Benchmarking APES against SAD for Single-Beam Background Simulations at BEPCII-U

Shiyuan Wang[1,2], Haoyu Shi[2,3], Bin Wang[2], Danhao Zhang[1], Chunxu Yu[1]

[1]School of Physical Sciences, Nankai University
[2]Institute of High Energy Physics, Chinese Academy of Sciences
[3]School of Physics, University of Chinese Academy of Sciences

Abstract

Under identical machine settings and physics models, we benchmark APES (Accelerator Physics Emulation Studio) against SAD (Strategic Accelerator Design) for single-beam background simulations at BEPCII-U. Ring parameters, optical functions, loss distributions near the interaction point and background-particle lifetimes are compared: ring parameters agree to better than **1%**, optical functions and IP-region loss distributions show good agreement in both rings, and lifetime deviations lie within **one statistical error**.

Tracking particles of the same scale (10^5), APES's GPU tracking outruns SAD by $\times$**32.959–33.433** for pure tracking and $\times$**2.728–2.875** for the full ring-level simulation. After further optimization of APES's GPU tracking, specifically for background simulations, the speedups relative to SAD reach $\times$**221–222** and $\times$**15.4–15.6**, respectively.

Introduction

Accelerator-physics simulation is a fundamental basis for accelerator design, beam-dynamics studies and machine operation, and its accuracy and reliability directly affect machine performance and physics research. For beam-background studies, accurately predicting beam lifetimes and loss distributions requires simulation software that both describes the relevant physics processes reliably and supports large-scale particle tracking. APES (Accelerator Physics Emulation Studio), newly developed at the Institute of High Energy Physics, Chinese Academy of Sciences, exactly matches these needs[1]. To evaluate its single-beam background simulation capability on a real accelerator lattice, we benchmark APES against SAD (Strategic Accelerator Design)[2], which has been extensively used for beam-background studies at BEPCII[3].

In single-beam background studies at BEPCII-U[4,5], lost background particles originate mainly from three processes[6–8]: Touschek scattering, beam-gas bremsstrahlung and beam-gas Coulomb scattering. Both rings use identical machine and beam-parameter settings, and APES and SAD use exactly the same input parameters and settings; the calculated ring parameters for the electron ring (BER) are listed in Table 1.

Parameter	SAD	APES	Diff. (%)
Horizontal tune	7.505616	7.505697	+0.001081
Vertical tune	5.575804	5.575777	−0.000494
Synchrotron tune	3.822643×10^{-2}	3.822641×10^{-2}	−0.000064
Momentum compaction	1.657748×10^{-2}	1.649890×10^{-2}	−0.474022
Horizontal emittance (m·rad)	1.404505×10^{-7}	1.397897×10^{-7}	−0.470522
Longitudinal emittance (m)	6.756492×10^{-6}	6.749357×10^{-6}	−0.105593
Horiz. damping time (s)	1.300762×10^{-2}	1.303240×10^{-2}	+0.190527
Vert. damping time (s)	1.258763×10^{-2}	1.258701×10^{-2}	−0.004926
Long. damping time (s)	6.194632×10^{-3}	6.188384×10^{-3}	−0.100869

Table 1: Calculated ring parameters for the electron ring (BER); Diff. (%) = (APES − SAD)/|SAD| × 100%.

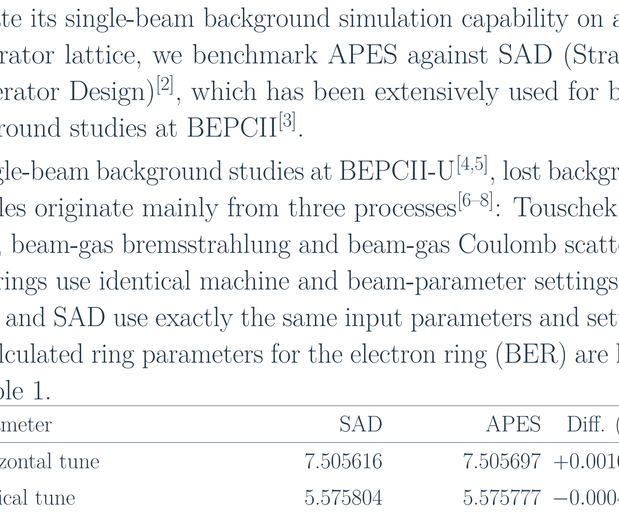


Figure 1: Optical functions along the BER: SAD vs. APES.
β_x, β_y beta functions
α_x, α_y alpha functions
η_x, $\eta_{x'}$ horizontal dispersion and its derivative

Touschek scattering is the intra-bunch scattering between particles: transverse momentum is converted into longitudinal momentum, pushing particles beyond the energy acceptance[9,10]. **Beam-gas bremsstrahlung** is the inelastic collision between a beam particle and a residual-gas nucleus: the particle loses energy by photon emission[11]. **Beam-gas Coulomb scattering** is the elastic deflection of beam particles by residual-gas nuclei: particles deviate transversely from the orbit[11].

Losses near the IP

Particles lost near the interaction point (IP) directly affect detector data taking and are therefore a key focus of this study.

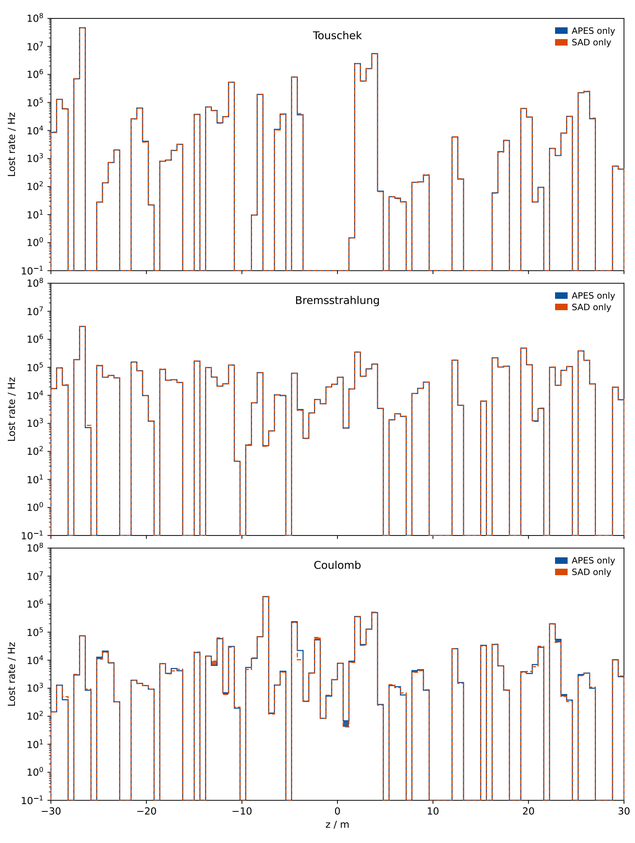


Figure 2: Longitudinal loss rates within ±30 m of the IP in the BER: APES vs. SAD.

Beam lifetimes

Table 2: Beam lifetimes over ten runs (hours): SAD vs. APES GPU.

Ring	Process	SAD (h)	APES GPU (h)	Agreement
BER	Touschek	15.404 ± 0.036	15.402 ± 0.020	0.017%
BER	Brem.	57.213 ± 0.005	57.215 ± 0.016	0.005%
BER	Coulomb	84.259 ± 0.399	84.318 ± 0.506	0.070%
BPR	Touschek	16.862 ± 0.038	16.865 ± 0.021	0.021%
BPR	Brem.	57.729 ± 0.004	57.734 ± 0.010	0.008%
BPR	Coulomb	87.025 ± 0.744	87.422 ± 0.671	0.456%

Values are ten-run means ± sample standard deviation (hours).

Lifetimes agree within one statistical error

Based on the mean lifetimes of ten independent runs, the lifetimes of the three background processes are compared for both rings: the difference of every case is smaller than one statistical error.

APES GPU Tracking Optimization

Within the background-simulation framework, APES's GPU tracking is optimized with four measures to raise the speedup.

Theta optimization. Skip rotation trigonometry at theta = 0

Device LTO (`-dlto`). Element-map functions inlined across compilation units

Particle compaction. Lost particles removed periodically

Single kernel. One launch for the whole ring

Speedups are relative to the previous GPU release, all at $\sim 10^5$ particles; the first three measures combine to $\times$**6.6–6.8** for pure tracking, and to $\times$**13–16** when particle compaction is enabled every 10 turns. In full ring-level runs of both rings, the optimized APES GPU tracking runs $\times$**5.4–5.7** faster than before optimization and $\times$**15.4–15.6** faster than SAD, with byte-identical output—the physics results are unaffected. The speedup is not a constant: it increases as the number of particles increases and saturates once the GPU is fully occupied.

GPU speedup

	prev GPU		new GPU	
Ring	Complete	Pure tracking	Complete	Pure tracking
BER	**2.728×**	**32.959×**	**15.6×**	**222×**
BPR	**2.875×**	**33.433×**	**15.4×**	**221×**

Complete = complete ring-level simulation; Pure = pure multi-turn tracking; both use $\sim 10^5$ particles. Values are ten-run mean cumulative times relative to SAD CPU; SAD uses a Xeon Gold 6140 CPU core, APES uses an NVIDIA V100 GPU.

Conclusions

Under identical BEPCII-U models and inputs, APES reproduces SAD's principal single-beam loss observables: ring parameters agree to better than **1%**, optical functions agree well, lifetime deviations lie within **one statistical error**, and the main IR loss patterns are consistent. GPU acceleration is considerable for tracking large particle ensembles ($\sim 10^5$ particles), reaching $\times$**221–222** for pure tracking and $\times$**15.4–15.6** for the complete simulation.

References
[1] W. Liu et al., "Advancements in the development of beam dynamics software APES for CEPC," Proc. IPAC'24, Nashville, TN, 2024, pp. 1021–1024.
[2] Y. Ohnishi et al., "Computer program complex SAD for accelerator design, simulation and commissioning," Proc. 16th Annual Meeting of Particle Accelerator Society of Japan, 2019, pp. 4–8.
[3] H.C. Shi et al., "Beam background simulation and experiment at BEPCII," Nucl. Instrum. Methods Phys. Res. A 1050 (2023) 168174.
[4] H. Geng et al., "Lattice design for BEPCII upgrade," Proc. IPAC'21, Campinas, Brazil, 2021, pp. 3756–3758.
[5] H. Geng et al., "An alternative design for BEPCII upgrade," Proc. IPAC'22, Bangkok, Thailand, 2022, pp. 1591–1593.
[6] N.-F. Zhou et al., "Monte Carlo simulation of BEPCII beam-related background (I): synchrotron radiation," Chin. Phys. C 28 (2004) 227–231.
[7] D.-P. Jin et al., "Monte Carlo simulation of the BEPCII/BESIII backgrounds: beam-gas interactions," Chin. Phys. C 28 (2004) 1197–1202.
[8] D.-P. Jin et al., "Monte Carlo simulation of the BEPCII/BESIII backgrounds: Touschek effects," Chin. Phys. C 30 (2006) 449–453.
[9] H. Bruck, *Circular Particle Accelerators*, LA-TR-72-10-REV, 1974.
[10] A. Piwinski, "The Touschek effect in strong focusing storage rings," arXiv:physics/9903034, 1999.
[11] H.C. Shi, "Analysis of beam background at electron-positron colliders in the tau-charm energy region," PhD thesis, University of Science and Technology of China, 2023.