Status of R&D for Time projection chamber module and prototype

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Institute of High Energy Physics, CAS
Tsinghua University
CEPC Workshop, Oxford, UK, April, 16, 2019
Outline

- Baseline design
- Requirements and challenges
- Feasibility study of TPC detector
- R&D activities
- Summary
Three Detector Concepts (CEPC CDR)

- **Baseline**: Silicon + TPC
- **FST**: all-silicon tracker
- **IDEA**: Silicon+Drift chamber (DCH)

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<table>
<thead>
<tr>
<th>Operation mode</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>$L$ per IP ($10^{34}$ cm$^{-2}$s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H$</td>
<td>240</td>
<td>3</td>
</tr>
<tr>
<td>$Z$</td>
<td>91.2</td>
<td>32 (*)</td>
</tr>
<tr>
<td>$W^+W^-$</td>
<td>158–172</td>
<td>10</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th></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>2</td>
<td></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>Circumference (km)</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synchrotron radiation loss/turn (GeV)</td>
<td>1.73</td>
<td>0.34</td>
<td>0.036</td>
<td></td>
</tr>
<tr>
<td>Crossing angle at IP (mrad)</td>
<td>16.5 $\times$ 2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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- **Detector length**: 1300 cm
- **Detector height**: 1100 cm
- **Preshower**
- **DCH R_{out}**: 200 cm
- **DCH R_{in}**: 30 cm
- **Cal R_{in}**: 250 cm
- **Cal R_{out}**: 450 cm

- **Silicon Wrapper**
- **Magnet z = +300 cm**
- **Yoke 100 cm**
TPC detector at CEPC

TPC could directly provide three-dimensional space points; the gaseous detector volume gives a low material budget; and the high density of such space points enables excellent pattern recognition capability.

Why use TPC detector as the tracker detector?

- Motivated by the H tagging and Z
- TPC is the perfect detector for HI collisions ...(ALICE TPC…)
- Almost the whole volume is active
- Minimal radiation length (field cage, gas)
- Easy pattern recognition (continuous tracks)
- PID information from ionization measurements (dE/dx)
- Operating under high magnetic field
- MPGD as the readout

Overview of TPC detector concept
TPC requirements for CEPC

TPC detector concept:
- Under 3 Tesla magnetic field (Momentum resolution: $\sim 10^{-4}$/GeV/c with TPC standalone)
- Large number of 3D space points ($\sim 220$ along the diameter)
- $dE/dx$ resolution: <5%
- $\sim 100$ µm position resolution in $r\phi$
  - $\sim 60$µm for zero drift, <100µm overall
  - Systematics precision (<20µm internal)
- TPC material budget
  - <1$X_0$ including outer field cage
- Tracker efficiency: >97% for $pT>1$GeV
- 2-hit resolution in $r\phi$ : $\sim 2$mm
- Module design: $\sim 200$mm $\times$ 170mm
- Minimizes dead space between the modules: 1-2mm
TPC possible limitations

- Ions back flow in chamber
- Calibration and alignment
- Low power consumption FEE ASIC chip
Feasibility study of TPC

- Would it be Limited by
  - Voxel occupancy
  - Primary ions along the track in the chamber
  - Amplification ions create the ions disk back to the chamber (\( \times \text{Gain} \))
  - Charge Distortion induced by the ions: Mainly from Ion back flow

Voxel size defined (3D space bucket): 
\[ \text{Pad size} \times T_{\text{sample}} \times V_{\text{drift}} \]

Total ions in chamber: \(~ \text{Back flow ions} \sim (1 + k), k = \text{Gain} \times \text{IBF} + \text{Primary}\)
Feasibility study of TPC at Z pole

- Occupancy simulation
  - Gain × IBF refers to the number of ions that will escape the end-plate readout modules per primary ionization, obtained by the multiplication of the readout modules gain and the ion backflow reducing rate (IBF)
  - L: the luminosity in units of $10^{34}\text{cm}^{-2}\text{s}^{-1}$
  - Voxel size: $1\text{mm} \times 6\text{mm} \times 2\text{mm}$ @DAQ/40MHz
  - Maximal occupancy at TPC inner most layer: $\sim 10^{-5}$ (safe)
  - Full simulation: 9 thousand Z to qq events
  - Bhabha events: a few nb
  - Background considered? (Need careful designed Shielding/detector protection)

To conclude, the TPC will be able to be used if the Gain × IBF can be controlled to a value smaller than 5.

ArXiv: 1704.04401

- Pad size: $1\text{mm} \times 6\text{mm}$
- $T_{\text{sample}}$: 25ns
- $V_{\text{drift}}$: 80$\mu\text{m}/\text{ns}$

Distortion on the hit position reconstruction
Technical challenges of TPC for CEPC

Ion Back Flow and Distortion

- **Goal:**
  - Operate TPC at high luminosity at Z pole run
  - No Gating options

- IBF control similar with ALICE TPC upgrade

- ~100 µm position resolution in \( r\phi \)

- Distortions by the primary ions at CEPC are negligible

- Manu ions discs co-exist and distorted the path of the seed electrons

- The ions cleaned during the \(~us\) period continuously

- Continuous device for the ions

- Long working time

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**Amplification ions from the endplate @CEPC**

<table>
<thead>
<tr>
<th></th>
<th>ALICE TPC</th>
<th>CEPC TPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum readout rate</td>
<td>&gt;50kHz@pp</td>
<td>w.o BG?</td>
</tr>
<tr>
<td>Gating to reduce ions</td>
<td>No Gating</td>
<td>No Gating</td>
</tr>
<tr>
<td>Continuous readout</td>
<td>No trigger</td>
<td>Trigger?</td>
</tr>
<tr>
<td>IBF control</td>
<td>Build-in</td>
<td>Build-in</td>
</tr>
<tr>
<td>IBF*Gain</td>
<td>&lt;10</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Calibration system</td>
<td>Laser</td>
<td>NEED</td>
</tr>
</tbody>
</table>

Compare with ALICE TPC and CEPC TPC
Feasibility study of TPC detector

Continuous IBF module:
- Operation at Higgs and Z-pole run
- Continuous Ion Back Flow due to the continuous beam structure
- Low discharge and spark possibility
- Space charge effect for IBF
- Gain: 5000-6000
- Good energy resolution: <20%

Laser calibration system:
- The ionization in the gas volume along the laser path occurs via two photon absorption by organic impurities (Nd:YAG laser @266nm)
- Laser calibration system around the chamber
- Calibration of the drift velocity, gain uniformity, the distortion
- High stability of the laser beam (<5µm)
Some R&D activities

- TPC detector module -> IBF control
- TPC detector prototype -> Calibration
- Low power consumption -> FEE ASIC chip
TPC detector module@ IHEP

- Study with GEM-MM module
- New assembled module
- Active area: 100mm × 100mm
- X-tube ray and 55Fe source
- Bulk-Micromegas assembled from Saclay
- Standard GEM from CERN
- Avalanche gap of MM: 128μm
- Transfer gap: 2mm
- Drift length: 2mm ~ 200mm
- pA current meter: Keithley 6517B
- Current recording: Auto-record interface by LabView
- Standard Mesh: 400LPI
- High mesh: 508 LPI

DOI: 10.1088/1748-0221/12/04/P0401 JINST, 2017.4
DOI: 10.1088/1674-1137/41/5/056003, CPC, 2016.11
GEM+MM@CEPC R&D

For $e^+e^-$ machine
Primary $N_{\text{eff}}$ is small: $\sim 30$
Pad size: $1\text{mm} \times 6\text{mm}$

GEM+MM module:
Photo peak and escape peak are clear!
Good electron transmission.
Good energy resolution.

One option for ALICE TPC
GEM+GEM+MM
Gain of mid GEM: $\times 0.5$
Gain of the hybrid structure detector

Key IBF factor: IBF × Gain < 5
From July, the high mesh of 508LPI has been assembled with CEA-Saclay collaboration. The preliminary results indicate that it could reach the lower IBF and better performance.
Check and answer- $\rho_{\text{ion}} \times d$

Current of Pad is very low in our Experiment results.
No any obvious space charge effect to decrease IBF.

Green: T2K,  Yellow: Ar/iso(95/5)

T2Kgas Ic: 4pA~59pA, $\sim 10^3$ (fC/cm$^2$)
Ar/iso gas Ic: 3.5pA~53pA, $\sim 10^3$ (fC/cm$^2$)
Update on the small prototype R&D
Motivation of the TPC prototype

- Study and estimation of the distortion from the IBF and primary ions with the laser calibration system

- Main parameters
  - Drift length: \(~510\text{mm}\), Readout active area: \(200\text{mm} \times 200\text{mm}\)
  - Integrated the laser calibration with 266nm
  - GEMs/Micromegas as the readout
  - Matched to assembled in the 1.0T PCMAG

Diagram of the TPC prototype with the laser calibration system
Study of laser position and energy

- Size: \(~0.85\text{mm} \times 0.85\text{mm}\)
- Transmission and reflection mirrors
- Duration of measurement time: 20 mins
- \(X\) direction of the beam’s center of gravity: <3.2 \(\mu\text{m}\)
- \(Y\) of the beam’s center of gravity: <2.8 \(\mu\text{m}\)
- Average of the energy: 46.53\(\mu\text{J}/\Phi 5\text{mm}\)
- Stability of the laser beam energy: 3.3%
Study of the drift velocity

Diagram of the TPC small prototype
Signal with the laser and $^{55}$Fe

- Readout board, 128 Channels electronics, DAQ and laser mirror and PCB board have been done and assembled
- TPC barrel mount and re-mount with the Auxiliary brackets
- TPC preliminarily tested with $^{55}$Fe and the different power laser beam
- Optimization of the laser studied

![Graph with output signal and energy density of the laser beam]
Energy spectrum of the detector module

\[ Q_{\text{distribution}} \]

\[ 210V/cm@T2K \]

Triggerless

\[ >300kHz \]

\[ n>3 \]

\[ ^{55}\text{Fe} \text{ radioactive source} \]

\[ 266\text{nm laser beam}@0.8\text{mm}^2 \]

\[ 210V/cm@T2K \]

Laser trigger

\[ 10Hz \]
Drift velocity of the electron in the chamber

$61.53 \pm 0.15 \, \mu m/\text{ns} @ 210 \, \text{V/cm} @ T2K$

Test and simulation results of the drift velocity of the electron in the chamber
$Z_0$ finding (GEM surface position)

**Preliminary**
Laser track test

Preliminary results of Laser tracker energy spectrum and tracker
Resolution of the prototype

Position resolution and $\chi^2$ with the laser beam
Low power consumption ASIC
Feasibility study of the low power consumption FEE

- Each endplate has a total of about 1 million channels
- Over 30,000 ASIC chips with 32 channels each
- Total power consumption of the front-end electronics is limited by the CO$_2$ cooling system to be several kilowatts in practice
- Two-phase CO$_2$ cooling/Micro-channel CO$_2$ cooling methods should be studied further
- TPC readout electronics are a few meters away from the collision point, and the radiation dose is rather low (< 1 krad), and radiation sophisticated design needs to be considered too

### Current TPC readout ASICs

<table>
<thead>
<tr>
<th></th>
<th>PASA/ALTRO</th>
<th>AFTER</th>
<th>Super-ALTRO</th>
<th>SAMPA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TPC</strong></td>
<td>ALICE</td>
<td>T2K</td>
<td>ILC</td>
<td>ALICE upgrade</td>
</tr>
<tr>
<td><strong>Pad size</strong></td>
<td>4x7.5 mm$^2$</td>
<td>6.9x9.7 mm$^2$</td>
<td>1x6 mm$^2$</td>
<td>4x7.5 mm$^2$</td>
</tr>
<tr>
<td><strong>Pad channels</strong></td>
<td>$5.7 \times 10^5$</td>
<td>$1.25 \times 10^5$</td>
<td>$1-2 \times 10^6$</td>
<td>$5.7 \times 10^5$</td>
</tr>
<tr>
<td><strong>Readout Chamber</strong></td>
<td>MWPC</td>
<td>MicroMegas</td>
<td>GEM/MicroMegas</td>
<td>GEM</td>
</tr>
<tr>
<td><strong>Gain</strong></td>
<td>12 mV/fC</td>
<td>18 mV/fC</td>
<td>12-27 mV/fC</td>
<td>20/30 mV/fC</td>
</tr>
<tr>
<td><strong>Shaper</strong></td>
<td>CR-(RC)$^4$</td>
<td>CR-(RC)$^2$</td>
<td>CR-(RC)$^4$</td>
<td>CR-(RC)$^4$</td>
</tr>
<tr>
<td><strong>Peaking time</strong></td>
<td>200 ns</td>
<td>100 ns</td>
<td>30-120 ns</td>
<td>80/160 ns</td>
</tr>
<tr>
<td><strong>ENC</strong></td>
<td>385 e</td>
<td>1000 e</td>
<td>520 e</td>
<td>482 e @ 180ns</td>
</tr>
<tr>
<td><strong>Waveform Sampler</strong></td>
<td>ADC</td>
<td>SCA</td>
<td>ADC</td>
<td>ADC</td>
</tr>
<tr>
<td><strong>Method</strong></td>
<td>ADC</td>
<td>SCA</td>
<td>ADC</td>
<td>ADC</td>
</tr>
<tr>
<td><strong>Sampling frequency</strong></td>
<td>10MSPS</td>
<td>25MSPS</td>
<td>40MSPS</td>
<td>20MSPS</td>
</tr>
<tr>
<td><strong>Dynamic range</strong></td>
<td>10bit</td>
<td>10bit</td>
<td>10bit</td>
<td>10bit</td>
</tr>
<tr>
<td><strong>Power consumption</strong></td>
<td>32mW/ch</td>
<td>6.2-7.5mW/ch</td>
<td>47.3mW/ch</td>
<td>8mW/ch</td>
</tr>
<tr>
<td><strong>CMOS Process</strong></td>
<td>250 nm</td>
<td>350 nm</td>
<td>130 nm</td>
<td>130nm</td>
</tr>
</tbody>
</table>

### Total number of channels

<table>
<thead>
<tr>
<th>AFE (Analog Front-End)</th>
<th>ENC (Equivalent Noise Charge)</th>
<th>1 million per endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain Shaper Peaking time</td>
<td>Gain CR-RC 100 ns</td>
<td>500e @ 10pF input capacitance</td>
</tr>
<tr>
<td>ADC Sampling rate Resolution</td>
<td>≥ 20 MSPS 10 bit</td>
<td>Output data bandwidth 300-500 MB/s 32</td>
</tr>
<tr>
<td></td>
<td>≤ 5 mW per channel</td>
<td>Channel number TSMC 65 nm LP</td>
</tr>
<tr>
<td></td>
<td>Power consumption</td>
<td>Process</td>
</tr>
</tbody>
</table>

Key specifications of the front-end readout ASIC for TPC
Results of FEE ASIC

- Develop a low power and highly integration front-end ASIC in 65 nm CMOS
- Each channel consists of the analog front-end (AFE) and a SAR ADC in 10b and up to 40 MSPS
- Less than 5 mW per channel

- AFE test summary

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>10mV/fC</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>&gt;120fC</td>
</tr>
<tr>
<td>INL</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Power consumption</td>
<td>2.50mW/ch</td>
</tr>
<tr>
<td>ENC</td>
<td>500e@10pF</td>
</tr>
<tr>
<td>Xtalk</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>

- SAR ADC test summary

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling rate</td>
<td>40 MSPS</td>
</tr>
<tr>
<td>Resolution</td>
<td>10 bit</td>
</tr>
<tr>
<td>INL</td>
<td>&lt;0.65 LBS</td>
</tr>
<tr>
<td>DNL</td>
<td>&lt;0.6 LSb</td>
</tr>
<tr>
<td>ENOB</td>
<td>&gt;9 bit</td>
</tr>
<tr>
<td>Power consumption</td>
<td>&lt;2.5 mW/ch</td>
</tr>
</tbody>
</table>
TPC R&D cooperation

- Any ideas and manpower are welcome
- TPC prototype cooperated with Tsinghua
- TPC module cooperated with CEA-Scalay
- Joined LCTPC international collaboration group
TPC prototype cooperated with Tsinghua

Photos of TPC prototype R&D

Kick off meeting and the review meeting /NSFC Key funding project
International cooperation

- CEA-Saclay IRFU group (FCPPL)
  - Three video meetings with Prof. Aleksan Roy / Prof. Yuanning / Manqi and some related persons (2016~2017)
  - Exchange PhD students: Haiyun Wang participates in Saclay’s R&D six months in 2017~2018
- Bulk-Micromegas detector assembled and IBF test
- IBF test using the new Micromegas module with more 590 LPI
- UV+ laser tracker
International cooperation

- LCTPC collaboration group (LCTPC)
  - Singed MOA and joined in LC-TPC collaboration @Dec. 14, 2016
  - As coordinator in ions test and the new module design work package
  - CSC funding: PhD Haiyun joint CEA-Scalay TPC group (6 months)
  - Joint beam test in DESY with our hybrid detector module in 2019
Summary and further R&D

Requirements and critical challenges for CEPC:

- High momentum resolution and position resolution
- Continuous beam structure and the ~25ns time space

Continuous IBF module for CEPC:

- Continuous Ion Back Flow supression
- Key factor: IBF×Gain=5 and less than (R&D)
- Low discharge and the good energy spectrum

Prototype with laser calibration for CEPC:

- It needs very sophisticated calibration in order to reach the desired physics performance at Z pole run
- Prototype has been designed with laser (Developed in IHEP and Tsinghua)
- Plan: Test with the TPC module and prototype in 1.0T magnetic field

A lot of progress in TPC module and prototype R&D. Next step, more hard works should be do for TPC R&D at CEPC with more cooperation.

Low power consumption ASIC chip:

- FEE electronics and DAQ collaborated with Tsinghua University
- Less than 5mV per channel
Thanks.