Korea-4GSR Accelerator Overview

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4GSR Outline

❖ **Multipurpose Synchrotron Radiation Construction Project**

- Period: 2021 July to 2027 June (6yrs)
- Budget: 1.0454 Trillion KRW (≈ USD 750M)
- Land: 540,000 ㎡ / Building: 69,400 ㎡
- Location: Ochang, Chungcheongbuk-do

Specifications

- Beam Energy: 4 GeV
- Beam Emittance: less than 100 pm·rad (TDR: 62 pm·rad)
- Circumference: 800m
- Beamlines : more than 40
- Accelerator: Gun, Injector LINAC, 4 GeV Booster
- Lattice: Hybrid 7 Bend Achromat (H7BA)

Design Features of Korea-4GSR

❖ **High photon beam performance from storage ring**

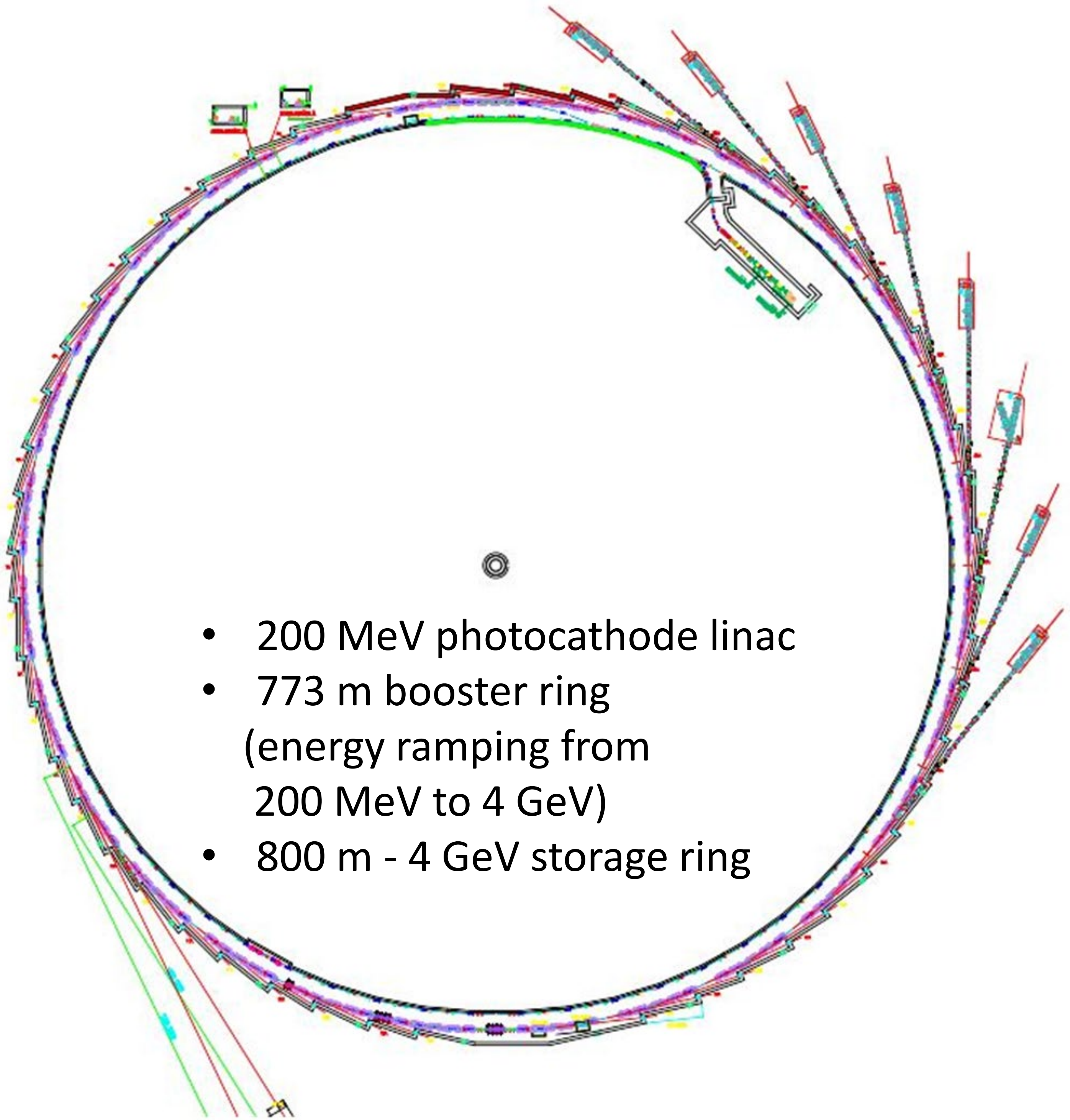
- The best performance in the range of 10 – 30 keV
- Capability to generate photon beam up to 100 keV

❖ **Considering well demonstrated technologies for the design**

- Off-axis injection with conventional injection scheme
- General technologies for magnet and vacuum systems
- On schedule user service and full performance

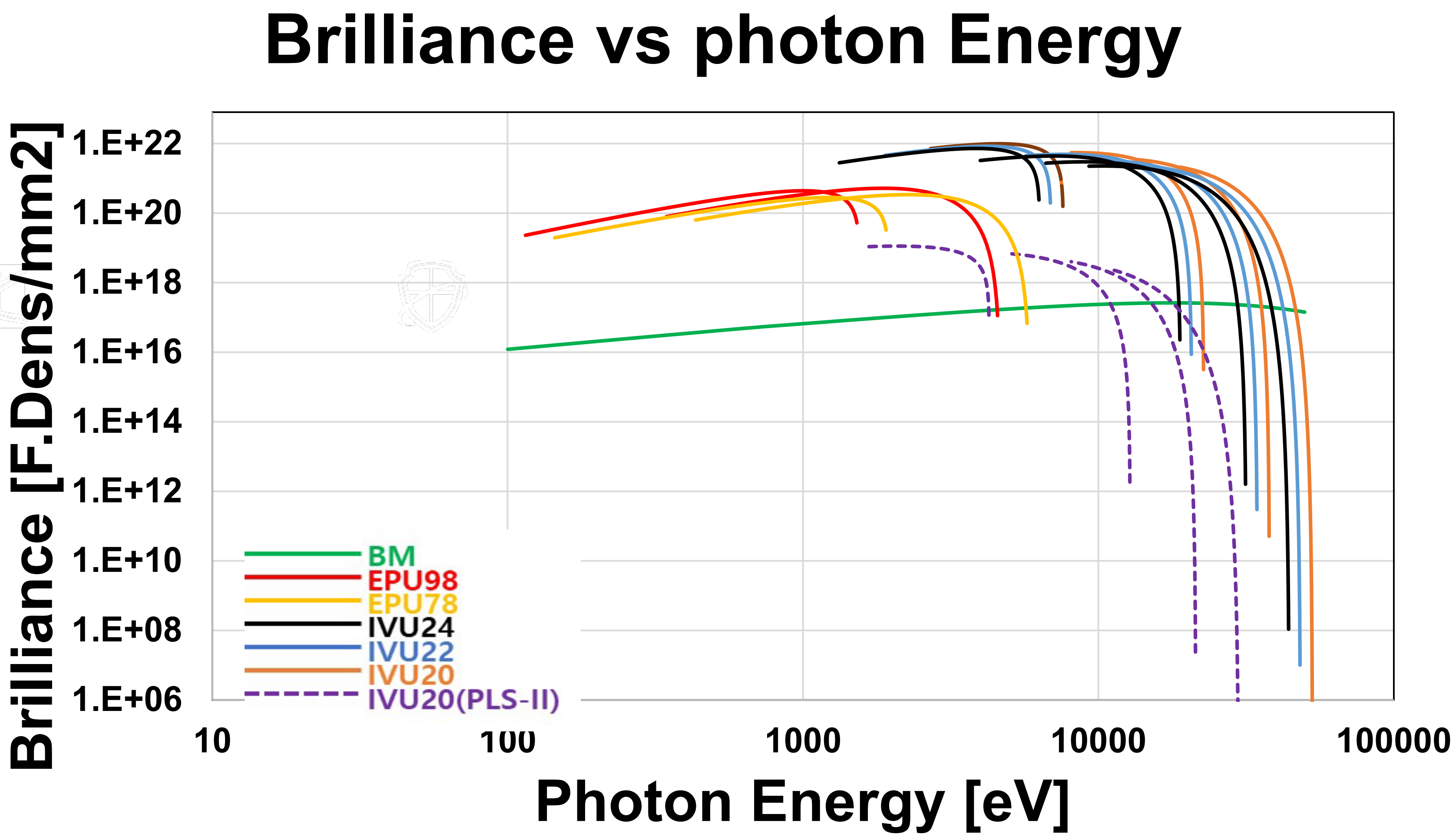
❖ **Synergy with PLS-II and PAL-XFEL**

- Supporting full range of synchrotron radiation application



- 200 MeV photocathode linac
- 773 m booster ring (energy ramping from 200 MeV to 4 GeV)
- 800 m - 4 GeV storage ring

Brilliance Curves



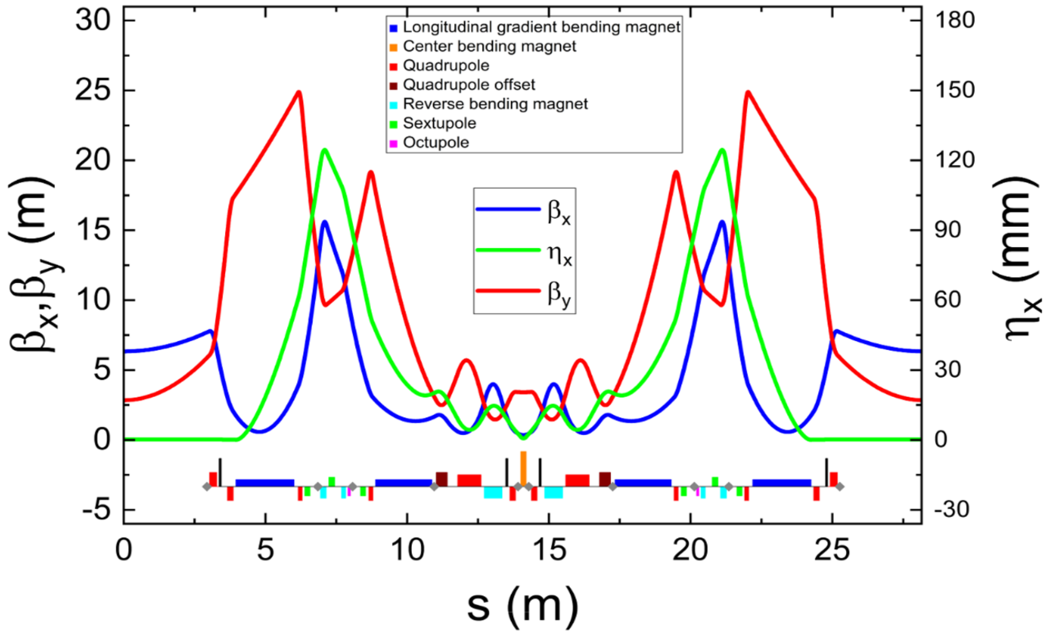
- 4 GeV electron beam energy is chosen for best performance of photon beam in the range of 10 – 30 keV
- ~100 times brighter photon beam than that of PLS-II

Beamlines

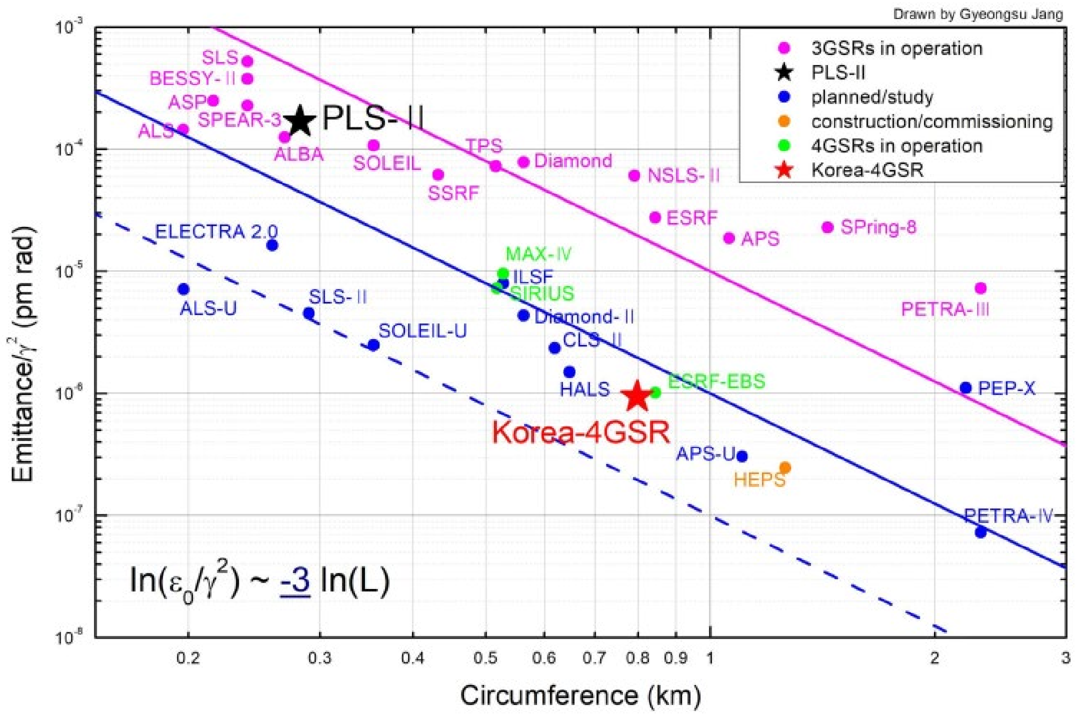
	Beamline
Industry oriented	① BioPharma BioSAXS
	② Material Structure Analysis
	③ Soft X-ray Nano-probe
Research oriented	④ Nanoscale Angle-resolved Photoemission Spectroscopy
	⑤ Coherent X-ray Diffraction
	⑥ Coherent Small-angle X-ray Scattering
	⑦ Real-time X-ray Absorption Fine Structure
	⑧ Bio Nano Crystallography
	⑨ High Energy Microscopy
	⑩ Nano-probe

Storage Ring Lattice Parameters

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	0.78×10^{-4}
Energy spread (σ_δ)	1.26×10^{-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**

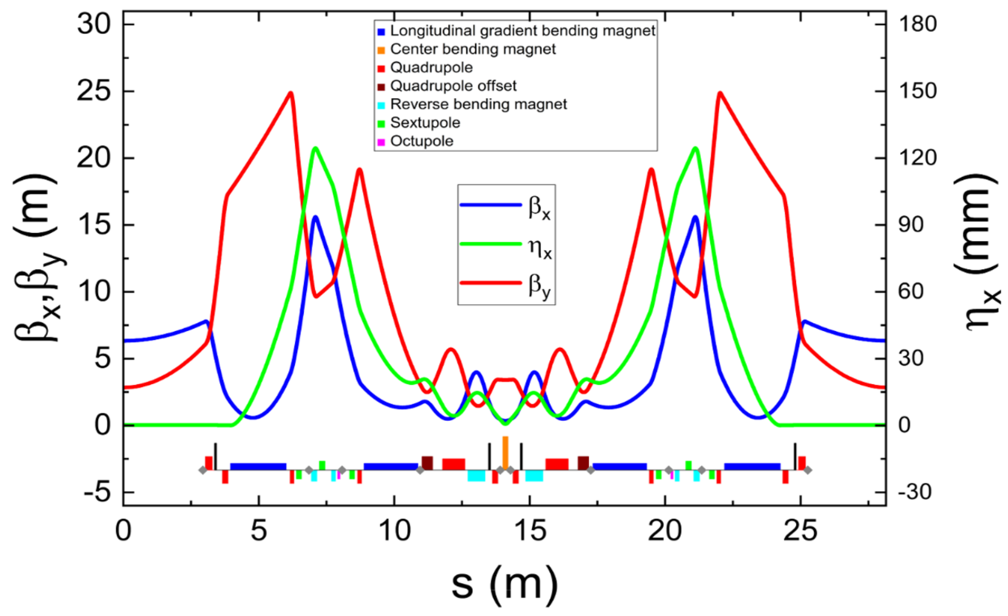


Unit cell of Korea-4GSR storage ring (H7BA)

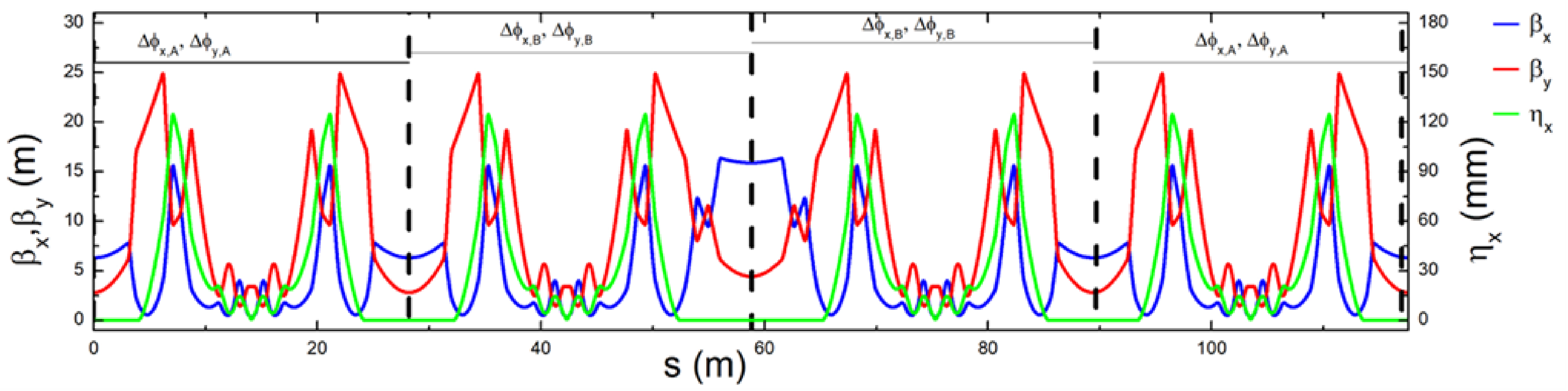


Normalized emittance vs. circumference
for 3GSRs and 4GSRs

Linear Optics



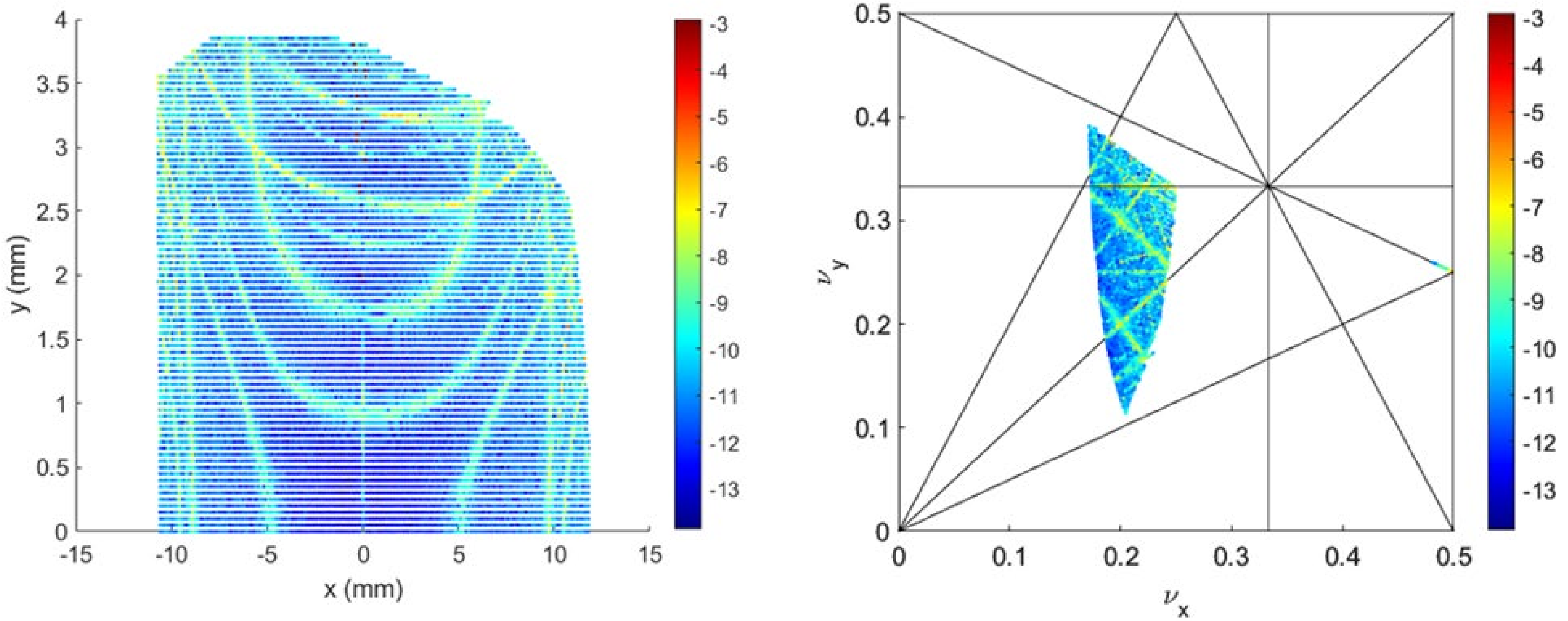
Unit cell



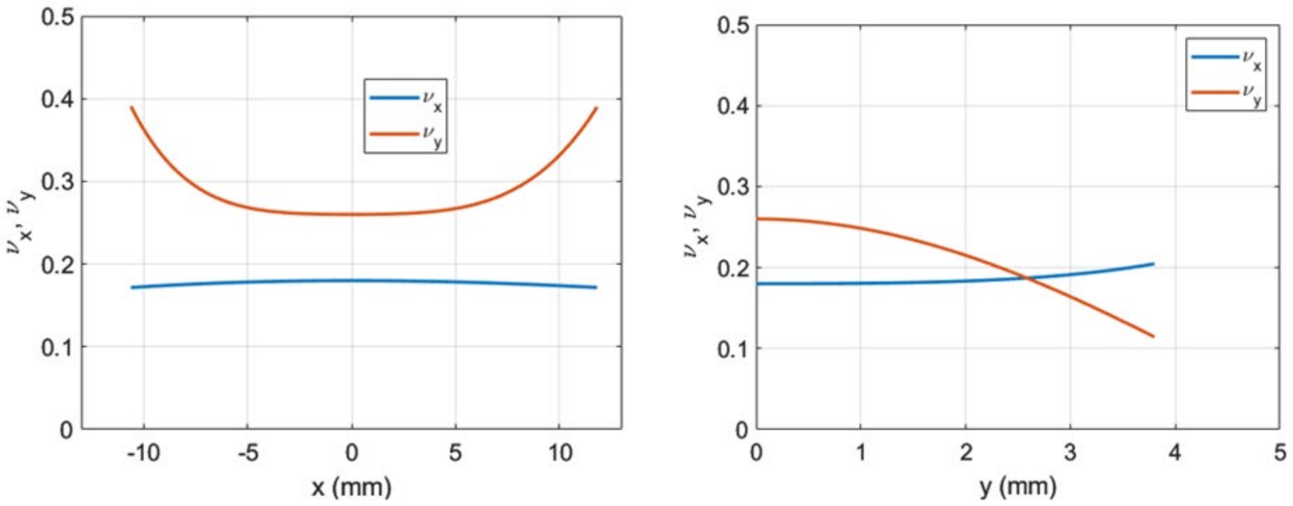
High-beta section

- The storage ring is a 800 m – 4 GeV – 28-cell ring with natural emittance of 62 pm
- The unit cell is a H7BA with 2-T center bend
- The ring is composed of 28 H7BA cells (28 identical arcs, 26 ID SS + 2 high-beta SS)
- Phase advance is matched ($\Delta\phi_{x,A}$ = $\Delta\phi_{x,B}$ 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 on-momentum phase advance
- One high-beta straight is dedicated for off-axis injection

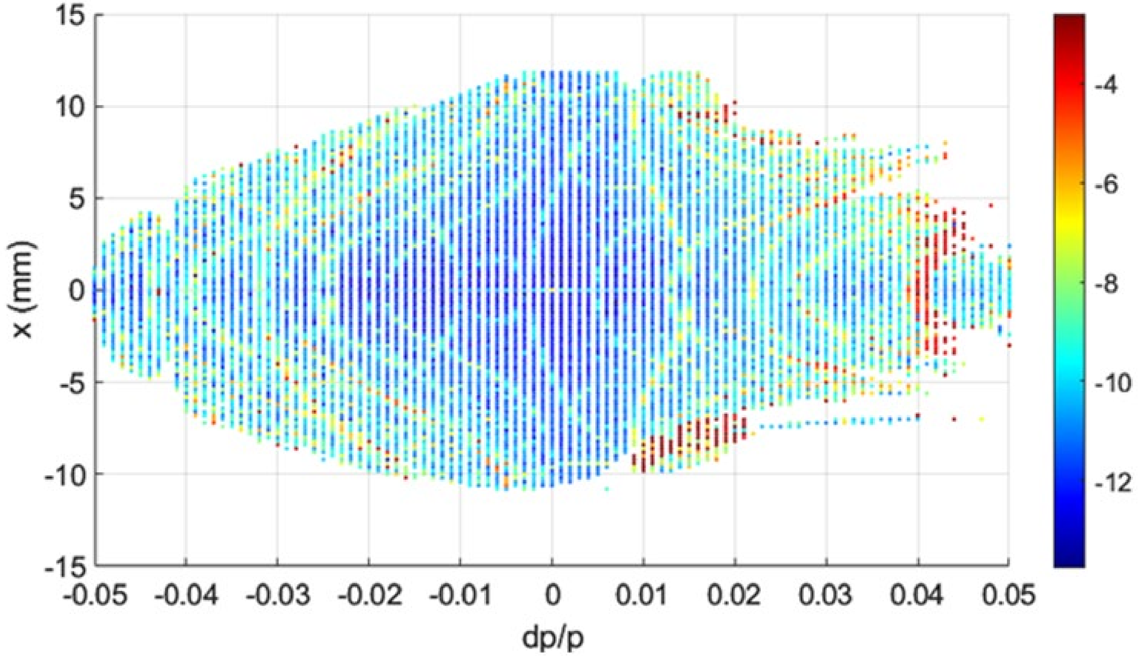
Nonlinear Dynamics



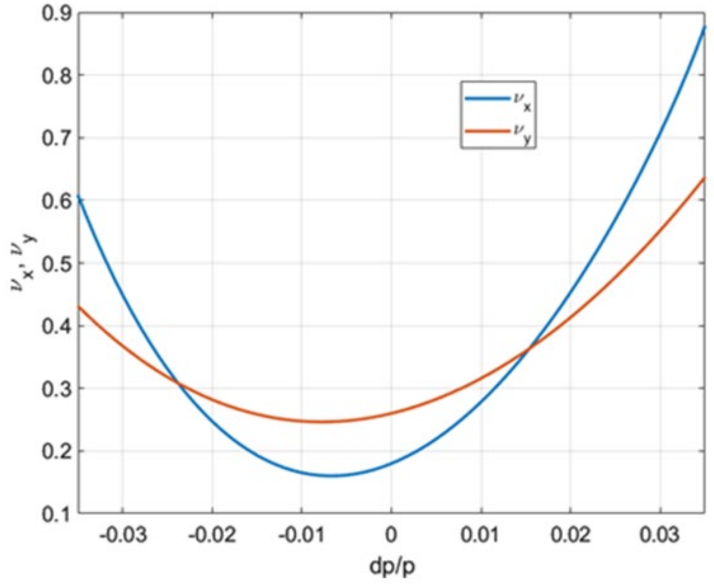
FMA with x-y offset



Amplitude dependent tune shifts (ADTS)



FMA with x-dp/p offset



Momentum dependent tune shifts (MDTS)

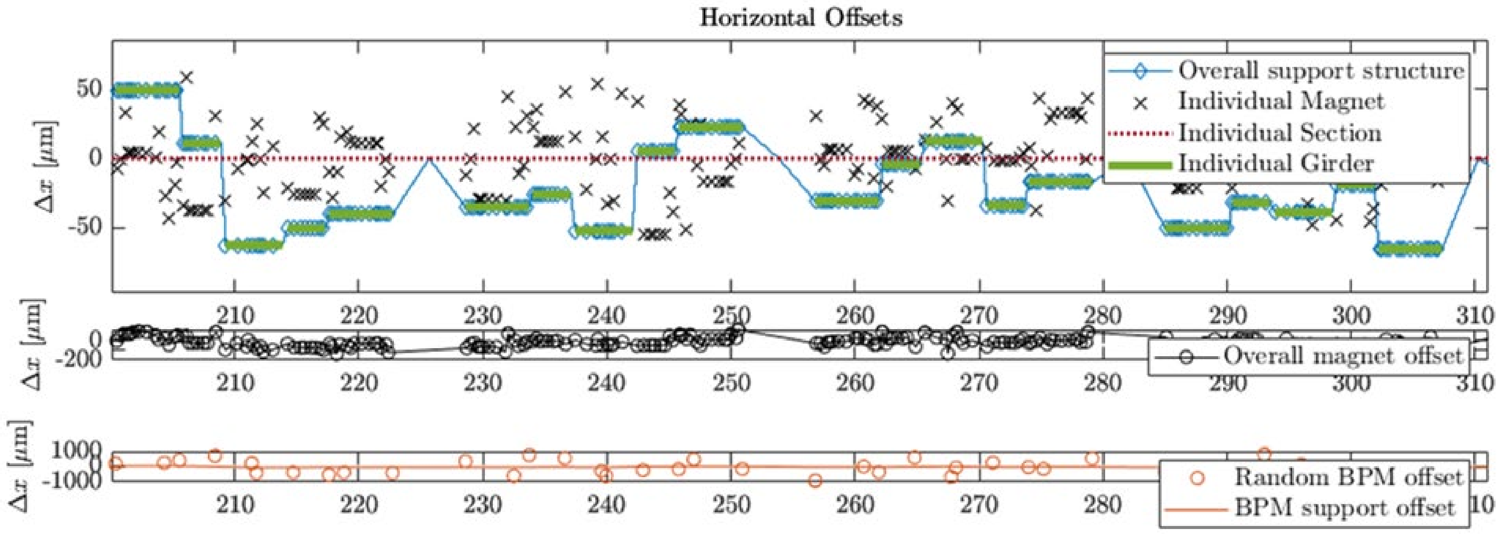
Error Tolerance

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 / - / -	

Magnet error

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

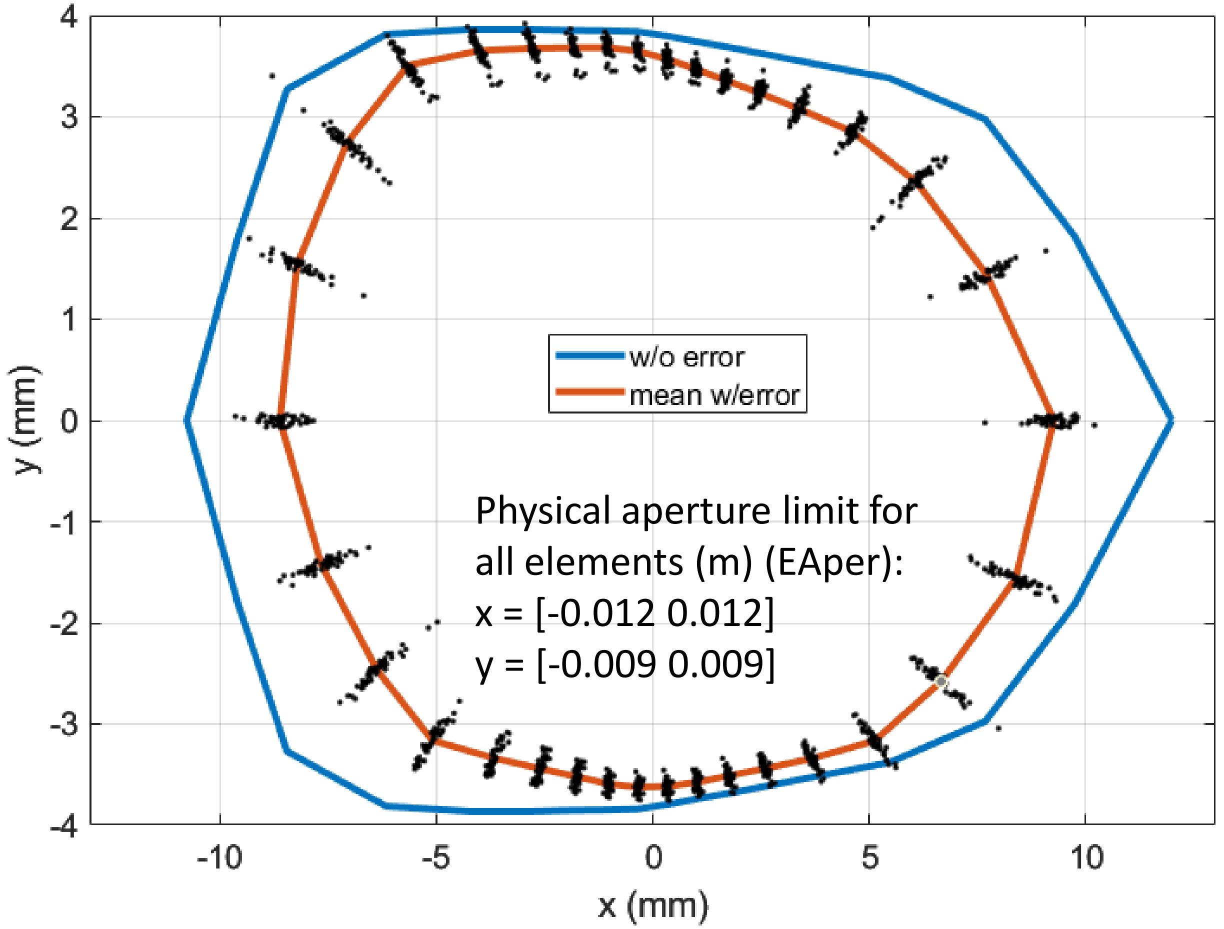
BPM error



Example of horizontal offset distribution over reference orbit

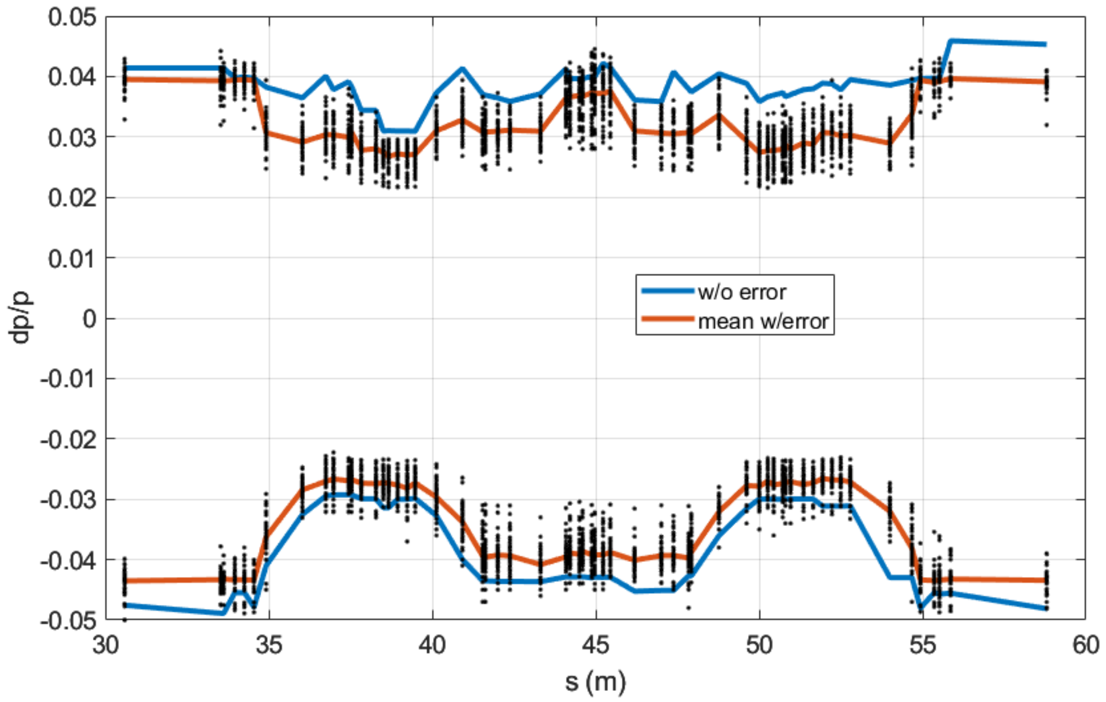
Overall offset = girder offset + magnet offset w.r.t girder

Dynamic Aperture and Momentum Aperture



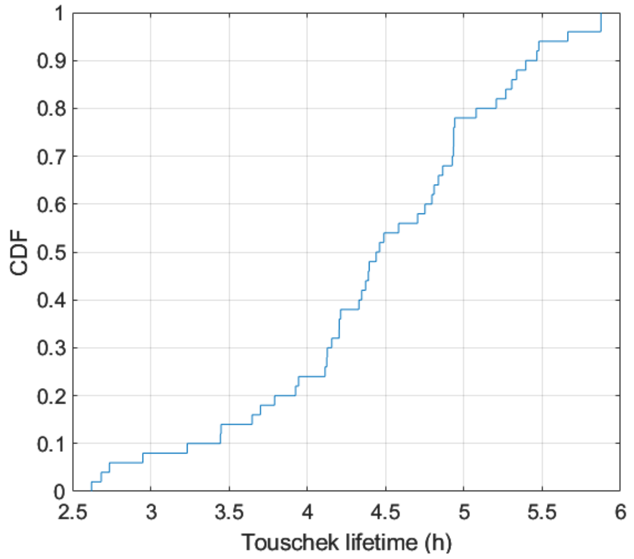
Dynamic aperture

x = -8.3 ± 0.6 mm



Momentum aperture

Touschek lifetime
= 3.36 ± 0.64 h



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

-Results with 50 random error seeds
-Realistic correction chain (orbit correction, LOCO, etc) is applied for each seed

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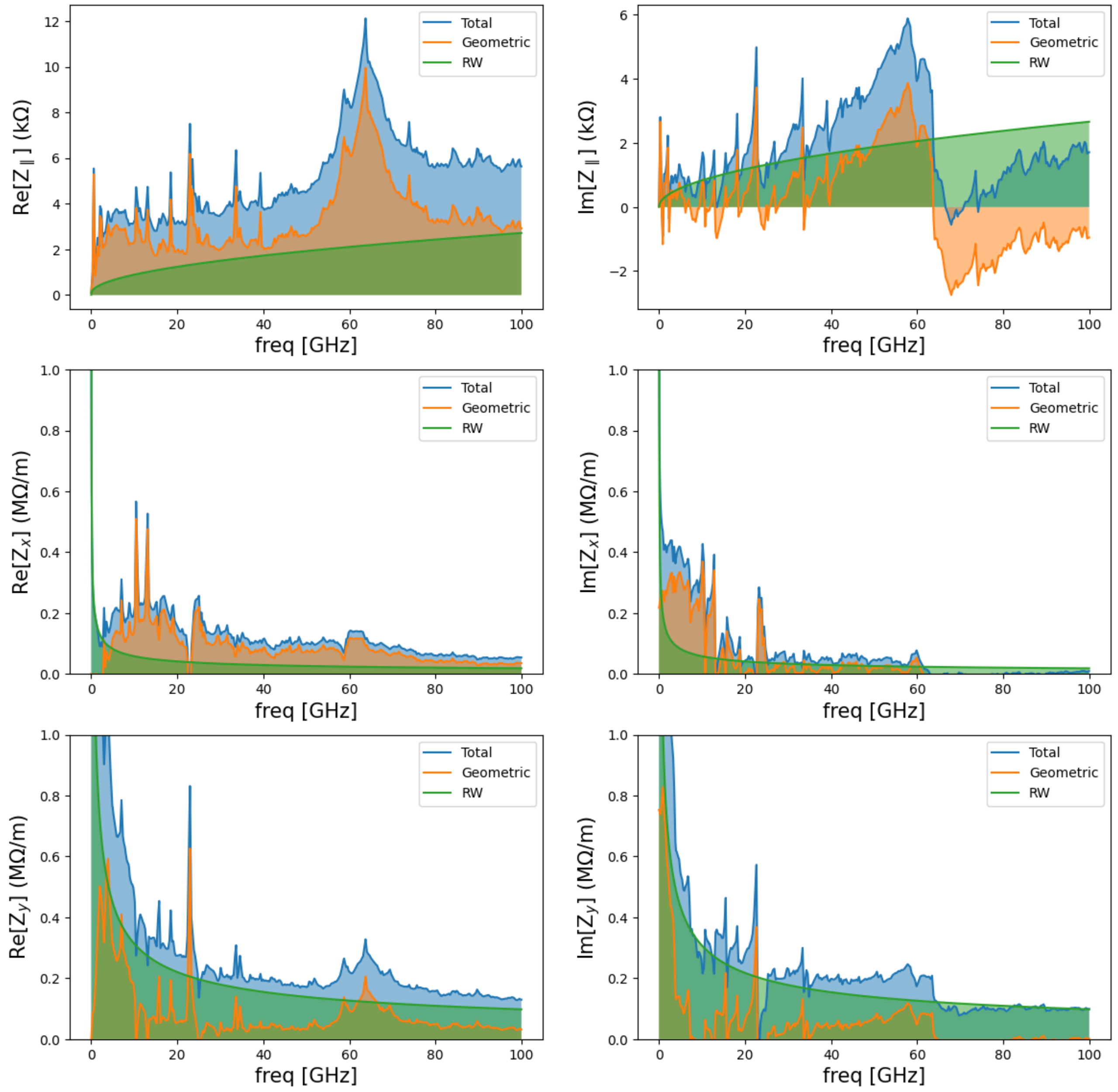
Impedance Budget

Bunch length **14 mm**

Element	Number	Loss factor (V/pC)	Hor. Kick factor (V/pC/m)	Ver. Kick factor (V/pC/m)	Remarks
Resistive wall	1	2.385	-1429.018	-7504.161	All IDs are closed
BPM	288	0.001	-1.548	0.237	
Bellows	750	0.000	-0.261	-0.321	
Flange	600	0.000	-0.083	-0.191	
Mask	84	0.000	0.000	0.000	
Gate valve	56	0.096	-6.730	-42.916	
Pumping tee	28	0.004	-10.771	2.226	
Main RF cavity	12	0.199	-2.090	-2.090	
LFB	2	0.240	-20.575	-22.173	Longitudinal feedback
TFB	2	0.027	1.343	-8.406	Transverse feedback
Sum		11.083	-2862.404	-10218.569	

*Impedance of ID section is in progress
*No HHC design yet



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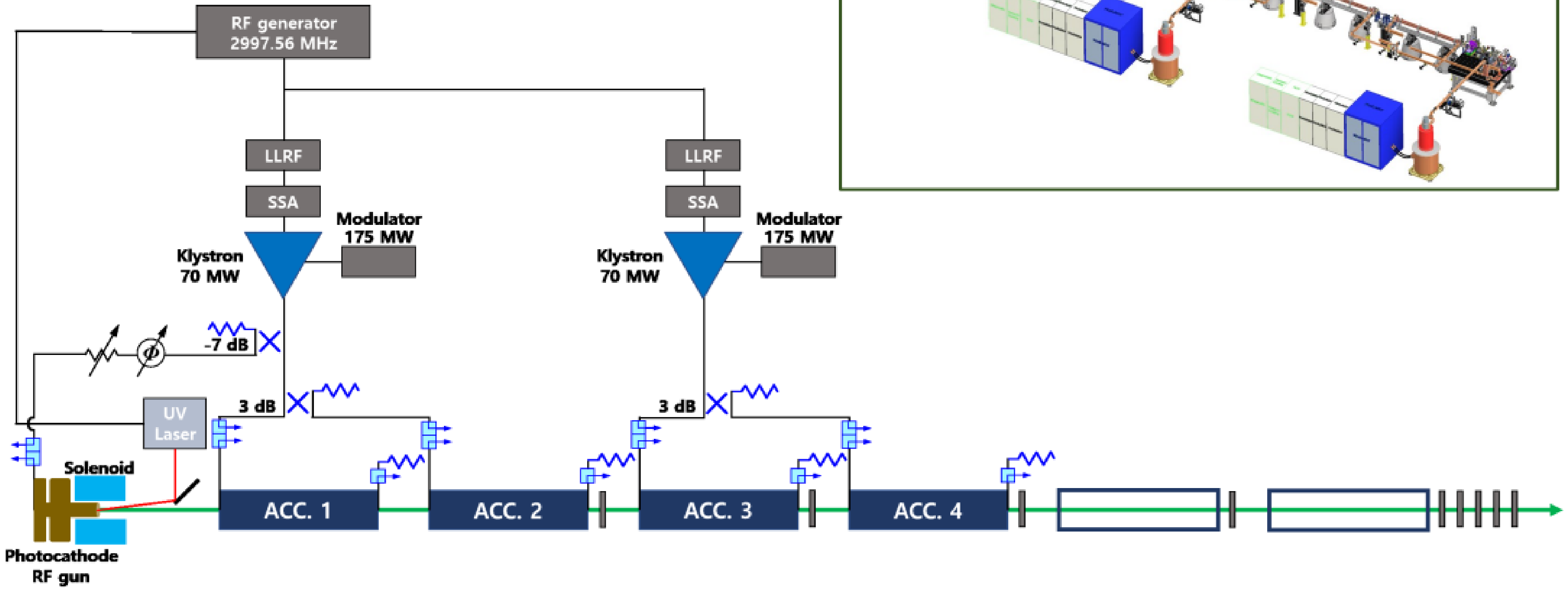
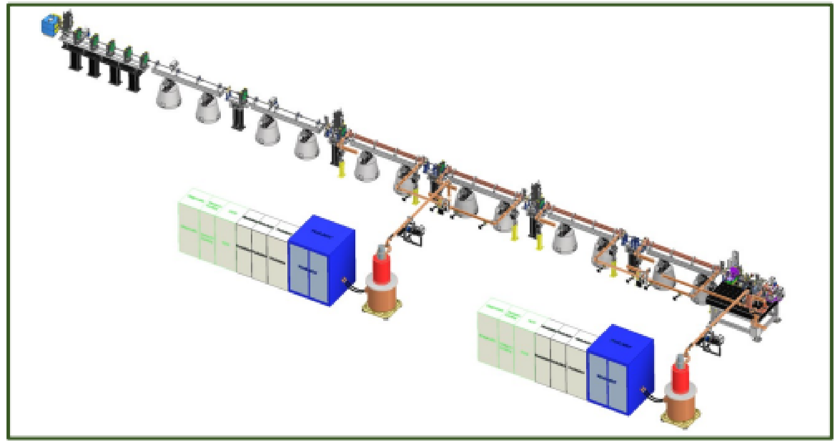
Linac

Linac parameters

Parameters	Multi-bunch	Single-bunch
Energy	**200 MeV**	**200 MeV**
Frequency	**2997.56 $\pm$ 0.1 MHz**	**2997.56 $\pm$ 0.1 MHz**
Emittance (at 200 MeV)	**$\leq$ 10 nm**	**$\leq$ 10 nm**
Relative energy spread (rms)	**$\leq$ 0.3%**	**$\leq$ 0.3%**
Pulse to pulse energy jitter (rms)	**$\leq$ 0.2%**	**$\leq$ 0.2%**
Bunch charge (charge stability)	**1 to 3 nC (5%)**	**0.01 to 1 nC (2%)**
Pulse duration	**$\approx$ 200 ns (102 or 17 bunches)**	**6-8 ps FWHM**
Repetition rate	**2 Hz**	**2 Hz (60 Hz)**

200 MeV Linear Accelerator





LCW parameters

- Acceleration tube : 28 $\pm$ 2°C (~50 kHz/ °C)
- Photocathode gun: 25 ~ 50 °C

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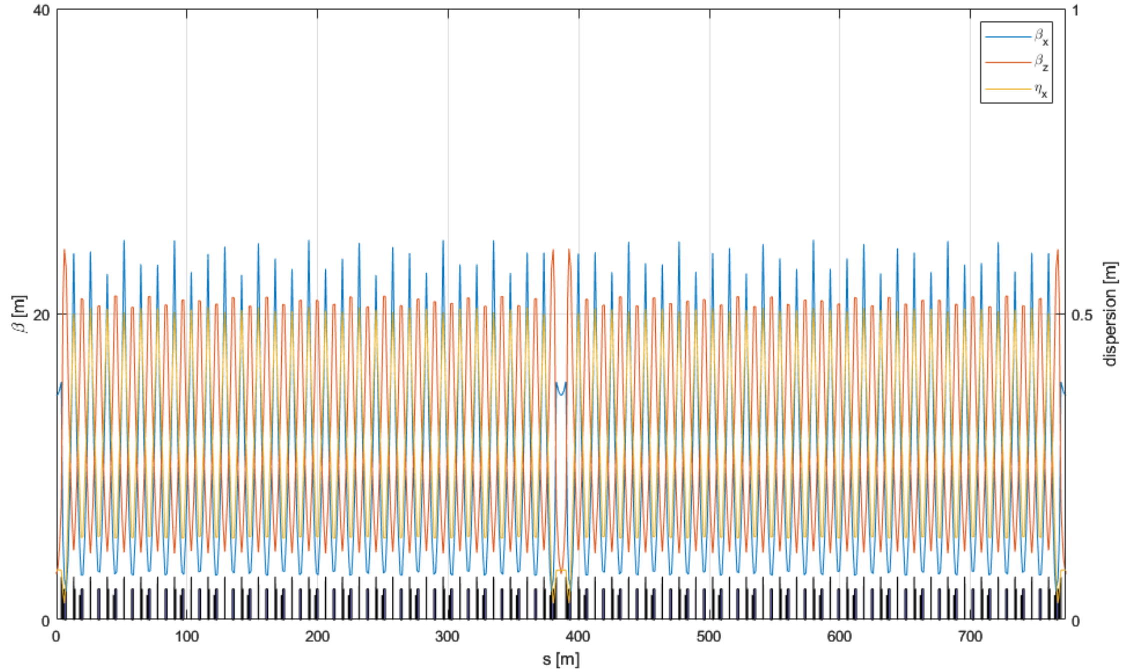
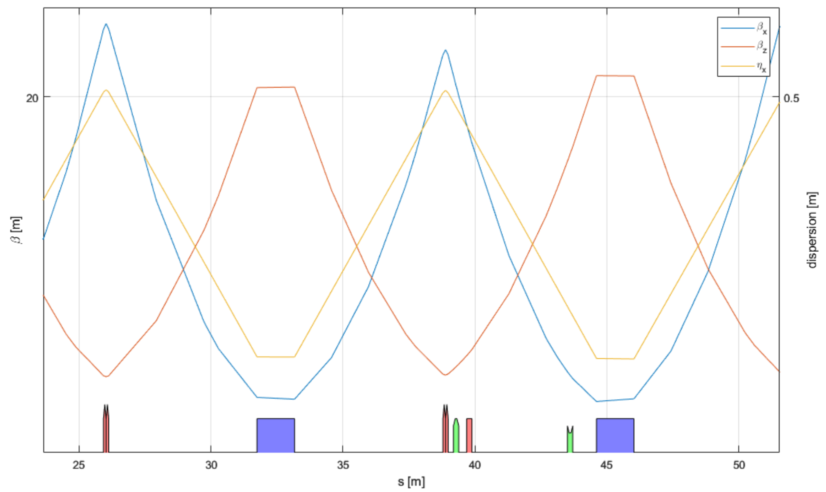
Booster



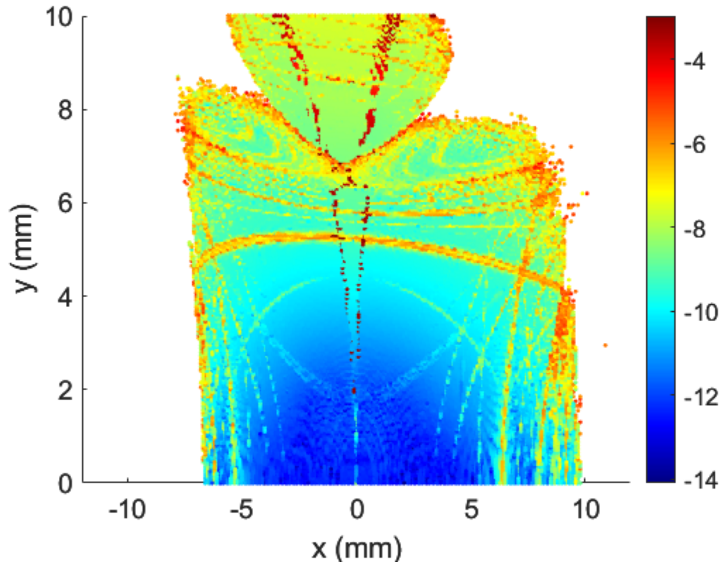
Lattice functions of booster ring



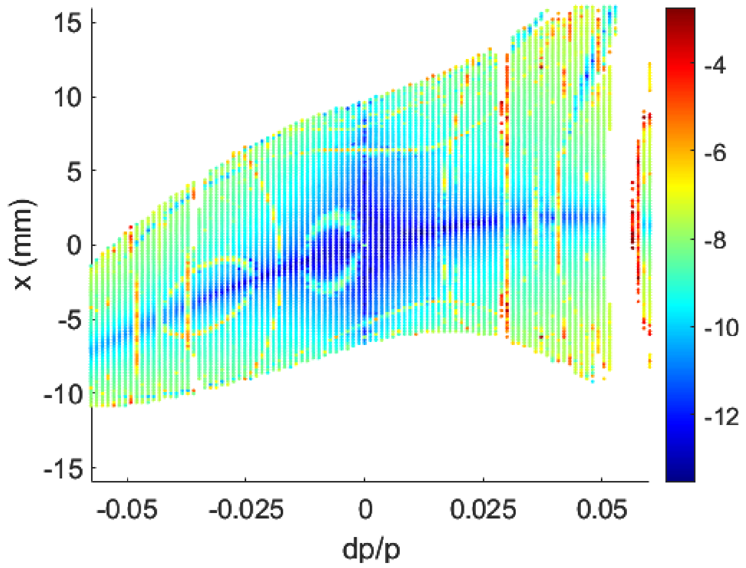
Lattice functions of booster ring unit cell

773 m Booster		Value	Unit
Design Parameters	Circumference	772.893	m
	Beam Energy (Inj. - Ext.)	0.2 - 4	GeV
	Cell number	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

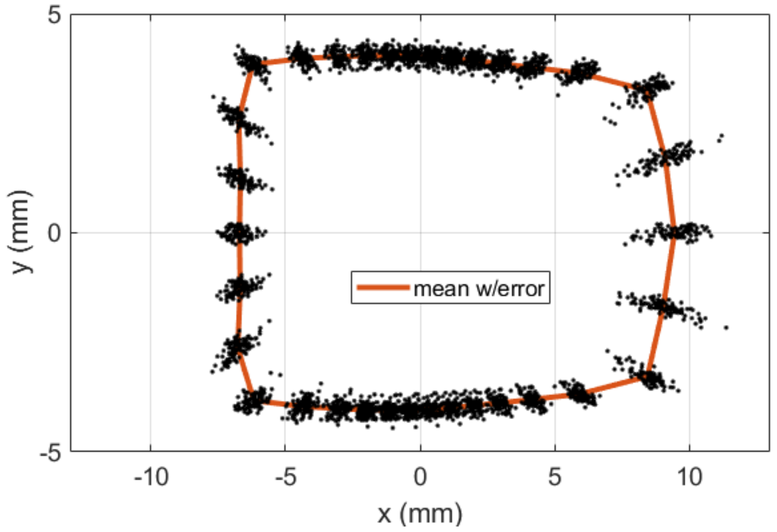
Booster Beam Dynamics



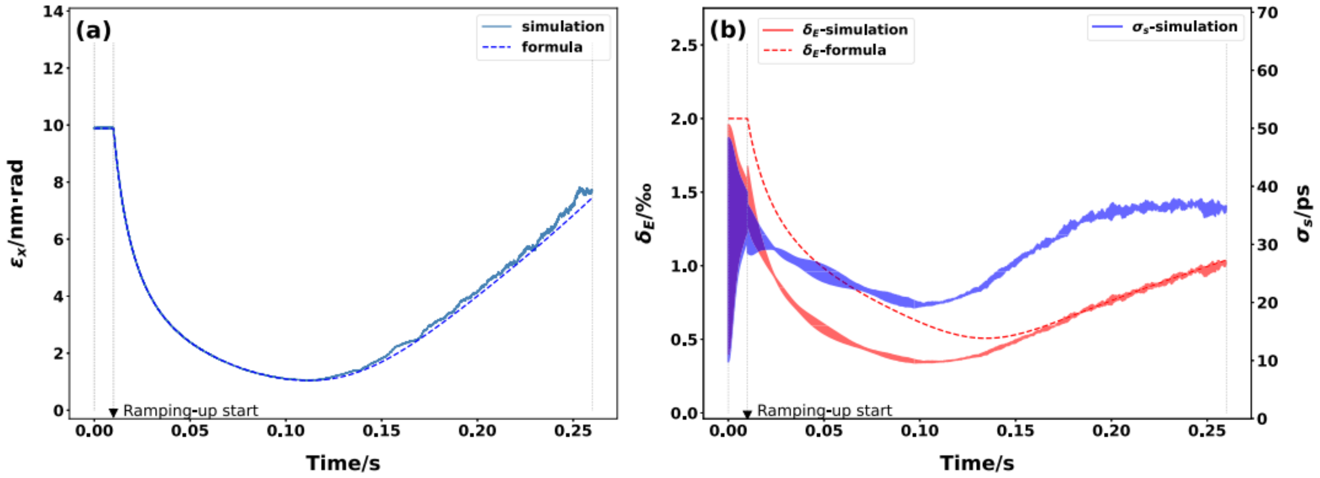
Dynamic aperture



Momentum aperture



Dynamic aperture w/ error



Evolution of emittance and energy spread during energy ramping

Y. Lee et al. ,Nuclear Instruments and Methods in Physics Research A 1060 (2024) 169074

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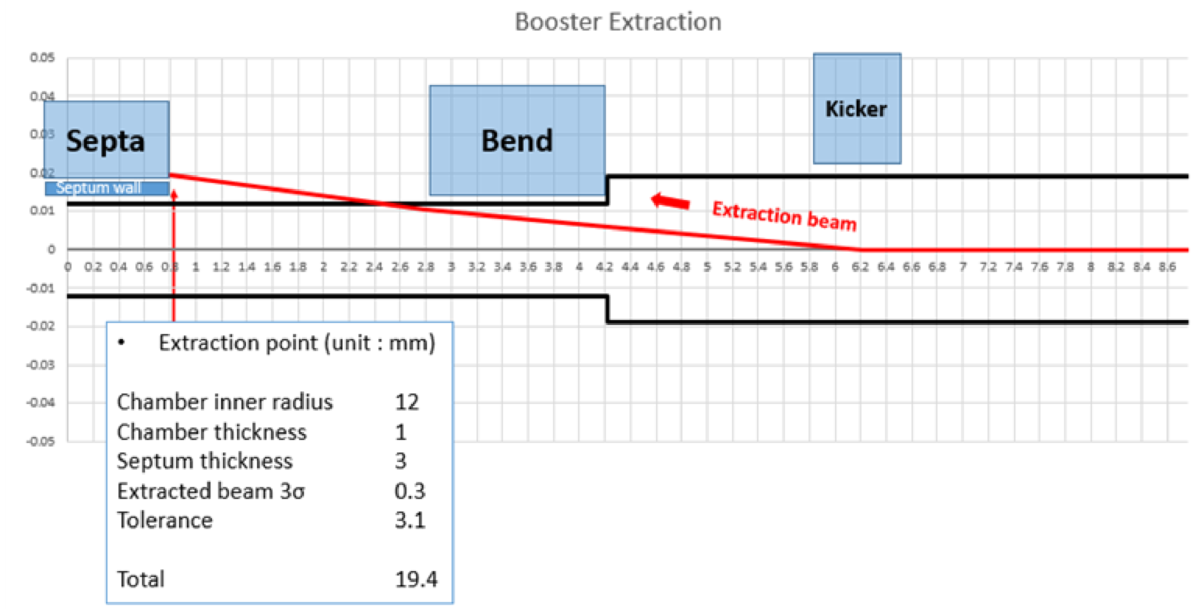
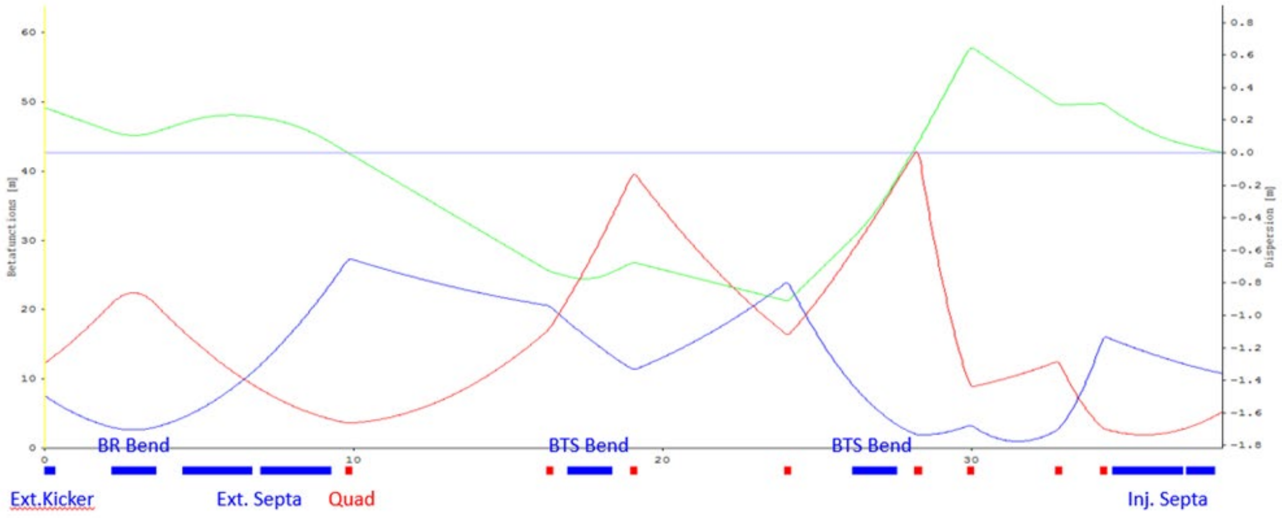
Injection to Storage Ring (4-Kicker Bump)

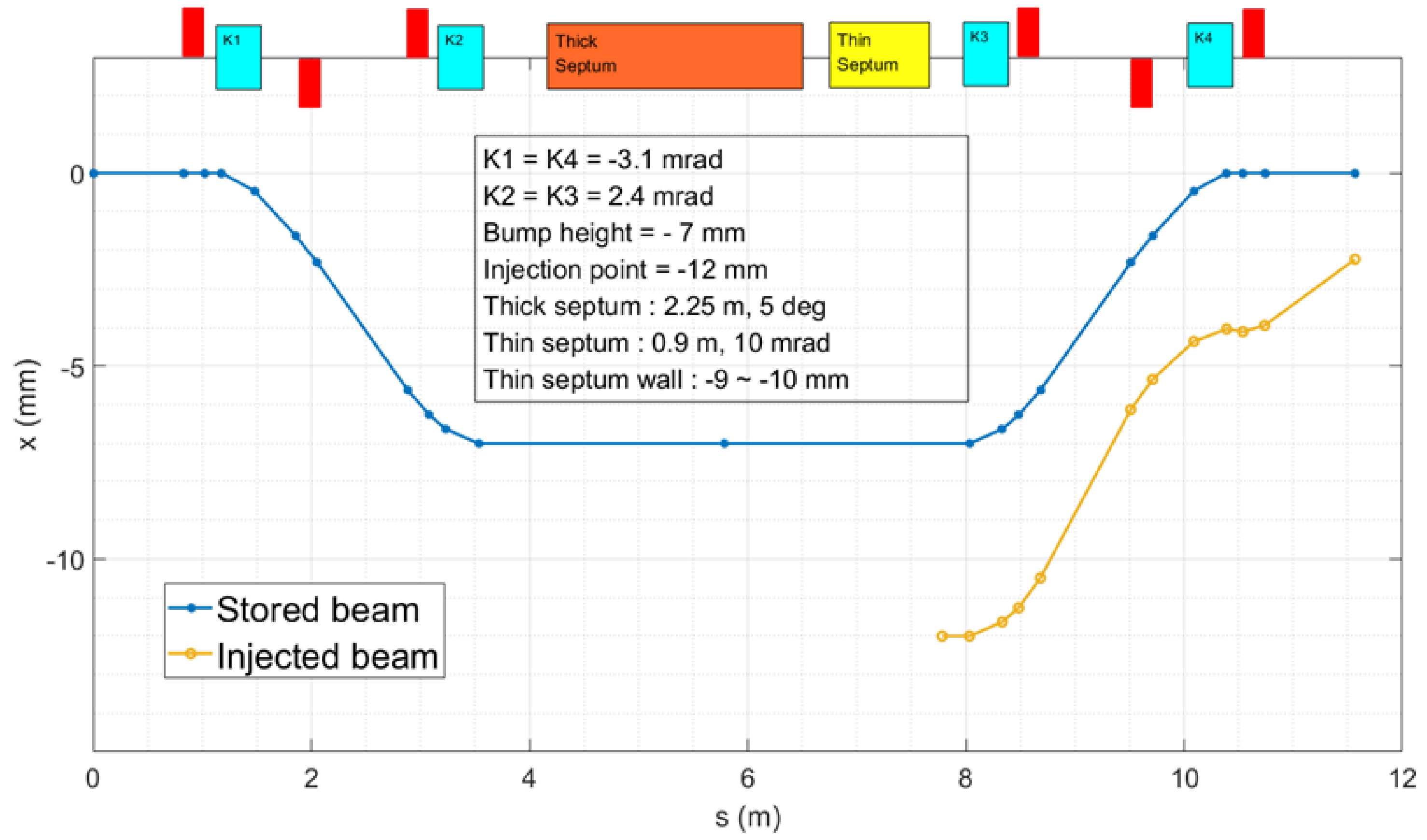


- At Kicker
x' = 0 mrad -> 3 mrad
- 2 m Drift
x = 0 mm -> 6 mm
x'= 3 mrad
- At Bending Magnet
(k = -0.149)
x = 6 mm -> 10.449 mm
x'= 3 mrad -> 4.461 mrad
- Before Septa
x = 19.372 mm
x'= 4.461 mrad

Booster extraction



Booster-to-Storage ring beam transport line



4-kicker bump injection

Beam Diagnostics Summary

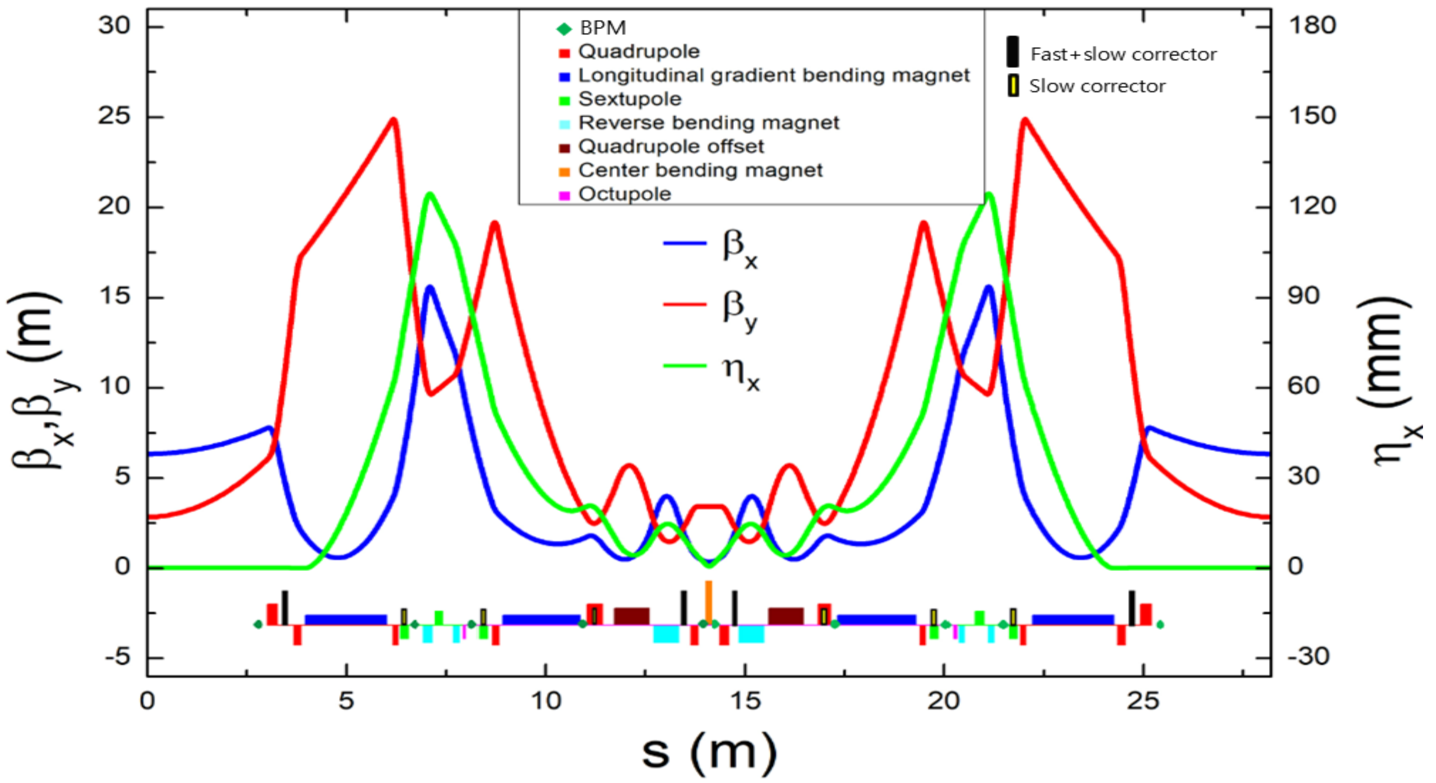
Types, Numbers & Locations (2023-Oct-24)

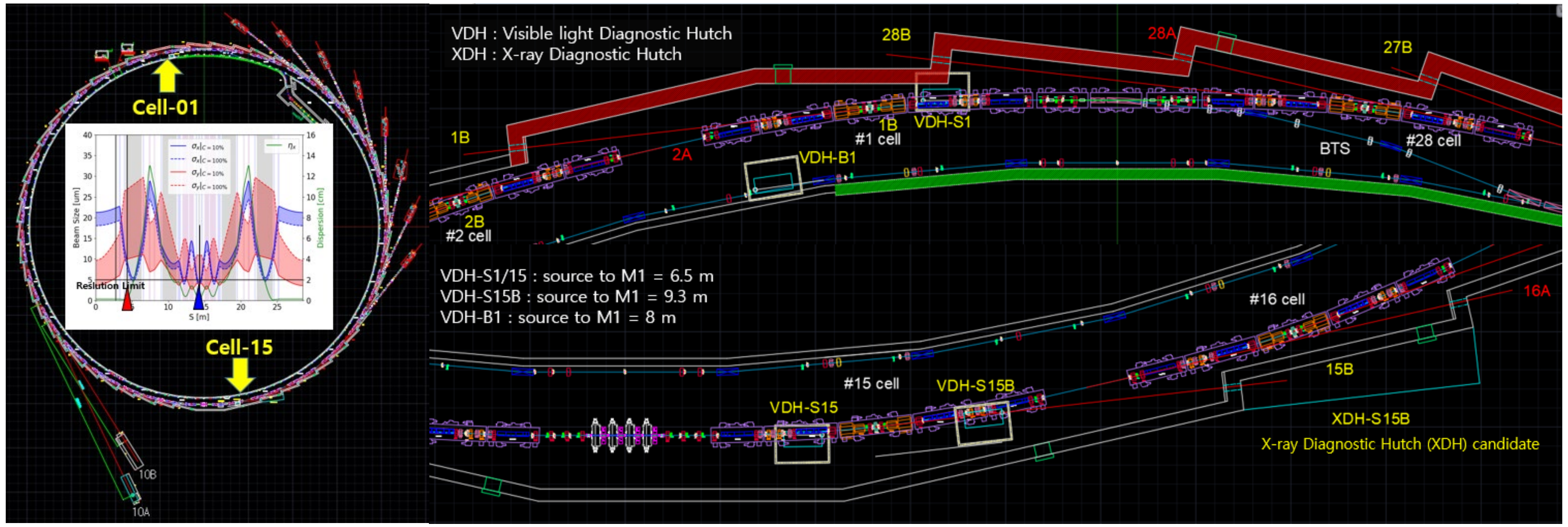
CODE	Type	Meas. Target	Numbers / Section				
			LINAC	LTB	BR	BTS	SR
1	BPM (BTN, STRL*)	Beam Position	10	7	120	6	288
2	BPRM (YAG/OTR)	2D Profile, Emittance, Energy	7	7		3	
3	X-ray Diagnostic Hutch	Beam Size, Emittance, Energy Spread					1
4	Visible light Diagnostic Hutch	Beam Size, Emittance, Bunch Length & Purity			1		3
5	Beam Loss Monitor(FAST-PMT)	Beam Loss			5		30
6	Beam Loss Monitor(SLOW-Scintillating Fiber)	Beam Loss	1	1	4	1	14
7	ICT	Pulse Beam Current	2	1		2	
8	DCCT	DC Beam Current			1		2
9	FCT	Filling Pattern			1		1
10	PBPM	Photon Beam Position					30
11	Tune Monitor	Tune			1		1
12	Faraday Cup	Beam Current	1				
13	TFS/LFS	Multi-bunch Feedback					2
Numbers in total			21	16	133	12	370

Storage Ring Beam Diagnostics Summary

Storage ring beam diagnostics

- Beam Position: Button BPM x 280+8 (28+2 periodic cell)
- Beam Size, Emittance, Bunch Length & Purity
  :Visible light Diagnostic Hutch x 3
- Beam Size, Emittance, Energy Spread
  :X-ray Diagnostic Hutch x 1
- Beam Loss: Slow BLM x 7 module, Fast BLM x 28
- Beam Current : DCCT x 2
- Filling Pattern : FCT x1
- Tune: Tune monitor x 1
- Photon beam position : PBPM x 30
- Bunch-by-bunch Feedback: TFS x 1, LFS x1
- PBPM Feedback*: Invar BPM x 4 (TBD)



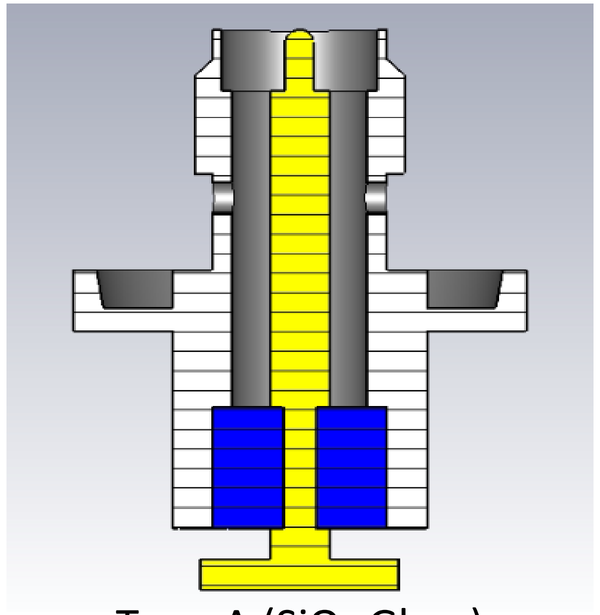


Diag. Hutch location: VDH (3+1), XDH 1

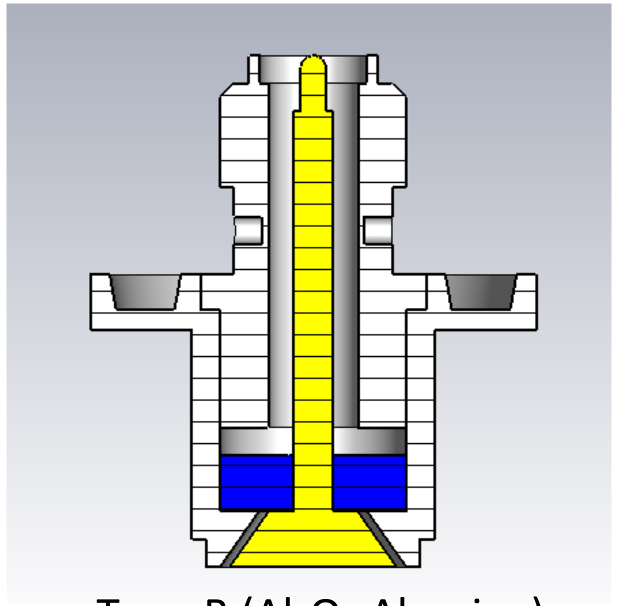
Storage Ring BPM system Summary

4GSR Button BPM

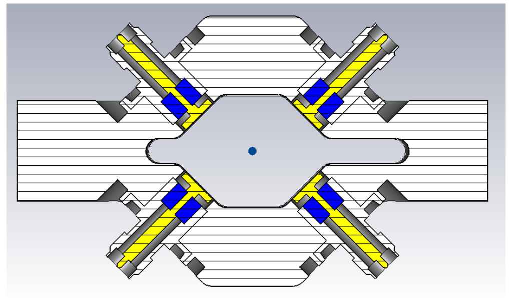
- Two type of buttons were designed
  - RF design was finished and under prototyping
    - Alumina Ceramic / Borosilicate Glass
  - Antenna design that meets the both operation conditions of w/ & w/o 3rd harmonic cavity
  - Temp. sensor & fiducial mark will be placed on BPM chamber
  - All BPM will be used button pick-up (Linac. to SR)



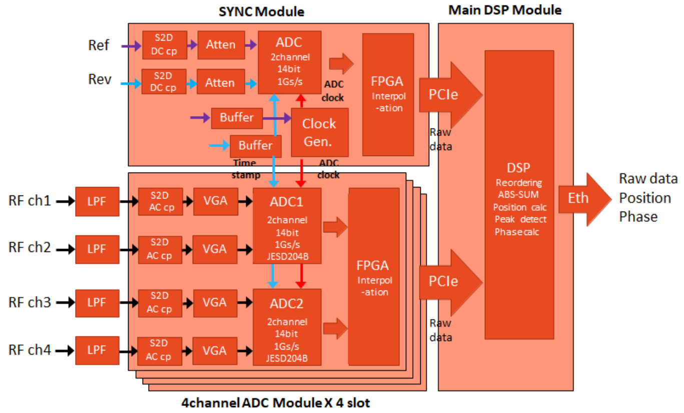
Type-A (SiO_2 Glass)



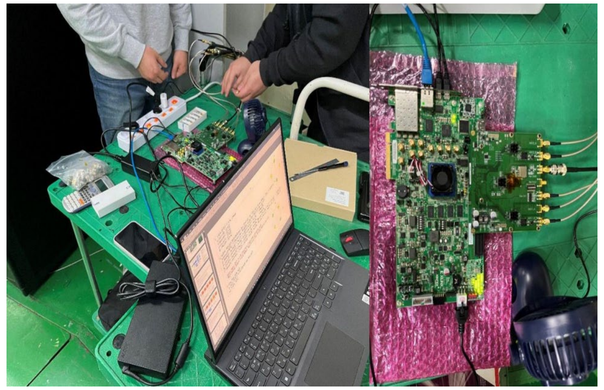
Type-B (Al_2O_3 Alumina)

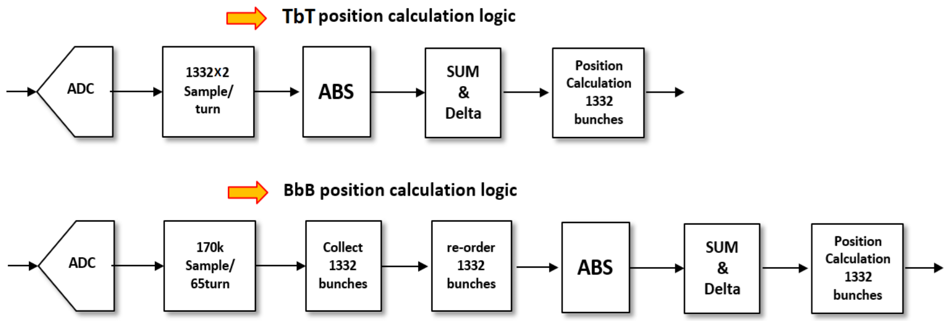


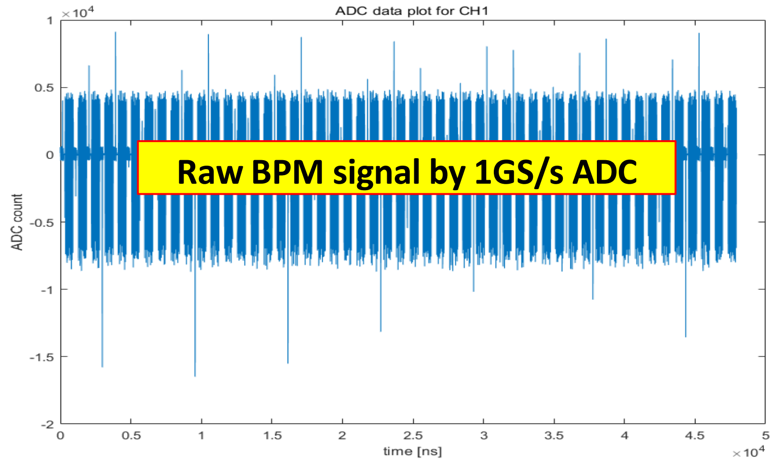
4GSR BPM electronics

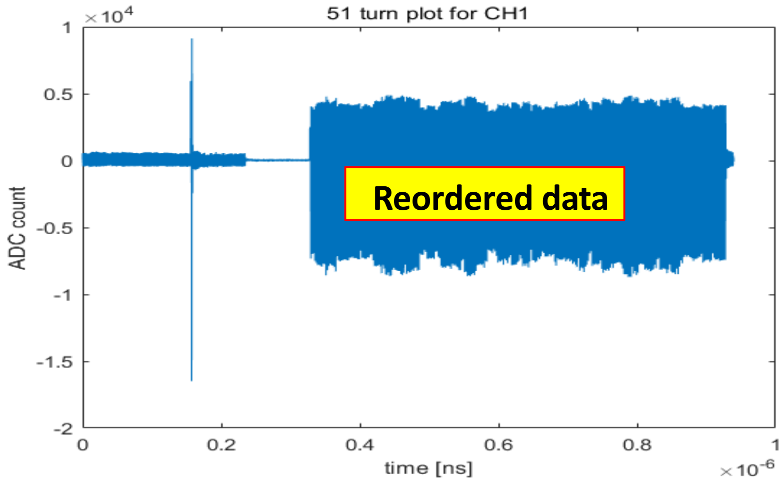


- Proto-type BPM electronics was tested @ PLS-II
- SR BPM electronics requirement
  - Turn by turn beam position @ 375kHz with 1um
  - Fast beam position @ 10kHz with 200 nm
  - Slow beam position @ 10Hz with 10 nm
  - Bunch-by-bunch monitoring also possible









Magnet Summary

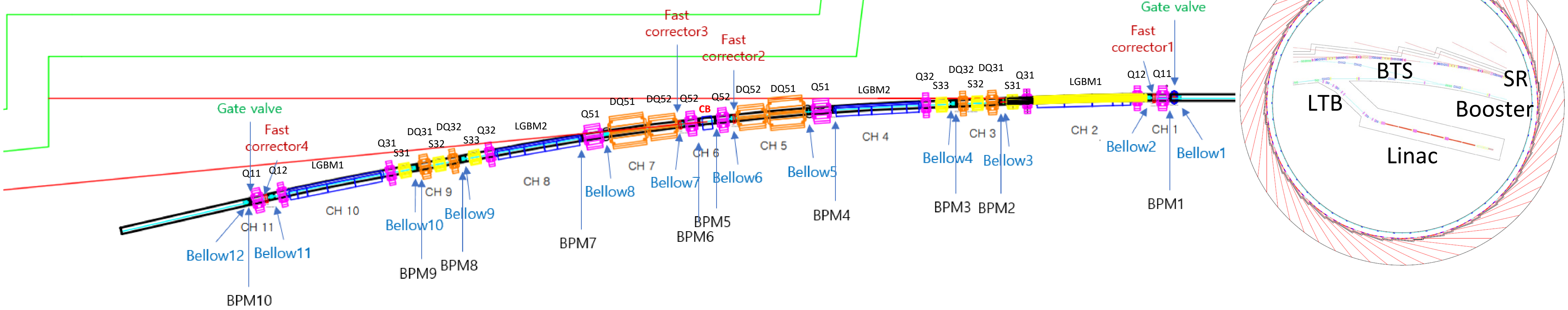
Magnet	Required Number	Remark
Combined Dipole	60	
Quadrupole	66	
Sextupoles	60	
Corr.	240	H120, V120
Total	426+	Total number of magnets

Booster Magnet Summary

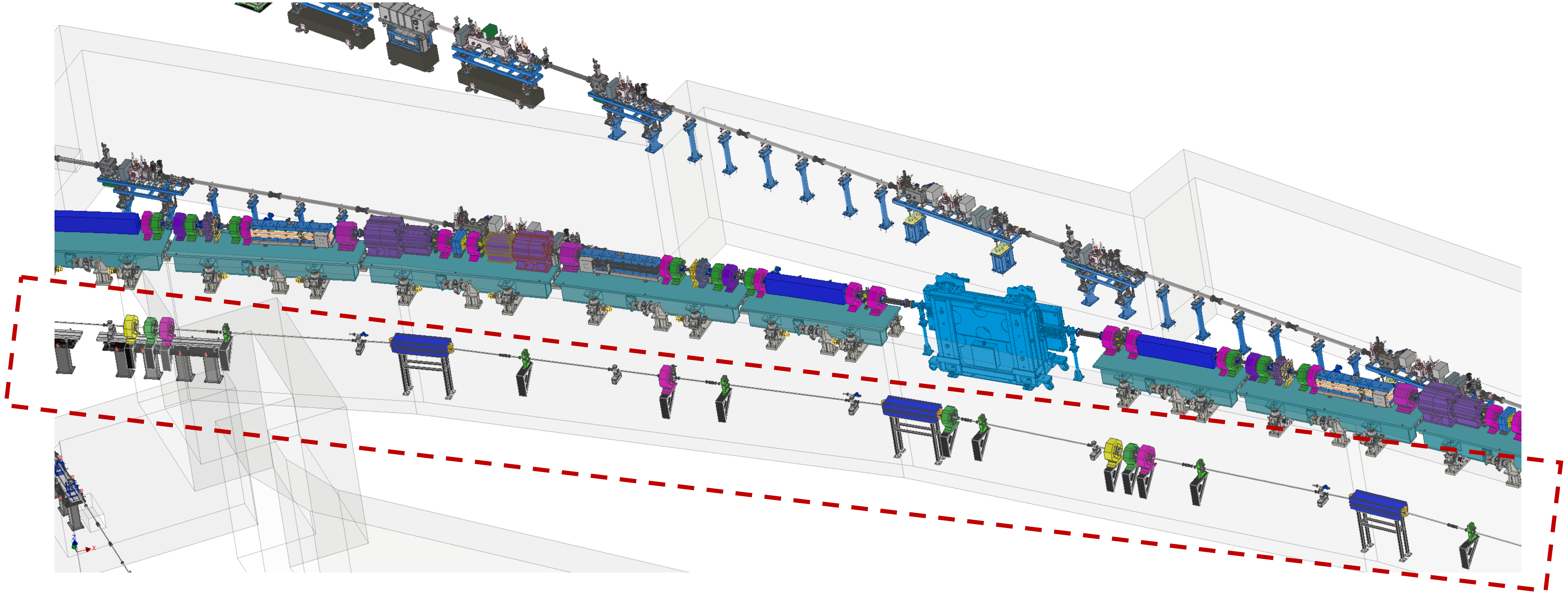
Magnet	Required Number	Remark
Central BM	28	1*28
Long. BM	112	4*28
Reverse Bend	168	2*3*28 (should have B, B')
Quad Bend	56	2*28 (should have B, B')
Quadrupoles	344	6*2*28+8(QH)
Sextupoles	168	6*28 (should have B", H/V Corr, Skew Quad)
Fast Corr.	112	4*28 (H/V combined corrector)
Octupole	56	2*28
Magnets/Sec	35	31+4 (fast Corr.)
Total	1044	Total number of magnets

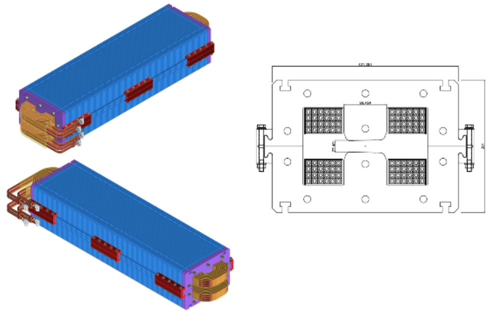
SR Magnet Summary

Additional 41+ magnets are required for LTB (Linac to Booster), and BTS (Booster to SR) and injection/extraction. Total 1511+ magnets are needed.

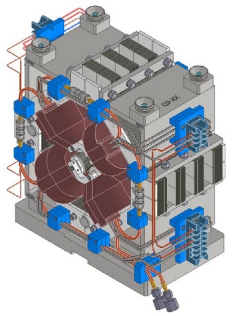


Booster Magnet Status Summary

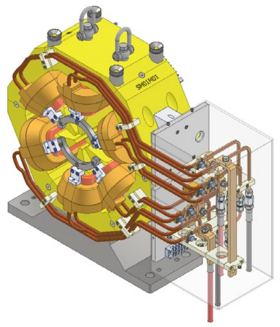




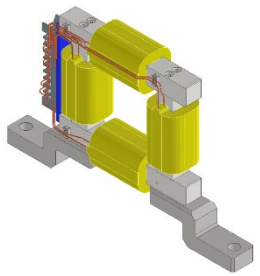
Combined Bending Magnet
(60EA, Procurement Plan: 2/2 of 2023)



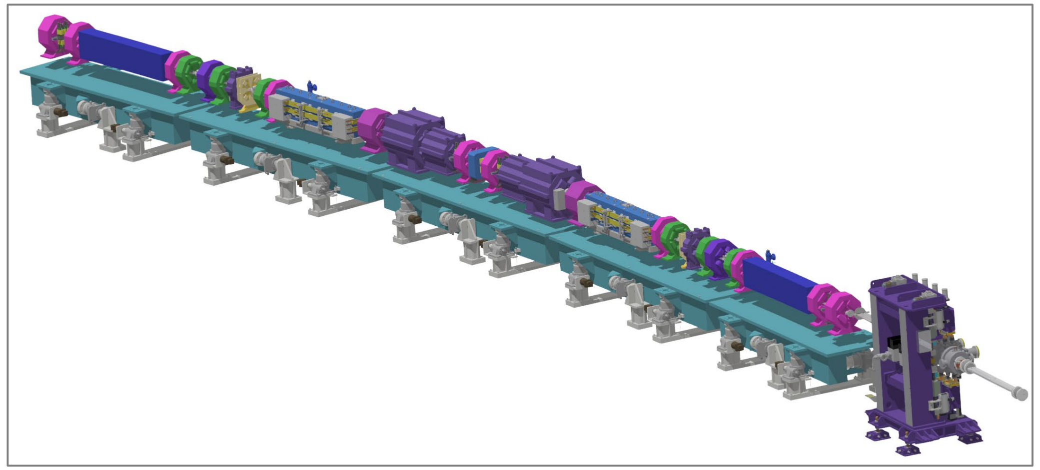
Quadupole
(66EA, Procurement Plan: 2/2 of 2023)



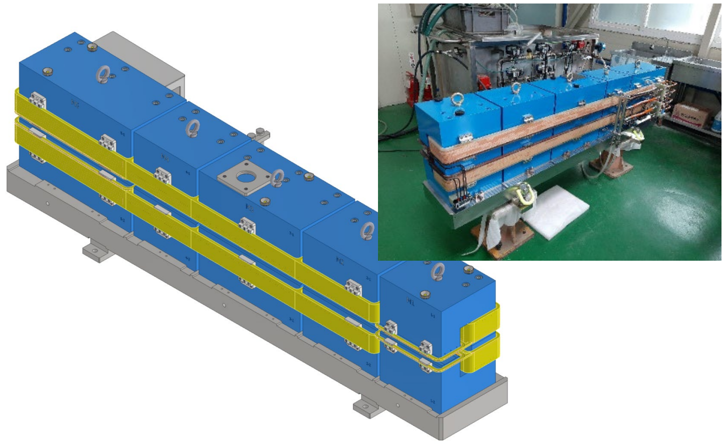
Sextupole
(60EA, Procurement Plan: 2/2 of 2023)



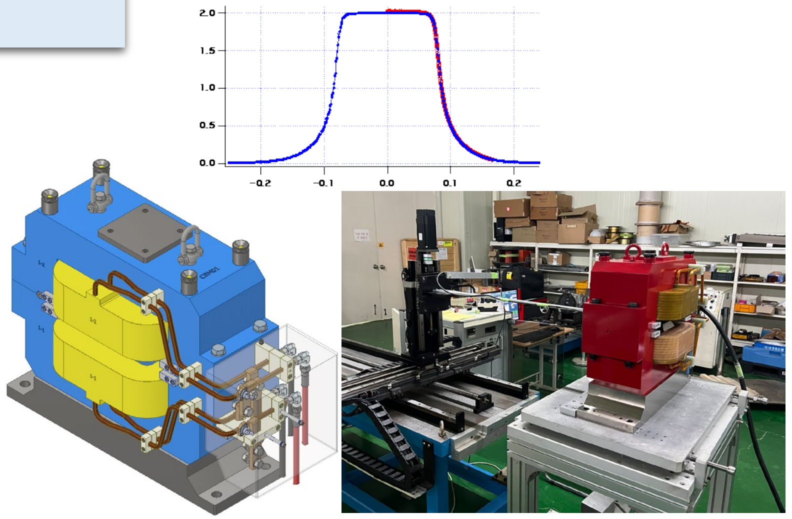
Corrector
(240EA, Procurement Plan: 2/2 of 2023)



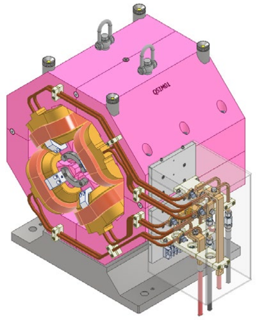
Storage Ring Magnet Status Summary



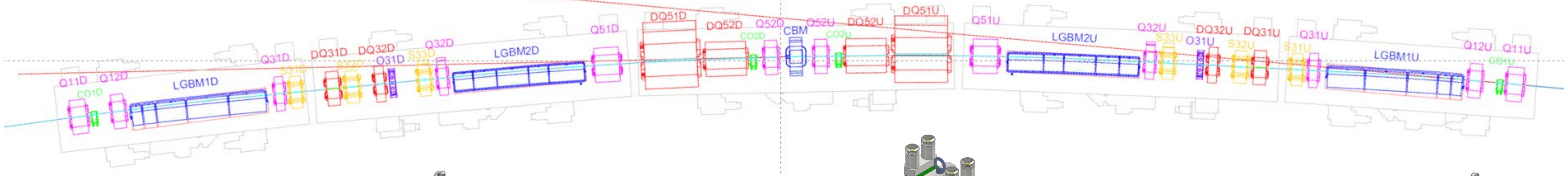
LGBM2 (56EA, On Manufacturing: 1/2 of 2023~)
LGBM1 (56EA, Procurement Plan: 2/2 of 2023)

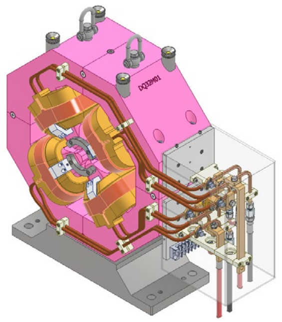


2T Center Bend
(28EA, On Manufacturing: 1/2 of 2023~)

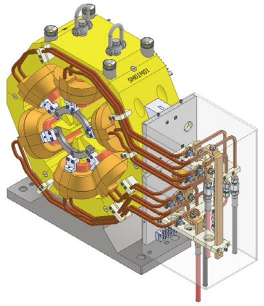


Quadrupole Magnet
(344EA, Procurement Plan: 2/2 of 2023)

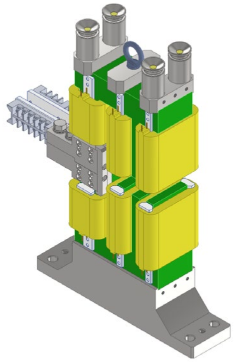




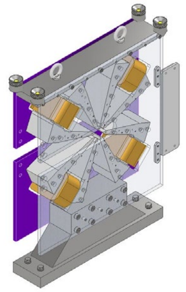
DQ
(224EA, Procurement Plan: 2/2 of 2023)



Sextupole Magnet
(116EA, Procurement Plan: 2/2 of 2023)



H/V Corrector Magnet
(112EA, On Manufacturing: 1/2 of 2023~)



Octupole Magnet
(56EA, Procurement Plan: 2/2 of 2023)

Selection of RF system

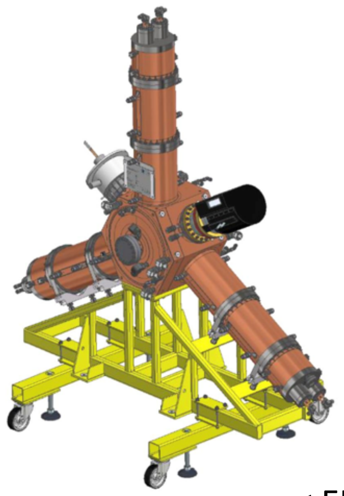
❖ Storage Ring RF System(10 RF Stations)

- Cavity : EU HOM Damped Normal Conducting Cavity
- HPRF : 150 kW SSPA
- LLRF : Pizza box type
- RF Transmission : WR1800 Waveguide

❖ Booster Ring RF System(3 RF Stations)

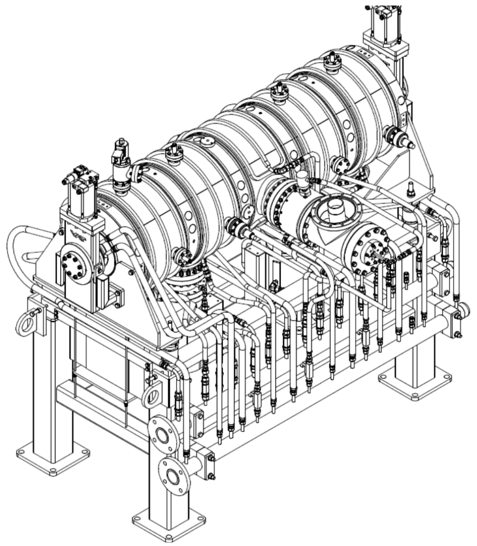
- Cavity : 5-cell PETRA Normal Conducting Cavity
- HPRF : 80 kW SSPA
- LLRF : Pizza box type
- RF Transmission : WR1800 Waveguide

Parameter	Unit	Values	Remark
Beam current	mA	400	
Revolution frequency	MHz	0.37528	
Harmonic number	-	1332	
RF frequency	MHz	499.594	
Electron energy loss /turn by bending magnet	keV	1097.65	
Electron energy loss /turn by IDs	keV	720.00	
Electron energy loss /turn by Others (estimated)	keV	60.00	loss by vacuum chamber
Total beam energy loss /turn by turn	keV	1877.65	



Parameter	Unit	Value
Resonant Frequency	MHz	499.594
Shunt Impedance	MOhm	3.4
Quality factor Q0	-	> 29,000
Coupling beta(variable)	-	1 ~ 6
Max. Power Coupler	kW	120
Eff. Gap Voltage at 70 kW	kV	700
Operating temperature	℃	25
Total water flow	l/m	143
Leak Rate	mbar l/s	< 2e-10

< EU HOM damped Cavity for SR>

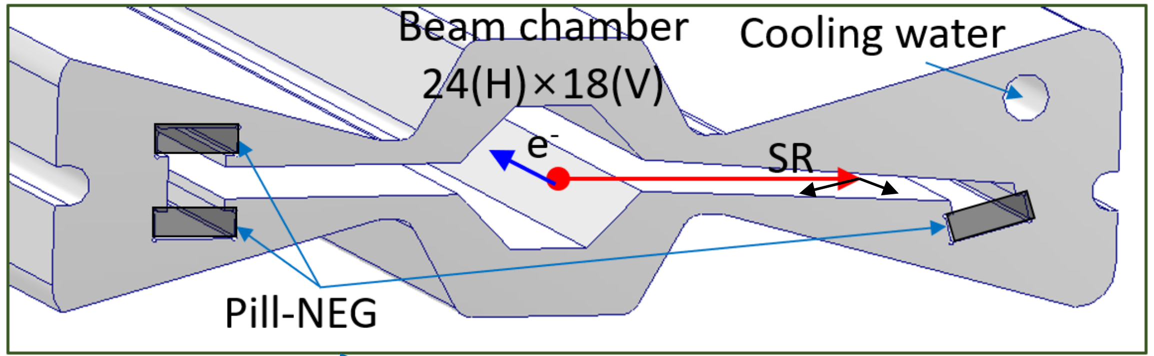


Operating Specification		
Resonant frequency	MHz	499.8
Operating Temperature range	°C	30...40
Tuning range of plungers	MHz	1
Quality factor Q_0 Coupling beta		>29 000
Coupling beta (adjustable)		1.0 -3.0
Shunt impedance $Rsh=U^2/(2Pin)$	MΩ	15
Length (flange-flange)	m	1.650
Typical input c.w. power	kW	60
Max. input c.w. power	kW	120
Acc. Voltage at 60kW	MV	1.3
Operating temperature (typ.)	°C	30
Coupler Cooling air overpressure	mbar	>10
Cooling air flow	m³/hour	23
Water pressure	bar	10
Pressure drop	bar	6
Water flow	l/min	150
Vacuum Leak Rate	mbarl/s	<1e-10

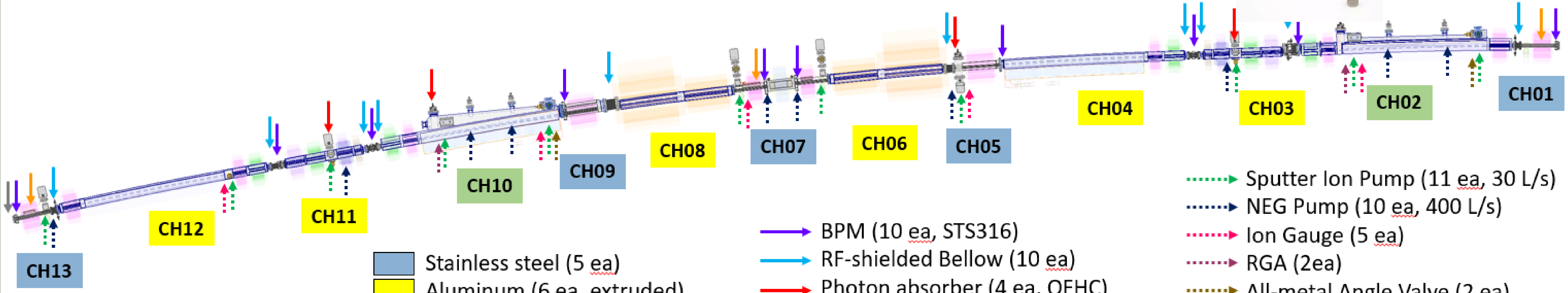
< 5-cell PETRA Cavity for BR>

Storage Ring Vacuum Chamber

SR vacuum chamber cross-section



▪ Vacuum system for arc section

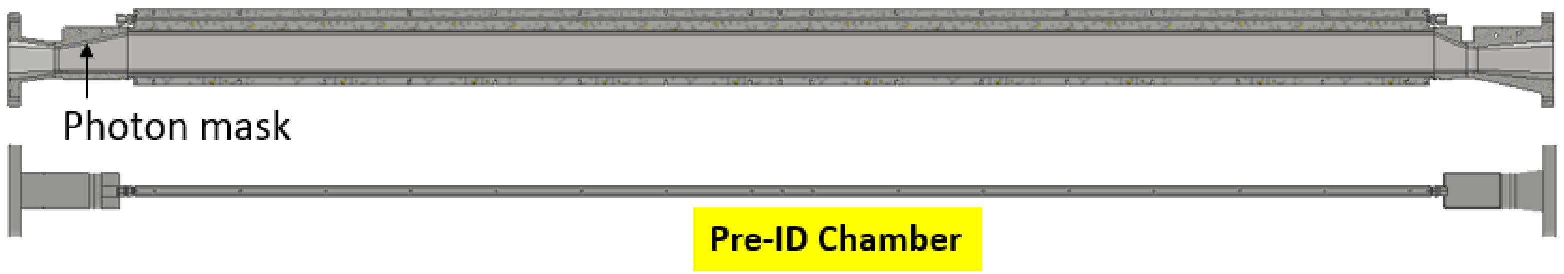


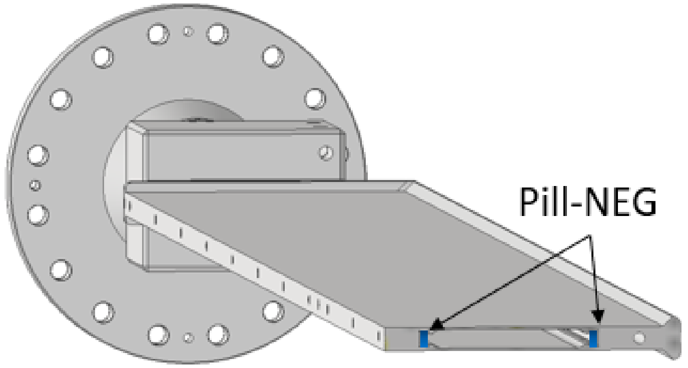
- Stainless steel (5 ea)
- Aluminum (6 ea, extruded)
- Aluminum (2 ea, machined)

- BPM (10 ea, STS316)
- RF-shielded Bellow (10 ea)
- Photon absorber (4 ea, OFHC)
- Photon mask (3 ea, OFHC)

- Sputter Ion Pump (11 ea, 30 L/s)
- NEG Pump (10 ea, 400 L/s)
- Ion Gauge (5 ea)
- RGA (2ea)
- All-metal Angle Valve (2 ea)
- RF-shielded Gate Valve (1 ea)

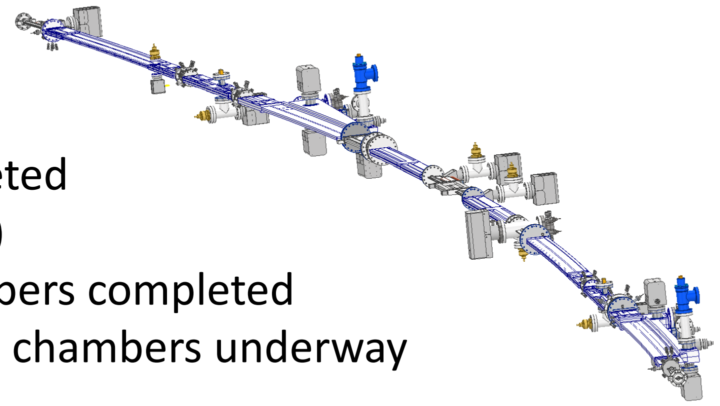
▪ Vacuum system for straight section





Vacuum Status Summary

▪ Design status



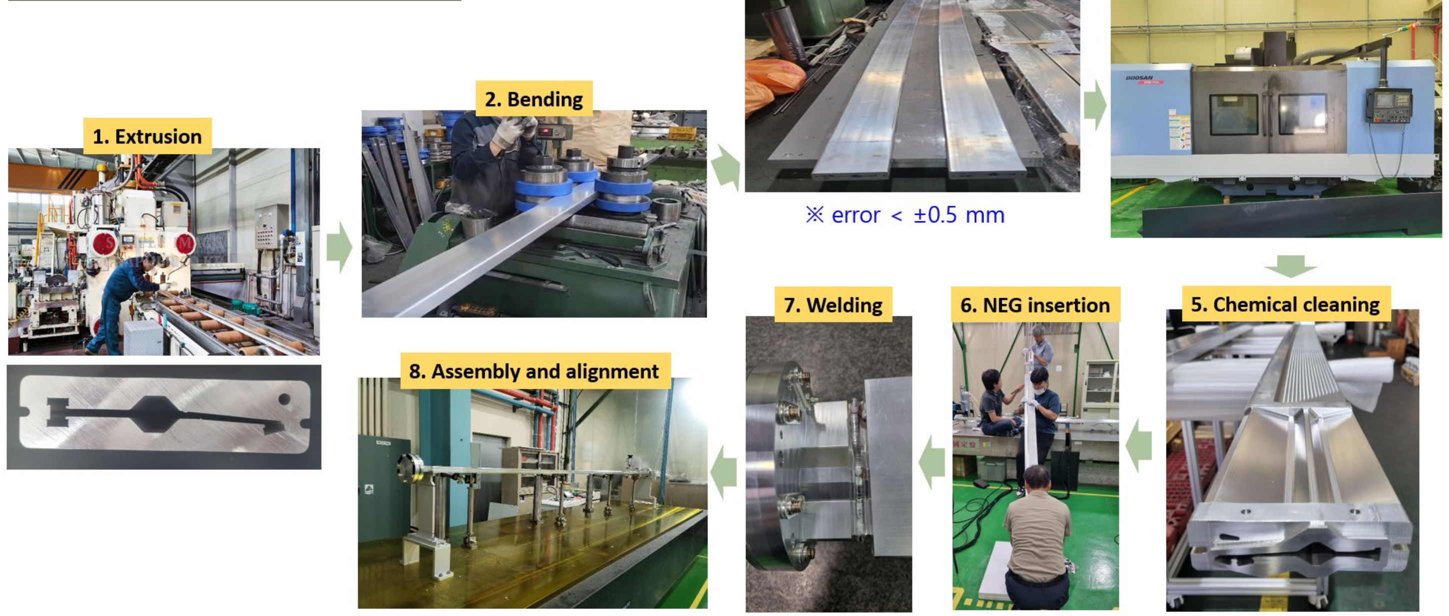
- 3D modeling completed
- Vacuum profile calculation completed
  (Average pressure = 1E-9 mbar)
- Thermal analysis of photon absorbers completed
- Design of insertion device vacuum chambers underway
- Design optimization within 2023

▪ Purchase and fabrication plan

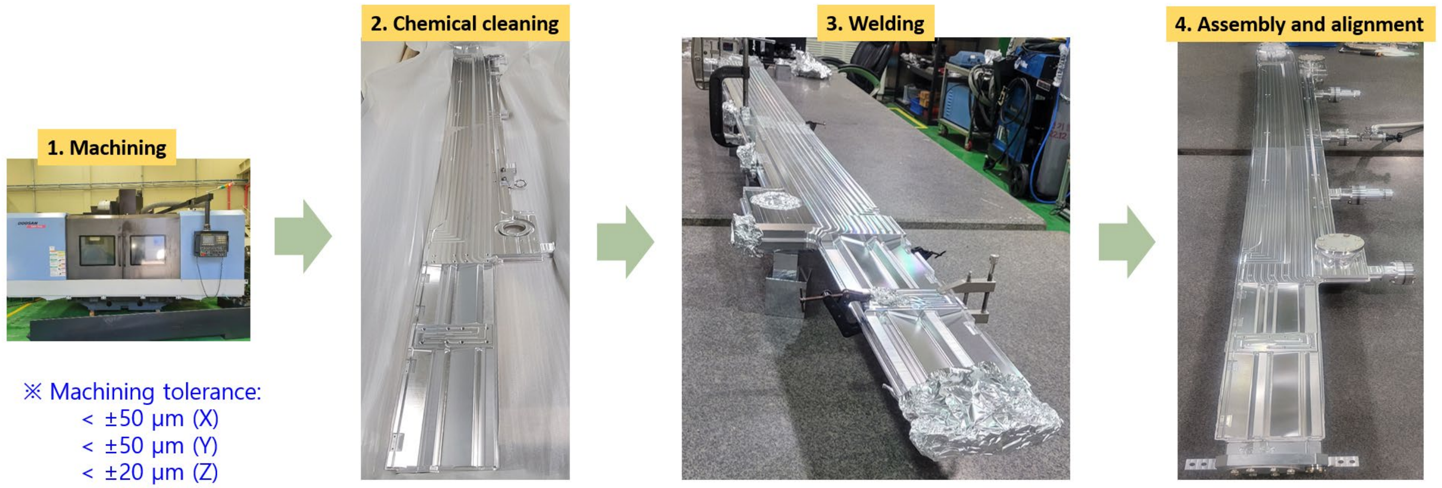
- Completion of manufacturing drawing: ~ 1/2 of 2024
- Vacuum chambers prototype: ~ 1/2 of 2024
- Purchase order of vacuum chambers: 2/2 of 2024
- Purchase order of commercial components : 2025
- Assembly and vacuum test: 2025 ~

▪ Vacuum chamber prototype

▪ Extruded Aluminum chamber (CH12)



▪ Machined aluminum chamber(CH02)



Summary

❖ **Multipurpose Synchrotron Radiation Project**

- The project aims to build 4 GeV storage ring with an emittance less than 100 pm
- Its circumference is 800 m
- It can host more than 40 beamlines. Initially, 10 beamlines will be ready

❖ **2 institutions working together**

- KBSI: Leading institution in charge of building and facility
- PAL: Partner institution in charge of Accelerator and beamlines

❖ **Construction will be completed by 2027**

- TDR has been finished
- Construction will be started in spring, 2024

Thank you for your attention