Accelerator Physics Studies for the High Energy Photon Source (HEPS) in Beijing

Yi Jiao(IHEP, Beijing)
On behalf of the HEPS physical design group
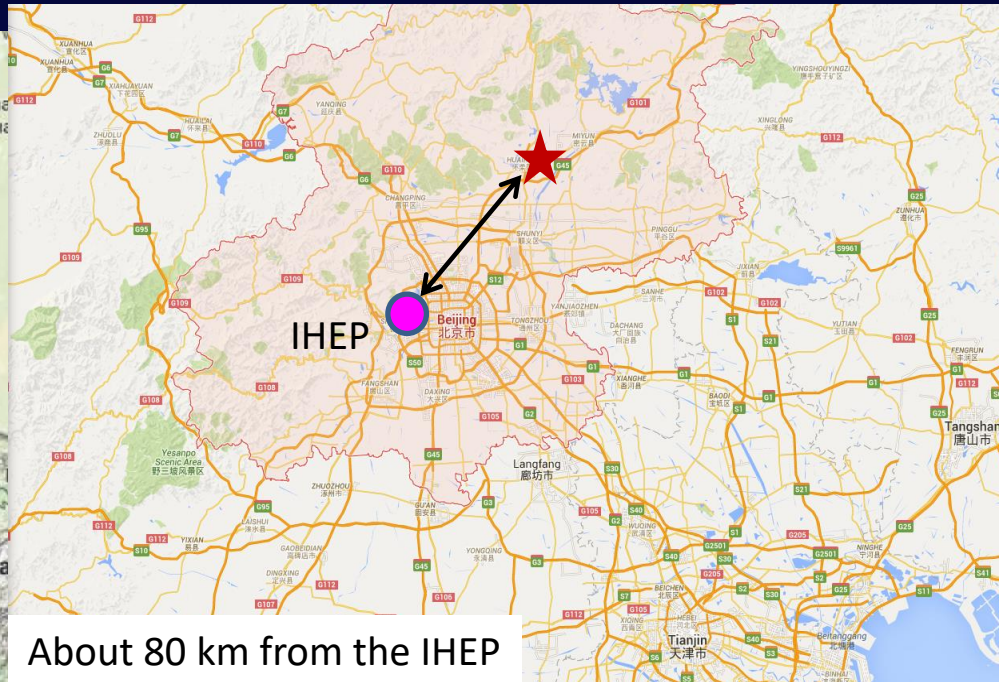
Mar. 5, 2018

The 60th ICFA Advanced Beam Dynamics Workshop (FLS2018)
Shanghai, China

The 60th ICFA Advanced Beam Dynamics Workshop

FLS2018

Mar. 5-9, 2018
Shanghai Institute of Applied Physics

HEPS: the next ring light source in China

A new photon science research center at the north of China

IHEP

About 80 km from the IHEP

HEPS

North Korea

Seoul

Preliminary studies started on 2008

The HEPS-test facility (TF) project (2016-2018)

- R&D on the accelerator and beam line techniques for a DLSR.

HEPS Project (planned from 2018)

- Selected in the 13th 5-year plan of the National Development and Reform Commission of China
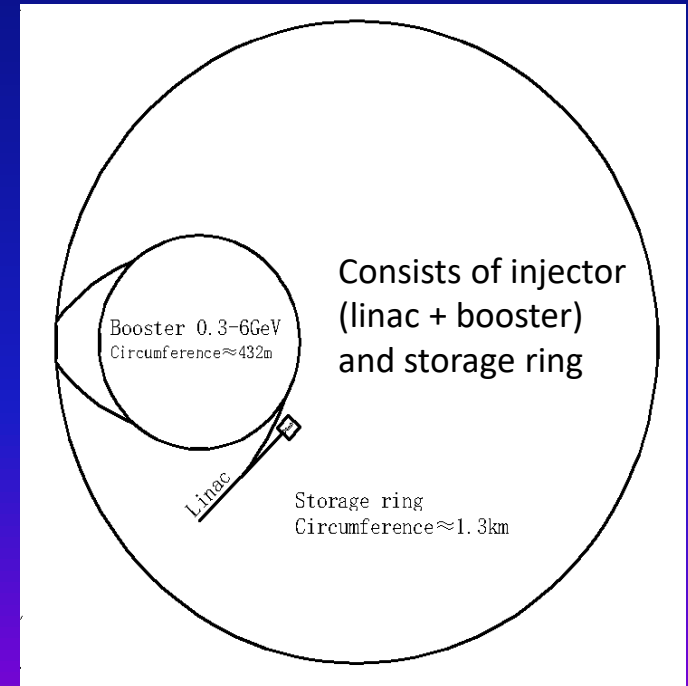- Finish conceptual design report and the feasibility study report
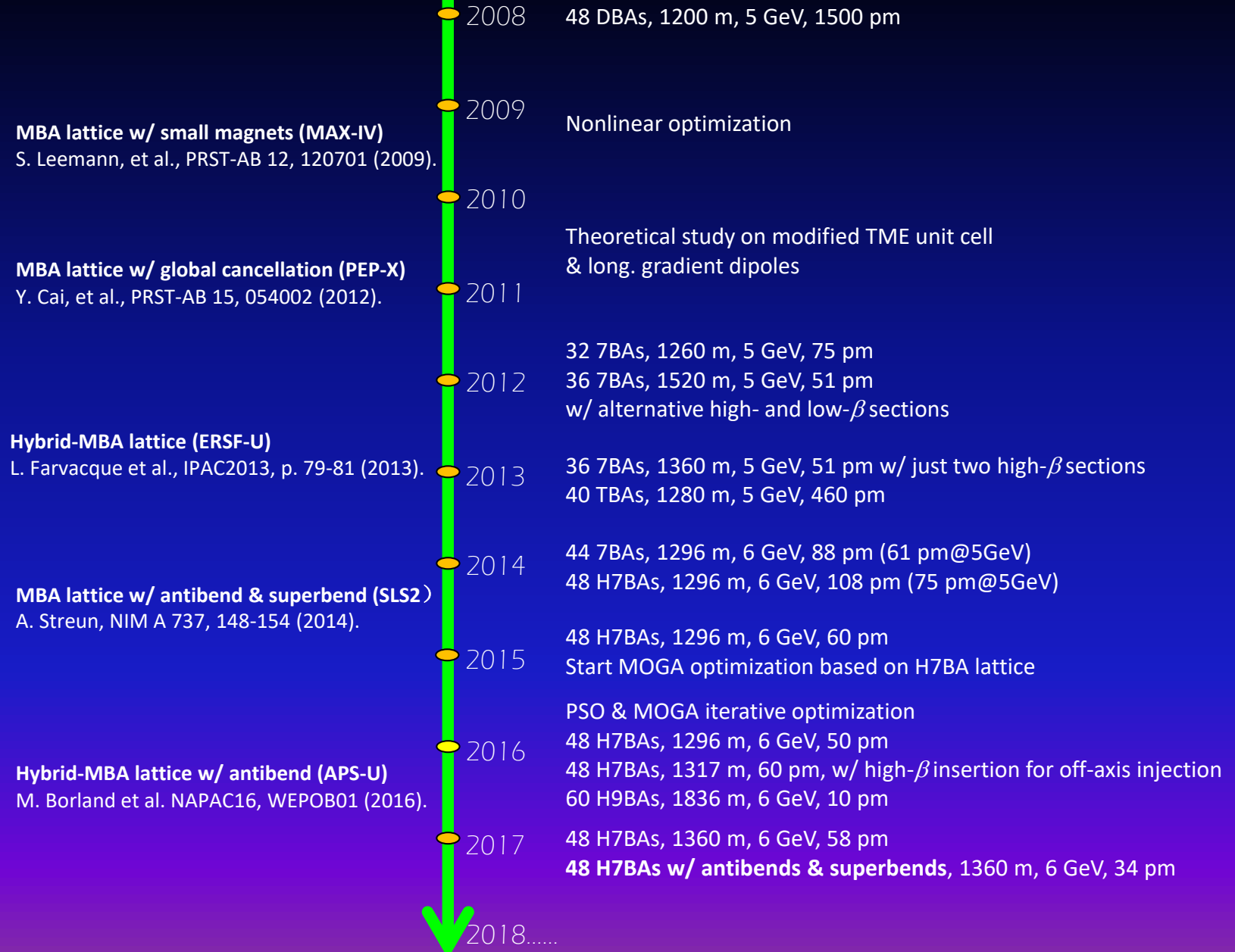
Design goals of the HEPS

Evolved along with the progress in the accelerator physics and technology

- Energy from 5 to 6 GeV (~2014)
- Emittance from ~1 nm to be smaller than 0.1 nm (100 pm) (~2015)
- Circumference changed from 1296 m to 1360.4 m (~2017)

Main parameters	Value	Unit
Beam energy	6	GeV
Circumference	~1300	m
Emittance	< 100	pm·rad
Beam current	$\geq$ 200	mA
Brightness	>10^{22}	Photons/s/mm^2/mrad^2/0.1%BW
Injection	Top-up	

Booster 0.3-6GeV
Circumference≈432m

Consists of injector (linac + booster) and storage ring

Linac

Storage ring
Circumference≈1.3km

Lattice continuously evolved over the past ten year

2008 — 48 DBAs, 1200 m, 5 GeV, 1500 pm

MBA lattice w/ small magnets (MAX-IV)
S. Leemann, et al., PRST-AB 12, 120701 (2009).

2009 — Nonlinear optimization

2010

MBA lattice w/ global cancellation (PEP-X)
Y. Cai, et al., PRST-AB 15, 054002 (2012).

Theoretical study on modified TME unit cell
& long. gradient dipoles

2011

2012 — 32 7BAs, 1260 m, 5 GeV, 75 pm
36 7BAs, 1520 m, 5 GeV, 51 pm
w/ alternative high- and low-β sections

Hybrid-MBA lattice (ERSF-U)
L. Farvacque et al., IPAC2013, p. 79-81 (2013).

2013 — 36 7BAs, 1360 m, 5 GeV, 51 pm w/ just two high-β sections
40 TBAs, 1280 m, 5 GeV, 460 pm

2014 — 44 7BAs, 1296 m, 6 GeV, 88 pm (61 pm@5GeV)
48 H7BAs, 1296 m, 6 GeV, 108 pm (75 pm@5GeV)

MBA lattice w/ antibend & superbend (SLS2）
A. Streun, NIM A 737, 148-154 (2014).

2015 — 48 H7BAs, 1296 m, 6 GeV, 60 pm
Start MOGA optimization based on H7BA lattice

2016 — PSO & MOGA iterative optimization
48 H7BAs, 1296 m, 6 GeV, 50 pm
48 H7BAs, 1317 m, 60 pm, w/ high-β insertion for off-axis injection
60 H9BAs, 1836 m, 6 GeV, 10 pm

Hybrid-MBA lattice w/ antibend (APS-U)
M. Borland et al. NAPAC16, WEPOB01 (2016).

2017 — 48 H7BAs, 1360 m, 6 GeV, 58 pm
48 H7BAs w/ antibends & superbends, 1360 m, 6 GeV, 34 pm
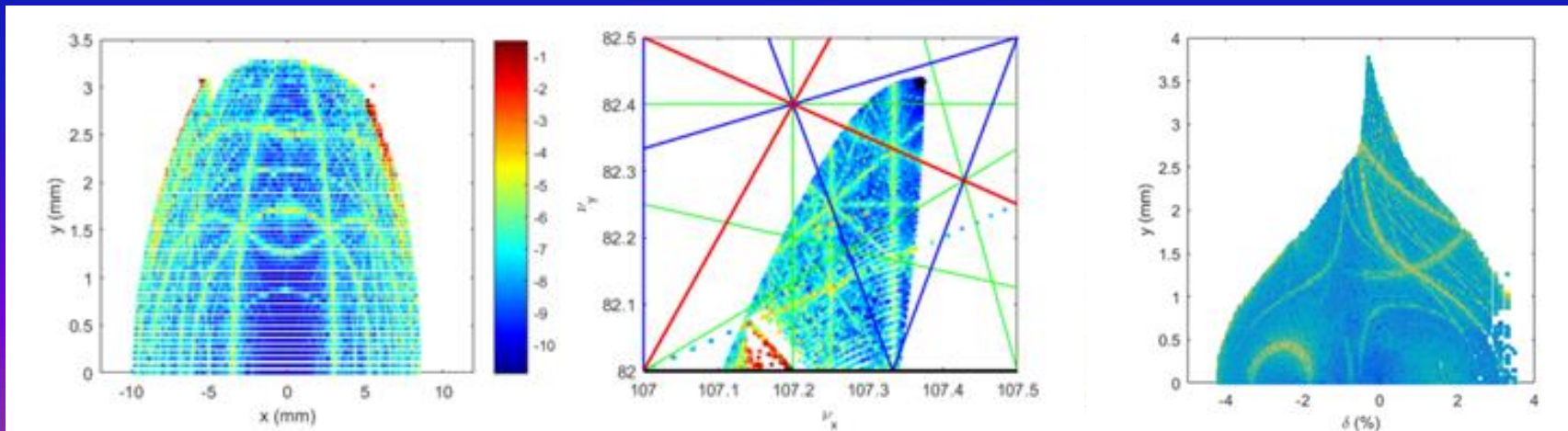
2018……

HEPS design with 48 hybrid-7BAs

Natural emittance: 58.4 pm, can reach ~ 45 pm with the same lattice structure

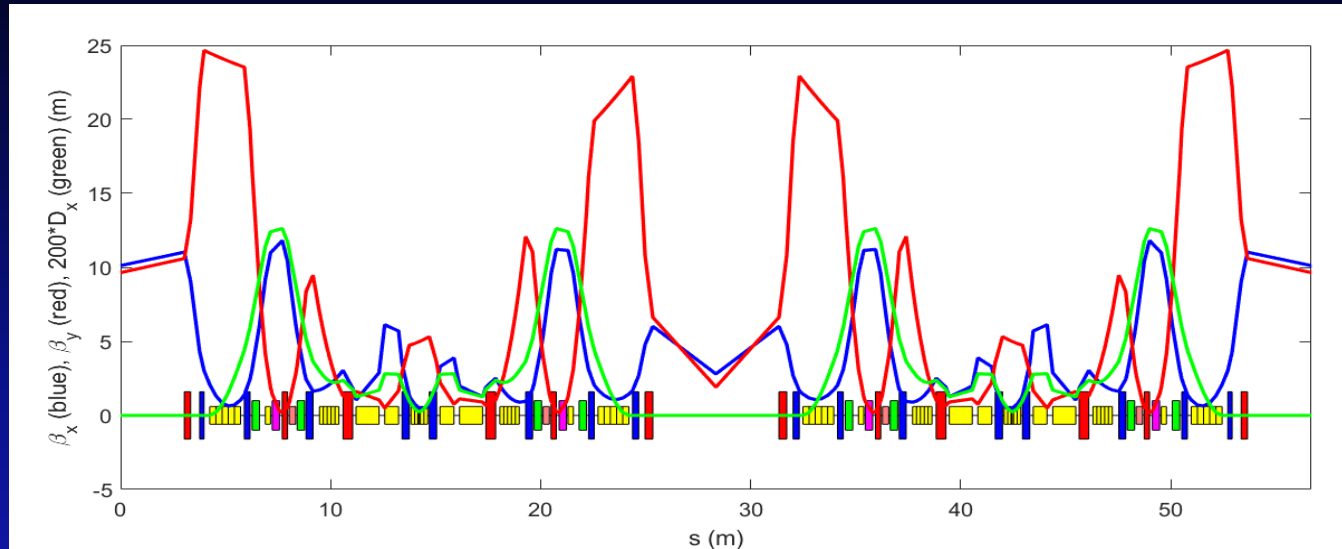Hybrid-7BA, first proposed for ESRF upgrade, then used in APS-U, ALS-II, HEPS, etc.
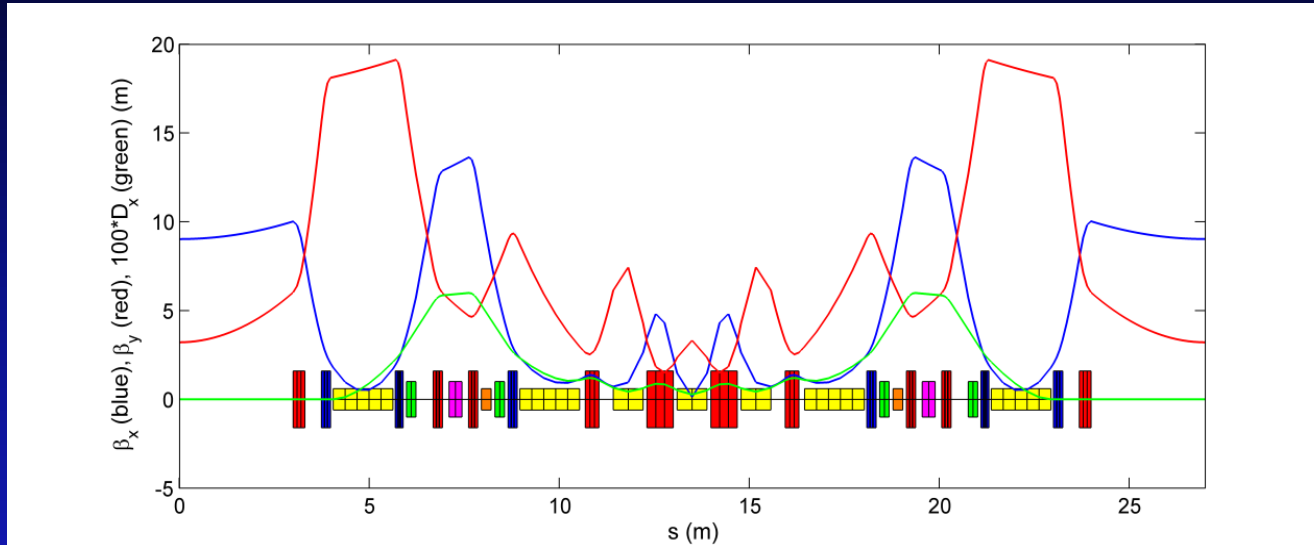
Bare lattice: effective DA: 8/3.3 mm in x/y plane (~350σ_x in x plane), effective MA size > 3.5%
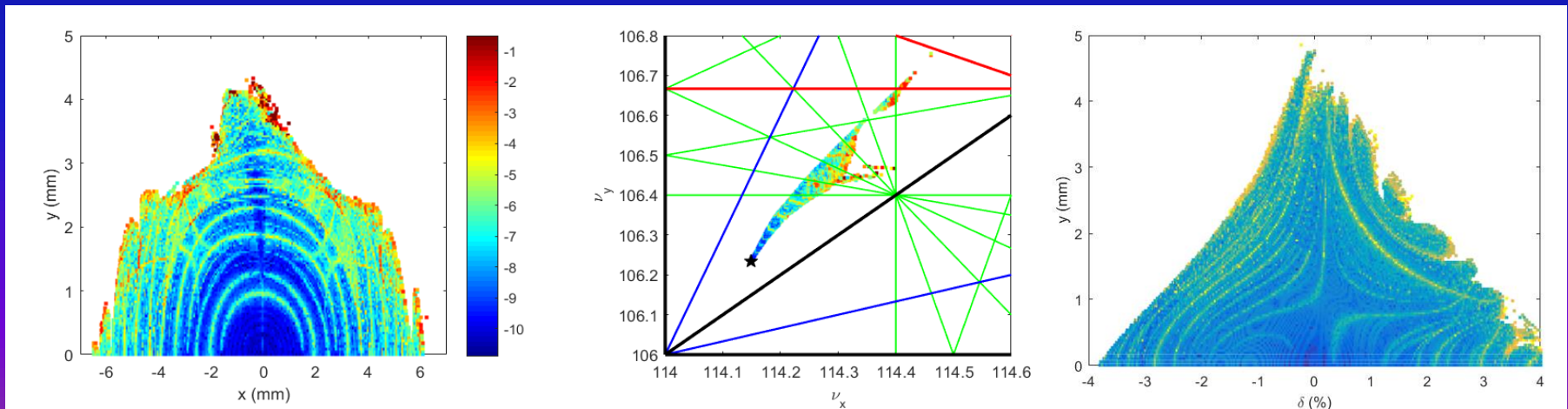
HEPS latest design with natural emittance of 34 pm

## *Still 48 hybrid-7BAs, but in 24 periods and w/ antibends & superbends*

Bare lattice: effective DA: ~6/4 mm in x/y plane at high-beta section (~320σ_x in x plane), effective MA size ~ 3%

Hybrid-7BA w/ antibend and superbend

Hybrid-7BA:
- 4 Bending magnets with longitudinal gradient (BLG)
- 3 Bending magnets with defocusing gradient (BD)
- 16 quads (8 families, some have 80 T/m gradient), 6 sextupoles & 2 octupoles)
- 3PW nearby the 4th dipole for bending magnet beam lines
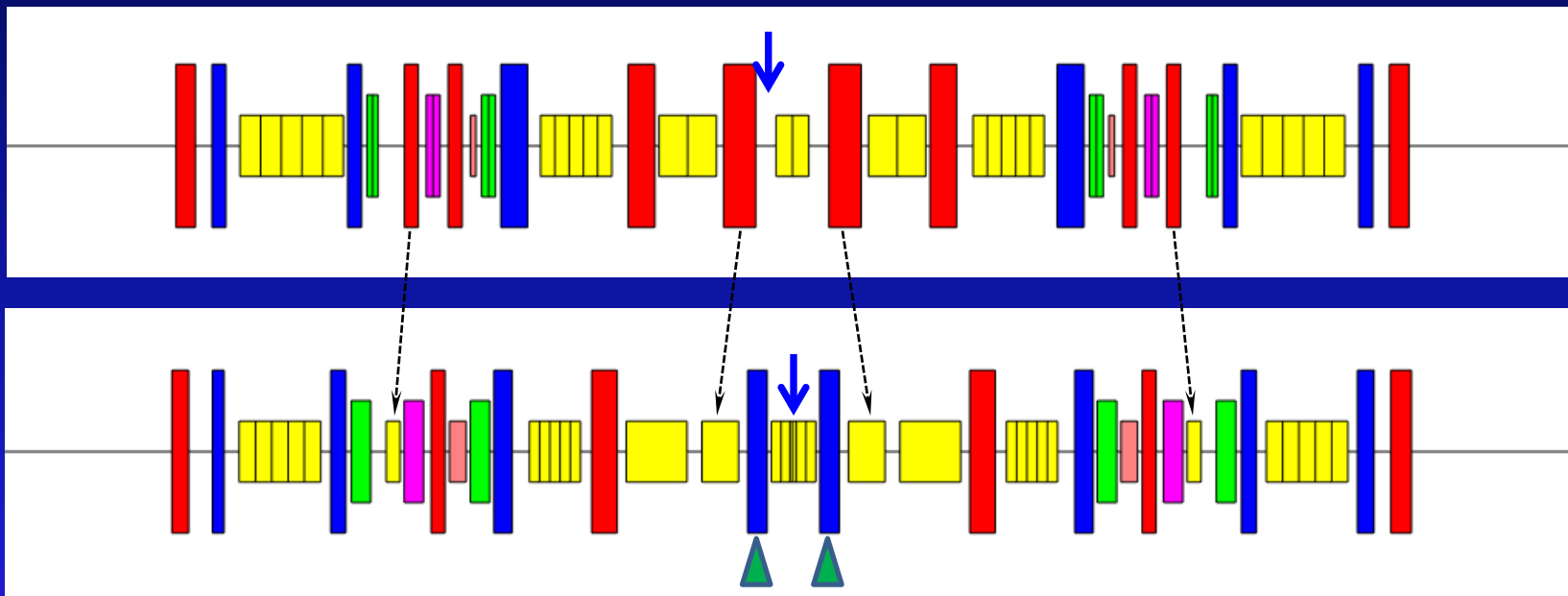
Modifications:
- Two families of *antibends* (small shift of quad center)
- *Superbend* in the central unit cell for bending magnet beam lines
- *One more family of quads* in the central unit cell

Superbend: flexible source for dipole beam lines

➤ In the central unit cell of the hybrid 7BA, use superbend with longitudinal gradient to *further reduce emittance*, by *better matching* of bending radius and *H* function [1, 2].

➤ The superbend can be used to emit *X-rays with different critical photon energy*, by changing the peak field of the central slice (e.g., 0.5-3 T).
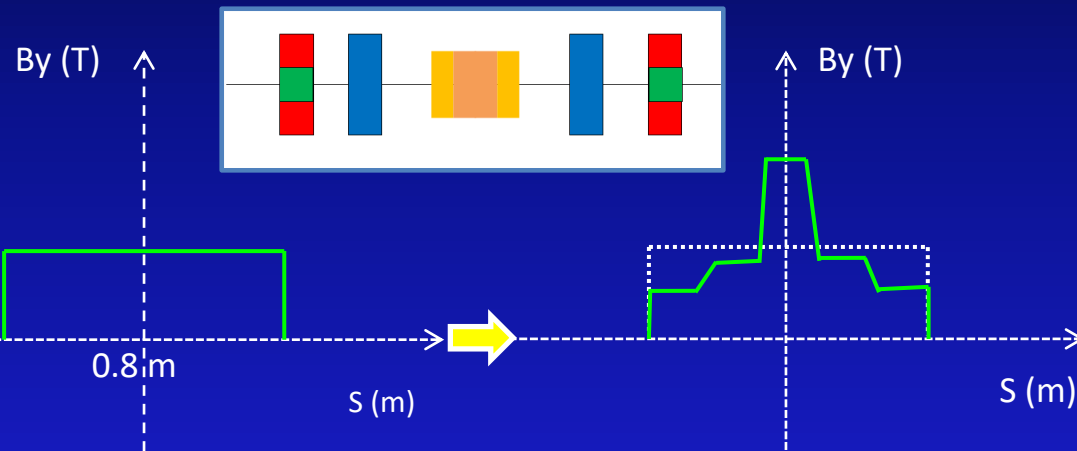
Peak field (T)	Critical photon energy (keV)	Peak power density (W/mrad²)
0.5T	12.0	702
0.85T	20.3	1194
1T	23.9	1405
1.5T	35.9	2107
2T	47.9	2810
3T	71.8	4215
3PW(1.6T)	38.3	2349

Little perturbation to ring performance, and easy to replace (if necessary)
—When changing the field profile, *the total bending angle and the dipole length are kept the same*, replacing the dipole causes little perturbation to optics & nonlinear performance.
—Since this dipole are separated with adjacent quadrupoles, replacing this superbend do not needs additional treatments on other elements of the ring.
—If the central dipoles of 48 periods are all changed (w/ 0.1m, 1 T superbend), U0 increases by 0.06 MeV, emittance decreases by ~5%.

[1] *J. Guo, T. Raubenheimer, EPAC2002, p. 1136.*
[2] *A. Streun, A. Wrulich, NIM-A 770 (2015) 98-112.*

Alternating high-low beta section design

Greatly decoupled Brightness and nonlinear optimization & appealing to users demanding higher brightness

Multi users and diverse user requirements
(1) high flux but not necessarily high coherence (high brightness)
(2) high flux, and high coherence (high brightness)
(3) large enough pulse interval (e.g., 140 ns), high flux and high coherence (for NRS experiments)
(4) low bandwidth (0.1% or close to 0.1%)
(5) covering a large photon energy by extending high harmonics
(6) polarity changeable, good performance in high harmonics, etc.

HEPS latest design (24 periods) provides two different straight sections

- One section with low beta functions in both x and y planes for highest possible brightness
- Another with high beta functions for only high flux. This essentially helps obtain large enough dynamic aperture for injection.
- While the 'high-beta' section could not be too large to induce strong instabilities. We limit the 'high-beta' not larger than 10 m, especially in in y plane.

Feasible to get higher brightness meanwhile large enough DA w/ iterative PSO and MOGA optimization [1]

- Brightness increase further by at least 30% (at the 'low-beta' section)
- When reducing emittance, dynamic aperture remains the same level (at the 'high-beta' section)
- Do not need to scarify DA to reach a higher brightness as in the case with all identical cells.
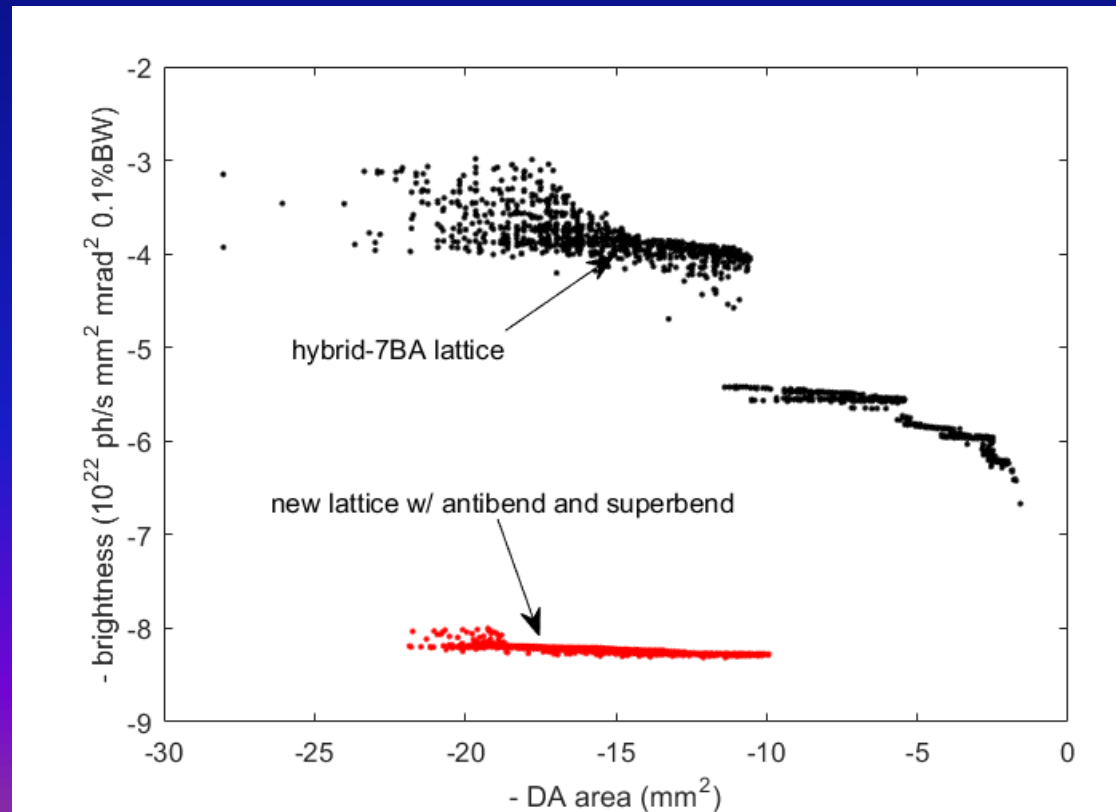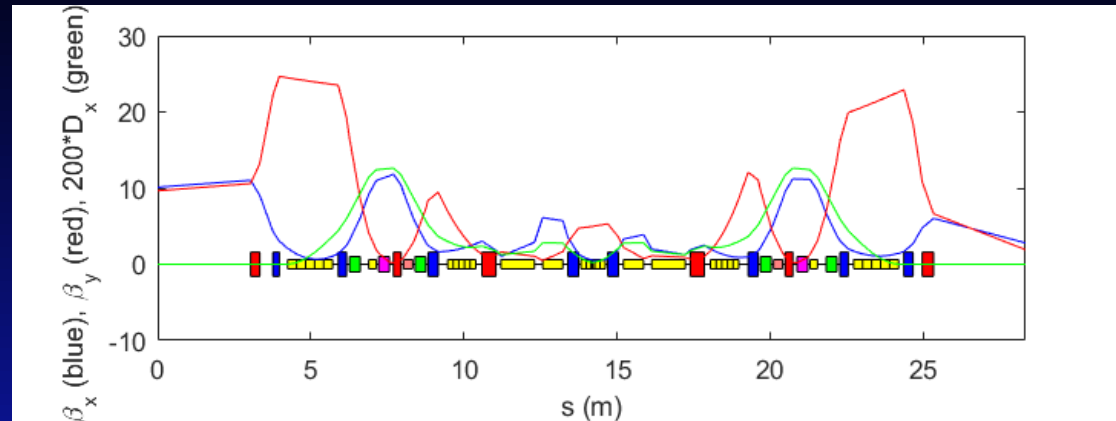
[1] Y. Jiao, G. Xu, *Chin. Phys. C*, **41**(2): 027001 (2017).

Lattice calibration simulation

It appears feasible to recover linear optics and emittance of ideal lattice in presence of errors

- ➢ Correction setup in each 7BA
  - 12 BPMs, their positions are reserved in lattice design
  - 10 orbit correctors (6 magnet coils and 4 fast correctors)
  - 3 skew quad correction coils

- ➢ Modeling practical errors in bare lattice
  - Magnet misalignments, girder errors
  - Magnetic nominal field errors and multipole components
  - BPM resolution (0.5 μm), offset (30 μm), gain, tilts

- ➢ Lattice calibration simulation
  - Present simulation assumes the average beam energy is exactly on 6 GeV, and do not consider insertion devices yet
  - Orbit corrected w/ ORM and SVD, after correction, orbit < 50μm (RMS) and 60 (RMS) in x and y planes
  - Optics corrected w/ *LOCO and sextupole alignment*, after correction, $\Delta\beta/\beta$ < 1% (RMS); dispersion < 1.5 mm (RMS) and 0.5 mm (RMS) in x and y planes; emittance almost recovered, below 35 pm and 4 pm in x and y planes

Nonzero offset in sextupole is the dominating error source of optics deviations in HEPS

|	Dipole	Quad	Sext.	Oct.	Girder
Trans. shift X/Y (μm)	200	30	30	30	50
Long. shift Z (μm)	150	150	150	150	200
Tilt about X/Y (mrad)	0.2	0.2	0.2	0.2	0.1
Tilt about Z (mrad)	0.1	0.2	0.2	0.2	0.1
Nominal field	3e-4	2e-4	3e-4	5e-4	\
Multipole field	5e-4	5e-4	1e-3	1e-3	\
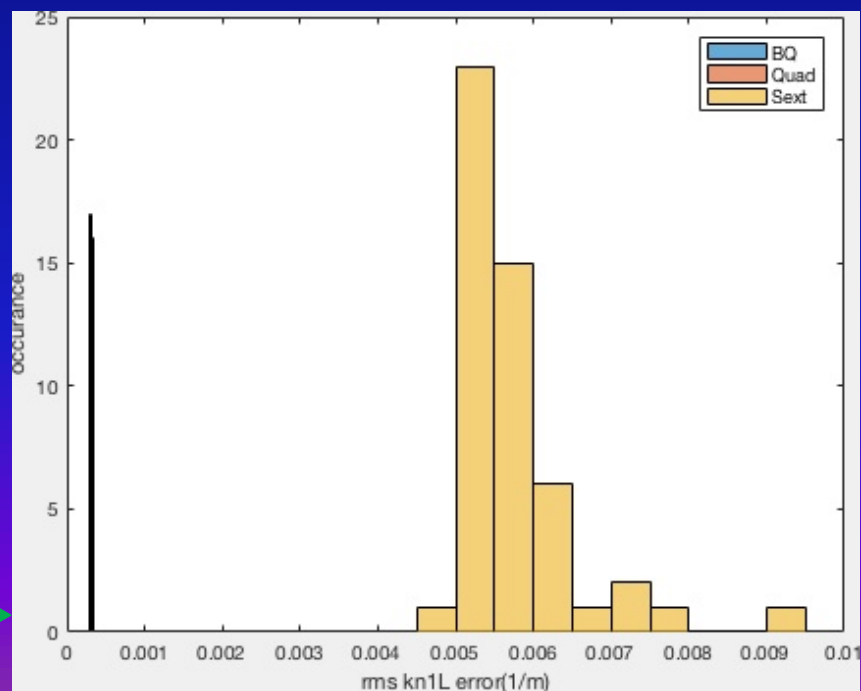
Nonlinear performance recovered as well

➢ The resolution of the beam-based magnet alignment can be greatly improved with the aid of *magnet movers* [1-2].

[1] *P. Tenenbaum et al., SLAC-PUB-7058, 1995.*
[2] *G. Bowden et al., NIM-A 368 (1996) 579-592*

➢ In HEPS girder design, *sexupoles can be moved in both x and y planes on-line.* By including beam-based sextupole alignment in optics correction, *better DA recovery* is achieved.
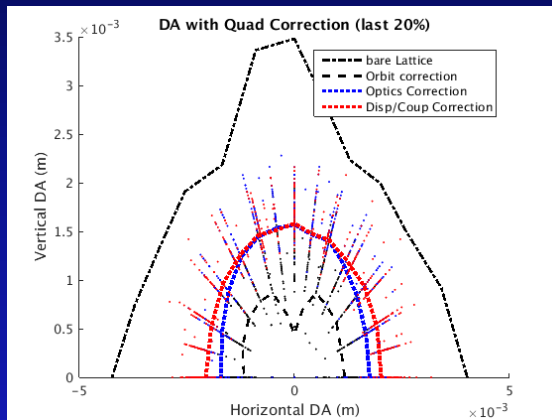
Optics correction w/ sextupole alignment, the DA can be restored to ~80% of that of the bare lattice (further disp/coup correction causes DA reduction but not necessary).

The LMA is largely recovered as well after correction.
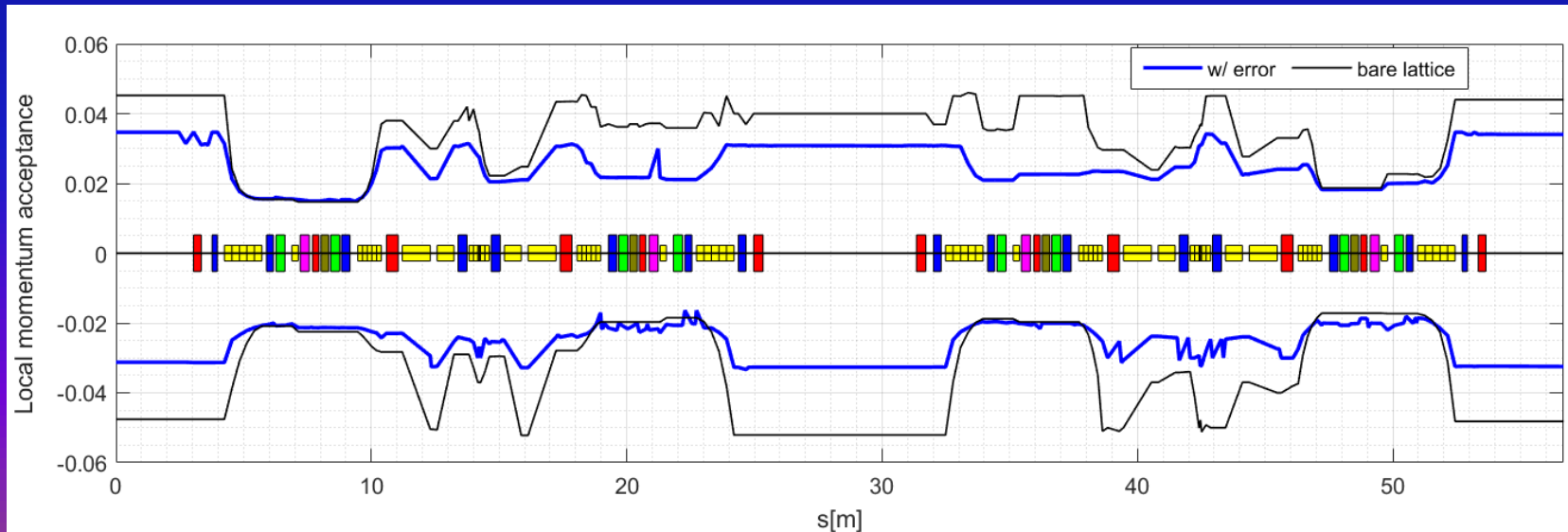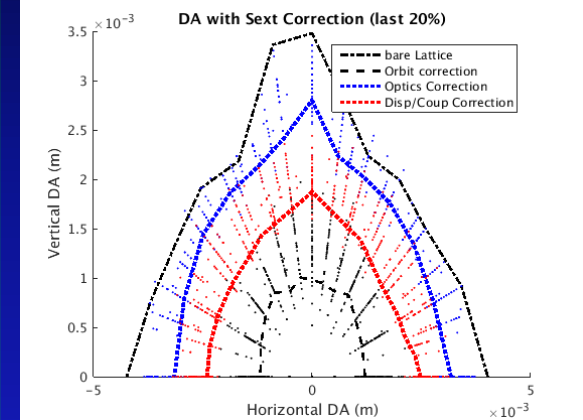
First-turn commissioning

- ➢ Challenging to first store the beam in ring
  - Turn off all sextupoles and octupoles
  - Including all possible practical errors and especially high BPM errors
  - It is very difficult to store the beam w/o any correction.

- ➢ Develop first-turn commissioning code
  - Based on the ORM of the bare lattice and the SVD method
  - First, steering the beam section by section with SVD method to get the first one turn orbit with the goals: making the transferring length be longest, the orbit be smallest and the corrector strength as small as possible (in reduced priority)
  - Secondly, steering the beam with all of the correctors and BPMs like the last step to make the beam transfer for multi-turns

The beam could be *100% accumulated* under typical error when corrector strength limit is *equal or greater than 0.2 mrad*.

Simulated BPM signal (~1000 turns) of the stored beam after correction
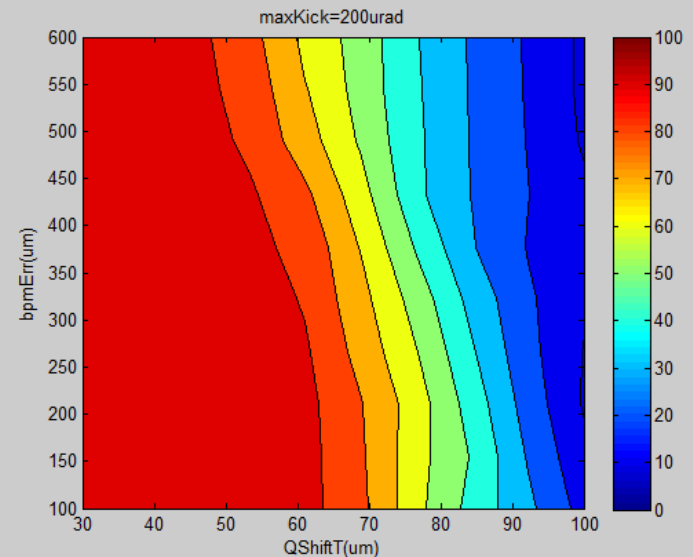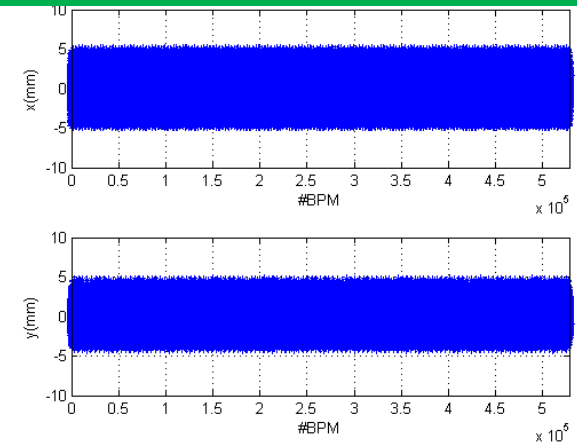
166 MHz + 500 MHz RF system in HEPS

➢ We have experience of operating 500 MHz RF cavities in IHEP existing machine.

➢ Considering the injection of *ring*, we choose *166 MHz and 500 MHz superconducting cavities* (the latter used as harmonic cavities) for bunch lengthening and compensating beam energy loss. For *booster*, we choose *500 MHz normal conducting 5-cell PETRA cavities.*

➢ Presently, we consider mainly *two filling patters*, **high-brightness mode** (680 bunches, 200 mA) and **timing mode** (63 bunches, 200 mA).

Bunch length and energy spread w and w/o harmonic cavity are calculated

- Bunch lengths are ~5/30 mm at 'zero' current
- ID radiation is included
- Bunch lengthening due to potential well distortion in presence of impedance is considered

Top-up injection is essentially required & planned for HEPS.

- For high-brightness mode, *Touschek lifetime* ~1.6/5 hrs when w/o and w/ H.C.
- For timing mode, *Touschek lifetime* ~0.3/0.7 hrs when w/o and w/ H.C.
- Assuming 10% coupling.

Parameters	Cases	
H.C. Condition	No H.C.	w/ H.C.
U0 [MeV]	7.352	
MCF α_c	$1.56*10^{-5}$	
Bucket Height	4.0%	
Peak Voltage of the Primary RF [MV]	8.009	8.839
Synchronous Phase of the Primary RF [rad]	1.978	1.931
Peak Voltage of the Harmonic Cavities [MV]	---	1.387
Synchronous Phase of the Harmonic Cavities [rad]	---	5.559
Bunch length for high-brightness/timing mode (mm)	9/19	32/47
Energy spread for high-brightness/timing mode (10^{-3})	1.06/3.1	1.1/1.9

On-axis injection in HEPS

We have considered several candidate injection schemes, and now we consider mainly the *on-axis swap-out injection*, while keeping on feasibility study of *longitudinal accumulation injection*.

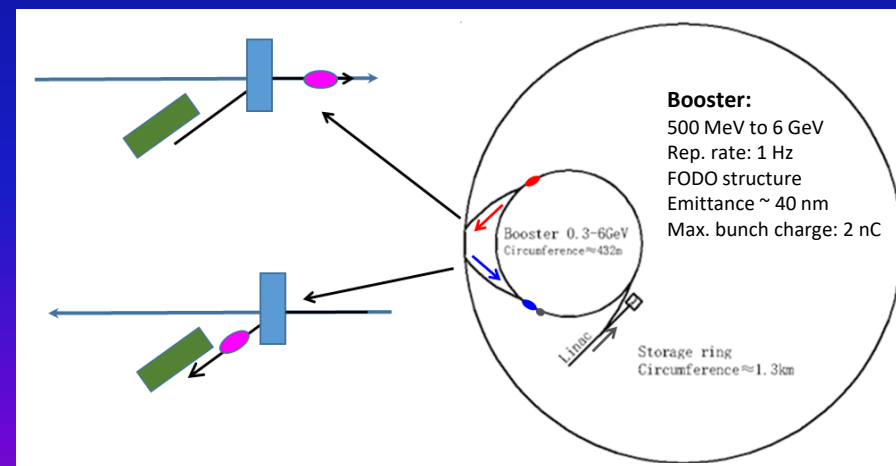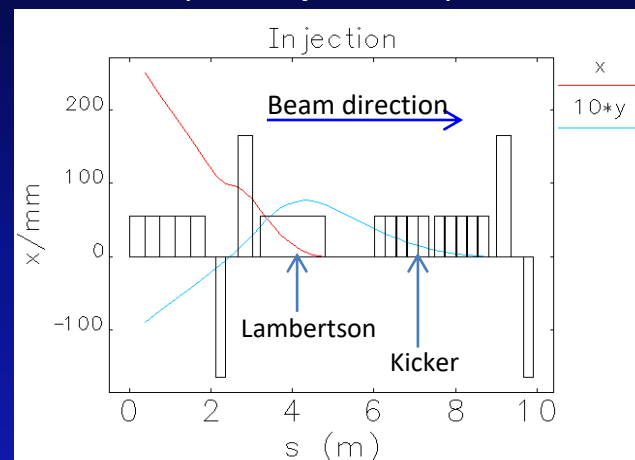Injection section layout similar to APS-U design [1]. It requires a fast kicker with pulse width of less than ~12 ns.

The injector (a linac + a booster for HEPS) needs to provide single bunch with a high charge
- 1.3 nC for high-brightness mode
- 14.4 nC for timing mode

After comparison of several candidate solutions, we now focus on *'High-Energy Accumulation'* scheme.
- *The booster at 6 GeV used as a full energy accumulator ring and build an extra transfer line from storage ring to booster*
- *Avoid acceleration of a 14-nC bunch in booster, and it just needs to store a single bunch of ~ 2 nC at lower energy of the booster*
- *Studies focus on improvement of the transfer efficiency between booster and ring.*

Swap-out injection layout

Booster:
500 MeV to 6 GeV
Rep. rate: 1 Hz
FODO structure
Emittance ~ 40 nm
Max. bunch charge: 2 nC

Booster 0.3-6GeV
Circumference≈432m

Storage ring
Circumference≈1.3km

Linac

[1] *e.g.,* M. Borland, *et al., J. Syn. Rad.* (2014) **21** 912-936

HEPS injector design

Design the injector according to the requirements of 'High-Energy Accumulation'

- To mitigate bunch charge limitation at lower energy of booster, we choose *relaxed booster lattice* with large momentum compaction, consisting of FODO cells and separate function dipoles, and *higher Linac energy* (from 300 to 500 MeV).

- At high energy (6 GeV), *lifetime* in booster is ~ 4 hrs, *long enough for beam re-injection, accumulation and extraction*.

	linac	LTB	booster	BTS(STB)
Length(m)	43	25	453	102
energy （GeV)	0.5	0.5	0.5-6.0	6.0

Emittance: 40 nm, α_p: 4.2×10^{-3} , circum.: 453.5 m
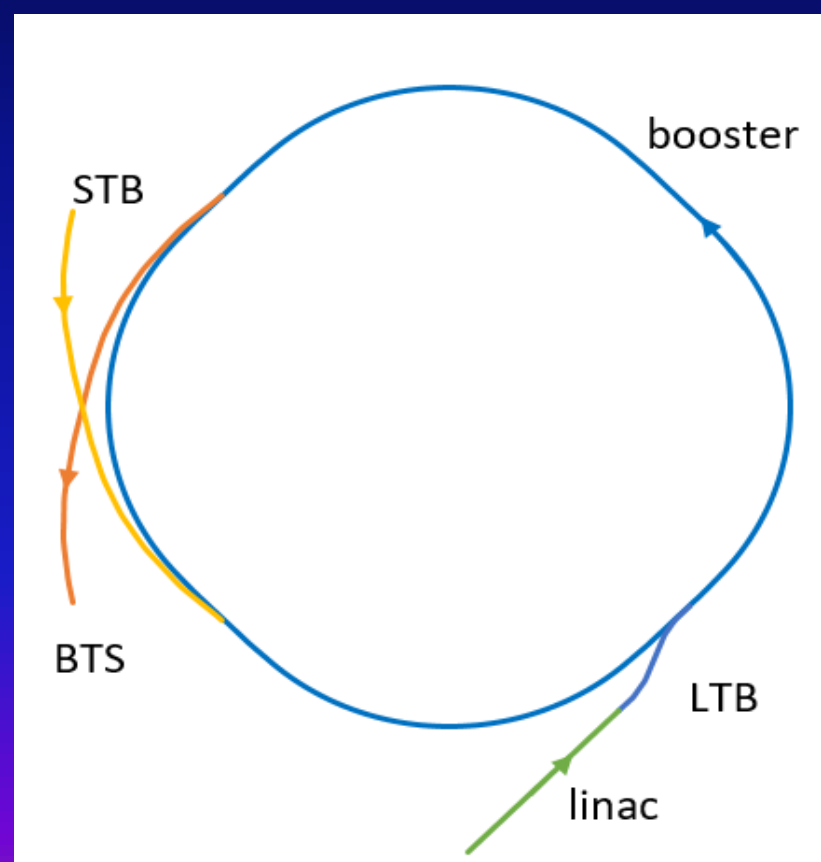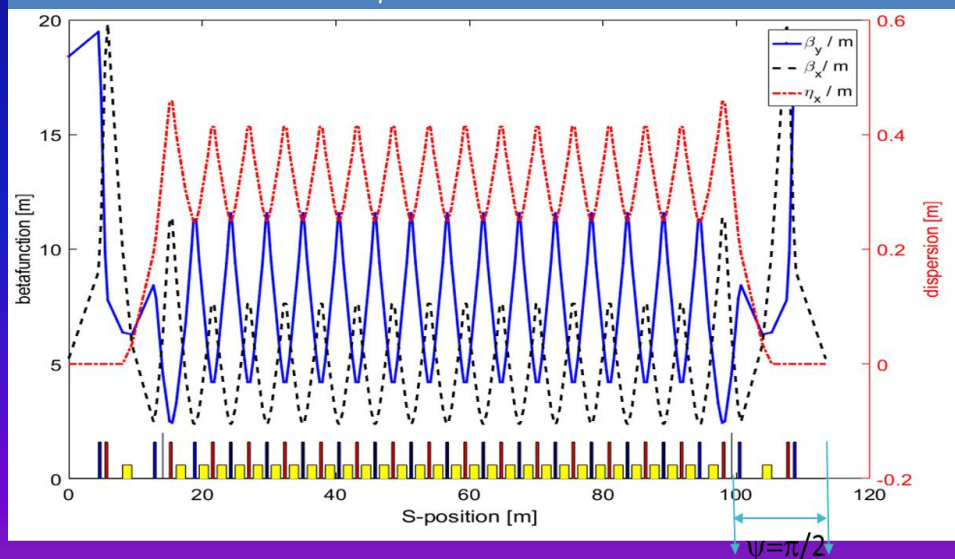
Insertion devices (IDs)

➢ In HEPS, there will be 41 ID sections
- 2 straight sections for injection and extraction
- 5 sections for RF system

➢ In the first construction stage, 14 ID beam lines will be built
- *ID parameters optimized for 10^{22} brightness*
- CPMUs and IVUs with gap of 5 mm
- IAUs with gap of 11 mm
- One IAW with gap of 12.7 mm

Dashed curves: 58 pm lattice
Solid curves: 34pm lattice
10% coupling factor assumed

➢ Effects of IDs to ring performance
• An increase of ~ 1.5 MeV in the synchrotron radiation energy loss per turn.
• A vertical tune shift of ~ 0.027.
• Small decrease in DA.

When total 41 ID sections considered, there will be *an obvious DA reduction (to ~ 1.5 mm in y)*. Correction studies are underway.
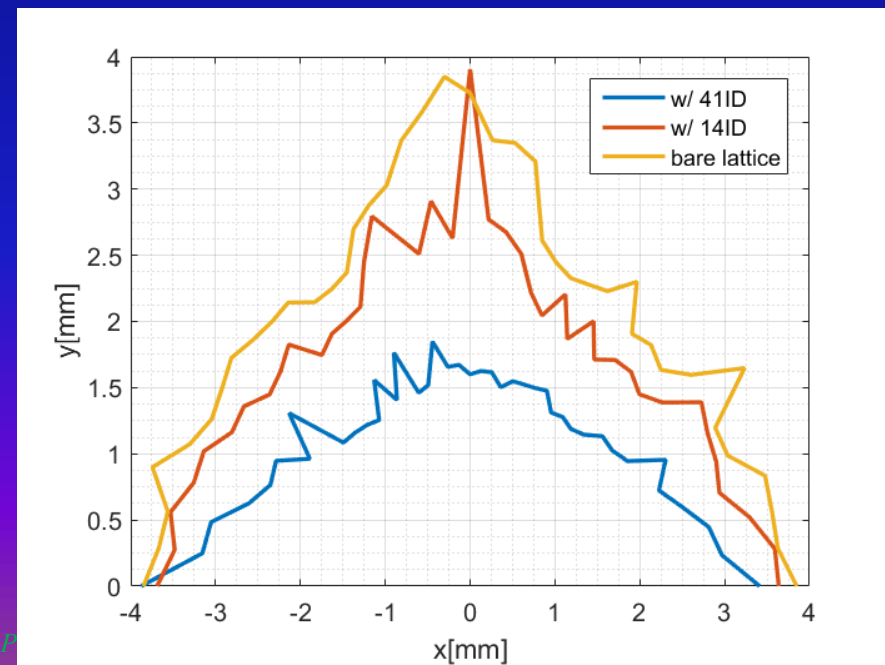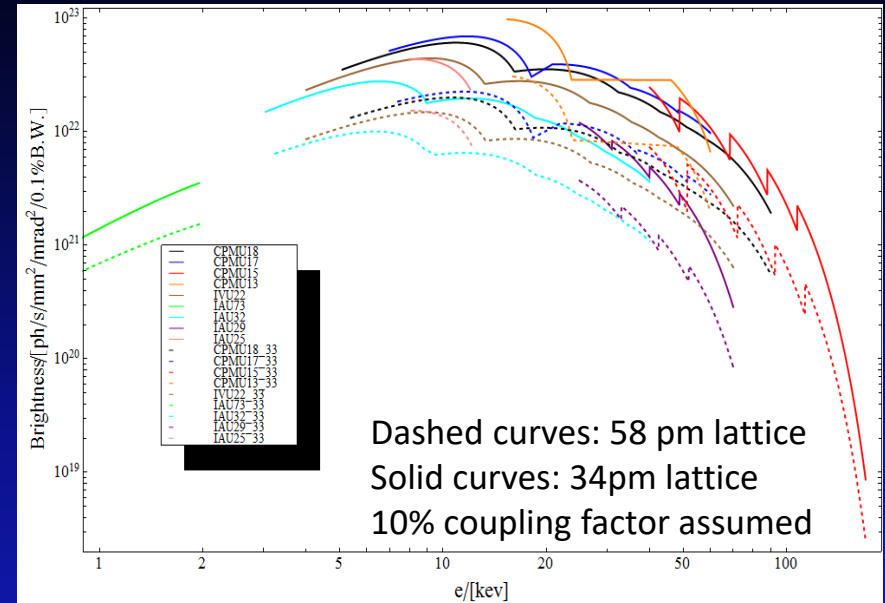
Impedance model built for instability studies

Various impedance contributors were included and some (BPM, AB, crotch chambers) to be updated

Longitudinal impedance dominated by **large number elements**, e.g., flanges.
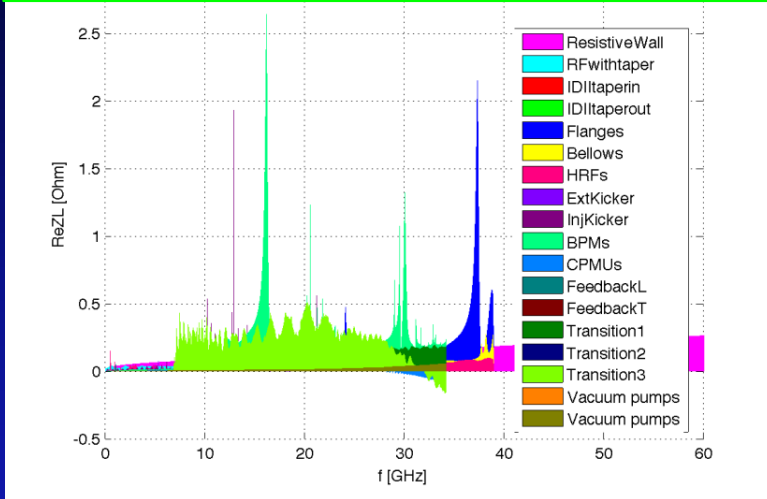
Transverse impedance is dominated by the **resistive wall impedance** due to the small aperture beam pipe
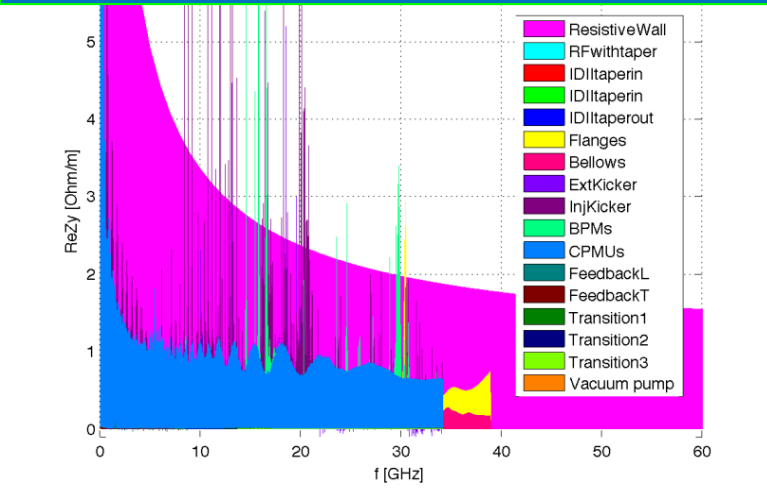

The **longitudinal loss factor** is mainly contributed by the **resistive wall, RF cavities, BPMs and the transitions.**

| Objects	$Z_{||}/n$ [mΩ]	k_l [V/pC]	k_y [kV/pC/m]
Resistive wall	28.8	22.4	19.0
RF cavities	2.3	10.7	0.1
Bellows	13.8	4.9	1.6
Flanges	26.3	2.2	2.2
ID tapers	9.1	0.6	1.6
Ext. kickers	0.1	2.9	1.2
Inj. kickers	0.3	12.5	4.2
BPMs	27.4	31.3	3.5
Harmonic RF	1.1	5.9	0.06
LF kicker	0.9	2.0	0.04
TF kicker	0.2	0.3	0.03
In-vacuum IDs	3.4	3.6	5.0
Pumping ports	10.6	2.6	1.2
Transitions	26.0	55.9	5.7
Total	150.4	157.6	45.3

Single bunch instabilities

➤ Microwave instability
- Threshold ~ 3.5 nC w. H.C., higher than the bunch charge of the high brightness mode.
- For the timing mode (14.4 nC), the bunch will be lengthened by a factor of 1.6, and the beam energy spread is increased by a factor of 1.9.
- Above threshold, beam will not get lost. But turbulent distributions are observed.
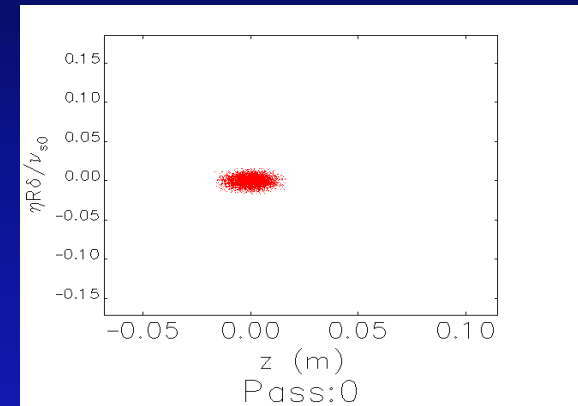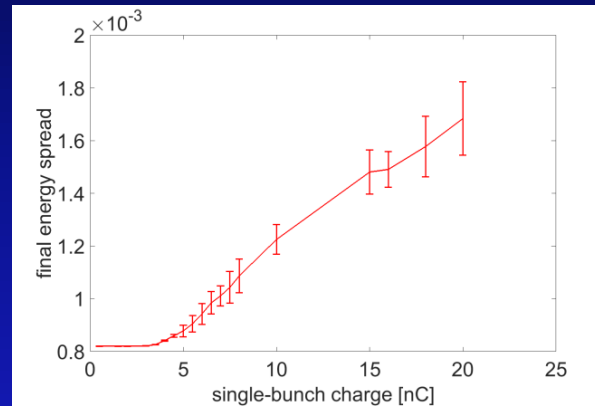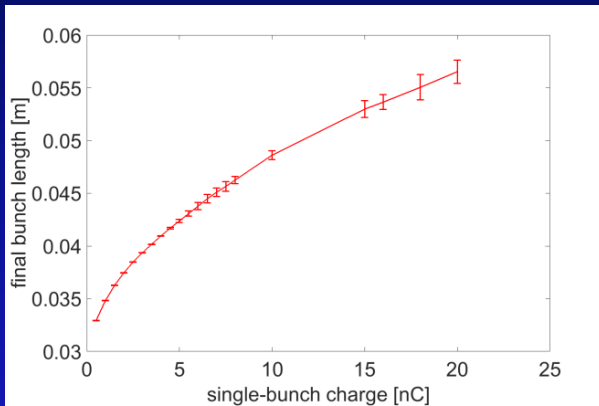
➤ Transverse mode coupling instability
- Threshold ~0.5nC with ξ = 0.
- Increased to ~9 nC with ξ = 1.
- Eigen-mode analysis & macro-particle tracking. Two approaches predict the same tendency.
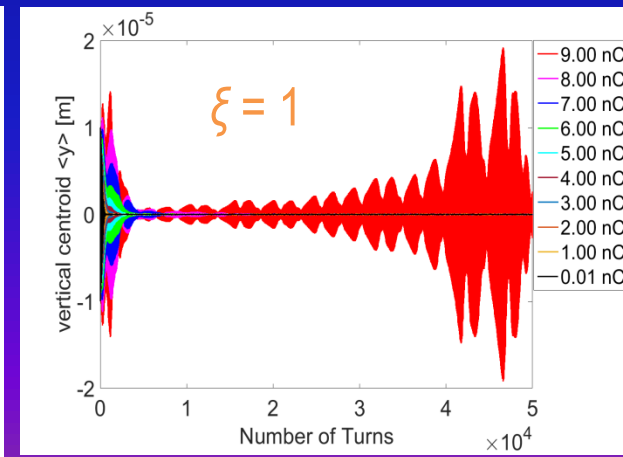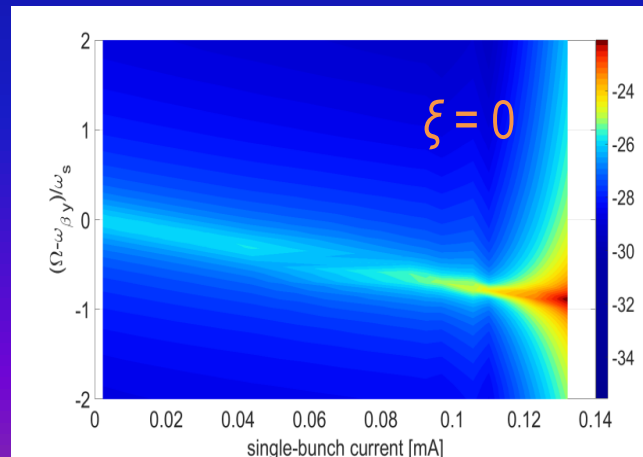
Coupled bunch instabilities

➢ **Fast ion instability** (see Dr. Tian, S.K. 's talk for detail)

• Growth time is ~ 4 ms, and can be damped with feedback system.

➢ **Resistive wall instability**

• The most dangerous mode gives instability growth time of 0.7ms.

• A positive chromaticity (e.g., $\xi = 1$) or feedback system can damp the instability.
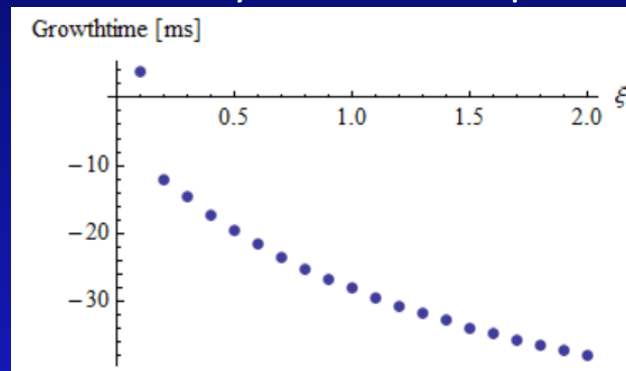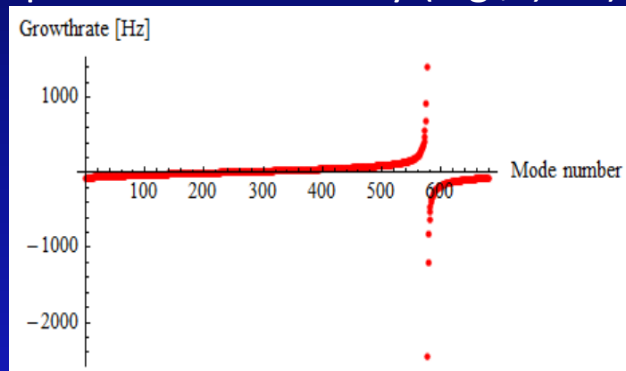
➢ **RF HOM induced instability**

• In the storage ring, HOM damper has been carefully designed and optimized to damp the HOMs of the superconducting cavities. With the damped HOMs, we did not observe HOM induced coupled-bunch instabilities at 200 mA for macro-particle simulations.

• While for the booster, there are many HOMs in the 500 MHz multi-cell normal conducting cavities. We are carrying out numerical and experimental studies to check whether the HOMs would cause problems in the booster.

In Closing...

- *After about 10 years' evolution, a diffraction-limited storage ring design was basically reached for the HEPS.*

- *Hopefully the project will be started in 2018.*

- *There are still many aspects and issues need to be look inside. Physical studies and optimization never ends.*

Thanks for your attention!

Backup slides

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DA is ~6/4 mm for the bare lattice,
LMA calculated (bare lattice), estimated lifetime is about 8.3 hrs for the high-brightness mode (680 bunches, 200 mA), and 0.8 hrs for the timing mode (63 bunches, 200 mA)
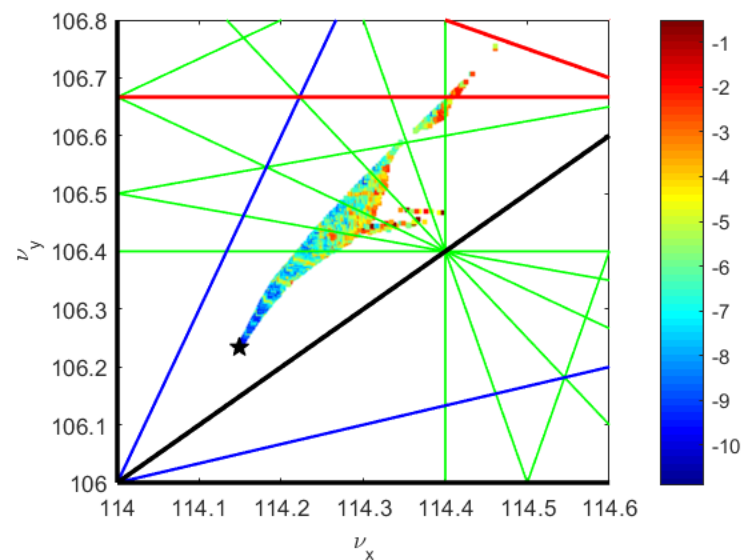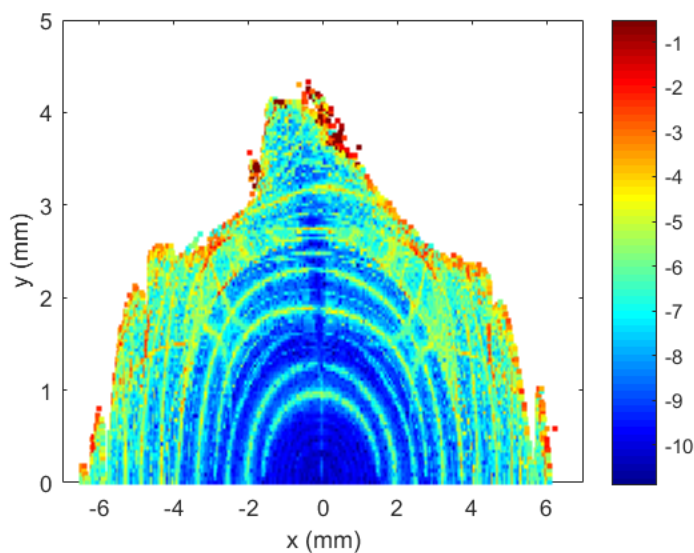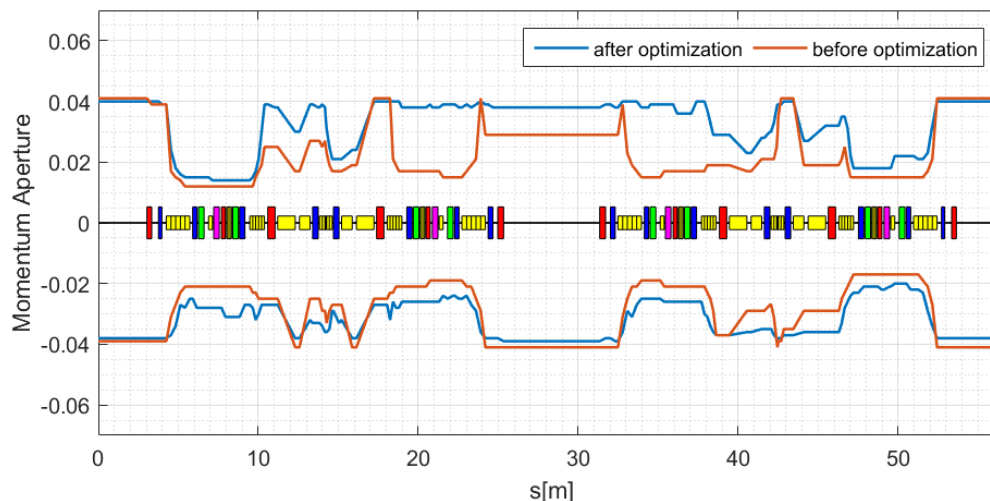
First-turn commissioning

- **First-turn commissioning simulation was developed**
  - ✓ To see whether the beam could be commissioned and saved under the real machine error level when the machine is prepared for the first time.
  - ✓ To make the first-turn beam commissioning be efficiency.

- **Main methods and correction steps**
  - ✓ Get the 'response matrix' with the ideal lattice
  - ✓ Generate various errors especially quadrupole misalignment error and BPM errors (BPM noise and shift errors are included).
  - ✓ Turn off all of the sextupoles and octupoles
  - ✓ Steering the beam section by section with SVD method to get the first one turn orbit with the goals: making the transferring length be longest, the orbit be smallest and the corrector strength as small as possible (in reduced priority)
  - ✓ Steering the beam with all of the correctors and BPMs like the last step to make the beam transfer for multi-turns

- **Simulations show that**
  - ✓ It is not likely to accumulate the beam without commissioning.
  - ✓ Chance of making the beam circulate for multi turns is impossible if the sextupoles are on.
  - ✓ With the current correction scheme, the beam could be accumulated under the typical error setting, even if the corrector strength limit less than 0.4mrad
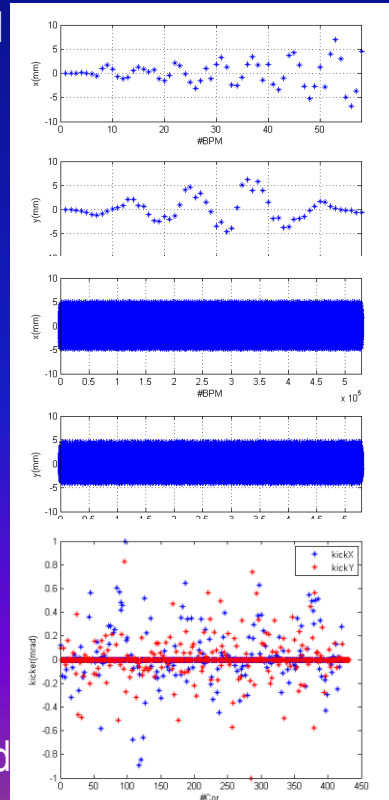
Quadrupoles error :	
· $\Delta X/\Delta Y/\Delta Z$	(30/30/150) um
· Roll(z)	(0.2) mrad
· dK/K	(2e-4)
· Multipole error	20 ranks, with random and system parts

Dipole error :	
· $\Delta X/\Delta Y/\Delta Z$	(200/200/150) um
· Roll (z)	(0.1) mrad
· dB/B	(3e-4)
· Multipole error	20 ranks, with random and system parts

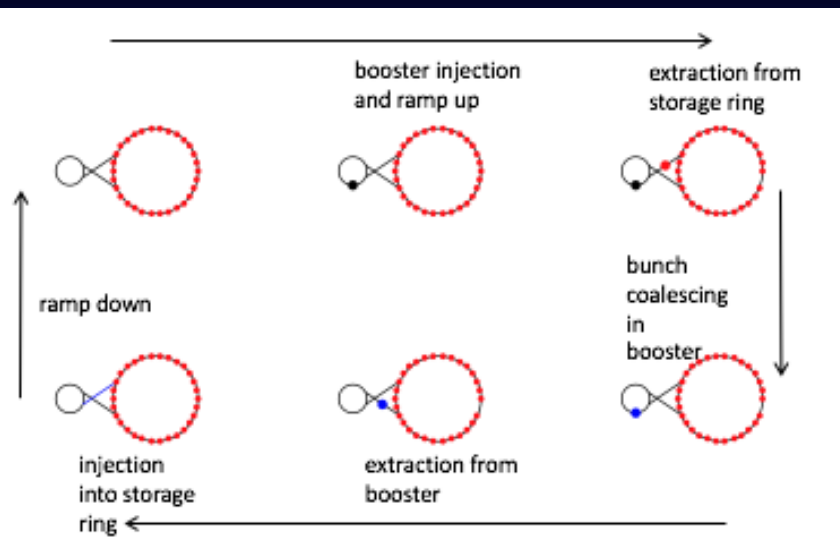| BPM error :	
· Shift (X,Y)	(100~600) um
· Noise (X,Y)	(100~600) um

BPM signal before correction; 1000 Turns simulation after correction; and corrector setting
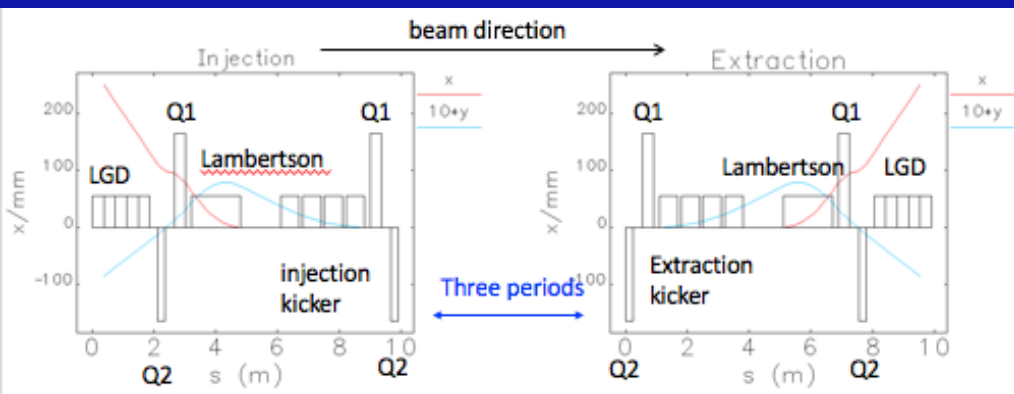
Swap-out injection

Booster is used also as a 6 GeV accumulator ring

Merits:

- relax the challenges in linac generation and booster acceleration of ~ 15 nC bunch charge in the timing mode.

Challenges:

- high transport efficiency is essential between the booster and the ring.

Regarding the small acceptance, we choose swap-out injection

| fill pattern	high brightness mode	timing mode
bunch number	680	63
single bunch charge (nC)	1.33 nC	14.4 nC
Touschek lifetime for bare lattice, 10% coupling (hour)	~ 8	~ 1
fractional droop	10%	10%
injection interval (second)	4	6

Alternative injection schemes for HEPS

Two on-axis longitudinal off-phase injection schemes have been proposed for HEPS.

✓ RF gymnastics with an active double RF system: 166MHz + 500MHz
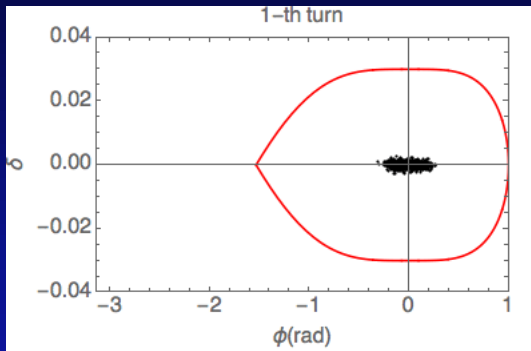
✓ Injection into the fat RF acceptance of a triple RF system: 166MHz +333MHz+500MHz
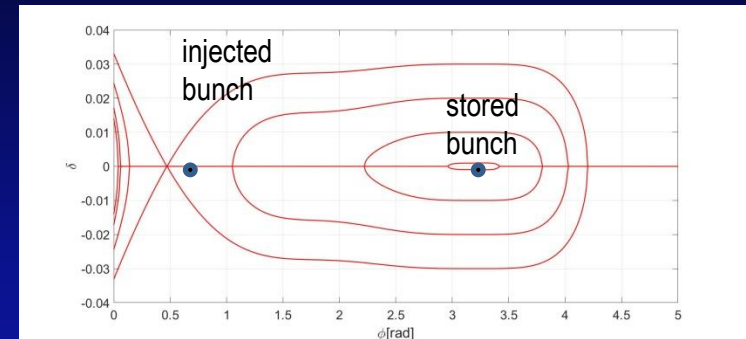
Comparison between these injection schemes

	swap-out	double RF gymnastic	triple RF static
injection kicker time structure	rise/fall < 6 ns flattop < 12 ns	rise < 2.1 ns full < 6 ns	fall < 2.5 ns full < 6 ns
extra hardware	Ring to booster transport line	LLRF design for fast RF ramping	333 MHz RF system
DA requirement	1~2 mm	1~2 mm	1~2 mm @ δ=3%
major physics challenge	transfer efficiency	tight tolerance and RF stability during RF ramping, sensitive to ID gap change	Robinson instability for triple RF system, sensitive to ID gap change

HEPS Injector design

At first, 3 plans were designed

plan1. All combined lattice like NSLS-II booster

Plan2. TME lattice with combined-function dipole

Plan3. Same tunnel FODO lattice

Booster ramping would affect the stored beam in SR and there would be conflict between ring construction and booster commissioning if booster sited in the same tunnel with SR.

The natural emittance of plan1 is lager than plan2.

Plan2 has more adjustable flexibility than plan1

Sep. 2016, Plan 2 was choose as our baseline .

Simulation of TMCI threshold need ap is lager than 3e-3

Aug. 2017 we designed use FODO lattice with separated-function magnet.

- ☐ Separate tunnel from the storage ring
- ☐ Four-fold symmetric FODO lattice
- ☐ 14 standard FODO cells and 2 match cells
- ☐ A specially designed π section is used for high energy injection using 2 kickers

Parameters	Units	Injection(0.5Gev)	Extraction（6Gev）
Energy	GeV	0.5	6
Current	mA	4	15
Emittance	nm·rad	41	42
Energy Spread		0.005	9.6×10^{-4}
RF voltage	MV	1.2	≥8
Bucket Height		2.3%	1.0 %
Tune （x/y）		16.83/10.73	
Momentum Compact Factor		4.2×10^{-3}	
Repetition Rate	Hz	1	
Circumference	m	453.47	
RF Frequency	MHz	499.8	

HEPS Injector design

|	linac	LTB	booster	BTS(STB)
Length(m)	43	25	453	102
energy（GeV）	0.5	0.5	0.5-6.0	6.0
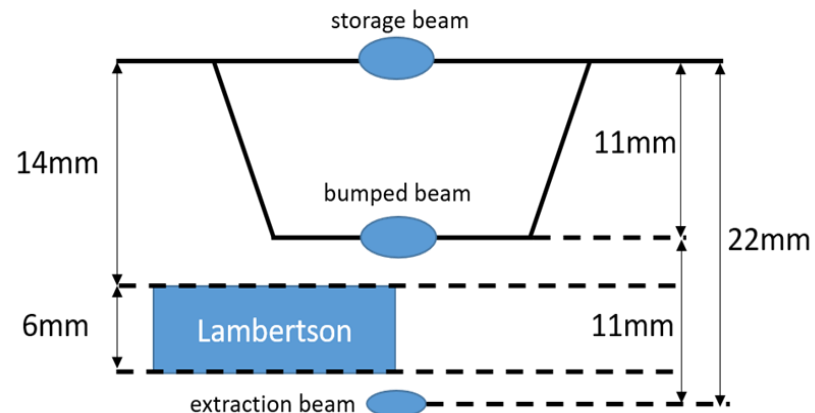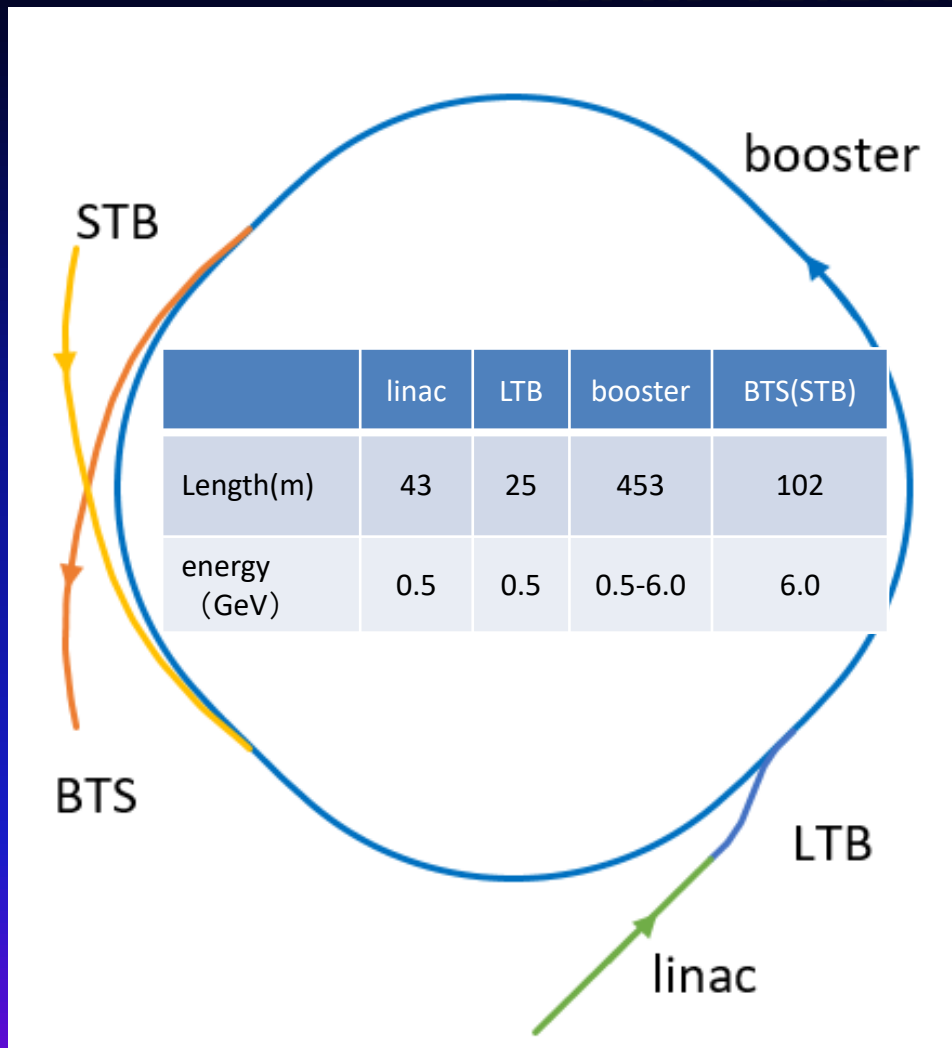
High energy extraction in booster
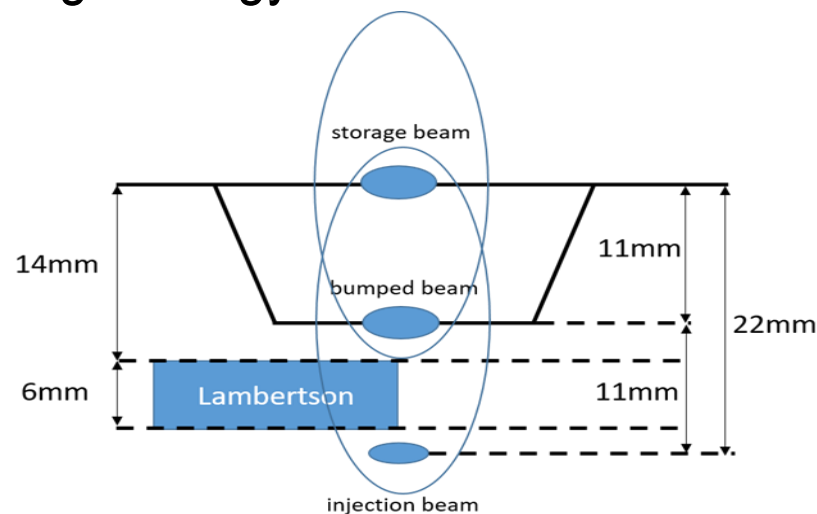
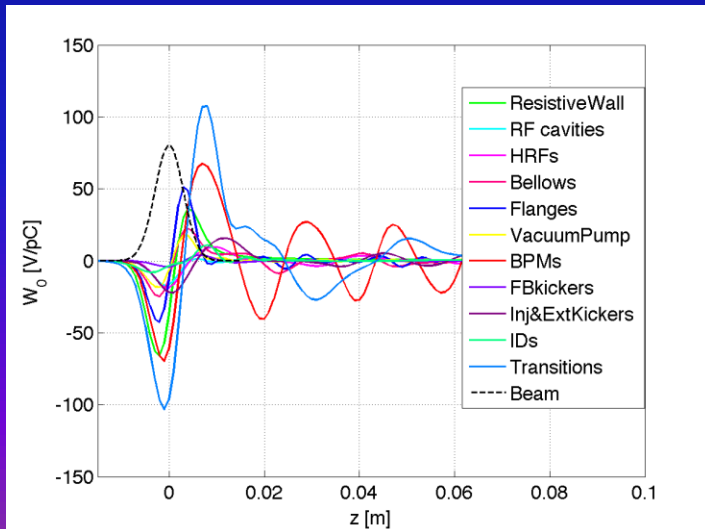
High energy injection in booster

Impedance calculations

- The impedance and wake are calculated with analytical formulae along with numerical simulations with ABCI and CST.
- Main sources: resistive wall, RF cavities, bellows, flanges, ID tapers, extraction kickers, injection kickers, In-vacuum IDs, BPMs, harmonic RFs, feedback kickers, pumping ports, vacuum transitions
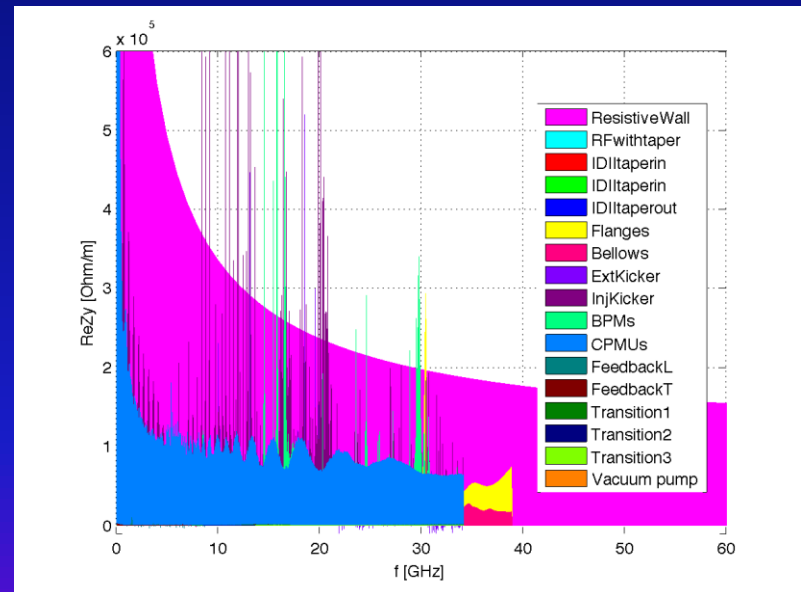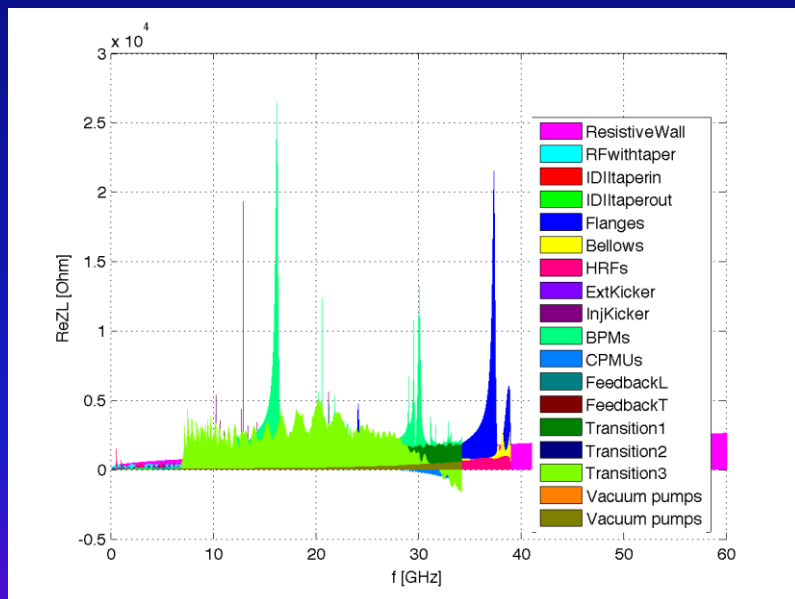
- Some elements are still missing in the model, such as photon absorbers, collimators, crotch chambers, etc.

Impedance budget

- Longitudinal and transverse impedances are dominated by resistive wall and elements with large amount.
- The longitudinal loss factor is mainly contributed by the resistive wall, RF cavities, BPMs and the transitions.
- Iteration between instability and impedance is needed for the following studies.


Objects	$Z_{||}/n$ [mΩ]	k_l [V/pC]	k_y [kV/pC/m]
Resistive wall	28.8	22.4	19.0
RF cavities	2.3	10.7	0.1
Bellows	13.8	4.9	1.6
Flanges	26.3	2.2	2.2
ID tapers	9.1	0.6	1.6
Ext. kickers	0.1	2.9	1.2
Inj. kickers	0.3	12.5	4.2
BPMs	27.4	31.3	3.5
Harmonic RF	1.1	5.9	0.06
LF kicker	0.9	2.0	0.04
TF kicker	0.2	0.3	0.03
In-vacuum IDs	3.4	3.6	5.0
Pumping ports	10.6	2.6	1.2
Transitions	26.0	55.9	5.7
Total	150.4	157.6	45.3

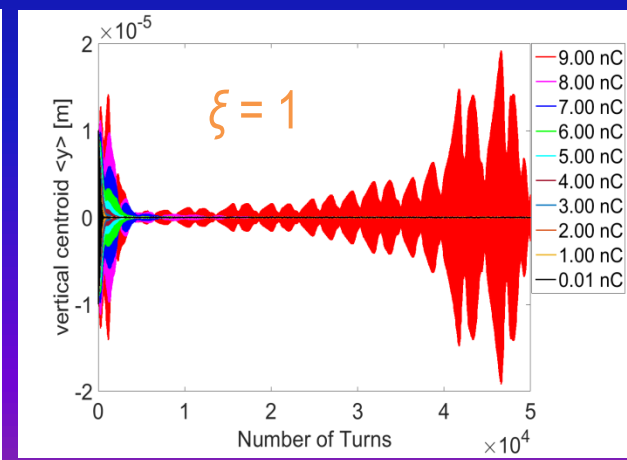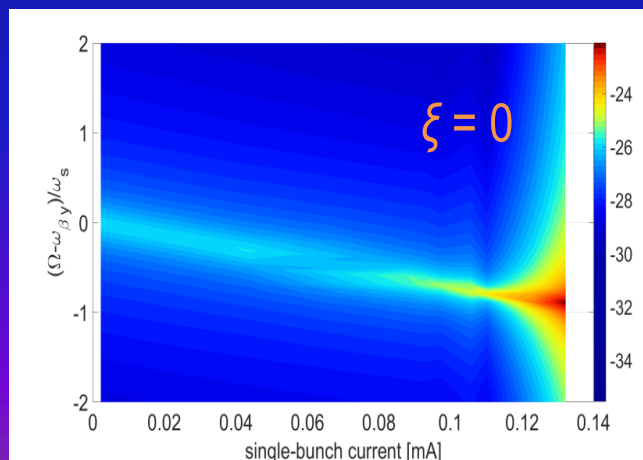# Collective effects

- ## Single bunch instabilities

  - Microwave instability

−Threshold is ~ 3.5 nC with HRF.

− It's higher than the intensity of the high brightness mode.

− For the timing mode (14.4 nC), the bunch is lengthened by a factor of 1.6, and the beam energy spread is increased by a factor of 1.9.
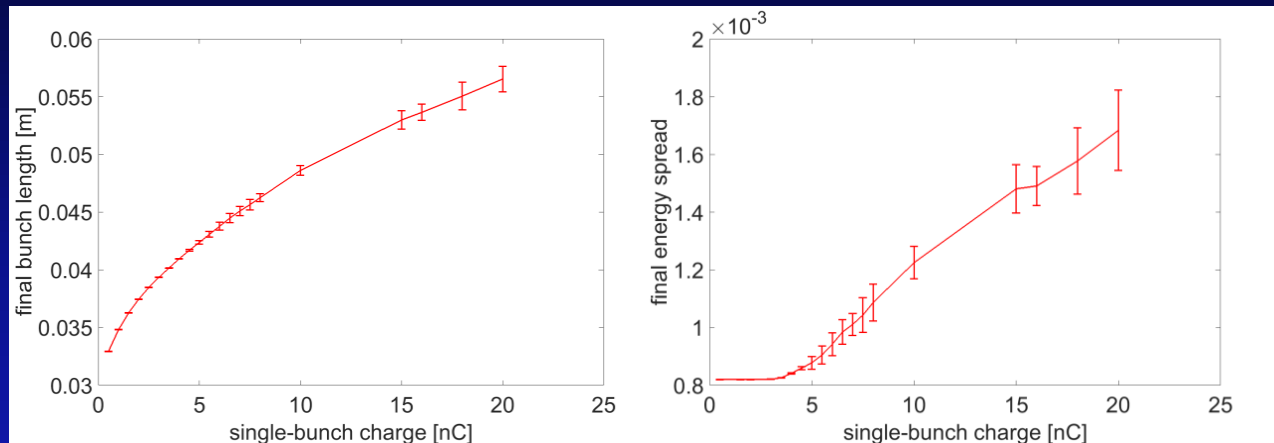
  - Transverse mode coupling instability

− TMCI threshold are calculated with Eigen mode analysis and macro-particle tracking. Both analyses give threshold at ~0.1mA (0.5nC) with $\xi = 0$.
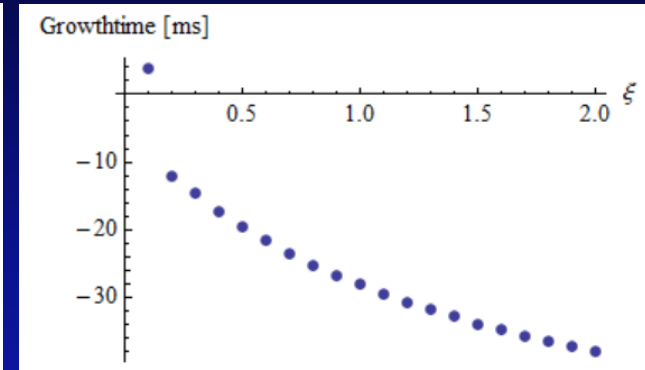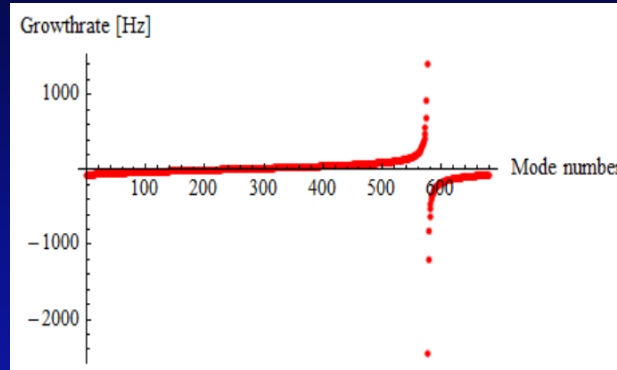
− With $\xi = 1$: $N_{e,th}$ = 9nC

$\xi = 0$

$\xi = 1$

Collective effects

- ## Coupled bunch instabilities

  - ### Transverse resistive wall instability

The most dangerous mode gives instability growth time of 0.7ms.

An effective feedback or a positive chroma is required to damp the instability


  - ### RF HOMs

With a sophisticated HOM coupler design and effective feedback damping, preliminary studies show that the transverse HOMs can be well damped. More detailed studies are underway.

Mode	Freq (MHz)	R/Q (Ω, kΩ/m)	Qext (Simulation)	Growth time (ms, no HC)	Growth time (ms, with HC)
M2	464.623	70.14/2	8.9E2	24.1	4.8
M3	700.789	46.47/2	1.3E3	16.5	3.3
D1, 1	431.907	0.470/2	9.8E2	56.3	56.3
D1, 2	432.961	0.364/2	1.7E3	41.9	41.9

HEPS-TF baseline: 6 GeV, ~1.3 km, 60 pm

Goal emittance: below 0.1 nm or namely 100 pm

Hybrid-7BA structure, first proposed for ESRF upgrade
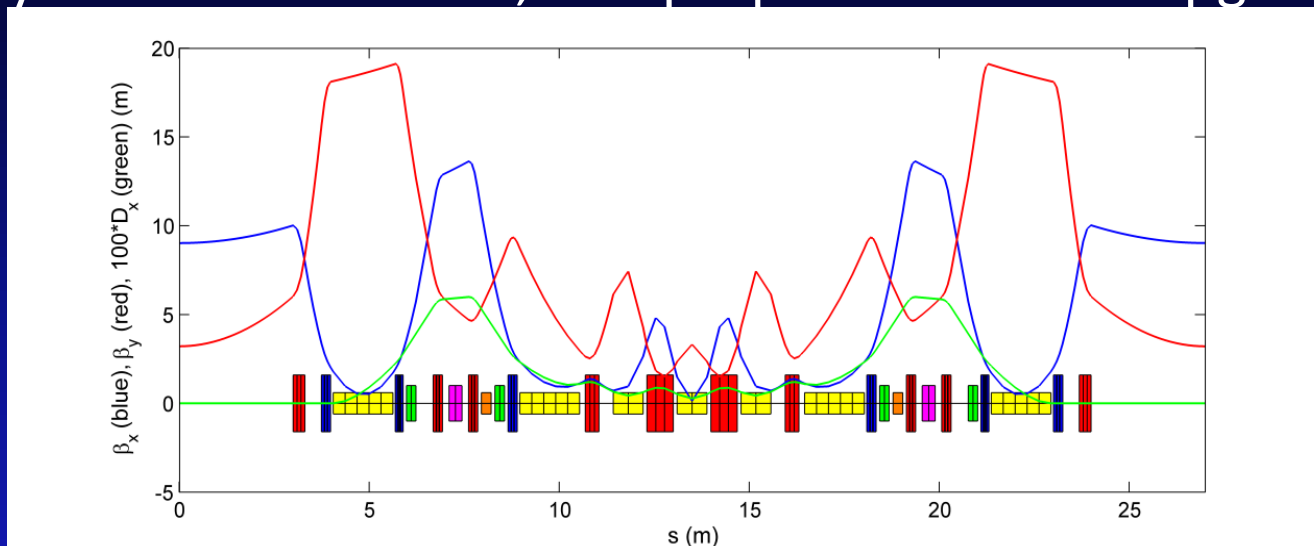
This type of lattice is able to create dispersion bumps which facilitate compensation for very large natural chromaticities, it also adopts aggressively strong focusing which results in a compact layout as well as an ultralow emittance. These features allow practical and cost effective storage ring designs, even when the natural emittance is reduced down to approaching the diffraction limit of hard X-rays.

Now ESRF-EBS, APS-U, HEPS, ALS-II, etc. adopts hybrid-MBA lattice.

Small DA, on-axis swap-out injection

w/ hybrid 7BA, still very difficult to get large dynamic acceptance

Nonlinear optimization w/ 4 families of multipoles (grid-scan):
- Effective on-momentum DA: ~2.5 mm in x and 3.5 mm in y; effective MA: ~3%.

'Effective' DA/MA: it is required not only the motion remains stable after tracking over a few thousand turns (traditional definition of the DA or MA), but also the tune footprint is bounded by the integer and half integer resonances nearest to the nominal tunes of the storage ring.
(Y. Jiao, et al., IPAC17-WEPAB055)

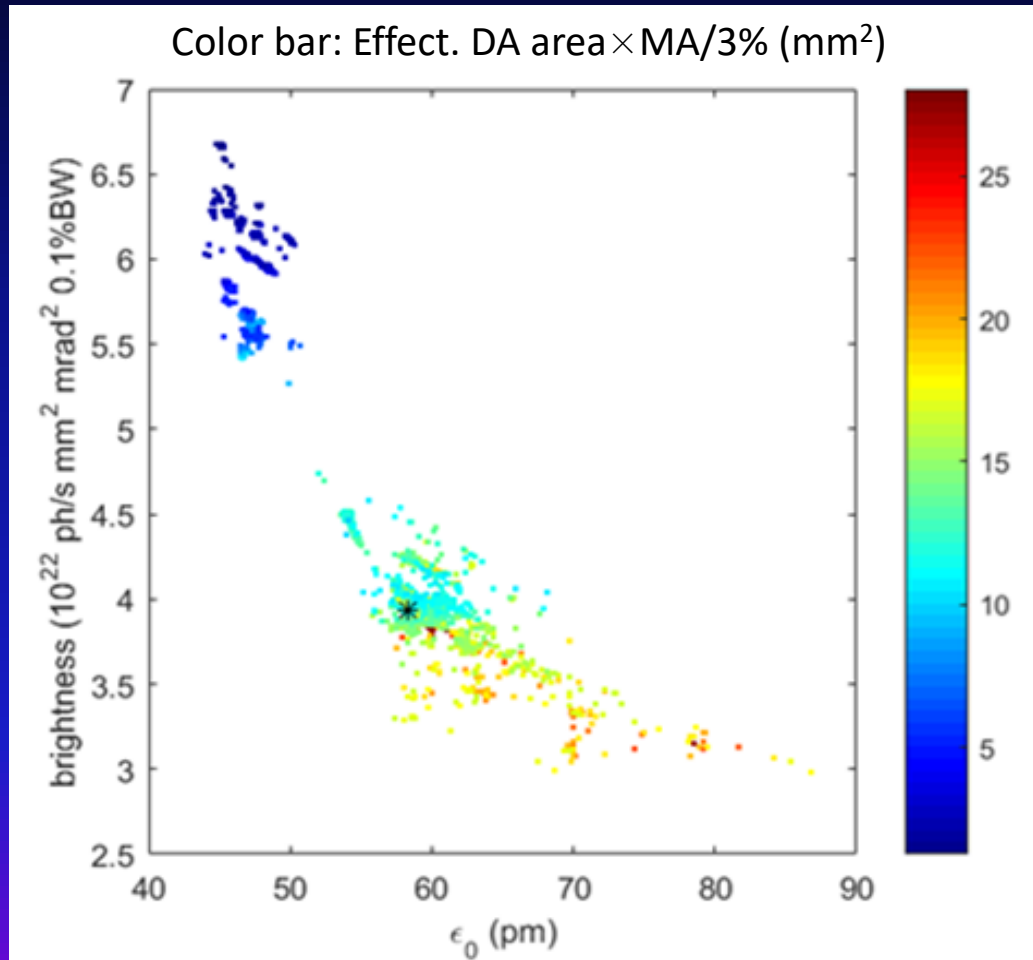## *Injection with high efficiency:*

On-axis swap-out injection   ✔

On-axis longitudinal accumulation   ✔ ❓

Off-axis injection & accumulation   ✖
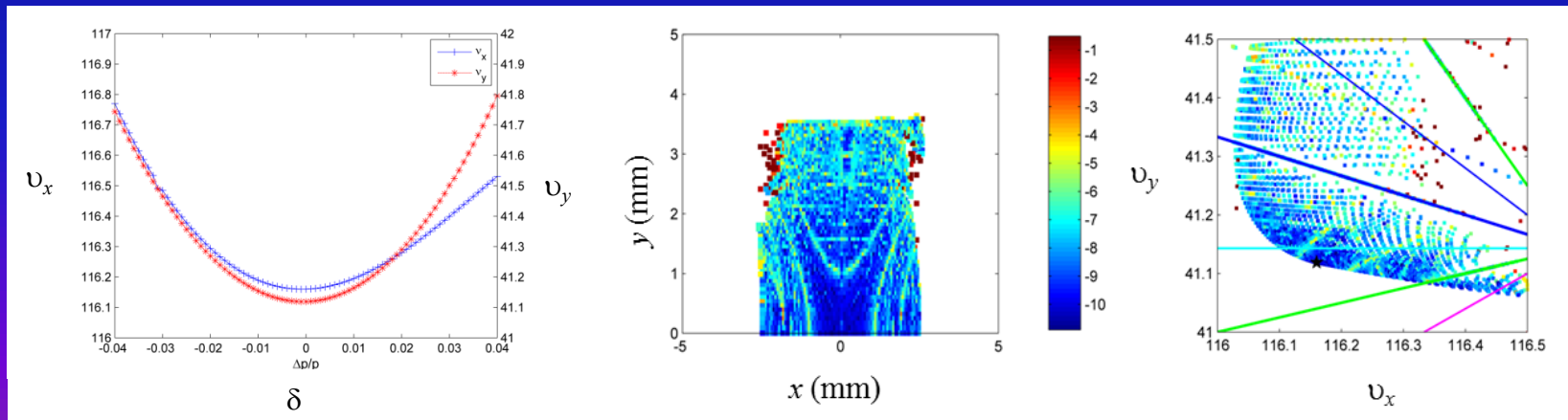
All tenable parameters scanned & linear and nonlinear dynamics simultaneously optimized


Color bar: Effect. DA area×MA/3% (mm²)

- ➤ If keeping 60 pm emittance, the DA can be increased to be close to (if not larger than) 10 mm in the injection plane

- ➤ If considering only on-axis swap-out injection, the emittance can be further pushed down to ~45 pm.rad

Y. Jiao, G. Xu, "Optimizing the lattice design of a diffraction-limited storage ring with a rational combination of particle swarm and genetic algorithms", Chin. Phys. C, 41(2): 027001 (2017).

w/o high-β section, effective DA: 8/3.3 mm in x/y plane, effective MA size > 3.5%
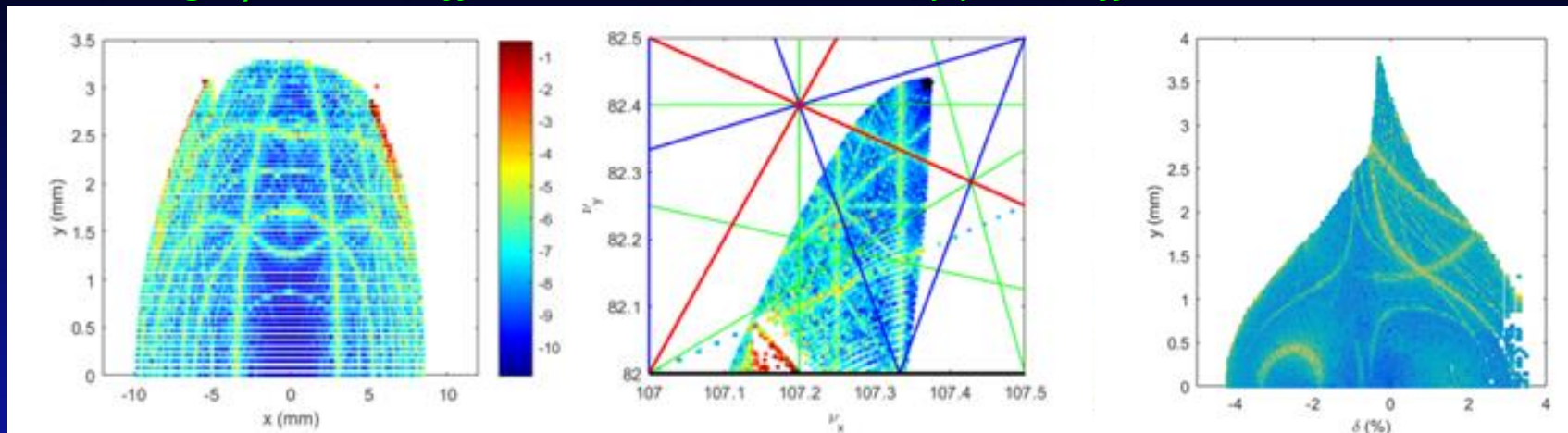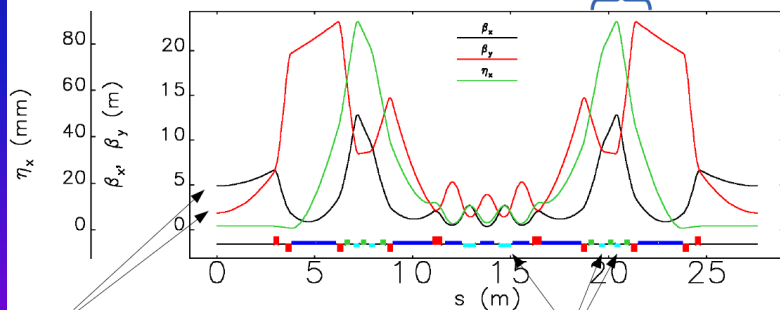

Very good, but can be even better!

41-pm RB lattice[1]

Replace several quadrupoles with reverse-direction bending magnets [2,3].
Increases energy loss per turn, somewhat decouples dispersion and beta functions.

Larger dispersion
Larger beta functions

Improved beta functions

Reverse bends

1: M. Borland et al., NAPAC16, WEPOB01.
2: J. Delahaye et al., PAC89, 1611.
3: A. Streun, NIM A 737, 148-154 (2014).

Courtesy of M. Borland

APS-U lattice design:
Hybrid-7BA lattice, 1104 m, 6 GeV, 67 pm, swap-out,
→ **Hybird-7BA w/ antibends** 41 pm, similar dynamic acceptance to the 67-pm lattice.

For HEPS, we are exploring and optimizing some novel structures. Very positive solutions have been obtained and will be shown soon.
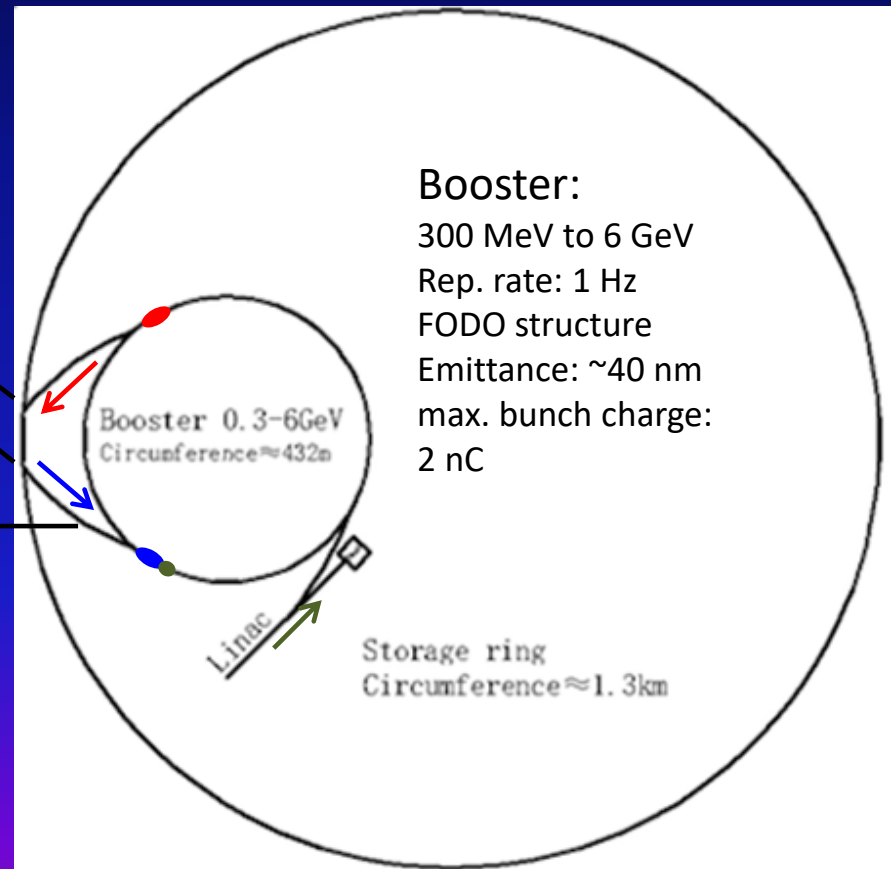
Swap-out injection

- Two operational modes with different filling patterns are considered, i.e., **low-charge mode** (200 mA with 680 bunches) and **high-charge mode** (200 mA with 63 bunches).
- For high-charge mode, it is difficult to store a high-charge bunch (14.5 nC) in booster.

Swap-out
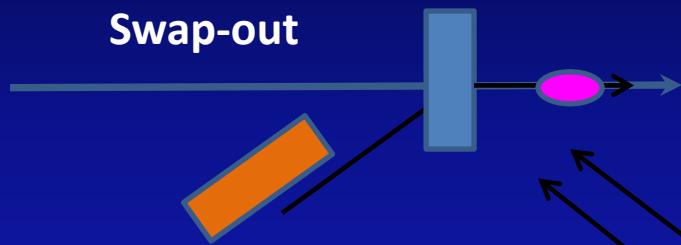
**An additional transport line between ring and booster**

The stored bunch in the ring is injected to the booster, merges with the existing bunch to compensate the beam loss, and is re-injected to the ring.

Booster:
300 MeV to 6 GeV
Rep. rate: 1 Hz
FODO structure
Emittance: ~40 nm
max. bunch charge:
2 nC

Booster 0.3–6GeV
Circumference≈432m

Linac

Storage ring
Circumference≈1.3km

Longitudinal injection

➢ On-axis longitudinal injection by RF gymnastics of a double-frequency (166.6/499.8 MHz) RF system (G. Xu *et al.*, IPAC16). This needs fast ramping of RF voltage and phase over a large range (10s ms).

➢ On-axis longitudinal injection with three-frequency (166.6/333.2/499.8 MHz) RF system (newly proposed by G. Xu), basically following the original idea of longitudinal injection. This avoids fast ramping of RF voltage and phase. This needs larger ring acceptance than that for swap-out (let us say, 4~5 mm on-momentum DA vs. 1~2 on-momentum DA).
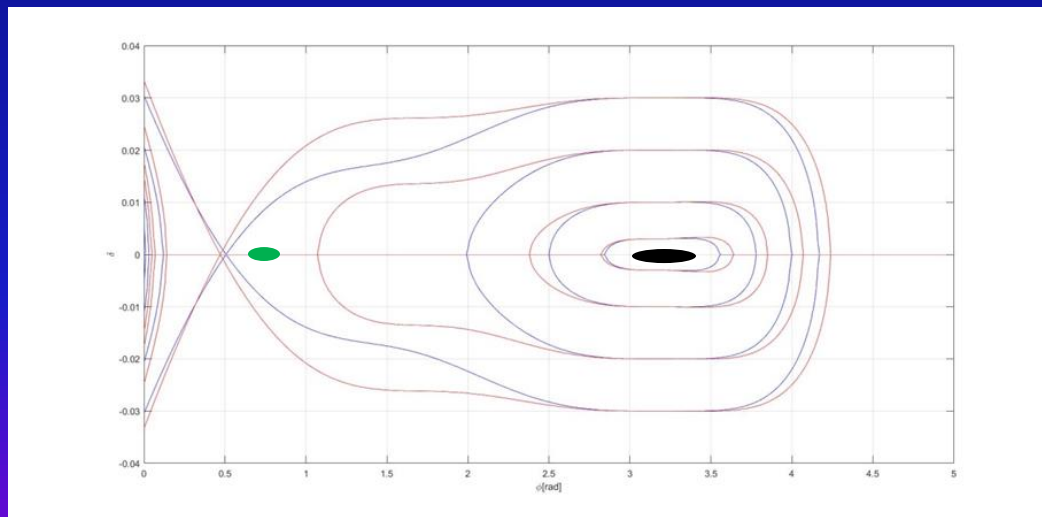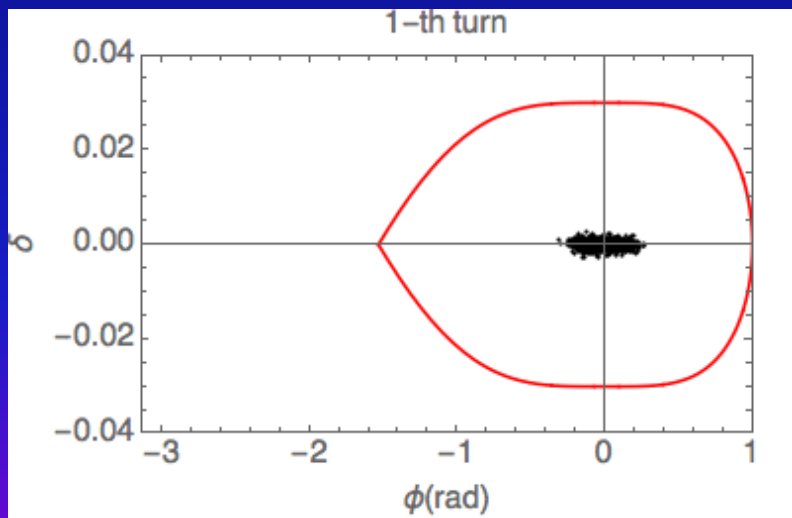
Two phases of HEPS

- R&D of HEPS project (HEPS-TF)
  - One of the 16 large scientific facilities in the list of National Development and Reform Commission in the 12th 5-year plan.
  - Scheduled from 2011 to 2015, but delayed.
  - Total budget: 321.6 M RMB (~48 M USD)
- HEPS project
  - Passed the review of the proposals for the large scientific facility, and shortlisted the 13th 5-year plan of the National Development and Reform Commission of China
  - Expected to start the construction in late 2018, completed at 2023.
  - Total budget: 4.5-5 B RMB (~0.7 B USD)

HEPS Injector design

At first, 3 plans were designed

plan1. All combined lattice like NSLS-II booster

Plan2. TME lattice with combined-function dipole

Plan3. Same tunnel FODO lattice

Booster ramping would affect the stored beam in SR and there would be conflict between ring construction and booster commissioning if booster sited in the same tunnel with SR.

The natural emittance of plan1 is lager than plan2.

Plan2 has more adjustable flexibility than plan1
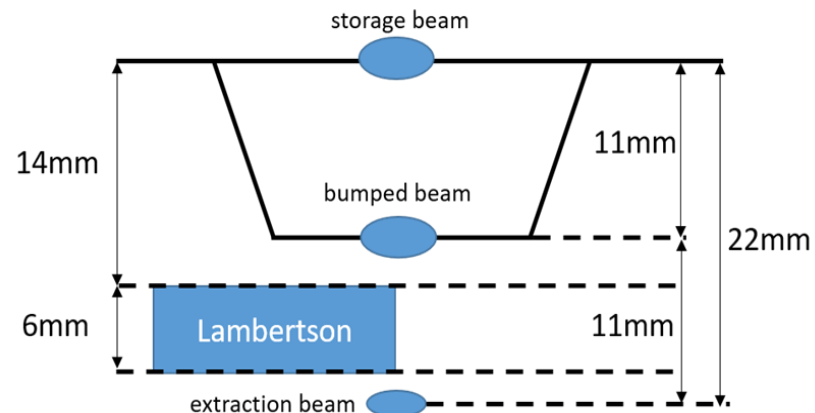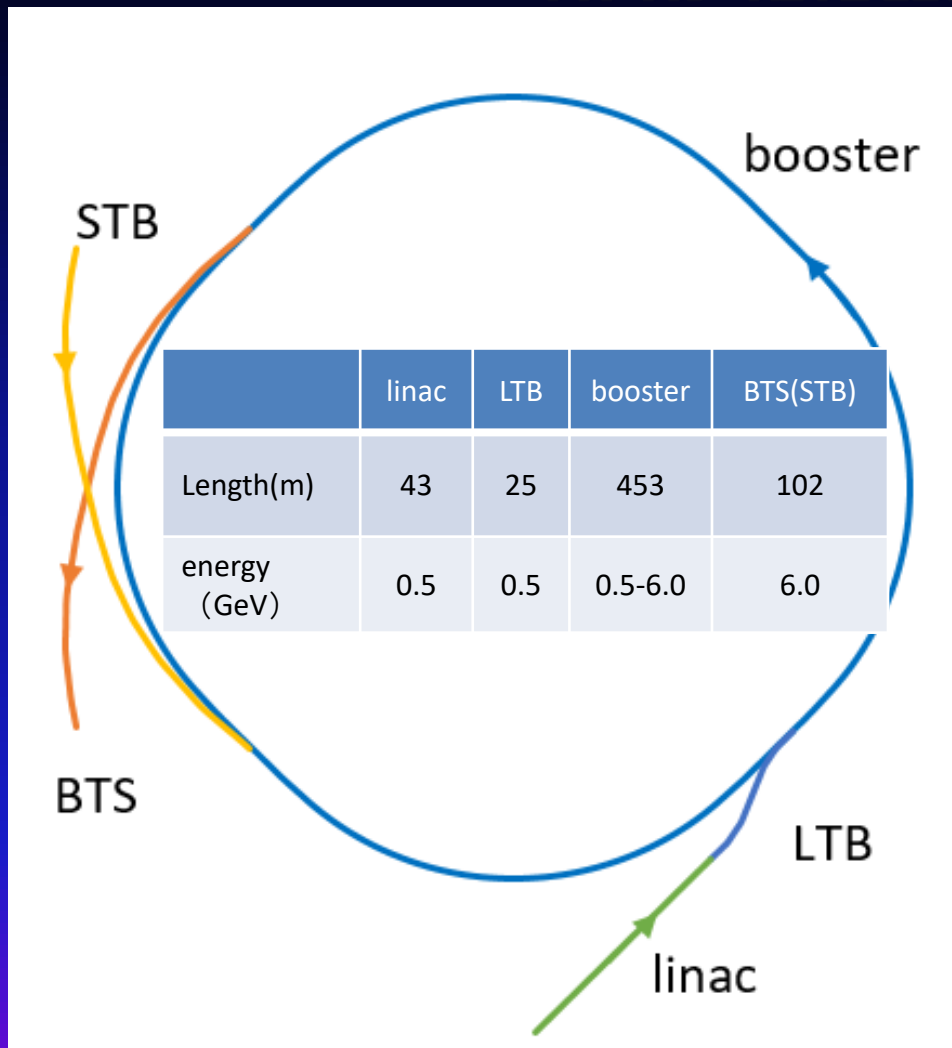
Sep. 2016, Plan 2 was choose as our baseline .

Simulation of TMCI threshold need ap is lager than 3e-3

Aug. 2017 we designed use FODO lattice with separated-function magnet.
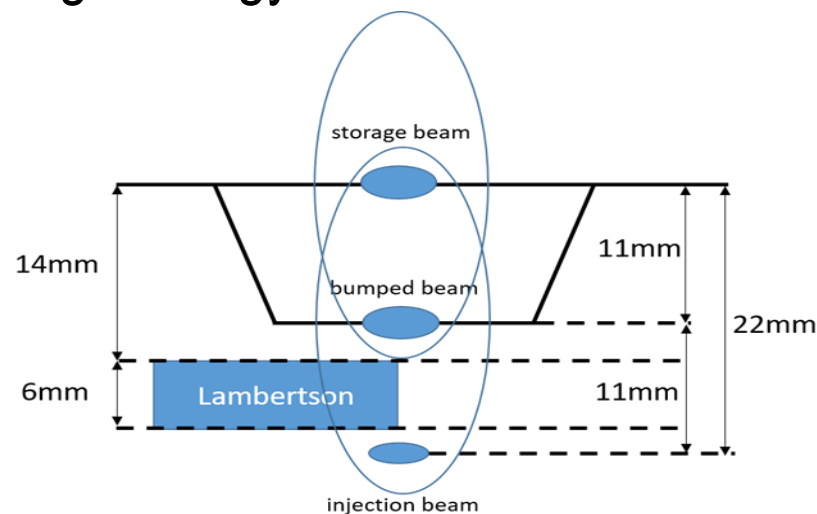
- ☐ Four-fold symmetric FODO lattice
- ☐ 14 standard FODO cells and 2 match cells
- ☐ Dispersion free straight sections are used for RF cavity, inj. & ext. systems
- ☐ A specially designed π section is used for high energy injection using 2 kickers

Parameters	Units	Injection(0.5Gev)	Extraction（6Gev）
Energy	GeV	0.5	6
Current	mA	4	15
Emittance	nm·rad	41	42
Energy Spread		0.005	9.6×10^{-4}
RF voltage	MV	1.2	≥8
Bucket Height		2.3%	1.0 %
Tune（x/y）		16.83/10.73	
Momentum Compact Factor		4.2×10^{-3}	
Repetition Rate	Hz	1	
Circumference	m	453.47	
RF Frequency	MHz	499.8	

	linac	LTB	booster	BTS(STB)
Length(m)	43	25	453	102
energy（GeV）	0.5	0.5	0.5-6.0	6.0

High energy extraction in booster

High energy injection in booster

Lattice calibration and error tolerance

	Dipole	Quadrupole	Sextupole	Octupole	Girder
Transverse shift X/Y (µm)	200	30	30	30	50
Longitudinal shift Z (µm)	150	150	150	150	200
Tilt about X/Y (mrad)	0.2	0.2	0.2	0.2	0.1
Tilt about Z (mrad)	0.1	0.2	0.2	0.2	0.1
Nominal field	3e-4	2e-4	3e-4	5e-4	\
Multipole field	5e-4	2e-4	1e-3	1e-3	\

	Accuracy (m)	Tilt (mrad)	Gain	Offset w/ BBA(mm)
BPM(10Hz)	1e-7	10	5%	30e-3

Correction Element per Cell	BPM	Corrector	Skew Q	Sextupole magnet online alignment
Amount	24	20	6	12

*Error term in shadow taken in to error model for now
  Gaussian distribution and cut-off at 3σ

The main error effect comes
from the Sextupole offset
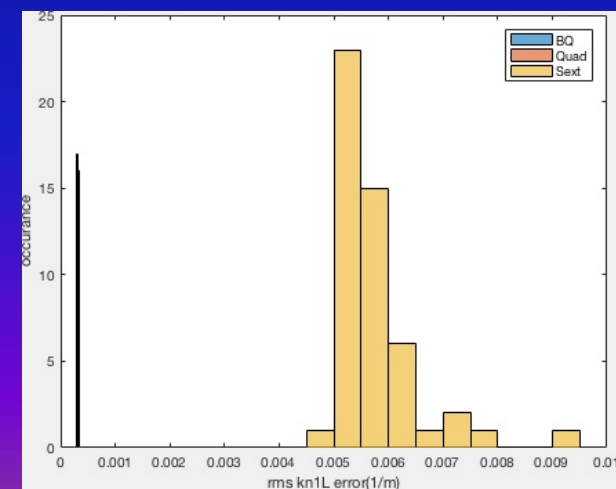
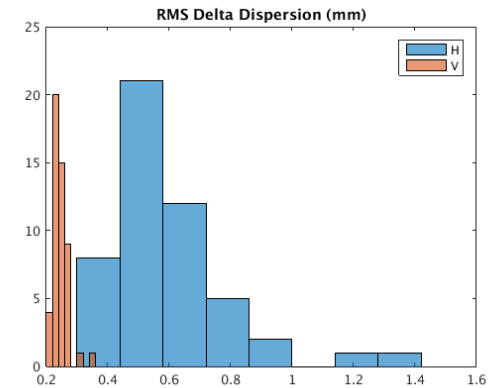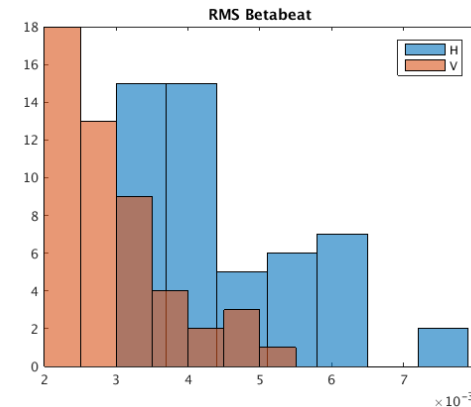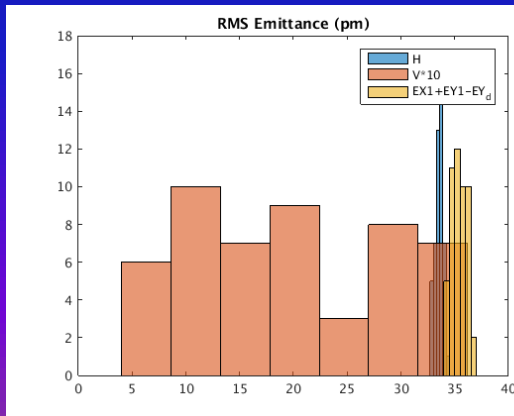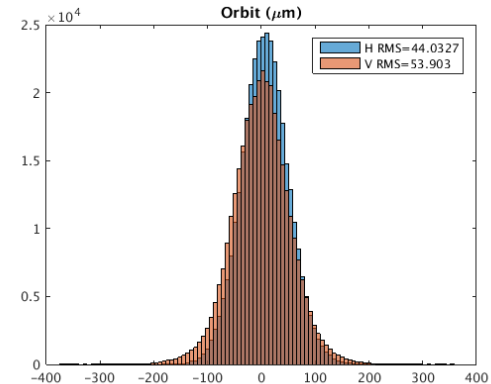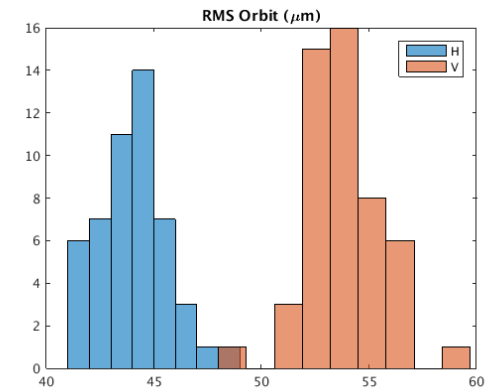# Lattice calibration and error tolerance

Orbit Correction By ORM and SVD

- **X < 50μm (RMS)**

- **Y < 60μm (RMS)**

Linear Optics with LOCO and Sextupole Alignment

- **RMS BetaBeating < 1%**

- **Dispersion X <1.5mm (RMS)**

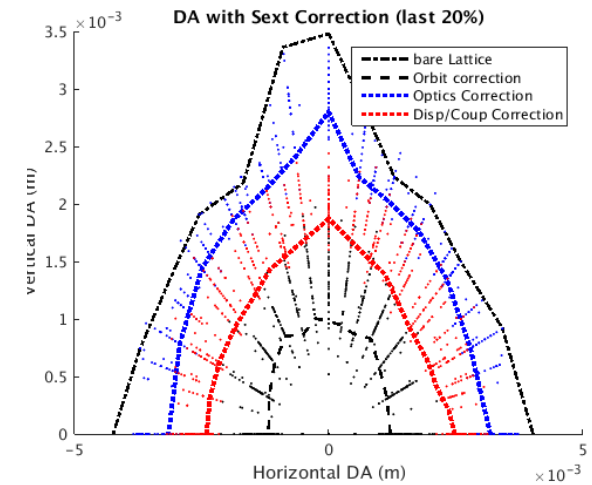- **Dispersion Y <0.5mm (RMS)**

Emittance almost recover : X < 35pm; Y < 4pm

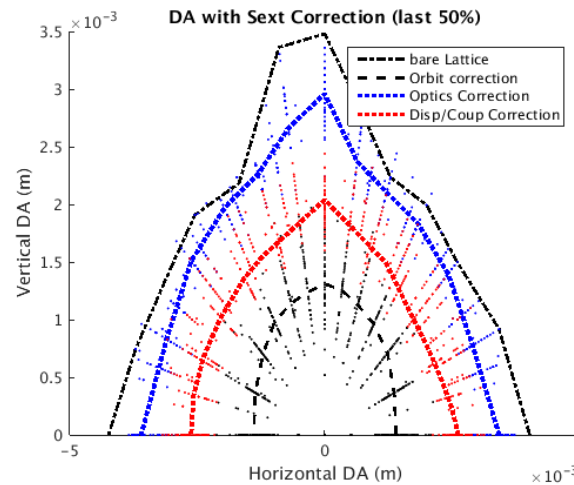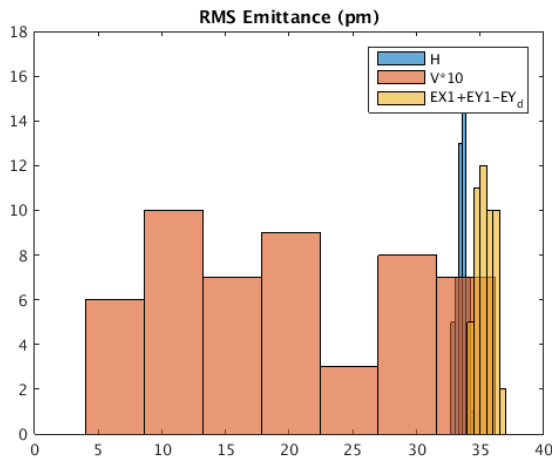# DA recovery including sextupole alignment

Emittance X < 35pm

Emittance Y < 4pm

DA recover to 80% of bare lattice in 80% case

Insertion devices (IDs)

Name_energy(Kev)	B0 Max (T)	λu (m)	Nu	U0(Mev)	ΔQy
CPMU5mm_6~20	1.35399	0.0184	228	0.175	0.0031
CPMU5mm_10~90	1.35399	0.0184	114	0.088	0.0016
CPMU5mm_15~20	0.904348	0.0135	148	0.039	0.0006
CPMU5mm_7~10	1.23231	0.017	117	0.072	0.0012
CPMU5mm_50~170	1.08629	0.0154	272	0.105	0.002
IVU5mm_4.5~40	1.21855	0.0222	189	0.142	0.0025
IVU5mm_5~25	1.21855	0.0222	189	0.142	0.0025
IVU5mm_25~70	1.21855	0.0222	189	0.142	0.0025
IAU11mm_4.5~40	0.77011	0.0319	156	0.067	0.0012
IAU11mm_4.8~45	0.77011	0.0319	156	0.067	0.0012
IAU11mm_5~15	0.77011	0.0319	156	0.067	0.0012
IAU11mm_5~18	0.77011	0.0319	156	0.067	0.0012
IAU11mm_5~25	0.77011	0.0319	156	0.067	0.0012
IAU11mm_7~40	0.77011	0.0319	156	0.067	0.0012
IAU11mm_8~12	0.53258	0.025	200	0.032	0.0006
IAU11mm_25~70	0.671644	0.029	172	0.051	0.0009
IAW12.7mm_40~300	1.71496	0.08	26	0.139	0.003