- **Chromatic RDTs**



- The pseudo-symmetry keeps symmetry of geometric RDTs over the ring
- Chromatic RDTs are not fully periodic since chromaticities of high-beta cells are not exactly matched

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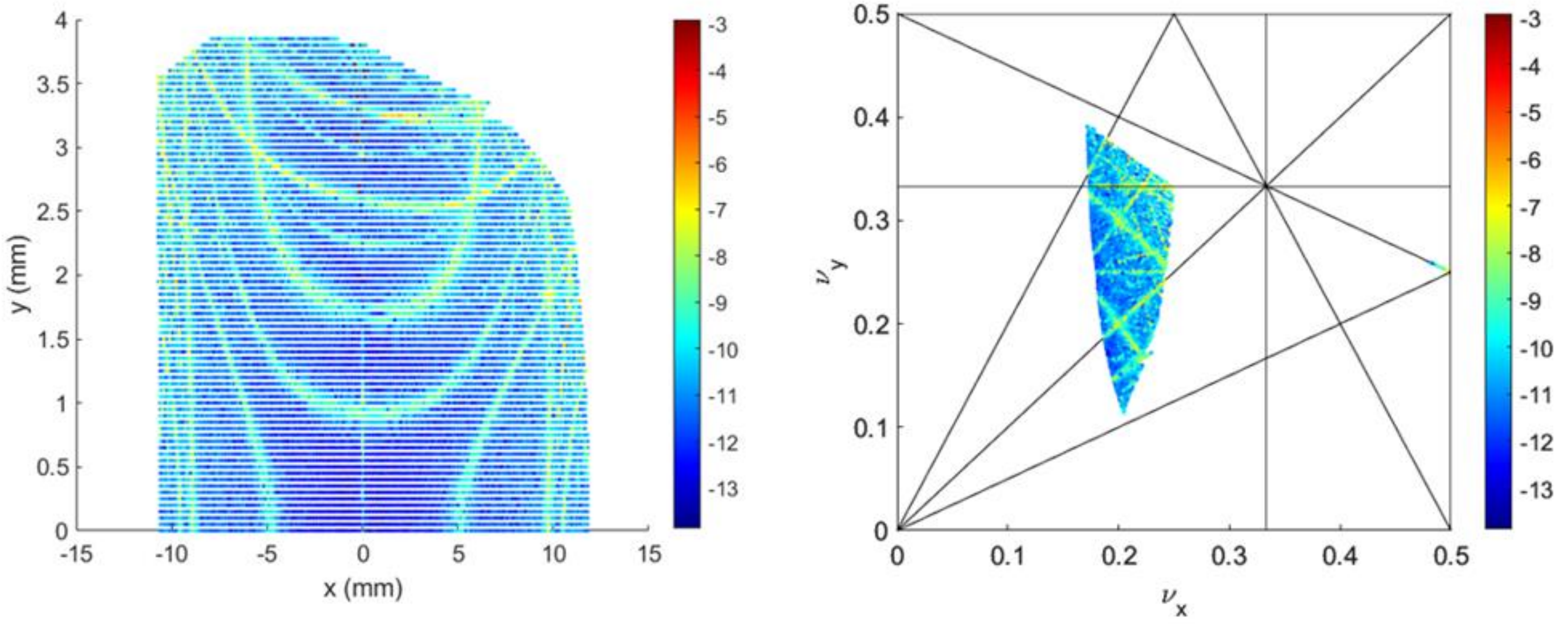
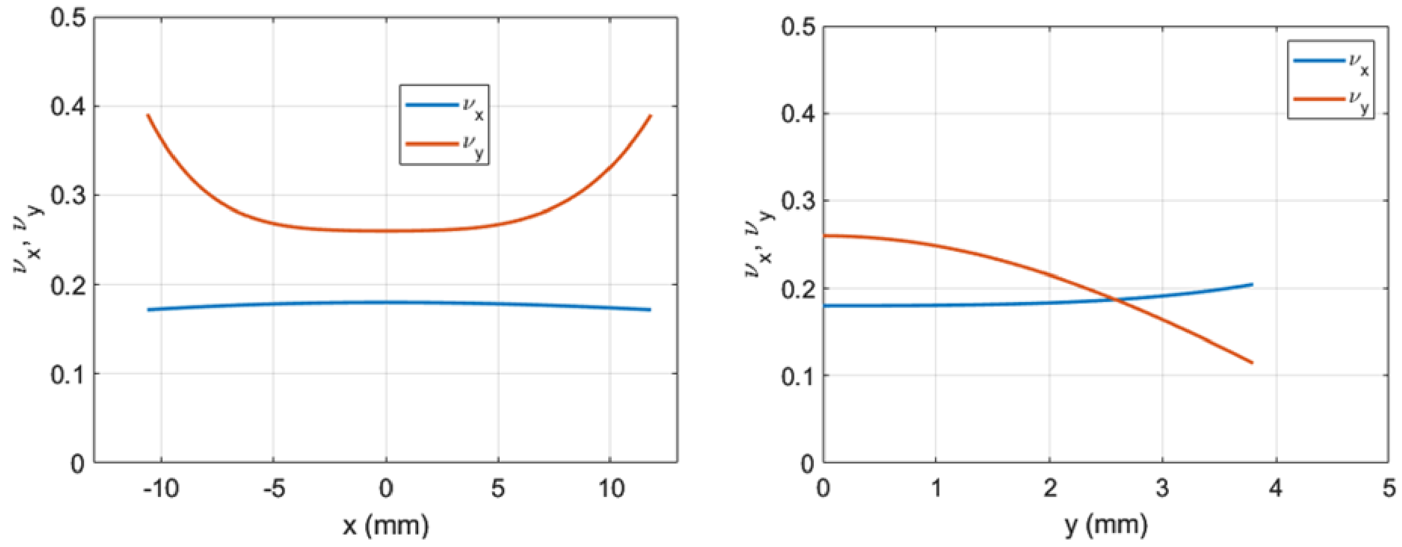
Nonlinear Dynamics in SR

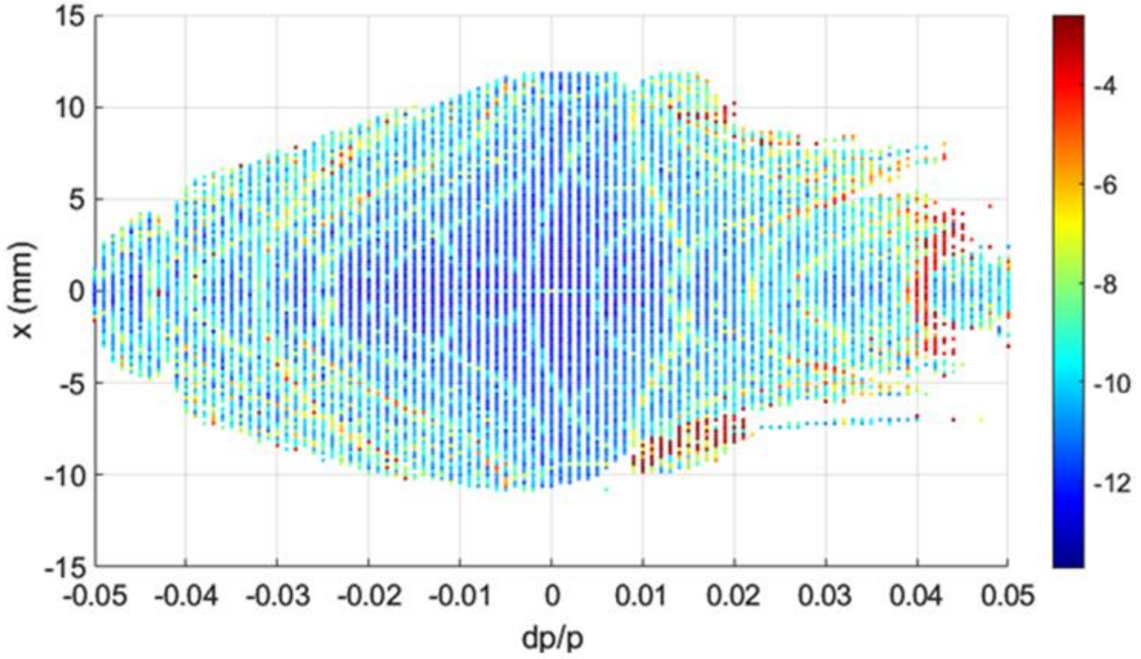
FMA with x-y offset



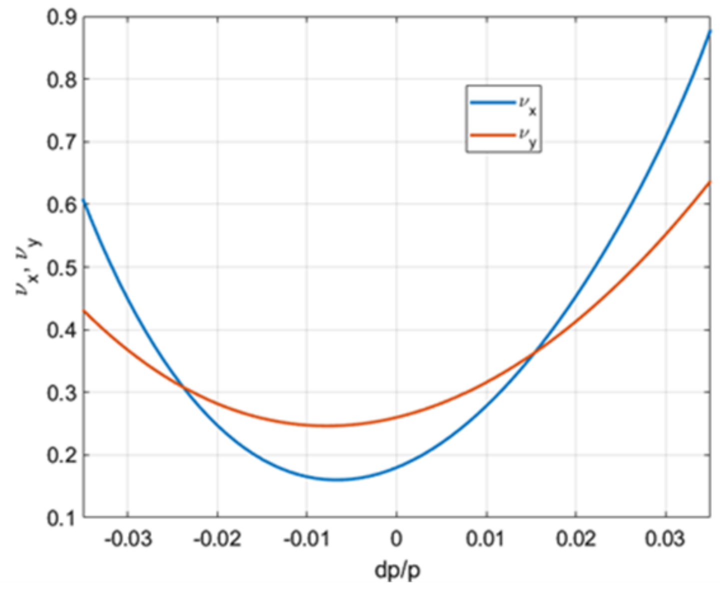
Amplitude dependent tune shifts (ADTS)



FMA with x-dp/p offset



Momentum dependent tune shifts (MDTS)



SR simulation with error tolerances

BPM error

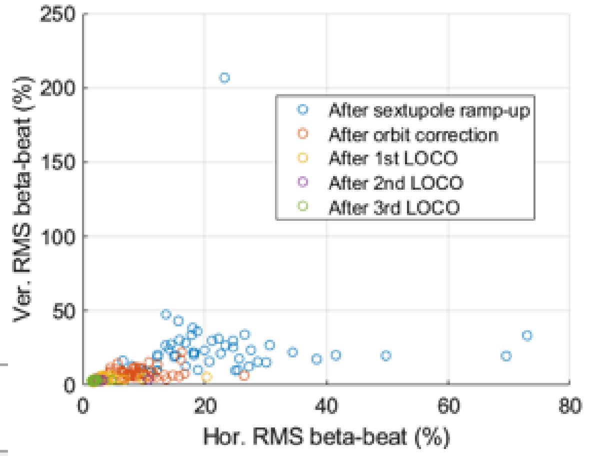
Offset (μm) (X/Y)	Roll (μrad)	Calibration error (%) (X/Y)
500 / 500	100	5 / 5

Magnet error

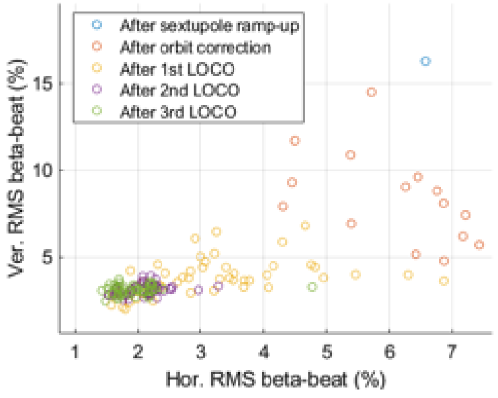
Magnet	Misalignment (μm) (X/Y/Z)	Rotation (μrad) (Roll/Pitch/Yaw)	Strength error (%)
LGBM	30 / 30 / 250	400 / 100 / 100	0.05
Combined-function magnet	30 / 30 / 250	400 / 100 / 100	0.05
Quadrupole	30 / 30 / 250	400 / 700 / 700	0.05
Center bend	30 / 30 / 250	400 / 100 / 100	0.05
Sextupole	30 / 30 / 250	400 / 700 / 700	0.05
Octupole	30 / 30 / 250	400 / 700 / 700	0.05
Girder	100 / 100 / 100	400 / - / -	

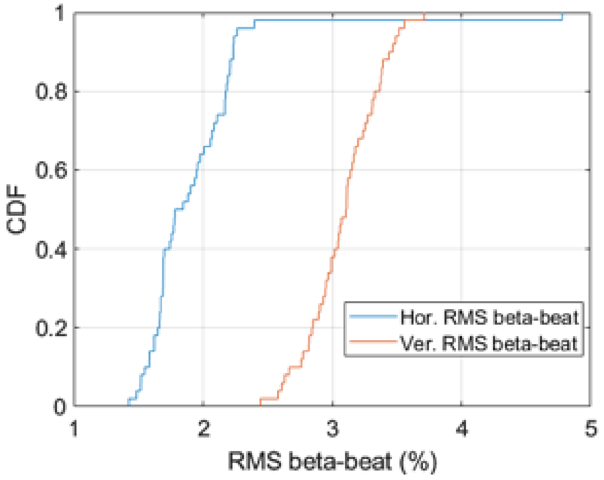
* 2-sigma cutoff is used for commissioning simulations

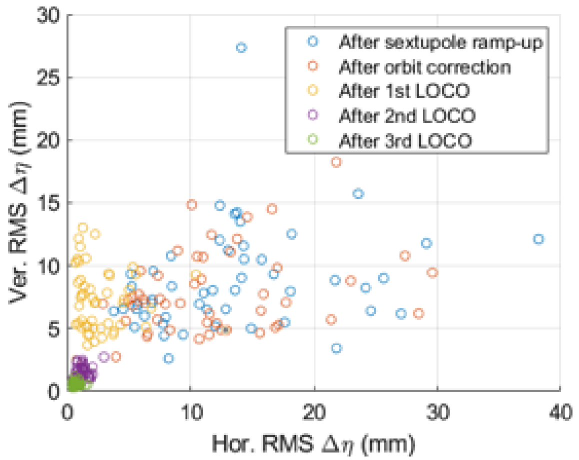
Improvement of beta-beat and dispersion-beat over each correction step



zoomed in







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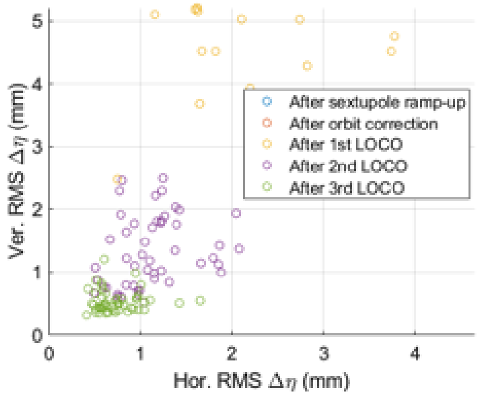
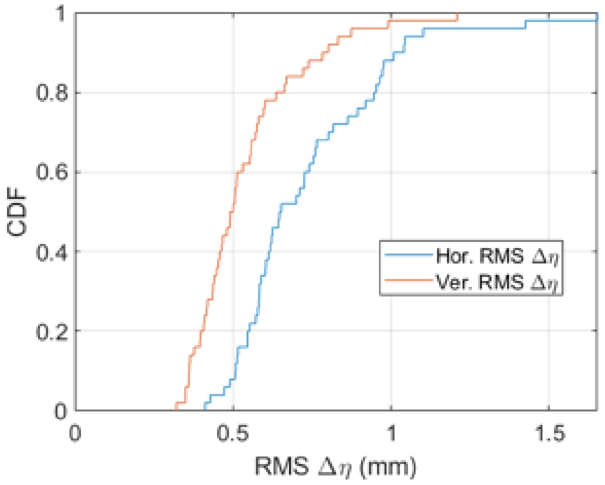
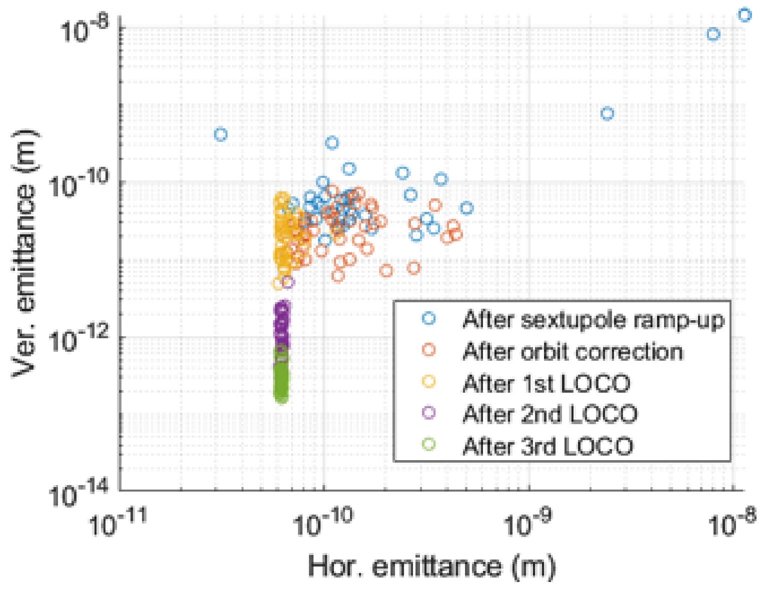




SR simulation with error tolerances

Equilibrium emittance



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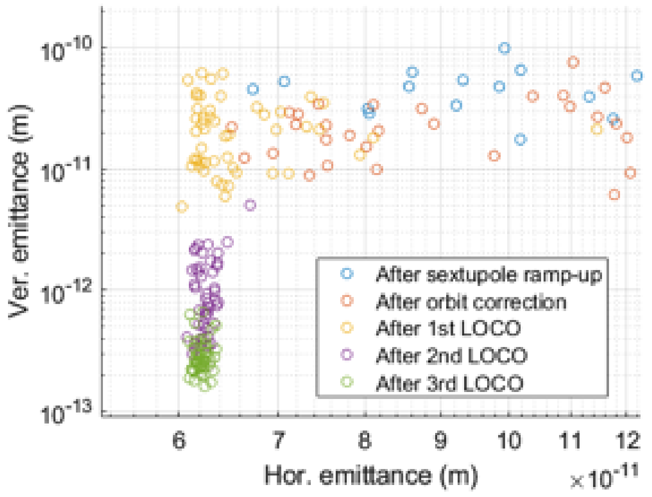
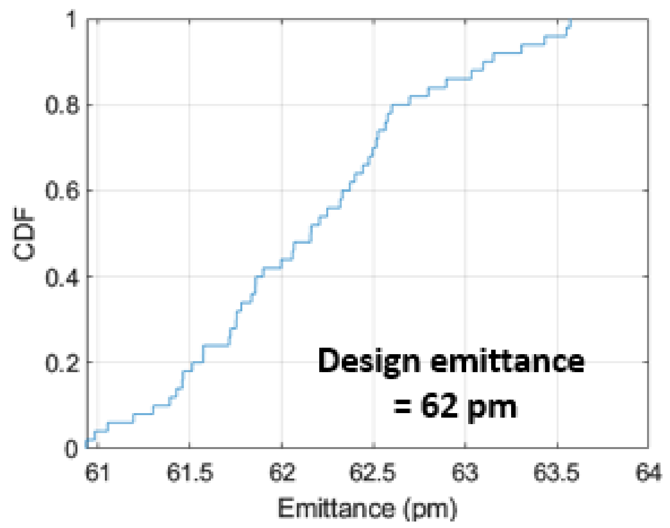
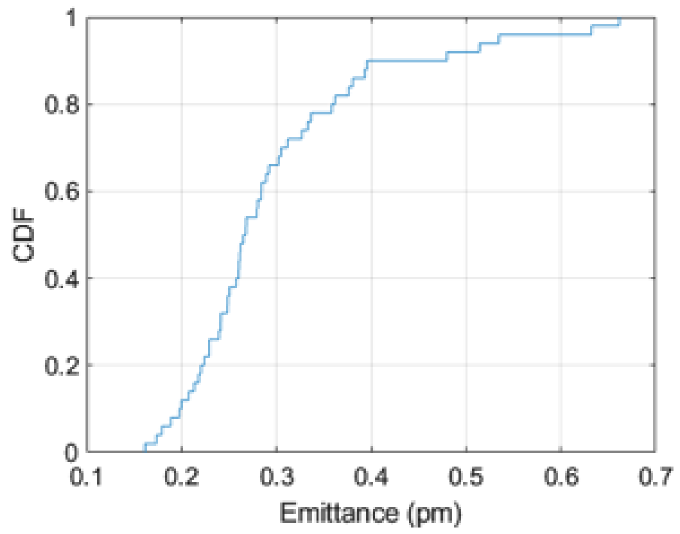


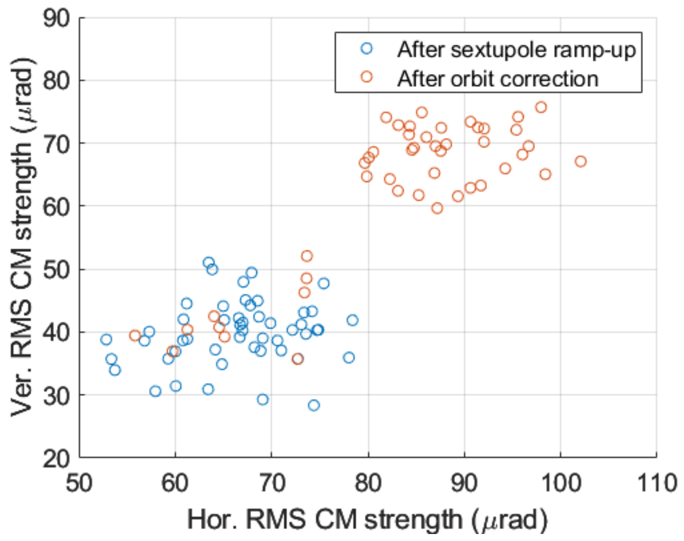


CDF of horizontal emittance after 3rd LOCO



CDF of vertical emittance after 3rd LOCO

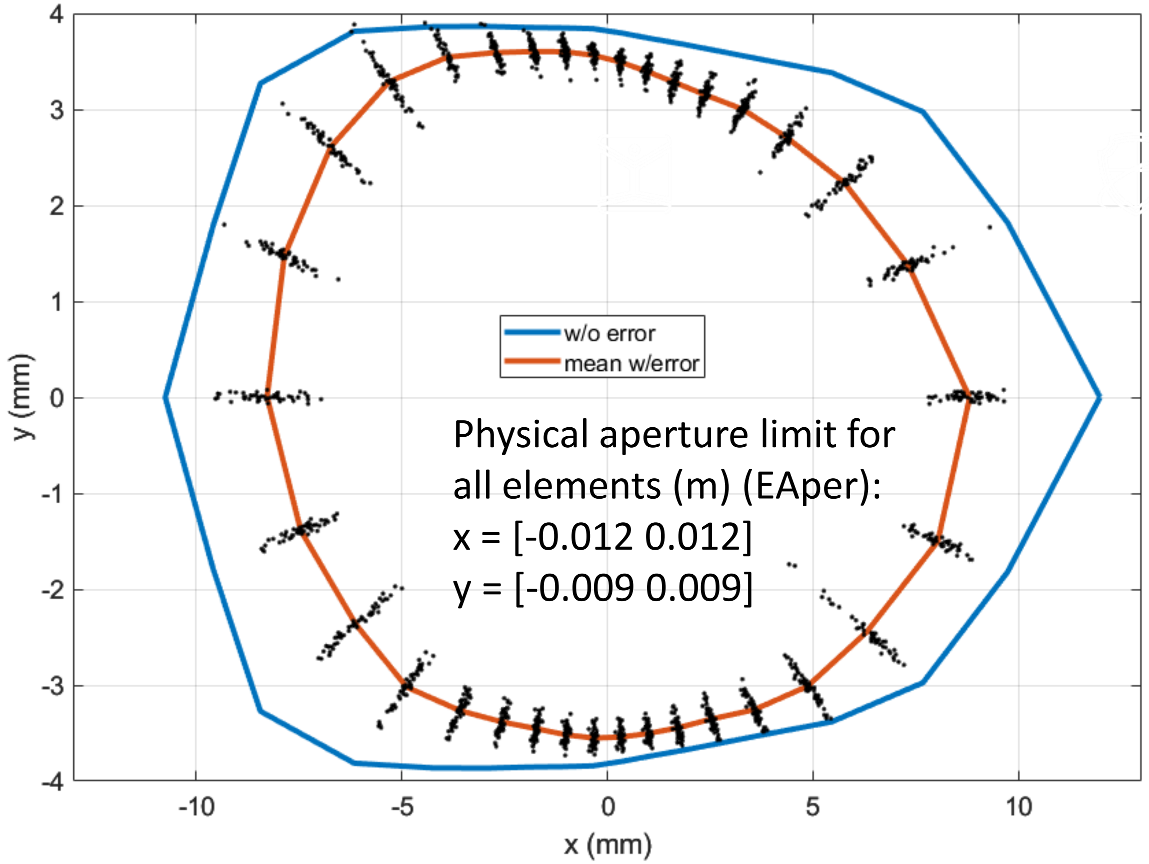
Corrector strength



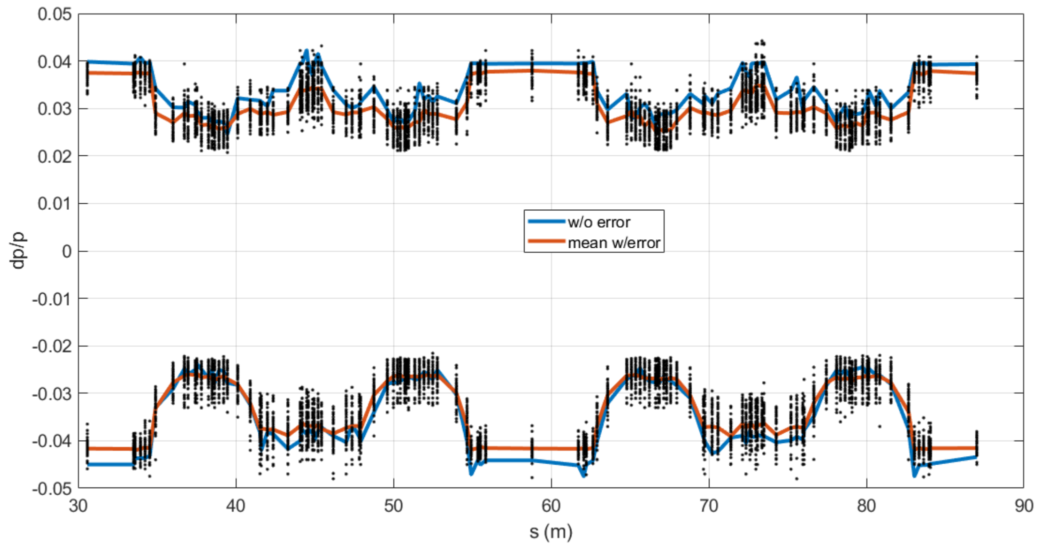
Corrector strengths after orbit correction are below mechanical limit (600 μrad)

Dynamic Aperture and Momentum Aperture

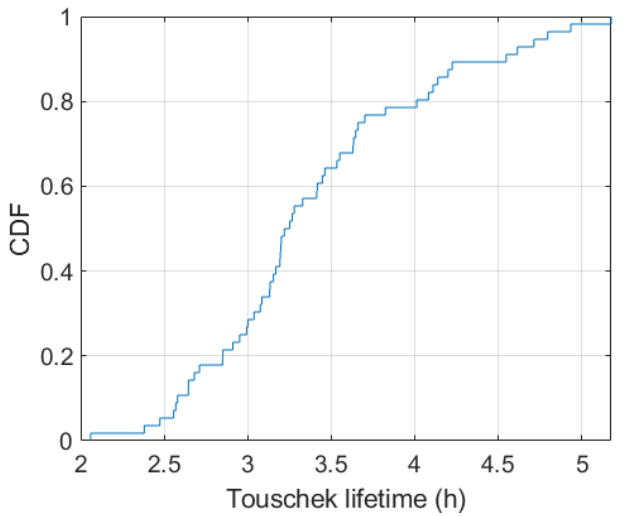
Dynamic aperture



Momentum aperture



Touschek lifetime
w/o error : 7.18 h

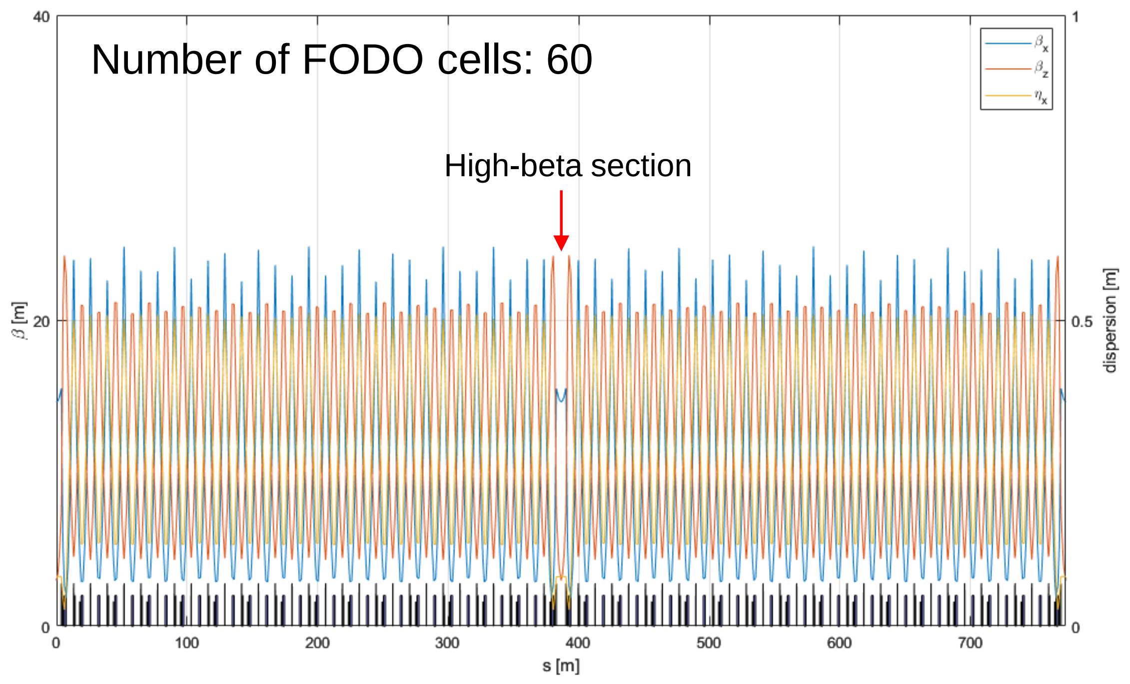


Charge set:
- a single bunch of 1 nC (or 0.375 mA)
- 400 mA = 1067×0.375 mA

Coupling ratio (emity/emitx) = 0.10

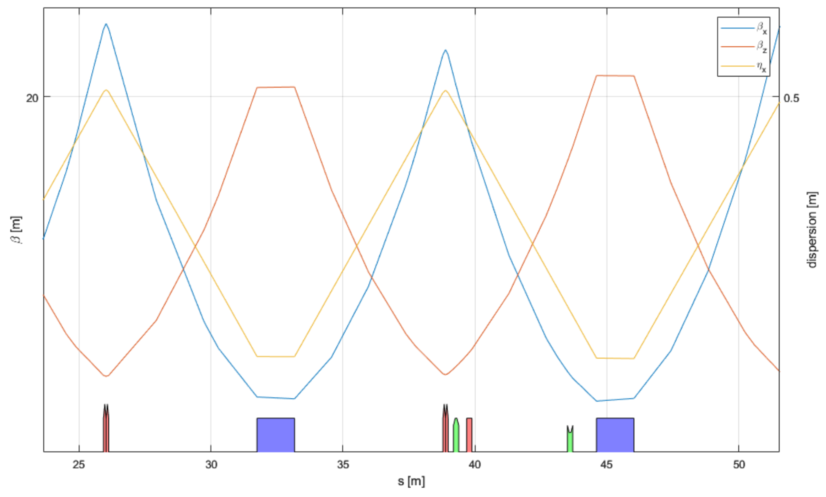
Booster Ring and Injection system

Booster Ring



Lattice functions of booster ring

Periodic cell = 2 FODO cells+ sextupole pair



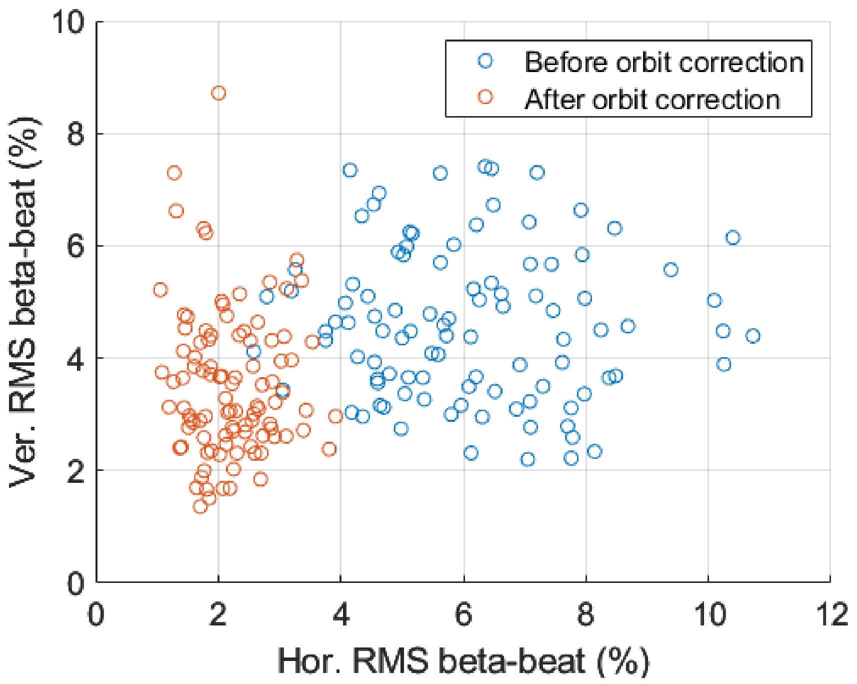
Lattice functions of booster ring unit cell

Booster		Value	Unit
Design Parameters	Circumference	772.893	m
	Beam Energy (Inj. - Ext.)	0.2 - 4	GeV
	Number of bends	60	
	Natural Emittance at 4 GeV	7886	pm rad
	Natural Emittance at 200 MeV	20	pm rad
	Momentum Compaction	0.000933	
Tune and Chromaticity	Horizontal Tune	19.226	-
	Vertical Tune	13.165	-
	Natural Horizontal Chromaticity	-27.1	-
	Natural Vertical Chromaticity	-18.2	-
	Horizontal Chromaticity	2	(target)
	Vertical Chromaticity	2	(target)
Radiation related quantities at 4GeV	Energy Loss per Turn	1671.3	keV
	Energy Spread	0.106	%
	Horizontal Damping Time	8.5	ms
	Vertical Damping Time	12.3	ms
	Longitudinal Damping Time	8.0	ms
	Synchrotron Frequency	4235	Hz
	Synchrotron Tune	0.0109	
	Bunch Length	11.1	mm

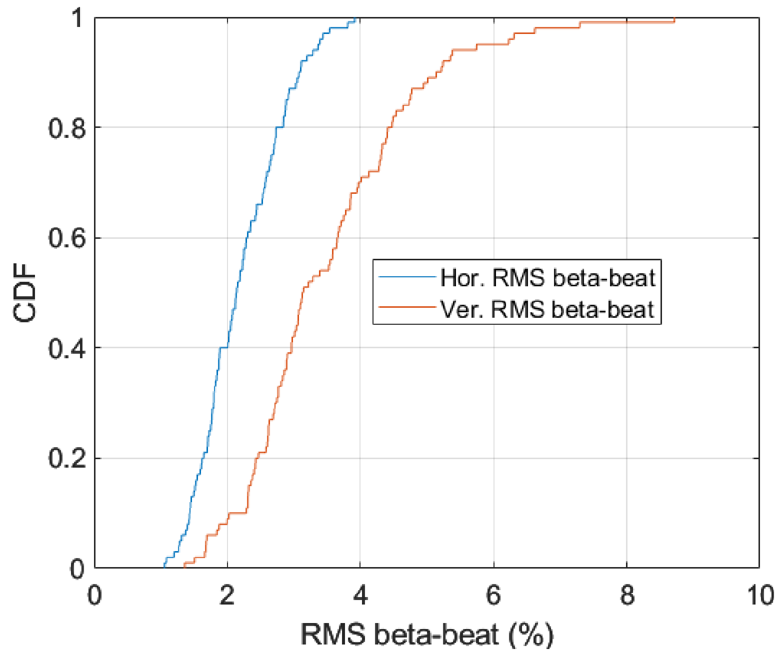
Booster Ring Error Analysis

Magnet	Misalignment (μm) (X/Y/Z)	Rotation (μrad) (Roll/Pitch/Yaw)	Strength error (%)
Bend (dipole-quadrupole)	200 / 200 / 400	400 / 100 / 100	0.10
Quadrupole	200 / 200 / 400	400 / 700 / 700	0.10
Sextupole	200 / 200 / 400	400 / 700 / 700	0.10

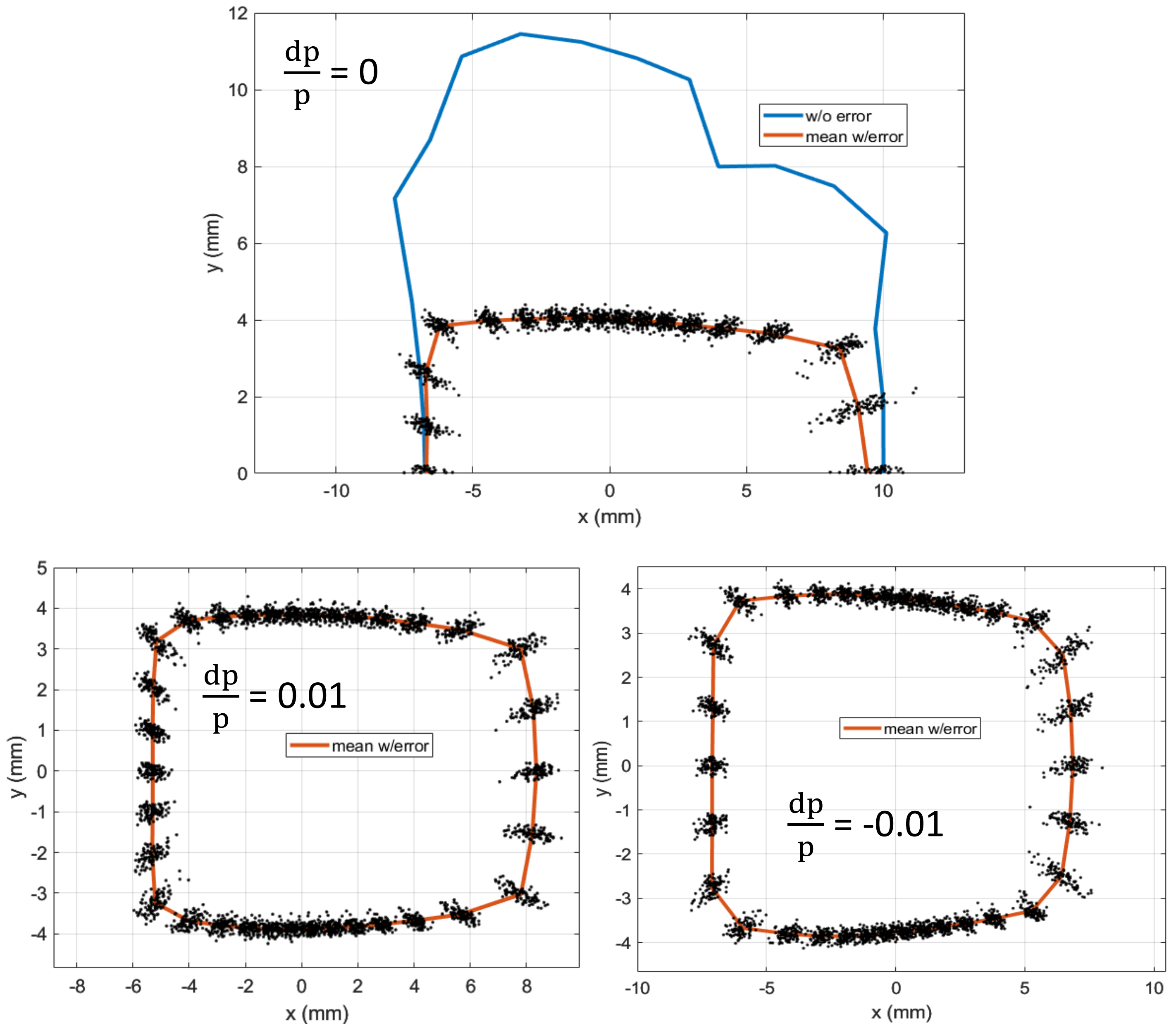
Error tolerance used for error analysis



Beta-beat before/after orbit correction



CDF of beta-beat after orbit correction

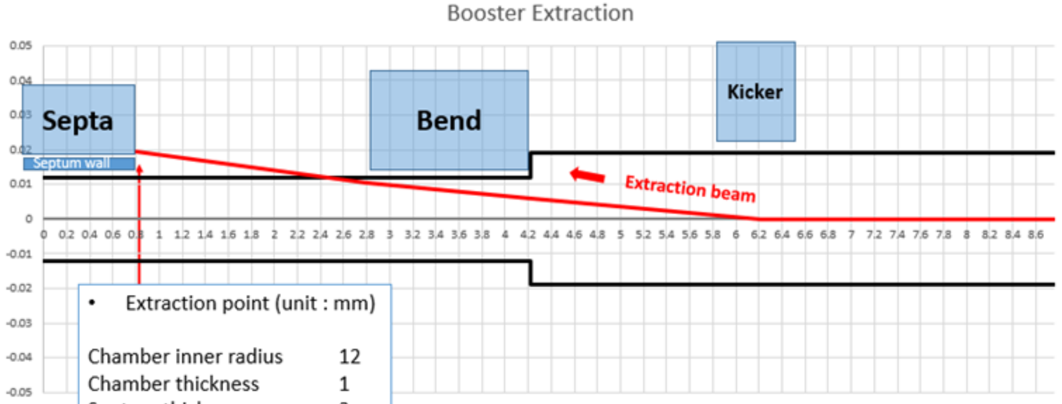


Dynamic aperture after orbit correction

*Booster ring has 120 H/V correctors and 120 BPMs

Booster to storage ring

Booster extraction

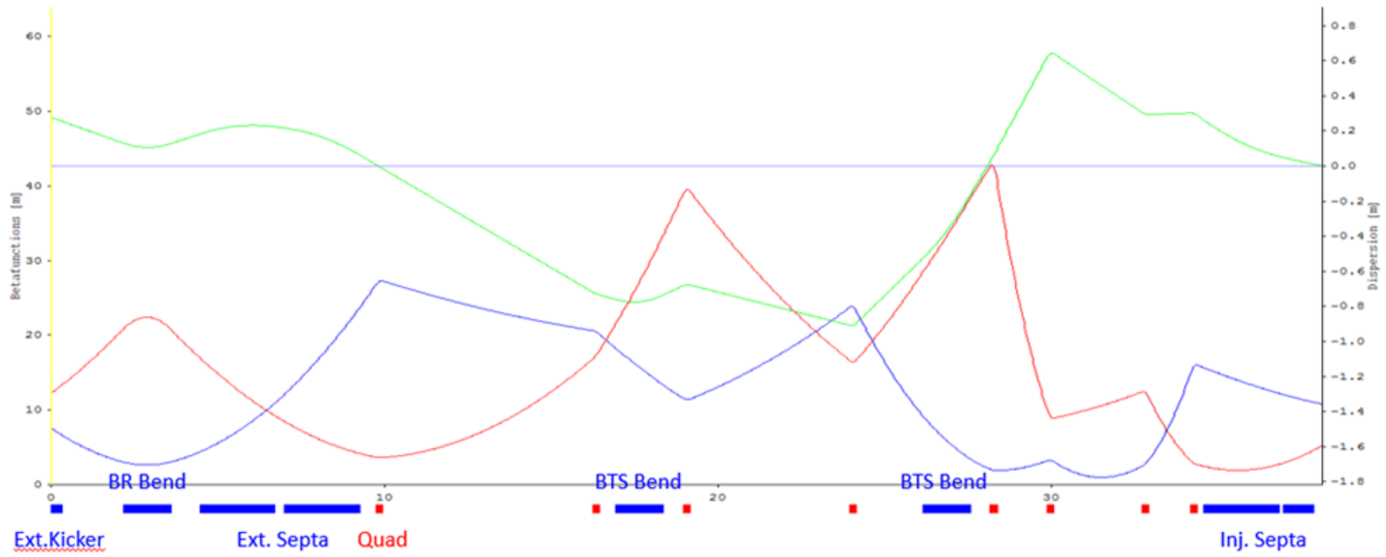


- Extraction point (unit : mm)

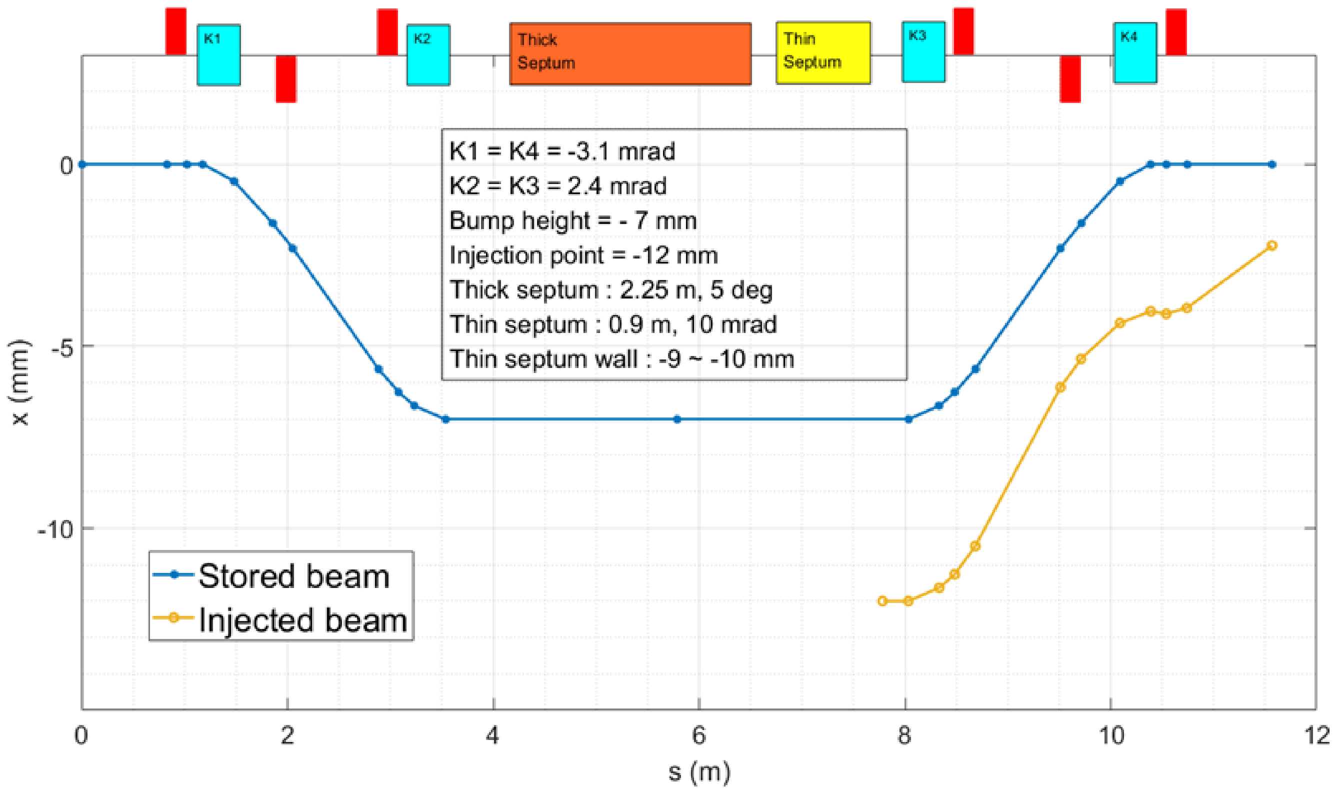
Chamber inner radius	12
Chamber thickness	1
Septum thickness	3
Extracted beam 3σ	0.3
Tolerance	3.1
Total	19.4

- At Kicker
x' = 0 mrad -> 3 mrad
- 2 m Drift
x = 0 mm -> 6 mm
x'= 3 mrad
- At Bending Magnet
(k = -0.149)
x = 6 mm -> 10.449 mm
x'= 3 mrad -> 4.461 mrad
- Before Septa
x = 19.372 mm
x'= 4.461 mrad

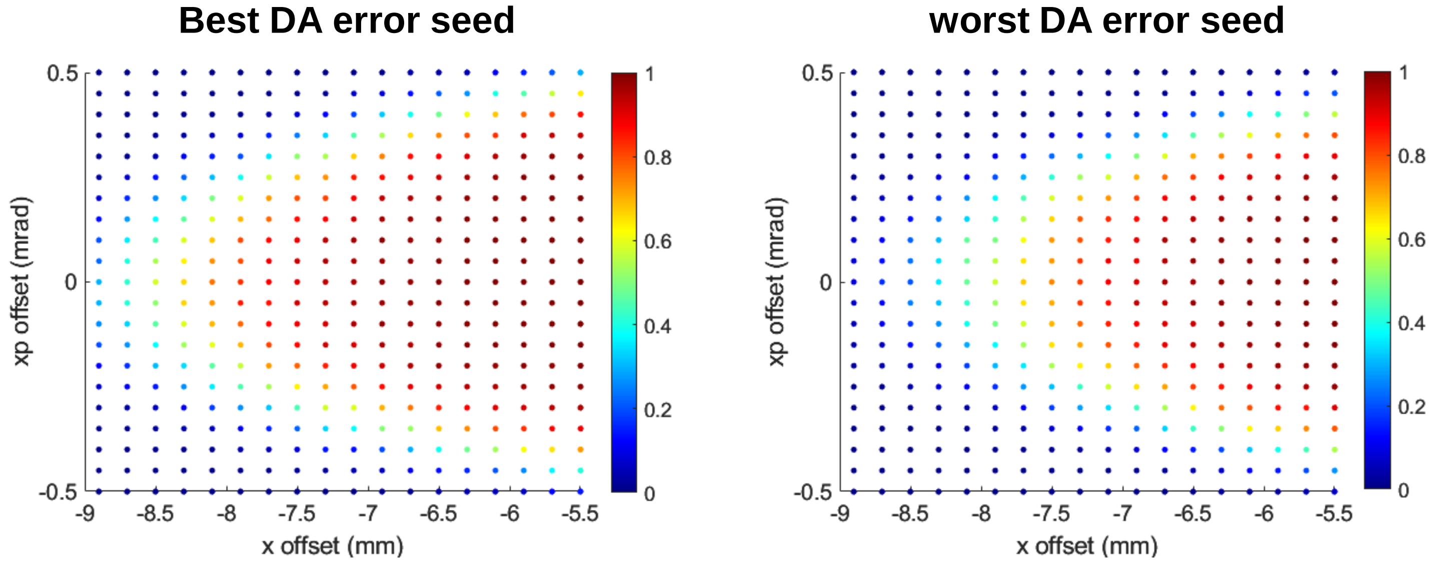
Booster-to-Storage ring beam transport line



4-kicker bump injection scheme



Injection efficiency scan results



Injected beam parameters:
ε_x = 7.83 nm, $\varepsilon_y = \varepsilon_x/100$
σ_z = 11.1 mm, σ_δ = 1.06E-3

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Summary

- Korea-4GSR adopted Hybrid 7 bend achromat for energy of 4 GeV and circumference of 800 m
- Storage ring composed of 28 unit cells, 26 ID sections and 2 high-beta sections.
- Even though the high-beta sections reduce the Touschek lifetime, we can secure larger dynamic aperture for off-axis injection.
- We investigated storage ring simulations with realistic error tolerances to prepare future commissioning.
- Booster has 60 FODO cells and increases the beam energy from 200 MeV to 4 GeV.
- Four kicker bump injection is being prepared for the storage ring.

Thank you for your attention

Backup

Beam Lifetime

Touschek lifetime with ideal lattice

Flat beam : coupling 10%			Round beam : coupling 100%		
Without HC	Without IBS	With IBS	Without HC	Without IBS	With IBS
Emittance (H/V)	58.40/5.84 pm	79.57/7.96 pm	Emittance (H/V)	39.91/39.91 pm	45.79/45.79 pm
Touschek lifetime	7.30 h	8.52 h	Touschek lifetime	17.04 h	17.38 h
With HC	Without IBS	With IBS	With HC	Without IBS	With IBS
Emittance (H/V)	58.40/5.84 pm	65.32/6.53 pm	Emittance (H/V)	39.91/39.91 pm	41.56/41.56 pm
Touschek lifetime	29.22 h	34.09 h	Touschek lifetime	68.18 h	66.39 h

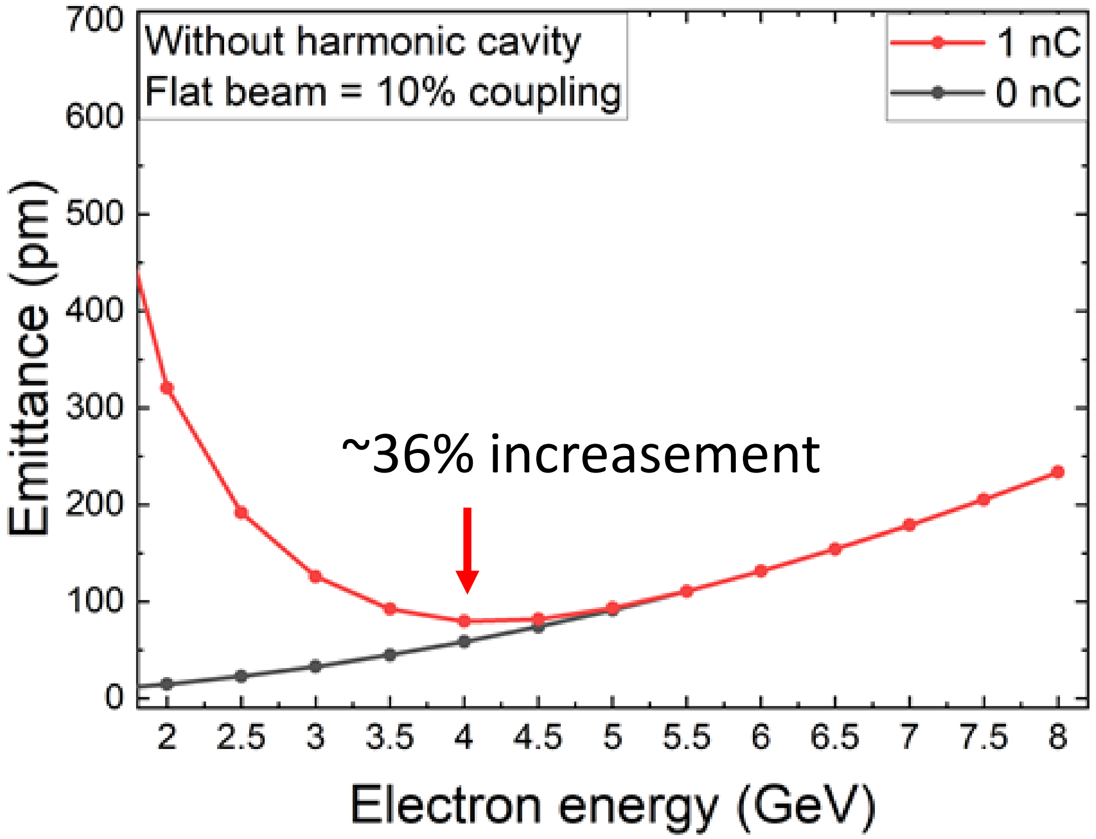
Elastic scattering lifetime under vacuum pressure of 10^{-9} mbar

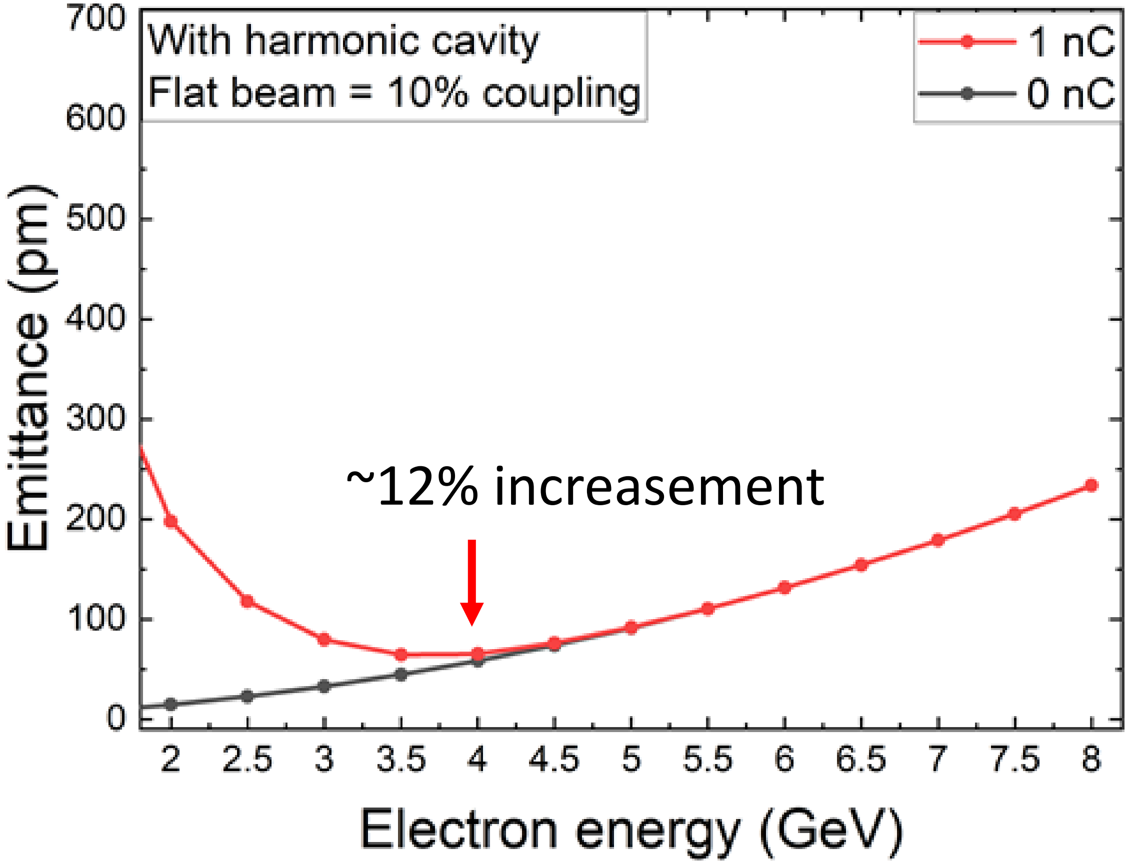
Gas	Lifetime [h]
H_2	1025.4
CO	36.0
CO_2	22.1
N_2	36.6

Bremsstrahlung lifetime under vacuum pressure of 10^{-9} mbar

Gas	Lifetime [h]
H_2	2273.3
CO	98.6
CO_2	60.6
N_2	100.1

Intra Beam Scattering



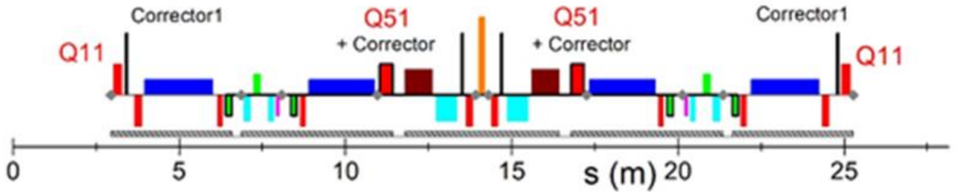


- Harmonic cavities help reducing emittance growth due to the IBS effect

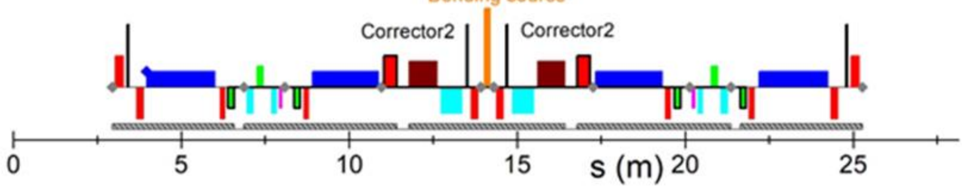
Choice of Corrector Positions

Amplification factor type	Magnet name	A_x	A_y	$A=\sqrt{A_x^2+A_y^2}$
Quadrupole $A_{\Delta x}$ with $\sigma_{\Delta x}^2=100\,\mu m$	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 $A_{\Delta B/B}$ with $\sigma_{\Delta B/B}^2=0.1\%$	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

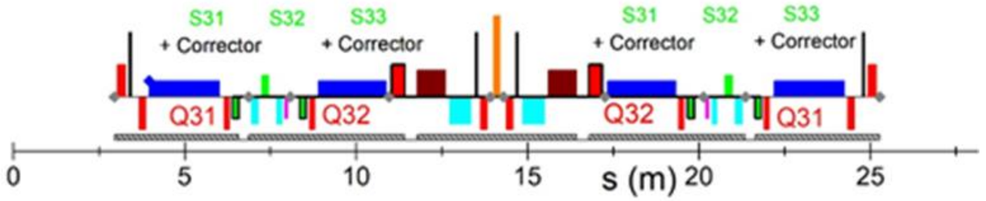
- 2 independent correctors near Q11
- 2 Q51 trim correctors



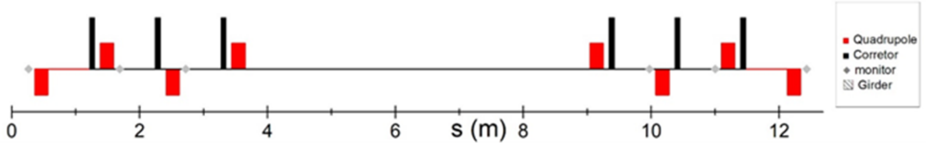
- 2 independent correctors near 2-T center bend



- 2 S31 trim correctors
- 2 S33 trim correctors



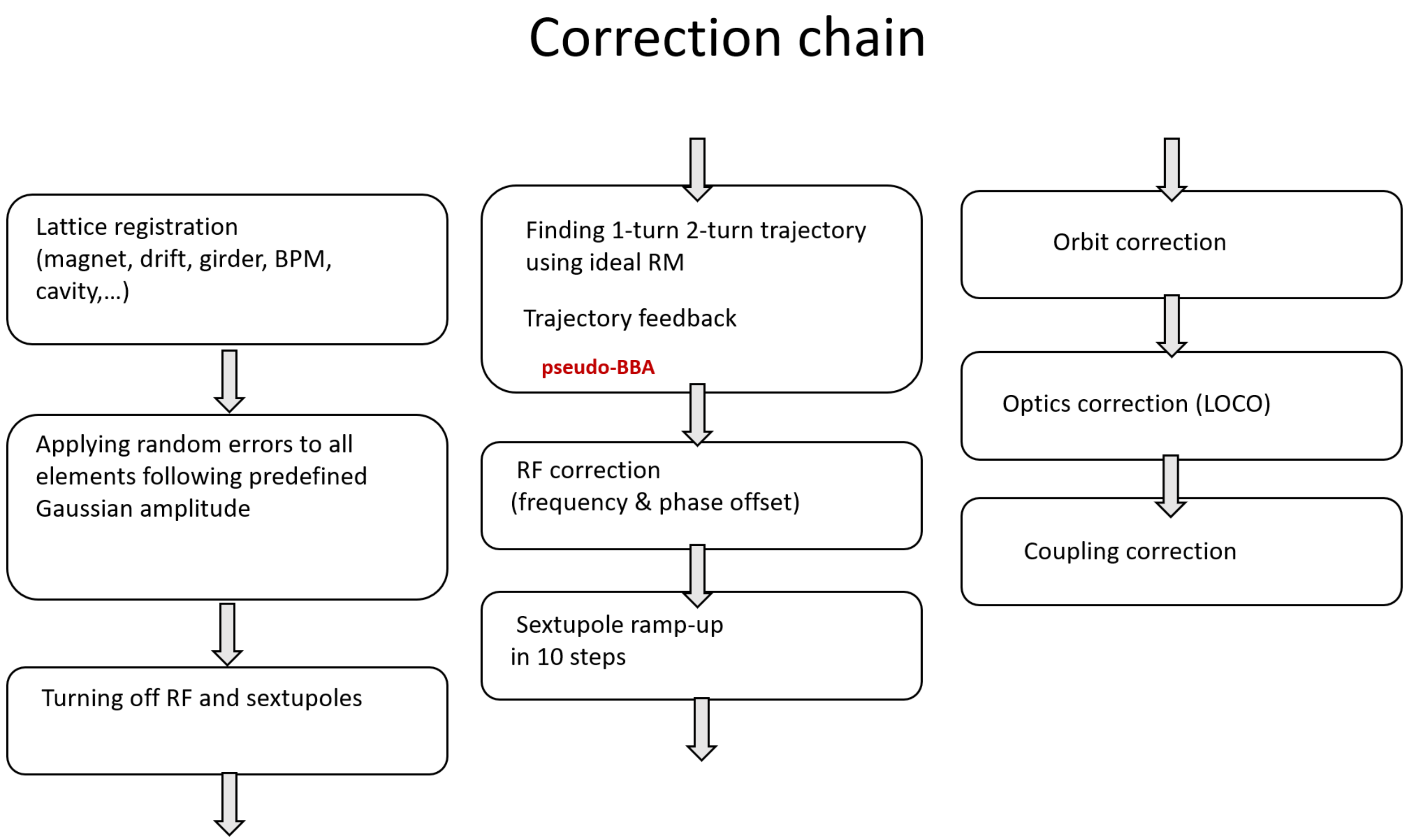
- 6 correctors at high-beta straights



Amplification factor type	Magnet name	A_x	A_y	$A=\sqrt{A_x^2+A_y^2}$
Embedded corrector $A_{\Delta\theta}$ with $\sigma_{\Delta\theta}^2=500\,\mu rad$	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 $A_{\Delta\theta}$ with $\sigma_{\Delta\theta}^2=500\,\mu rad$	Corrector1	54.11	55.38	77.43
	Corrector2	33.81	27.69	43.71

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

Correction Chain



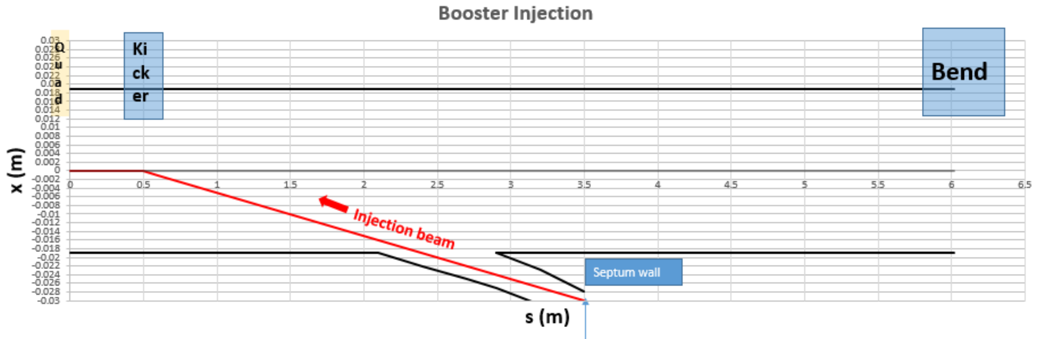
- Existence of closed orbit and beam transmission need to be checked at each step

Toolkit for Simulated Commissioning (SC):
https://sc.lbl.gov/

- Lattice ensemble of 50 random error seeds is generated after applying the correction chain to each error seed
- In the simulation,
  - Existence of 1-turn trajectory means that 1 turn transmission is achieved
  - Existence of closed orbit means that a fixed point x exists such that $x = Mx$ *where* M *is one turn map* (AT function 'findorbit6' is used)

Booster ring

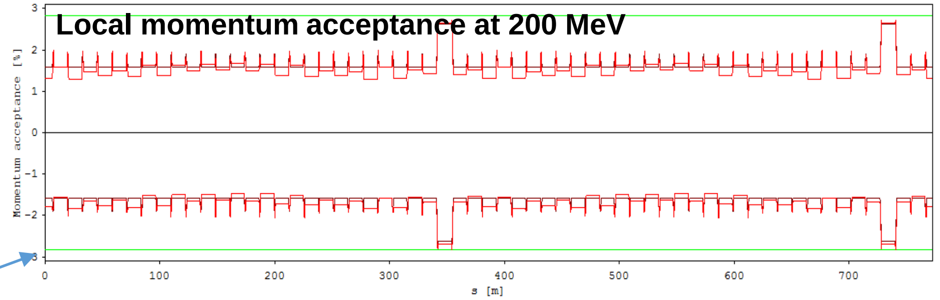
- Septum
Length : 50 cm,
Angle : 20 deg
- After Septum
x = -30 mm
x'= 10 mrad
- 3.0 m Drift
x = -30 mm -> 0 mm
- At Kicker
x' = 10 mrad -> 0 mrad

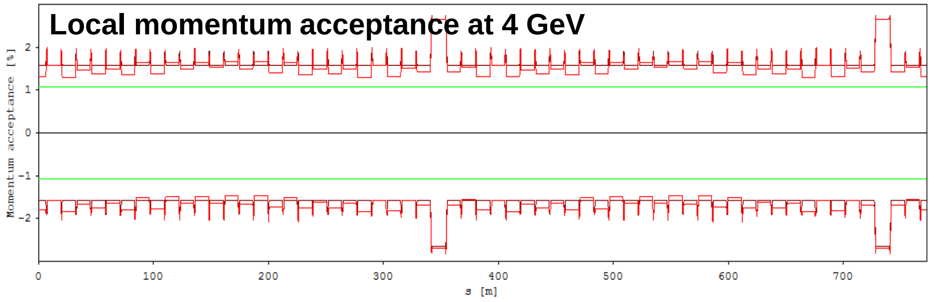


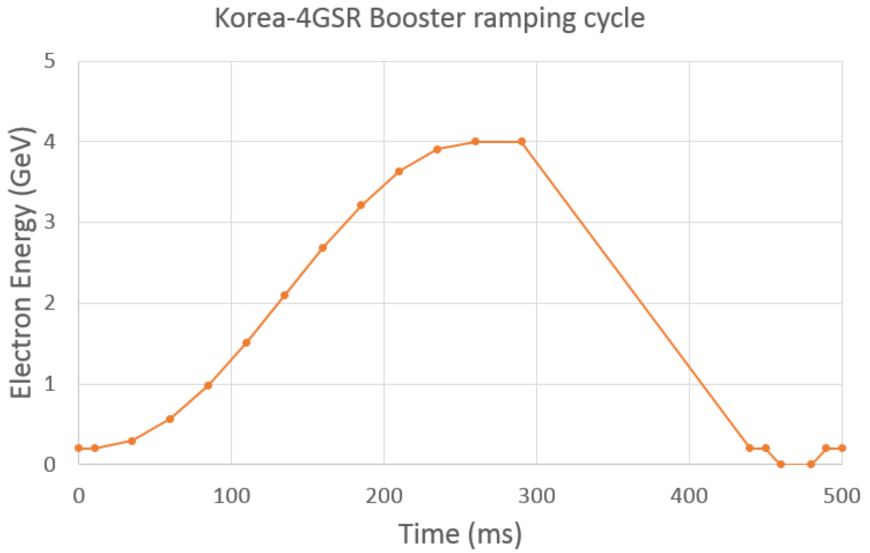
- Injection point
(unit : mm)

Chamber inner radius 19.35
Chamber thickness 1
Septum thickness 3
Injected beam 3σ 2
Tolerance 4.65
Total 30 mm

RF acceptance

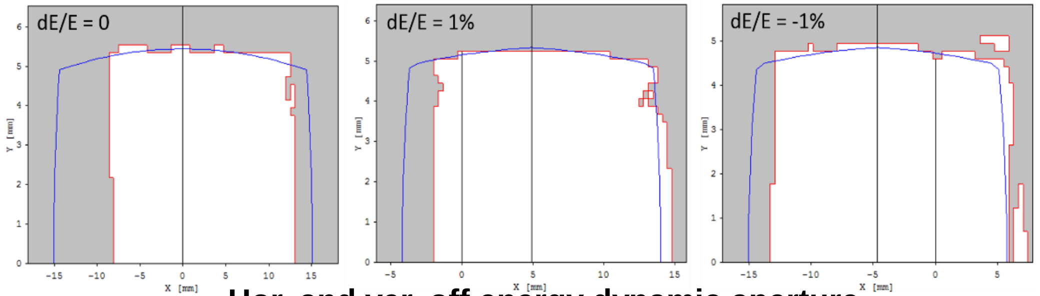




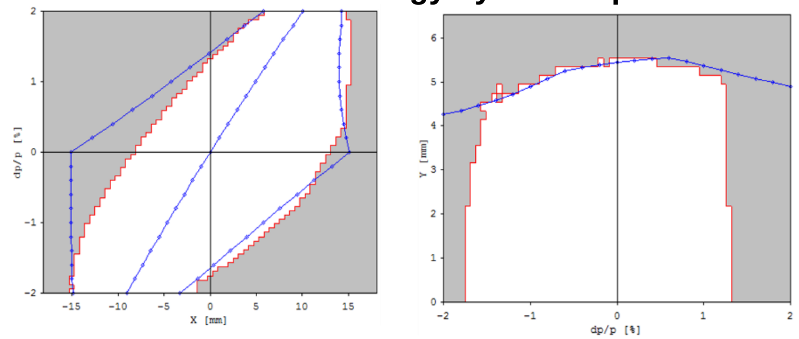


Parameter	Value
Maximum current	1 mA
Injection speed	2 mA/s
Repetition rate	2 Hz
Harmonic number	1288
Time to fill SR up to 400 mA	200 s
RF voltage	0.3 MV (@ 200 MeV) 3 MV (@ 4 GeV)

Off energy dynamic aperture

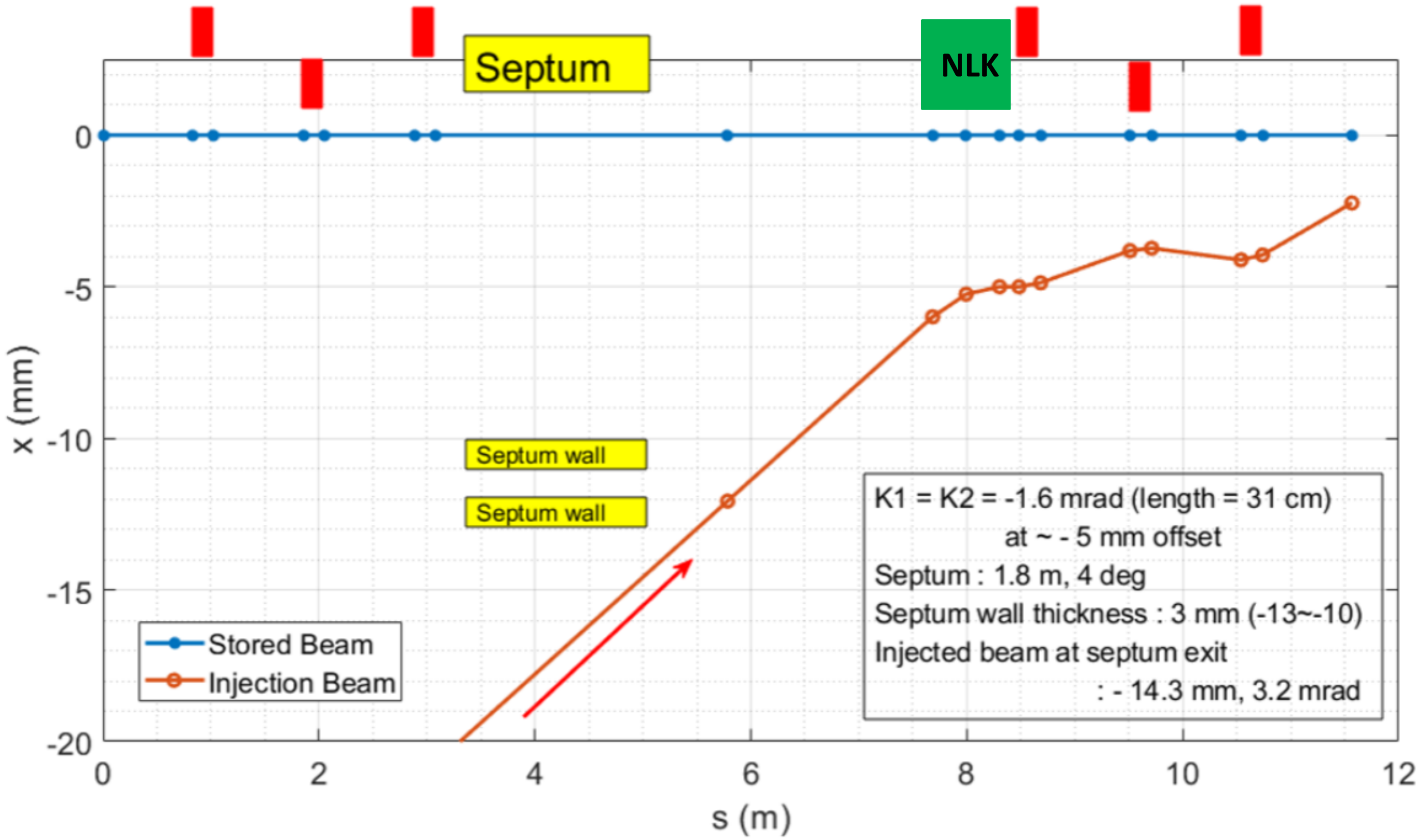


Hor. and ver. off energy dynamic aperture



POHANG ACCELERATOR LABORATORY

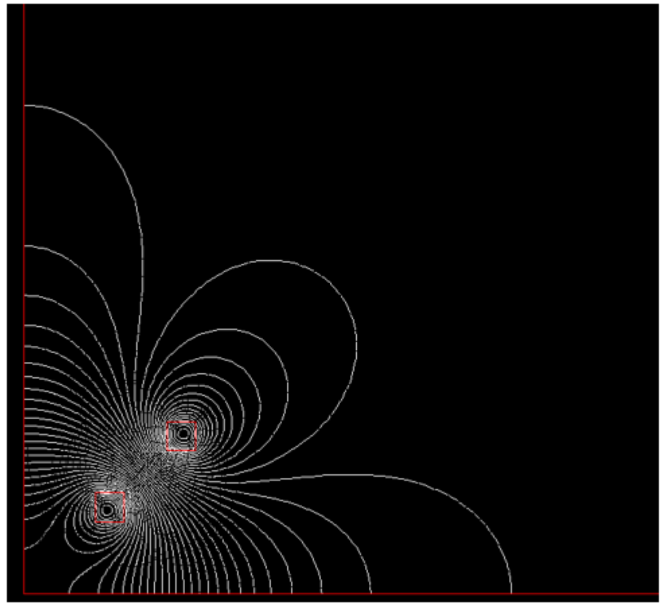
Nonlinear kicker for Korea-4GSR

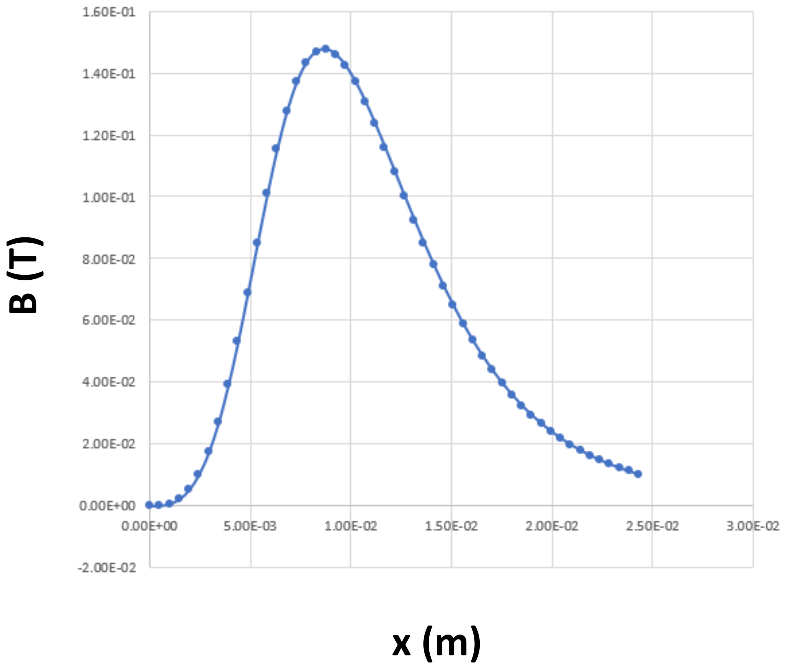


Schematic layout of nonlinear kicker injection for Korea-4GSR

- It is known that nonlinear kicker injection is one of methods to realize transparent injection
- Currently used at MAX-IV, SIRIUS, SOLEIL
- 4-Kicker injection scheme is still main injection scheme for Korea-4GSR, and nonlinear injection scheme could be applied for Korea-4GSR upgrade
- We started R&D to make a nonlinear kicker which has optimized specification for Korea-4GSR

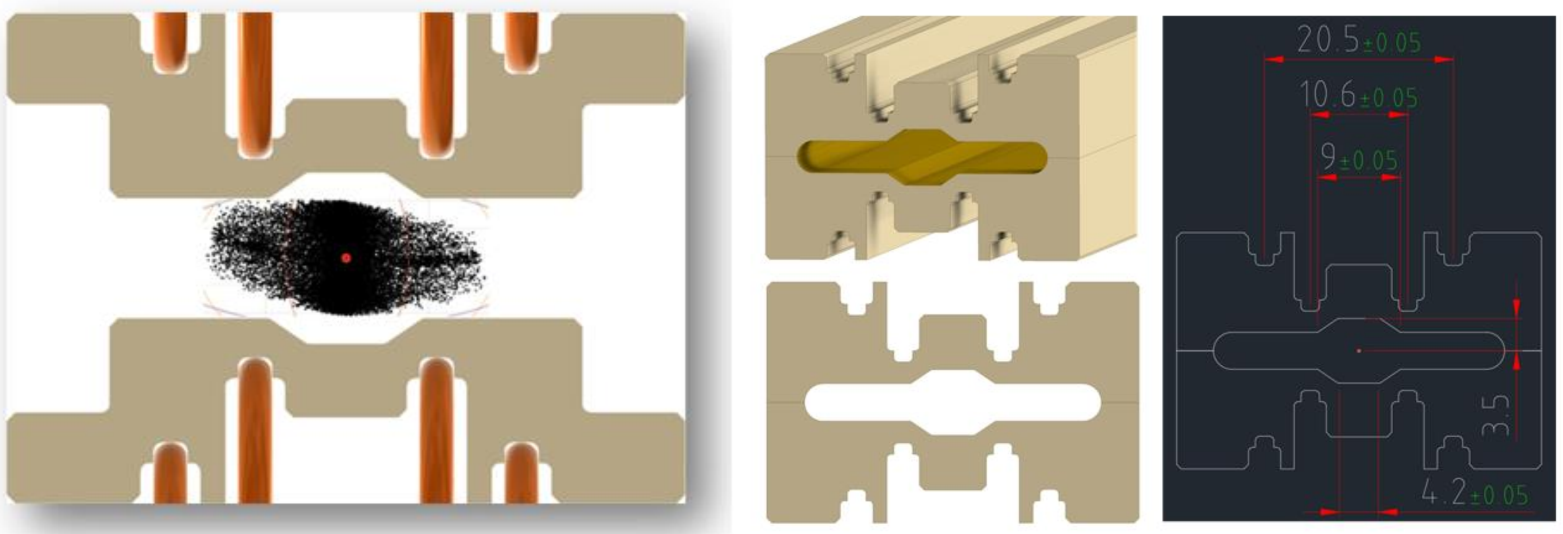
R&D Status





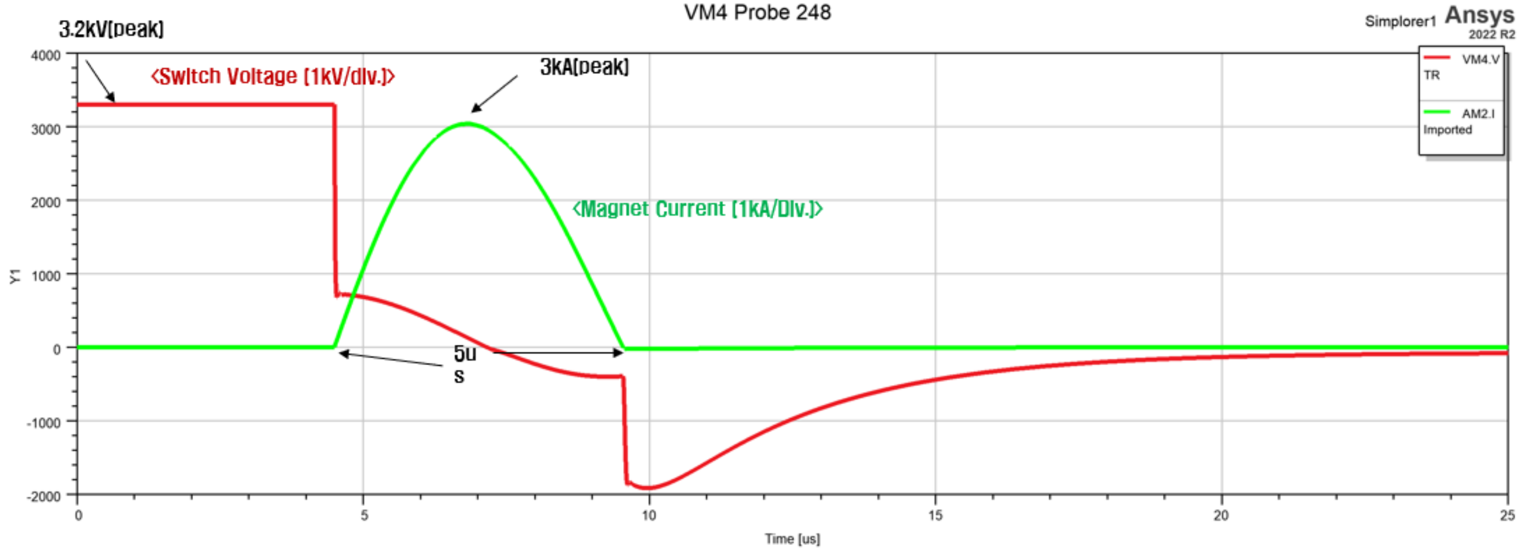
Field flux shape (one quadrant) and field profile along x-direction of a 525 mm nonlinear kicker

- A 200 mm test model will be tested soon



Beam stay clear H ~ ±9.15 mm
V ~ ±3.66 mm

Ceramic vacuum chamber



<Simulation Result @ NLK Inductance 0.68uH>

Kicker modulation simulation result

Comparison of Nonlinear Kicker Specifications

Storage ring	Storage ring energy (GeV)	Storage ring circumference / revolution time	Nonlinear kicker type	Injection point	Pulse length (1/4 sine wave, from zero to peak)	Peak field	Peak current
PF	2.5	187 m / 0.62 us	PSM	15 mm	0.6 us	40 mT at x=15 mm	3000 A
BESSY-II	1.7	240 m / 0.80 us	MIK	-12 mm	0.75 us	25 mT at x=12 mm	2800 A
MAX IV	3.0	528 m / 1.76 us	MIK	-5 mm	-	-	-
SOLEIL	2.75	354 m / 1.18 us	MIK	-10 mm	1.2 us	82 mT at x=-10 mm	3300 A
SIRIUS	3.0	518 m / 1.73 us	MIK	-8 mm	1.64 us	107 mT at x=-9 mm	1850 A
*Korea-4GSR	4.0	800 m / 2.67 us	MIK	-5 mm	2.50 us	148 mT at x = -9 mm	3000 A

*Under R&D study