SppC Lattice Design and Compatibility Study with CEPC

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Content

- SppC lattice design and nonlinearity optimization
- Error correction scheme
- Geometric compatibility between CEPC and SppC

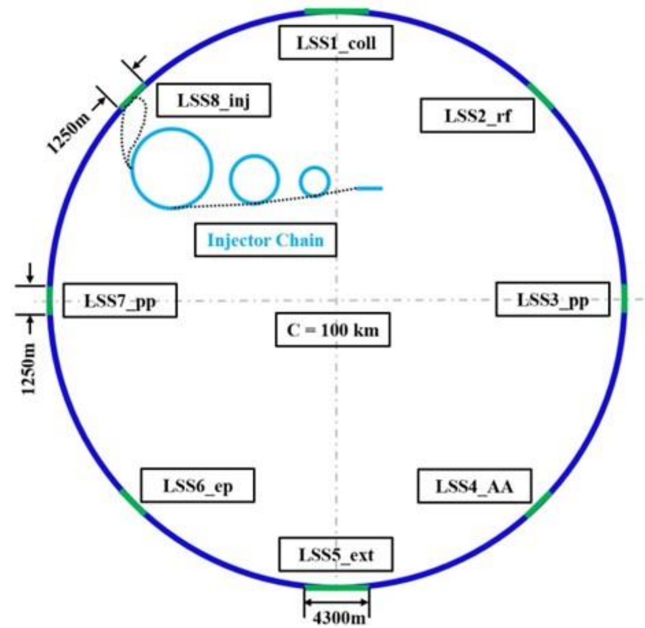
SppC parameters

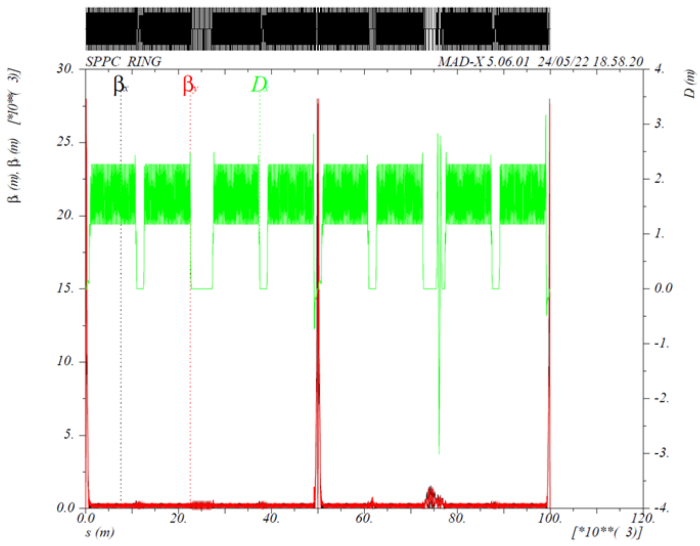
Parameter	Value	Unit
General design parameters		
Circumference	100	km
Beam energy	62.5	TeV
Lorentz gamma	66631	
Dipole field	20	T
Dipole curvature radius	10415.4	m
Arc filling factor	0.78	
Total dipole magnet length	65.442	km
Arc length	83.9	km
Number of long straight sections	8	
Total straight section length	16.1	km
Energy gain factor in collider rings	19.53	
Injection energy	3.2	TeV
Number of IPs	2	
Revolution frequency	3.00	kHz
Physics performance and beam parameters		
Initial luminosity per IP	4.3´10^{34}	$cm^{-2}s^{-1}$
Beta function at collision	0.50	m
Circulating beam current	0.19	A
Nominal beam-beam tune shift limit per IP	0.015	
Bunch separation	25	ns
Number of bunches	10080	
Bunch population	4.0´10^{11}	
Accumulated particles per beam	4.0´10^{15}	
Normalized rms transverse emittance	1.2	mm
Beam life time due to burn-off	8.1	hours
Total inelastic cross section	161	mb
Reduction factor in luminosity	0.81	
Full crossing angle	73	mrad
rms bunch length	60	mm
rms IP spot size	3.0	mm
Beta at the first parasitic encounter	28.6	m
rms spot size at the first parasitic encounter	22.7	mm
Stored energy per beam	4.0	GJ
SR power per beam	2.2	MW
SR heat load at arc per aperture	26.3	W/m
Energy loss per turn	11.4	MeV

*CEPC TDR

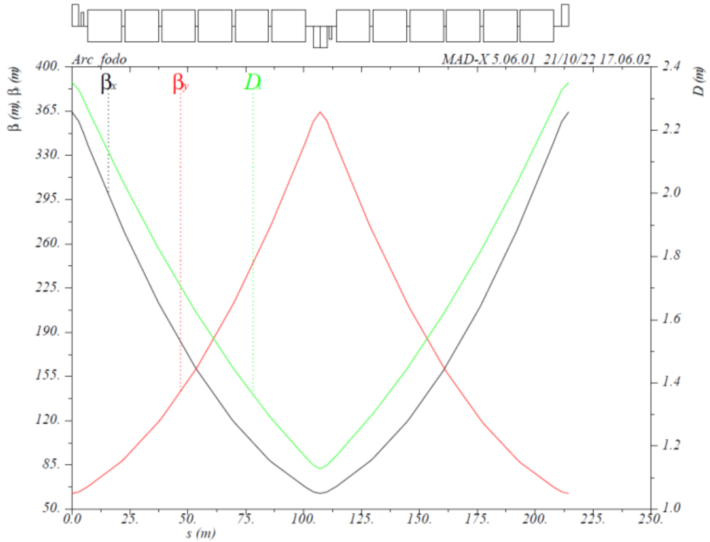
SppC lattice design

- Compatible with CEPC, 100km, 2 IPs
- 8 arc sections
  - 2-in-1 yoke-sharing magnets
  - both interleaved and non-interleaved sextupoles studied
- 4 short straight sections
  - RF region, dual-harmonic RF system (800 and 400 MHz)
  - injection section after injection chain
  - Space reserved for e-p collision
- 2 long straight sections
  - collimation section for both betatron and momentum
  - extraction section
- 2 interaction regions
  - anti-symmetric interaction region
  - chromaticity corrected with arc sextupoles

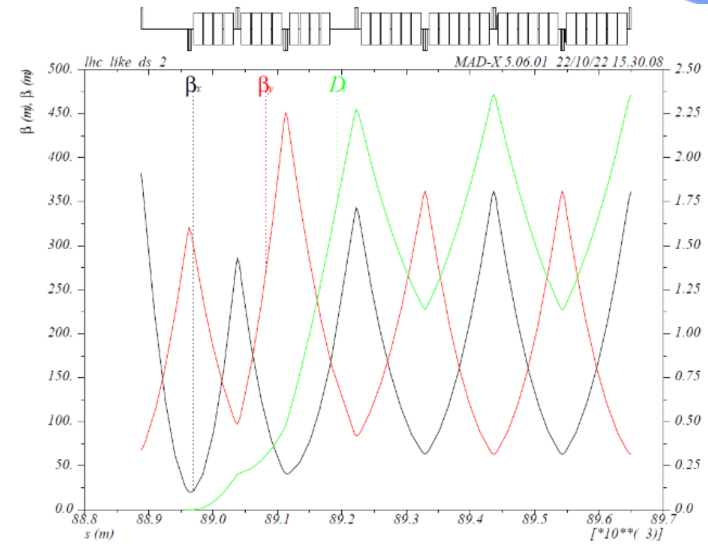




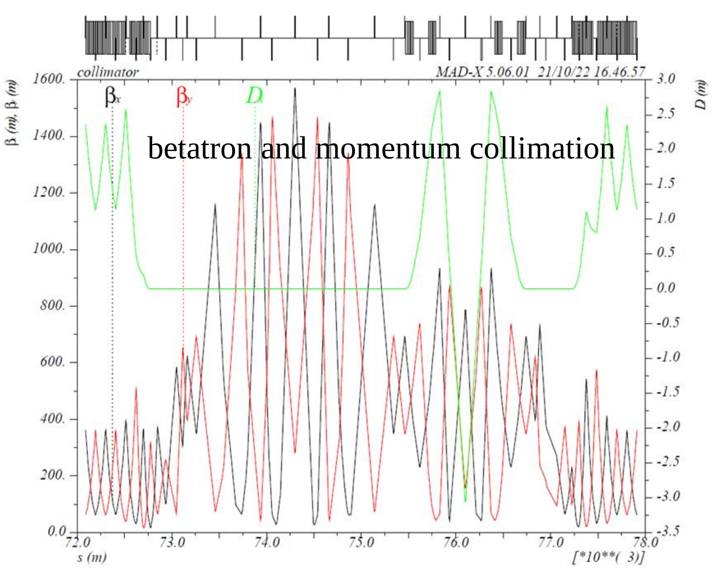
Lattice optics



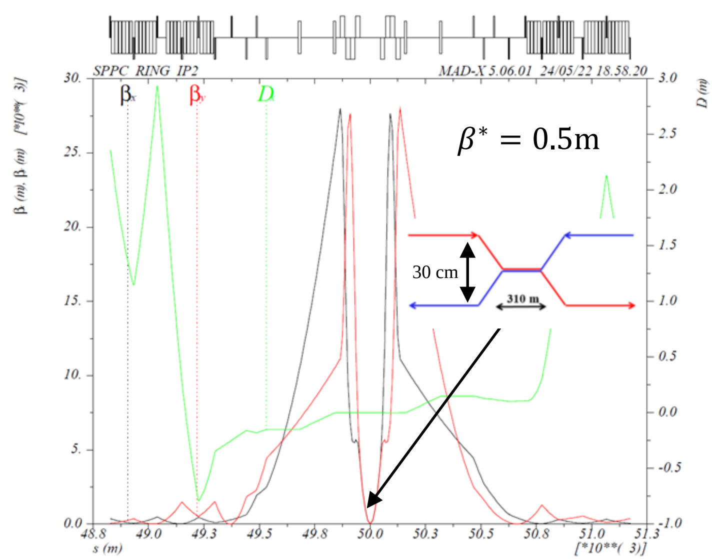
Arc FODO cell



Dispersion suppressor



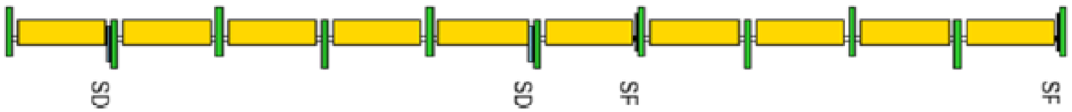
Collimation section

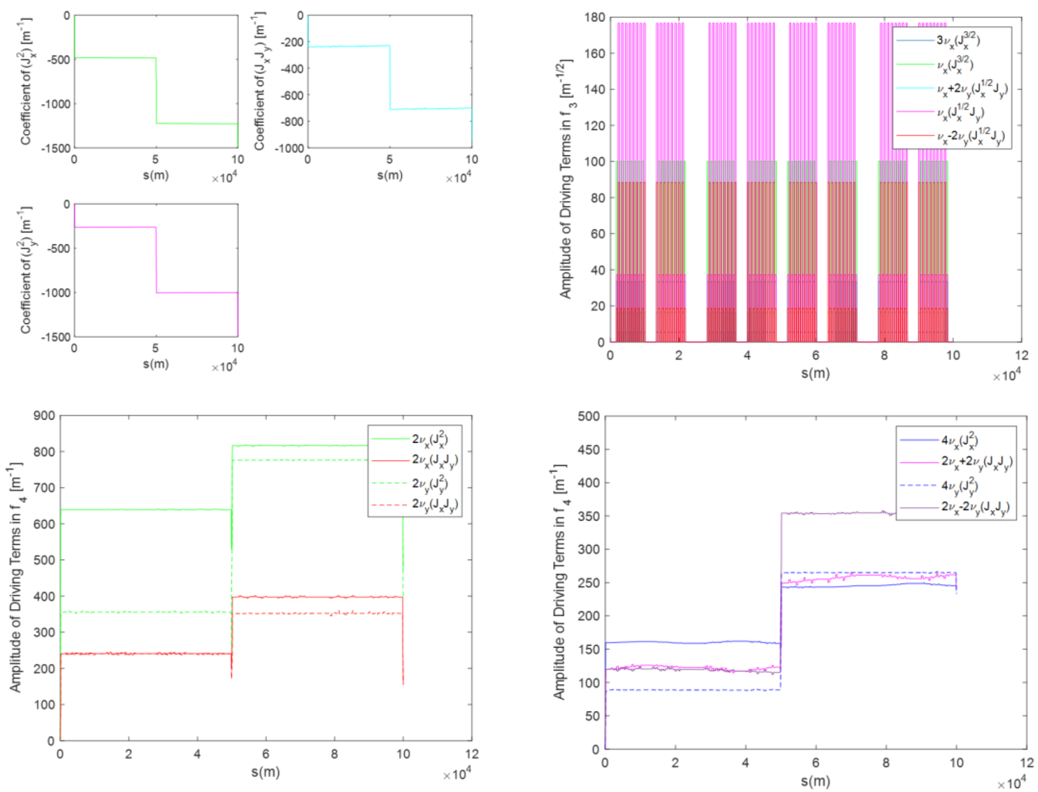


Interaction region

Nonlinearity optimization

- 5 FODO cells per period. Most nonlinearities are cancelled in 4 periods and the tune shifts are significantly reduced compared with the interleaved scheme.
- Since the number of sextupoles is less than interleaved scheme, the sextupoles in arc will be stronger, thus the length of sextupoles is doubled to 1m to weaken the sextupoles.



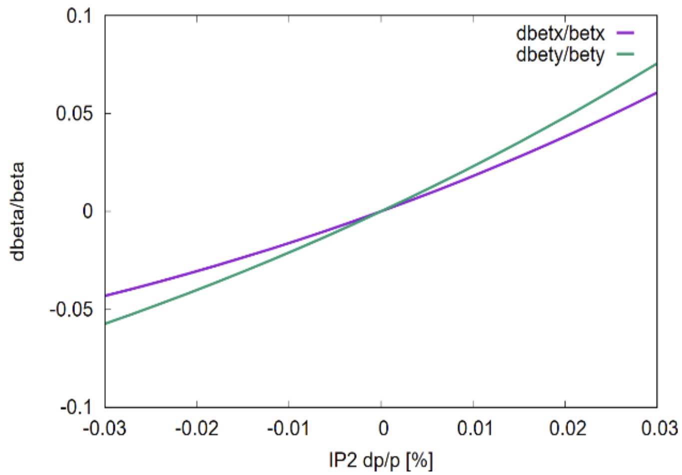


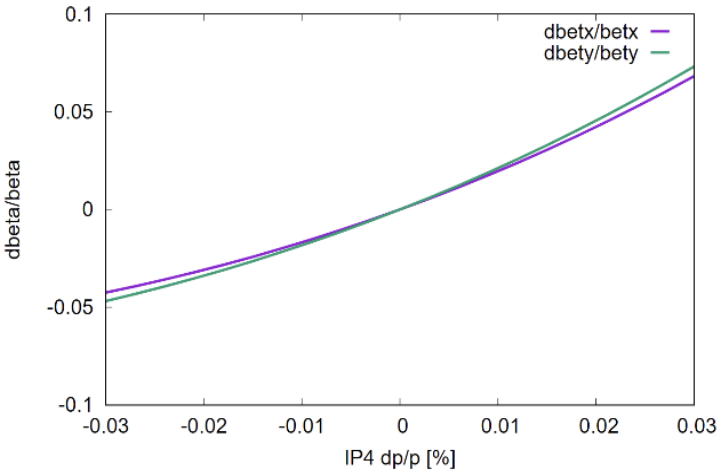
Tune shift coefficients and RDTs

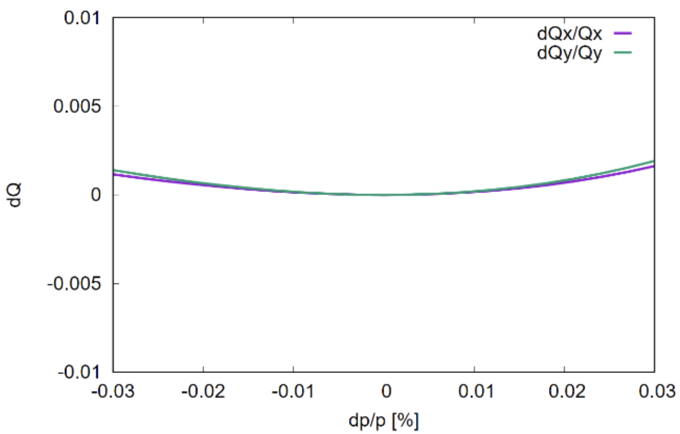
Chromatic function optimization

- Adjust the phase advance between different sections to optimize the 2nd order chromaticity and W-functions, which can reduce the energy-dependent deviation of β^*.

$$W_x = \sqrt{a_x^2 + b_x^2}, \qquad b_x = \frac{1}{\beta_x}\frac{\partial \beta_x}{\partial p_t}, \qquad a_x = \frac{\partial \alpha_x}{\partial p_t} - \frac{\alpha_x}{\beta_x}\frac{\partial \beta_x}{\partial p_t}$$







Consideration of Landau octupoles

Landau damping

- Octupoles are installed adjacent to arc quadrupoles, providing a tune spread of about 0.2×10^{-3} on both planes with a footprint of $J_x + J_y < 6\varepsilon_{x,y}$, to replicate similar Landau damping as in FCC-hh.

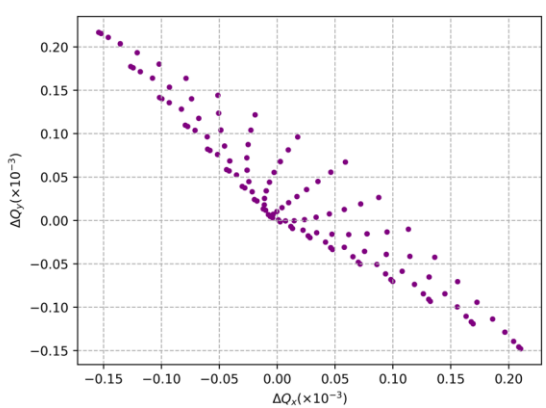
Octupolar Hamiltonian*:

*Moohyun Yoon 1998 *Jpn. J. Appl. Phys.* **37** 3626

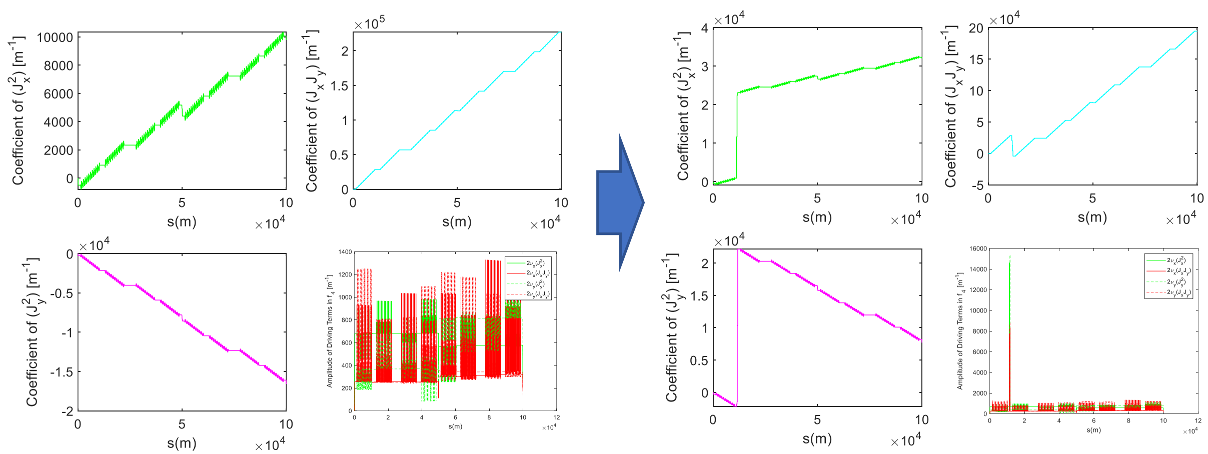
- $V(I,\phi;s) = V_0(I;s) + \frac{B'''}{48B\rho}\left[\beta_x^2 J_x^2(\cos 4\phi_x + 4\cos 2\phi_x) - 6\beta_x\beta_y J_x J_y\{\cos 2(\phi_x+\phi_y) + \cos 2(\phi_x - \phi_y) + 2\cos 2\phi_x + 2\cos 2\phi_y\} + \beta_y^2 J_y^2(\cos 4\phi_y + 4\cos 2\phi_y)\right].$

- Mainly care about 2nd order RDTs as the working point (0.12, 0.13) is far from 4th order resonances.

- Pairs of octupoles with equal strength and phase advance $\Delta\phi_x = \Delta\phi_y = 90°$ works.



Tune shift provided by Landau octupoles

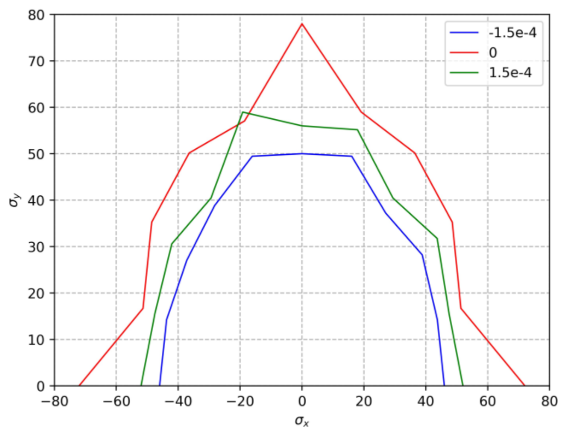


Changes to tune shifts and 2nd order resonance

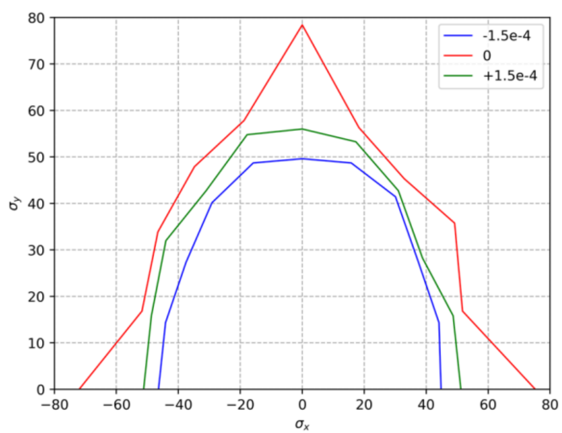
Consideration of beam-beam effect

- Weak-strong beam-beam effect simulation is performed by SAD. The calculated luminosity can fit with that in parameter table:

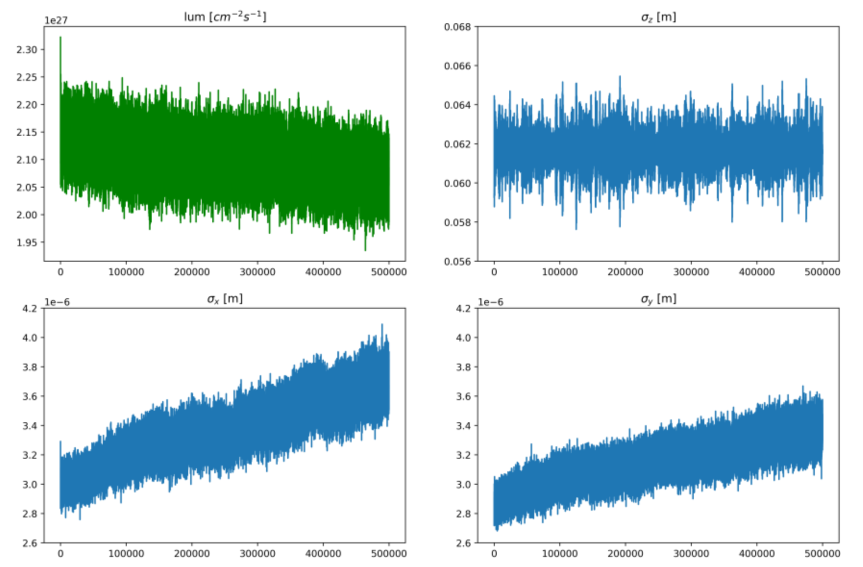
$$L = L_{per} N_b f = 2.2 \times 10^{27} \times 10080 \times 3000 \text{ cm}^{-2}\text{s}^{-1} = 6.7 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$$



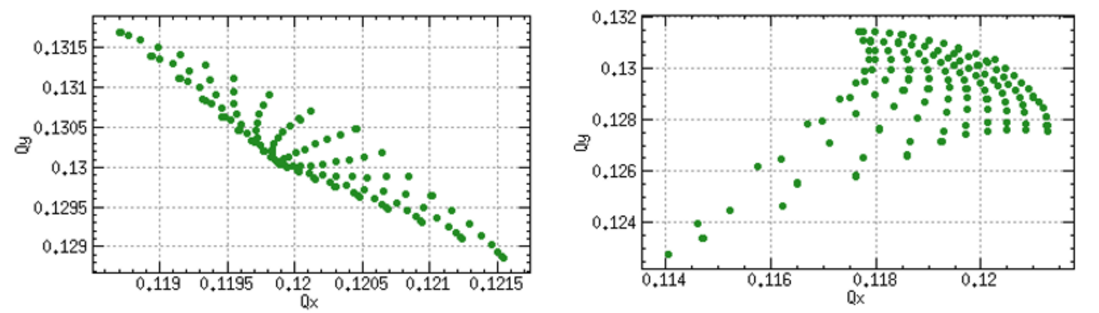
Bare lattice



Bare lattice + beam-beam



Luminosity, bunch length and bunch size



FMA results with amplitude of lower than 10σ

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SppC lattice error table

- Gaussian distribution, and truncated at 3σ;
- Referring to FCC-hh, and adjust to be suitable with SppC lattice.

Element	Error	Error desc.	Units	Main dipole	Separation dipole
Dipole	$\sigma(x), \sigma(y)$		mm	0.3	0.3
	$\sigma(\psi)$	roll angle	mrad	0.5	0.5
	$\sigma(\delta B/B)$	random b1	%	0.1	0.05
	$\sigma(\delta B/B)$	random b2	10^{-4} units	0.9	0.1/1.1
	$\sigma(\delta B/B)$	random a2	10^{-4} units	1.0	0.1/0.2
	$\sigma(\delta B/B)$	uncert. a2	10^{-4} units	0.5	TBD
	$\sigma(\delta B/B)$	random b3	10^{-4} units	1.0	TBD
				Main quadrupole	IR triplet / other
Quad.	$\sigma(x), \sigma(y)$		mm	0.3	0.1/0.3
	$\sigma(\psi)$	roll angle	mrad	0.5	0.05/0.5
	$\sigma(\delta B/B)$	random b2	%	0.1	0.005/0.1
BPM	$\sigma(x), \sigma(y)$		mm	0.2	0.2
	$\sigma(read)$		mm	0.05	0.05

*Reference radius of field error is 17 mm.

Ref: D.Boutin et al, optic corrections for Fcc-hh, IPAC2019

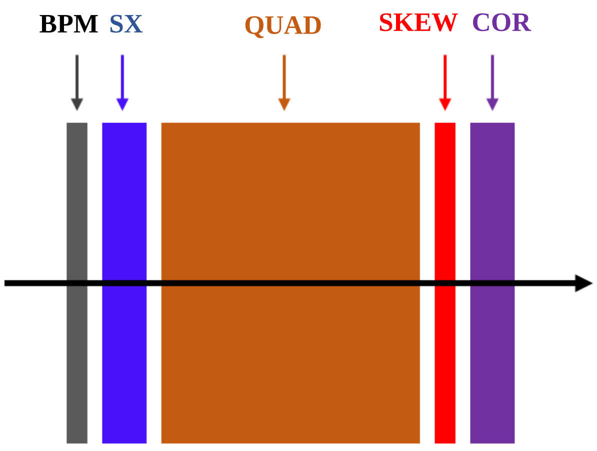
SppC lattice correction scheme

Based on response matrix method

- Software： Accelerator Toolbox (AT) on MATLAB

1. Apply the errors and turn off sextupoles
2. First turn trajectory correction
3. Closed orbit correction with increasing sextupole strength
4. Beta-beating and horizontal dispersion correction (LOCO)
5. Coupling and vertical dispersion correction
6. Tune and chromaticity correction

Iterate for several times (steps 4–5)



Response matrix represents the relationship between the strength variation of the dipole correction magnet in the storage ring and the resulting closed orbit distortion of the beam：

$$\begin{pmatrix}\Delta x\\ \Delta y\end{pmatrix} = R\begin{pmatrix}\Delta\theta_x\\ \Delta\theta_y\end{pmatrix}$$

SppC lattice correction scheme

938 BPMs and 477 dipole correctors installed near the quadrupoles in the ring.

First turn trajectory correction：

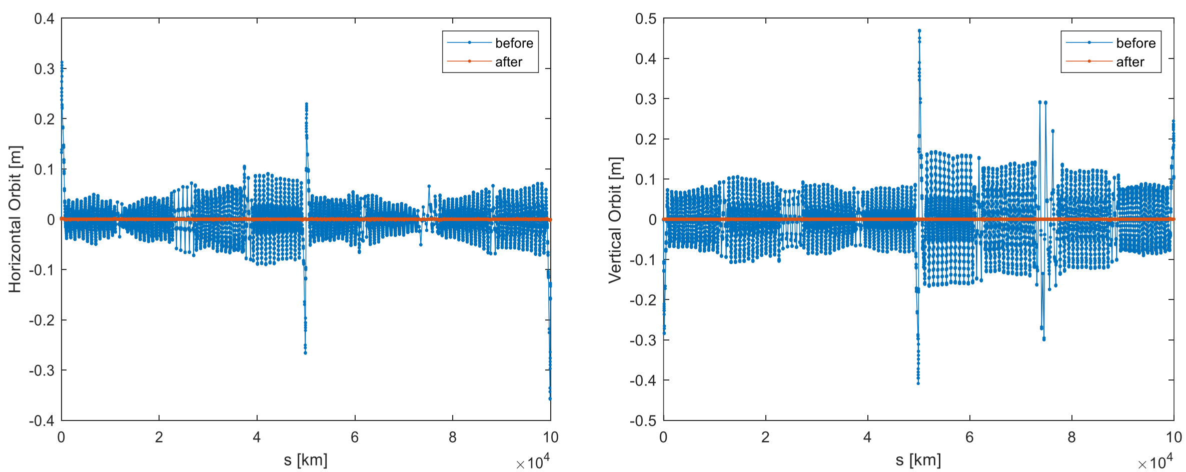
- Use BPMs and dipole correctors to find the closed orbit, 85% of the machines with errors can be corrected successfully in this step.

Closed orbit correction：

- Solve the equation with the response matrix of lattice： $\boldsymbol{\vec{u}} + \boldsymbol{A\vec{\theta}} = \mathbf{0}$

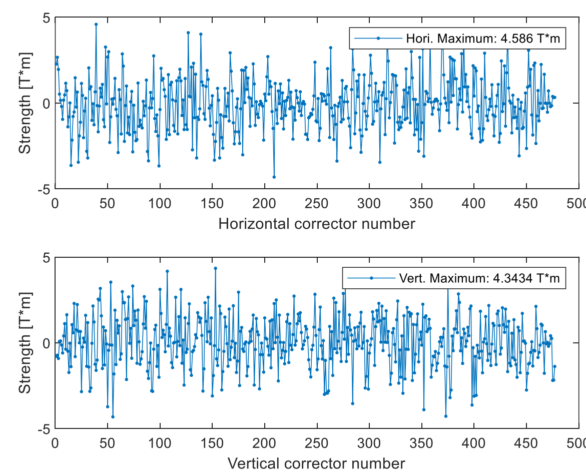
  $\vec{u}$: vector of orbit at BPM, A: response matrix, $\vec{\theta}$: vector of corrector strength

- Sextupole off, then after each 10% increase, the closed orbit is corrected once until the set value is reached.



$\mathrm{COD}_{x,y,rms} < 0.4\ mm$

Comparison of closed orbit before and after correction



Corrector strength less than 5 T*m

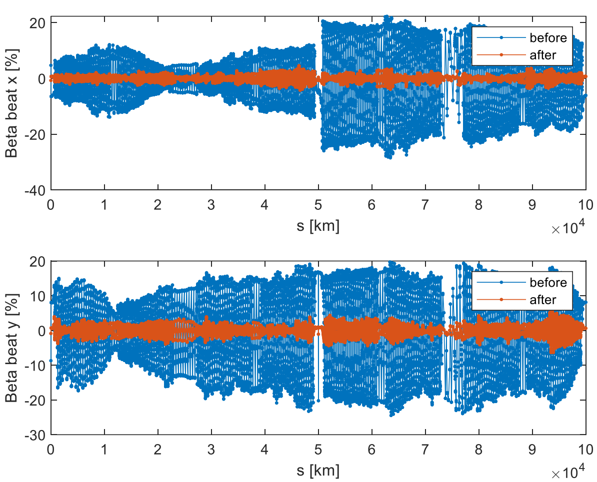
SppC lattice correction scheme

Beta-beating and horizontal dispersion correction：

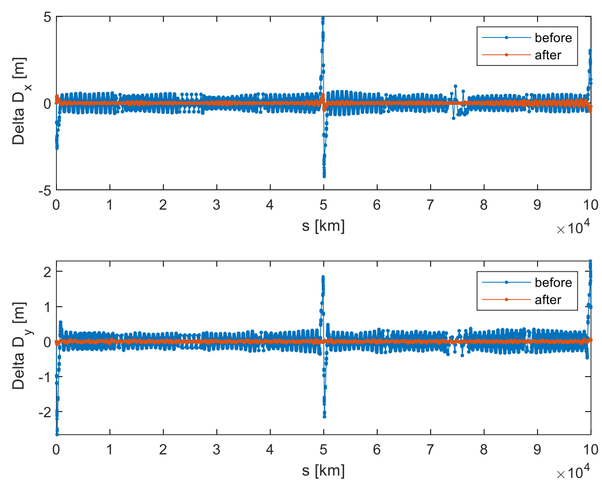
- Use the LOCO program to fit the response matrix itself.
- Minimize the difference between measured and theoretical response matrix by varying the quadrupole strength to correct the beam envelope function：

$$\chi^2 = \sum_{i,j} \frac{\left(M_{meas,ij} - M_{model,ij}\right)^2}{\sigma^2}$$

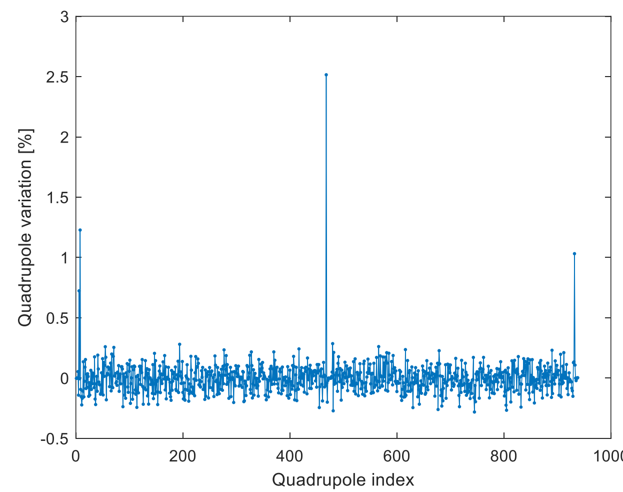
σ: BPM noise given by multiple measurements of BPMs。



Beta-beating
before and after correction



Dispersion deviation
before and after correction



Quadrupole variation less than 3%

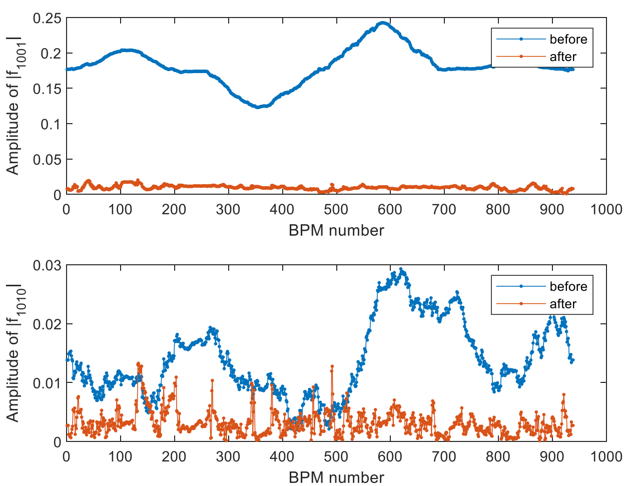
SppC lattice correction scheme

Coupling and vertical dispersion correction：

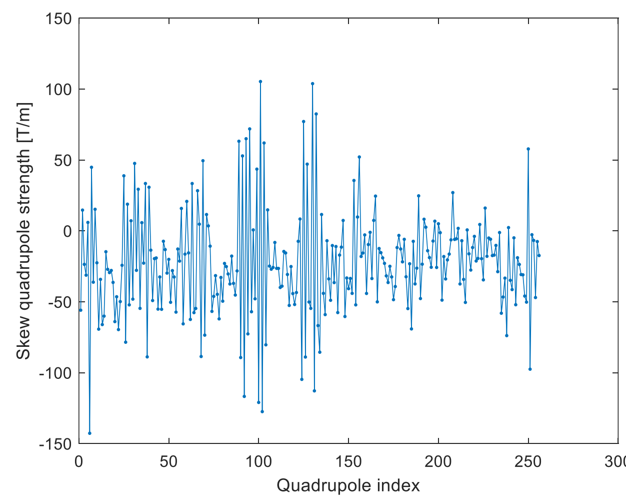
- Correct the linear coupling RDTs by the skew quadrupoles in lattice：

$$\begin{pmatrix} \overrightarrow{f_{1001}} \\ \overrightarrow{f_{1010}} \\ \overrightarrow{D_y} \end{pmatrix}_{meas} + M\overrightarrow{K_s} = 0$$

- f_{1001} and f_{1010}: RDTs of difference and sum resonance, respectively; K_s: Skew quadrupole strength.
- Focus more on the correction of f_{1001} since the tune is close to difference resonance.



Linear coupling RDTs
before and after correction



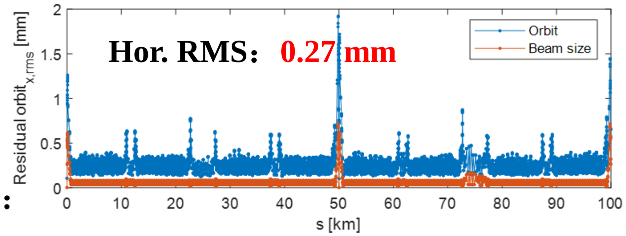
Skew quadrupole strength
less than 150T/m

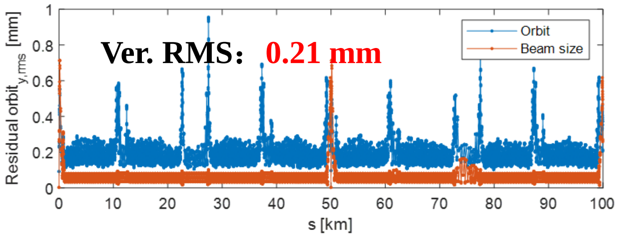
SppC lattice correction results

For collision

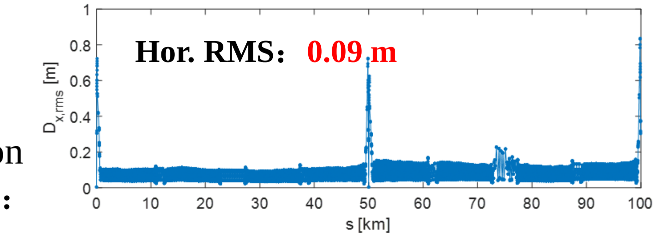
- 90 of 100 machines successfully corrected. Figures show the RMS results of those machines.

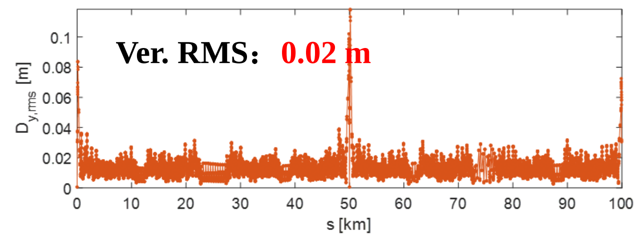
Residual orbit and beam size：



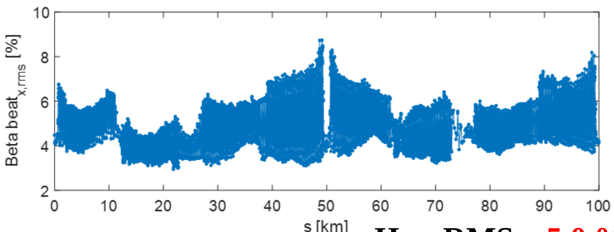


Dispersion deviation：



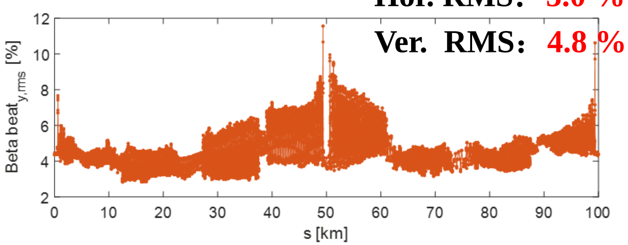


Beta-beating：

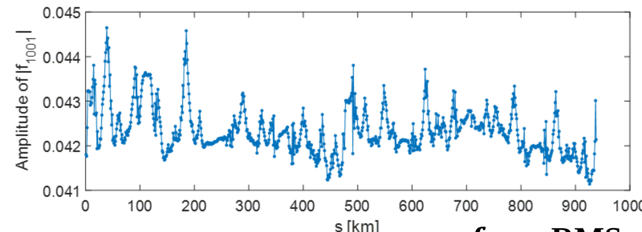


Hor. RMS： 5.0 %

Ver. RMS： 4.8 %

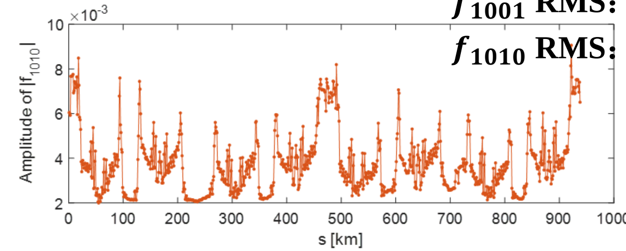


Linear coupling：



f_{1001} RMS： 0.042

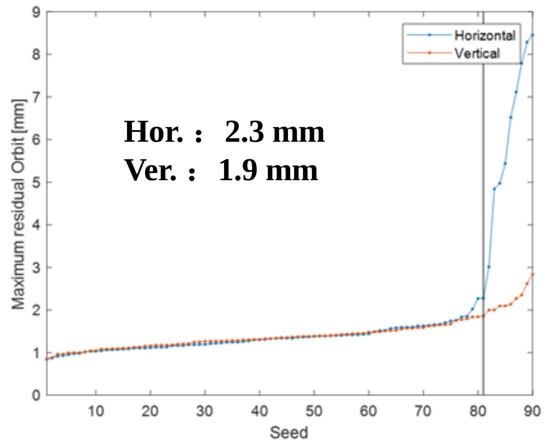
f_{1010} RMS： 0.004



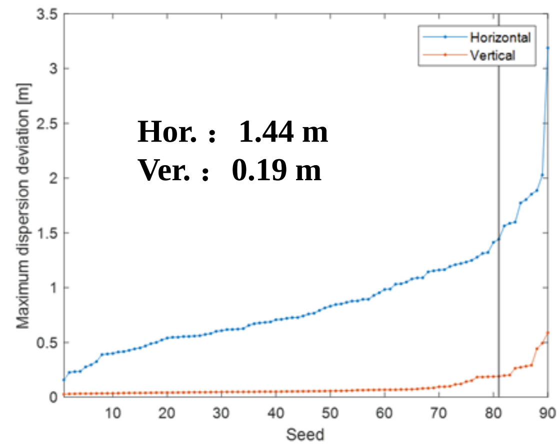
SppC lattice correction results

For collision

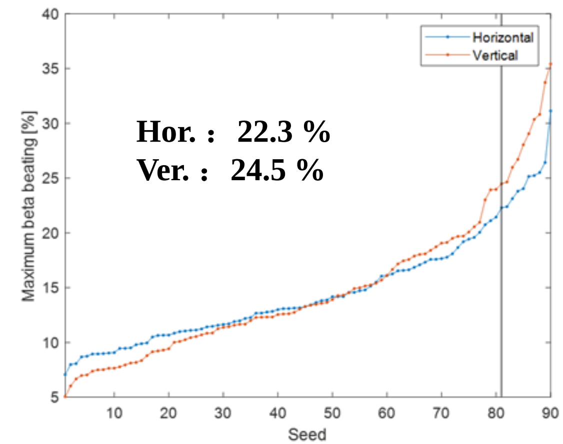
- From the maximum values distribution the 90-percentile is calculated over all 84 machines.



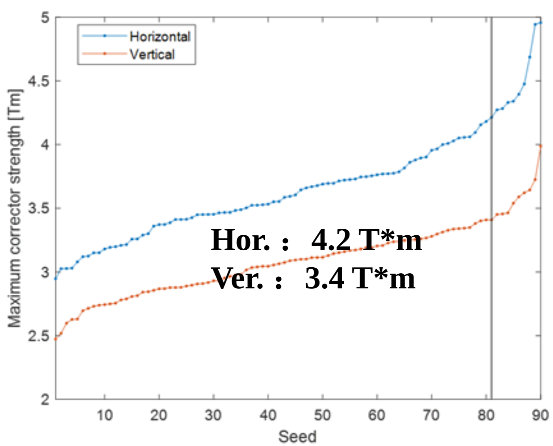
Residual orbit



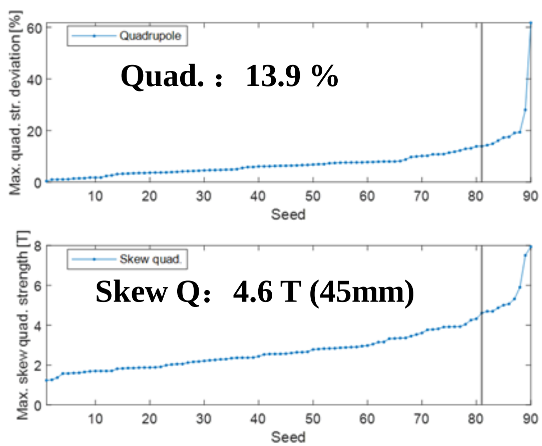
Dispersion deviation



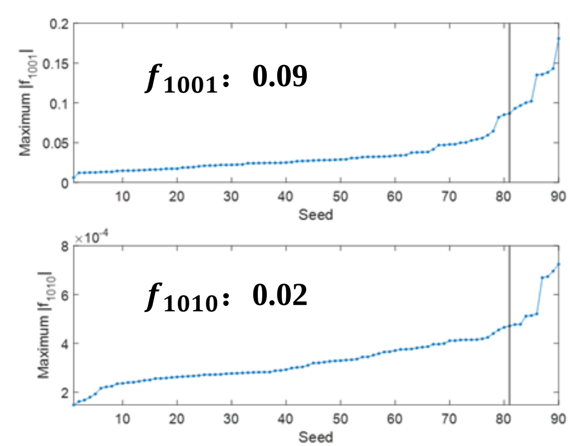
Beta-beating



Corrector strength



Quadrupole deviation and skew quadrupole strength

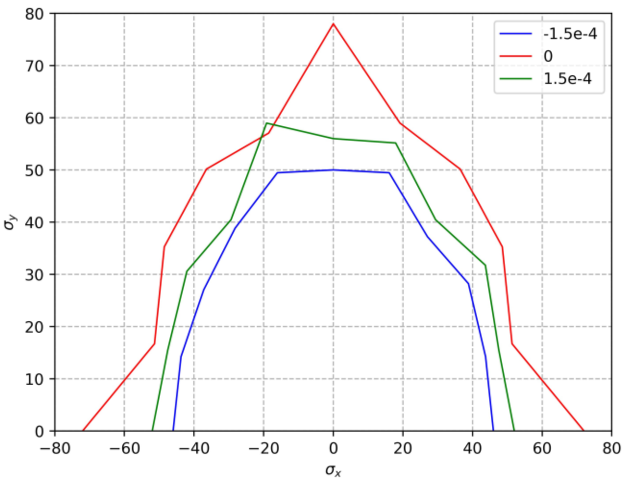


Linear coupling RDTs

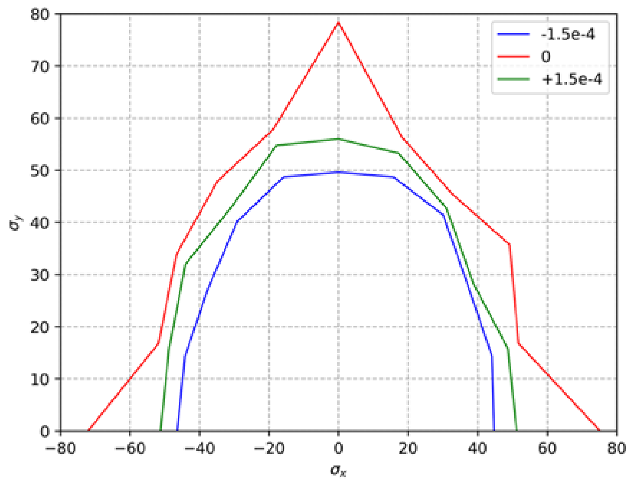
Dynamic aperture

Performed by SAD code, with error correction scheme and RF on;

- Tracking for 100,000 turns;
- Energy deviation set to 1.5×10^{-4} since the RF bucket half height is 3×10^{-4};
- Synchrotron radiation has not been included yet.

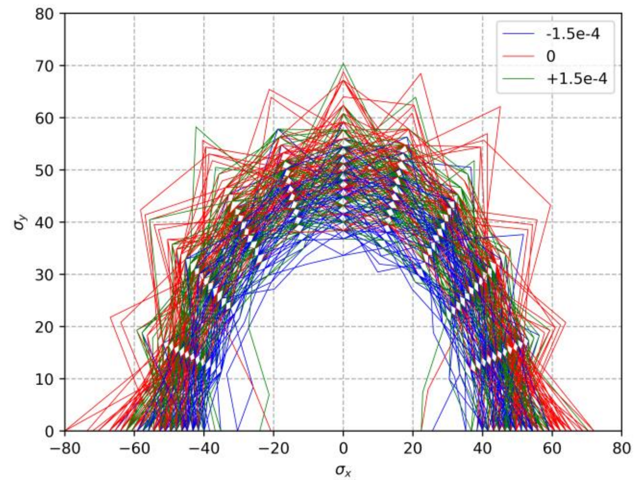


Bare lattice



Bare lattice + beam-beam

90 cases



Bare lattice + beam-beam
+ error correction

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CEPC-SppC compatibility

- Geometry compatibility of the CEPC and SPPC
  - The SPPC will share the tunnel of CEPC as much as possible.
  - The SPPC locates outside of CEPC
  - In the 8 arc regions and 4 short straight sections, two machines share the tunnel (distance of machine centers=3.5m)
  - In the 4 long straight sections, the SPPC will bypass the CEPC (distance of machine centers at IPs=23m as the big size of CEPC and SPPC detectors)
    - IP1 and IP3 for CEPC interaction and SPPC collimation, IP2 and IP4 for CEPC RF and SPPC interaction

Tunnel in the ARC

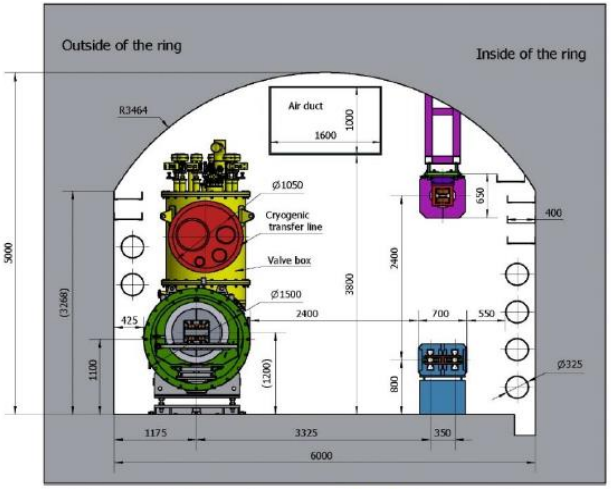
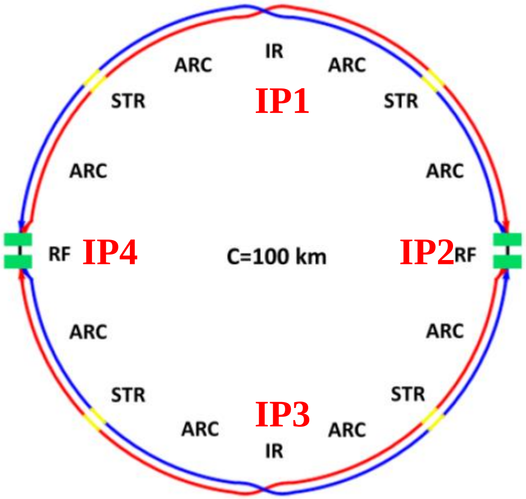
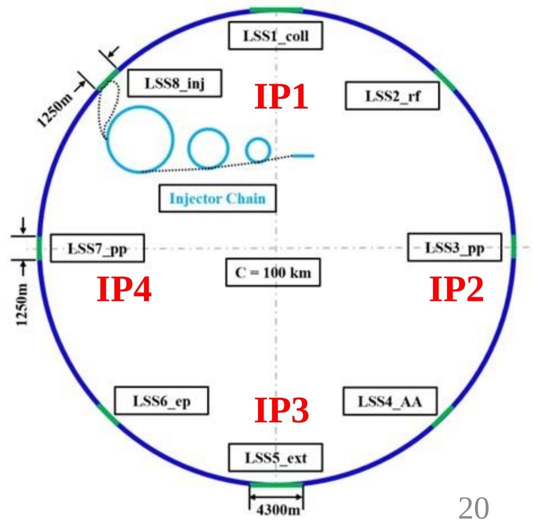


Figure 2.1: Tunnel cross section in the arc region

CEPC Layout



SPPC Layout



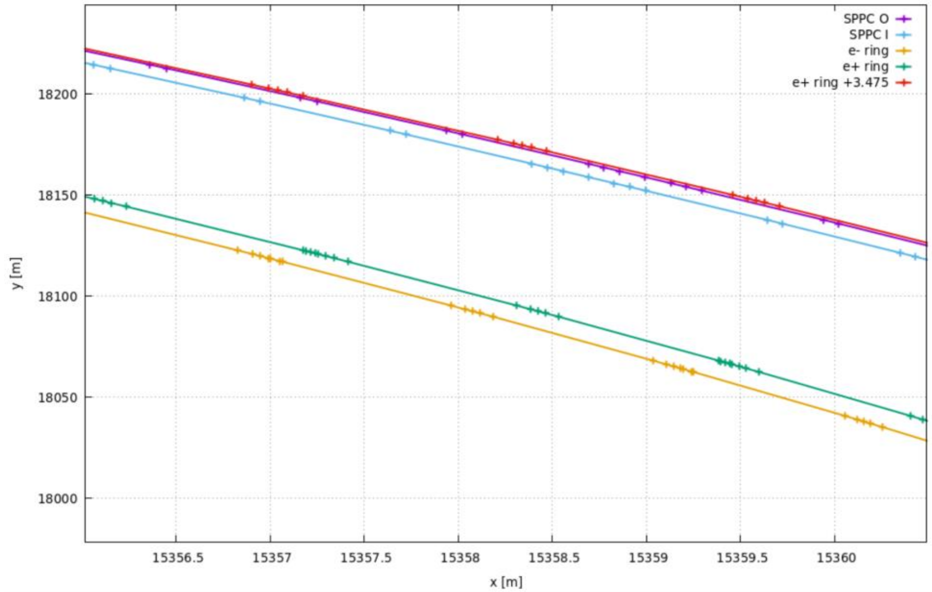
With bypass

SPPC updated to double ring:

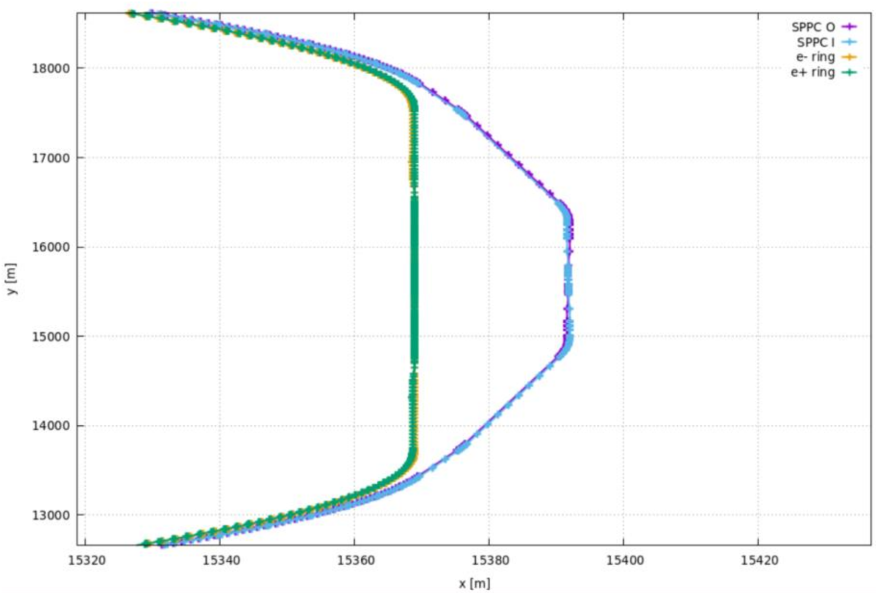
- Strength of dipole (arc and bypass): 20.31 T
- Swap at IP2 and IP4
- Double ring separation: 30 cm

Distance of two machine's centers:

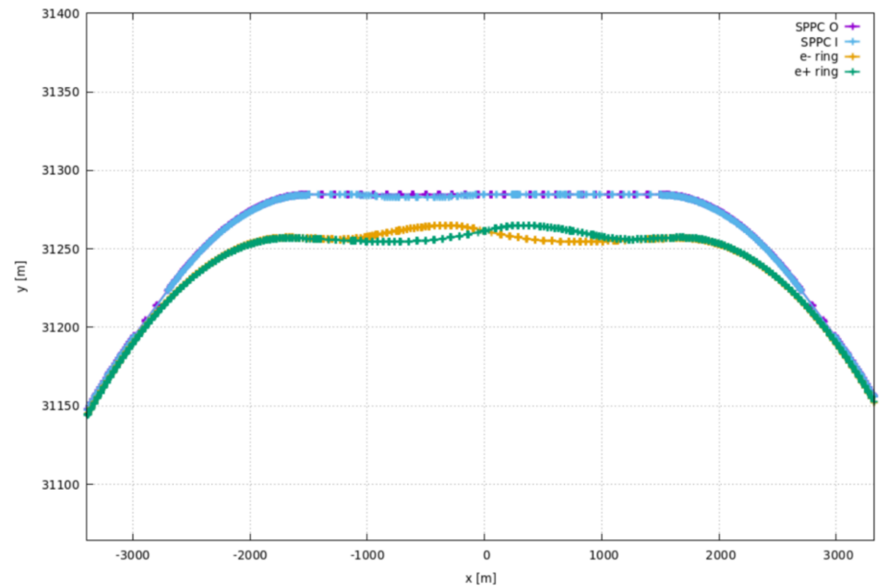
- Separation with CEPC at ARC: 3.5 m
- Separation with CEPC at IPs: 23 m



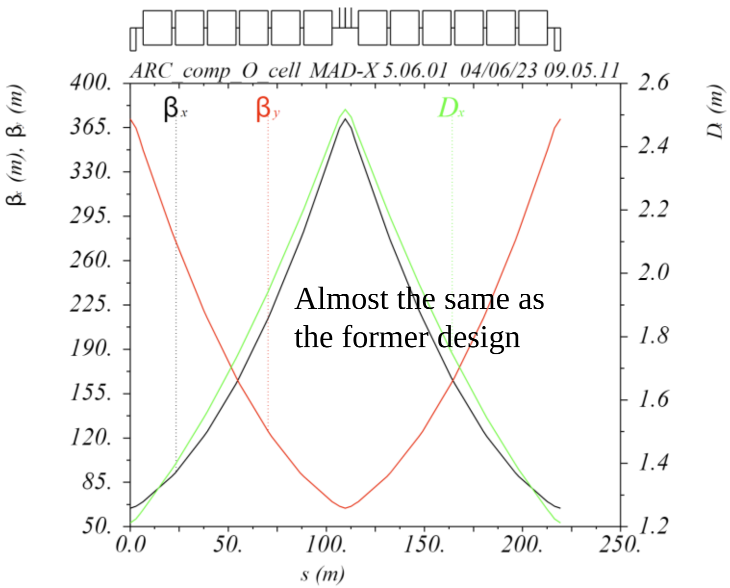
Geometry of arc section



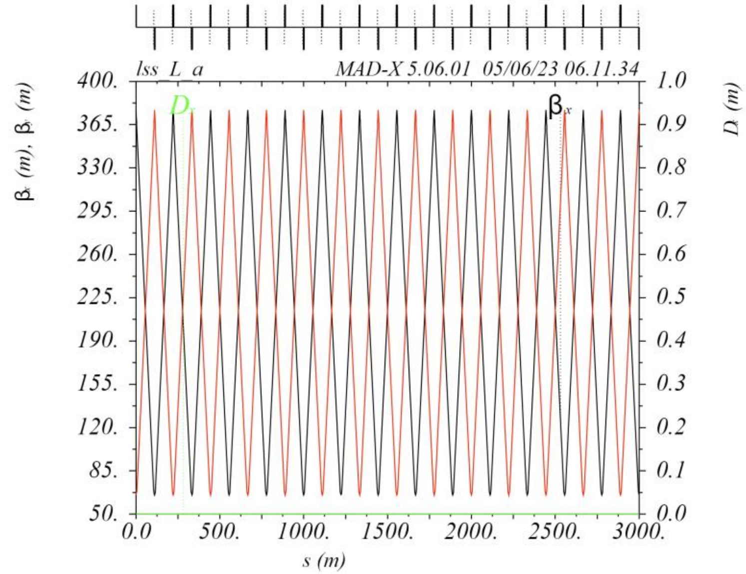
Geometry of bypass at IP2
with a total length of 4399 m



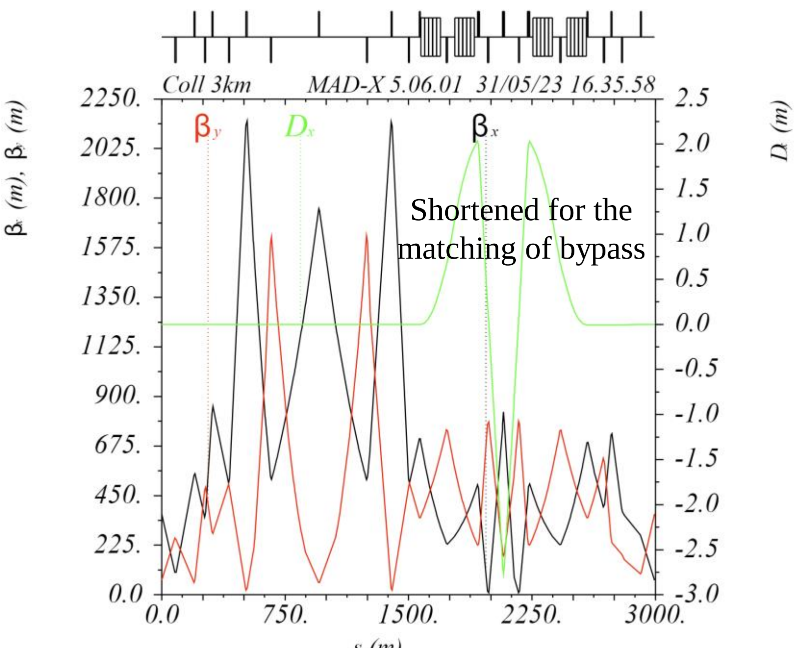
Geometry of bypass at IP3
with a total length of 5985.34 m



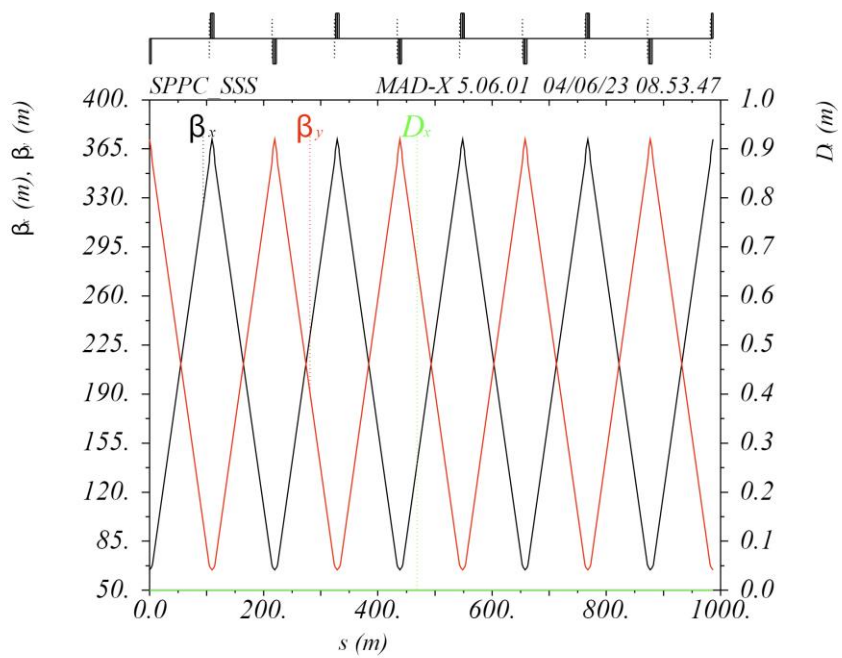
New Arc cell



3 km long straight section



3 km collimation section



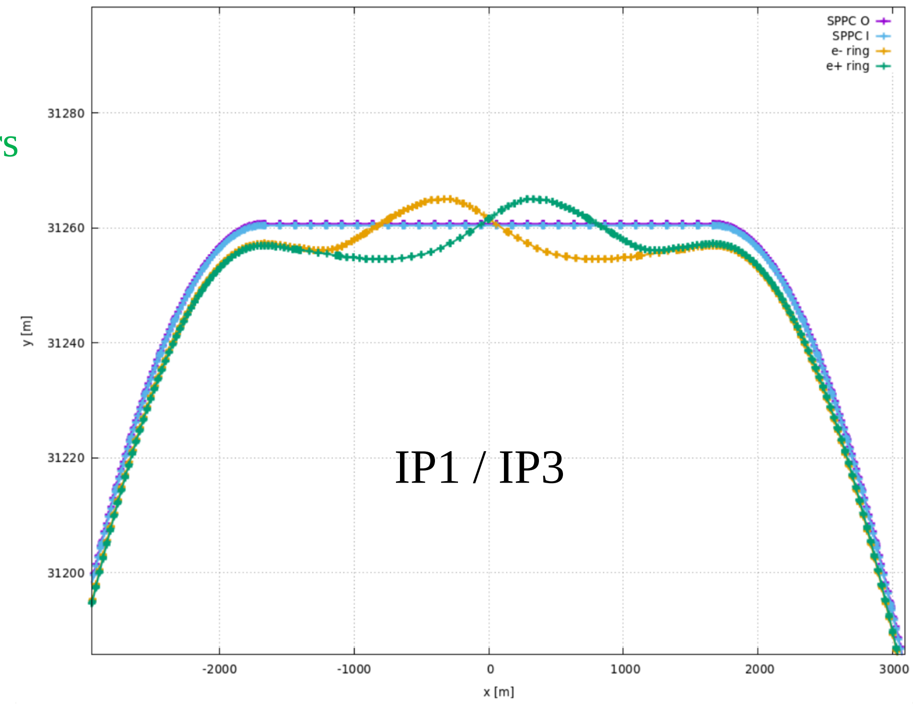
986.84 m short straight section

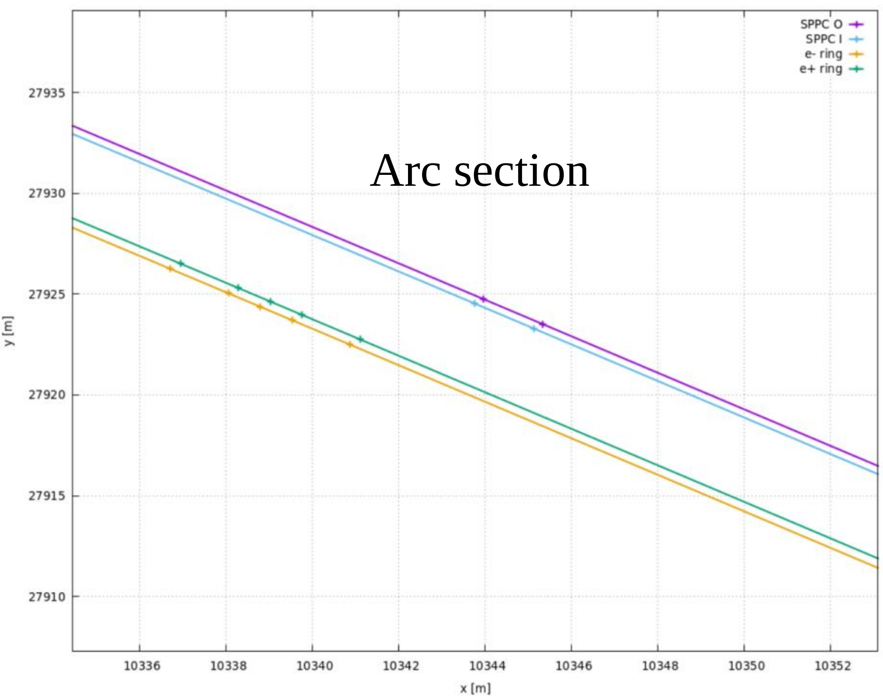
Without bypass for the absence of CEPC detectors

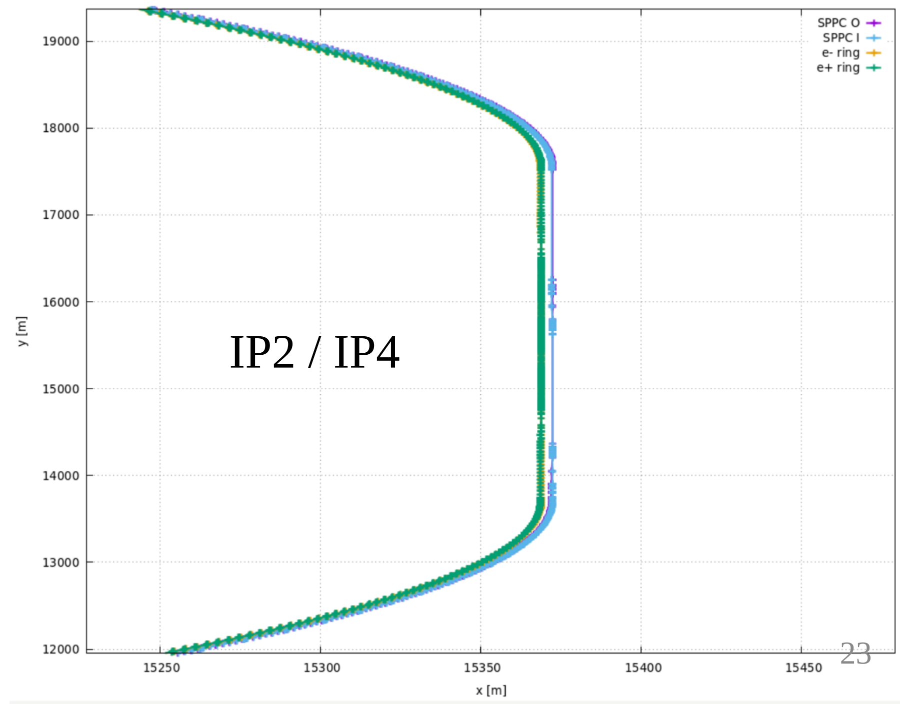
SPPC updated to double ring:

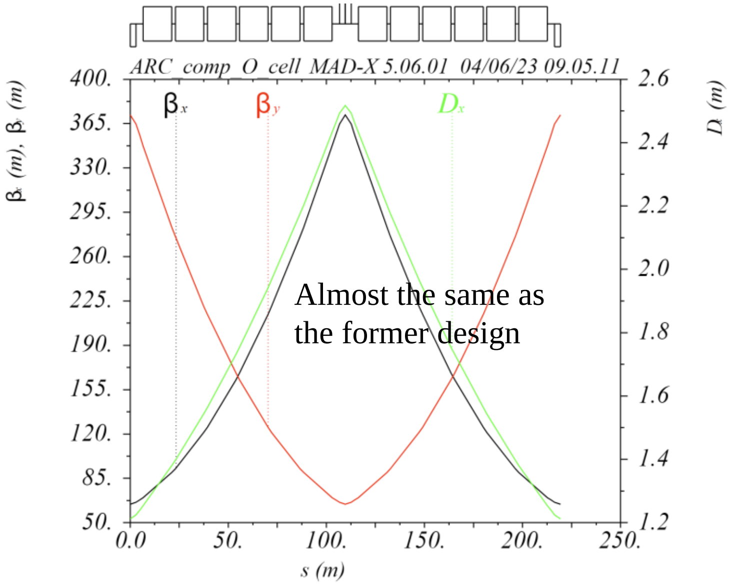
- Strength of dipole (arc and bypass): 20.31 T
- Swap at IP2 and IP4
- Double ring separation: 30 cm

Distance of two machine's centers: 3.5 m

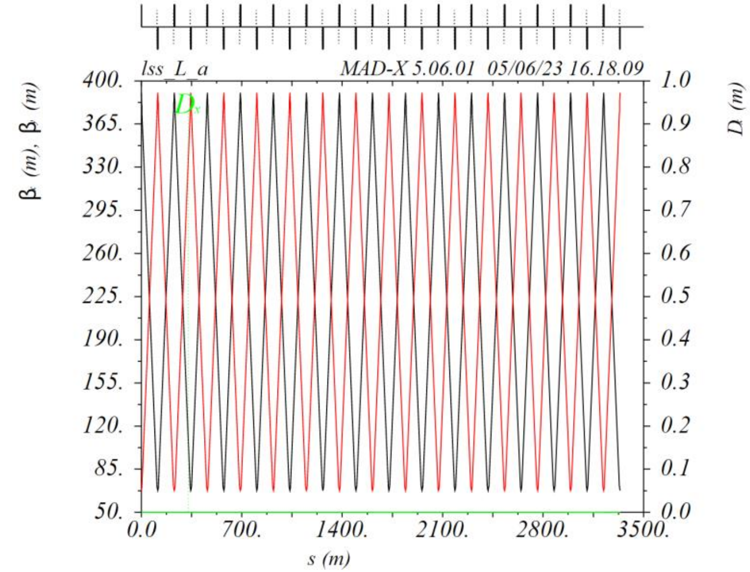




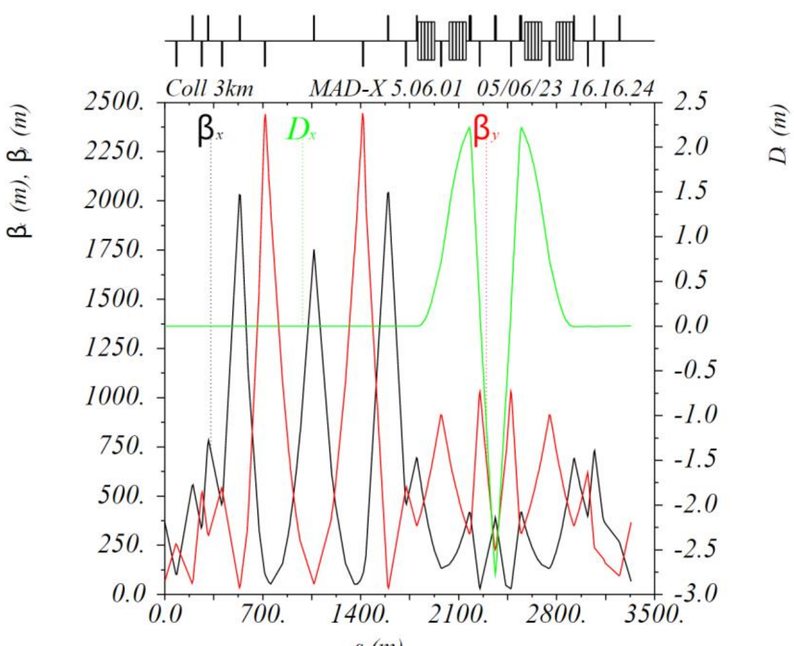




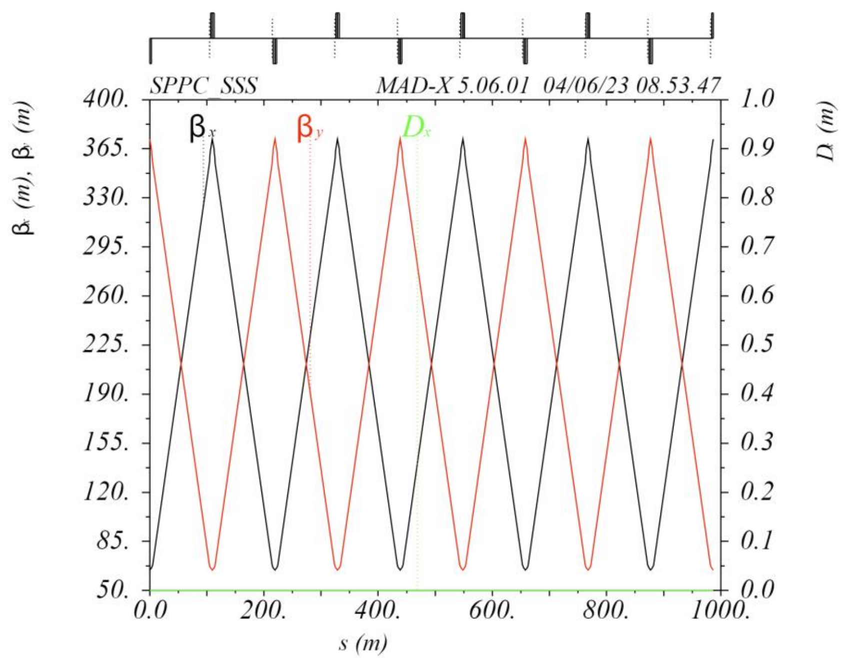
New Arc cell



3337.13 m long straight section



3337.13 m collimation section



986.84 m short straight section

Geometric parameters of SPPC and CEPC

With bypass:

	SPPC before	SPPC after	CEPC
Arc between SSS and final focus	10487.52 m	9962.31 m	10270.44 m
Arc between SSS and collimation/extraction	10487.52 m	8865.69 m	10185.70 m
Arc cell	213.42 m	219.32 m	54.63 m
Linear section at IP1/IP3	4300 m	3000 m	3337.13 m
Linear section at IP2/IP4	1250 m	1250 m	3776.90 m
Short straight section	1250 m	986.84 m	986.84 m
Bypass at IP1/IP3	/	5985.34 m	/
Bypass at IP2/IP4	/	4399 m	/
Circumference	100000 m	100027.44 m	100000.0 m

*Arc including DIS sections

Without bypass:

	SPPC before	SPPC after	CEPC
Arc between SSS and final focus	10487.52 m	10273.29 m	10270.44 m
Arc between SSS and collimation/extraction	10487.52 m	10188.55 m	10185.70 m
Arc cell	213.42 m	219.32 m	54.63 m
Linear section at IP1/IP3	4300 m	3337.13 m	3337.13 m
Linear section at IP2/IP4	1250 m	3776.90 m	3776.90 m
Short straight section	1250 m	986.84 m	986.84 m
Circumference	100000 m	100021.84 m	100000.0 m

*Arc including DIS sections

Summary

- A global correction scheme based on response matrix method is presented. Lattices at collision energy with errors have been corrected.

- For the compatibility of CEPC and SppC, two kinds of SppC lattice design are presented for the presence or absence of bypass respectively.

- Further improve the global correction results to get a more relaxed tolerance.

Thanks for your attention!