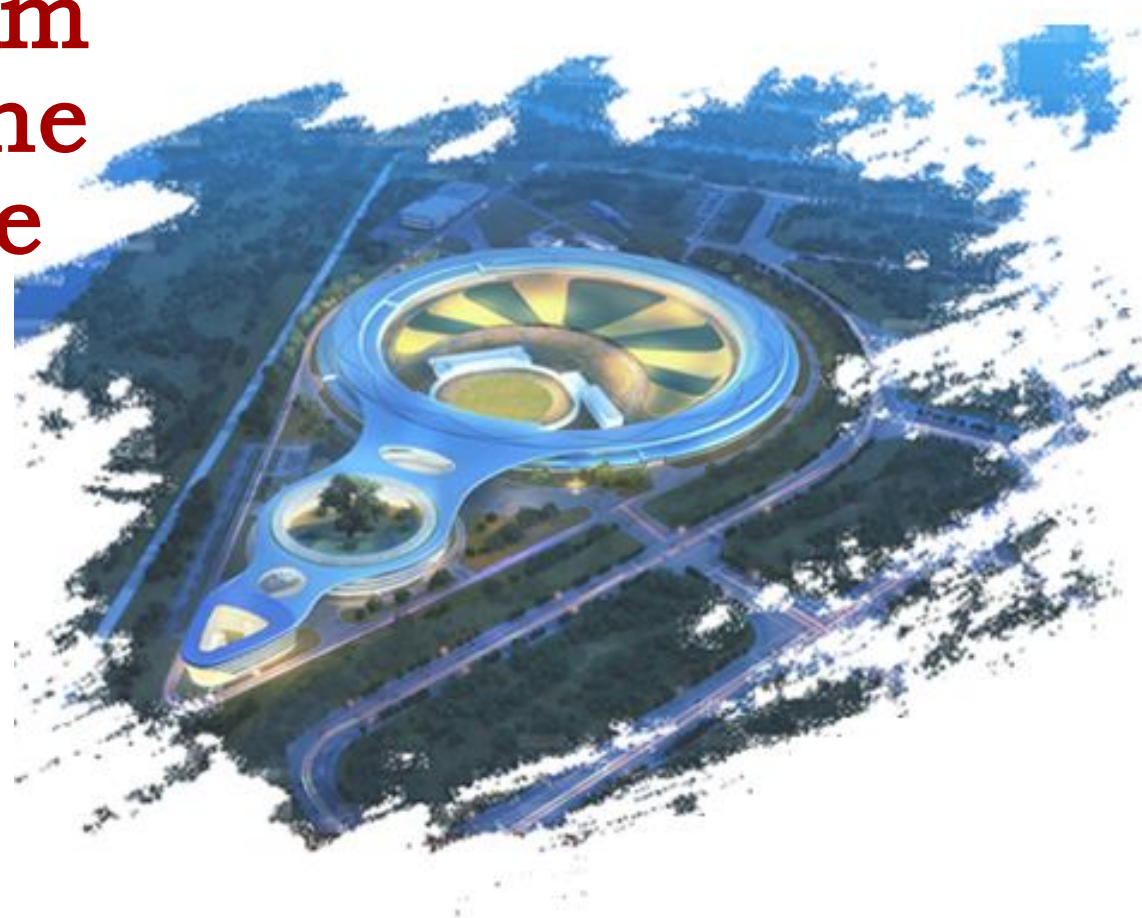


Swap-out injection with beam recycling in the booster @ the High Energy Photon Source

Zhe Duan

on behalf of the HEPS team

May 21, 2025



4th generation synchrotron radiation light sources

Natural emittance

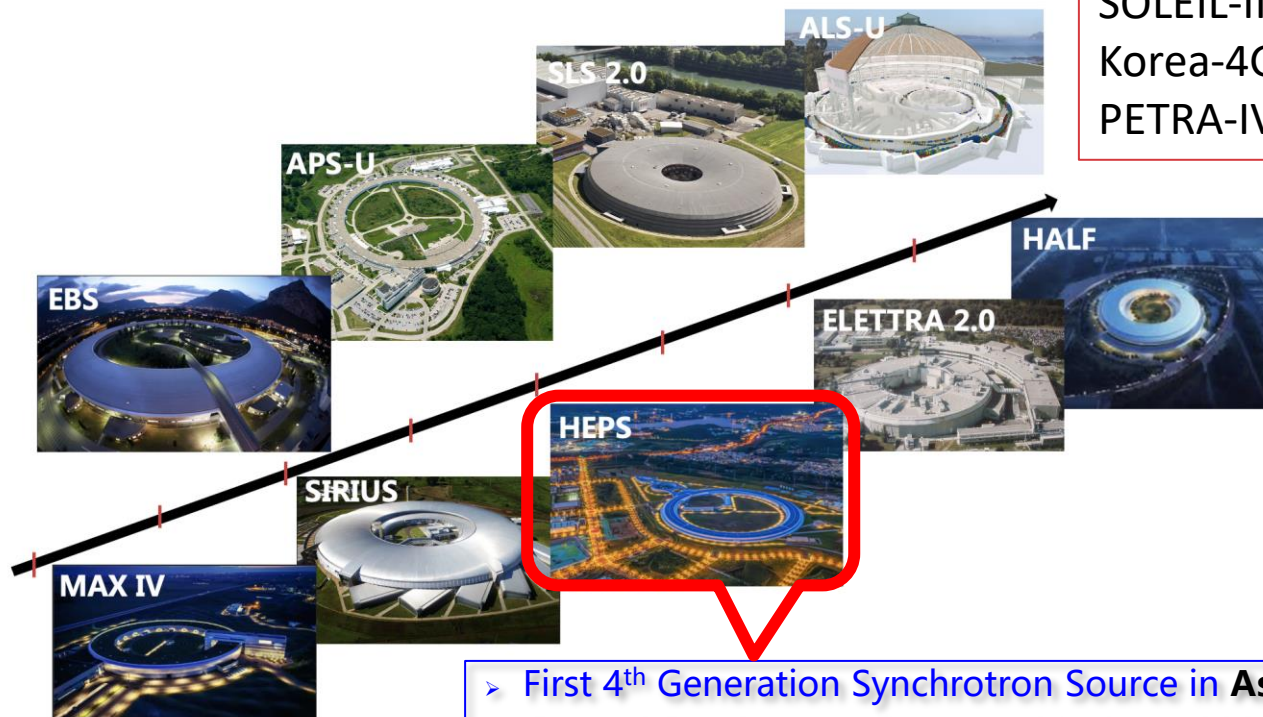
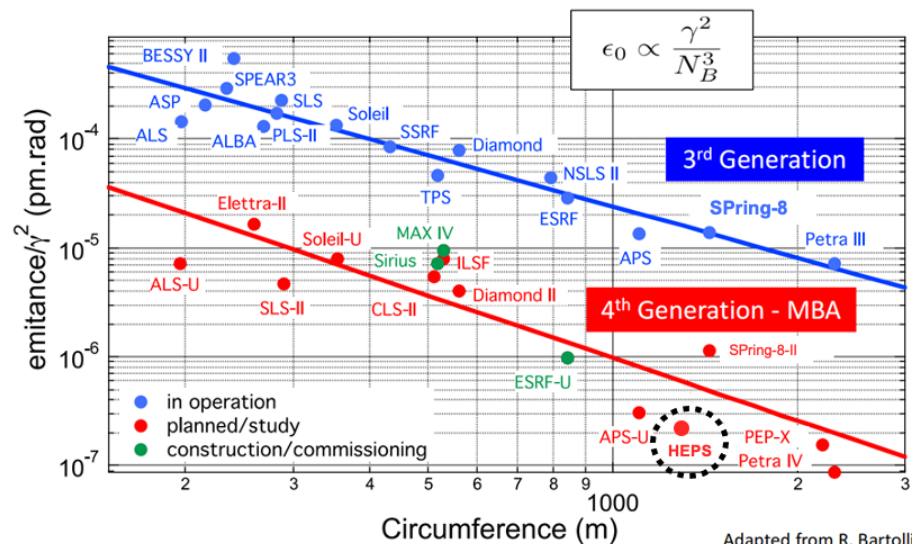
- 1-2 order smaller compared to 3rd generation
- approaching 10pm, diffraction limit of hard X-ray photons

More to come:
SKIF,
Diamond II,
Spring8-II,
SOLEIL-II,
Korea-4GSR,
PETRA-IV etc

3rd generation



4th generation



- First 4th Generation Synchrotron Source in Asia
- Second Synchrotron Source achieving <100pm emittance in the world (following APS-U)
- First high-energy Synchrotron Source in China

High Energy Photon Source

HEPS key indicators

circumference	1360.4	m
beam energy	6	GeV
natural emittance	≤ 0.06	nm·rad
brightness	$> 1 \times 10^{22}$	phs/s/mm ² /mrad ² / 0.1%BW
max number of beamlines	≥ 90	14 + 1 in Phase I
photon energy	0.1-300	keV

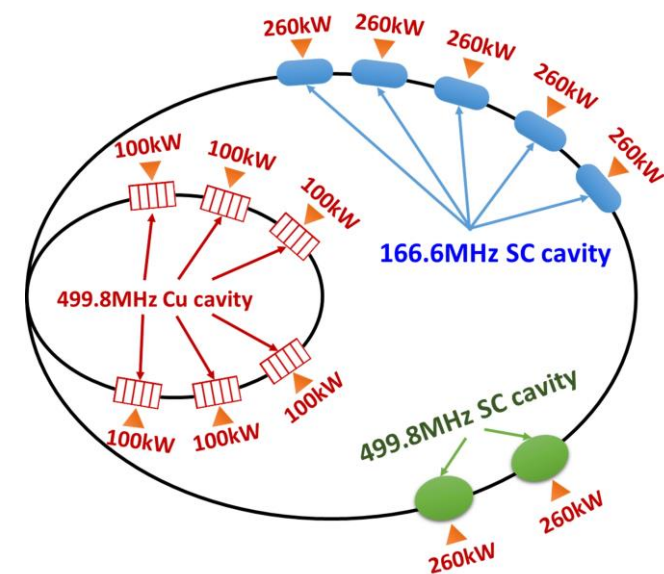
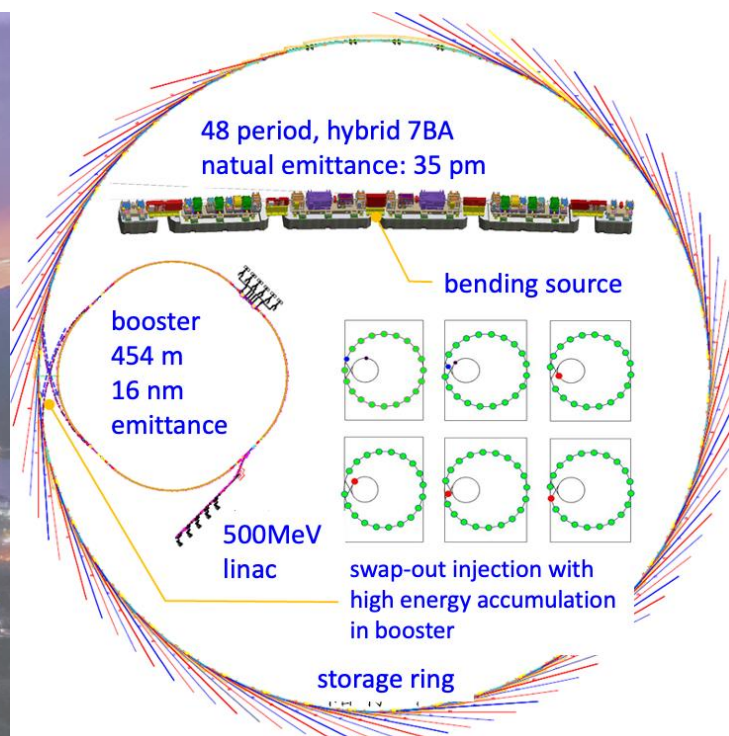
Construction period: 2019. 7 to 2025. 12

Location: Huairou Science city, Beijing
near Yanqi Lake, 70 km to city center



HEPS

HIGH ENERGY
PHOTON SOURCE



**Parameters
for lattice w/o IDs**

**High-brightness
mode, 200 mA**

**High-bunch-charge
mode, 200 mA**

Units

Beam energy

6

6

GeV

Number of bunches

680

63

Bunch charge

1.33

14.4

nC

Bunch spacing

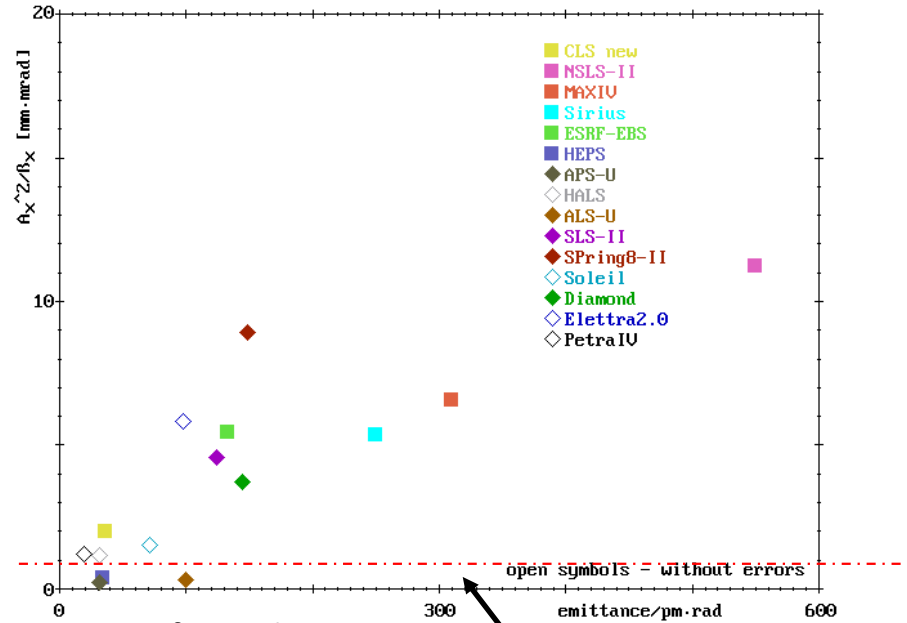
6

72

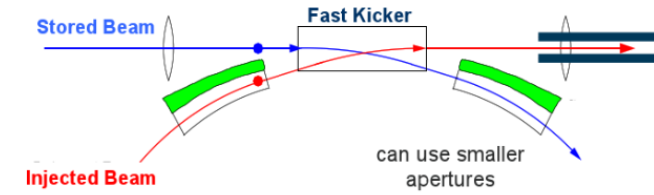
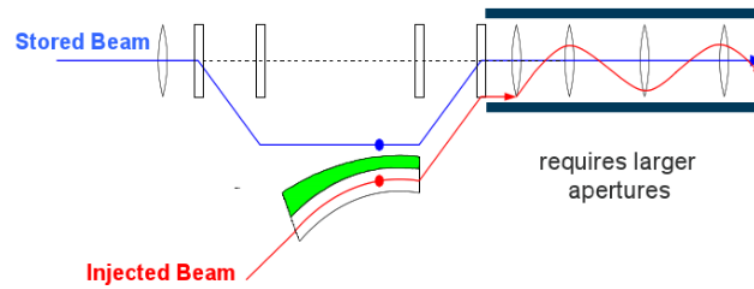
ns

Injection challenges in 4th generation synchrotron sources

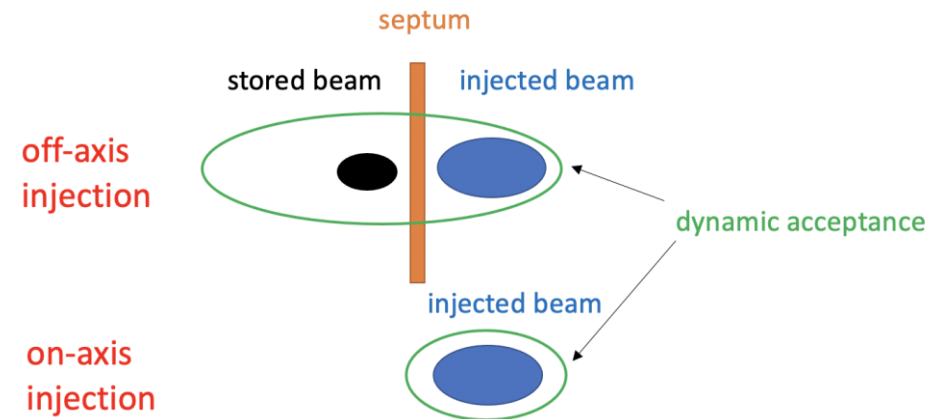
the smaller emittance,
the smaller horizontal acceptance



Courtesy of P. Kuske



on-axis injection relaxes requirements on dynamic acceptance



pursuing ultimate performance requires development of on-axis (swap-out) injection



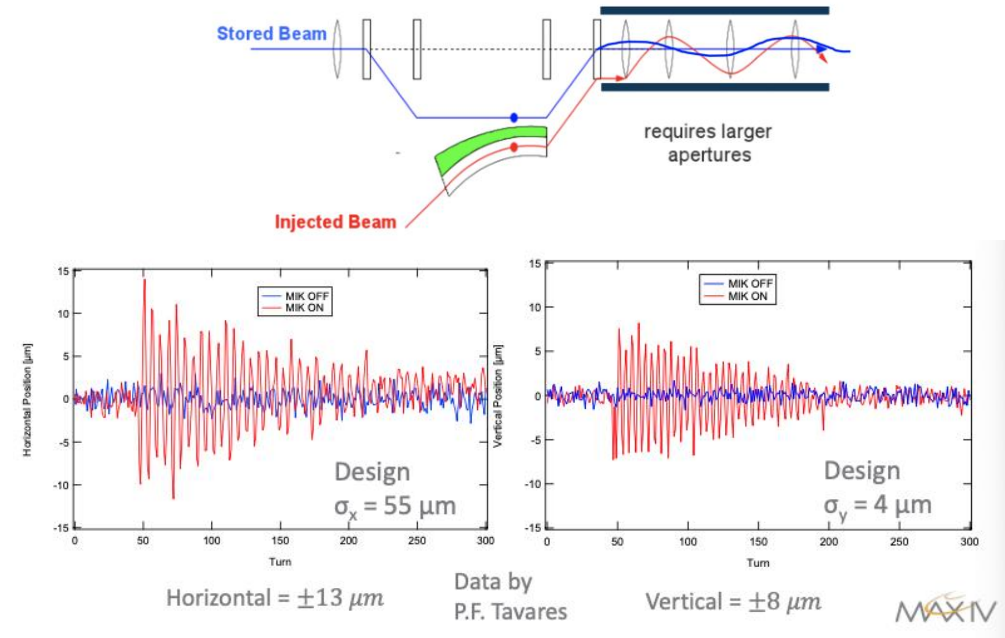
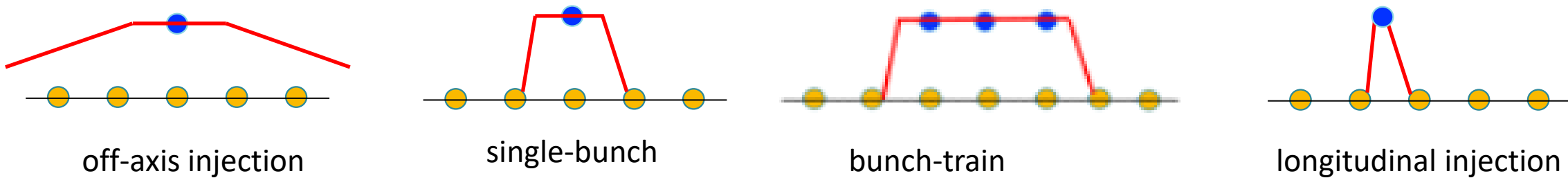
Injection challenges in 4th generation synchrotron sources

- Transparent injection

- dipole injection kicker -> nonlinear injection kicker

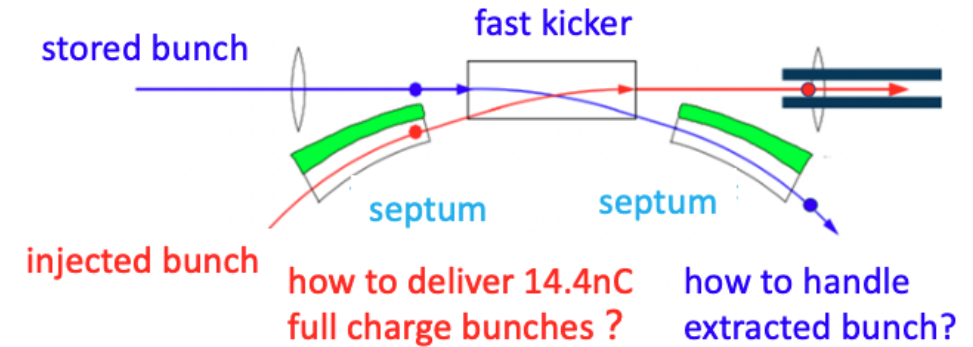


- microsecond kicker pulse -> nanosecond kicker pulse

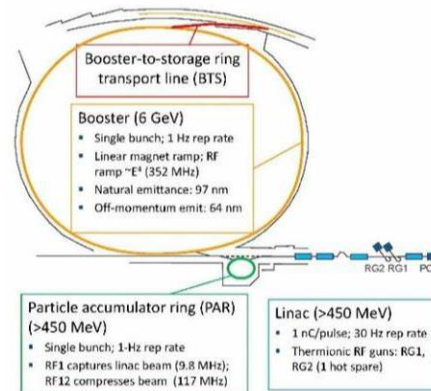


Challenges of swap-out injection

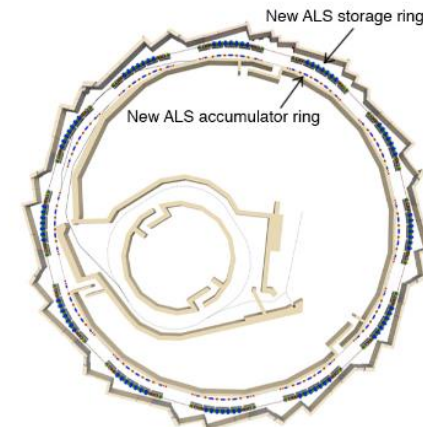
- Ultra-fast kicker, compact injection straight section, no previous demonstration
- Full-charge injected bunch
 - very hard for convention linac + booster scheme
 - For HEPS (APS-U), timing experiment requires 63 (48) bunches with ~15nC
 - APS-U: linac + PAR (low-energy accumulator) + booster, dump the extracted depleted bunches
 - ALS-U: linac + booster + full-energy accumulator, recycle the extracted depleted bunches
 - short time lifetime (~1h) requires very frequent injection to maintain almost constant beam current



APS-U scheme

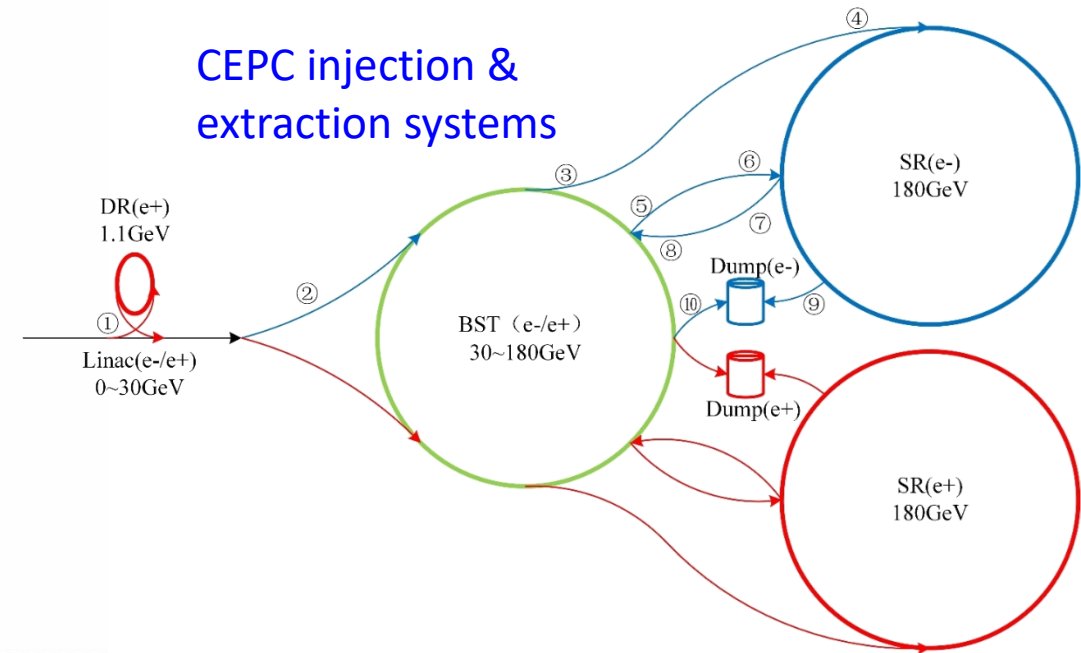
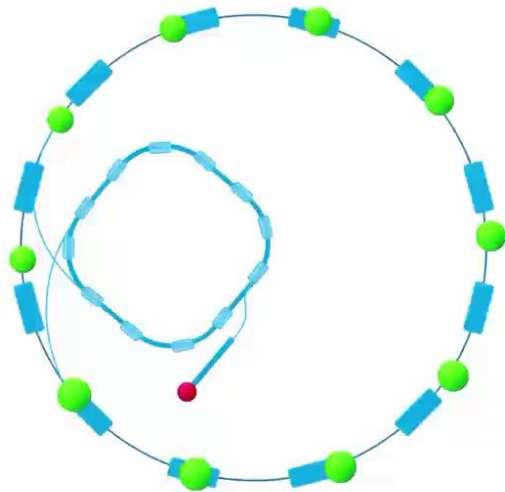


ALS-U scheme

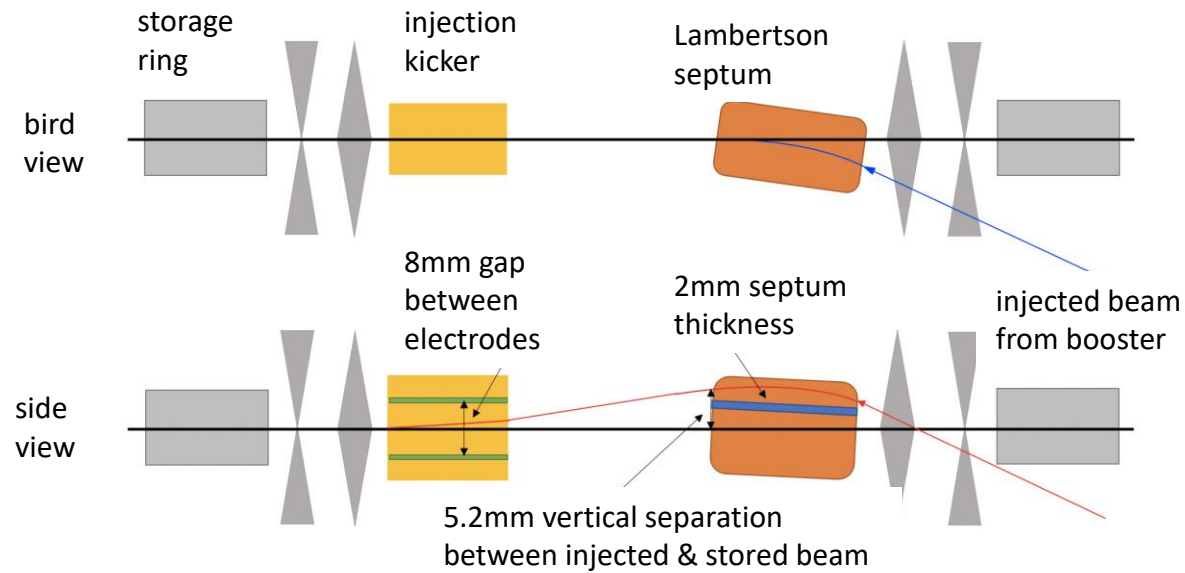


Injection scheme of HEPS

- Swap-out injection, with bunch recycling in the booster as a full energy accumulator ring
 - save $\frac{3}{4}$ costs relative to the scheme with a dedicated accumulator ring
 - Decrease the bunch charge requirement of booster LE by $\frac{1}{2}$, improving the reliability of booster design

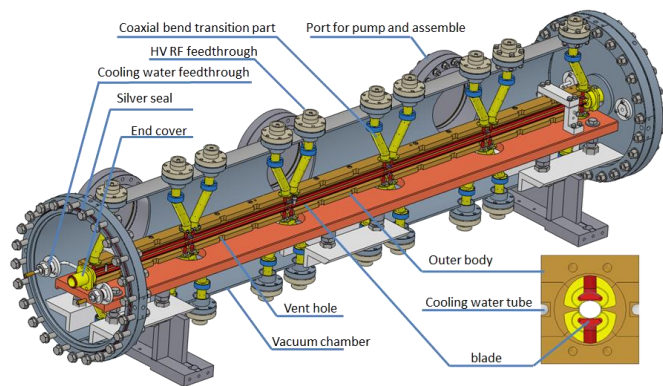


SR injection region design

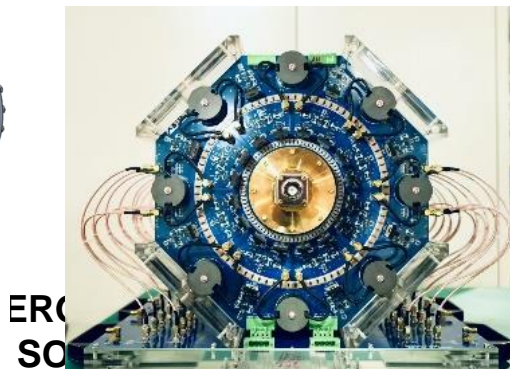


stripline kicker and high voltage pulser	5-cell stripline kicker module	
	stripline length/gap	300 mm / 8 mm
	pulse shape	pseudo Gaussian pulse width ≤ 10 ns
	working voltage of pulser	± 15 kV
Lambertson septum	half in vacuum, FeCoV septum, positioned with 3D rotation	
	integral magnetic field	1.6 T · m
	septum thickness	2 mm
	dipole leakage field	< 2mT · m

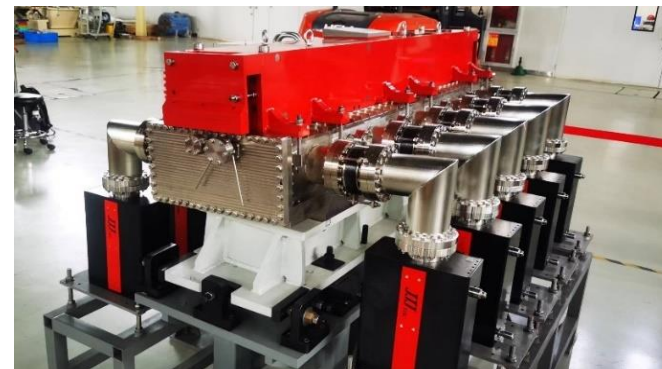
5-cell stripline kicker module



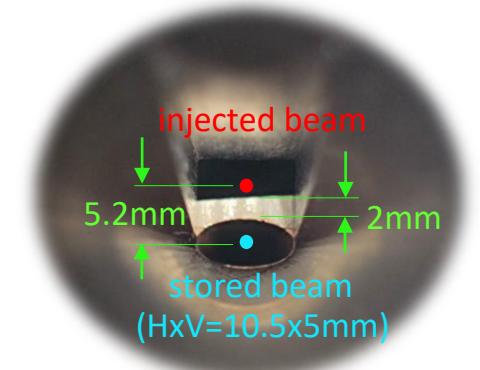
10 ns HV kicker pulser



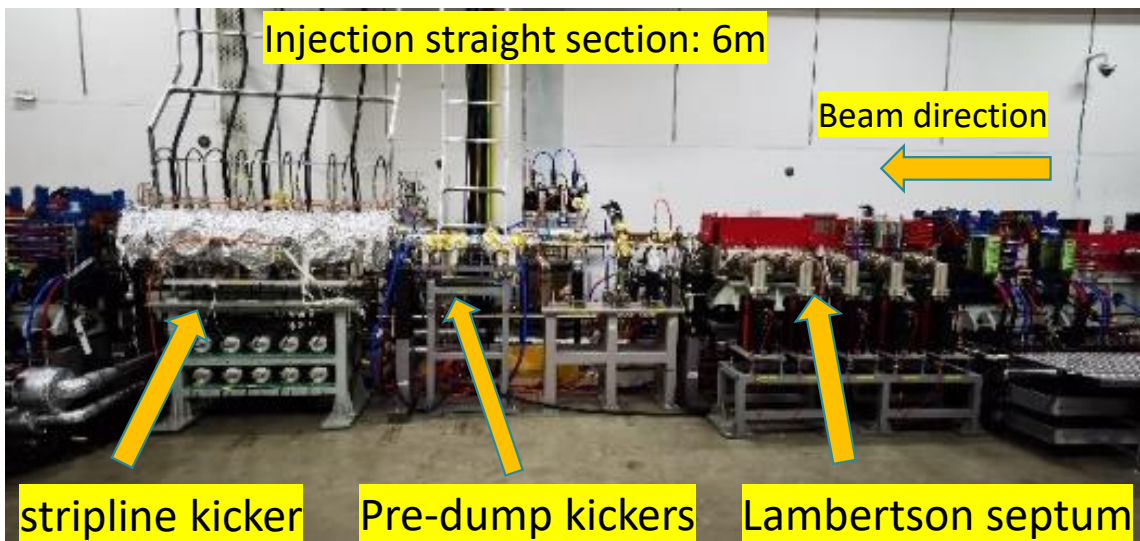
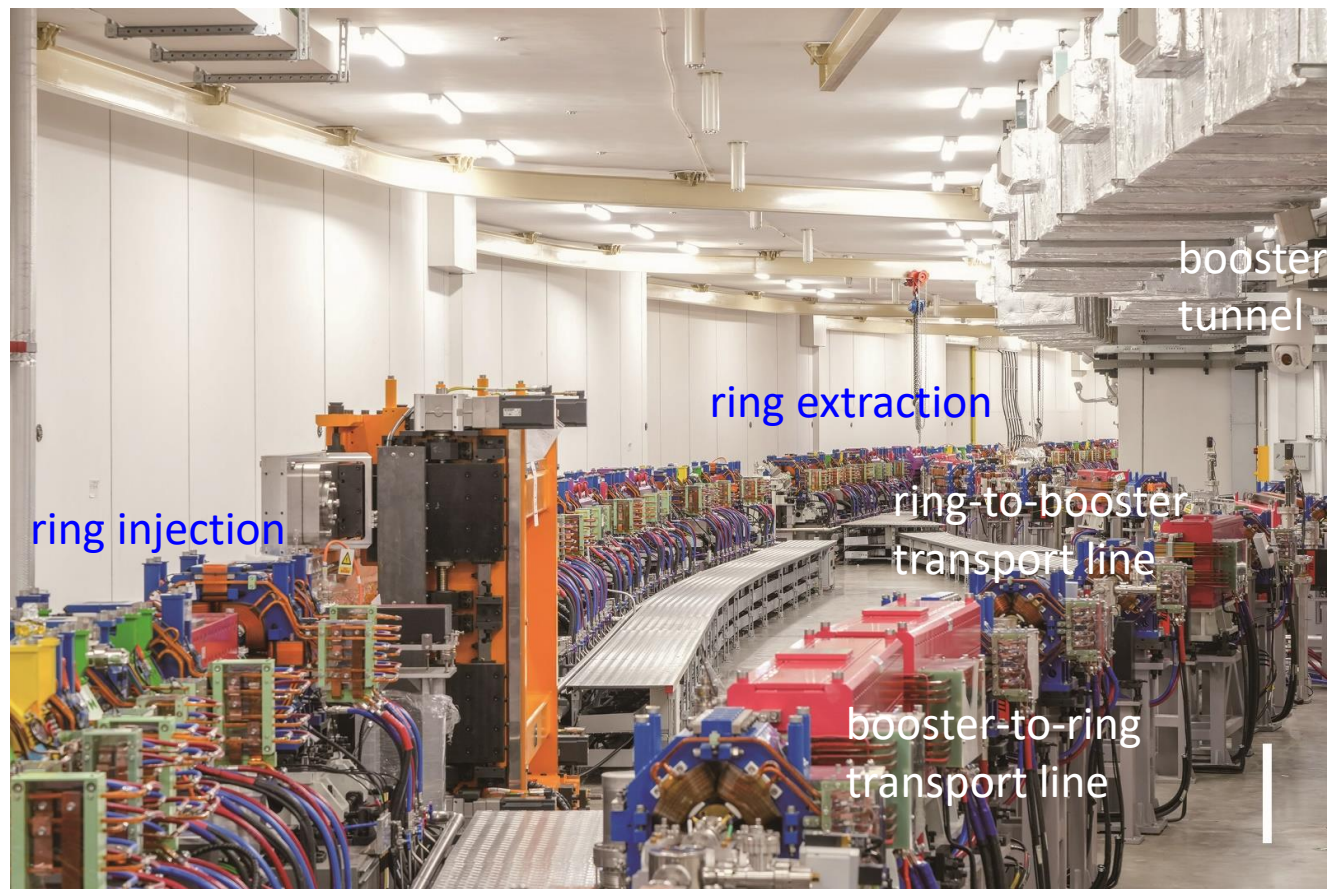
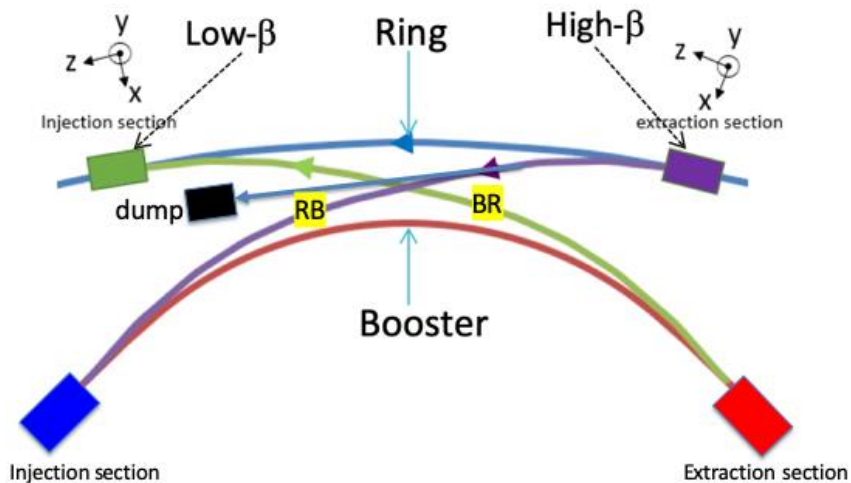
Lambertson septum



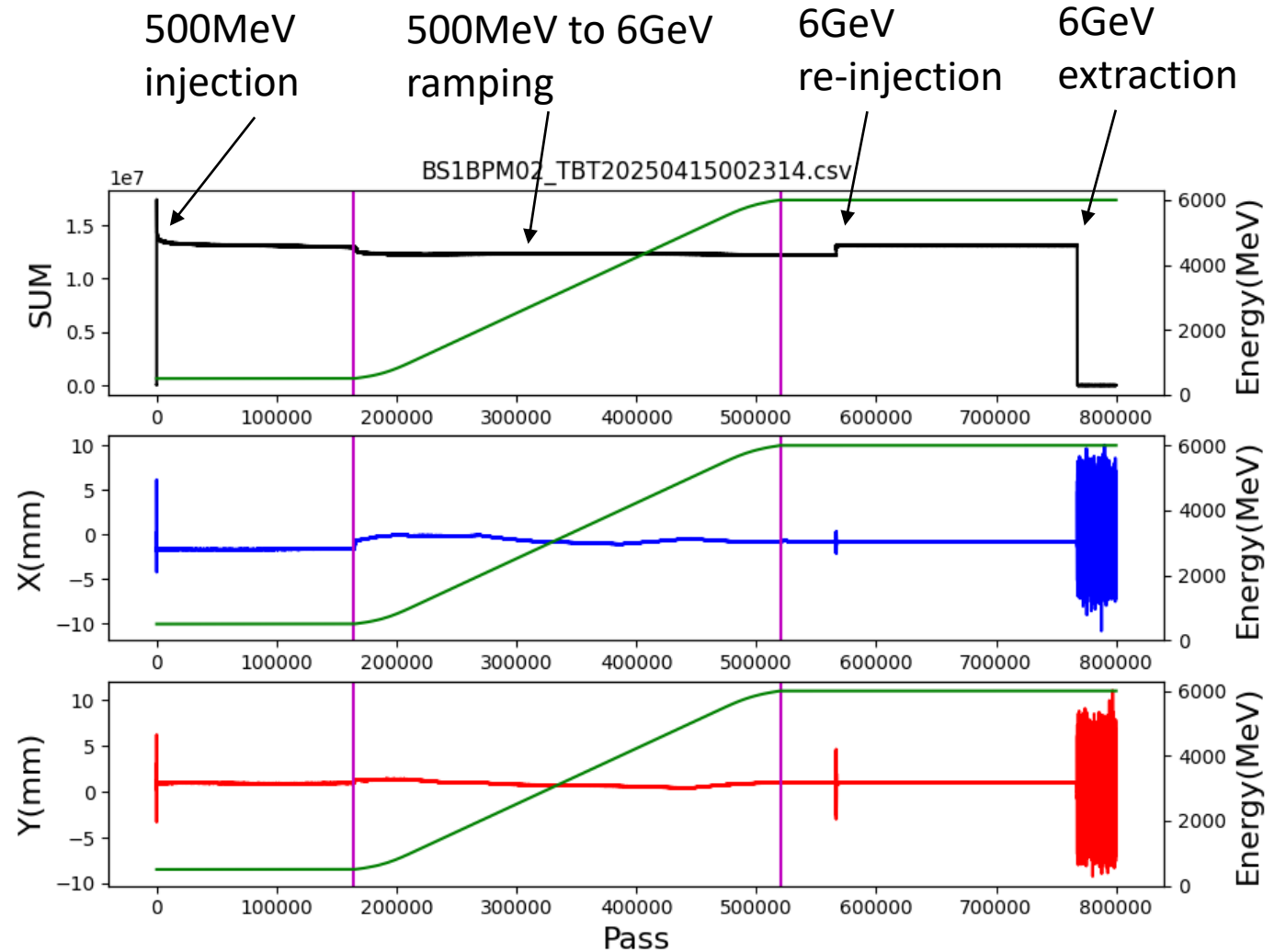
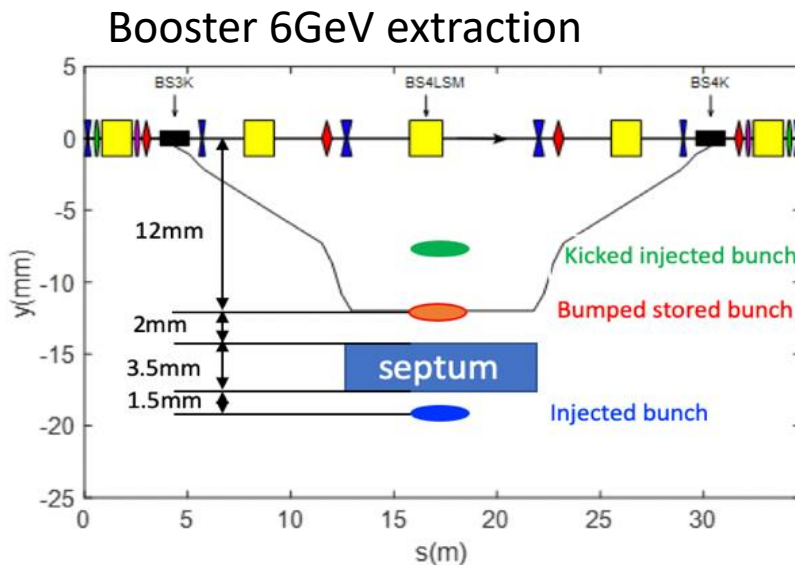
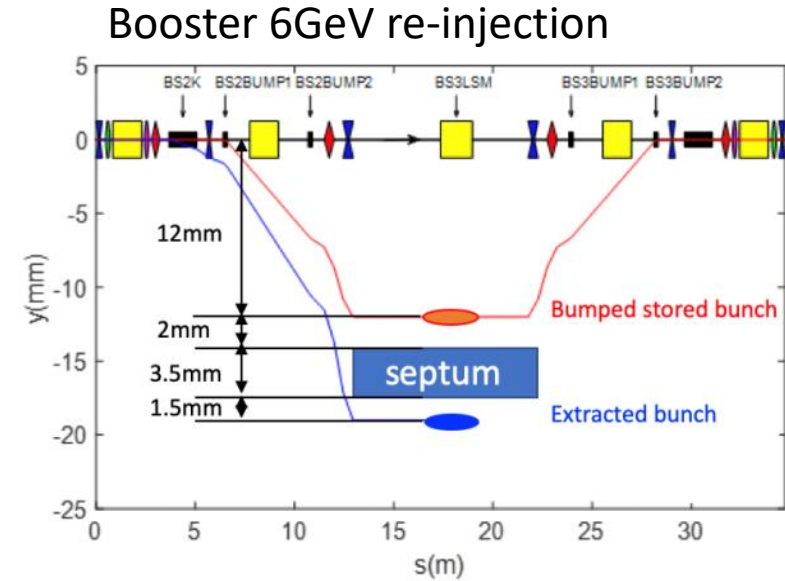
aperture @ exit of Lambertson septum



Symmetric injection & extraction region



Booster high-energy extraction, re-injection design



Key design issues

Synchronization

- Wise choice of booster harmonic number & transport line lengths
- Variation in the circumferences within error tolerance

transmission efficiency

- trade-off between injected beam emittance, injection error and DA
- mechanism & mitigation of injection transient instabilities

hardware specs

- challenging hardware
- tolerance of pulse magnets
- alignment tolerance of Lambertson septum

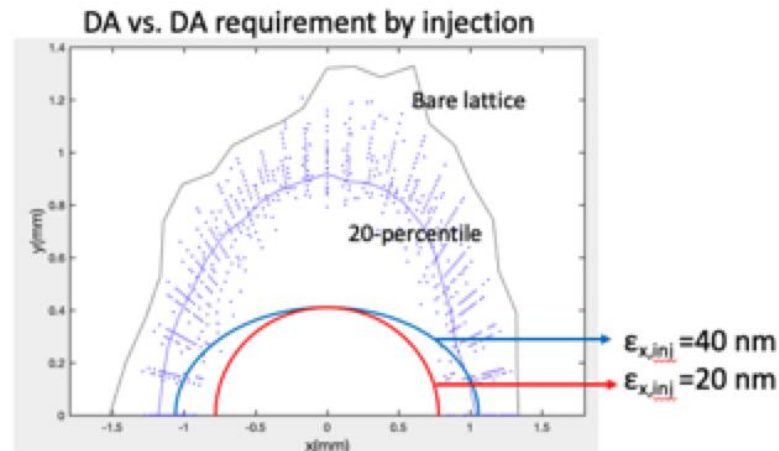
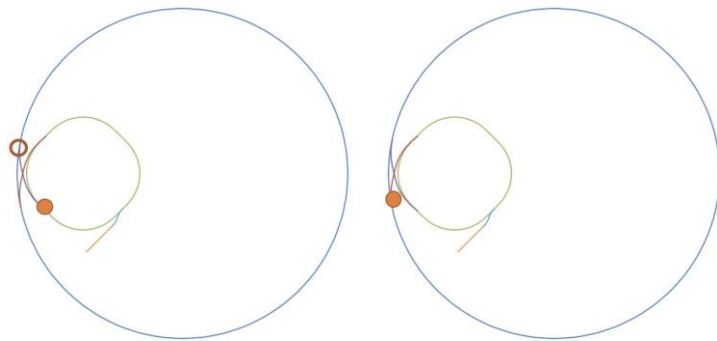
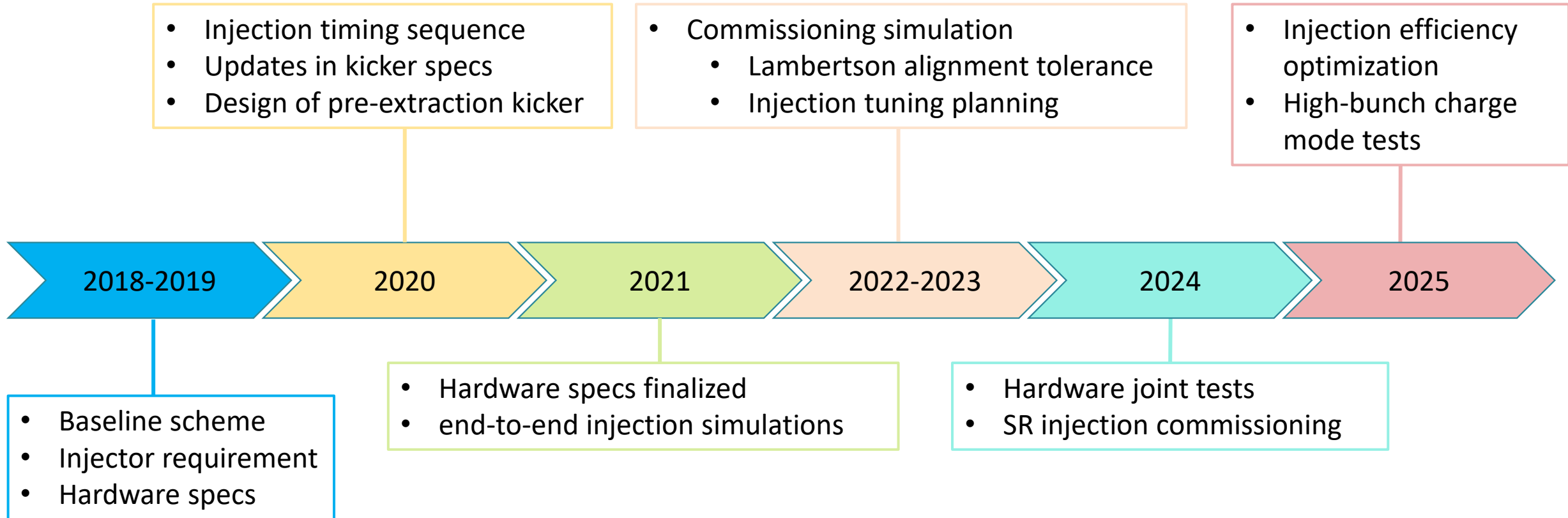


表 1. 储存环注入引出物理设计主要参数演化

参数名称		V0	V1	V2	V2.1	V3
储存环 lattice 类型		48 周期		24 周期, 高、低 β 直线节交替排列		
直线节中点水平/垂直 β 函数(m)	注入	9/3.2	8.9/4.1	10.12/9.64	2.61/1.87	2.56/2.31
	引出	9/3.2	8.9/4.1	2.80/1.91	7.4/7.1	8.18/5.0
Stripline kicker	电极长度(mm)	注入 300	300	300	300	300
		引出 750	300	300	300	300
	数量	注入 10	10	8	5	5
		引出 4	10	8	5	5
	极板间距(mm)	10	10	10	10	8
积分偏转角 (mrad)	/	3	2.656	1.611	1.611	
Lambertson 磁铁	切割板厚度 (mm)	/	2.0	2.0	2.0	2.0
	有效长度	/	1.6	1.6	1.6	1.6
	偏转角(mrad)	/	79.5	79.97	79.95	
	翻滚角 (mrad)	/	113	109	76	
	循环束真空盒截面形状	/	8×6mm 椭圆	Φ16 圆形, 循环束中心距切割板 2.5mm	Φ13.5 圆形, 循环束中心距切割板 2.5mm	10.5×5mm 椭圆
注入束(引出)同循环束的垂直分离量 (mm)	/	7	7.1	5.2	5.2	



Design evolution



Milestones of the HEPS project



May 12, 2022
The Linac Vacuum-sealing in the tunnel completed



Jan. 13, 2023
The Booster Vacuum-sealing in the tunnel completed



Feb. 1, 2023
The first girder was installed in the storage ring tunnel



Mar. 14, 2023
The first electron beam



Nov. 17, 2023
Electron Beam Ramped Up to 6 GeV



July. 1, 2024
Full-circumference vacuum sealing of the storage ring completed



July. 23, 2024
Storage ring commissioning commenced



June 29, 2019
Groundbreaking ceremony



July 1, 2020
The first steel beam was installed



Apr. 13, 2021
Utility installation in NO.2 Hall commenced



June 27, 2021
Roof-sealing work for the main ring building completed



June 28, 2021
HEPS Installs First Piece of Accelerator Equipment in Linac Tunnel.



Nov. 3, 2023
Civil Construction for ancillary buildings completed

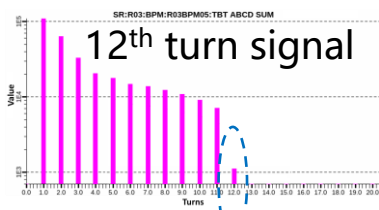


HEPS storage ring commissioning



Commissioning Commenced

2024.07.23



12th turn signal

circulation > 10 turns

2024.08.04



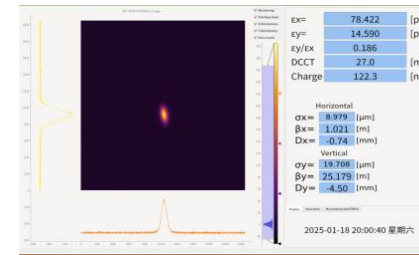
beam current reaches 12mA

2024.08.18



First light from ID

2024.09.22



Emittance better than 100pm

2025.01.02

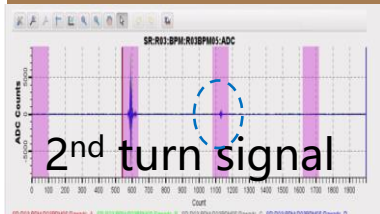


First monochromatic light from ID

2025.03.18

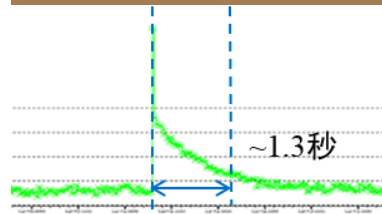
2024.07.23

1st complete turn



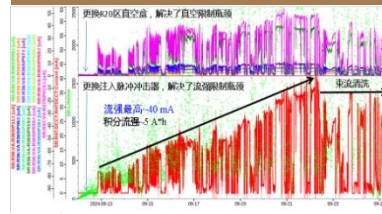
2nd turn signal

First stored beam

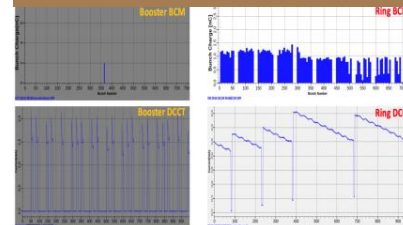


~1.3秒

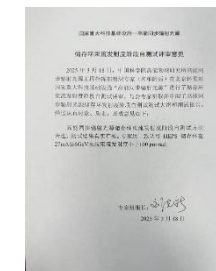
beam current reaches 40mA



injection scheme demonstrated



Emittance result passed review

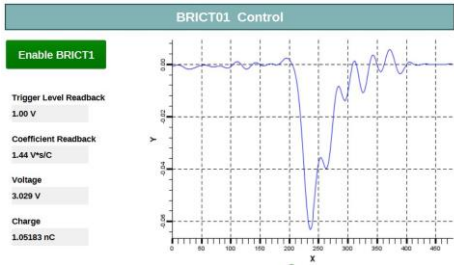


- HEPS is in shutdown for installation of 166 MHz SRF cavities, necessary to reach > 100mA beam current
- Will resume operation in early September, aiming to pass the national acceptance test within 2025



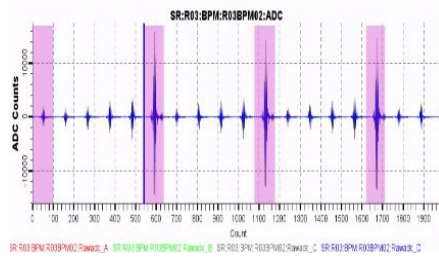
HEPS HIGH ENERGY PHOTON SOURCE

Commissioning of the injection scheme



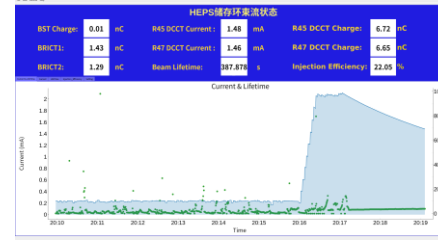
first booster extraction

2024.05.17



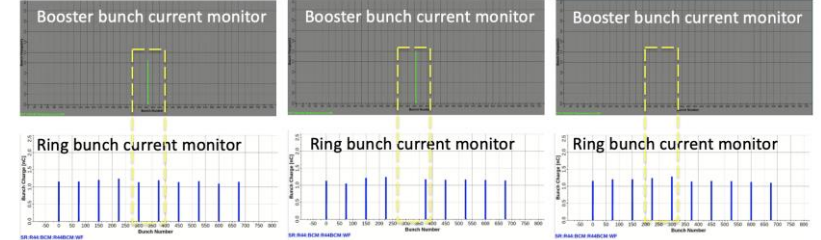
first multi-bunch injection

2024.08.08



first SR injection w/ stripline kicker

2024.09.12



first swap-out injection w/ high energy accumulation in booster

2025. 01. 02

2024.07.23

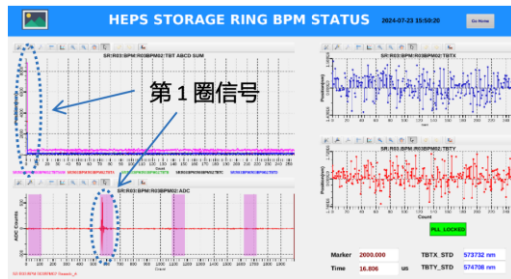
2024.08.24

2024.12.28

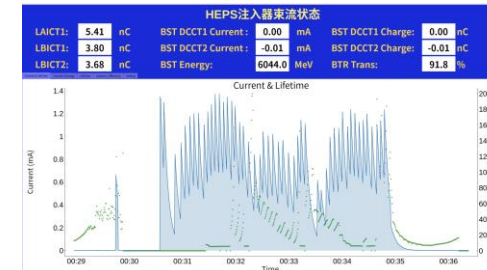
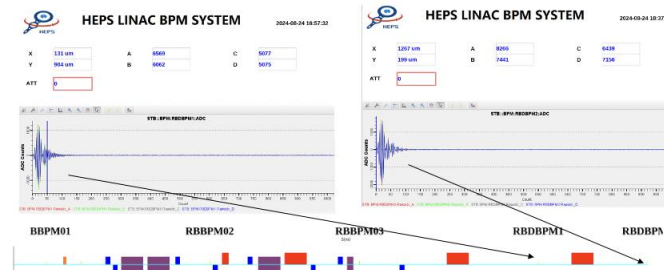
first SR injection after 3 hours commissioning

first SR extraction w/ stripline kicker

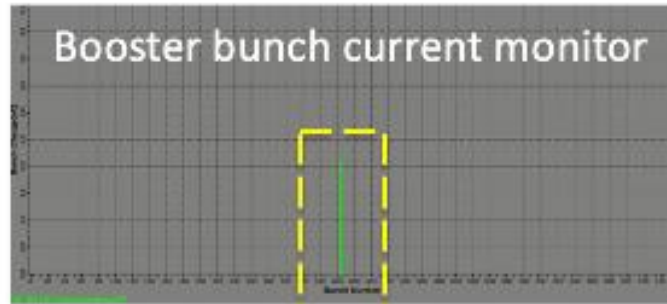
first high energy injection into booster



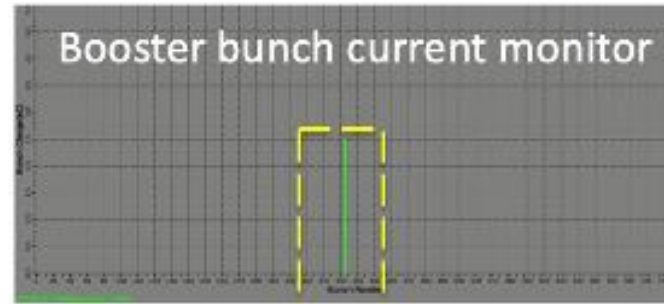
with a slotted-pipe kicker



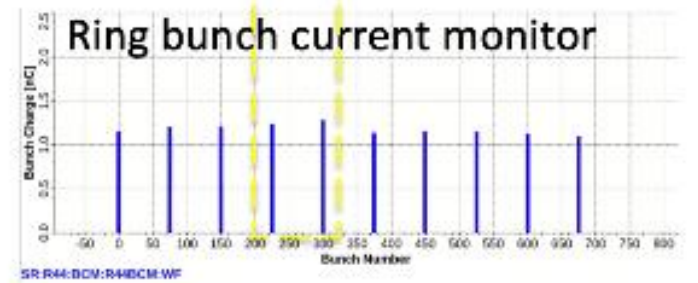
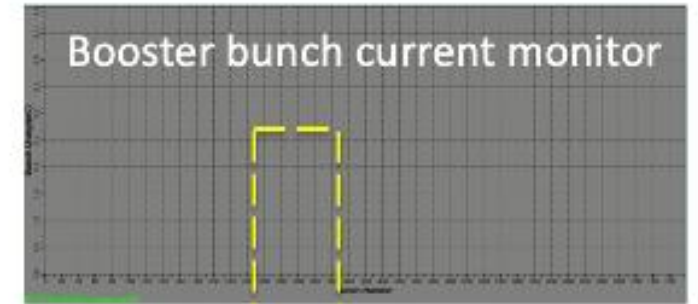
Swap-out with “booster high energy accumulation”



Booster ramp to 6 GeV, after injection @ 500 MeV



Merge between extracted bunch from Ring and circulating bunch in Booster

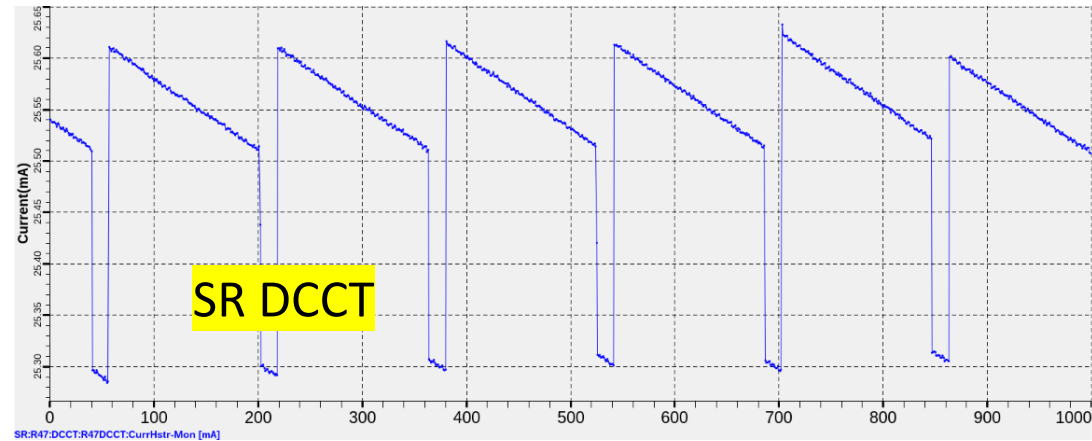
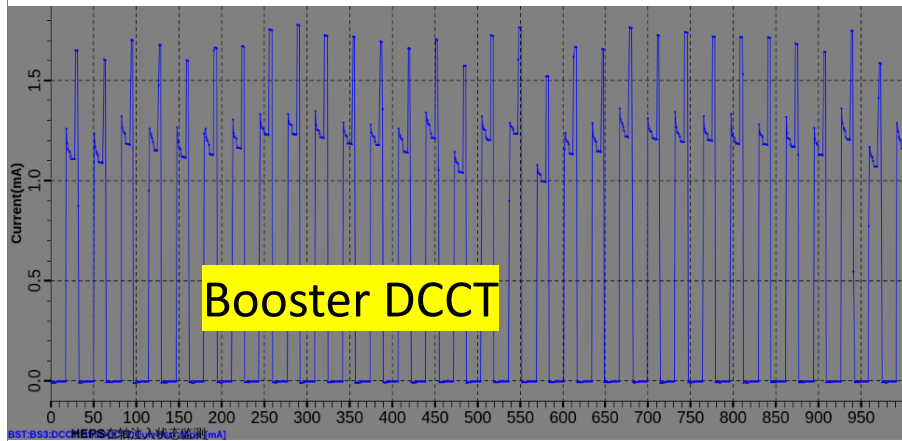
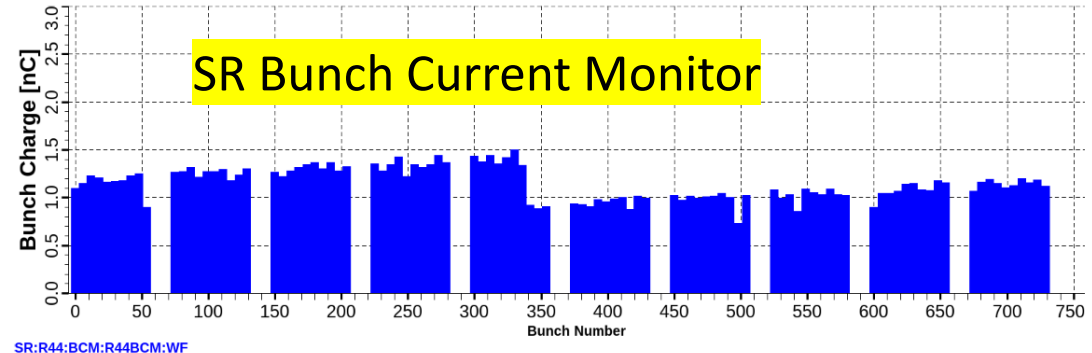
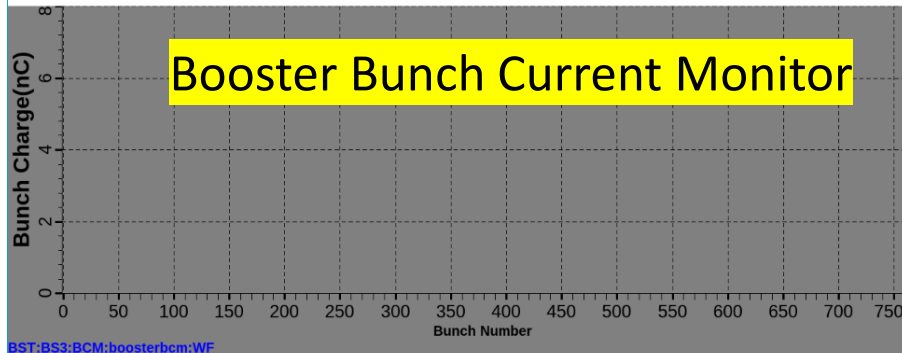


Full-charge bunch re-injected into the Ring. Booster ramp down

First demonstration in 2025. 01. 02.

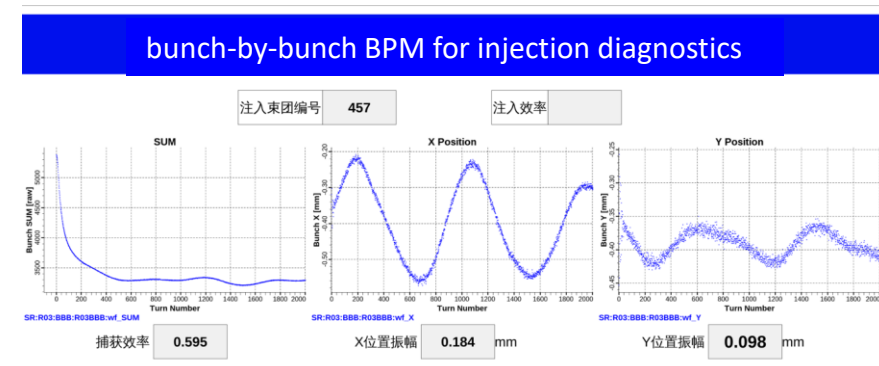
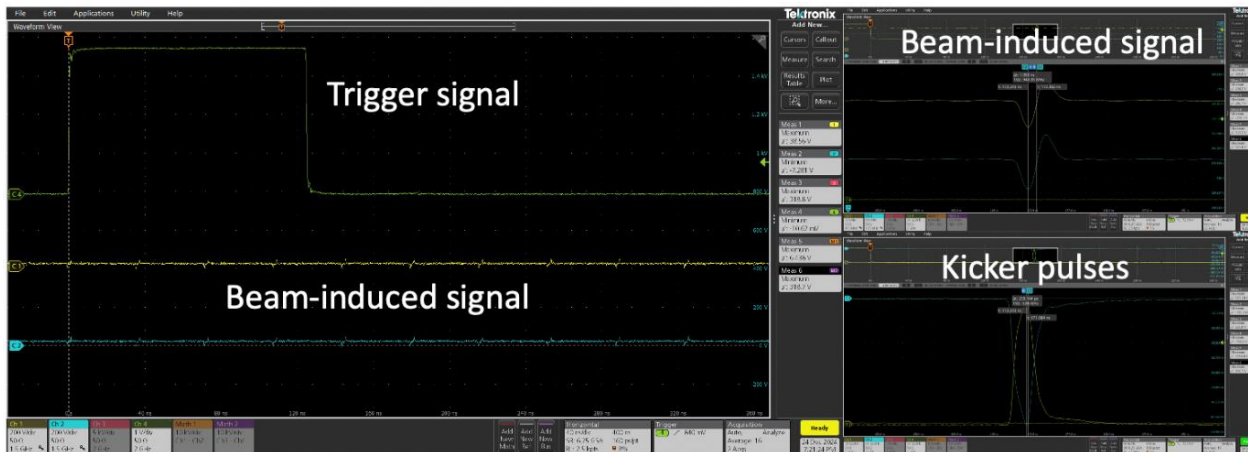
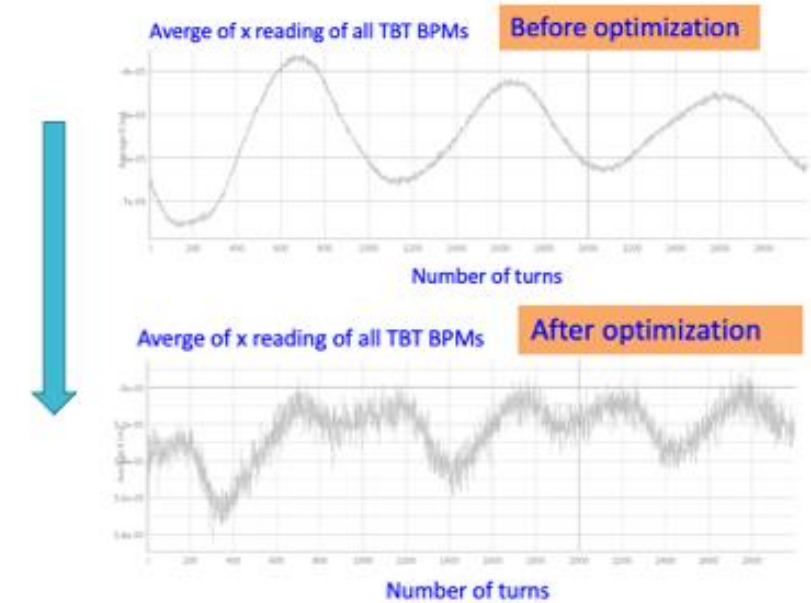
Swap-out injection in operation

HEPS Swap-out injection status monitor



Lessons learned in the commissioning

- Progressive beam tests of key hardware and the timing system
- Oscilloscope is essential in debugging and delay measurement
- Swap-out injection requires more from beam diagnostics
 - Turn-by-turn & bunch-by-bunch BPM provides real-time measurements of injection efficiency / residual oscillation / energy oscillation
 - streak camera (and maybe beam size monitor) captures the transient effect
- Manual optimization -> (semi)-auto optimization



Summary

- The swap-out injection scheme with beam recycling in the booster has been demonstrated and utilized in routine operation at HEPS
- Novel injection hardware (stripline kicker module, half-in-vacuum Lambertson, HV pulser based on DSRD & inductive adder) has been fully tested and running smoothly
- Next step
 - Realize 100mA beam current goal for national acceptance test
 - High-bunch-charge mode commissioning
 - Continue injection efficiency optimization
 - evaluate potential influences to users





Thanks!



HEPS | HIGH ENERGY
PHOTON SOURCE

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