Status and Perspectives of The CEPC

Jianchun Wang
IHEP, CAS

For the CEPC working group
The CEPC aims to start operation in 2030’s, as a Higgs (Z) factory in China.

- To run at $\sqrt{s} \sim 240$ GeV, above the $ZH$ production threshold for ~1M Higgs; at the $Z$ pole for ~Tera $Z$, at the $W^+W^-$ pair (possible $t\bar{t}$ pair) production threshold.

- High precision Higgs, EW measurements, studies of flavor physics & QCD, probes of physics BSM.

- Possible $pp$ collider (SppC) of $\sqrt{s} \sim 50–100$ TeV in the future.

**Potential CEPC Sites**

- Changchun
- Qinhuangdao
- Huangling
- Changsha
- Huzhou
- Shenshan
Inspired by the discovery of the Higgs boson at the LHC

Ideal case

- Release of accelerator TDR
- Site selection, engineering design, technology & system verification
- MoU, international collaboration

- Tunnel and infrastructure construction
- Accelerator components production; Installation, alignment, calibration and commissioning
- Decision on detectors and release of detector TDR; Construction, installation and commissioning

- 2016.6 R&D funded by MOST
- 2018.5 1st Workshop outside of China
- 2018.11 Release of CDR

- 2013.9 Project kick-off meeting
- 2015.3 Release of Pre-CDR

- 2018.2 1st 10 T SC dipole magnet
- 20 T SC dipole magnet R&D with Nb$_3$Sn+HTS or HTS

- 15 T SC dipole magnet & HTS cable R&D
The CEPC Operation Plan

<table>
<thead>
<tr>
<th>Operation mode</th>
<th>ZH</th>
<th>Z</th>
<th>W+W-</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ [GeV]</td>
<td>~240</td>
<td>~91.2</td>
<td>158-172</td>
</tr>
<tr>
<td>Run time [years]</td>
<td>7</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>$L/IP \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>3</td>
<td>32</td>
<td>10</td>
</tr>
<tr>
<td>$\int L , dt$ [ab$^{-1}$, 2 IPs]</td>
<td>5.6</td>
<td>16</td>
<td>2.6</td>
</tr>
<tr>
<td>Event yields [2 IPs]</td>
<td>$1 \times 10^6$</td>
<td>$7 \times 10^{11}$</td>
<td>$2 \times 10^7$</td>
</tr>
<tr>
<td>Latest $L/IP \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>5.0</td>
<td>105.5</td>
<td>15.4</td>
</tr>
</tbody>
</table>

The large samples from 2 IPs: $\sim 10^6$ Higgs, $\sim 10^{12}$ Z, and $\sim 10^8$ W bosons,

The large samples of H, Z & W bosons from the CEPC provide a unique opportunity

- Higgs physics white paper, arXiv:1810.09037
- Model independent measurement of Higgs boson width.
- Delivers ≤ 1% precision in some key measurements of Higgs properties, some are not accessible @ LHC.
- Sensitive to invisible decay modes of Br ~0.3%, and exotic decay channels.

Precision EW measurements,
Flavor physics (b, c, tau),
Study of QCD,
Probe physics BSM.

K_2 uncert. ~ 0.13%
Most others ~ 1%
The CEPC Collider

- Double ring baseline design (30 MW/beam, upgradable to 50)
- Switchable between H & Z, W modes without hardware change (magnet switch).

650 MHz SRF system for the collider ring (100 km)

1.3 GHz SRF system for the booster ring (100 km), which is above the collider ring

A very active accelerator R&D program towards a TDR ~ the end of 2022
Both exceeded the CEPC spec, a milestone towards the TDR

**Collider ring 650MHz 2-cell cavity**
N-infusion adopted, $Q = 6.0 \times 10^{10} @ 22$ MV/m

**Booster 1.3GHz 9-cell cavity**
> 30 MV/m, max 36 MV/m.
$Q = 3.4\sim4.5 \times 10^{10} @ 16\sim22$ MV/m
Accelerator R&D: High Efficiency Klystrons

- The 1st prototype finished its fabrication and passed the maximum power test.
- Output power reaches 700 kW in CW mode and 800 kW in pulsed mode. Power transfer rate ~ 62%.
- one of the key technology and breakthrough for CEPC
Conceptual Detector Designs

**Baseline Design**
- Particle Flow Approach
- Magnet (3T/2T)
- LumiCal
- Si Pixel Vertex
- SIT TPC, SET
- FTD, ETD

**IDEA concept**
- (also proposed for FCC-ee)
- Preshower ($\mu$-RWELL)
- Dual-readout calorimeter
- Yoke + Muon ($\mu$-RWELL)

**FST concept**
- (Full Silicon Tracker)
- PFA HCAL
- PFA ECAL
- SIT TPC, SET
- FTD, ETD

**The 4th Concept**
- (To-be-named)
- PFA HCAL
- Partially Yoke
- Magnet (3T/2T)
- PID (DC+ToF)
- Crystal ECAL (Transverse bar)
Requirements of The CEPC Detector

The physics motivations dictate our selection of detector technologies

<table>
<thead>
<tr>
<th>Physics process</th>
<th>Measurands</th>
<th>Detector subsystem</th>
<th>Performance requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZH, Z \to e^+e^-, \mu^+\mu^-$</td>
<td>$m_H, \sigma(ZH)$</td>
<td>Tracker</td>
<td>$\Delta (1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\text{GeV}) \sin^{3/2} \theta}$</td>
</tr>
<tr>
<td>$H \to \mu^+\mu^-$</td>
<td>BR($H \to \mu^+\mu^-$)</td>
<td>Vertex</td>
<td>$\sigma_{\gamma\phi} = \frac{10}{p(\text{GeV}) \times \sin^{3/2} \theta} \text{ (\mu m)}$</td>
</tr>
<tr>
<td>$H \to b\bar{b}/c\bar{c}/gg$</td>
<td>BR($H \to b\bar{b}/c\bar{c}/gg$)</td>
<td>Vertex</td>
<td>$\sigma_{\gamma}/E = 3 \sim 4% \text{ at 100 GeV}$</td>
</tr>
<tr>
<td>$H \to q\bar{q}, WW^<em>, ZZ^</em>$</td>
<td>BR($H \to q\bar{q}, WW^<em>, ZZ^</em>$)</td>
<td>ECAL, HCAL</td>
<td>$\Delta E/E = \frac{0.20}{\sqrt{E(\text{GeV})}} \oplus 0.01$</td>
</tr>
</tbody>
</table>

- Flavor physics ⇒ Excellent PID, better than 2\sigma separation of π/K at momentum up to ~20 GeV.
- EW measurements ⇒ High precision luminosity measurement, $\delta L / L \sim 10^{-4}$. 

05/24/2021
Silicon Vertex Detector

2 layers / ladder $R_{in} \sim 16$ mm

Goal: $\sigma(IP) \sim 5 \, \mu m$ for high P track.

CDR design spec:
- Single point resolution $\sim 3 \, \mu m$.
- Low material (0.15% $X_0$ / layer),
- Low power ($< 50 \, mW/cm^2$)
- Radiation hard (1 Mrad/year)

Silicon pixel sensor develops in 3 series:
**JadePix / MIC, TaichuPix, CPV**

**JadePix-3** Pixel size $\sim 16 \times 23 \, \mu m^2$

**TaichuPix-2** 64x192 array $25 \times 24 \, \mu m^2$ pixel size

CPV4 (SOI-3D), 64x64 array $\sim 21 \times 17 \, \mu m^2$ pixel size

Upper chip

Full size TaichuPix-3 to be used for prototyping ladder

Lower chip

Tower-Jazz CiS process

05/24/2021
- Area of the silicon tracker is very big: ~70 m² in SiTrk+TPC, or ~140 m² in FST plans. R&D focuses on cost effective and high performance.
- A HV-CMOS solution based on the ATLASPix3 designed by KIT.
- Study ATLASPix3 with radioactive source, cosmic ray, & particle beam.
- A short stave demonstrator will be constructed.
- A CEPC-version of pixel size 25×150 μm² is to be fabricated with the HLMC 55nm technology.

ATLASPix3
132×372 pixels
150×50 μm² pixel size.
Time resolution: O(10ns)

Fe-55 with collimator
Interaction Region Design

Crossing angle: 33 mrad,
Focal length: 2.2 m

Final focusing magnets (QD0, QF1) with
Segmented Anti-Solenoidal Magnets

Beam Pipe
\( \phi \ 28 \rightarrow 20 \text{ mm}, \ Be \ thickness: \ 0.85 \rightarrow 0.35 \text{ mm} \)

LumiCal Tracker

Silicon Tracker
Time Projection Chamber

Challenge: Ion backflow (IBF) affects the resolution. It can be corrected by a laser calibration at low luminosity, but difficult at high luminosity Z-pole.

Exploring potential solutions, e.g. Pixel TPC with double meshes, or micromegas.

When Gain×IBF=1, distortion <16 μm @ L= 32 ×10^{34} cm^{2}s^{-1}, <49 μm @10^{36} cm^{2}s^{-1}. 

Baseline main tracker
σ(r-Φ) ~100 μm
The main tracker in IDEA design

- **Gas:** He/iC$_4$H$_{10}$ (90:10)
- **Spatial resolution:** <100 μm
- **Max drift time:** ~350 ns

**DAQ** for prototype drift tube to study front end data compression.

Cluster counting for PID

- **AD9689 – 2000 EBZ**
- **Xilinx KCU105**

**Tracking efficiency** $\varepsilon \approx 1$

for $\theta > 14^\circ$ (260 mrad)

97% solid angle

- **0.016 $X_0$ to barrel calorimeter**
- **0.050 $X_0$ to end-cap calorimeter**
Both TPC & DC in the two designs have good PID, with dE/dX or dN/dX (cluster counting).

The FST solution needs a supplement PID. A combination of different PID detectors is also possible.

Aim is to for have $2\sigma \pi/K$ separation for $P<\sim20$ GeV/c.

① **Drift chamber** between the outer layers of FST. The dN/dX method is more efficient. It is a joint R&D effort with the IDEA DC. But the DC can be optimized for PID only, not its tracking capability.

② **Time of flight** detector, e.g. LGAD. The time resolution ~20-30 ps today. Resolution of 10 ps is possible by the time of CEPC.

Other options, e.g. an aerogel **RICH**, will also be considered.
An alternative PFA ECAL in CDR: scintillator + SiPM as sensitive detector, tungsten as absorber, totals 24X_0 radiation length.

A 32-layer prototype: 3.2 mm thick W-Cu plate, scintillator bar size 5×45 mm², 1 SiPM/bar.

It has been tested with cosmic rays, and an electron beam at IHEP (Nov 2020). When possible it will be tested in a higher intensity electron beam at DESY.
High Granularity Crystal ECAL

- Timing at two ends for positioning along bar.
- Significant reduction of number of channels.

Goal
- Comparable BMR resolution as with the Sci+W ECAL.
- Much better sensitivity to $\gamma/e$, especially at low energy.

Bench Test
- Test board for KLauS-5 in BGA package

Design Idea
- MC Simulation
  - SiW ECAL
    - Mean = 123.6
    - RMS = 11.29
    - $\chi^2$/ndf = 116.2/61
    - Constant = 102.1 ± 5.0
    - Mean = 125.3 ± 1.1
    - Sigma = 3.52 ± 0.130
  - Crystal ECAL
    - Mean = 121.7
    - RMSG = 11.76
    - $\chi^2$/ndf = 161.8/10
    - Constant = 227.8 ± 12.3
    - Mean = 124.6 ± 0.0
    - Sigma = 1.22 ± 0.347

Recon. Algorithm
- Energy & time matching solves ambiguity

Goal
- Comparable BMR resolution as with the Sci+W ECAL.
- Much better sensitivity to $\gamma/e$, especially at low energy.
- **AHCAL of Steel, Plastic scintillator, SiPM+SPIROC**
  Prototype in production, size $72 \times 72 \times 100$ cm$^3$, 40 layers, Steel+Scint+PCB=$20+3+2=25$ mm, cell size $40 \times 40$ mm$^2$

- **SDHCAL based on GRPC:**
  Prototype size $1 \times 1 \times 1.3$ m$^3$, 48 layers, $1 \times 1$ cm$^2$ detector cell, 2 cm steel absorber.

- **SDHCAL based on MPGD**
  Constructed a $100 \times 50$ cm$^2$ RWell detector.
A 3×3 towers ECal-size prototype has been built, waiting for testbeam.

Dual Readout calorimeter in the IDEA design

Combining Crystal ECAL and DR Calorimeter by Eno, Lucchini, and Tully et al. (arXiv:2008.00338)

Timing layer \( \sigma_t \sim 20 \text{ ps} \)
- LYSO Ce crystal (~1\( X_0 \))
- 3×3×54 mm\(^3\) active cell
- 3×3 mm\(^2\) SiPMs (15-20 \( \mu \text{m} \))

ECAL layer \( \sigma_E/E \sim 3\%/\sqrt{E} \)
- PbWO crystals
- Front segment (~6 \( X_0 \))
- Read segment (~16 \( X_0 \))
- 10×10×200 mm\(^3\) Crystals
- 5×5 mm\(^2\) SiPMs (10-15 \( \mu \text{m} \))
Muon Detector

- **RPC** R&D applies to both SDHCAL & Muon.

- An alternative is **μ-RWELL** technology. The concept was proved. Currently focus mainly on industrialization and cost reduction.

- **Scintillator** Muon detector. R&D overlaps with Belle II KLM.
  - Building a prototype detector
  - Scintillator strips, improving quality & cost-reduction.
  - WLS fiber: purchased Kuraray, focusing on optical couplings.
  - SiPM Hamamatsu S13360-13**CS, and MPPC option.

Achieved $\sigma \approx 2$ns, Aim for 100-200 ps.
The CEPC aims to explore Higgs, EW, QCD, flavor physics and BSM at Higgs (Z) factory.

The International Advisory Committee operates since 2015. International Accelerator Review Committee, and International Detector R&D Review Committee started in 2019.

International workshops (with emphasis on CEPC):
- In China: Beijing (2017.11, 2018.11, 2019.11), Shanghai (2020.10), Nanjing (2021.11)
- In Europe: Rome (2018.05), Oxford (2019.04), Marseille (2022.05 ?)
- In USA: Chicago (2019.09), DC (2020.04, remote)

Annual IAS HEP program (HKUST) since 2015; Various topic specific workshops every year.

Actively participated in the European Strategy Update and the Snowmass Process for particle physics, and international detector R&D collaborations: CALICE, LPTPC, RD*, ...

Aim for the accelerator TDR ~ the end of 2022.

The detector R&D progresses towards TDR. Two international experiment collaborations will be formed before that time. The current working group consists of ~1/3 international members.

Supported by various funding sources in China: MOST, NSFC, CAS, institutes, local governments…
Backup Slides
Solenoid Magnet

Challenges
Low mass, ultra-thin, high strength cable

Al stabilized ReBCO stacked tape cable
The Experimental Area

Main cavern to host the detector
- 40\times 30\times 30 \text{ m}^3 (L\times H\times W)
- One main access shaft, Ø16 m
- An 1K-ton gantry crane for large heavy objects

Auxiliary cavern for peripheral equipment and devices
- 80\times 18\times 18 \text{ m}^3 (L\times H\times W)
- One service shaft of Ø9 m
- One personnel access shaft Ø6 m
CEPC Software

- Core software, external libraries & tools are the base of the CEPCSW. More packages and components will be added when available.

- CEPC applications are created for CDR design. With new type of detectors introduced, corresponding codes are being developed.

- Recent added CEPC applications:
  - Software for SiTrk + DC design, detector description and track fitting.
  - Cluster counting method of DC
  - Simulation and simplified digitization of the crystal bar ECal.

- Work to be done
  - Further development of simulation & reconstruction for SiTrk+DC and Crystal bar ECal.
  - Non-uniform magnetic field & piling-up of beam backgrounds in simulation
  - Algorithms for building reconstructed particles
  - Continue to check the consistence of software, with benchmark performance studies.

CEPCSW structure

- **Generator**
- **Simulation**
- **Reconstruction**
- **Analysis**

**Core Software**
- GeomSvc
- FWCore
- EDM4hep
- Gaudi framework

**External Libraries & Tools**
- LCIO
- PODIO
- DD4hep
- ROOT
- Geant4
- CLHEP
- Boost
- Python
- Cmake