Introduction and Status of APES: A code for CEPC circular collider

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Motivations

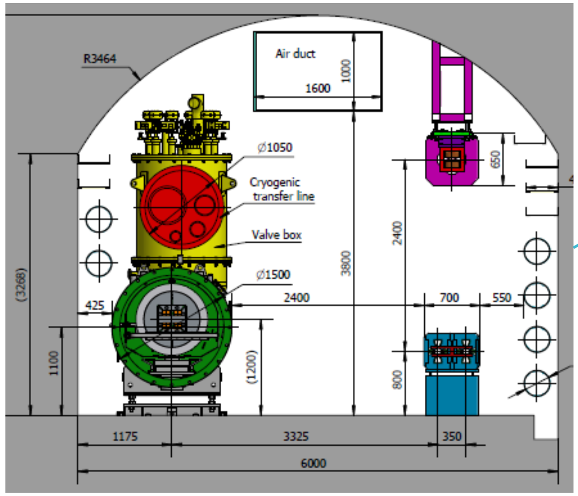
Brief Introduction to CEPC[1]

The CEPC aims to start operation in 2030's, as a Higgs (Z / W) factory in China.

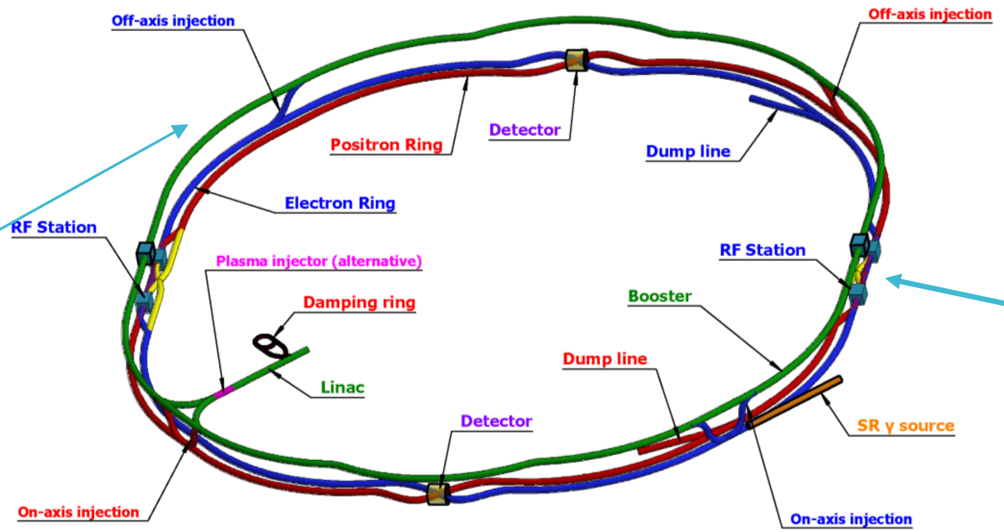
100km circumference, e+e- double ring collider: 45.5 GeV→180GeV

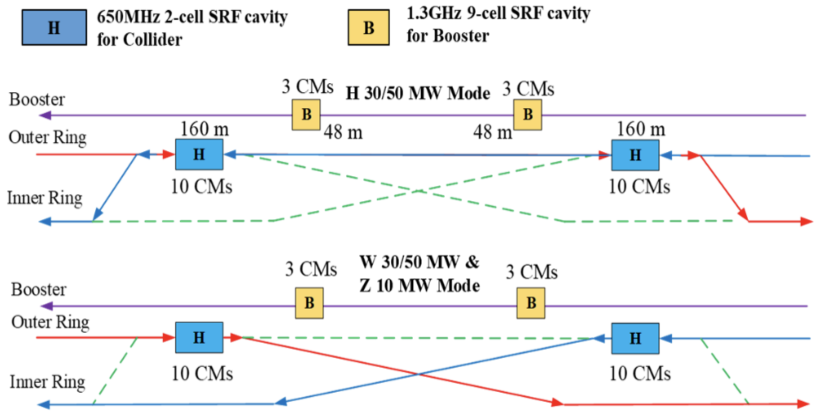
Possible pp collider (SppC) of 50–100 TeV in the far future

100km



Common tunnel for booster/collider & SppC





Compatible Operation for Higgs, W /Z & ttbar

CEPC Study Group, "CEPC Conceptual Design Report: Volume 1 - Accelerator". doi:10.48500/arXiv.1809.00285

CEPC baseline parameters

	Higgs	W	Z	ttbar
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	**30**			
Energy [GeV]	**120**	**80**	**45.5**	**180**
Bunch number	268	11934	1297	35
Emittance (εx/εy) [nm/pm]	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Beta functions β_x^*/β_y^* (m/mm)	0.3/1	0.21/1	0.13/0.9	1.04/2.7
Beam size at IP (σx/σy) [um/nm]	14/36	6/35	13/42	39/113
Bunch length (SR/total) [mm]	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Beam lifetime (Bhabha/beamstrahlung) [min]	40/40	90/2800	60/195	81/23
Beam-beam parameters (ξx/ξy)	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
Luminosity per IP[10^{34}/cm^2/s]	**5.0**	**115**	**16**	**0.5**

New demands on codes

- Ultra-high luminosity and performance requirements
  - High energy
  - Strong radiation
  - Crab-waist collision
  - Beamstrahlung effect
  - Small β_y^*
  - ……

- Facing challenges
  - Sawtooth effect
  - Rad-COD
  - Rad-Tapering
  - Strong lattice non-linearity
  - Bunch lengthen and energy spread increasing
  - Small dynamic aperture
  - X-Z instability
  - Accurate simulation of collision process
  - ……

Developing a program with more accurate modeling and simulation is essential for CEPC-like accelerators.

Group introduction

- For these reasons, Accelerator Physics Emulation System was proposed in 2021 and received support from the IHEP Innovative Fund in 2022

Long-term cooperation： Prof. Kazuhito Ohmi， Prof. Demin Zhou

Code Status

Code Overview

- Finished
- Underway
- Not started

Step1

- Modeling of complicate lattice and get the survey
- Particle tracking
- Synchrotron Radiation
- Optics calculation
- Emittance
- Rad COD
- Radiation tapering

Step2

- Parallelization
- Beam-beam
- Beamsstrahlung
- Short-range wakefield
- E-cloud incoherent(ECIC)
- Error Analysis
- Spin
- Transverse feedbacks

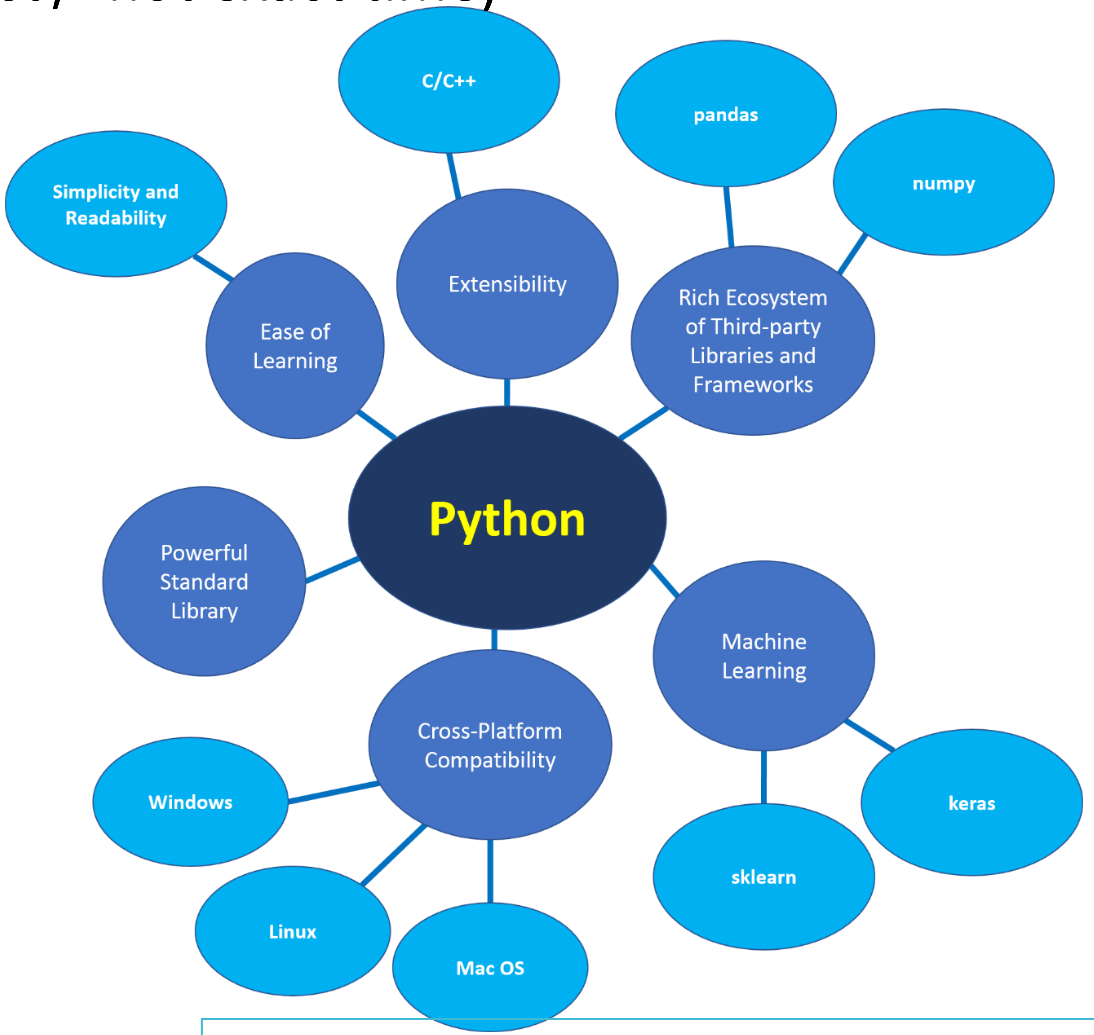
Step3

- Matching and Optimization
- Long-range wakefield
- E-cloud self-consistent
- Ion instability
- Advanced collimation feature
- Space-charge effect
- …

Python is selected as the Primary language

Investigation of popular codes in the past(not full list， not exact time)

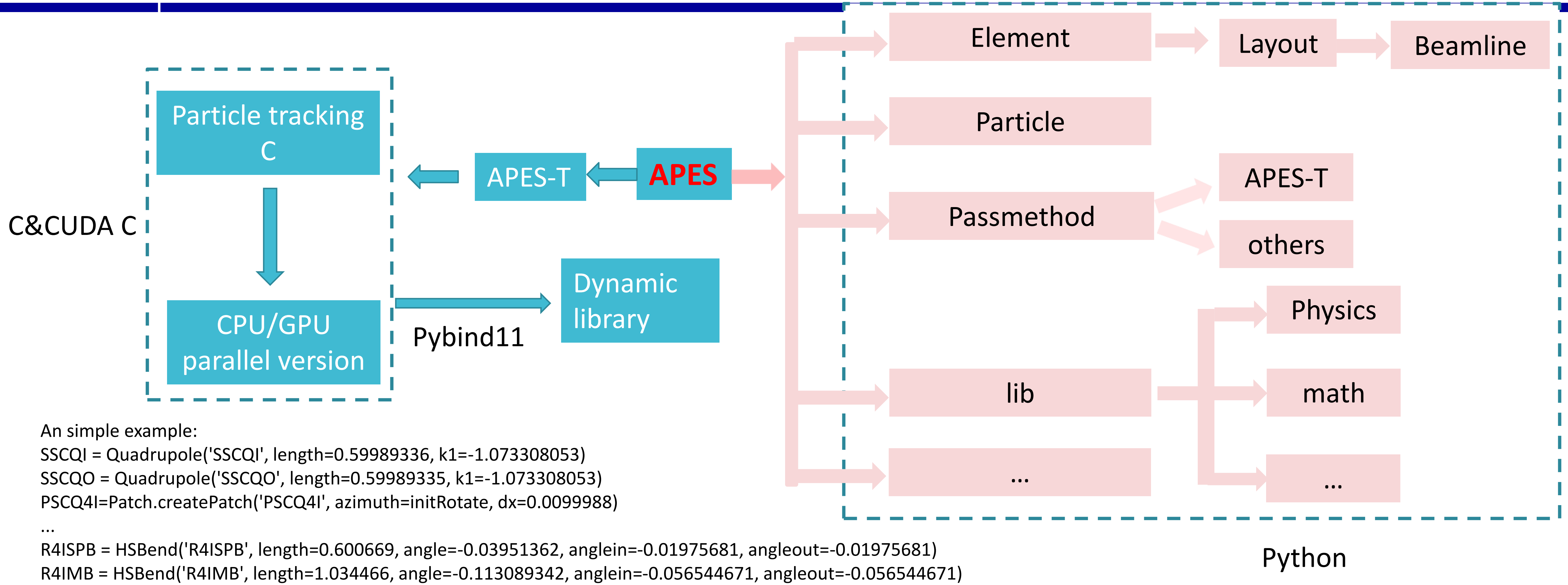
Code	language	Year
BMAD/TAO[1]	Fortran	1996
SAD	Fortran	1986
PTC/FPP	Fortran	1990s
MAD8/MAD-X	C, C++, Fortran	2002
Elegant	C,C++	2000
TraceWin	C++	2009
AT/pyAT	Matlab, C++/Python, C++	2000/2021
Orbit/pyOrbit	C++/python	1999/2015
Ocelot	Python	2011
Pyapas	Python	2021



Python, the primary language; C, the tracking engine

The references are appended on the last page

APES Framework

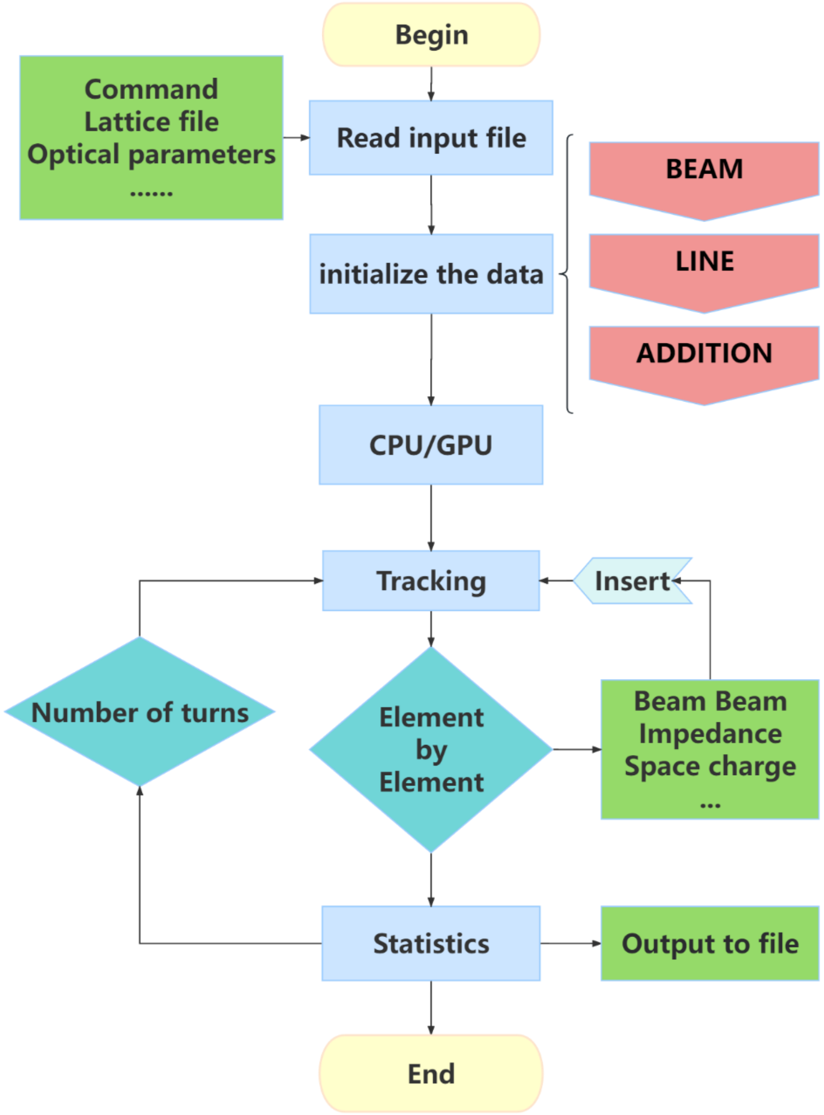


An simple example:

```
SSCQI = Quadrupole('SSCQI', length=0.59989336, k1=-1.073308053)
SSCQO = Quadrupole('SSCQO', length=0.59989335, k1=-1.073308053)
PSCQ4I=Patch.createPatch('PSCQ4I', azimuth=initRotate, dx=0.0099988)
...
R4ISPB = HSBend('R4ISPB', length=0.600669, angle=-0.03951362, anglein=-0.01975681, angleout=-0.01975681)
R4IMB = HSBend('R4IMB', length=1.034466, angle=-0.113089342, anglein=-0.056544671, angleout=-0.056544671)
...
BPRList = [IP, D4I01, R4CBPM00, D4I01P, PSCQ4I, SCQI, ...]
BPRLayout = Layout('BPR', entryLGCT=startAT, elementList=BPRList)
surveytable = BPRLayout.getSurveyTable(level=1)
beamline = TPLayout.getBeamLine('TP', refParticle=refParticle, isRing=False, alignmentError=True)
result = beamline.calBeamLineTwiss(X0=np.zeros(6), betax=12.5, alphax=0, betay=12.5, alphay=0)
```

Particle Tracking： APES-T

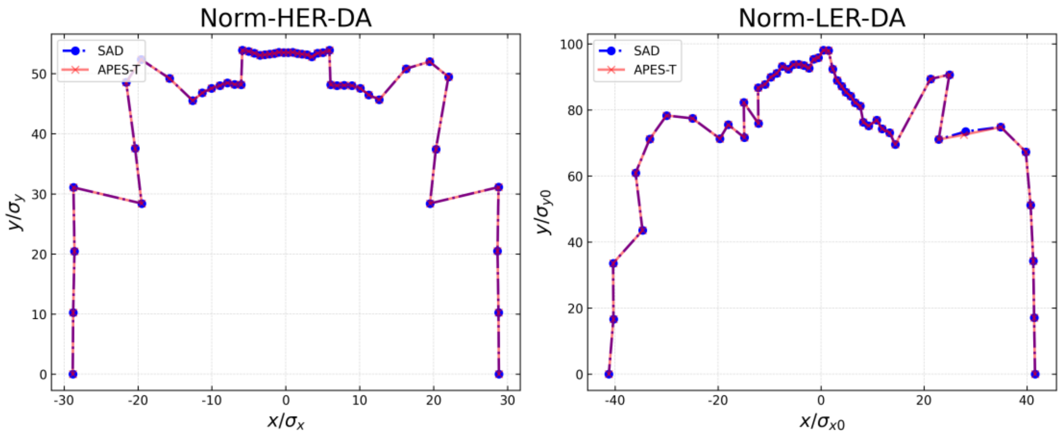
Responsed by Zhiyuan, Li



- Independent Code
- Element mapping section is drawn inspiration and reference from other codes, especially SAD[1][2]
- Developed with C and CUDA C
- Supports 6D full-symplectic tracking element by element
- Supports parallel computing on both GPU and CPU
- Beam-beam effect is included
- Non-parallel version code of tracking part has been compiled to python library with Pybind11

[1] D. Zhou and K. Oide , "Maps Used in SAD" (unpublished).
[2] https://acc-physics.kek.jp/SAD/

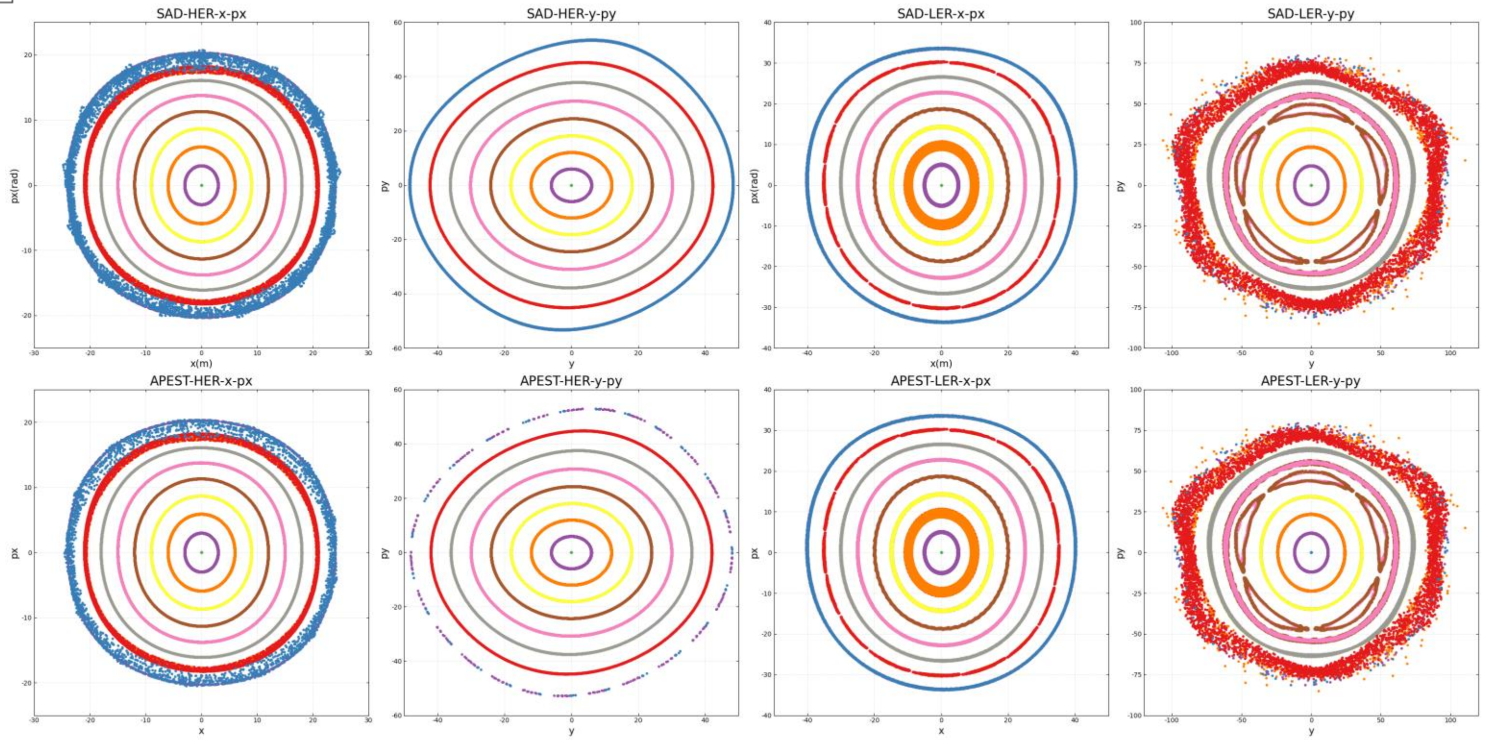
APES-T: Benchmark with SAD



Select SKEKB's ring for benchmarking

- Comparison of DA found by the two codes (SAD and APES-T) without radiation.
- The DA found by the two codes is essentially the same.

- Comparison of Hamiltonian contours in horizontal phase space
- The island-like structures show that the two codes have very similar results in horizontal tune values.



APES-T: Parallelization

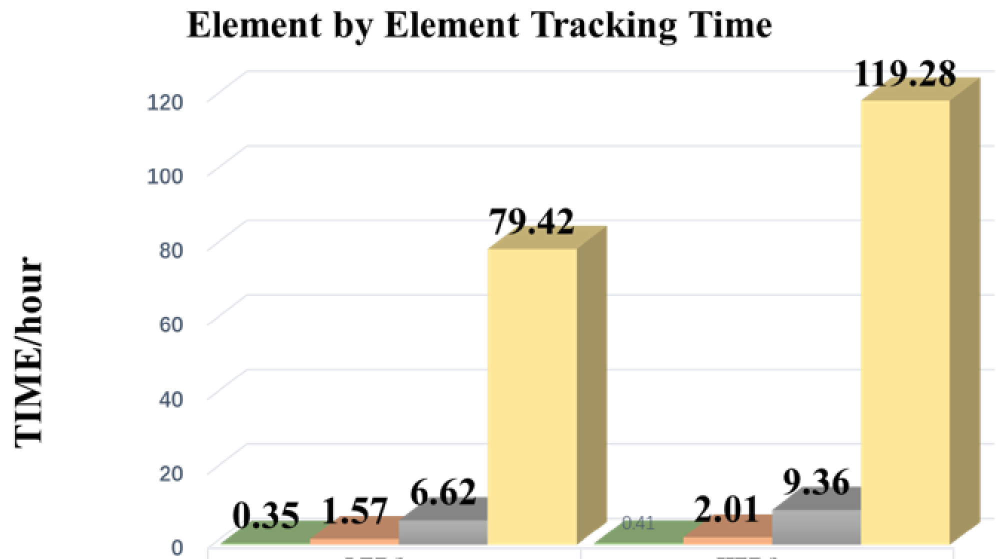
- **SUPERKEKB's double ring was used**
- **In particular tracking, the acceleration ratio：**

➢ **GPU /CPU(single core) ≈ 250**

➢ **GPU /MPI (node 10) ≈ 20**

➢ **GPU /MPI (node 100) ≈ 4.50**

GPU vs CPU(Single Core)
Ideal acceleration ratio：
float : ≈700
double : ≈350



	LER/hour	HER/hour
GPU	0.35	0.41
MPI NODE=100	1.57	2.01
MPI NODE=10	6.62	9.36
CPU SINGLE CORE	79.42	119.28

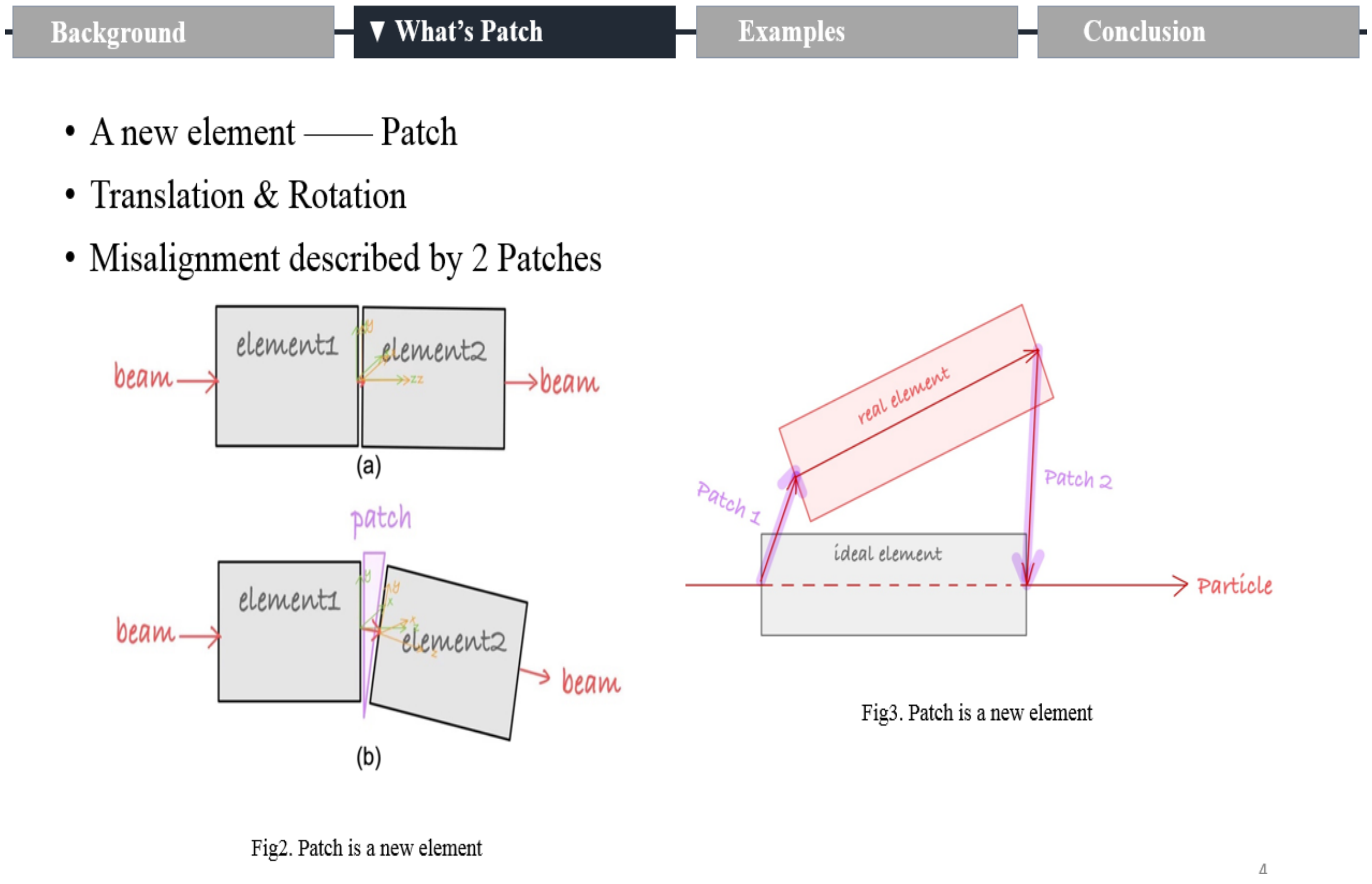
Consuming time in different parallelization scheme

Condition

GPU:NVIDIA A100 FP64： 9.746 TFLOPS (1:2)
CPU: Intel(R) Xeon(R) Gold 6348 CPU @ 2.60GHz
Numerical precision: double

Patch

- The concept "patch" is borrowed from code "PTC"
- "Patch" is an affine transformation between different frames.
- "PatchPassMethod" for phase space transformation
  - Single "Patch" affects the reference orbit downstream
  - "Patches" for errors affect local orbit only(appear in pairs).
  - A pair of "Patch" are used to model 'specially installed equipment'.



"Implementation of geometric transformation "patch" and associated passmethod in pyAT" , Mengyu SU, this workshop

Emittance calculation considering radiation

- APES can calculate the emittance of Gaussian distributed beam when synchrotron radiation exists
- Two methods have been implemented and checked with each other.
- More benchmarks based on HEPS lattice and BEPCII lattice are underway.

- SLIM method[1] :
  - $\varepsilon_k = C_L \frac{\gamma^5}{c\alpha_k} \oint \frac{|E_{k5}(s)|^2}{|\rho(s)|^3} ds$, $k = 1,2,3$
  - The damping matrix of bends which relates to the horizontal coordinate is considered.

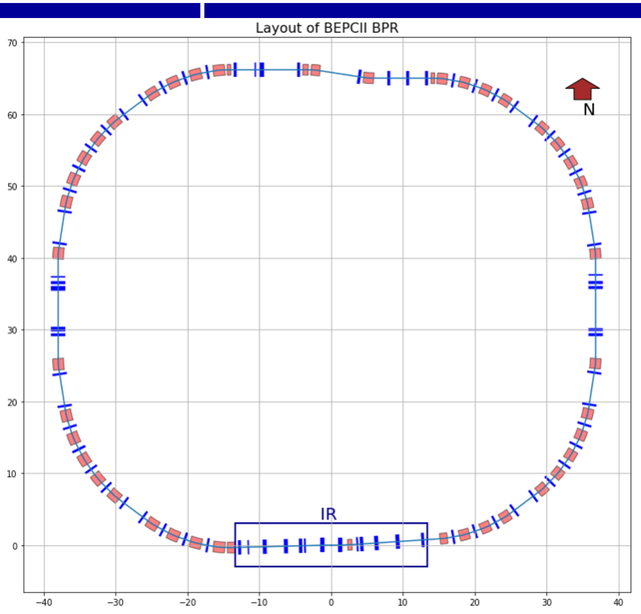
$$\frac{U(\Delta E) - U(0)}{E_0} = \frac{1}{cE_0} \int 2P_\gamma(0)\delta ds + \frac{1}{cE_0} \int 2P_\gamma(0)x ds$$

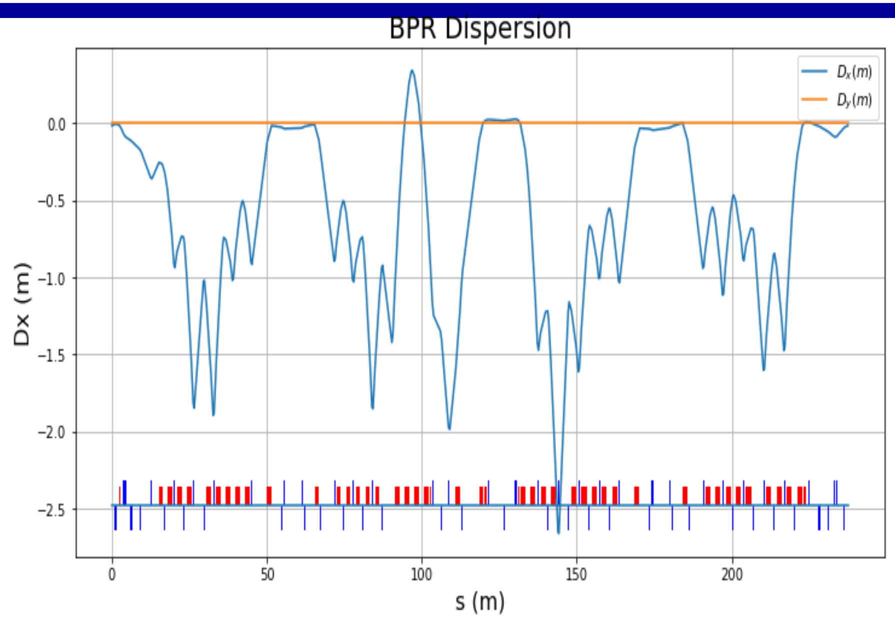
- Envelope matrix method(also used in SAD)[2]
  - $\frac{d\vec{x}}{ds} = -[H(\vec{x}), \vec{x}] + \xi(\vec{x}, s)$ ➔linearize
  - $\frac{d\vec{x}}{ds} = [S\hat{H} - D]\vec{x} + \hat{\xi}(s)$
  - $\vec{x}(s) = M(s, s_0)\vec{x} + \int_{s_0}^{s} M(x', s_0)\,\hat{\xi}(s) dx'$
  - $\langle x_i x_j \rangle = M(s, s_0) R_{ij}(s_0) M^T(s, s_0) + \int_{s_0}^{s} \int_{s_0}^{s} M(s, s_1) \langle \hat{\xi}(s) \hat{\xi}^T(s) \rangle M^T(s, s_2) ds_1 ds_2$

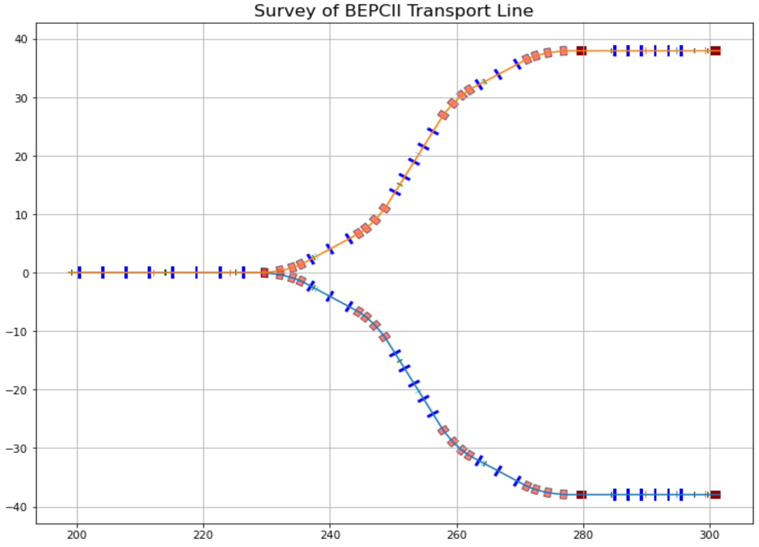
[1] Chao A W. Evaluation of beam distribution parameters in an electron storage ring[J]. Journal of Applied Physics, 1979, 50(2): 595-598.
[2] Kazuhito Ohmi, et al. From the beam-encelope matrix to synchrotron-radiation integrals[J]. Physical Review E, 1994:V49 751-765.

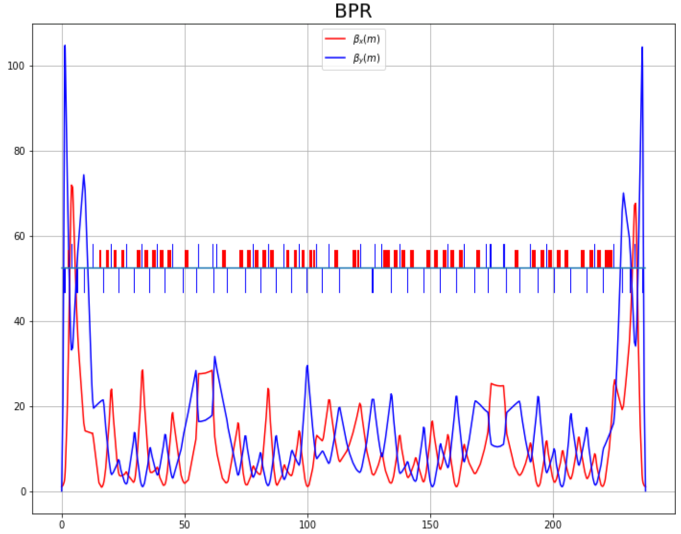
Some Examples

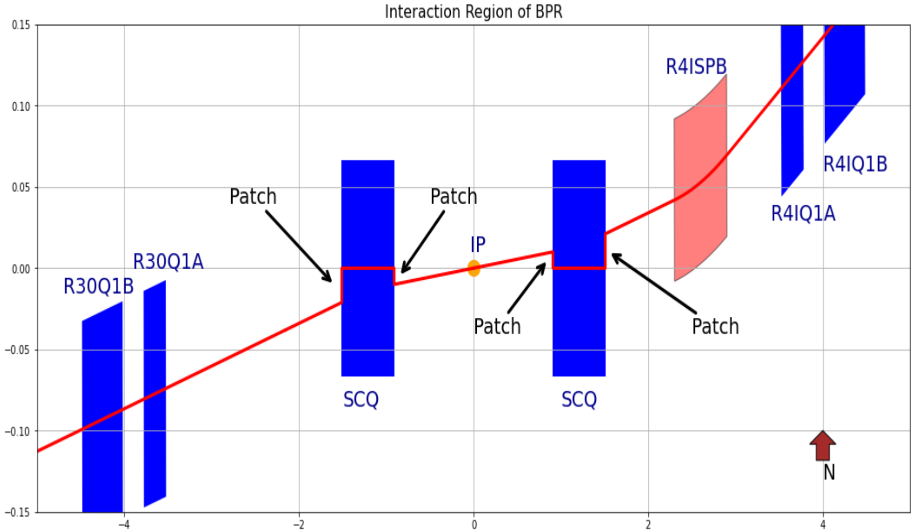
Modeling of BEPCII lattice

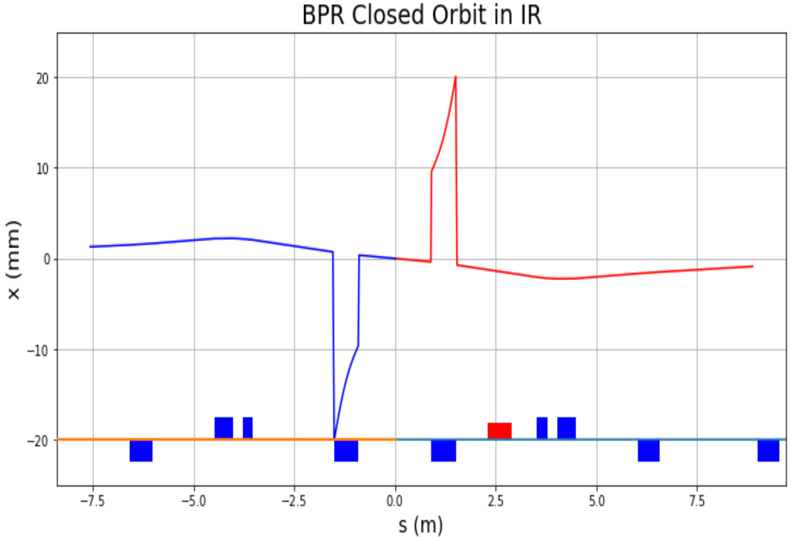




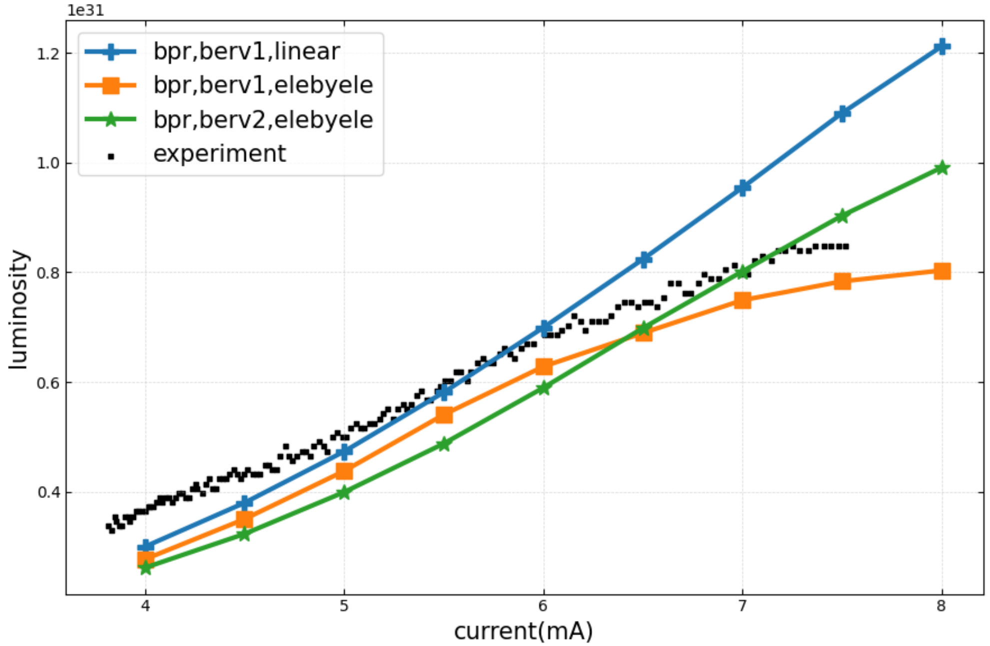




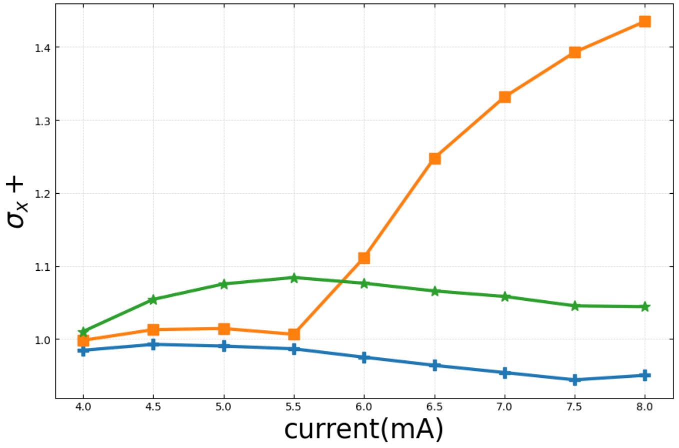


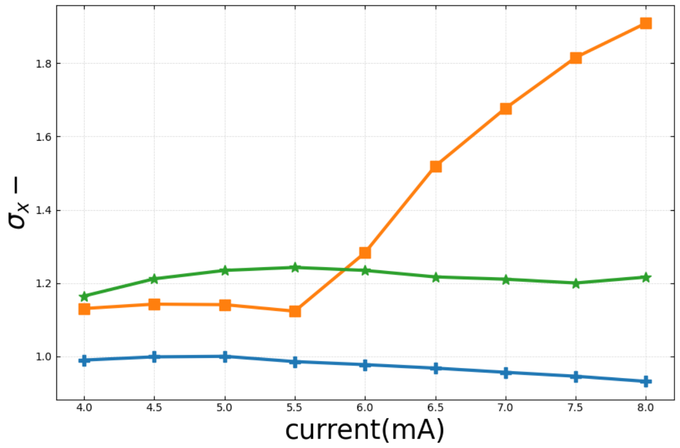


Tracking and strong-strong beam-beam simulation on BEPCII



- Two Version of lattices applied sequentially in BEPCII machine
  - Ber-V1: serious luminosity loss is found in real machine
  - Ber-V1: horizontal blowup was found in the element by element tracking with beam-beam effect considered
  - Ber-v2 : simulated luminosity is increased after optimizing sextupole by trial and error
- More researches need to be done

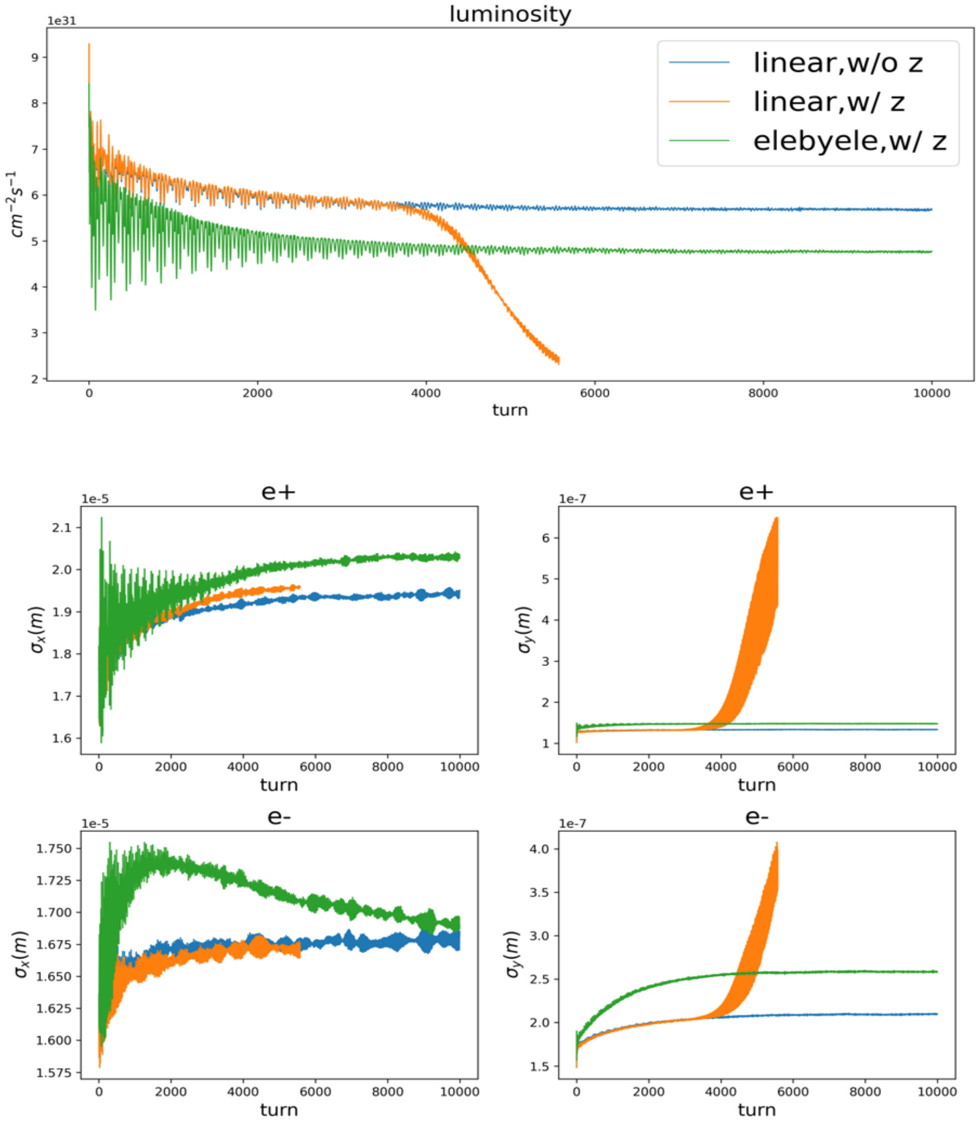




Beam size blowup was found in Ber-V1 lattice in element by element tracking

BER*BPR
100k × 100k particles,120000turns
BB : 7 × 7 slices ,Gaussian approximation

Tracking and strong-strong beam-beam simulation on SKEKB



- Strong-strong beam-beam effect included
- Simulation with linear model
  - Vertical instability can be see when machine impedance is considered.
- Element-by-element tracking is introduced
  - Beam blowup phenomenon disappeared
  - The vertical beam size of HER slightly increased
  - The luminosity decreased slightly compared to the linear lattice.
- More research need to be done

Conclusions

- APES, a code for future CEPC circular collider, is proposed.
- Some functionalities have already been implemented and checked
  - modeling of explicit accelerator
  - optics calculation
  - particle tracking in GPU/CPU parallel mode with beam
  - emittance calculation
  - …
- The benchmark and addition of more physical effects are still being progressed.
- We hope that this tool will provide strong assistance for future CEPC designs

Reference

- D. Sagan, “Bmad: A relativistic charged particle simulation library”, Nuclear Instruments and Methods in Physics Research Section A, Volume 558, Issue 1, 1 March 2006, Pages 356-359
- E. Forest, F. Schmidt, and E. McIntosh. Introduction to the Polymorphic Tracking Code. Technical Report CERN-SL2002-044, KEK-Report 2002-3, 2002.
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- J. Galambos, “ORBIT – A RING INJECTION CODE WITH SPACE CHARGE”, Proceedings of the 1999 Particle Accelerator Conference, New York, 1999
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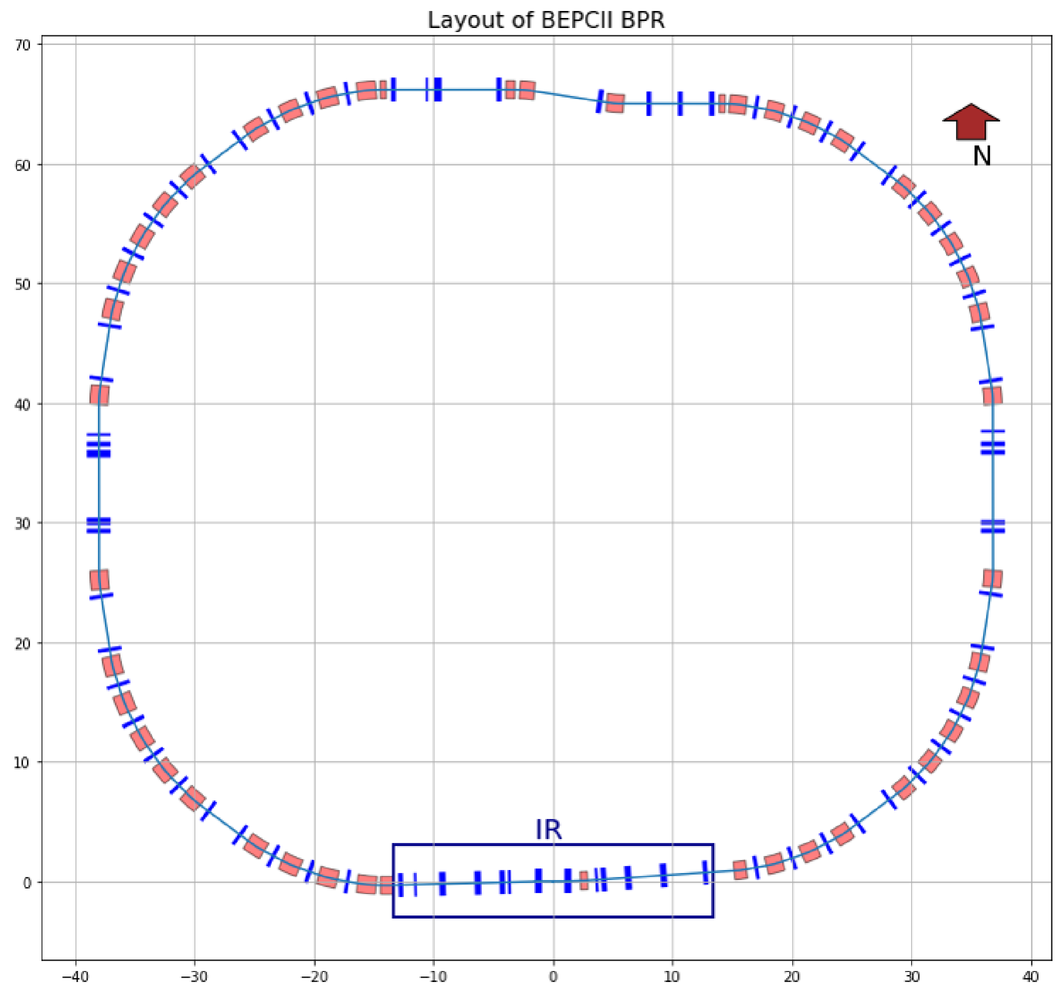
- M. Borland, ”elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation,” Advanced Photon Source LS-287, September 2000.
- I. Agapov et al., “OCELOT: a software framework for synchrotron light source and FEL studies", Nucl. Instr. Meth. A. 768 (2014) pp. 151-156
- https://code.ihep.ac.cn/heps-hla/pyapas.git

Thank you for your attention!

BackUp pages

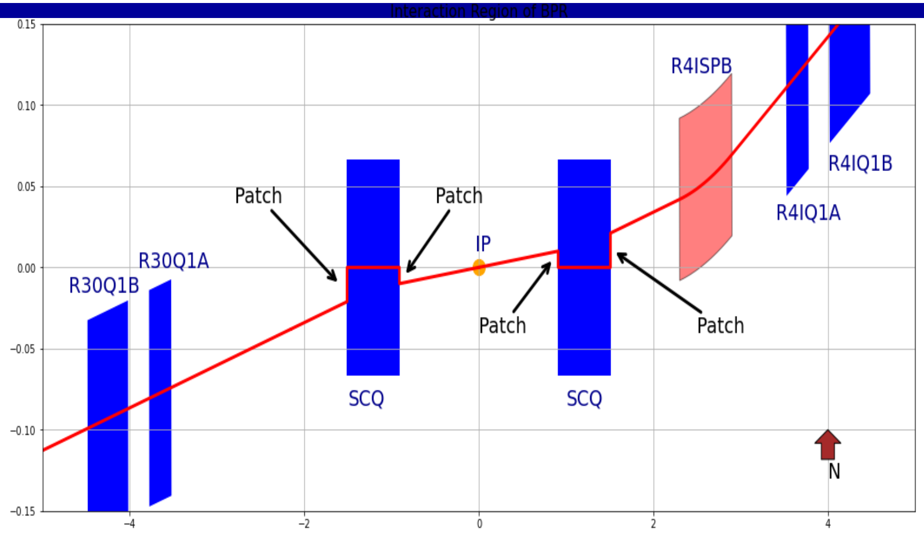
BEPCII parameters



Modeling of BEPCII BPR

Parameters	Design	Achieved	
		BER	BPR
Energy (GeV)	1.0～2.1，1.89	1.0～2.47，1.89	1.0～2.47，1.89
Beam current (mA)	910	950	950
Bunch number	93	118	118
Beam-beam parameter	0.04	0.041	
β_x^*/β_y^* (m)	1.0/0.015	1.0/0.0135	1.0/0.0135
Inj. Rate (mA/min)	200 e^- / 50 e^+	>1000	>200
Lum. ($\times 10^{33} cm^{-2}s^{-1}$)	1.0	1.1	

BEPCII interaction section



- from apes.acc.Layout import *
- from apes.acc.Element import *
- from apes.acc.Particle import *
- from apes.lib.math.AffineTransformation import *
- ...
- ...
- initRotate = -0.011
- startAT = AT.createAT(azimuth=initRotate)
- ...
- SSCQI = Quadrupole('SSCQI', length=0.59989336, k1=-1.073308053)
- SSCQO = Quadrupole('SSCQO', length=0.59989335, k1=-1.073308053)
- PSCQ4I=Patch.createPatch('PSCQ4I', azimuth=initRotate, dx=0.0099988)
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- result = beamline.calBeamLineTwiss(X0=np.zeros(6), betax=12.5, alphax=0, betay=12.5, alphay=0)
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