Geometric Optimization Simulation of the CEPC Vertex Detector

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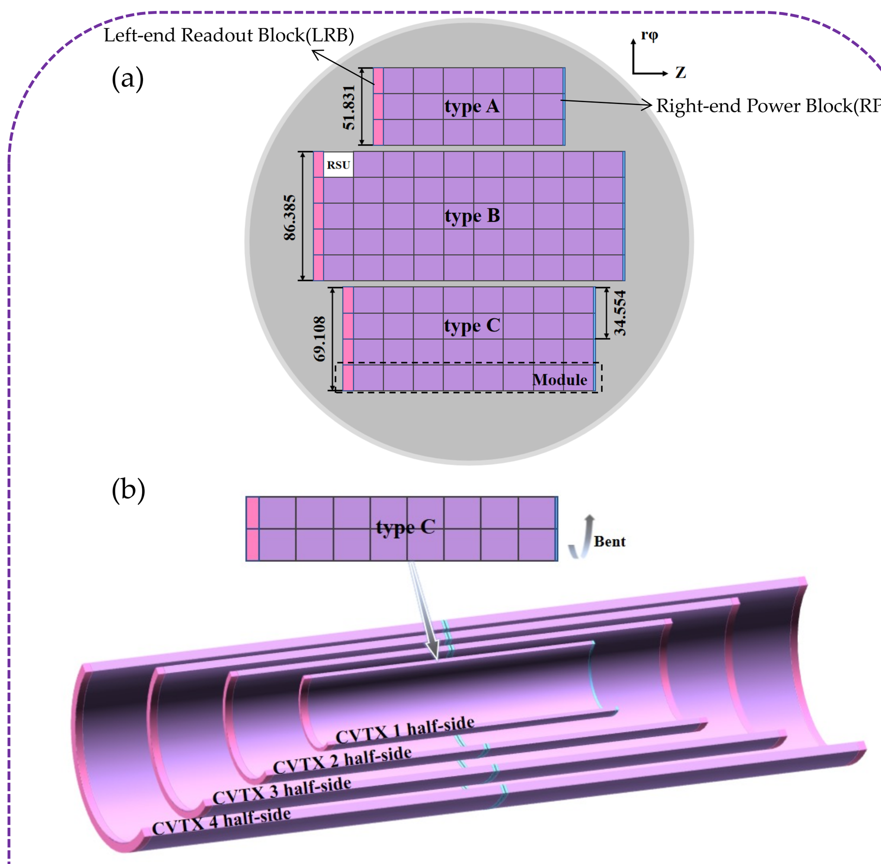
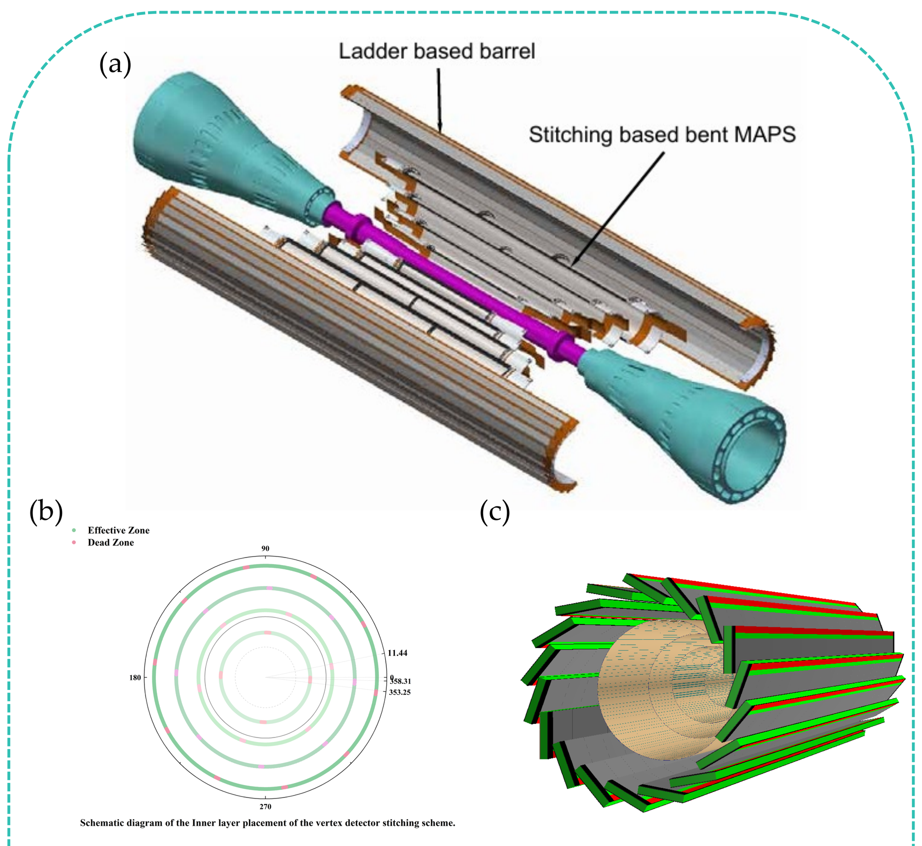
The identification of heavy-flavored quarks and τ leptons is an important physics goal of the Circular Electron Positron Collider (CEPC). The Vertex Detector (VTX) of the CEPC is capable of obtaining precise track parameters of charged particles in the vicinity of the Interaction Point to reconstruct the decay vertex of short-lived particles. The CEPC vertex detector currently employs an advanced sensor design scheme to achieve low mass and low dead zone objectives. The first four layers of the VTX are formed using stitched Monolithic Active Pixel Sensor (MAPS), while the fifth and sixth layers are constructed using traditional MAPS. This dual-sensor approach substantially reduces the detector mass to an average of 0.134% X_0 per layer while enabling stable construction for high-precision d_0 and z_0 resolution of 3.4 μm @ 10 GeV and 3.7 μm @ 10 GeV respectively. Additionally, we present the performance of the VTX under scenarios involving partial chip damage or even complete layer failure. Furthermore, considering potential deformations of the chips after the installation of the VTX, we have explored a feasible alignment solution.

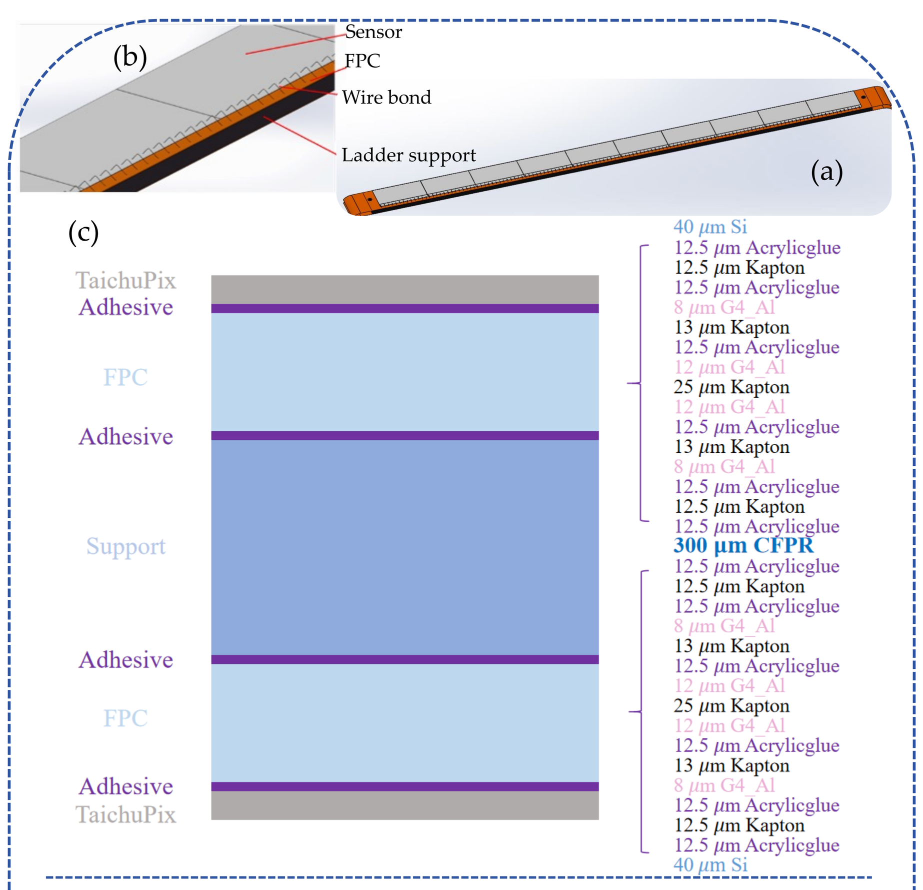
Structure



a) The arrangement of stitching frames on a 300 mm wafer. The shorted-dashed line area represents a module consisting of several RSUs, one LRB, and one RPB.
b) The Type C sensor is diced into a two-module sensor and bent along the ϕ-direction to form a semi-cylindrical structure for the Curved Vertex Layer (CVTX) 1.



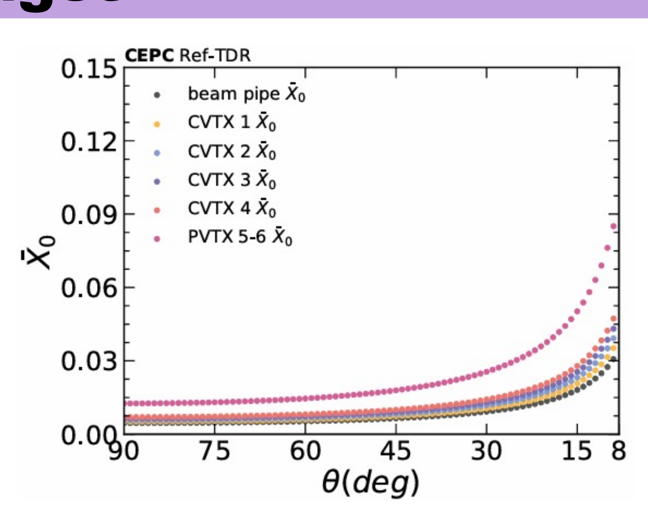
a) and c) Diagram of the VTX. The composition of the first four layers is shown on the left. The last two layers is shown on the right. Geometric configuration parameters seen in Table 1.
b) Considering the inefficient region in the ϕ direction of the stitched sensor, layers of the CVTX are rotated by an angle when mounted.



a) Full view of a ladder;
b) Close-up view of a ladder showing sensors wire bonded to the FPC.
c) Schematic transverse cross-section of a double-sided ladder structure used in layers 5 and 6, referred to as the Planar Vertex Layers (PVTXs) of the VTX.

Material budget

- Average material budget $\overline{X_0}$ as a function of the polar angle θ, averaged over the full azimuthal angle ϕ, for each layer of the VTX and the beam pipe, is shown in a stacked plot.
- As θ decreases (i.e., moving toward the forward region), the effective path length through the detector increases, leading to a higher accumulated material budget.

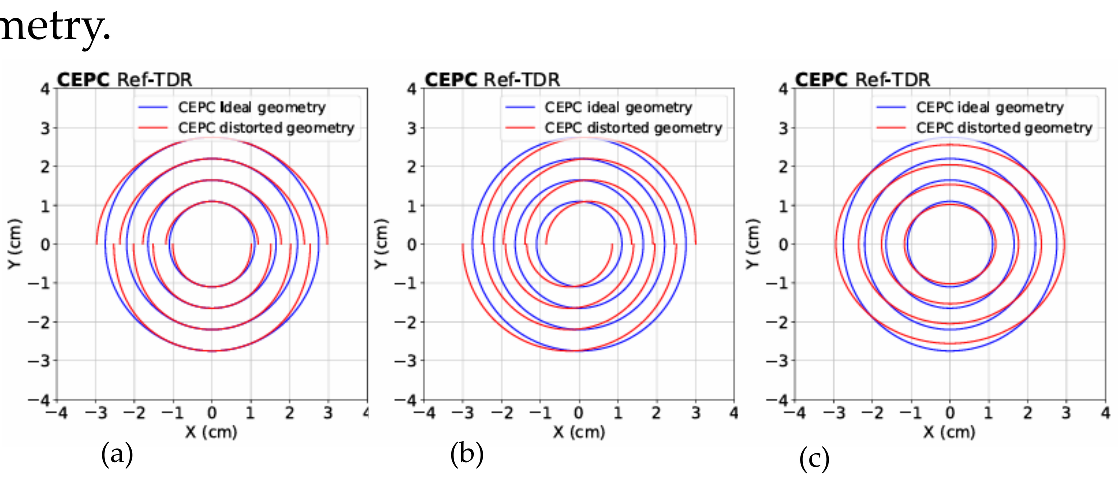


Unit	BeamPipe	CVTX 1	CVTX 2	CVTX 3	CVTX 4	PVTX 5-6
$\overline{X_0}(X_0)$	0.45%	~0.07%	~0.06%	~0.06%	~0.06%	~0.56%

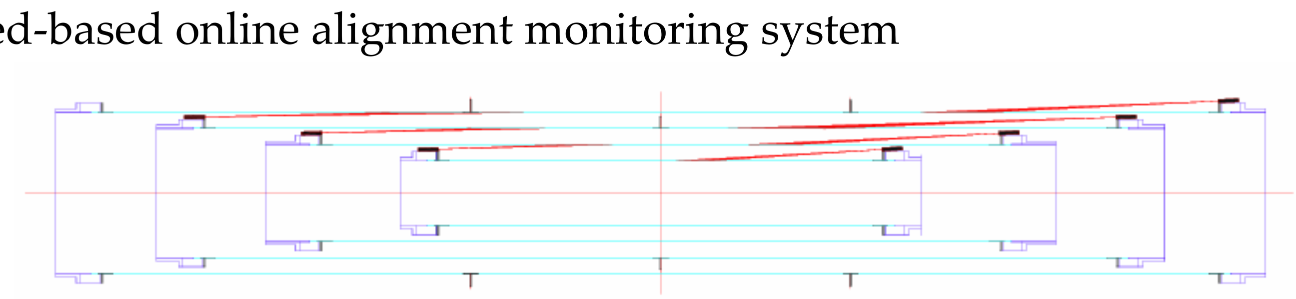
Alignment

- Illustration of hit positions in the transverse plane with ideal vertex geometry and three deformed geometry.

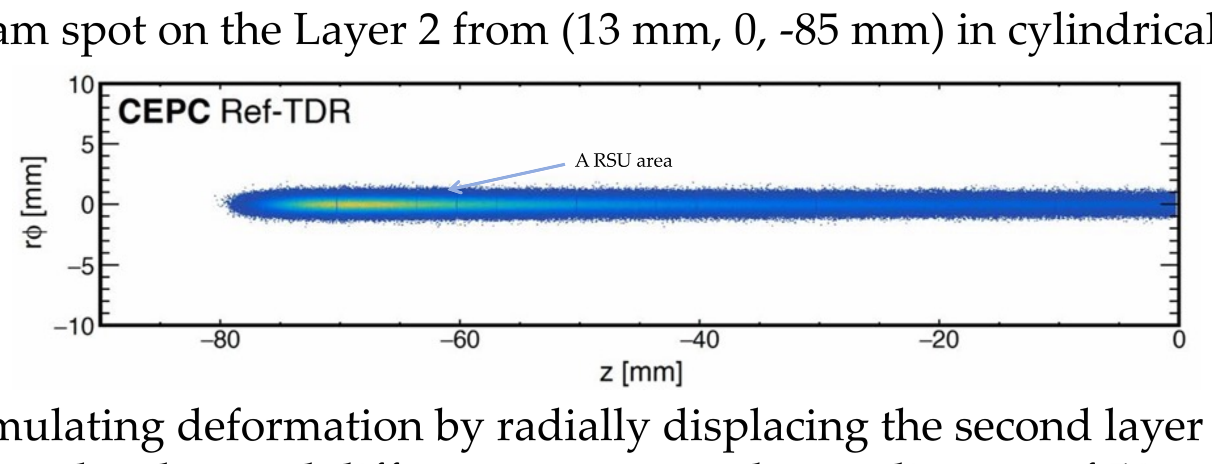
a) The radius of curvature differs from the nominal radius
b) Half-layer edge deviation from cylindrical shape
c) Compression causes cylindrical deformation into an ellipsoid



- A lased-based online alignment monitoring system



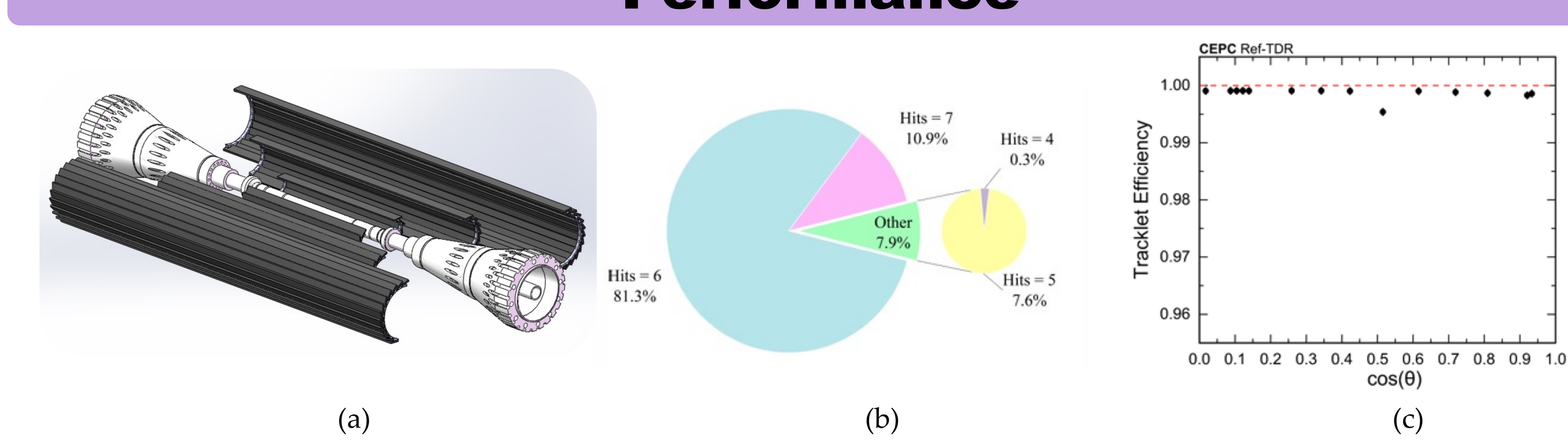
- Laser beam spot on the Layer 2 from (13 mm, 0, -85 mm) in cylindrical system.



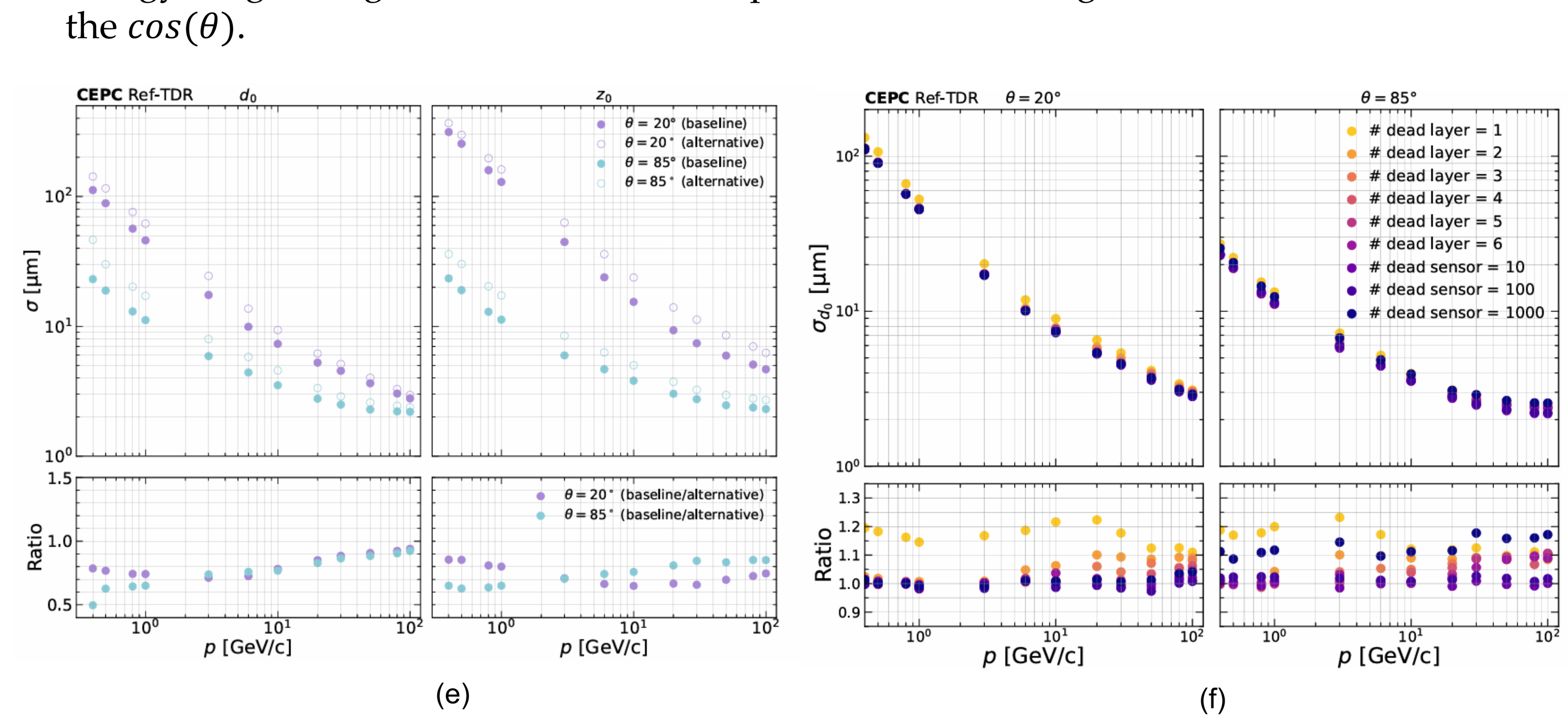
- When simulating deformation by radially displacing the second layer outward by $d = 10$ μm, the observed difference corresponds to a distance of 50 μm, which is consistent with relationship $d/tan\theta \approx 57$μm.

Table 1	CVTX/PVTX X	radius .mm	length .mm	arc length .mm	support thickness .μm
Baseline design	CVTX 1	11.1	161.4	69.1	45
	CVTX 2	16.6	242.2	103.7	32
	CVTX 3	22.1	323.0	138.2	31
	CVTX 4	27.6	403.8	172.8	29
	PVTX 5-6	39.5	682.0		300
Alternative design	PVTX 1-2	12.46	260.0		300
	PVTX 3-4	27.89	494.0		300
	PVTX 5-6	43.79	749.0		300

Performance



- Figure (a) illustrates an alternative VTX design featuring three layers of double-sided ladders with planar MAPS, with specific dimensions detailed in Table 1.
- Figure (b) shows the distribution of the number of hits per track for 10000 charged Geantinos with $p = 20$ GeV and $\theta = 20^{\circ}$.
- Figure (c) illustrates the tracklet efficiency of charged Geantino particles at 20 GeV energy, originating from the interaction point and traversing the VTX, as a function of the $cos(\theta)$.



- Figure (e): $\sigma_{d_0} \approx$ 3.4 μm @ 10GeV and 85°, $\sigma_{z_0} \approx$ 3.7 μm @ 10GeV and 85°;
- The performance of baseline design is better than alternative design.
- Figure (f) demonstrates that as the number of damaged sensors increases and the damaged detector layer approaches the collision point, resolution deteriorates, with a maximum decline of 25% compared to the baseline.

Summary

- VTX achieves an extremely low material budget due to its use of stitched MAPS.
- The tracklet efficiency remains above 99.6% across all polar angles, demonstrating robust tracking performance.
- The VTX can achieve excellent resolution, and the damage to the innermost layer results in the largest performance drop, which does not exceed 25%.
- The laser calibration system can infer positional changes through the distribution of pixel IDs, and the expected precision is at the micrometer level.

Reference:

I. Chengdong Fu, “Silicon Tracking at CEPC ”, The 2023 international workshop on the High EnergyCircular Electron-Positron Collider, 23-27 October 2023, Nanjing.
II. Hao Zeng, “Optimization of Silicon Pixel Vertex Detector for CEPC”, Joint Workshop of the CEPC Physics, Software and New Detector Concept, 14-17 April 2021, Yangzhou.
III. http://code.ihep.ac.cn/cepc/CEPCSW

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