ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPC11

ADVANCEMENTS IN THE DEVELOPMENT OF BEAM DYNAMICS SOFTWARE APES FOR CEPC*

Weibin Liu†[1], Yuan Zhang[1], Tianmu Xin, Zhe Duan, Zhiyuan Li[1],
Yaliang Zhao, Mengyu Su[1], Yixian Dai[1], Ande Ma[1], Huiping Geng, Letong Yang[1],
Siyuan Feng[1], Yuanyuan Wei, Xiaohan Lu, Zhennan Chang[1], IHEP, Beijing, China
[1]also at UCAS, Beijing, China

Abstract

The design and study of the Circular Electron Positron Collider (CEPC) present a significant challenge, requiring the proper modeling of various physical phenomena such as the crab-waist collision scheme with a large Piwinski angle, strong nonlinear effects, energy sawtooth, beam-beam interactions, and machine impedances. In response to this challenge, the APES software project was proposed in 2021 and received support from the IHEP Innovative Fund in 2022. This paper provides an overview of the progress made in the APES project, encompassing modeling for special cases, orbital and spin tracking with synchrotron radiation, optics and emittance calculation, particle tracking, and more. Additionally, the paper discusses future developments.

BACKGROUND AND PURPOSE OF APES SOFTWARE DEVELOPMENT

The CEPC was initially introduced as a circular Higgs factory in 2012, with the publication of its conceptual design report in 2018 [1]. Similarly, the FCC-ee project proposed at CERN is also focused on the exploration of high-energy physics. During the design of these future colliders, the beam lifetime limitation due to the beamstrahlung effect, the synchrotron radiation induced by collision leading to a bunch lengthening and an increase in the beam energy spread, has been found and studied [2]. Different from conventional colliders, not only the transverse beam size, but also the longitudinal dynamics would be clearly influenced by the collision. That is why the 3D flip-flop instability may appear in CEPC or FCC-ee [3].

There would also be strong synchrotron radiation in the arc bending magnets of the machines, leading to a substantial "sawtooth"-shape variation of the central beam energy along the ring, which is the so-called sawtooth effect. The magnet tapering method has been proposed to mitigate this effect [4]. This requires new optics calculation method to consider the energy change along the ring.

After the crab-waist scheme was proposed around 2006 [5], the new collision scheme has become the baseline design for the following high performance circular e+e- colliders. However sub-millimeter scale β_y^* in future machines would induce strong lattice non-linearity and a very small dynamic aperture. During the lattice design and optimization, it has been found that the short-term dynamic aperture tracking could not predict the long-term beam lifetime [6].

In recent years, a new horizontal coherent beam-beam instability (X-Z instability) has been found [7]. The following simulation and analysis also show that the potential-well distortion effect would impact the behaviour of X-Z instability clearly [8, 9] . This tells us the cross-talk between beam-beam and longitudinal impedance could not be ignored.

APES (Accelerator Physics Emulation System), a beam dynamics software project, has been developed to address beam physics challenges in the CEPC by offering modeling of the collider, lattice design, performance evaluation, prediction, and evaluation of collider performance, as well as integration with detector and machine protection systems. These capabilities are expected to empower users to design, analyze and optimize accelerator systems with improved accuracy and efficiency.

OVERVIEW OF APES

APES, as a comprehensive accelerator simulation software, will involve complex accelerator modeling, intensive computation and extensive data processing. Additionally, we will face challenges such as integrating various software, facilitating cross-platform usage, and enabling collaborative development among multiple individuals. Python, a rapidly growing programming language in recent years, provides numerous advantages for coding and future development. Based on its ease of learning, versatility, powerful standard library, rich ecosystem of third-party libraries and frameworks, and cross-platform compatibility, we have selected Python as the development platform for the APES software.

APES Software Structure

In the APES package, a foundational set of classes has been developed to serve as the core of the framework. The hierarchical structure of APES can be seen in Figure 1. Several key classes are introduced below. For a more comprehensive understanding of the technological implementation and hierarchical connections between classes will be provided in the user manual.

Element

The "Element" class in the APES code is a foundational base class with attributes and methods that are common for deriving specific types of elements. Within the Element class, there is also a set of patch generators that handle transformations between ideal and real frames. When combined

* Work supported by IHEP Innovative Fund
† liuwb@ihep.ac.cn

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPC11

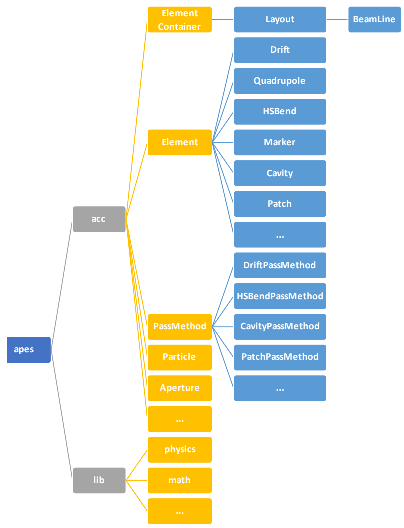

Figure 1: APES hierarchical structure diagram.

with the transfer map of each subclass derived from the Element class, the chain of patches and maps forms the primary sequence of operations that particles undergo during the tracking process.

Patch

In APES, "Patches" are used to describe frame transformations caused by factors like frame shifts from specialized installations or misalignments due to installation errors. Each Patch represents an affine transformation in real space and a 6D transformation for the particle's coordinates.

PassMethod

The "PassMethod" class is the core calculation class, with specialized subclasses like DriftPassMethod, QuadrupolePassMethod, HBendPassMethod, and PatchPassMethod designed for specific component types. Each subclass assigns tracking maps for its corresponding element type. During optics calculations or particle tracking, a list of PassMethod instances is automatically generated, allowing for flexible configuration of pass methods for different elements as needed.

Layout

The "Layout" class serves a dual purpose. Firstly, it constructs the layout of the accelerator and computes survey information for elements in the Global Frame. Secondly, it generates an "element table" that is essential for subsequent particle tracking. Elements and patches are added to the "table" attribute of a Layout object during accelerator construction using methods such as "append" or "insert".

BeamLine

The "BeamLine" class is crucial for encapsulating information extracted from Layout and plays a key role in generating a sequence of maps essential for optics and tracking calculations. This class also includes commonly used calculations such as Jacobian Matrix calculation, closed orbit calculation, Twiss calculation, and more. Continuous development and integration of additional functionalities further enhance the class's capabilities, making it a versatile tool for optimizing beamline design and analysis.

Tracking Map of APES

The design of colliders requires accurate symplectic map of magnets to ensure right beam dynamics result. Due to very small β_y^*, the non-linearity of drift must be considered in modern/future high-performance e+ e- colliders. Nonlinear Maxwellian fringe fields of magnets must also be taken into account. Tracking maps of various magnetic elements, such as drifts, dipoles, quadrupoles, sextupoles, octupoles, RF-cavities, solenoids, and multipoles, are implemented using the SAD method in C for optimized computational speed [10]. This method supports the modeling of hard and soft edge fringe fields, tilted strong solenoids for particle detection in interaction regions (IRs), and the handling of combined solenoid/multipole elements. An optional map for the patch according to Etienne Forest is available [11]. Surface methods and implicit integrators can be employed to achieve precise modeling by obtaining a symplectic transfer map from complex magnetic fields.

A C/C++ program called APES-T (tracking module of APES) has been developed for large-scale particle tracking in parallel. APES-T supports both CPU and GPU platforms and integrates the strong-strong beam-beam code IBB [12]. It enables simulations with various features like impedance, collisions with large Piwinski angles, beamstrahlung effects, multiple bunches, and multiple interaction points (IPs). Through element-by-element tracking of the real lattice with beam-beam interactions and hybrid parallel acceleration using CUDA and MPI, APES-T allows for accurate and efficient simulations.

EXAMPLES OF SOFTWARE UTILIZATION

We have finalized the core modules of the APES Framework and integrated various beam physics calculation features. The following are some instances illustrating the application of APES.

Layout Modeling for Special Cases

BEPCII is an asymmetric double-ring collider with a cross angle at the interaction region. The utilization of Patch simplifies the modeling of special cases like the interaction region of BEPCII (as shown in Figure 2). By incorporating patch elements before and after the off-center superconducting quadrupoles (SCQs), the complexity of treating them as combined bend and quadrupole magnets is eliminated. The closed orbit of the BEPCII BPR in the interaction region, calculated using APES, is shown in Figure 3, illustrating the beam orbit relative to the center of the SCQ magnets.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPC11

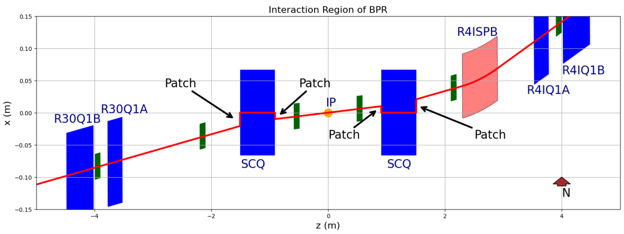

Figure 2: Interaction region of BEPCII BPR.

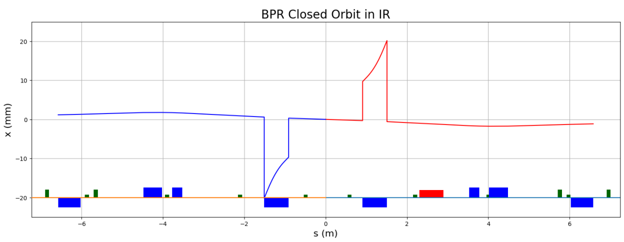

Figure 3: BEPCII BPR horizontal closed orbit in IR.

Synchrotron Radiation Effects

With the synchrotron radiation switch toggled on, the sawtooth effect is noticeable in the CEPC lattice. By scaling magnets based on local momentum, this effect can be eliminated, confining the central orbit with rad-taper within approximately 1 micron, as illustrated in Figure 4.

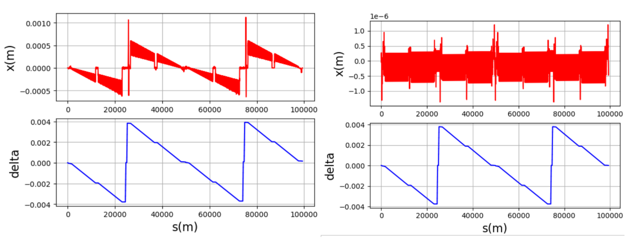

Figure 4: Sawtooth orbit deviation from synchrotron radiation in the CEPC lattice and beam center after rad-taper.

Alignment Error

The Patch class and its pass method simplify managing element misalignment, involving rotation and translation. Activating the alignment error switch generates a BeamLine with alignment errors. Figure 5 displays the horizontal orbit of the misaligned BEPCII e+ transport line before orbit correction.

Luminosity Simulation with APES-T

Benchmarking of APES-T against SAD using the SuperKEKB lattices has been conducted, and the program has been applied to the CEPC to explore the interplay among beam-beam interaction, beamstrahlung, and full lattices. As illustrated in Figure 6, a 16% decrease in luminosity resulting from realistic lattices has been identified compared to the linear arc map method, as elaborated in reference [13].

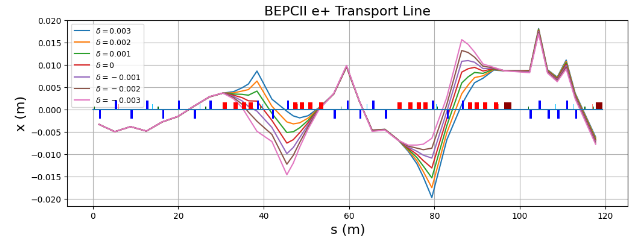

Figure 5: The BEPCII e+ transport line horizontal orbit affected by alignment errors measured in 2022.

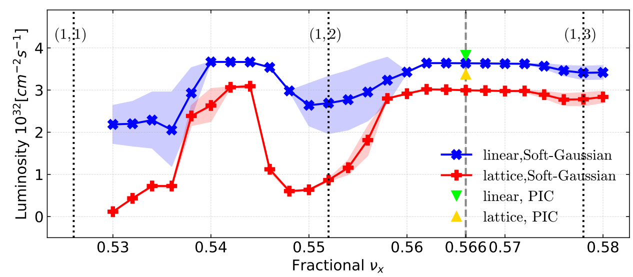

Figure 6: Luminosity calculated by IBB with linear arc maps (blue line) and by APES-T with full lattices (red line).

Beam Cavity Interaction

This study employs the APES_CBI module to benchmark the Beam Loading effects using existing data from the BEPCII electron ring. The primary focus of this simulation is to investigate the longitudinal tune shifts, as shown in Figure 7, providing comparisons among different results [14].

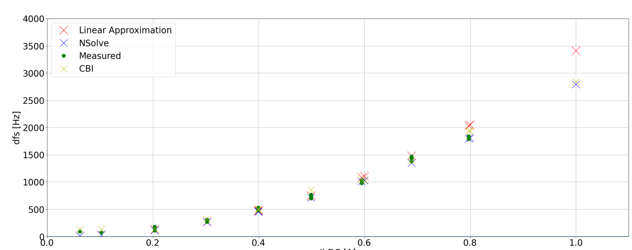

Figure 7: Comparison of APES_CBI simulation results with numerical and linear approximation solutions for tune shifts in the BEPCII electron ring.

SUMMARY

APES has completed its core architecture and now has basic accelerator design and calculation capabilities. In the future, we will gradually expand the program's functionality, improve computational speed, and optimize user experience to ensure that users can more easily use the software for accelerator design and calculation.

ACKNOWLEDGEMENTS

The authors would like to thank K. Ohmi, D. Zhou, K. Oide and E. Forest for their support and fruitful discussions. This project is supported by IHEP Innvotation Study.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPC11

REFERENCES

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

[2] V.I. Telnov, " Restriction on the energy and luminosity of e^+e^- storage rings due to beamstrahlung ", *Phys. Rev. Lett.*, vol. 110, p. 114801, 2013. doi:10.1103/PhysRevLett.110.114801

[3] D. Shatilov, " FCC-ee Parameter Optimization ", *ICFA Beam Dyn. Newslett.*, vol. 72, p. 30, 2017.

[4] K. Oide *et al.*, "Design of Beam Optics for the Future Circular Collider e+e- Collider Rings", *Phys. Rev. Accel. Beams*, vol. 19, p. 111005, 2016. doi:10.1103/PhysRevAccelBeams.19.111005

[5] P. Raimondi, "Introduction to Super B-Accelerators", presented at the 2nd Workshop on Super B-Factory, Frascati, Italy, Mar. 2006.

[6] J. Wu *et al.*, "Dynamic aperture optimization with diffusion map analysis at CEPC using differential evolution algorithm", *Nucl. Instr. and Meth. A*, vol. 959, p. 163517, 2020. doi:10.1016/j.nima.2020.163517

[7] N. Kuroo *et al.*, "Cross-wake force and correlated head-tail instability in beam-beam collisions with a large crossing angle"*Phys. Rev. Accel. Beams*, vol. 21, p. 031002, 2018. doi:10.1103/PhysRevAccelBeams.21.031002

[8] Y. Zhang *et al.*, "Self-consistent simulations of beam-beam interaction in future e^+e^- circular colliders including beamstrahlung and longitudinal coupling impedance", *Phys. Rev. Accel. Beams*, vol. 23, p. 104402, 2020. doi:10.1103/PhysRevAccelBeams.23.104402

[9] C. Lin, K. Ohmi, and Y. Zhang, "Coupling effects of beam-beam interaction and longitudinal impedance", *Phys. Rev. Accel. Beams*, vol. 25, p. 011001, 2022. doi:10.1103/PhysRevAccelBeams.25.011001

[10] https://acc-physics.kek.jp/SAD/

[11] E. Forest *et al.*, "The correct local description for tracking in rings", *Gordon and Breach Science Publishers, S.A.*, to be published.

[12] Y. Zhang *et al.*, "Development of a Beam-Beam Simulation Code for e+e- Colliders", in *Proc. PAC'05*, Knoxville, TN, USA, 2005, pp. 4176-4178. doi:10.1109/PAC.2005.1591756

[13] Z. Li *et al.*, "Strong-strong beam-beam simulations with lattices of circular e+ e-colliders", *Nucl. Instr. and Meth. A*, vol. 1064, p. 169386, 2024. doi:10.1016/j.nima.2024.169386

[14] Jiunn-Ming Wang, "Modes of storage ring coherent instabilities", *AIP Conference Proceedings*, vol. 153, p. 697, 1987. doi:10.1063/1.36361