Accelerator Design Overview



KBSI KOREA BASIC SCIENCE INSTITUTE

PAL POHANG ACCELERATOR LABORATORY

Design Features of Korea-4GSR

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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

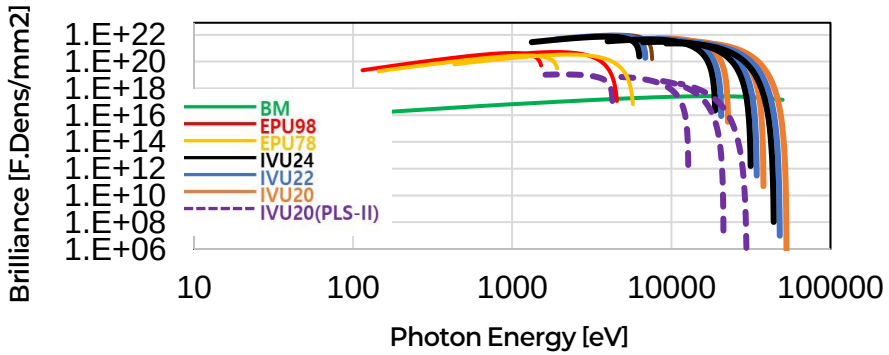
Considering well demonstrated technologies for the design

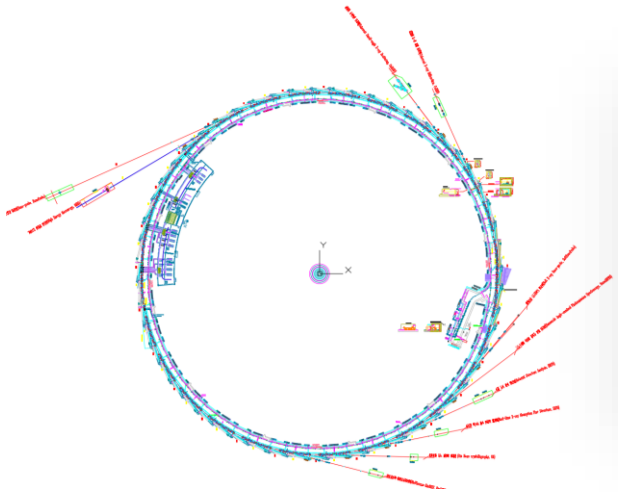
- Off-axis injection with conventional injection schemeCapability to generate photon beam up to 100 keV
- General technologies for magnet and vacuum systems
- On schedule user service and full performance

Synergy with PLS-II and PAL-XFEL

- Supporting full range of synchrotron radiation application

Brilliance vs photon Energy

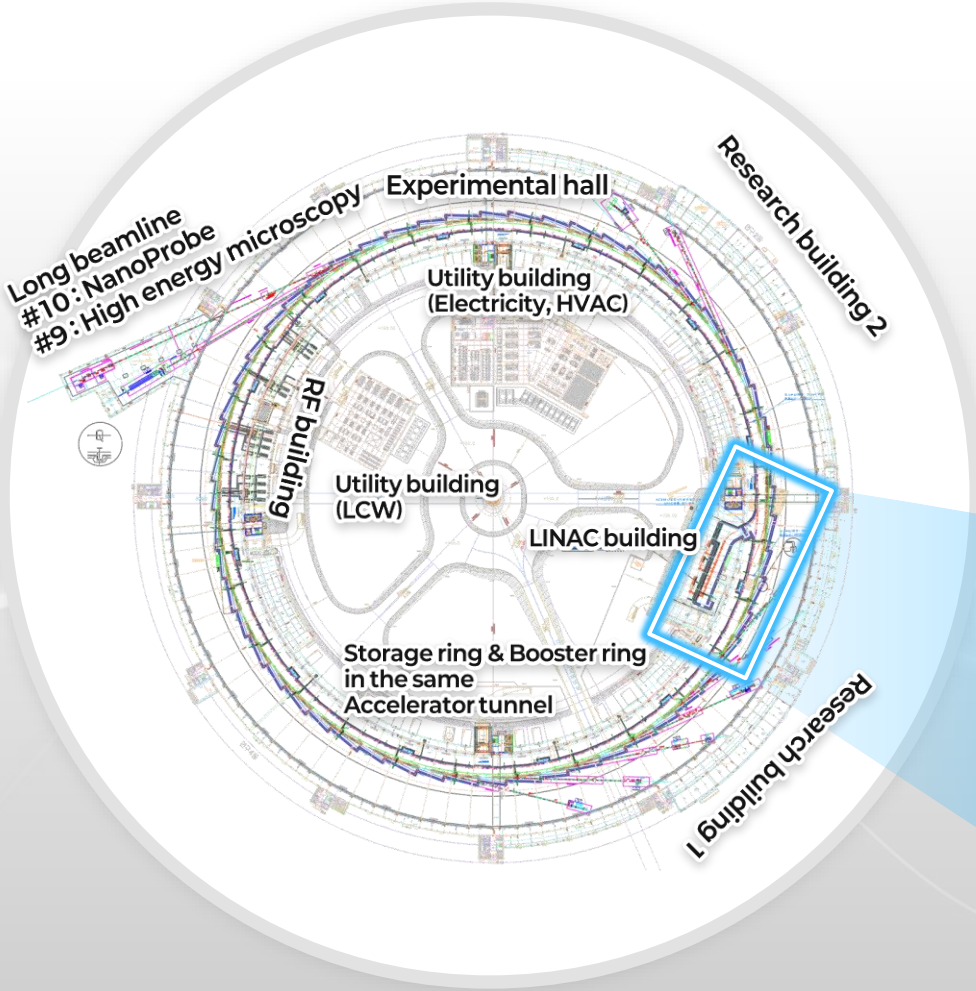


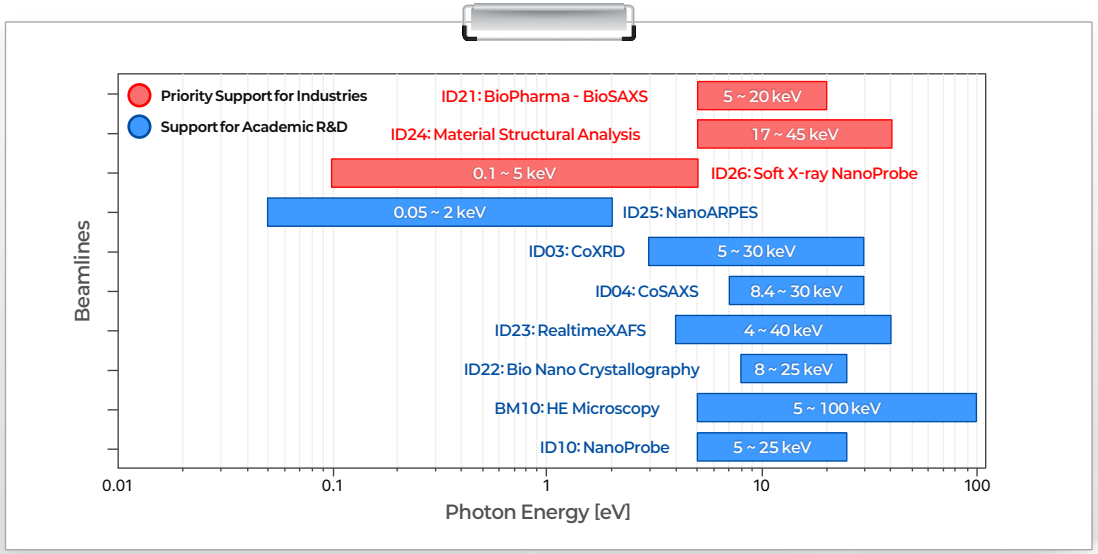


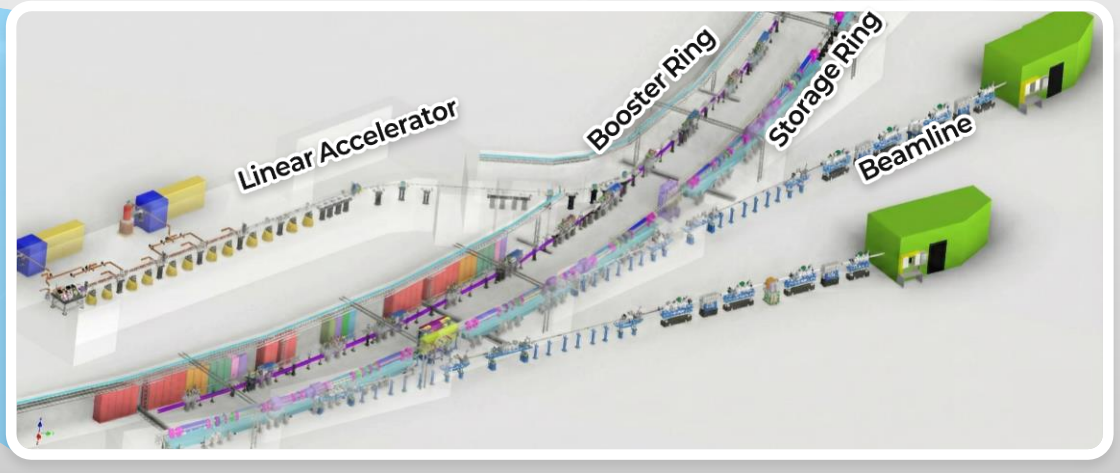
28 straight sections

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

Overall View of Accelerator Facility





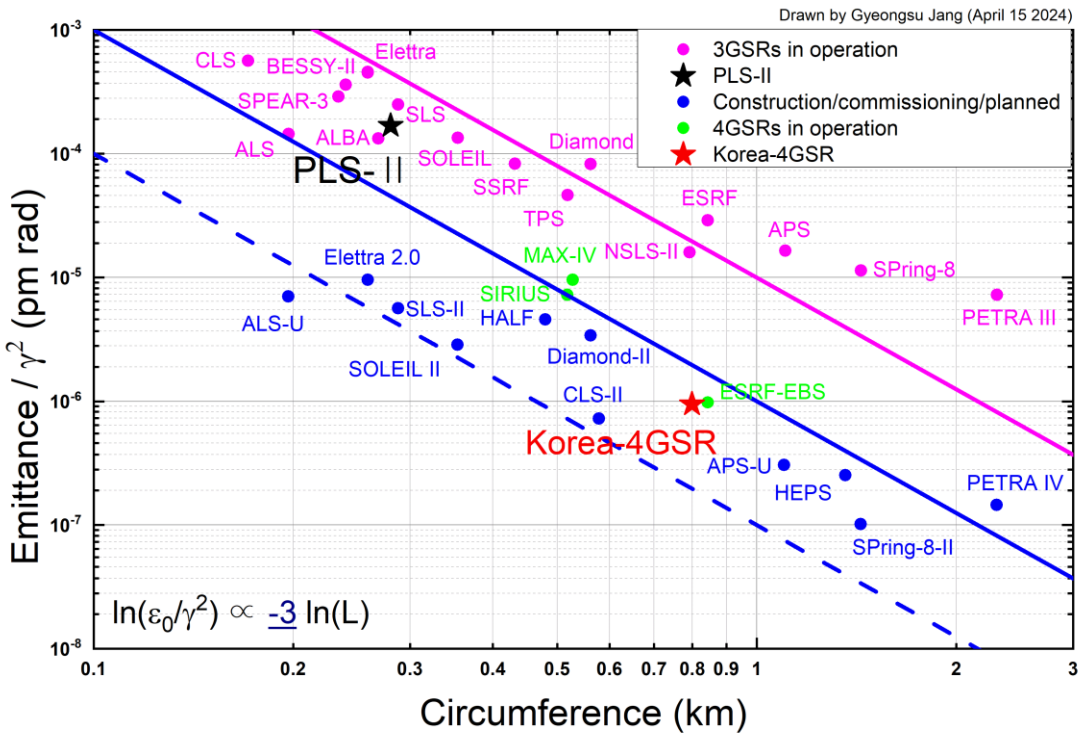


Parameters of Korea-4GSR Storage Ring

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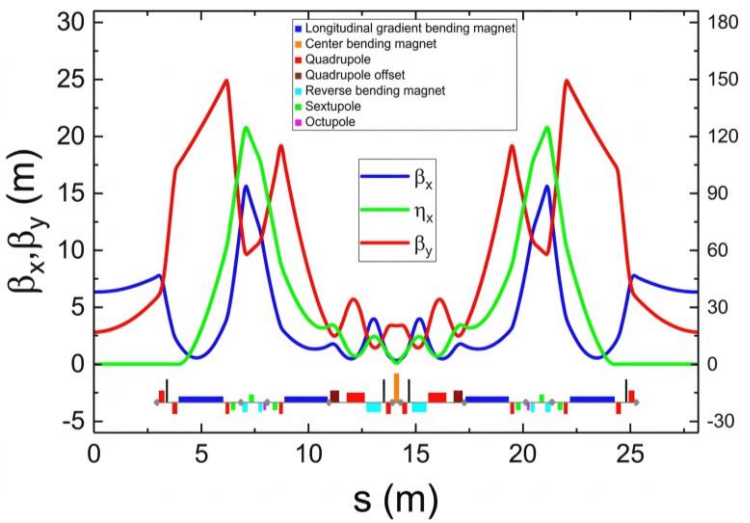
Ring/RF Parameter	Value
Energy [GeV]	4
Beam current [mA]	400
Nat. Emittance [pm·rad]	61.57(w/o IDs) / 52.55(w/ IDs)
Emittance coupling [%]	10
Energy spread	1.26E-03
Bunch Length(rms) [mm]	3.6(w/o HC) / 14.4(w/ HC)
Lattice	Hybrid 7 Bend Achromat
Ring Circumference [m]	799.297
Length of Straight Sections [m]	6.06
Tune (H/V)	68.179 / 23.260
(corrected) Chromaticity (H/V)	5.8 / 3.5
Momentum compaction factor	7.80E-05
Number of buckets	1332
Injection scheme	4 kicker bumps, off-axis, 2Hz
RF frequency [MHz]	499.593
RF Voltage [MV]	3.080(w/o IDs) / 3.5(w/ IDs)
Energy loss per turn [KeV]	1098(w/o IDs) / 1449(w/ IDs)

Emittance vs. Circumference for world-wide storage rings

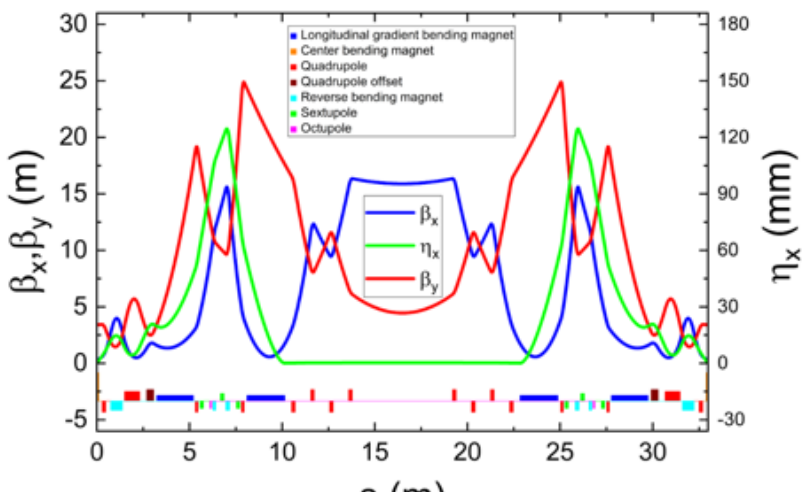


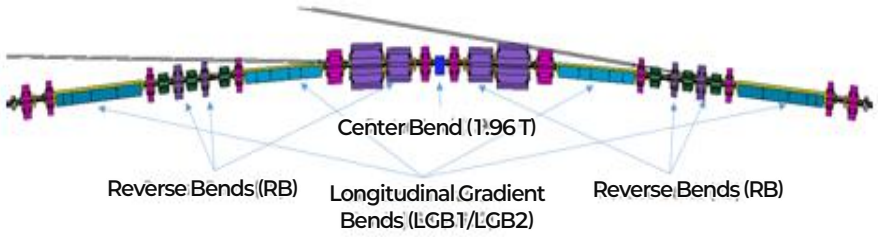
Beam Dynamics – SR Lattice (Hybrid 7-Bend Achromat, H7BA)

Arc + ID straight section



Arc + High-beta straight section





Features

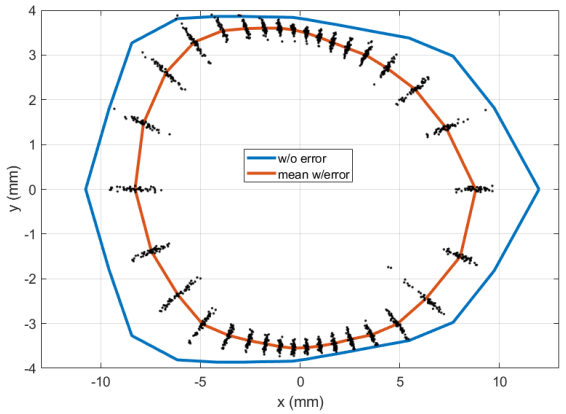
- The storage ring is a **800 m – 4 GeV – 28-cell** ring with natural emittance of 62 pm
- The unit cell is a H7BA with 2-T center bend
- It exploits longitudinal gradient bends (LGBMs) and reverse bend (RBs) to suppress emittance
- The storage ring design has been evolved from a circular ring to a race-track ring to achieve best compromise between dynamic aperture, Touschek lifetime and matching between photon beam and electron beam

Beam Dynamics – SR Dynamic Aperture and Touschek lifetime

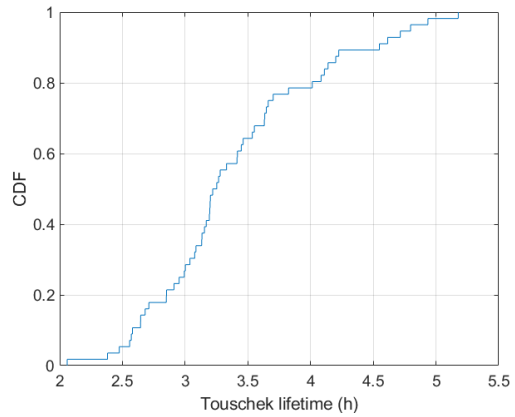
Magnet	Misalignment (μm) (X/Y/Z)	Rotation (μrad) (Roll/Pitch/Yaw)	Strength error (%)
LGBM	30 / 30 / 250	400 / 100 / 100	0.05
Combined-function magnet	30 / 30 / 250	400 / 100 / 100	0.05
Quadrupole	30 / 30 / 250	400 / 700 / 700	0.05
Center bend	30 / 30 / 250	400 / 100 / 100	0.05
Sextupole	30 / 30 / 250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

Error tolerance used for SR commissioning simulations (rms value)

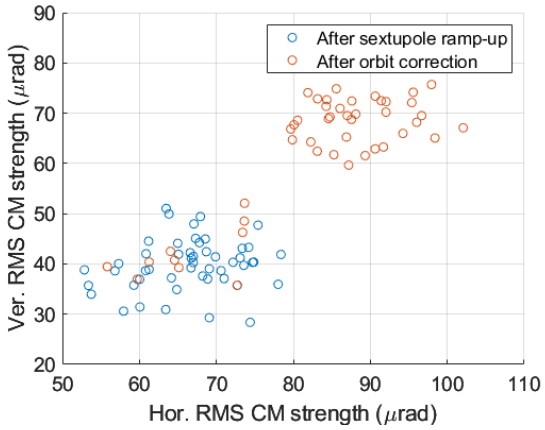
Results of SR commissioning simulations with 50 random error seeds



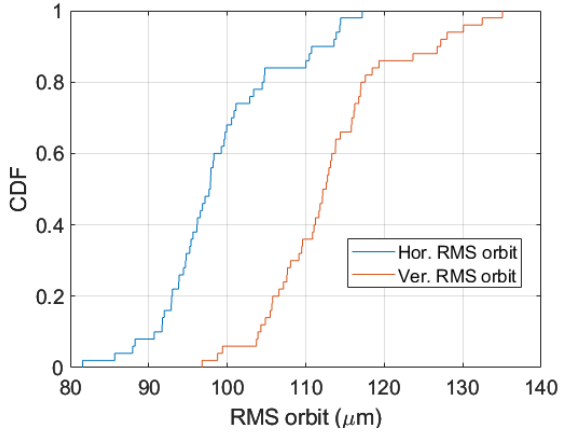
Dynamic aperture



Touschek lifetime (w/o 3HC)



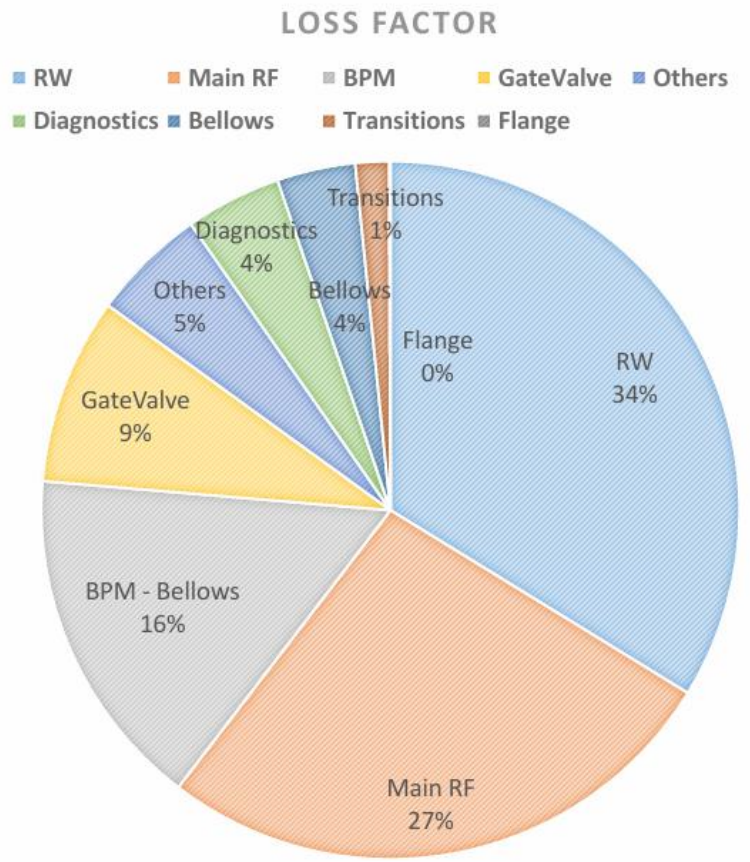
Corrector strength



RMS orbit

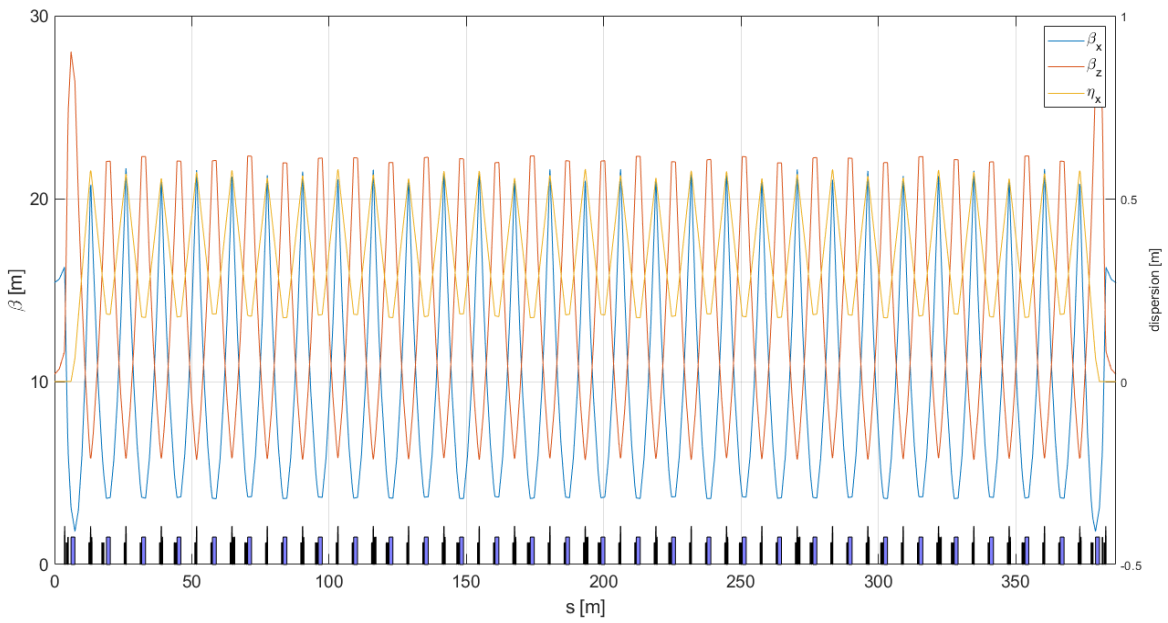
Beam Dynamics – SR Impedance Budget

Components	Number	Single Component k_z [V/pC]	Single Component Zn_z [mOhm]	Sum k_zT [V/pC]	Sum Zn_zT [mOhm]
Resistive Wall	1	14.78	158.20	14.78	158.2
Main RF cavity	10	1.17	5.98	11.65	59.80
LGBM1U chamber	28	2.34E-02	0.16	0.65	4.37
LGBM2D chamber	28	3.42E-02	0.34	0.96	9.39
BPM	176	2.30E-02	0.17	4.05	30.62
Gate valve	112	3.38E-02	0.30	3.79	33.82
ID taper	26	2.56E-03	0.89	0.07	23.17
Bellows	224	7.09E-03	0.07	1.59	15.19
BPM-Bellows 1	56	2.72E-02	0.23	1.52	12.94
BPM-Bellows 2	56	2.50E-02	0.23	1.40	12.94
Flange	840	3.00E-05	0.02	0.03	15.96
RF taper	6	7.70E-02	1.89	0.46	11.32
LFS	1	1.58E+00	6.30	1.58	6.30
RF transition chamber	5	8.50E-02	0.75	0.43	3.76
Pump tee	56	5.16E-03	0.13	0.29	7.45
TFS (vert-)	1	1.82E-01	0.67	0.18	0.67
TFS (hori-)	1	1.82E-01	0.67	0.18	0.67
Center bend chamber	28	3.52E-03	0.21	0.10	5.88
CH08 entrance	56	7.90E-04	0.03	0.04	1.68
CH08 exit	56	1.82E-04	0.01	0.01	0.73
Collimator	4	TBD		TBD	
Total				44	415
				Loss factor	Effective impedance



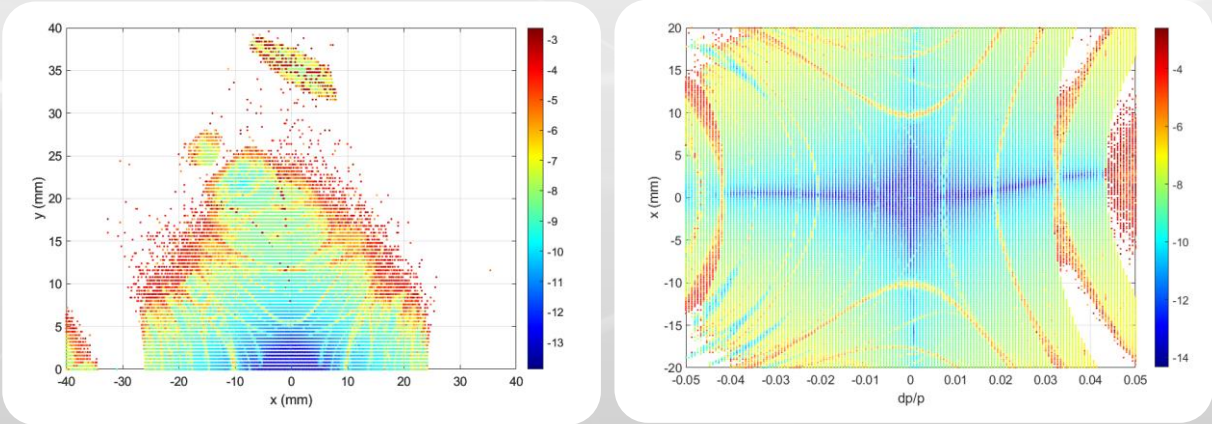
Beam Dynamics – Booster

- Booster shares the same tunnel with the storage ring
- FODO optics
- Race-track shape with two dispersion-free straights



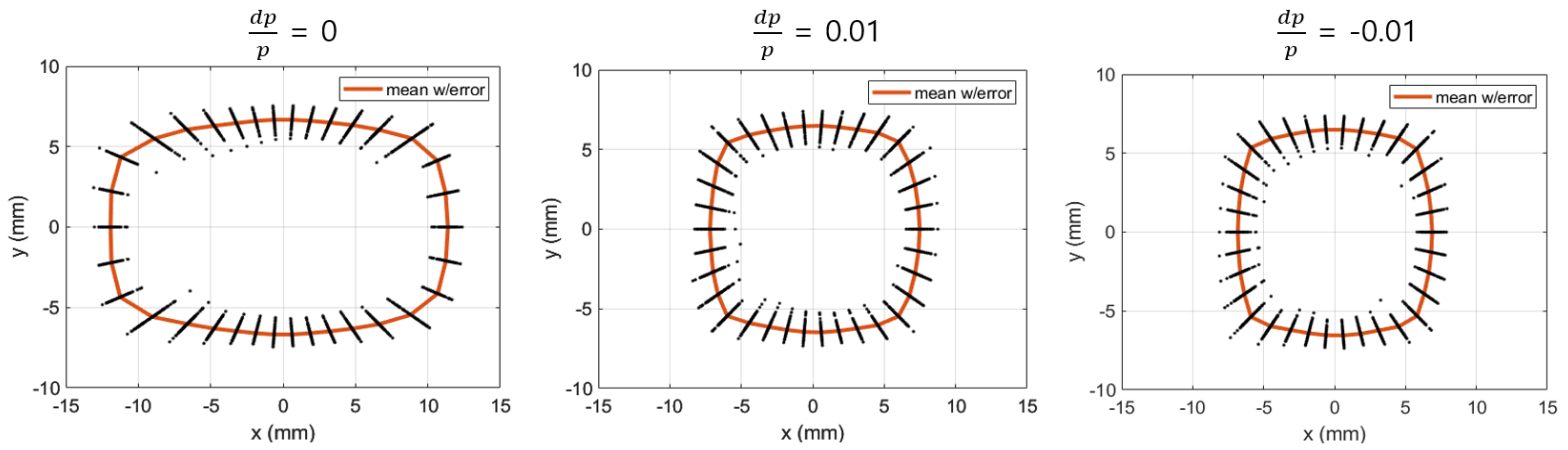
Half- cell optics

Booster Parameters		Value	Unit
Design Parameters	Number of Cells	30	-
	Circumference	772.9	[m]
	Beam Energy	0.2 - 4	[GeV]
	Natural Emittance (4 Gev)	10.9	[nm rad]
	Max. Beam Current	2	mA
Tune and Chromaticiy	Tune (H/V)	17.77 / 10.70	-
	Natural Chromaticity (H/V)	-22.3 / -15.1	-

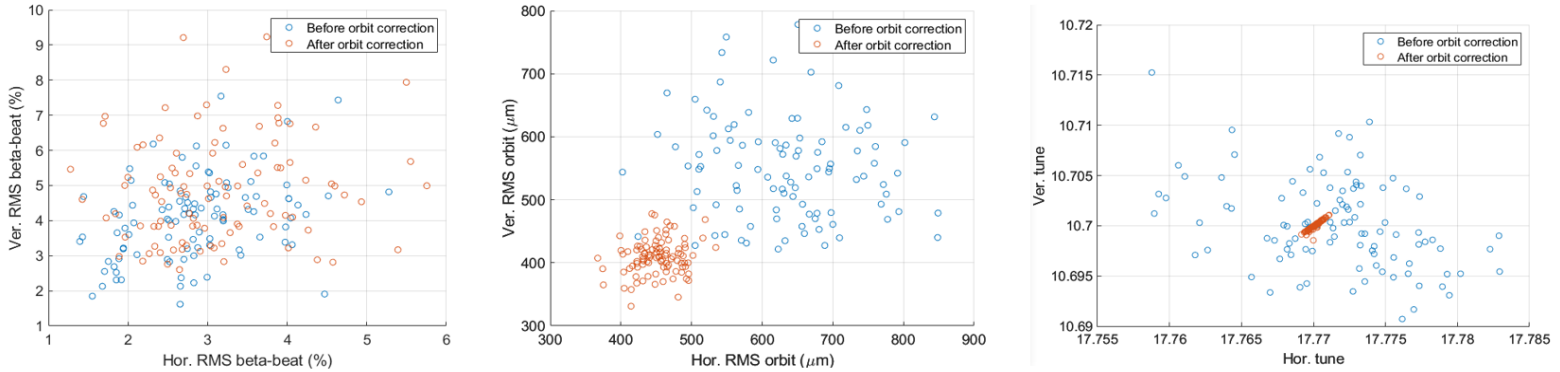


Frequency map analysis (w/o physical aperture)

Beam Dynamics – Booster Error Study



DA with errors



Beta-beat, rms orbit, and tune

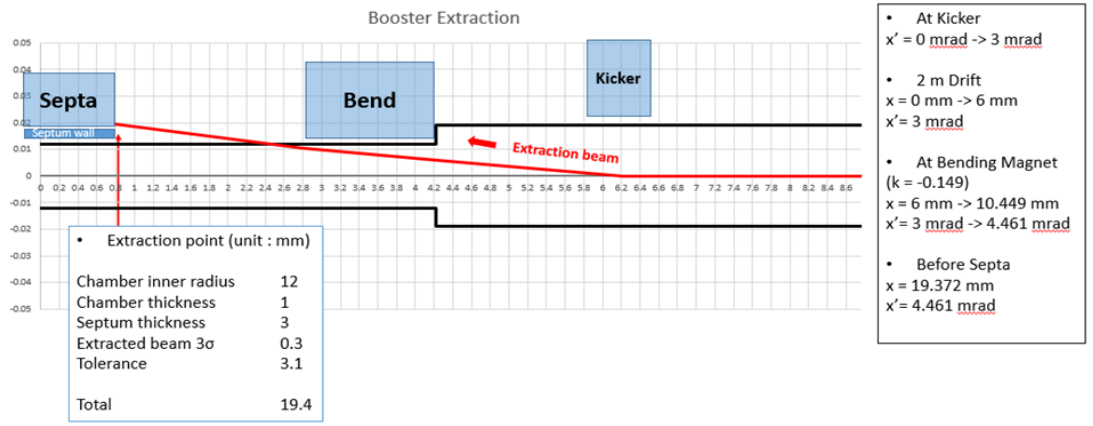
Magnet	Misalignment (μm) (X/Y/Z)	Rotation (μrad) (Roll/Pitch/Yaw)	Strength error (%)
Dipole	100 / 100 / 200	400 / 100 / 100	0.10
Quadrupole	100 / 100 / 200	400 / 700 / 700	0.10
Sextupole	100 / 100 / 200	400 / 700 / 700	0.10

Booster correction chain

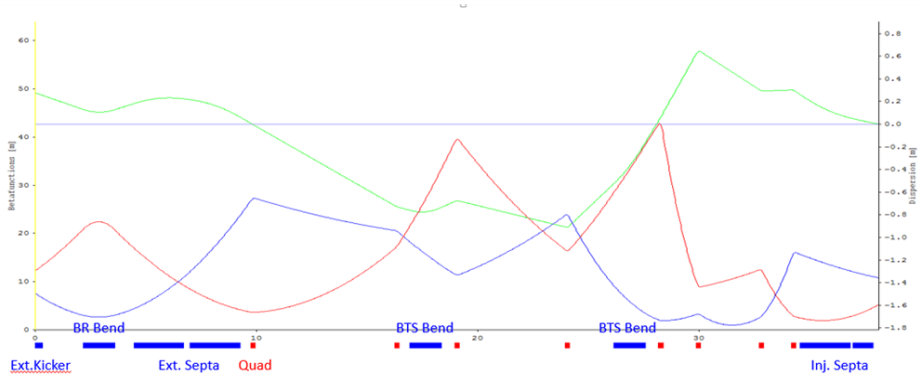
- trajectory correction
- RF correction
- orbit correction
- no BBA and no LOCO assumed

Beam Dynamics – Injection to Storage Ring

Booster extraction

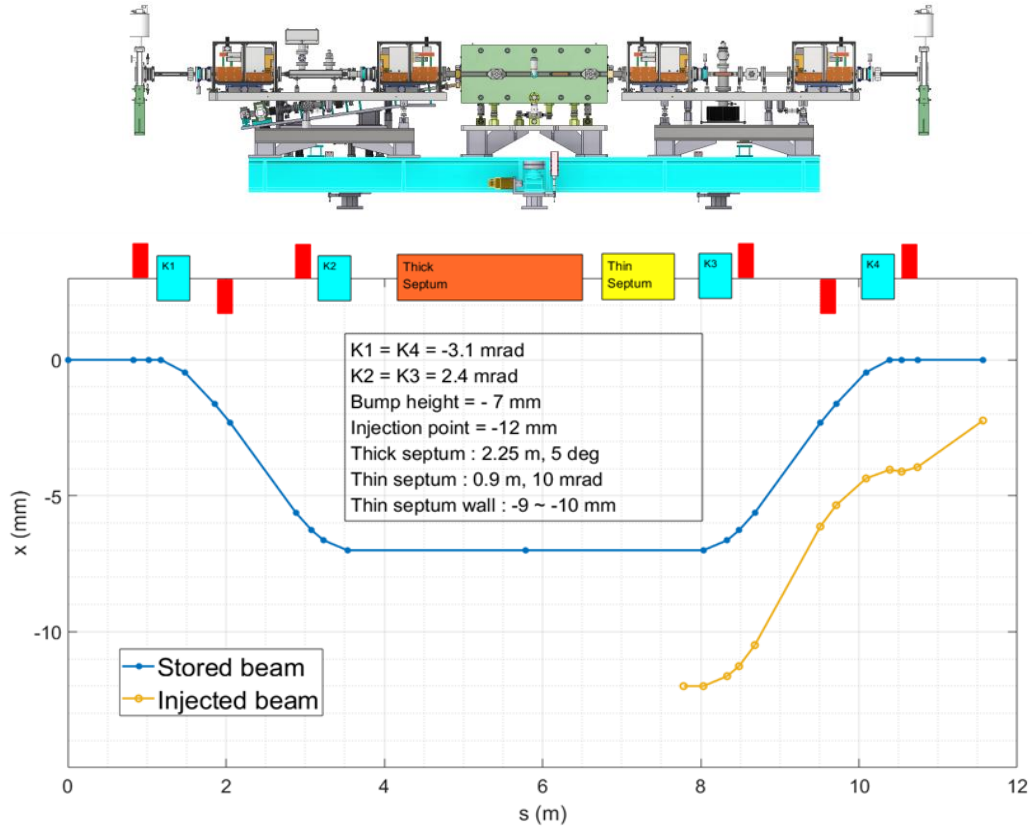


Booster-to-Storage ring beam transport line(BTS)

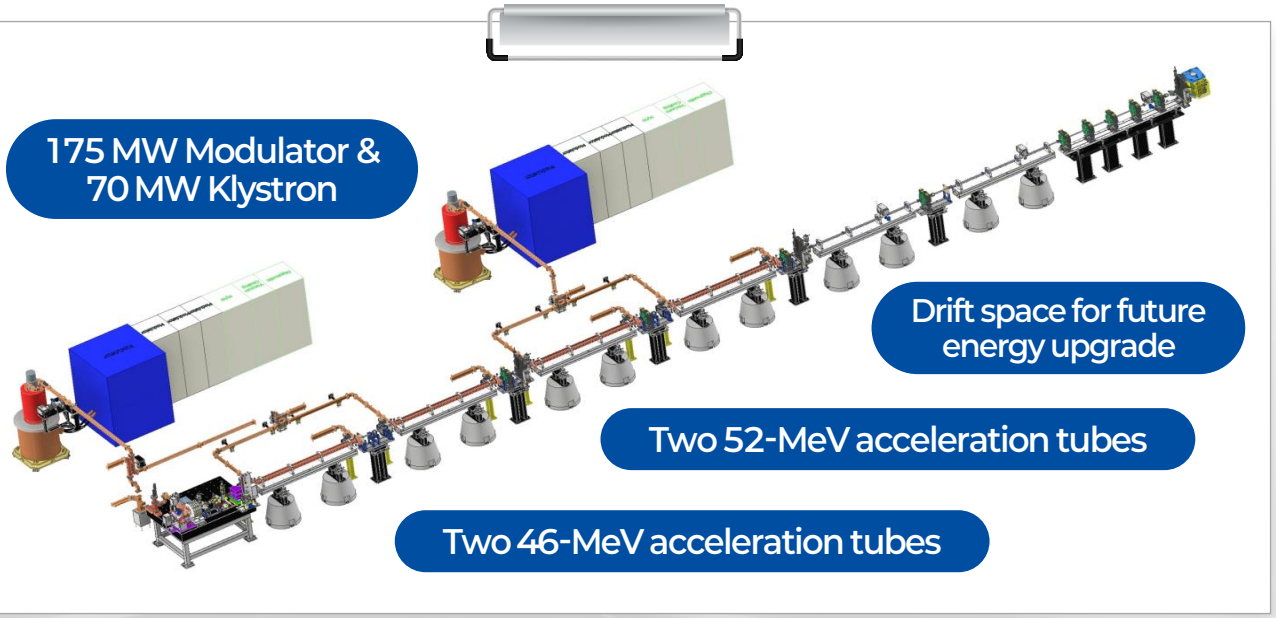


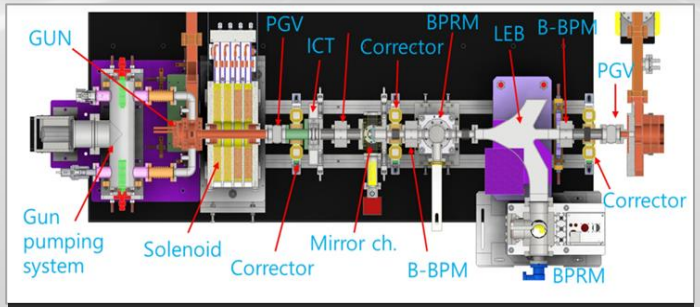
Baseline design: SR 4-kicker bump, off-axis injection

Alternative design: Non-linear kickers



200 MeV Injector Linac





Pre-Injector, including photo-cathode electron gun (Alternative design: thermionic DC electron gun)



Prototype of 3GHz Acceleration tube

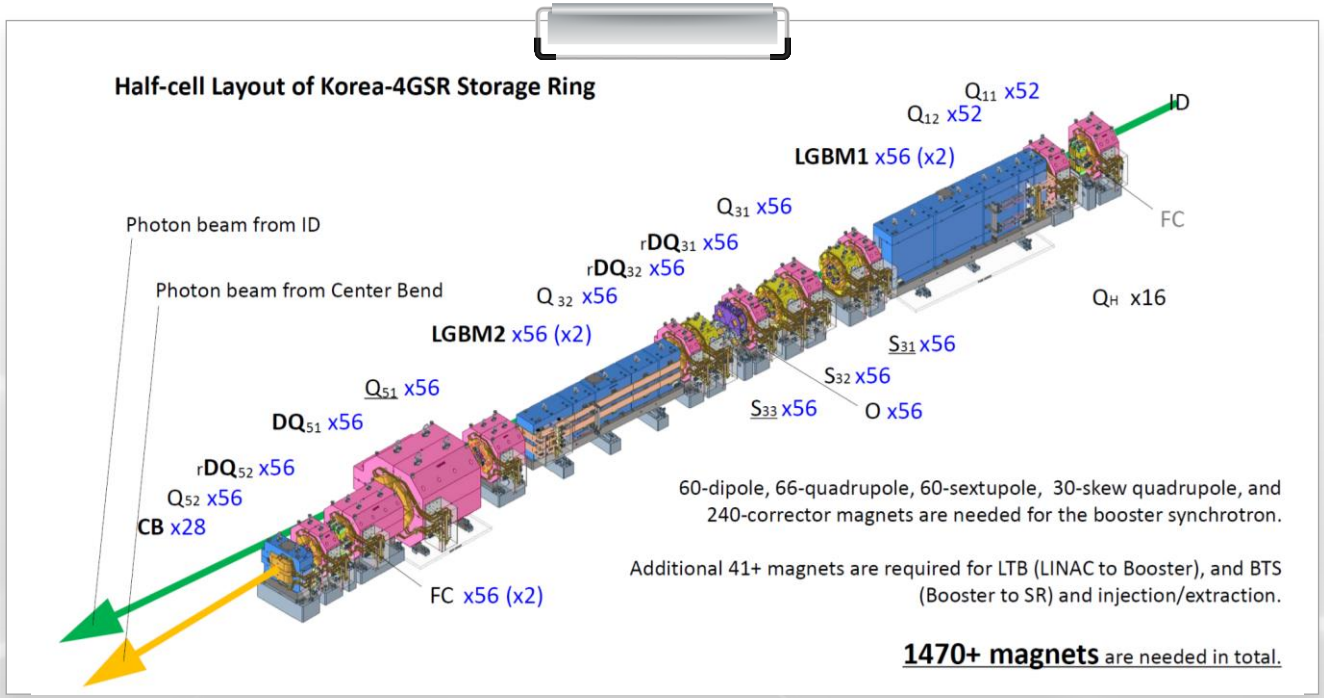
LINAC parameters

Parameters	Multi-bunch	Single-bunch
Energy	200 MeV	200 MeV
Frequency	2997.56 ± 0.1 MHz	2997.56 ± 0.1 MHz
Emittance (at 200 MeV)	≤ 10 nm	≤ 10 nm
Relative energy spread (rms)	≤ 0.3%	≤ 0.3%
Pulse to pulse energy jitter (rms)	≤ 0.2%	≤ 0.2%
Bunch charge (charge stability)	1 to 3 nC (5%)	0.01 to 1 nC (2%)
Pulse duration	≈ 128 ns (64 bunches)	6-8 ps FWHM
Repetition rate	2 Hz	2 Hz

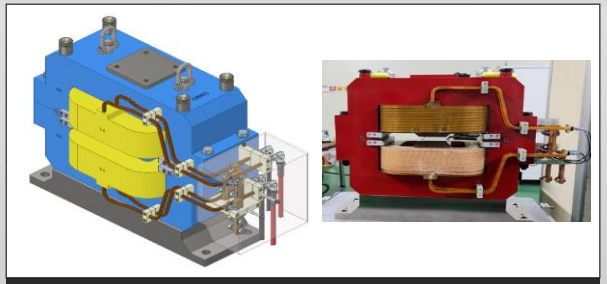
Electron gun parameters

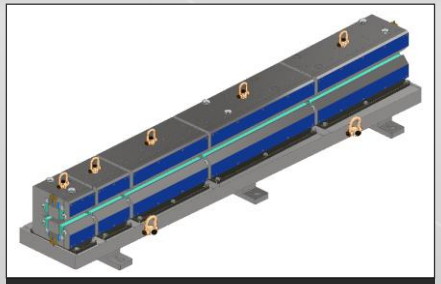
Parameters	Multi-bunch	Single-bunch
Beam energy	4 MeV	4 MeV
Charge	1~3 nC	0.01~1 nC
Pulse length	128 ns (64 pulses)	≤20 ps
Repetition rate	2 Hz	2 Hz

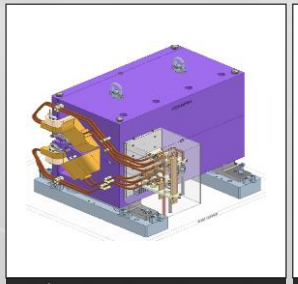
Magnet System – Storage Ring

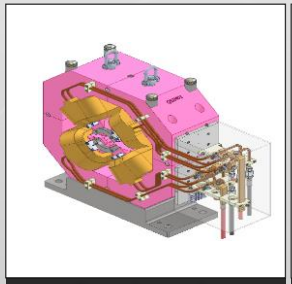


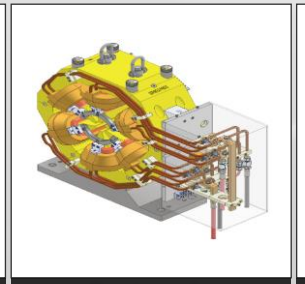
Magnet	Required Number	Remark
Center BM (2T)	28	1*28
Long. BM	112	4*28
Reverse Bend	168	2*3*28 (should have B, B')
Quad Bend	56	2*28 (should have B, B')
Quadrupoles	344	6*2*28+8(QH)
Sextupoles	168	6*28 (should have B", H/V Corr, Skew Quad)
Fast Corr.	112	4*28 (H/V combined corrector)
Octupole	56	2*28
SUM	1044	Total number of SR magnets

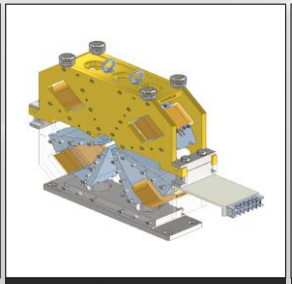

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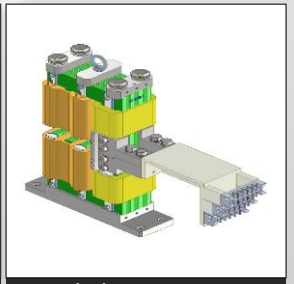

LGBM


Dipole-Quadrupole (DQxx, 56ea)


Quadrupole (Qxx, 344ea)


Sextupole (Sxx, 168ea)


Octupole (Oxx, 56ea)


H/V/S Corrector (Cxx, 112ea)

Magnet System – SR LGBM (Permanent Magnet version)

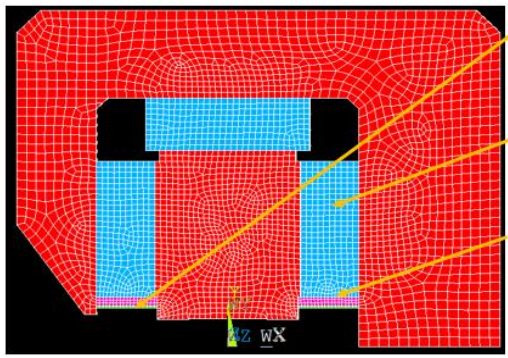
- LGBM has longitudinal field profile ranging from 0.15 T – 0.75 T to minimize beam emittances..
- Old design used electric excitation following APS-U for concerns on the long term radiation damage.
- But ESRF-EBS operating experience shows no radiation damage after 2 year operation.
- 2023 MAC (Machine Advisory Committee) recommended to consider PM version also.
- PM Version can save energy costs, Assuming, 1 kwh=200 Won, the design change can save 300 MW/year, 6,000 MWon for 20 year operation. (about 420kUSD/20 years)
- Also costs for MPS can be saved.

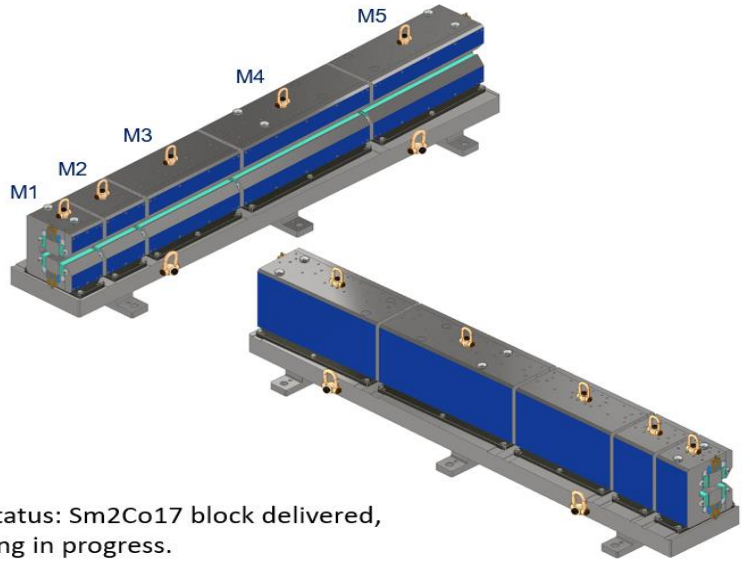
Technical Challenges

- No tunability like EM excitation, The final field profile should be met during measurement/tuning stage.
- Sm2Co17 PM has a temperature dependence $\Delta B/B / \Delta T = -3.3E-4/K$.
- There is cross talk between the modules.

Engineering Solution

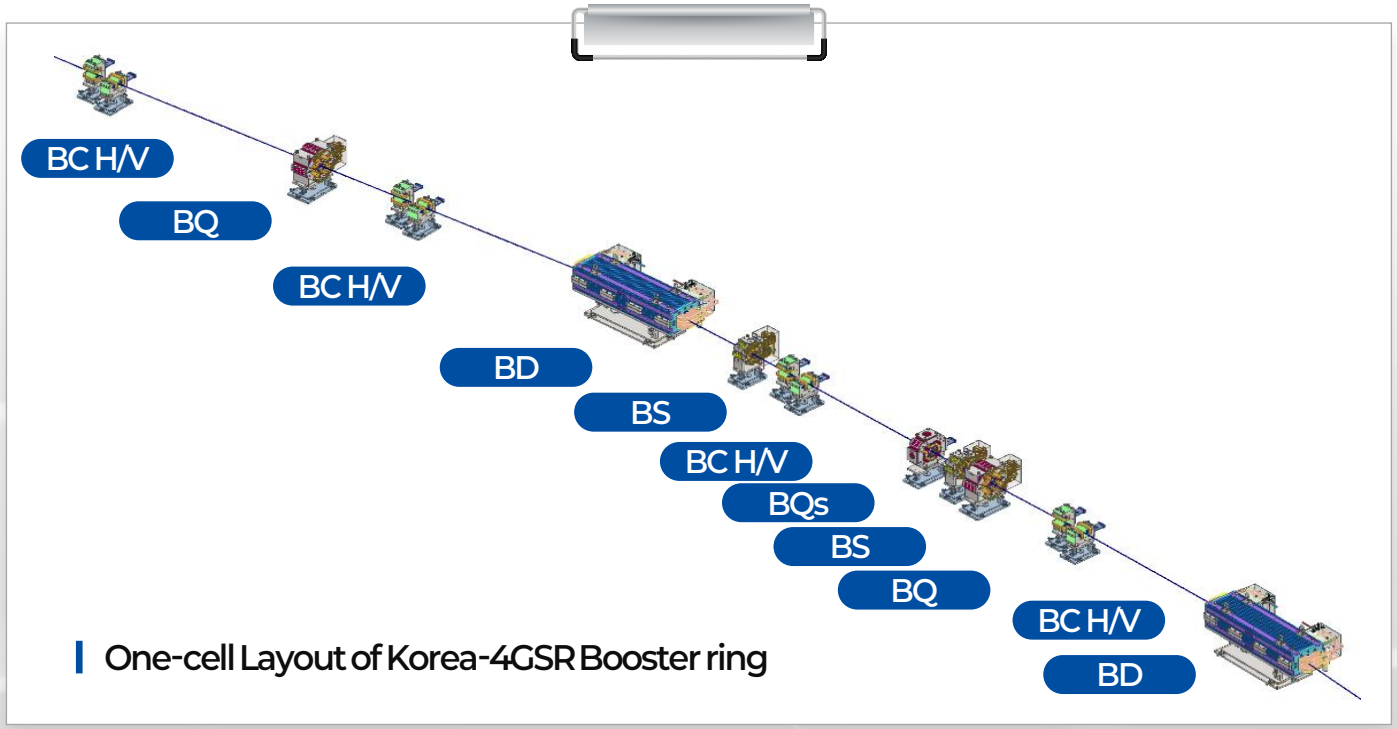
- Tunability using FeSi (Silicon Steel) shunts. (always in decreasing direction).
- Weakening of Temperature dependence using FeNi (Ni steel) plate.
- Magnetic design taking into account the Cross-talk between the modules.





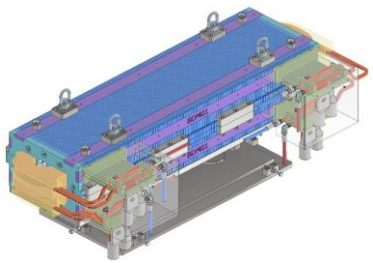
Current status: Sm2Co17 block delivered, prototyping in progress.

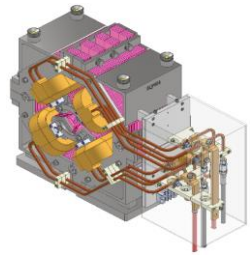
Magnet System – Booster Ring

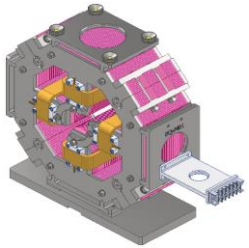


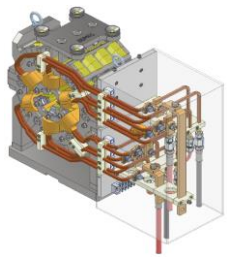
One-cell Layout of Korea-4GSR Booster ring

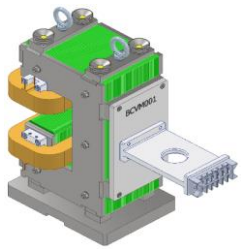
Magnet	Required Number	Remark
Combined Dipole	60	56 (6.07deg)+4(5.02deg)
Quadrupole	76	Normal 66, Skew 10
Sextupoles	60	
Corr.	240	H120, V120
Sum	436+	Total number of magnets

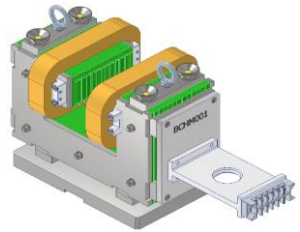

Combined Bending Magnet (BD, 60ea)


Quadrupole (BQ, 66ea)


Quadrupole Skew (BQs, 10ea)


Sextupole (BS, 60ea)

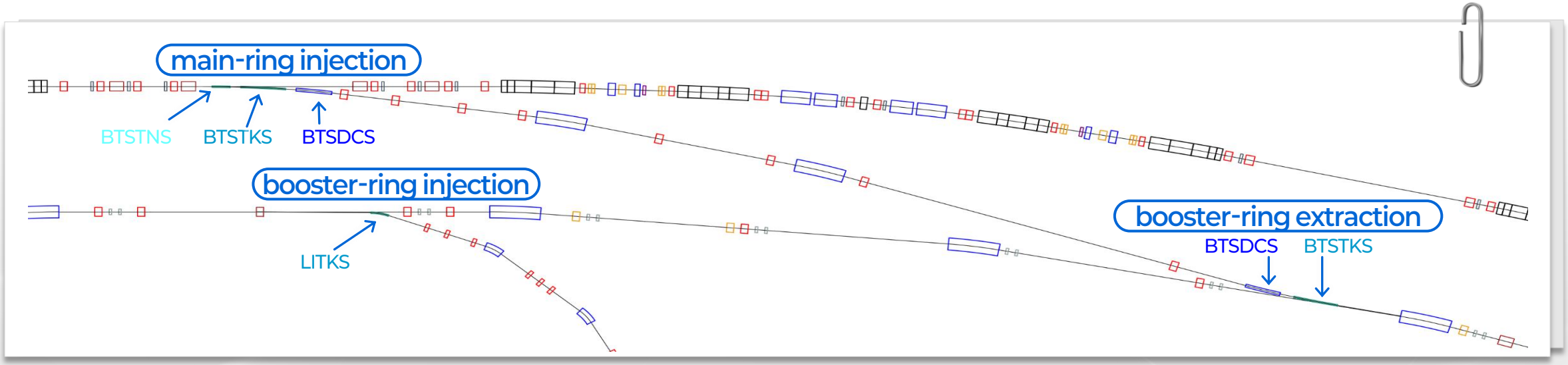

Corrector (BCH, 120ea)


Corrector (BCV, 120ea)

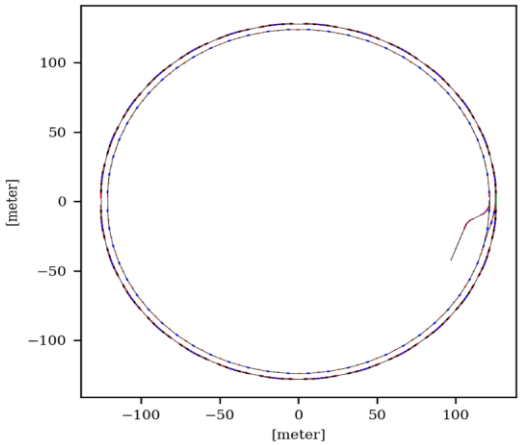
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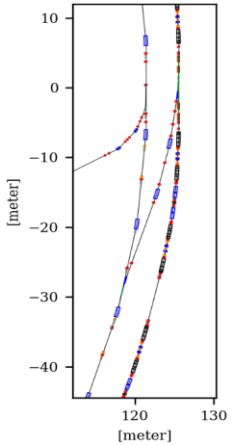
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Magnet System – SR Extraction/Injection Layout, Septum Parameters



4GSR Septums & Kickers	20241029			
	LITKS	BTSTKS	BTSTNS	BTSDCS
Type	pulsed	pulsed	pulsed	DC
Number of Used	1	2	1	2
Bending angle [deg]	20.0	3.0	1.432	3.5
[rad]	0.349	0.052	0.025	0.061
S mag length [mm]	500	1250	500	1000
V gap [mm]	15	15	13	22
H width [mm]	30	26	16	26
rho0 [m]	1.4	23.9	20.0	16.4
Peak B0 [T]	0.47	0.56	0.67	0.82
Peak Current [kA]	5.6	6.7	7.0	14.4
Inductance [uH]	1.23	2.67	0.76	1.46
Half-sine Pulse Width [us]	100.00	100.00	16.70	-
Hor. Displacement [mm]	90.1	32.7	6.3	30.6

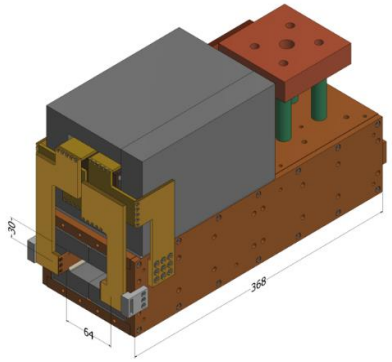


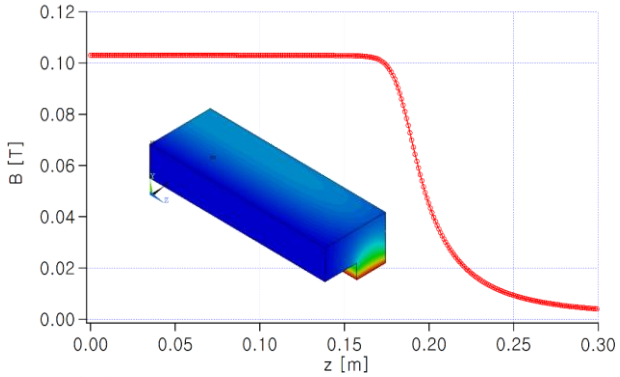


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Magnet System – Conventional Ferrite Kicker Magnets & Power System





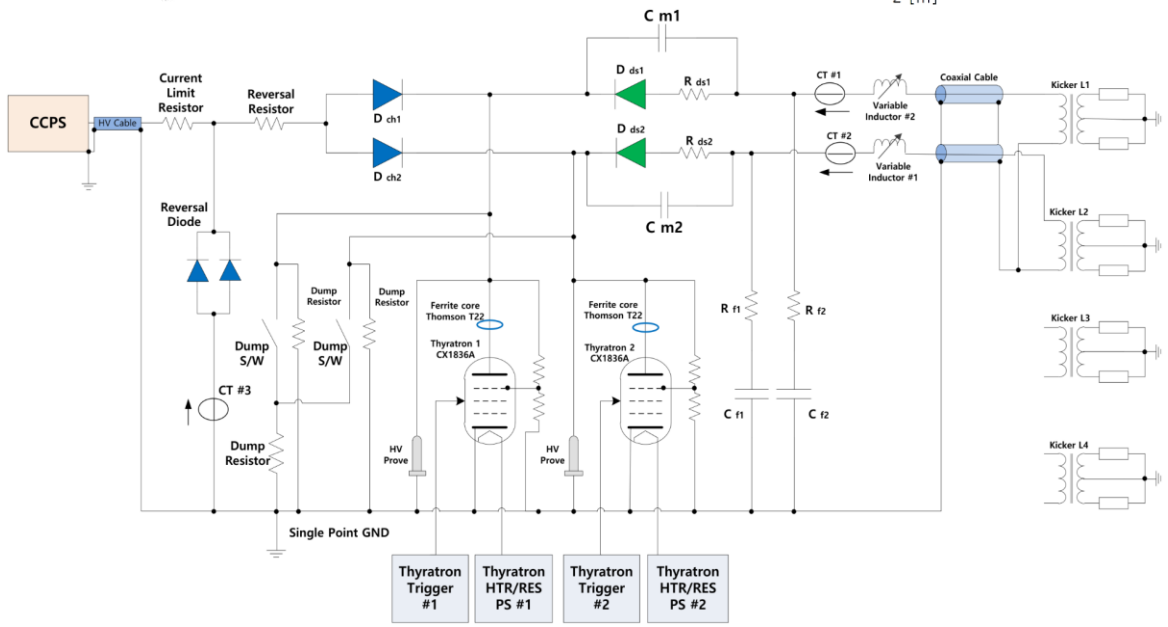


Table 1 : Major Parameters of SR Kicker1, 4

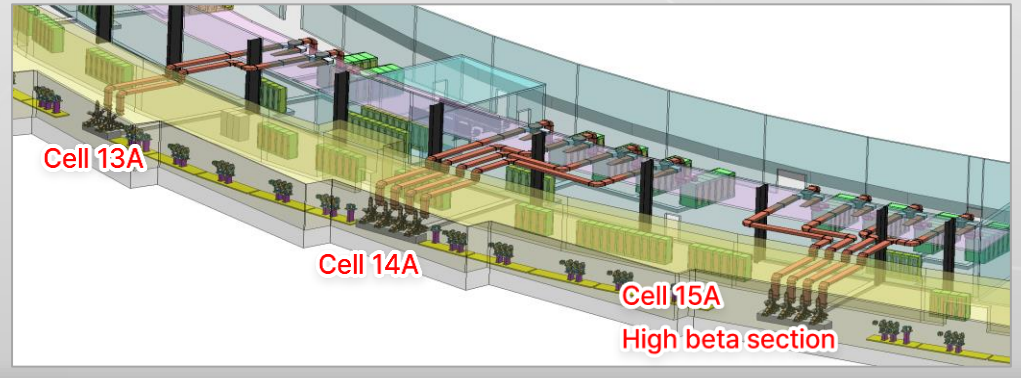
Parameters	Values
Max kick angle@4GeV	3.179 mrad
Field integral	4.24×10^{-2} Tm
Vertical Gap	30.0 mm
Horizontal Clearance	64.0 mm
Core Length	368.0 mm
Effective Lengthy	412.0 mm
Conductor Current	2.5 kA
Central field @ Imax	0.1030 T
Inductance before transformer	0.55 μH

Table 2 : Major Parameters of SR Kicker Power Supply

Parameters	Values
Pulse Current (Max)	7 kA
Pulse-width	< 5.0 μs
DC voltage at thyratron anode	14 kV
Flat-top width	200 ns
Repetition Rate	2 Hz
Energy per Pulse	70 J
Magnet Inductance	0.54 μH
Power Supply System Inductance (coaxial cable, variable inductance, line inductance, and others)	< 2.3 μH
Pulse Current Difference	± 0.2 %
Maximum Operable Beam Energy	4 GeV

RF System – Storage Ring

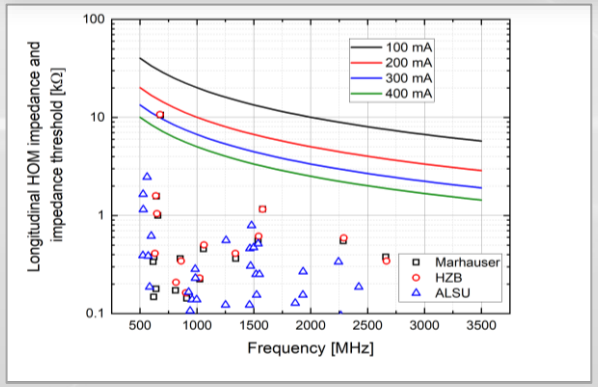
Parameters	Values	Unit
Energy [GeV]	4.0	GeV
Current [mA]	400	mA
Circumference [m]	799.297	m
Revolution time [sec]	2.67E-6	sec
Harmonic number	1332	-
Electron energy loss/turn (keV) with IDs	1877.65	keV
Beam loss power by synchrotron radiation [kW]	751.06	kW
RF frequency [MHz]	499.593	MHz
Accelerating Voltage [MV]	3.5	MV
Number of RF cavities	10	ea



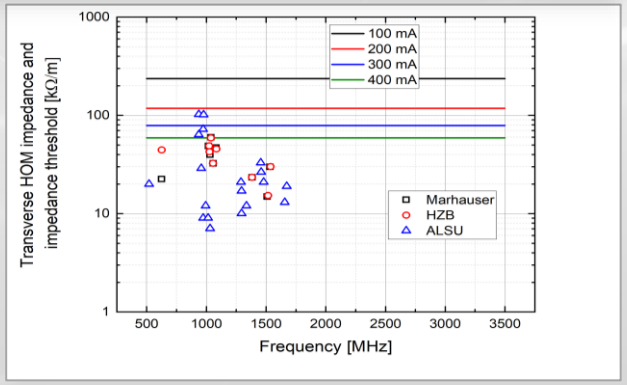
Characteristics of SR RF System

- Cavity : HOM-damped normal conducting cavity
- HPRF : 150 kW solid state amplifier per unit
- LLRF : digital type
- RF Transmission : WR1800 Waveguide
- Independent 10 RF circuit, occupying 2.5 straights





Longitudinal HOM impedance

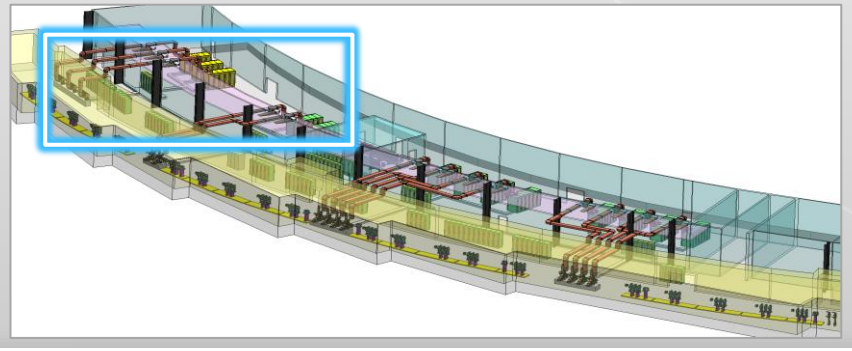


Transverse HOM impedance

The auxiliary system such as TFS/LFS and/or harmonic cavity to suppress coupled-bunch instability (CBI) is necessary for storing >300 mA.

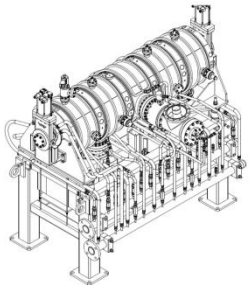
RF System – Booster Ring

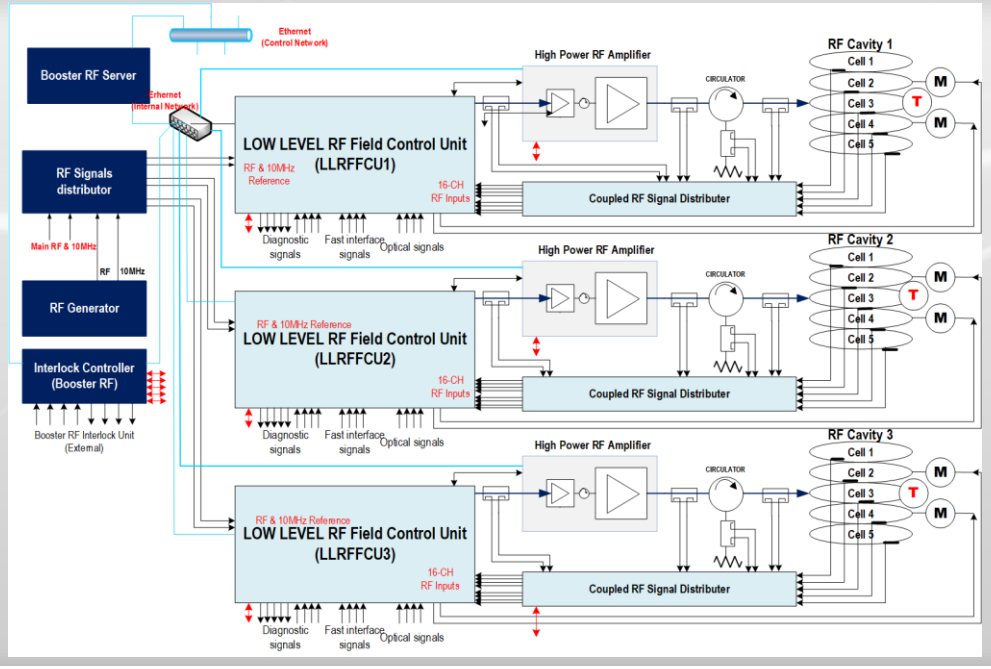
Parameters	Values	Unit
Beam energy	0.2 – 4.0	GeV
Beam Current with single / multi bunch	1 / 3	mA
Circumference	772.9	m
Harmonic number	1288	-
Revolution frequency	387.9	kHz
Synchrotron Frequency	4.24	KHz
repetition rate	2	Hz
Accelerating Voltage @ 0.2 GeV	0.3	MV
Accelerating Voltage @ 4.0 GeV	3.0	MV
RF Frequency	499.594	MHz
Energy loss per turn @ 4.0 GeV	1.671	MeV



Characteristics of booster RF system

- Cavity : 5-cell PETRA normal conducting cavity
- HPRF : 80 kW SSPA per unit
- LLRF : digital type
- RF Transmission : WR1800 Waveguide
- Independent 3 RF circuits, occupying 2 straights





Beam Diagnostics – Summary

Types, Numbers & Locations (2024-Nov-13)

CODE	Type	Meas. Target	Numbers / Section				
			LINAC	LTB	BR	BTS	SR
1	BPM	Beam Position	10	8	120	6	288
2	BPRM (YAG/OTR)	2D Profile, Emittance	7	6		3	
3	X-ray Diagnostic Hutch*	Beam Size, Emittance, Energy Spread					1
4	Visible light Diagnostic Hutch	Beam Size, Emittance, Bunch Length & Purity			1		2
5	Slow BLM	Beam Loss (Slow)	1	1	4	1	14
6	Fast BLM	Beam Loss (Fast)			5		30
7	ICT	Pulse Beam Current	2	1		2	
8	DCCT	DC Beam Current			1		2
9	PBPM	Photon Beam Position					20
10	Tune Monitor	Tune			1		1
11	TFS/LFS	Multi-bunch Feedback					3
Numbers in total			20	16	132	12	361

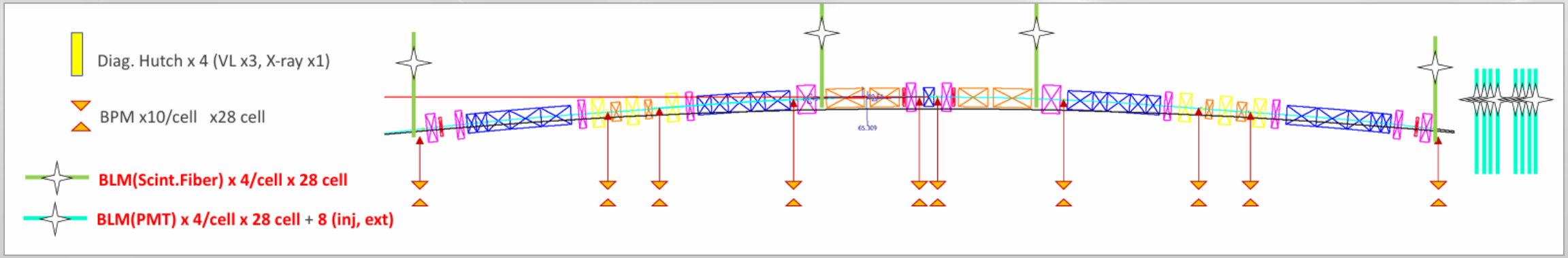
※ X-ray diagnostic hutch: location & budget assigned, installation pending.

Beam Diagnostics – SR

Storage Ring DIAG Update list

- BPM body design has been modified and finalized.
- Prototypes of BPM pick-ups were tested in the PLS-II storage ring.
- The second prototype of BPM electronics will be tested next year.
- Specifications for SOFB & FOFB have been determined.
  (1um for TbT & ~300 Hz suppression bandwidth)
- The #1 cell Beam Diagnostic Hutch was removed.
- A commercial BbB FB processor for 4GSR was tested in PLS-II.
- A gas chamber type PBPM was developed and will be tested in PLS-II.
- The Slow BLM design was modified to achieve greater sensitivity.

Property	Devices
Beam Position	SR BPM
Current	DCCT for BR
Beam Size & Emittance	Diag. Hutch with Interferometer
Fill pattern & bunch length	Diag. Hutch with streak camera & Online Bunch Length monitor
Beam Loss	Fast & Slow BLM
TFS/LFS	BbB FB system
Tune	BPM+S/A and BbB FB processor
Energy	BM MPS current or Spin polarization

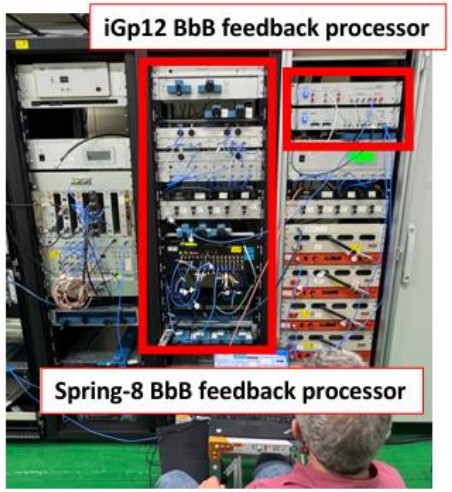


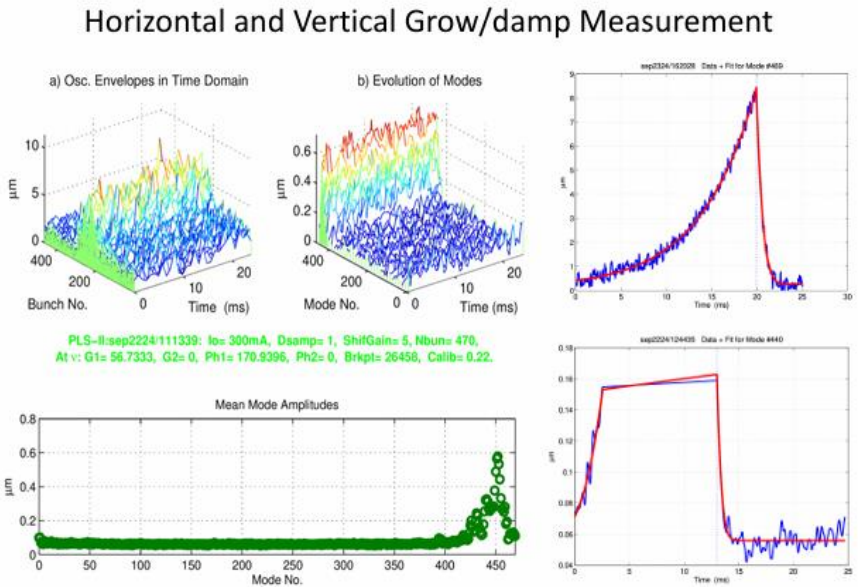
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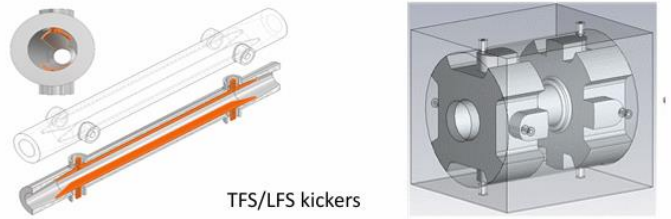
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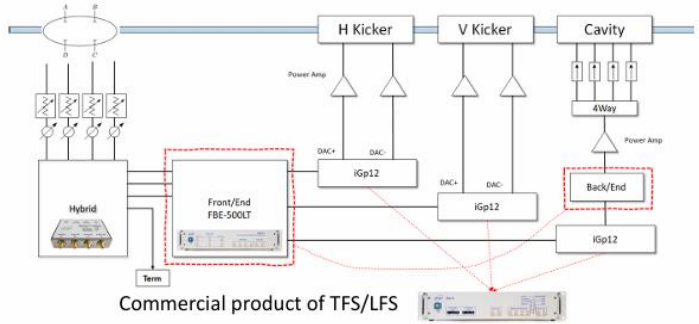
Beam Diagnostics – TFS/LFS for BbB FB system

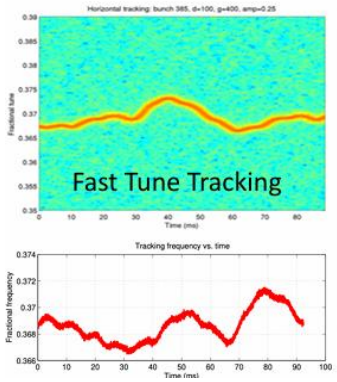
- TFS/LFS strip-line kicker and cavity kicker EM design was done
- TFS electronics by Dimtel was tested at PLS-II in Sep. 2024
- BbB feedback system can be measure storage ring Tune in H/V
- For high current operation mode as 400mA, BbB FB is essential
- Bunch cleaning can be make good purity of multi-bunch train.
- Most of system will be used commercial product.

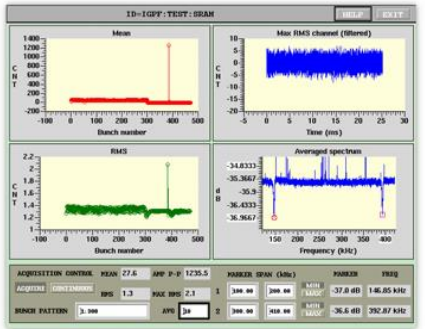












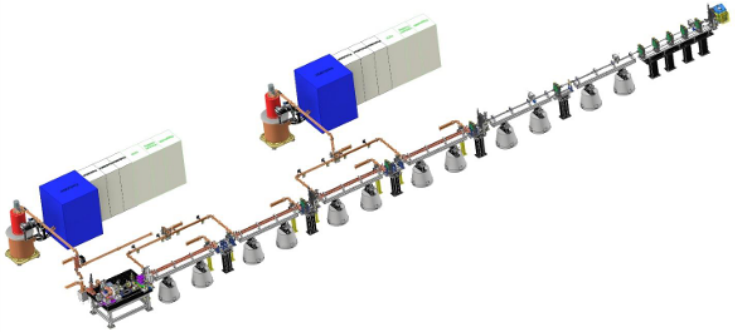
Vacuum System – Summary

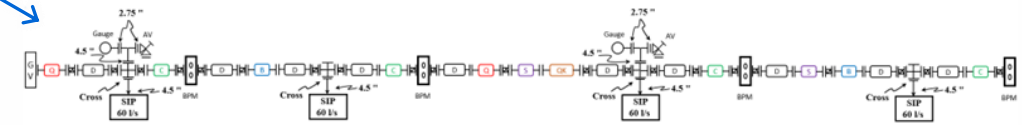
1 Linac vacuum
- Electron beam energy 0 → 200 MeV
- Four S-band accelerating columns with two modulator-klystron stations
- Photo-cathode E-gun (~10^{-11} mbar), AC and wave guide (~10^{-8} mbar)

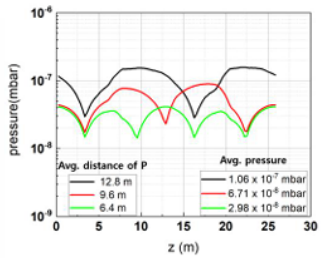
2 Booster vacuum
- Electron beam energy 200 MeV → 4 GeV
- Circumference ~770 m with 30 cells
- Beam duct OD Ø24~32 mm, thickness 0.7 mm (low eddy current)
- Chamber materials: SS316L (0.7 mm-thick) → Max. stress < 2.5 MPa
- Vacuum requirement ~10^{-8} mbar

3 Beam transfer system vacuum
- Transfer line length ~ 40 m
- Special chambers for the injection system
  (Ceramic kicker chamber, In-vacuum septum chamber, …)

4 Storage ring vacuum
- Electron beam energy 4 GeV & beam current 400 mA
- Circumference ~800 m with 28 cells
- Beam duct Inner diameter Ø18(V) x 24(H) mm
- Vacuum requirement during operation ~10^{-9} mbar





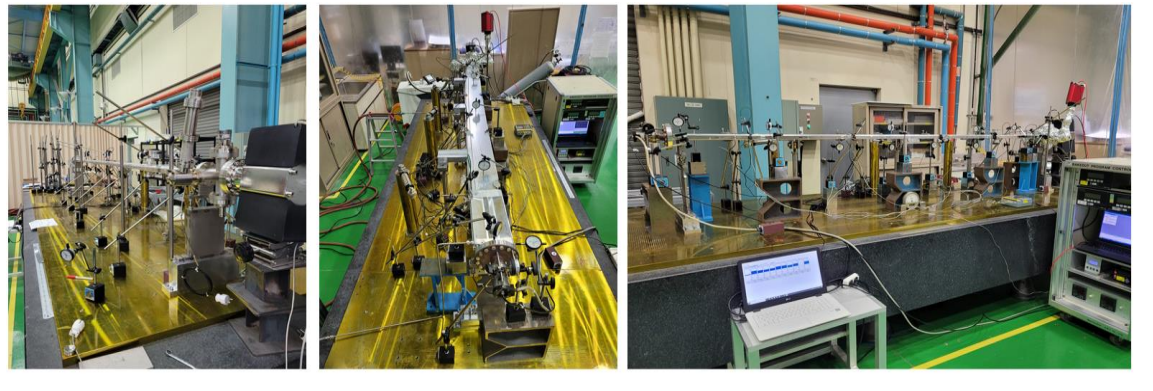


※ Pressure distribution w.r.t. pump distance

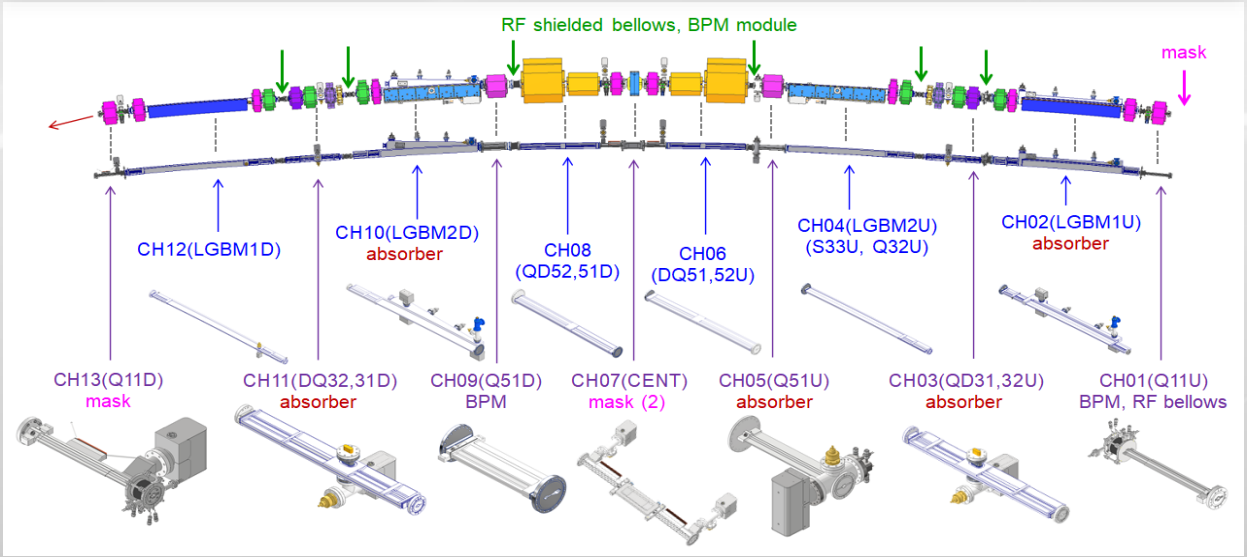
Vacuum System – SR Vacuum Chamber

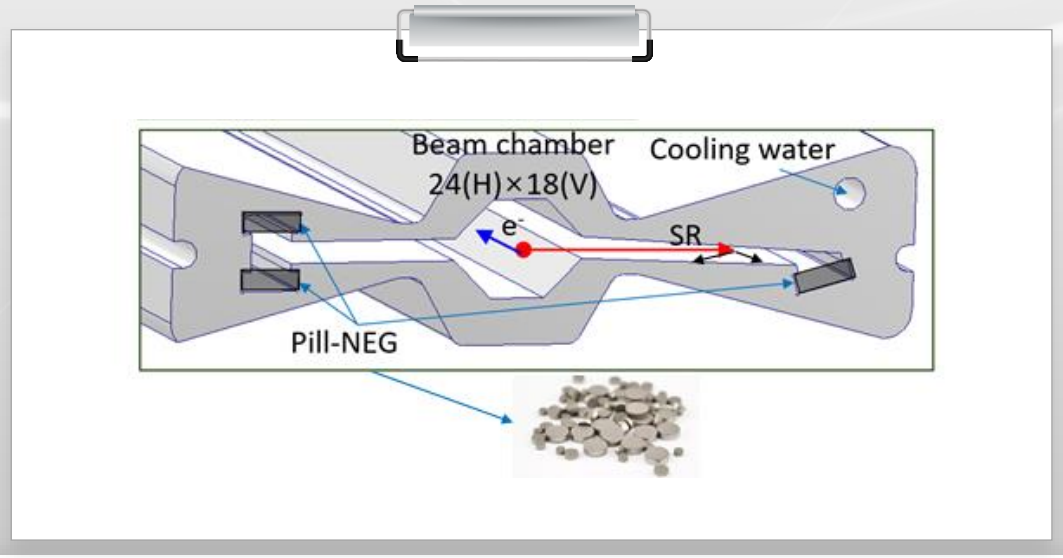
Characteristics of SR Vacuum System

- Octagon shape (24 mm,H) x (18 mm,V), except for center bend
- 10 mm vertical aperture at center bends
- 8 RF-bellows each sector for installation and stress reduction
- Gate valve at the both ends of each arc sector
- 7 sputter ion pumps for noble gas pumping.
- > 0.6 mm clearance between the vacuum chamber and the magnets



Prototype





Thank You



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