Status Update on CEPC Beam-Induced Background Studies

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July 2026

Status Overview

Beam-induced backgrounds are critical to detector and physics performance.

The two most important backgrounds are incoherent pair creation (IPC) and synchrotron radiation (SR).

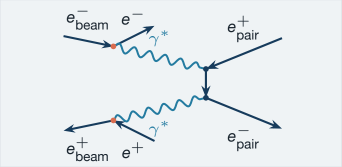
Workstream	Motivation	Status
IPC model validation	Guinea-Pig is a legacy generator with limited maintenance; its IPC rates, composition, and phase space therefore require validation. IHEP-VINCA joint group	**VALIDATION ONGOING**
Fast IPC generation	Beam-beam interaction simulations are expensive. An efficient ML-based generator is needed to produce large IPC event samples.	**DEMONSTRATED**
SR mitigation	Control SR power loads and photon escape rates by optimizing apertures, masks and shielding.	**OPTIMIZATION ONGOING**
Detector integration	Integrate IPC and SR sources into CEPCSW/Key4HEP detector simulation workflow.	**IN DEVELOPMENT**

Together, these studies address relevant requirements for MDI optimization: trustworthy, high-statistics IPC generation and a simulation-to-geometry feedback loop.

Incoming beam particles emit virtual or real photons, which interact to produce a secondary e^+e^- pair.

Representative beam-level topologies are shown below.

LANDAU–LIFSHITZ (LL)

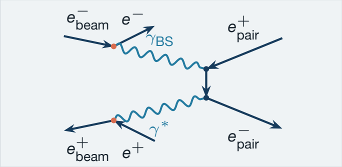


Two virtual photons γ^*.

$e^-e^+ \to e^-e^+e^-e^+$

80.5% of generated pairs

BETHE–HEITLER (BH)

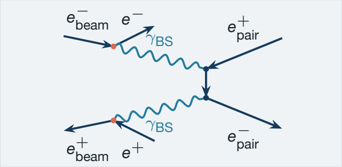


$\gamma_{\text{BS}} + \gamma^*_{\text{beam}}$.

$e^\pm\gamma_{\text{BS}} \to e^\pm e^+e^-$

18.3% of generated pairs

BREIT–WHEELER (BW)



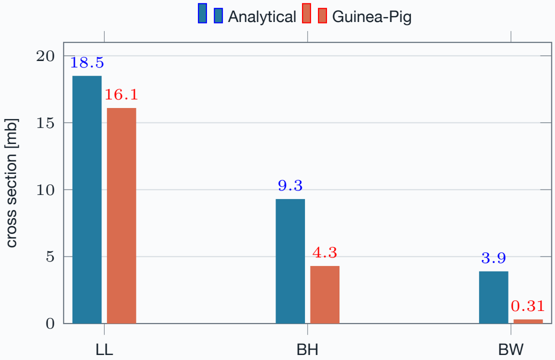
Two beamstrahlung photons γ_{BS}.

$\gamma_{\text{BS}}\gamma_{\text{BS}} \to e^+e^-$

1.2% of generated pairs

Reference sample: 2,157 $\pm$ 64 particles per bunch crossing, with energies from 0.5 MeV to 100 GeV and a strongly forward-peaked distribution.

Each QED process can be calculated from first principles and cross-checked with independent generators.
In practice, generators apply cutoffs to soft and collinear events, reducing the effective cross section.



CROSS SECTIONS AT 240 GEV [MB]

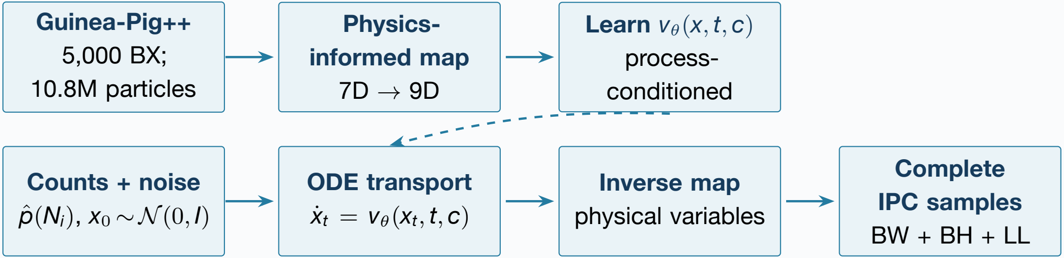
LL ratio, GPig / analytic	0.87
BH ratio	0.46
BW ratio	0.08
Analytical total	31.7
Guinea-Pig total	20.7

LL is broadly consistent; resolving the BH/BW normalization remains an ongoing validation task.

ONGOING

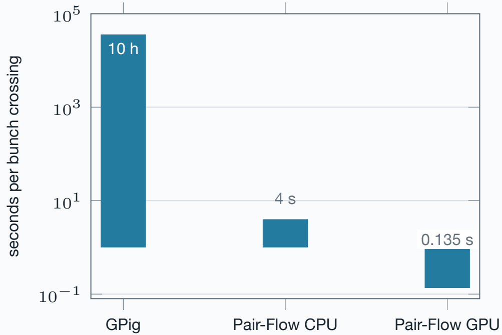
LEP data; WarpX comparison.

CEPC-PairFlow is trained once to learn the process-conditional distribution generated by Guinea-Pig++; subsequent event generation becomes numerical transport rather than a new beam–beam simulation.



v_θ	The learned velocity field that transports x_t through feature space during generation.
Features	Raw 7D variables $E, \boldsymbol{\beta}, \mathbf{r}$ are transformed into a 9D representation using log-E, p_T/ϕ, quantile-β_z, and standardized vertex features; this regularizes extreme scales and boundaries for stable learning.

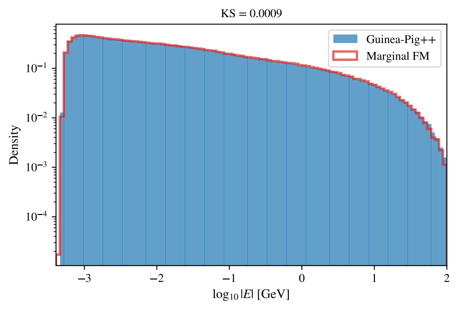
PERFORMANCE IMPROVEMENT



$10\,\mathrm{h}/0.1\,\mathrm{s} \approx 3.6 \times 10^5$ speed-up per BX.

At the reported rate, 10^5 BX require ~3.7 GPU hours.

VALIDATION AGAINST GUINEA-PIG++



Kolmogorov–Smirnov (KS) statistic: maximum difference between cumulative distributions; lower is better.

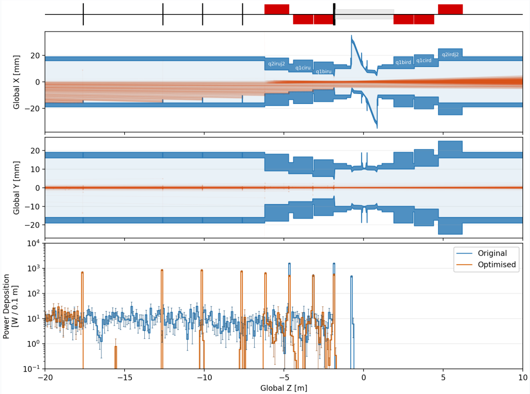
$|E|$ KS	0.0009
θ KS	0.0020
p_T KS	0.0017

Overall agreement is close.

Since the release of the TDR, the SR simulation workflow has been migrated to a more efficient framework. This enables a practical simulation-to-geometry optimization loop.

A Gaussian beam is initialized at the upstream dipole and tracked through the MDI region.

AFTER OPTIMIZATION



REPORTED BEFORE / AFTER

Quantity	Before	After	Change
Escaping photons / BX	20,000	3,000	-85%
Power at mask1	1.6 kW	0.6 kW	-63%
Power at mask3	1.5 kW	0.6 kW	-60%

GEOMETRY CHANGE

Final SR-mask half-aperture: 6.0 mm $\rightarrow$ 4.5 mm.

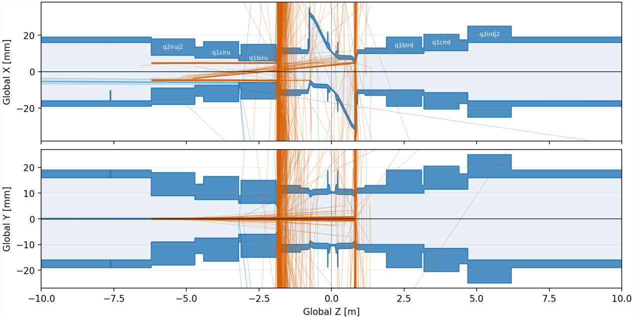
New upstream shielding elements work together with the mask; remaining hot spots move farther from the IP.

Beam halo is generated in the $5–10\,\sigma$ region of the x–x' phase space.

Earlier MDI optimization targeted the beam core; the halo is largely unaffected.

The beam halo photon escape rate remains high, and optimization is ongoing.

REMAINING ISSUE



A tungsten shell sits beside the beam pipe near the hot spot. The next step is to increase its length and thickness.

REPORTED RATES

Quantity	Original core	Optimized core	Halo model (assuming 1%)
Escaping photons / BX	20,000	3,000	450,000
Escaped energy / BX	0.42 GeV	–	200 GeV
Hot-spot power scale	>1 kW	<1 kW near IP	~ 10 W

Summary and next step

Workstream	Status and next focus
Pair source	LL is consistent; BH/BW normalization remains unresolved. Next: cross-check with data and independent generators.
Fast generation	CEPC-PairFlow is fast enough for practical use and agrees closely with Guinea-Pig++. Next: extend validation and deployment.
SR and integration	Beam-core mitigation is effective; beam-halo mitigation remains ongoing. Next: refine shielding and integrate with CEPCSW/Key4HEP.

Together, these ongoing efforts move toward a validated, flexible, and optimization-ready workflow for MDI design iteration.

BACKUP

Backup: pair cross sections

	Analytical [mb]			Guinea-Pig [mb]			BDK [mb]
Scenario	LL	BH	BW	LL	BH	BW	LL
CEPC, 240 GeV	18.5	9.3	3.9	16.1	4.3	0.31	–
LEP1, 91 GeV	14.3	0.42	0.0029	15.2	0.38	0.00066	12.0
LEP2, 208 GeV	17.9	1.8	0.33	18.5	1.6	0.072	13.5

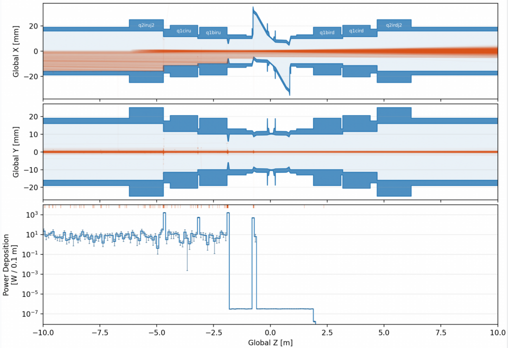
- LL depends mainly on beam energy and agrees at the reported level.
- BH and BW depend on the beamstrahlung-photon treatment and show larger differences.
- LEP data and an independent simulation provide the proposed external checks.

Backup: surrogate validation

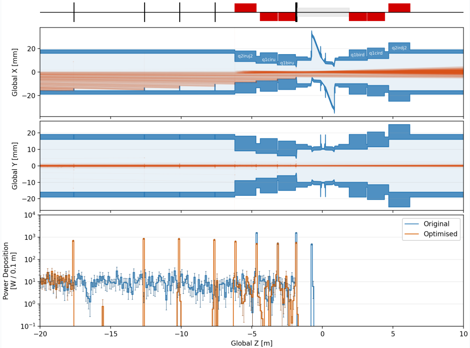
Metric	Kernel density	Marginal flow	Combined flow
$\|E\|$ KS	0.030	0.0009	0.0011
β_x KS	0.139	0.0012	0.0009
β_y KS	0.170	0.0014	0.0022
β_z KS	0.024	0.0132	0.0143
x KS	0.094	0.0012	0.0011
y KS	0.156	0.0117	0.0088
z KS	0.055	0.0015	0.0017
p_T KS	0.297	0.0017	0.0015
θ KS	0.308	0.0020	0.0021
MMD	2.82×10^{-3}	2.8×10^{-5}	1.17×10^{-4}
Speed [ms / BX]	6	135	219

Backup: beam-core SR before / after optimization

BEFORE OPTIMIZATION



AFTER OPTIMIZATION



Backup: SR mitigation settings

Element	Original location / aperture	Optimized location / aperture	Original power	Optimized power
jaw1	–	-17.6 m / 14.2 mm	–	0.6 kW
jaw2	–	-12.6 m / 13.5 mm	–	0.8 kW
jaw3	–	-10.1 m / 12.0 mm	–	0.8 kW
jaw4	–	-7.6 m / 10.4 mm	–	0.8 kW
mask0	–	-6.2 m / 9.0 mm	–	0.7 kW
mask1	-4.7 m / 11.5 mm	-4.7 m / 7.5 mm	1.6 kW	0.6 kW
mask2	-3.19 m / 10 mm	-3.19 m / 6.0 mm	0.6 kW	0.6 kW
mask3	-1.9 m / 6.0 mm	-1.9 m / 4.5 mm	1.5 kW	0.6 kW

The main reported improvement is associated with the additional upstream shielding and the narrower mask3 aperture.