中国科学院高能物理研究所
Institute of High Energy Physics
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APES Development: Progress Report & Current Status

Tianmu Xin

On behalf of APES team

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Outline

- Motivation
- Design philosophy
- Modeling and Optics
- Tracking and Simulation
- Summary

Motivation

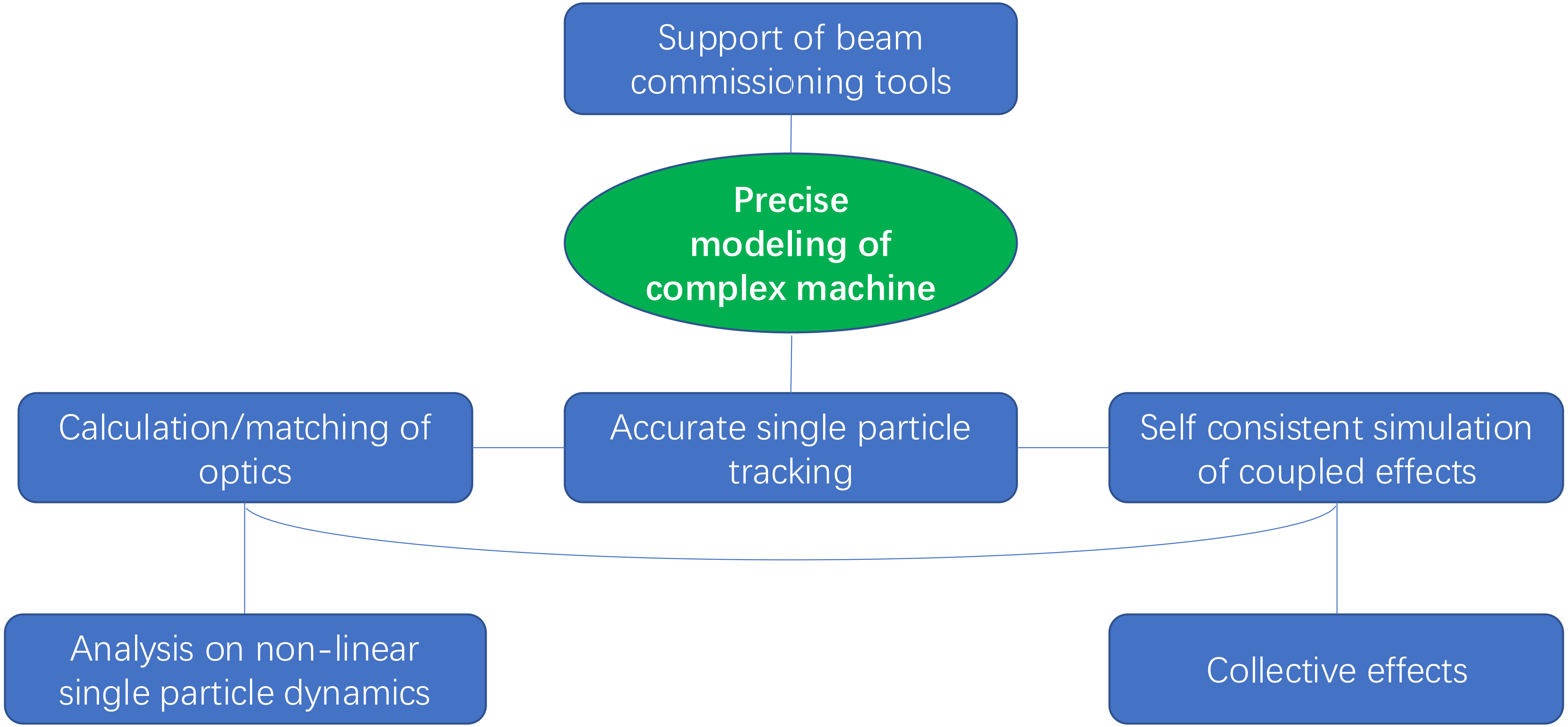
Supported by IHEP Innovation Fund from 2022 to 2024

To meet the requirements of beam dynamics study in CEPC

- Modeling complicated lattice easily
  - IR, overlapped field, …
- Combined effects should be studied self-consistently
  - Beam-beam interaction + impedance/feedback/lattice, …
- Application of new IT technology
  - CPU, Openmp/MPI -> GPU, CUDA

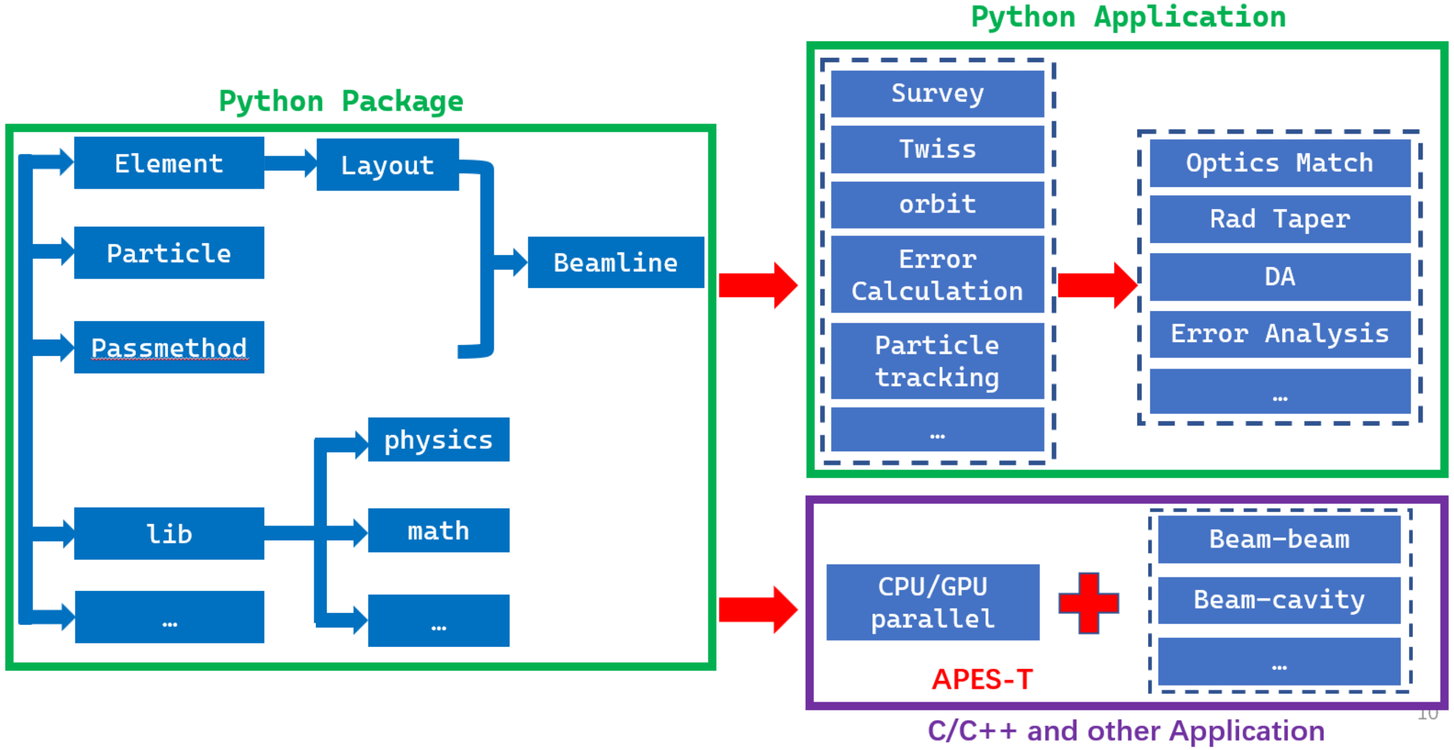
More user-friendly, more accurate, powerful and faster

Design philosophy



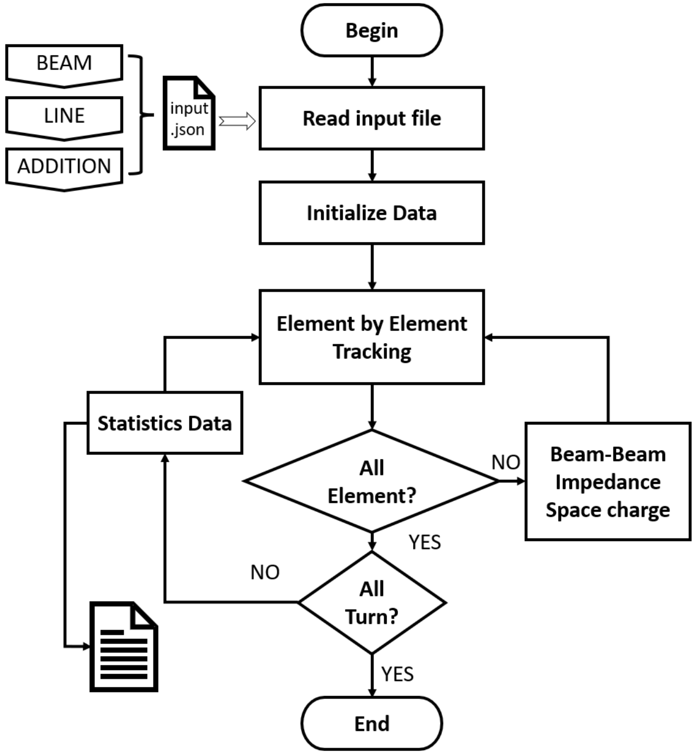
Design philosophy

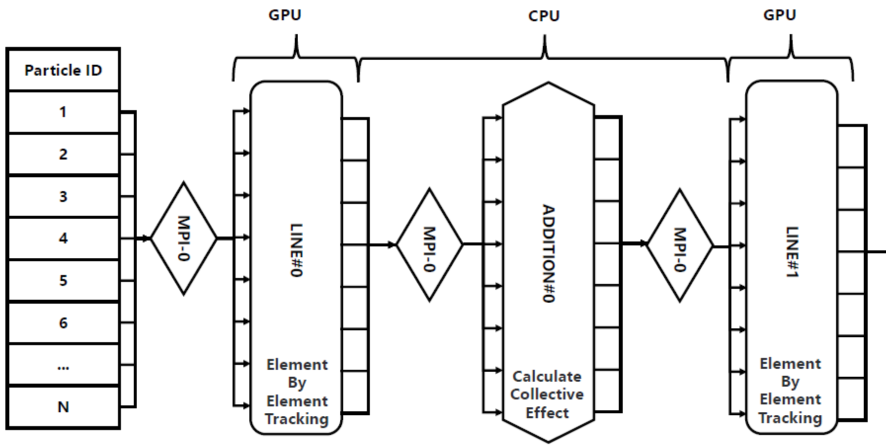
- Python, C/C++
- Bottom-up and top-down synchronized development
  - Python-based modeling, analysis, computation logistic
  - High-efficiency Parallel Computing for Multi-Particle Tracking
  - Same underlying map

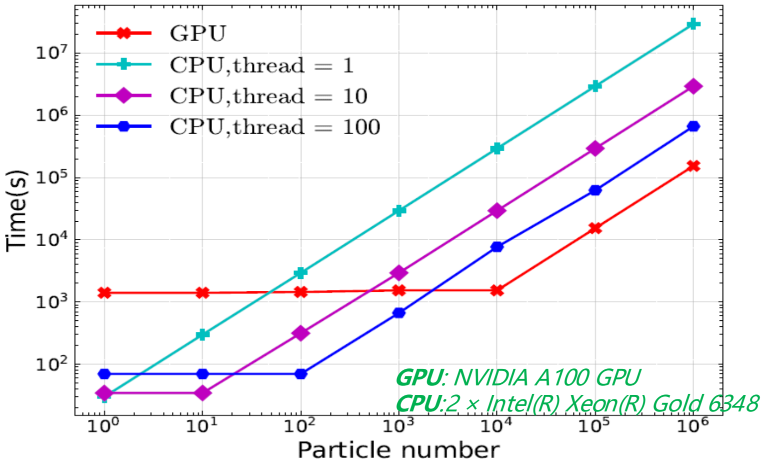


Design philosophy
Multi-particle tracking

- Focus on High-performance simulation
- Tracking through simple Element in parallel on GPU
- Tracking through special element on CPU:
  - Strong-strong beam-beam interaction
  - Feedback
  - Collective effects
    - Short-range Wakefield
    - Space Charge (Ohmi)
    - Beam-Cavity
    - Electron Cloud
    - Ion effects
    - Intra-beam Scattering
    - …
- CUDA+MPI





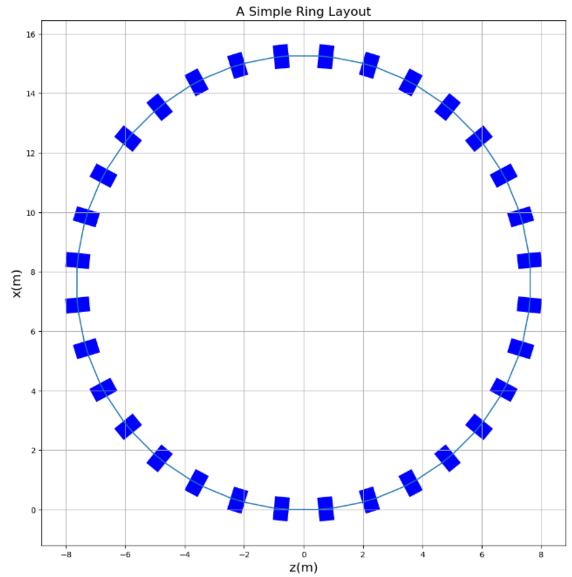


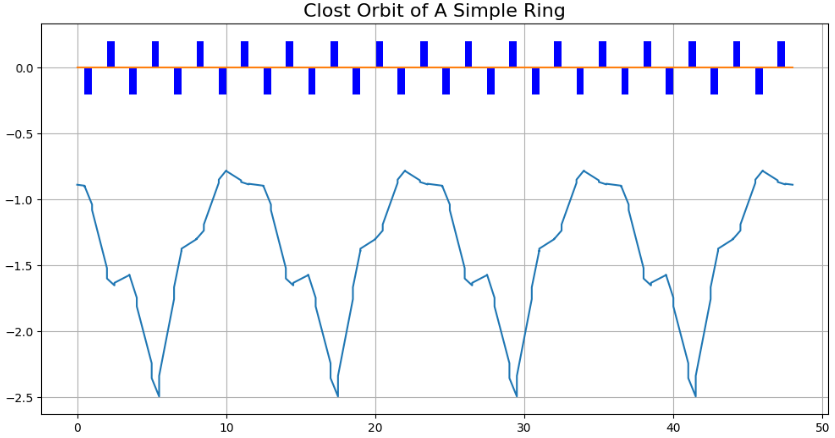
Design philosophy

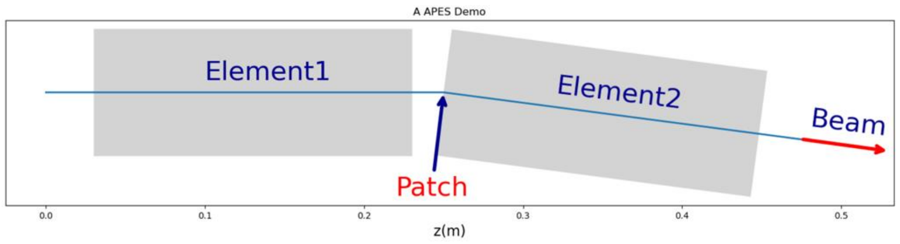
The idea of **Patch** coming from PTC

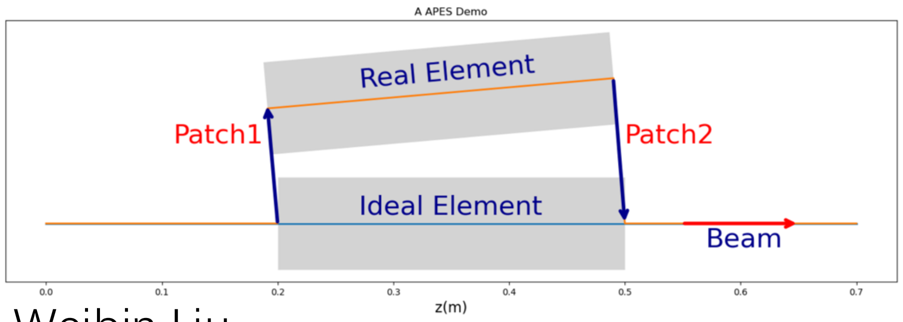
- Affine transformation in geometry
- Maps in particle tracking
- Single “Patch” affects the downstream survey.
- Allows for special installation configurations / misalignment

A ring with only Quadrupoles









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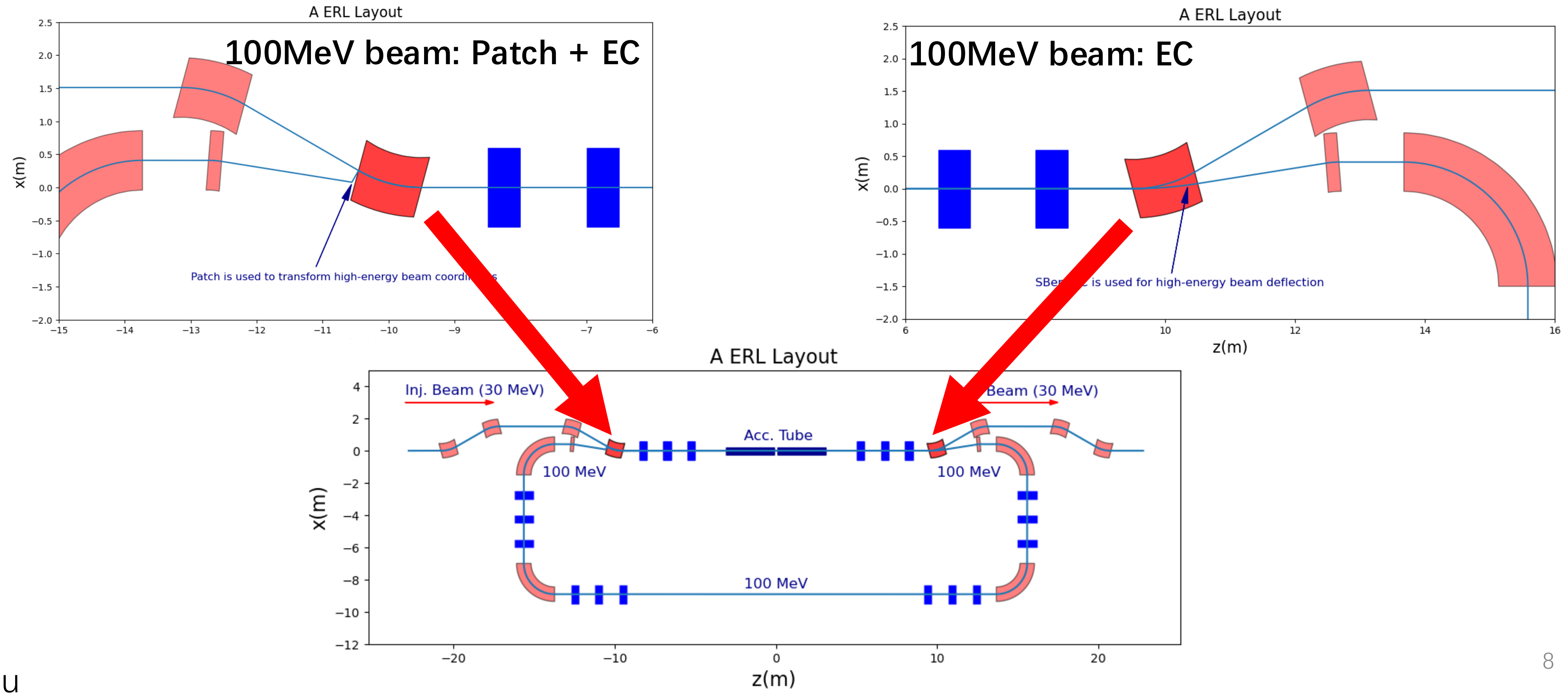
Design philosophy

Element Container

- Encapsule one or more components
- Ensemble positional error for co-mounted components
- Different beam go through same component
- Forward or backward traversal



Weibin Liu

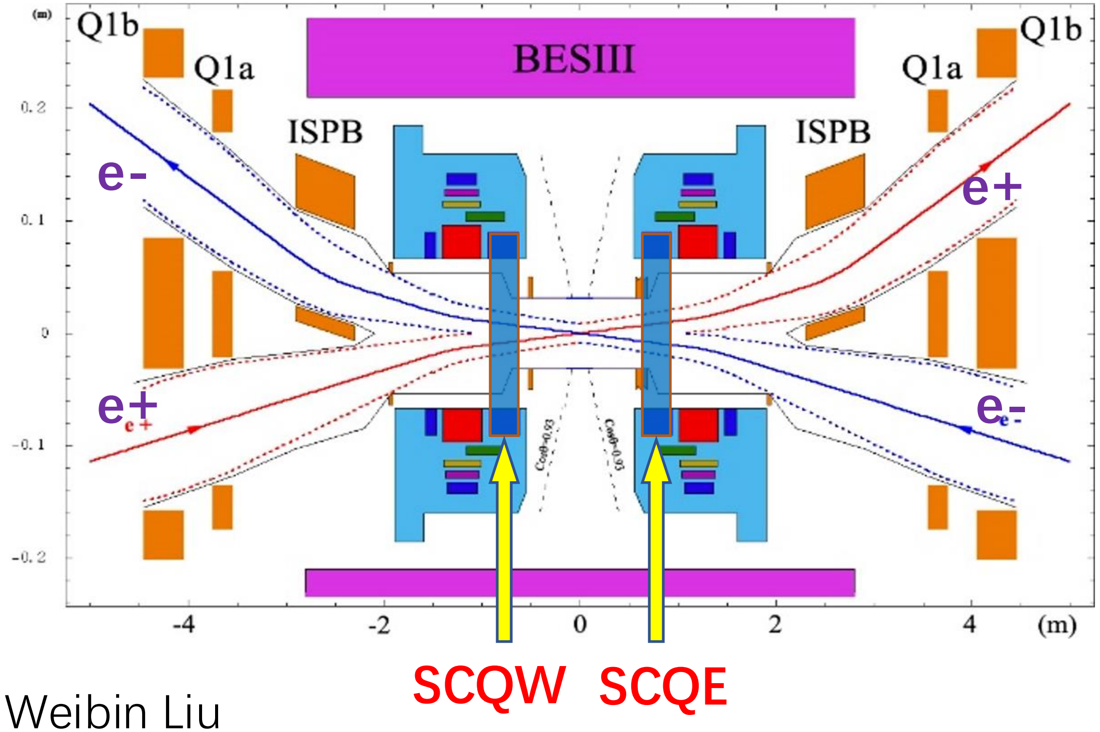
Modeling and optics

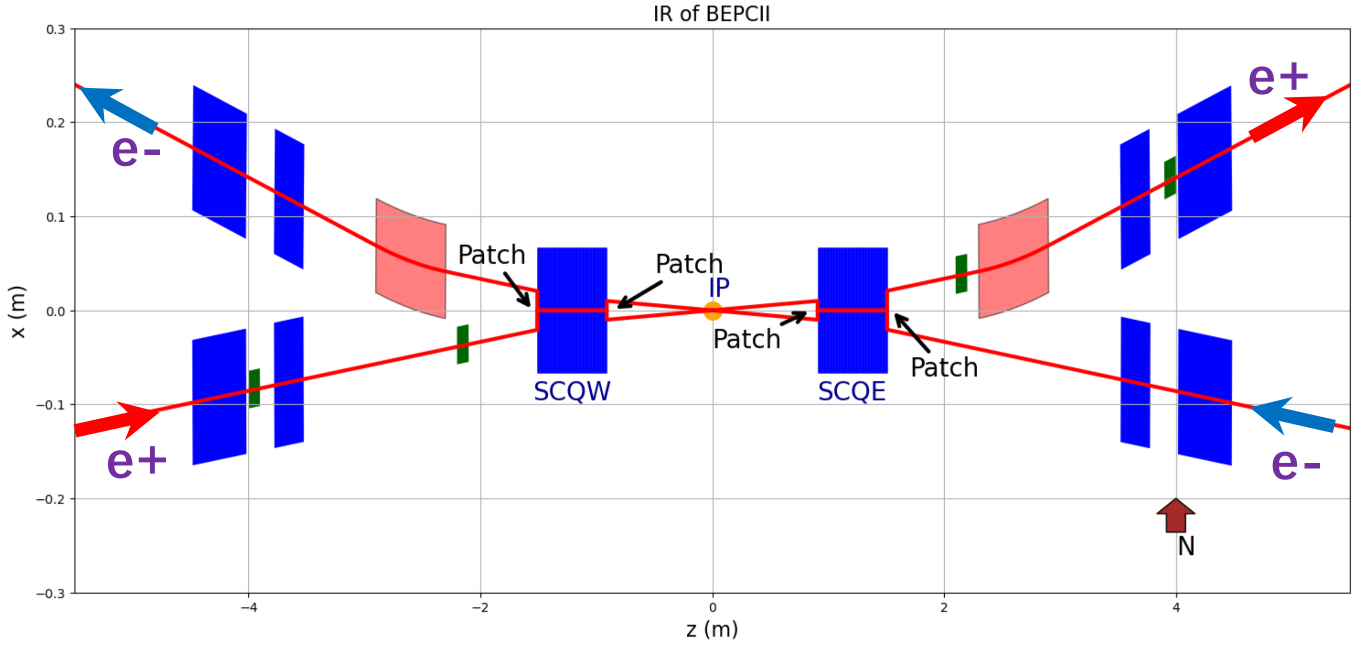
IR modeling of BEPCII

Patch1+SCQ+Patch2

```
BPR4IR = [IP, D4I01, R4CBPM00, D4I01P, P_SCQ_4II, SCQE, P_SCQ_4IO]

BER4IR = [P_SCQ_R4OO, ~SCQE, P_SCQ_R4OI, D4O01P, R4CBPM00, D4O01, IP]
```



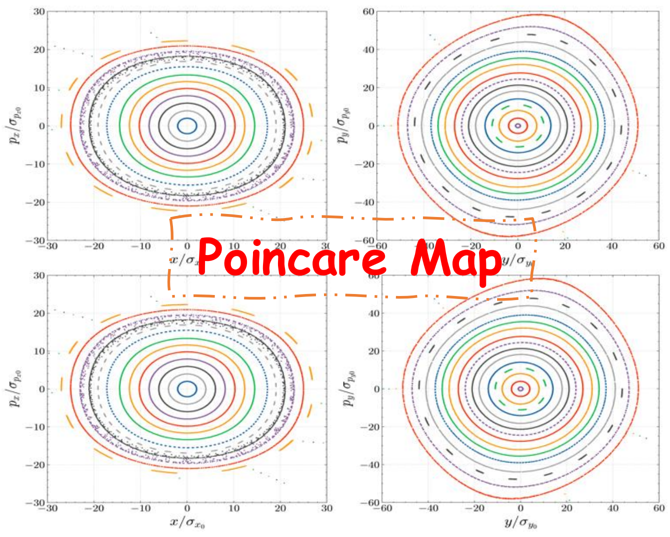


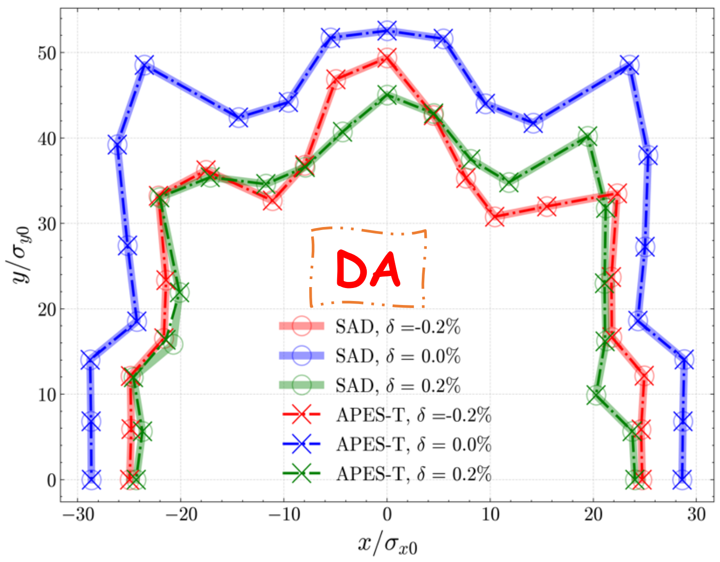
Modeling and optics

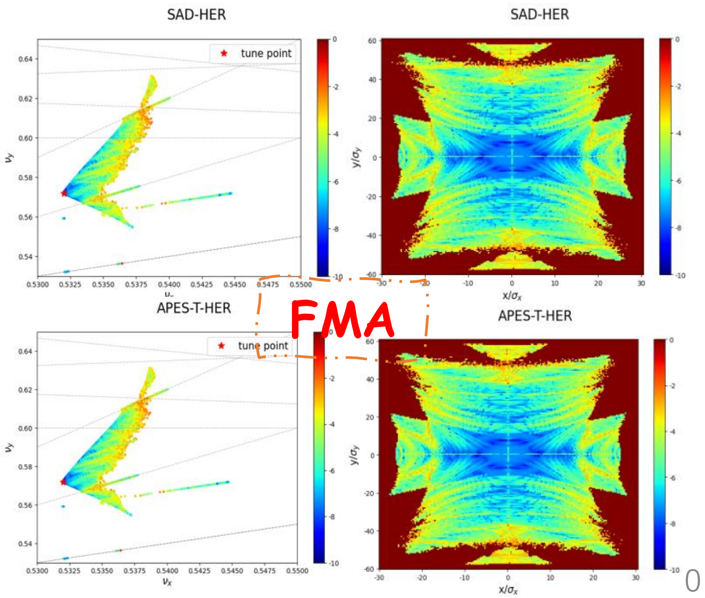
Transfer Map referring to SAD

- 6D full-symplectic tracking
- Linear soft edge + nonlinear Maxwellian fringe
- Field overlap of solenoid and multipoles

Benchmark of single particle tracking with SuperKEKB



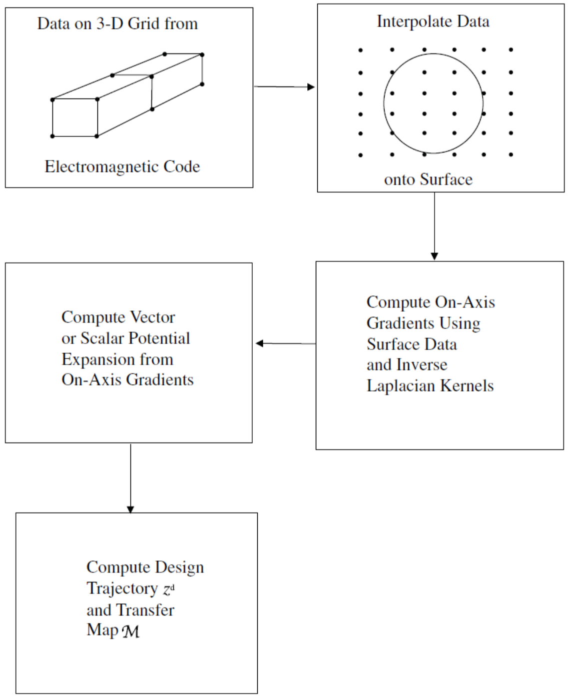


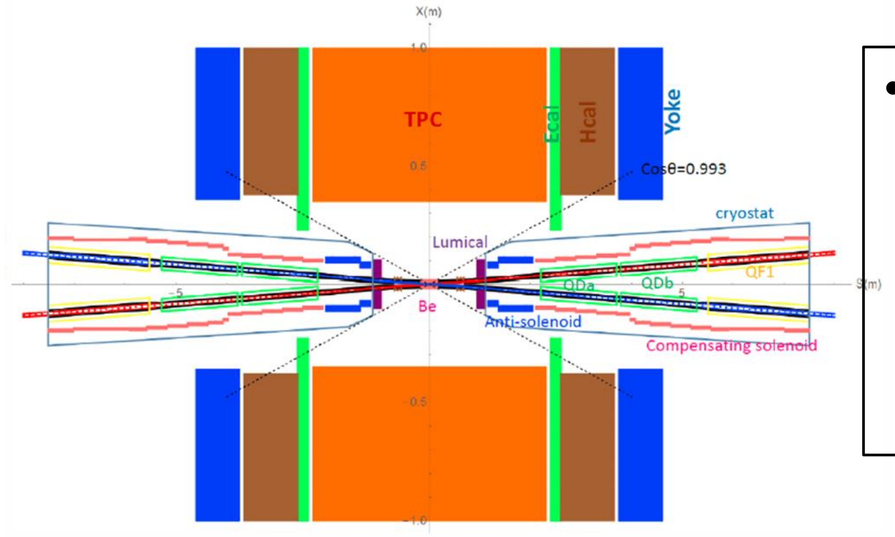


Modeling and optics

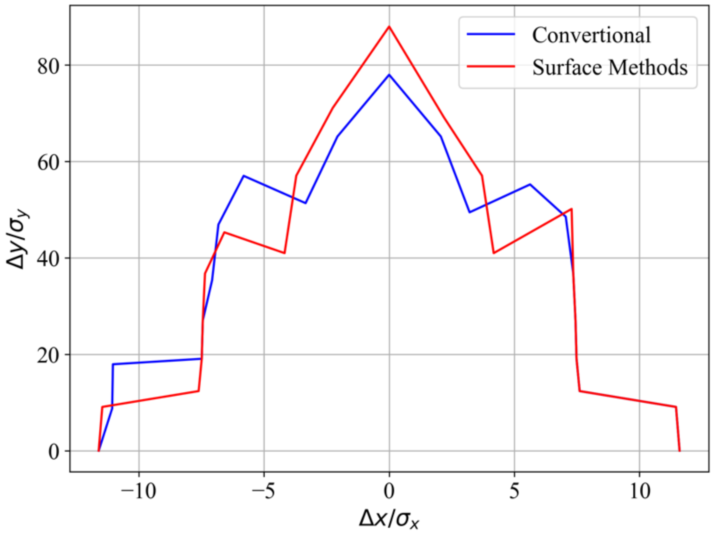
Implementation of Surface Method

- Exact modeling of multipoles and fringe fileld
- Inverse Laplacian Kernels help reducing the field noise
- Implicit symplectic integrator





- Final focus region of CEPC
  - 6 dual-aperture SC quad
  - 3 T detector solenoid
  - Anti-solenoid
  - Dipole corrector and skewQ



Ande Ma

Modeling and optics

Optics function

4D,5D and 6D with SR damping

- General Twiss function
  - Closed orbit
  - Jacobian Matrix
  - Linear Normal Form Analysis

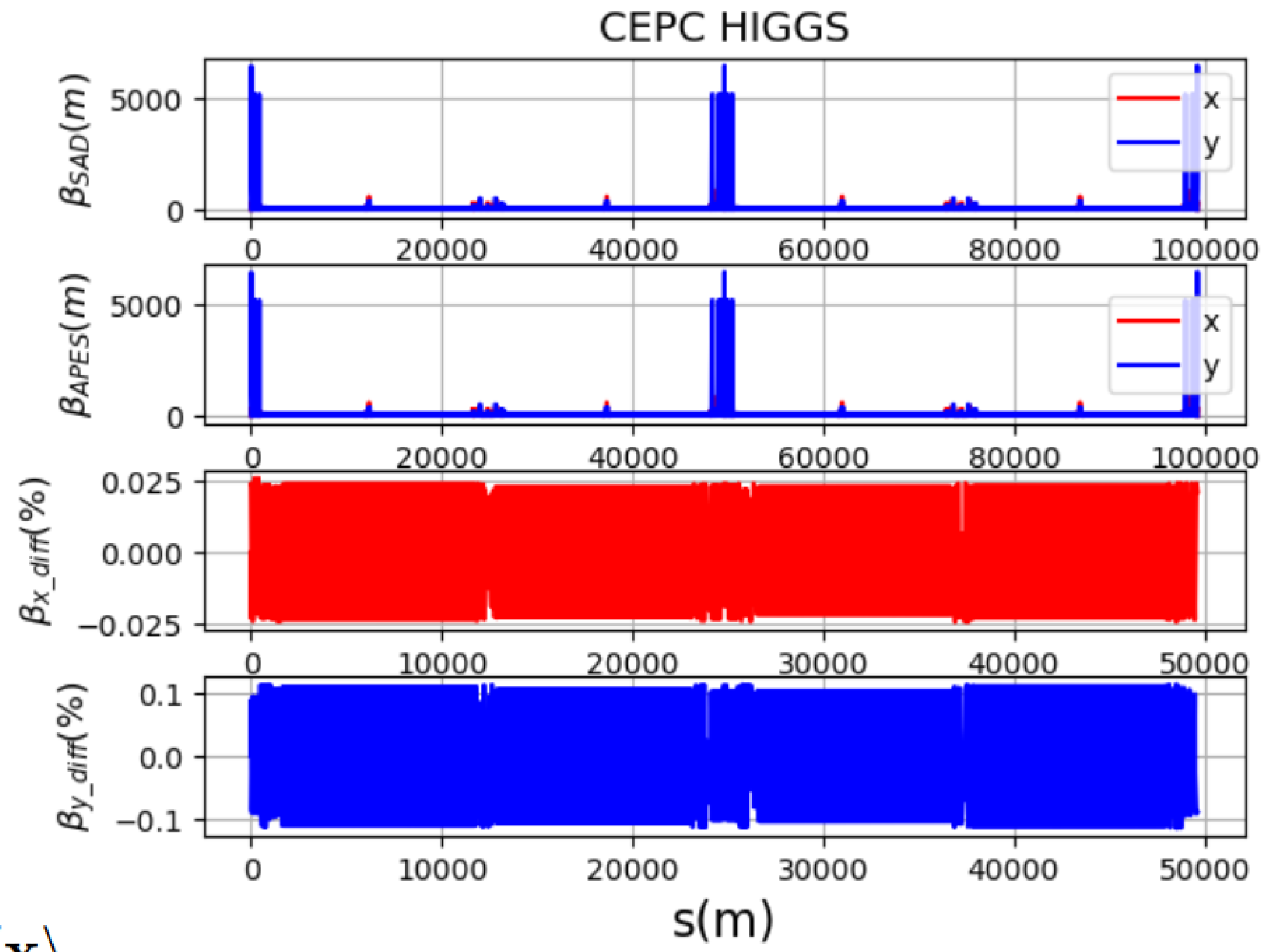
$$\Sigma = \sum_{I,II,III} B^K \epsilon_K$$

$$\beta_x = B^I_{11}, \quad \beta_y = B^{II}_{33}$$
$$\alpha_x = -B^I_{12}, \quad \alpha_y = -B^{II}_{34}$$
$$\gamma_x = B^I_{22}, \quad \gamma_y = B^{II}_{44}$$

$$\mathbf{x} = \mathbf{x_0} + D\delta + D^z z$$

$$D = \frac{\partial}{\partial \langle \delta \rangle_C} \langle \mathbf{x} \rangle_C$$

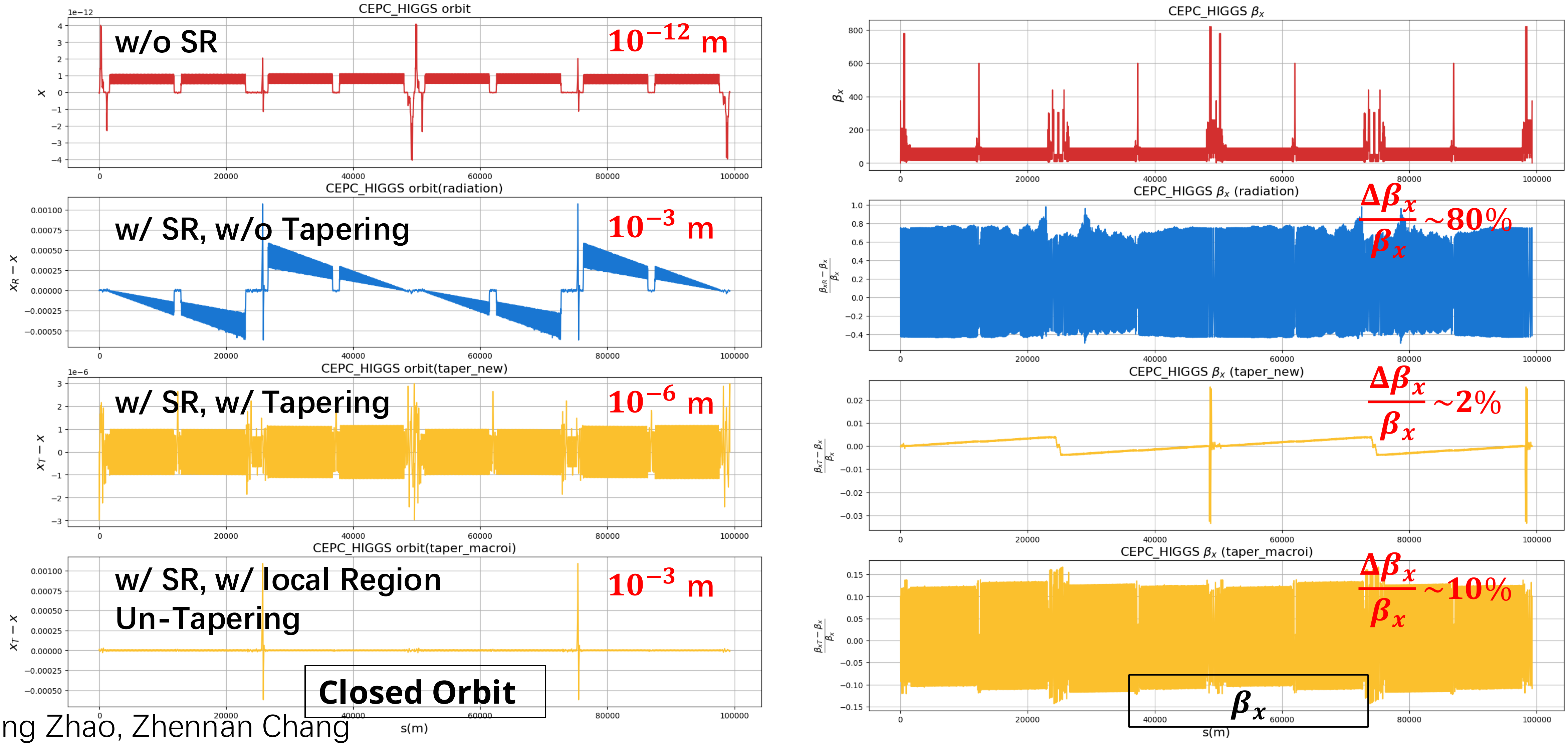
$$\langle \mathbf{x} \rangle_C = \langle \mathbf{x_0} \rangle_C + D \langle \delta \rangle_C + D^z \langle z \rangle_C \quad D^z = \frac{\partial}{\partial \langle z \rangle_C} \langle \mathbf{x} \rangle_C$$



Difference from SAD ~ 0.1%

Modeling and optics
Synchrotron Radiation and tapering

- Energy deviation along the ring
- Magnet tapering mitigate the orbit distortion
- Selectively taper the magnets is possible



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Modeling and optics

Emittance

- Ohmi's envelope method

$$\Sigma = M\Sigma M^T + \bar{B}$$

Equivalence matrix at s

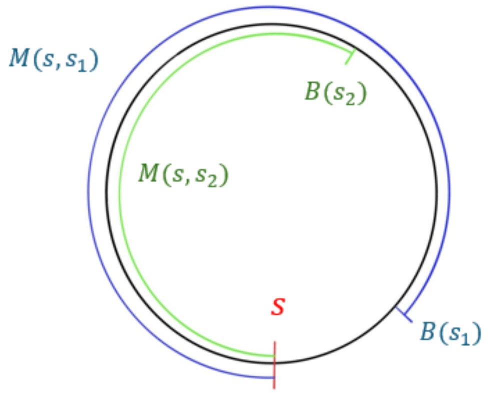
One-turn Matrix

Quantum Excitation (Diffusion Matrix)

$$\bar{B} = \int_{s_0}^{s} M(s,s')B(s')\,M^T(s,s')ds'$$

Transfer matrix from s' to s.

Quantum excitation at s'



$$\bar{B} = M(s,s_1)B(s_1)M^T(s,s_1) + M(s,s_2)B(s_1)M^T(s,s_2) + \cdots$$

HEPS	Elegant	APES	Difference
Damping in x	4.178e-4	4.187e-4	0.23%
Damping in y	2.201e-4	2.199e-4	~0
Damping in z	2.424e-4	2.412e-4	0.52%
Emittance x	3.482e-11	3.479e-11	0.096%
Energy spread	1.018e-3	1.020e-3	0.20%

CEPC HIGGS	SAD	APES	Difference
Damping in x	7.523e-3	7.550e-3	0.37%
Damping in y	7.523e-3	7.550e-3	0.36%
Damping in z	1.488e-2	1.510e-2	1.49%
Emittance x	6.648e-10	6.646e-10	0.029%
Energy spread	1.013e-3	1.013e-3	0.003%

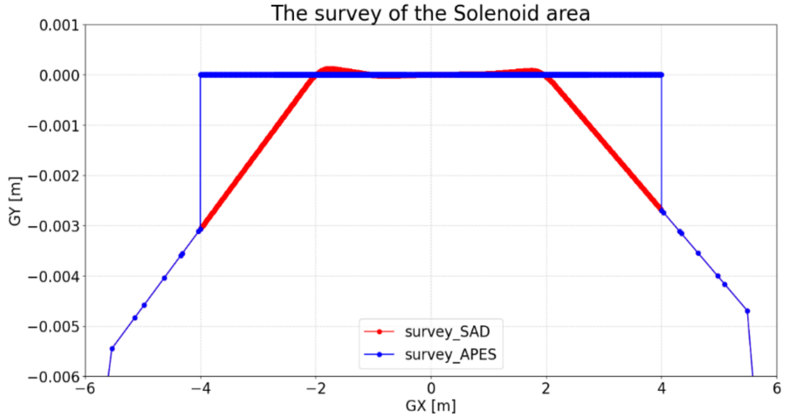
Modeling and optics

Modeling LER of SuperKEKB in APES

- SAD
  - Uses GEO and BOUND to define a solenoid boundary
  - Composed of interleaved SOL (Bz<>0) and MULT (K_0, K_n, SK_n)
  - Solenoid data from field maps with magnetic field expansion on beam pipes
  - The coordinate frame transforms at the entry and exit of the solenoid
- APES (Transfer map referring to SAD)
  - No BOUND defined, components in solenoid have "Insol" flag
  - Interleaved components with field data from SAD
  - Use patches to calibrate the survey to SAD's at the boundary of solenoid

Patch at solenoid boundary

Patch at solenoid boundary



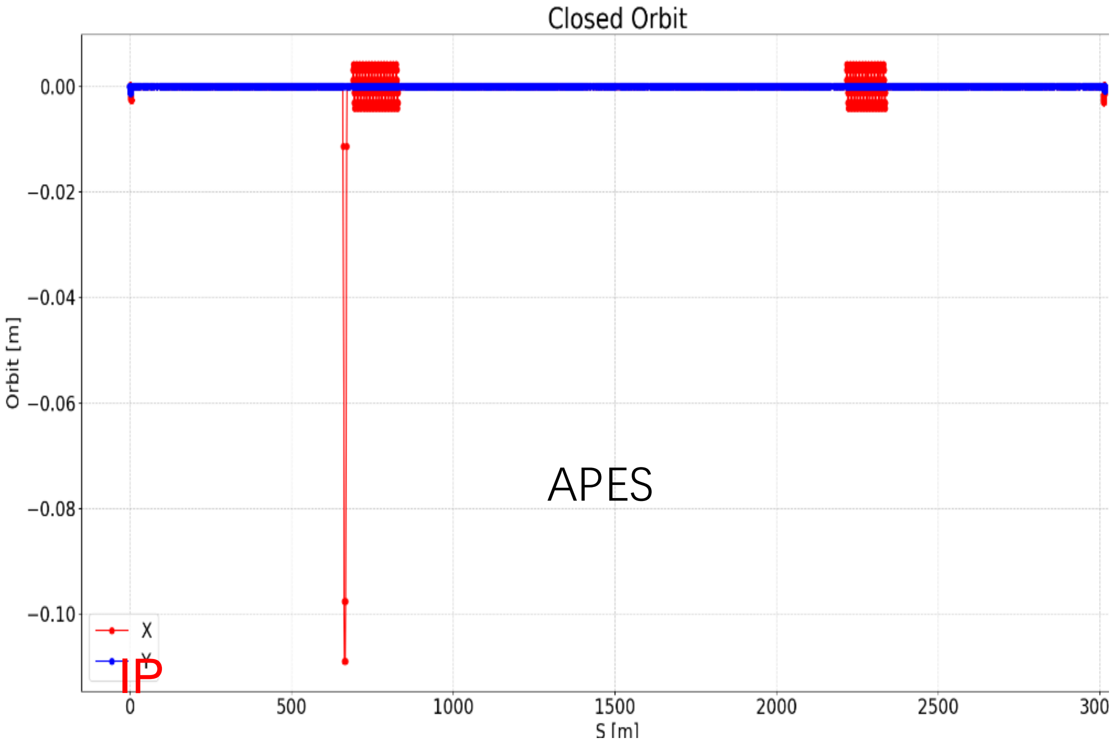
Solenoid axis

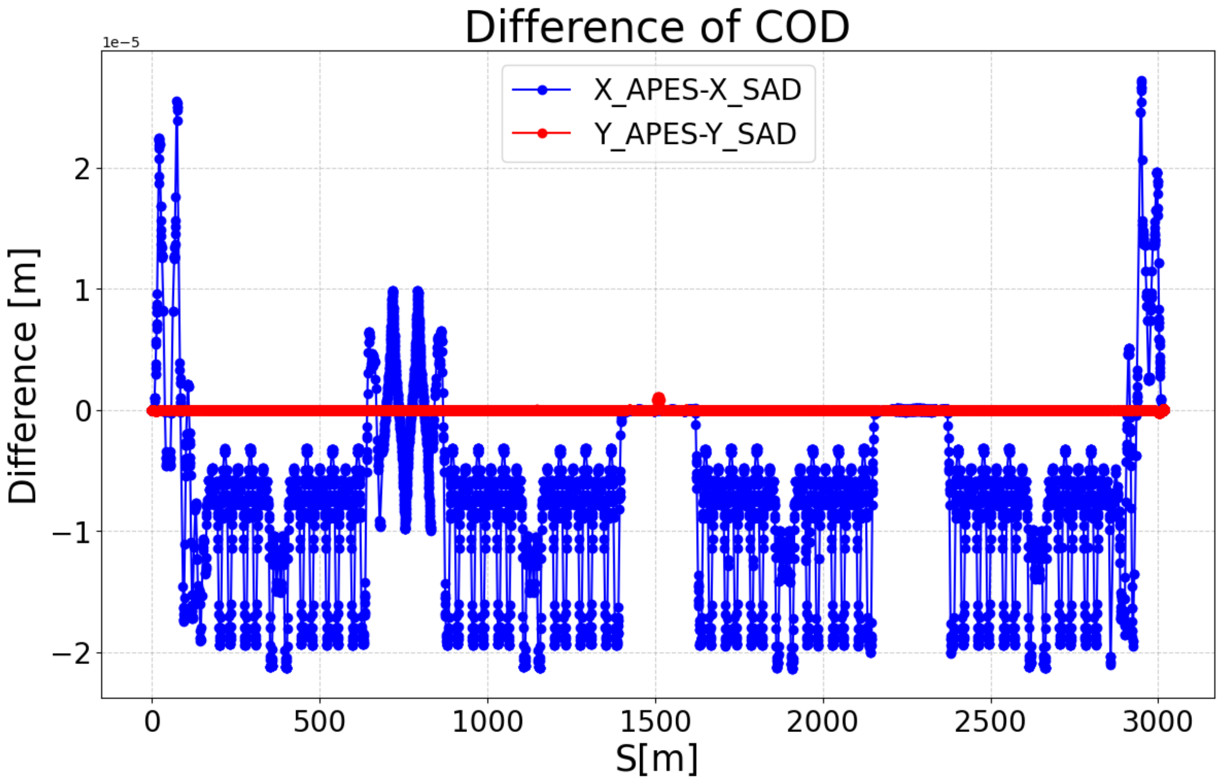
Patch1+Solenoid+Patch2

Modeling and optics

Modeling LER of SuperKEKB in APES

- Orbit closure
- Good agreement with SAD
- Difference smaller than ±2.5um





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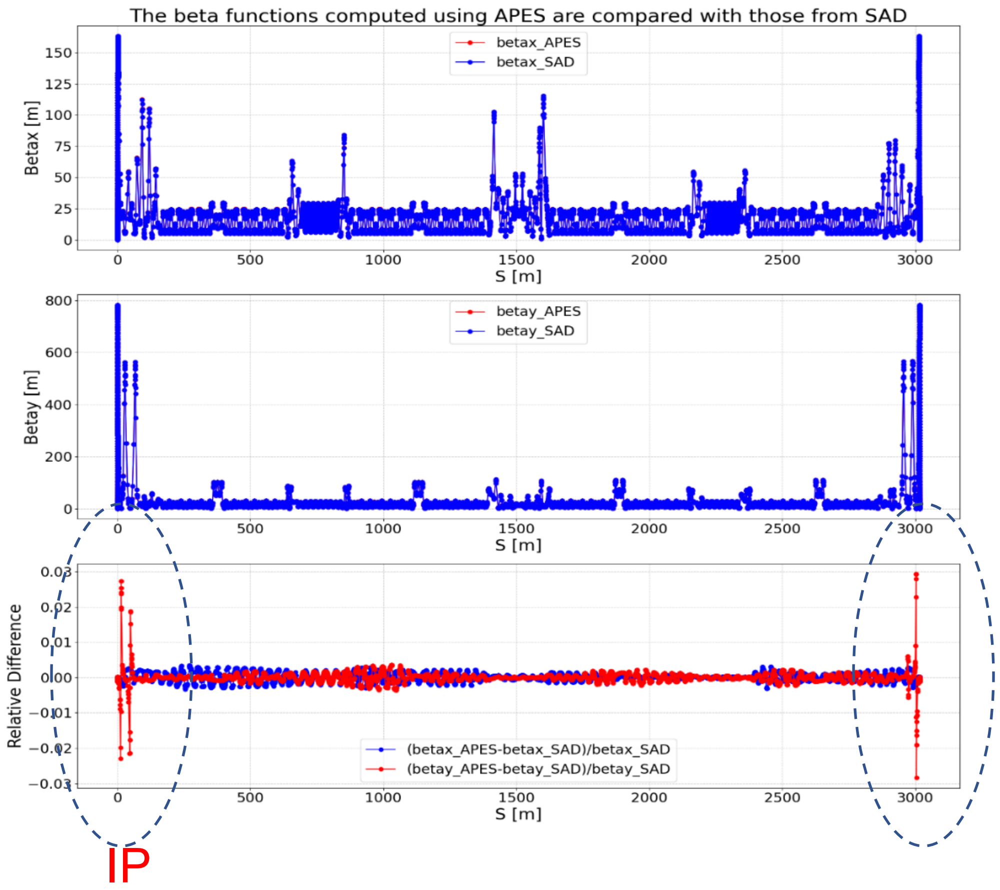
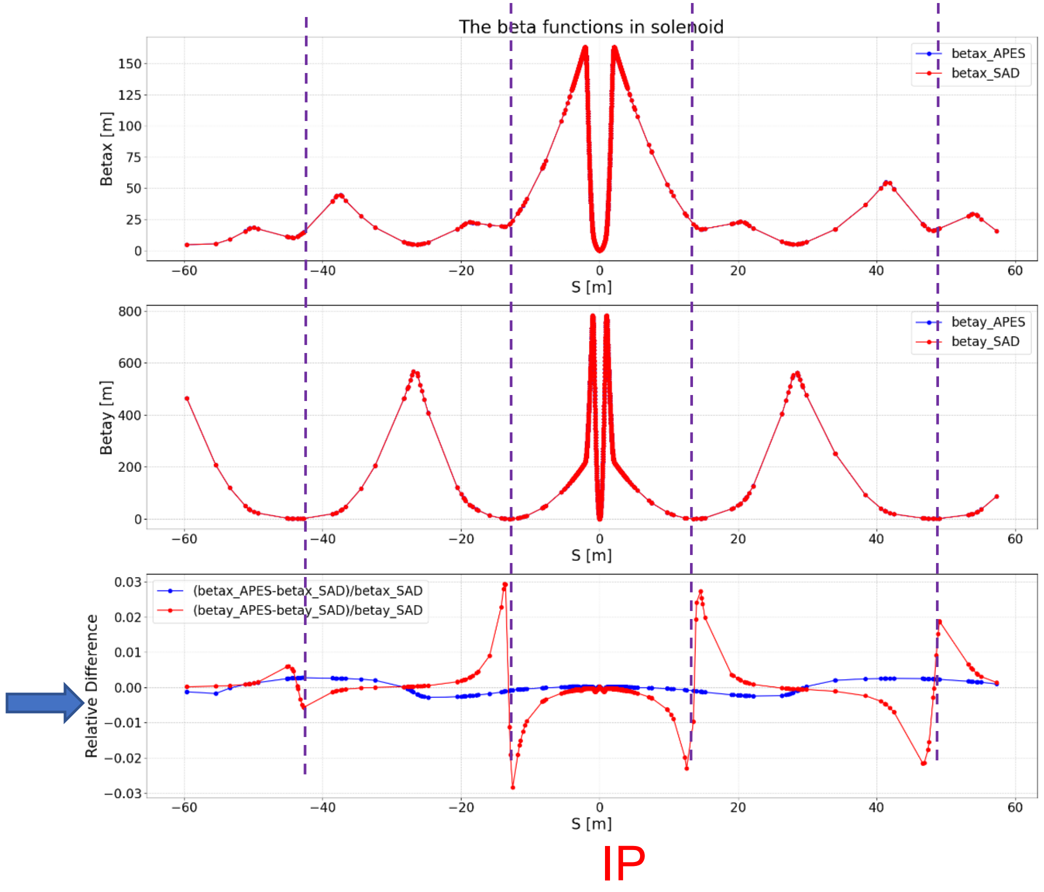
Modeling and optics

Modeling LER of SuperKEKB in APES

- 6D calculation in APES, "emit" command in SAD
- Beta functions have good agreements with SAD
- Beta beating smaller than 0.5% except some deviation due to nominal values close to zeros





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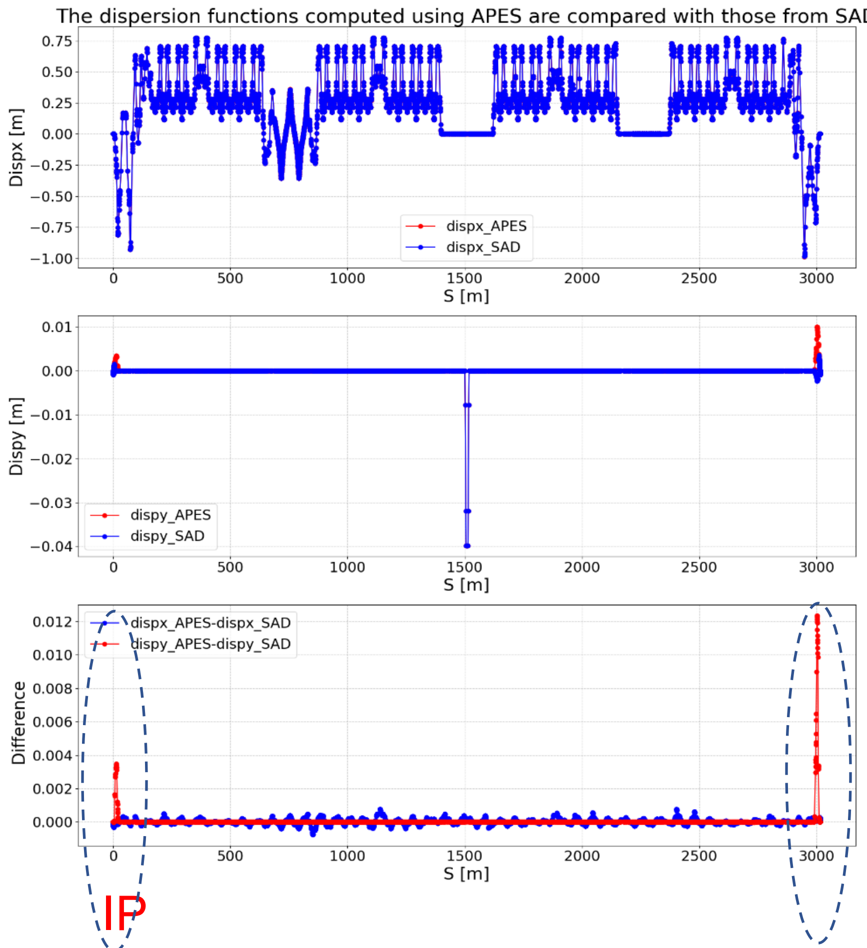
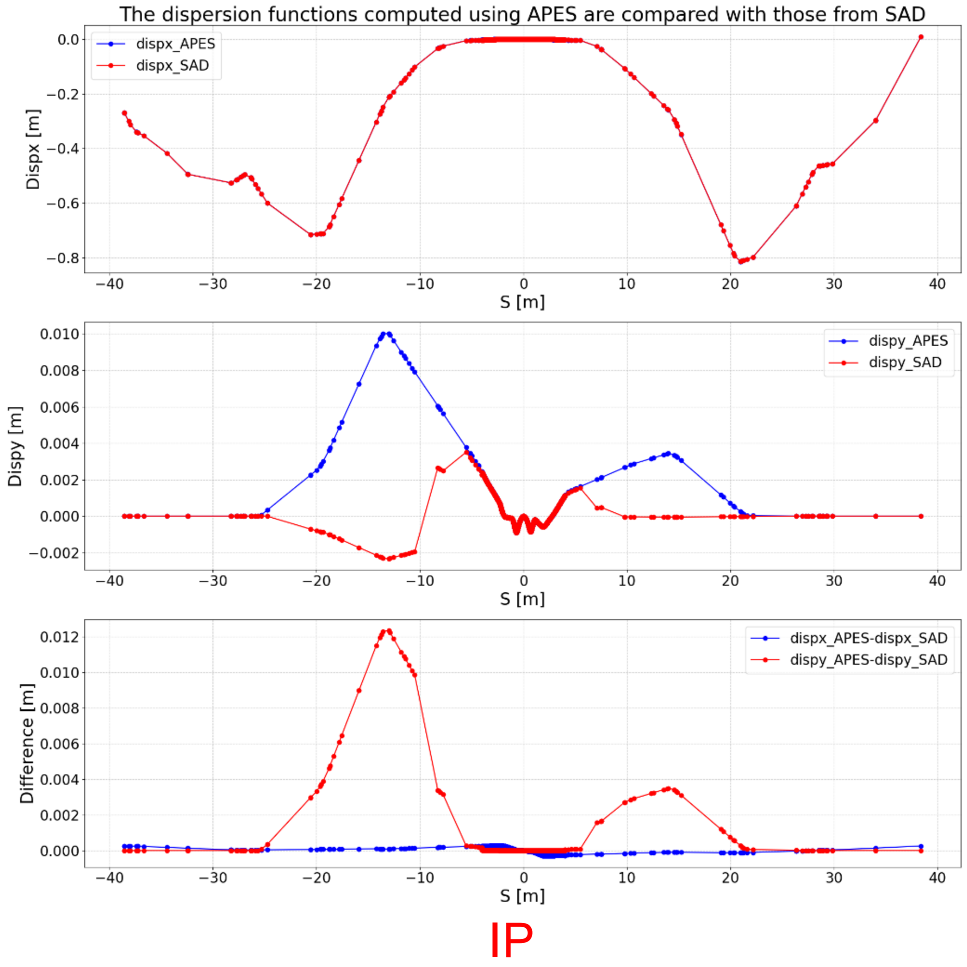
Modeling and optics

Modeling LER of SuperKEKB in APES

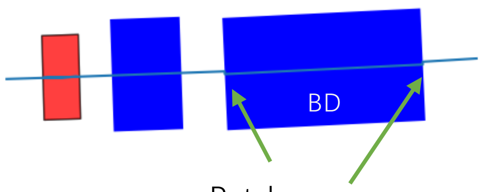
- Dispersion functions have good agreements with SAD except for region around solenoid boundary.
- The discrepancy calls for further investigation.





Modeling and optics

Modeling HEPS SR with APES



- Built the lattice with **Patch + quads.**

名称	elegant	APES (Bend) (wo radiation)	APES(Patch + quads) (wo radiation)	Note
Circ.	1360.399968000	1360.3999680000	1360.399810093565	
Emittance	34.82pm	34.76pm	35.36pm	
Horizontal Chromaticity	**4.9511**	5.088	**5.172**	Maybe related to beta-beating
Vertical Chromaticity	**5.0028**	5.014	**2.036**	
Momentum compaction factor	1.83e-5	1.83e-5	1.83e-5	
fRF	166600340	166600340	166600360	Real machine setup: 166600360
Tunex	115.1519	115.1520	115.0178	Measured: 115.677 105.356
Tuney	104.2912	104.2905	105.3722	

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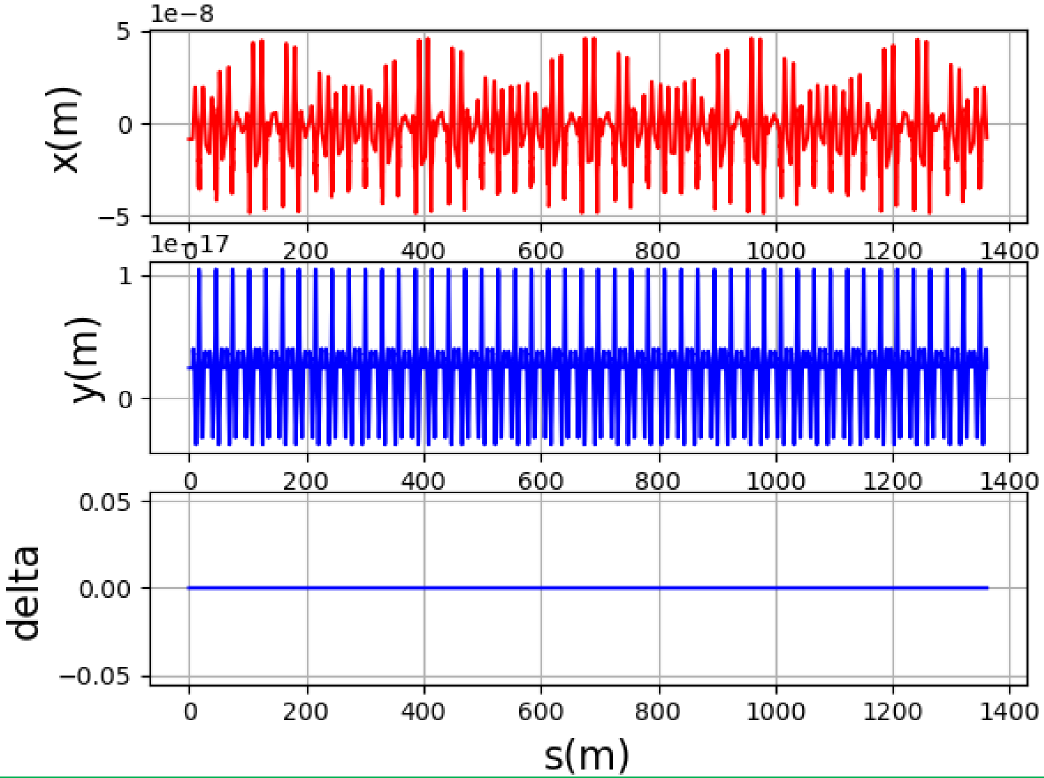
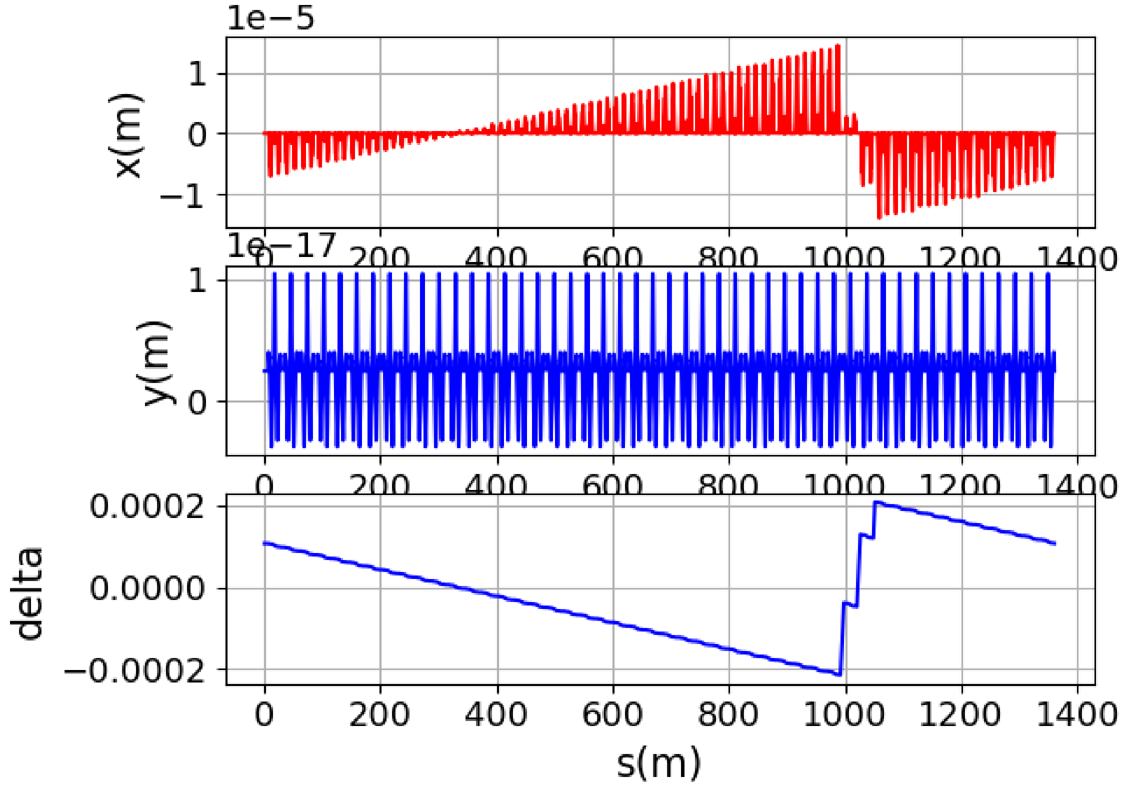
Modeling and optics

Modeling HEPS SR with APES

Closed orbit (wo./w. radiation)





- Lattice was built with BEND in Elegant, closed orbit is 0；
- Lattice was rebuilt with Patch+QUAD in APES,
  - without radiation， COD is at 1e-8 m level.
  - with Radiation (and RF), COD goes to 1e-5 m level.

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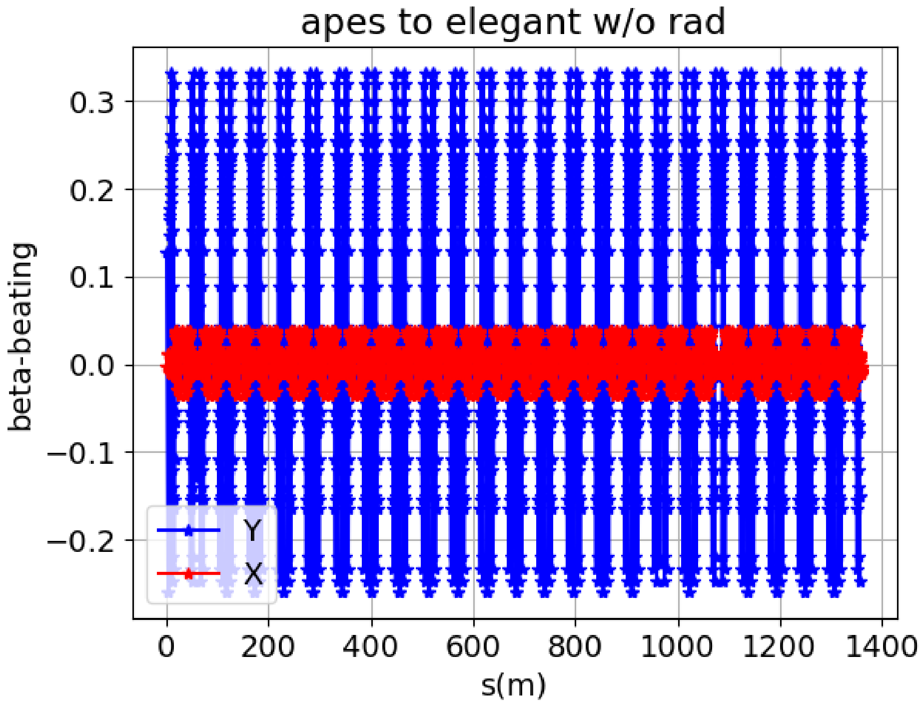
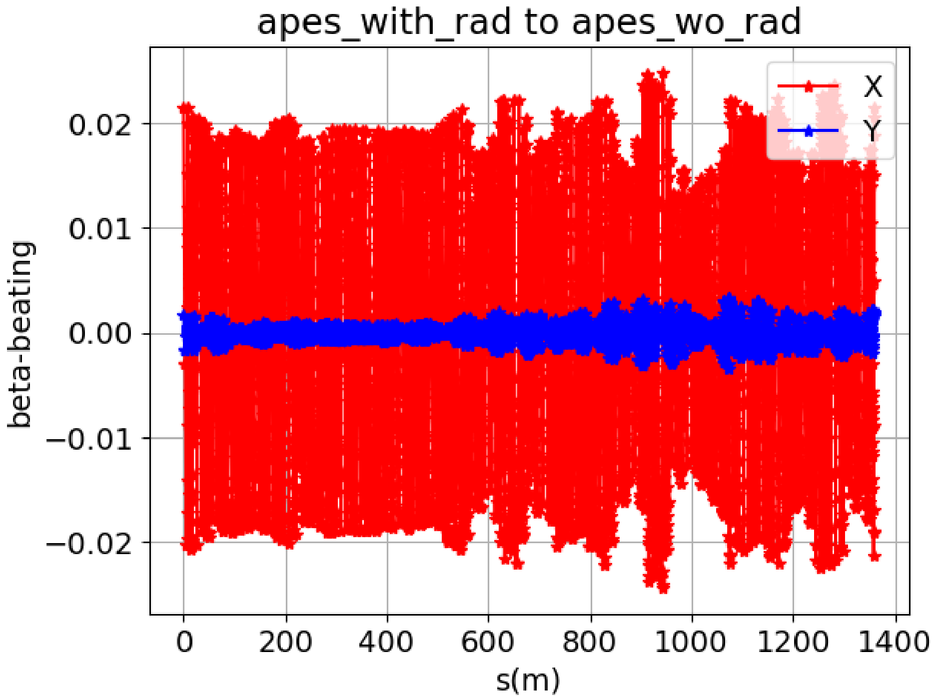
Modeling and optics

Modeling HEPS SR with APES

Beta-beating(and the effect of radiation)





- compare to elegant: beta-beating~5%、33%==》there is a integer number of difference in the working point
- In APES：radiation induced beta-beating(hori. and vert.) is ~0.5%、2.5%

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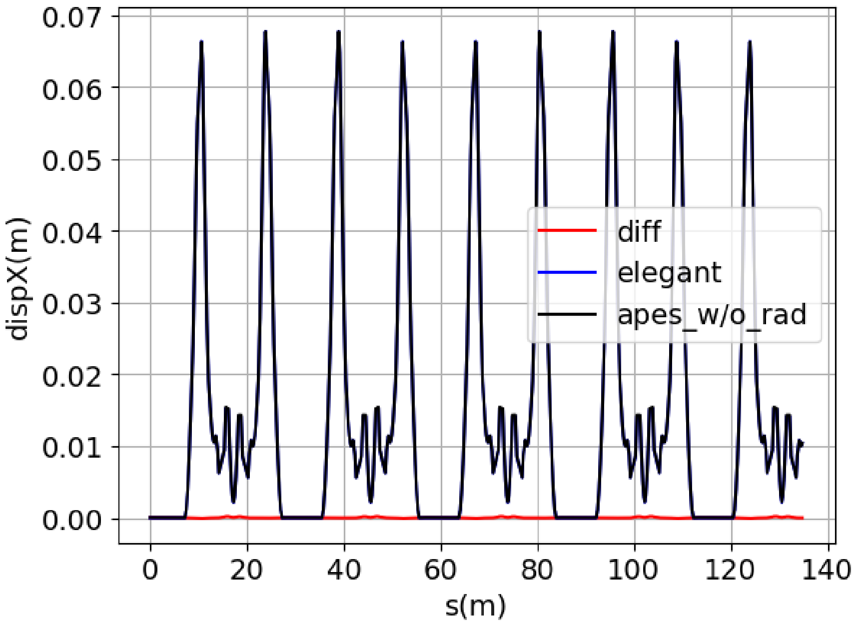
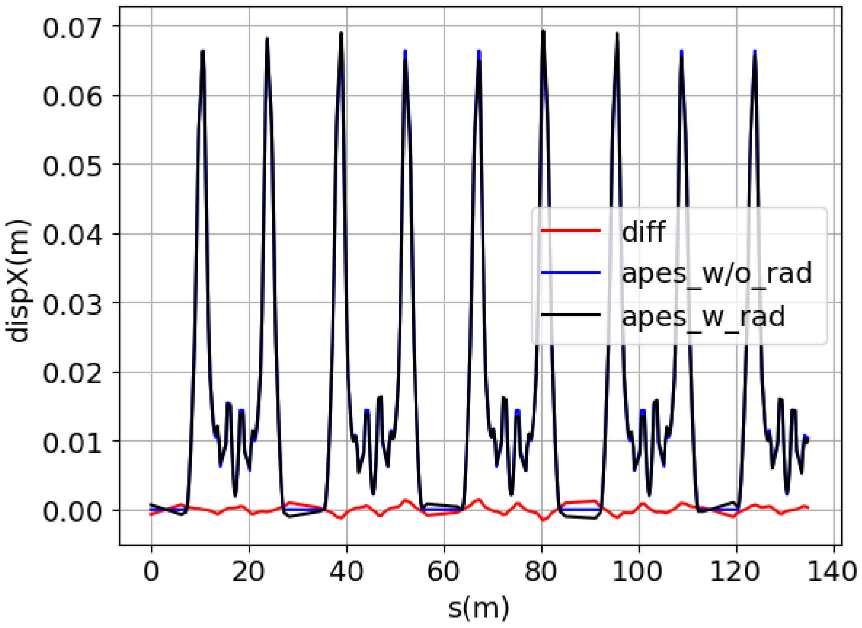
Modeling and optics

Modeling HEPS SR with APES

Dispersion (and the effect of radiation)






```
Dx_ave(apes-elegant): 1.0069194426867802e-05
Dy_ave(apes-elegant): -1.8554290666412e-18
Dx_rms(apes-elegant): 5.891495402200572e-05
Dy_rms(apes-elegant): 2.6604152570272852e-17
```

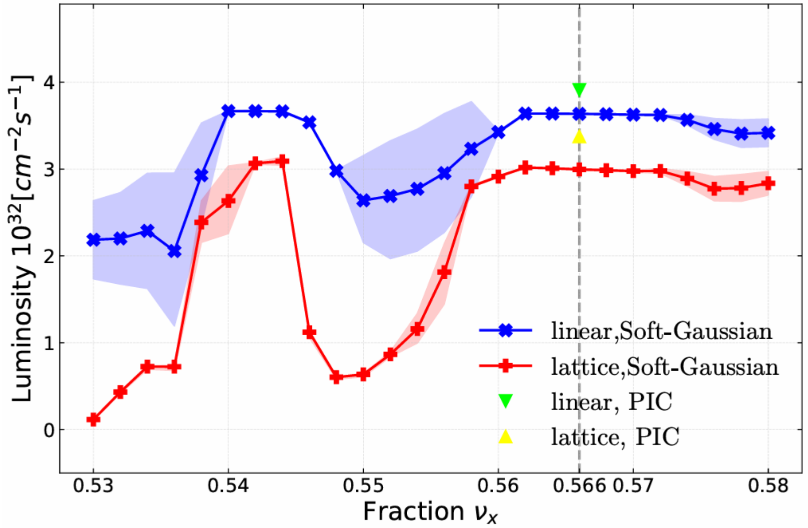
```
Dx_ave(apes-apes0): 2.226806829525856 5e-05
Dy_ave(apes-apes0): 2.0367974243171904e-17
Dx_rms(apes-apes0): 0.0005724117987769504
Dy_rms(apes-apes0): 1.286160900772154e-15
```

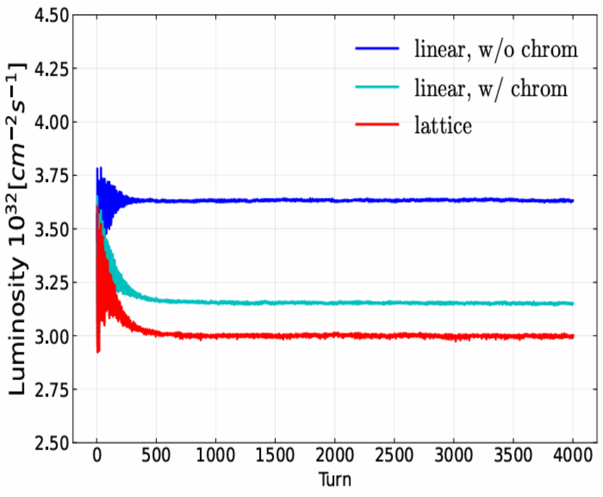
- Compare to Elegant: the average and rms values for horizontal and vertical dispersion are ~1e-5 and 1e-17 , respectively.
- Radiation induced horizontal and vertical dispersion are at 2e-5 and 6e-4 level, respectively.

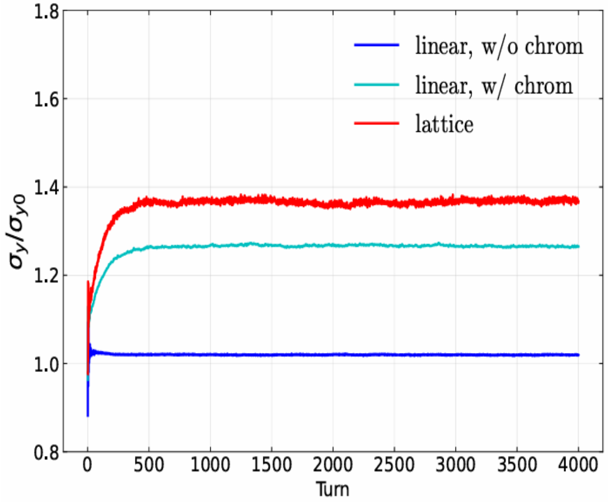
Zhiyuan Li etal., NIMA 1064 (2024) 169386

Tracking and Simulation

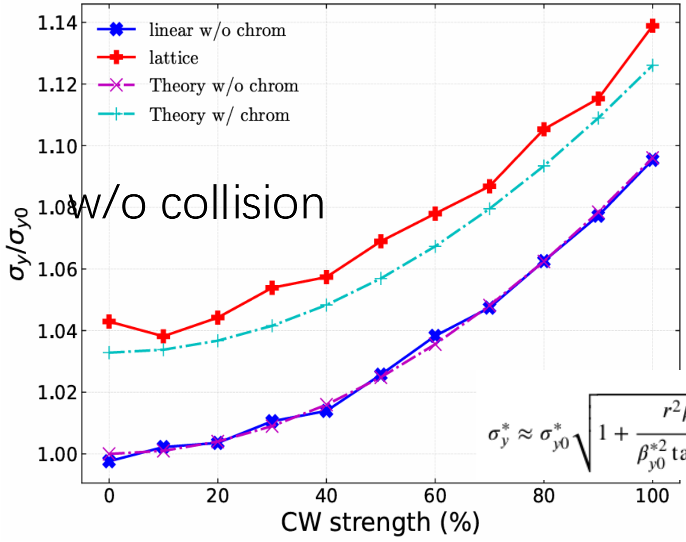
Simulation of CEPC Higgs (symmetric)







w/o collision



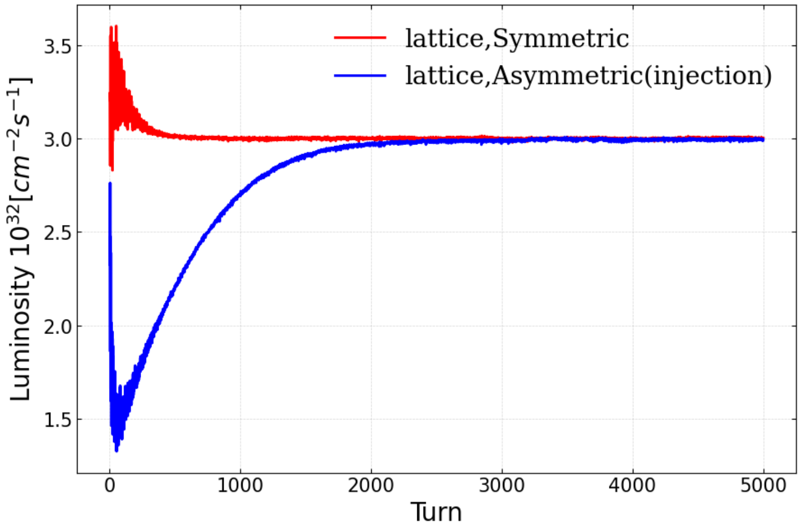
$$\sigma_y^* \approx \sigma_{y0}^* \sqrt{1 + \frac{r^2 \beta_{y0}^* \epsilon_x}{\beta_{y0}^{*2} \tan^2(2\theta_c)} + (b_2 + a_1^2)\sigma_\epsilon^2}$$

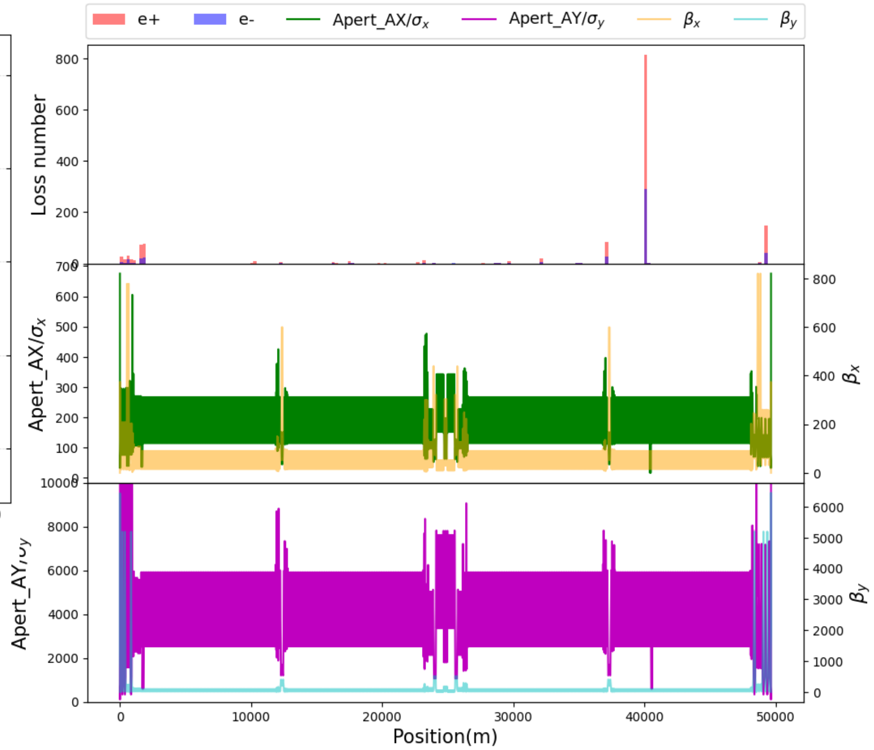
- 16% luminosity loss due to lattice
- chromaticity and crab-waist induce the reduction

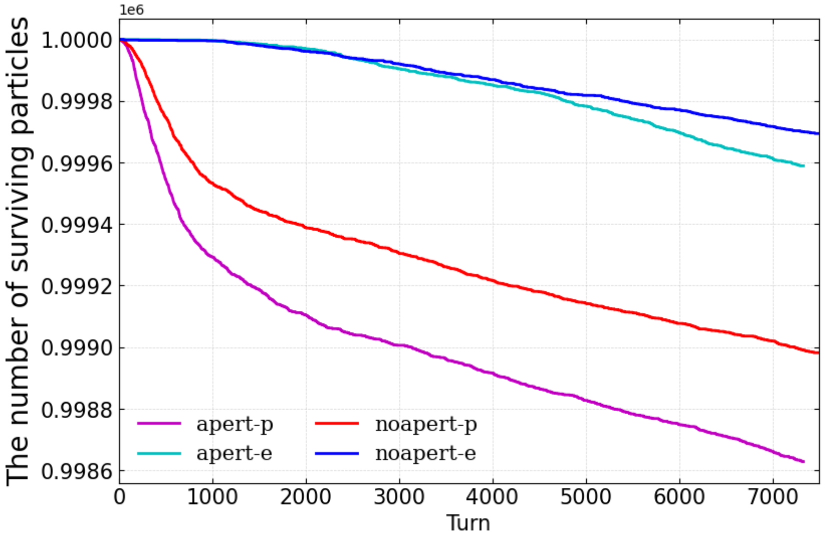
Self-consistent simulation of injection !!!

Tracking and Simulation

Simulation of Swap-out injection (Higgs)







e+(inj.) / e-

w/o apert: 39/42(min)

w/ apert: 29/37(min)

- **Initial beams: e+ (collider SR equilibrium) vs e- (booster SR equilibrium)**
- Luminosity: same between symmetric and asymmetric collision
- **Clear lifetime reduction (e+) with physical aperture**

Zhiyuan Li

Manual

APES Manual

- Introduction
- Overview
- User Manual
- Physics Manual
- Programmer Manual

User Manual

In this chapter, we'd like to walk you through so
accelerator topologies. During the process, we
application in the machine design process, we a
of using the package.

Accelerator Examples

- BEPCII Transport Line
- BEPCII Positron Ring with IR
- Chicane
- Collider
- ERL

Particle

- Particle
- Positron
- Electron
- Proton

Physics Manual

Last edited by **xintm@ihep.ac.cn** 6 days ago

- Beam life time
- Beam-Beam
- Bending Magnet
- Cavity Beam Interaction
- Cavity
- Coordinate Conventions and Conversion
- CSR
- Drift
- Emittance
- Error
- Fields in magnet
- Fringe
- Linear
- Map
- Mult
- Multi-particle Simulation
- Old_map
- Optics calculation
- Photon Tracking
- Plasma Acceleration
- Quad
- Rad
- Relative and Absolute time
- Sodd
- Sol

Programmer Manual

Last edited by **liuwb@ihep.ac.cn** just now

- Introduction
- Implementation of the Elements
- Customizing the Element

Team

Contact Info:
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zhangy@ihep.ac.cn
xintm@ihep.ac.cn

- No full-time staff
- 1 full-time postdoc (July. 2024-June.2026)
- Great help from K. Ohmi, E. Forest, K. Oide and D. Zhou
- Weekly meeting (> 3 Years)

What is coming next ?

- More collaboration with CEPC design team
- Optimize the Matching module
- Development of More Features
  - Beam loading, long term wake
  - Space charge
  - Electron cloud
  - Ion effects
  - Intra-beam Scattering
  - Spin dynamics
  - …
- Beyond CEPC

Summary

- APES is becoming more and more productive
- APES is is under active development
- Your usage feedback is greatly appreciated and helpful
- Thanks the hard work of APES team!