The CEPC Detector
Highlights and R&D Program

João Guimarães da Costa
(IHEP, Chinese Academy of Sciences)

ICHEP CEPC Satellite meeting – Seoul
6 July 2018
Organization of the **Physics and Detector** Working Group

**Conveners**

Joao Barreiro Guimaraes Costa (IHEP)  
Yuanning Gao (Tsinghua Univ.)  
Shan Jin (Nanjing Univ.)

<table>
<thead>
<tr>
<th>Machine Detector Interface</th>
<th>Vertex</th>
<th>Tracker</th>
<th>Calorimeter</th>
</tr>
</thead>
</table>
| Hongbo Zhu                 | Ouyang Qun  
Sun Xiangming  
Wang Meng            | Qi Huirong  
Yulan Li             | ECal  
Hu Tao               |
| Sha Bai                    |         |         | HCal  
Liu Jianbei  
Yang Haijun          |

**Calorimeter**

- ECal: Hu Tao
- HCal: Liu Jianbei, Yang Haijun
- Muons: Li Liang, Zhu Chengguang

**Physics analysis and detector optimization**

- Ruan Manqi  
Li Gang  
Li Qiang  
Fang Yaquan

[http://cepc.ihep.ac.cn/~cepc/cepc_twiki/index.php/Physics_and_Detector](http://cepc.ihep.ac.cn/~cepc/cepc_twiki/index.php/Physics_and_Detector)
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This talk

Next talk by Manqi
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Higgs</th>
<th>W</th>
<th>Z (3T)</th>
<th>Z (2T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of IPs</td>
<td></td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam energy (GeV)</td>
<td>120</td>
<td>80</td>
<td>45.5</td>
<td></td>
</tr>
<tr>
<td>Crossing angle at IP (mrad)</td>
<td></td>
<td></td>
<td>16.5×2</td>
<td></td>
</tr>
<tr>
<td>Number of particles/bunch N_e (10^{10})</td>
<td>15.0</td>
<td>12.0</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>Bunch number (bunch spacing)</td>
<td>242 (0.68µs)</td>
<td>1524 (0.21µs)</td>
<td>12000 (25ns+10%gap)</td>
<td></td>
</tr>
<tr>
<td>Beam size at IP σ_x/σ_y (µm)</td>
<td>20.9/0.068</td>
<td>13.9/0.049</td>
<td>6.0/0.078</td>
<td>6.0/0.04</td>
</tr>
<tr>
<td>Bunch length σ_z (mm)</td>
<td>3.26</td>
<td>5.9</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>Luminosity/IP L (10^{34} cm^{-2}s^{-1})</td>
<td>2.93</td>
<td>10.1</td>
<td>16.6</td>
<td>32.1</td>
</tr>
</tbody>
</table>
Detector Conceptual Designs

Baseline detector (3 Tesla)
ILD-like
(similar to pre-CDR)

Low magnetic field concept
(2 Tesla)

Full silicon tracker concept

Final two detectors likely to be a mix and match of different options
CEPC baseline detector: ILD–like

- **Impact parameter resolution:** less than 5 μm
- **Tracking resolution:** $\delta(1/P_t) \sim 2 \times 10^{-5}$ (GeV$^{-1}$)
- **Jet energy resolution:** $\sigma_E/E \sim 30\%/\sqrt{E}$

- Magnetic Field: 3 Tesla — changed from preCDR
- **Flavor tagging**
- **BR(Higgs $\rightarrow \mu\mu$)**
- **W/Z dijet mass separation**
CEPC baseline detector: ILD–like: Design Considerations

Major concerns being addressed

1. MDI region highly constrained
   \( L^* \) increased to 2.2 m
   Compensating magnets

2. Low-material Inner Tracker design

3. TPC as tracker in high-luminosity
   Z-pole scenario

4. ECAL/HCAL granularity needs
   Passive versus active cooling

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Magnetic Field: 3 Tesla — changed from preCDR

- **Impact parameter resolution**: less than 5 μm
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- **Jet energy resolution**: \( \sigma_E/E \sim 30\%/\sqrt{E} \)

- Flavor tagging
- \( BR(\text{Higgs} \rightarrow \mu\mu) \)
- W/Z dijet mass separation
Low magnetic field detector concept

Proposed by INFN, Italy colleagues

Magnet: 2 Tesla, 2.1 m radius
Thin (~ 30 cm), low-mass (~0.8 $X_0$)

Vertex: Similar to CEPC default
* Drift chamber: 4 m long; Radius ~30-200 cm

Preshower: ~1 $X_0$
* Dual-readout calorimeter: 2 m/8 $\lambda_{int}$
* (yoke) muon chambers

Integrated test beam
September 2018
Looking for helpers
Updated baseline parameters:

- Head-on collision changed to crossing angle of 33 mrad
- Focal length ($L^*$) increased from 1.5 m to 2.2 m
- Solenoid field reduced from 3.5 T to 3 T

One of the most complicated issues in the CEPC detector design

Rates at the inner layer (16 mm):
- Hit density: $\sim 2.5$ hits/cm$^2$/BX
- TID: 2.5 MRad/year
- NIEL: $10^{12}$ 1MeV $n_{eq}$/cm$^2$

(Safety factors of 10 applied)
Baseline Pixel Detector Layout

3-layers of double-sided pixel sensors

- ILD-like layout
- Innermost layer: $\sigma_{SP} = 2.8 \, \mu m$
- Polar angle $\theta \sim 15$ degrees
- Material budget $\leq 0.15\%X_0/\text{layer}$

Implemented in GEANT4 simulation framework (MOKKA)

| Layer  | $R(\text{mm})$ | $|z|(\text{mm})$ | $|\cos\theta|$ | $\sigma(\mu m)$ | Readout time($\mu s$) |
|--------|----------------|-----------------|----------------|-----------------|------------------|
| Layer 1| 16             | 62.5            | 0.97           | 2.8             | 20               |
| Layer 2| 18             | 62.5            | 0.96           | 6               | 1-10             |
| Layer 3| 37             | 125.0           | 0.96           | 4               | 20               |
| Layer 4| 39             | 125.0           | 0.95           | 4               | 20               |
| Layer 5| 58             | 125.0           | 0.91           | 4               | 20               |
| Layer 6| 60             | 125.0           | 0.90           | 4               | 20               |

CMOS pixel sensor (MAPS)

Integrated sensor and readout electronics on the same silicon bulk with “standard” CMOS process:
- low material budget,
- low power consumption,
- low cost ...
### Current R&D activities

- **Initial sensor R&D targeting:**

<table>
<thead>
<tr>
<th>Specs</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single point resolution near IP:</td>
<td>&lt; 3-5 μm</td>
</tr>
<tr>
<td>Power consumption:</td>
<td>&lt; 100 mW/cm²</td>
</tr>
<tr>
<td>Integration readout time:</td>
<td>&lt; 10-100 μs</td>
</tr>
<tr>
<td>Radiation (TID)</td>
<td>1 MRad</td>
</tr>
</tbody>
</table>

- **Need improvement**
- **Need to continue trying to lower by a factor of 2**
- **Need 1 μs for final detector**
- **Need 2.5× higher /year**

- **New project**

### Sensors technologies:

<table>
<thead>
<tr>
<th>Process</th>
<th>Smallest pixel size</th>
<th>Chips designed</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMOS pixel sensor (CPS)</td>
<td>TowerJazz CIS 0.18 μm</td>
<td>22 × 22 μm²</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Founded by MOST and IHEP</td>
</tr>
<tr>
<td>SOI pixel sensor</td>
<td>LAPIS 0.2 μm</td>
<td>16 × 16 μm²</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Funded by NSFC</td>
</tr>
</tbody>
</table>

- **Institutions**
  - CCNU, NWTU, Shandong, Huazhong Universities and IHEP (IPHC in Strasbourg, KEK)
- **New project**: Full size CMOS sensor for use in real size prototype
Silicon Vertex Detector Prototype – MOST (2018–2023)

- Design full size CMOS sensor with high resolution and good radiation hardness

**Double sided ladder**

- Layer 1 (11 mm x 62.5 mm)
  - Chip size: 11 mm X 20.8 mm
  - 3 X 2 layer = 6 chips

- Layer 2 and 3 (22 mm x 125 mm)
  - Chip size: 11 mm X 20.8 mm
  - 6 X 2 layer = 12 chips

**Mechanical prototype**

- Requires study/simulation of new layout

**International Collaboration**

- Liverpool Univ.
- Oxford Univ.
- Barcelona Univ.
- University of Mass
- RAL
- others.....

**Minimal goals:**
- 3-layer prototype
- Sensor:
  - 1 MRad TID sensor
  - 3-5 μm SP resolution

**Integrated electronics readout**

- Design and produce light and rigid support structures

- Extended goals if manpower and support available
In addition to the vertex detector (Section 6.2) and the TPC (Section 6.4), the CEPC tracking system also includes a silicon tracker, exploring a similar scenario to that adopted for the ILD detector design [2]. Complementary to the continuous tracking provided by the main tracker TPC, the CEPC silicon tracker, together with the vertex detector, provides several additional high-precision space-points on the track trajectory before and after the TPC, yet with sufficiently low material as to minimise the multiple-scattering effect. Such a tracking system, using a mixture of detector technologies, enables efficient and robust reconstruction of charged particles and precise determination of the particle momenta, with excellent resolution of

\[
\frac{1}{p_T} = 2 \times 10^{-5} \quad \frac{1}{p_T} \cdot \sin \theta.
\]

Figure 6.8 Preliminary layout of the CEPC silicon tracker. The red lines indicate the positions of the vertex detector layers and the blue lines the SIT and FTD for the silicon tracker. The SET and ETD, which sit outside the TPC, are not displayed.

6.3.1 Baseline Design

The baseline design for the CEPC silicon tracker adopts the same concept of "Silicon Envelope" [31] as for the ILD detector, but necessary modifications are made to cope...
Time Projection Chamber (TPC)

- Allows for particle identification
- Low material budget:
  - 0.05 $X_0$ including outfield cage in $r$
  - 0.25 $X_0$ for readout endcaps in $Z$
- 3 Tesla magnetic field $\rightarrow$ reduces diffusion of drifting electrons
- Position resolution: $\sim$100 $\mu$m in $r\phi$
- $dE/dx$ resolution: 5%
- GEM and Micromegas as readout
- Problem: Ion Back Flow $\rightarrow$ track distortion

Operation at $L > 2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ being studied

Prototype built

R&D by IHEP, Tsinghua and Shandong
Funded by MOST and NSFC
Drift Chamber Option – IDEA proposal

Lead by Italian Colleagues

Low-mass cylindrical drift chamber

Follows design of the KLOE and MEG2 experiments

- Length: 4 m
- Radius: 0.3-2 m
- Gas: 90%He – 10%C_{4}H_{10}
- Material: 1.6% X_{0} (barrel)

- Spatial resolution: < 100 μm
- dE/dx resolution: 2%
- Max drift time: <400 nsec
- Cells: 56,448

Layers: 14 SL × 8 layers = 112
Cell size: 12 - 14 mm

MEG2 prototype being tested

Stereo angle: 50-250 mrad
Full silicon tracker concept

Replace TPC with additional silicon layers

CEPC-SID:
- 6 barrel double strip layers
- 5 endcap double strip layers

SIDB: SiD optimized
- 5 barrel single strip layers
- 5 endcap double strip layers

Collaboration with Argonne and Berkeley

Drawbacks: higher material density, less redundancy and limited particle identification (dE/dx)
Calorimeter options

Chinese institutions have been focusing on Particle Flow calorimeters

R&D supported by MOST, NSFC and IHEP seed funding

Electromagnetic

ECAL with Silicon and Tungsten (LLR, France)
(*) ECAL with Scintillator+SiPM and Tungsten (IHEP + USTC)

Hadronic

(*) SDHCAL with RPC and Stainless Steel (SJTU + IPNL, France)
SDHCAL with ThGEM/GEM and Stainless Steel (IHEP + UCAS + USTC)
(*) HCAL with Scintillator+SiPM and Stainless Steel (IHEP + USTC + SJTU)

New

(*) Dual readout calorimeters (INFN, Italy + Iowa, USA)
ECAL Calorimeter — Particle Flow Calorimeter

Scintillator-Tungsten Sandwich ECAL

Superlayer (7 mm) is made of:
- 3 mm thick: Tungsten plate
- 2 mm thick: 5 x 45 mm²
- 2 mm thick: Readout/service layer

Plastic scintillator
5 x 45 mm² (2 mm thick)

SiPM

R&D on-going:
- SiPM dynamic range
- Scintillator strip non-uniformity
- Coupling of SiPM and scintillator

Mini-prototype tested on testbeam at the IHEP

Cell size: 5 x 5 mm² (with ambiguity)
HCAL Calorimeter — Particle Flow Calorimeter

Scintillator and SiPM HCAL (AHCAL)

32 super modules

40 layers

AHCAL barrel

AHCAL super module

Readout channels:
~ 5 Million (30 x 30 mm$^2$)
~ 2.8 Million (40 x 40 mm$^2$)

Prototype to be built: MOST (2018-2023)
0.5x0.5 m$^2$, 35 layer (4$\lambda$), 3x3 cm$^2$ module
Dual Readout Calorimeter

Lead by Italian colleagues: based on the DREAM/RD52 collaboration

Projective $4\pi$ layout implemented into CEPC simulation
(based on 4th Detector Collaboration design)

Expected resolution:
- EM: $\sim 10\%/\sqrt{E}$
- Hadronic: $30-40\%/\sqrt{E}$

Covers full volume up to $|\cos(\theta)| = 0.995$
with 92 different types of towers (wedge)

4000 fibers (start at different depths to keep constant the sampling fraction)

Expected resolution:
- EM: $\sim 10\%/\sqrt{E}$
- Hadronic: $30-40\%/\sqrt{E}$

Studying different readout schemes
PMT vs SiPM

Several prototypes from RD52 have been built
Superconductor solenoid development

Updated design done for 3 Tesla field (down from 3.5 T)

Main parameters of solenoid coil

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central magnetic field</td>
<td>3 T</td>
</tr>
<tr>
<td>Operating current</td>
<td>15779 A</td>
</tr>
<tr>
<td>Stored energy</td>
<td>1.3 GJ</td>
</tr>
<tr>
<td>Inductance</td>
<td>10.46 H</td>
</tr>
<tr>
<td>Coil radius</td>
<td>3.6-3.9 m</td>
</tr>
<tr>
<td>Coil length</td>
<td>7.6 m</td>
</tr>
<tr>
<td>Cable length</td>
<td>30.35 km</td>
</tr>
</tbody>
</table>

Design for 2 Tesla magnet presents no problems

Double-solenoid design also available

Default is NbTi Rutherford SC cable (4.2K)

Solutions with High-Temperature SC cable also being considered (YBCO, 20K)
Muon detector

Baseline Muon detector
- 8 layers
- Embedded in Yoke
- Detection efficiency: 95%

New technology proposal (INFN): μRWell

Technologies considered
- Monitored Drift Tubes
- Resistive Plate Chambers (RPC)
- Thin Gap Chambers (TGC)
- Micromegas
- Gas Electron Multiplier (GEM)
- Scintillator Strips

Baseline: Bakelite/glass RPC

Muon system: open studies

Good experience in China on gas detectors but currently no strong direct work on CEPC — rather open for international collaboration

- Layout optimization:
  - Justification for number of layers
  - Implications for exotic physics searches
  - Use as a tail catcher / muon tracker (TCMT)
  - Jet energy resolution with/without TCMT
Funding Support for Detector R&D

Multiple funding sources

- Ministery of Sciences and Technology (MOST)
- National Science Foundation of China
  - Major project funds
  - Individual funds
- Industry cooperation funds
- IHEP Seed Funding
- Others

<table>
<thead>
<tr>
<th>Detector</th>
<th>Funding (M RMB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>18.2</td>
</tr>
<tr>
<td>TPC</td>
<td>7.0</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>21.3</td>
</tr>
<tr>
<td>Magnet</td>
<td>8.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>55.2</strong></td>
</tr>
</tbody>
</table>

Currently secured funding
Conceptual Design Report (CDR) – Status

Pre-CDR completed in 2015

- No show-stoppers
- Technical challenges identified → R&D issues

(http://cepc.ihep.ac.cn/preCDR/volume.html)

Detector and Physics - Conceptual Design Report (CDR)

- **Goal:** A working concept on paper, including alternatives

- **Draft-0 released in November 2017**
  - Mini international review

- **Early fall 2018: Planned public release date**
  - Soon after CEPC accelerator CDR is released
  - Accommodate new accelerator design parameters and solenoid magnetic field

- **Still**
  - Opportunities for people to contribute editing, reviewing

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CEPC
Conceptual Design Report
Volume II - Physics & Detector

The CEPC Study Group
Fall 2018

IHEP-CEPC-DR-2018-XX
IHEP-TH-2018-XX

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Final remarks

- Significant work done towards the CEPC Detector CDR
  - Two significantly different detector concepts are emerging
    - High-magnetic field (3 Tesla): PFA-oriented — with TPC or full-silicon tracker
    - Low-magnetic field (2 Tesla): with drift chamber and dual readout calorimeter
- Key technologies are under R&D and put to prototyping:
  - Vertex detector, TPC, calorimeters, magnets
  - International colleagues getting more heavily involved, participating in CDR
    - e.g. Drift chamber, dual readout calorimeter and muon chamber
- CEPC funding adequate for required R&D program
  - Support from several sources in China: NSFC, MOST, etc
- International collaboration expanding
  - INFN, SLAC, Iowa State Univ., Belgrade, LLR, IPNL, LC–TPC, Liverpool, Oxford, Barcelona, etc...

CDR Expected final release: Early Fall 2018

From 2018-2022, CEPC TDR will be finished
Thank you for the attention!