TPC at CEPC and how to address its limitations and feasibility

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Institute of High Energy Physics, CAS
Tsinghua University
Mini-Workshop: Experiment/Detector - Tracking and Calorimetry at Colliders, Jan., 18, 2019
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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)

### Table

<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>
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<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>0.636</td>
<td></td>
</tr>
<tr>
<td>Crossing angle at IP (mrad)</td>
<td>16.5 × 2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Diagrams

- Detector dimensions and layout
- Schematic of detector components (Silicon Wrapper, Dual Readout Calorimeter, VTX, Preshower, DCH R = 200 cm, DCH R_in = 30 cm, Cal R_in = 250 cm, Cal R_out = 450 cm)

### ArXiv:1811.10545

<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 (32 (*))</td>
</tr>
<tr>
<td>$Z$</td>
<td>91.2</td>
<td>10</td>
</tr>
<tr>
<td>$W^+ W^-$</td>
<td>158–172</td>
<td></td>
</tr>
</tbody>
</table>
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
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: $<5\%$
- $\sim 100 \mu m$ position resolution in r$\phi$
  - $\sim 60 \mu m$ for zero drift, $<100 \mu m$ overall
  - Systematics precision ($<20 \mu m$ internal)
- TPC material budget
  - $<1X_0$ 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
Gas amplification detector module and pad size

Micro pattern detector:

- GEM and Micromegas detector
- Electron cluster using Center-of-Gravity
  - Pitch: ~1mm
  - Pad Size: ~1mm × 6mm
- High gain (5000-10000)
- High rate capability: MPGDs provide a rate capability over $10^5$ Hz/mm² without discharges that can damage electronics.
- Intrinsic ion backflow suppression: Most of the ions produced in the amplification region will be neutralized on the mesh or GEM foil and do not go back to the drift volume.
- A direct electron signal, which gives good time resolution (< 100 ps) and spatial resolution (100 μm).

The profile of an electron cluster in GEMs detector
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 (× 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: \(~ Back flow ions \sim (1 + k), k = \text{Gain} \times \text{IBF} + \text{Primary}~\)
Occularity 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**: $\sim10^{-5}$ (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.
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 rφ
- 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

<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
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
GEM+MM@CEPC R&D

Photo peak and escape peak are clear!
Good electron transmission.
Good energy resolution.

e+e- machine
Primary $N_{\text{eff}}$ is small: $\sim 30$
Pad size: $1\text{mm} \times 6\text{mm}$
Gain of the hybrid structure detector

\[ E_d = 200\text{V/cm}, \ E_t = 200\text{V/cm}, \ V_{\text{Mesh}} = 400\text{V} \]

- **T2K gas**
- **Ar/iC_4H_{10}(95/5)**

Gain: 5000

![Graph showing gain vs. V_GEM (V)]
Key IBF factor: $\text{IBF} \times \text{Gain}$

$E_d = 200\,\text{V/cm}$, $E_t = 200\,\text{V/cm}$, $V_{\text{Mesh}} = 400\,\text{V}$

- **T2K gas**
- **Ar/iC4H10(95/5)**

$K_{\text{IBF}} (=\text{IBF} \times \text{Gain})$

$V_{\text{GEM}}$ [V]
From July, the high mesh of 508LPI has been assembled with CEA-Saclay collaboration. The preliminary results indicates that it could reach the lower IBF and better performance.
- Space charge to decrease IBF -
High rate and lots of ions make space charge effect to decrease IBF possibility !!!
Check and answer - Gain

Single GEM with very low Gain in our Exp.

DOI: 1609.08010
Check and answer: $I_{pad}$

Current of Pad is very low in our Exp.

Green, T2K, $E_t=200\,\text{V/cm}, E_d=200\,\text{V/cm}, V_{\text{mesh}}=400\,\text{V}, V_{\text{Gem}}=30\sim300\,\text{V}$

Yellow, Ar/iso(95/5), $E_t=200\,\text{V/cm}, E_d=200\,\text{V/cm}, V_{\text{mesh}}=400\,\text{V}, V_{\text{Gem}}=30\sim300\,\text{V}$
Check and answer- $\rho_{\text{ion}} \times d$

Current of Pad is very low in our Exp.

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

T2K gas Ic: $4pA \sim 59pA, \sim 10^3 \text{ (fC/cm}^2\text{)}$
Ar/iso gas Ic: $3.5pA \sim 53pA, \sim 10^3 \text{ (fC/cm}^2\text{)}$
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
Laser map in drift length

- Size: ~0.85mm × 0.85mm
- Transmission and reflection mirrors
- Aluminum board integrated the laser device and supports
- Drift velocity in Z
- Uniformity in X-Y plane

Detector with the laser system
Preliminary test with the laser

- 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 55Fe and the different power laser beam
- Optimization of the laser studied

![Graphs showing laser spectrum and data tables with channel counts and parameters like Mean, RMS, Constant, and Sigma for different laser and 55Fe signals.]
Laser track test

Preliminary results of Laser tracker energy spectrum and tracker
- 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

Key specifications of the front-end readout ASIC for TPC

<table>
<thead>
<tr>
<th>Total number of channels</th>
<th>ENC (Equivalent Noise Charge)</th>
<th>1 million per endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFE (Analogue Front-End)</td>
<td>Gain, Shaper, Peaking time</td>
<td>500e @ 10pF input capacitance</td>
</tr>
<tr>
<td>ADC</td>
<td>Sampling rate, Resolution</td>
<td>10 mV/µC, CR-RC 100ns</td>
</tr>
</tbody>
</table>

- Power consumption
- Output data bandwidth: 300–500 MB/s
- Channel number: 32
- Process: TSMC 65 nm LP

≤ 5 mW per channel
### ASIC FEE ASIC chips

#### 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>TPC</td>
<td>ALICE</td>
<td>T2K</td>
<td>ILC</td>
<td>ALICE upgrade</td>
</tr>
<tr>
<td>Pad size</td>
<td>4x7.5 mm²</td>
<td>6.9x9.7 mm²</td>
<td>1x6 mm²</td>
<td>4x7.5 mm²</td>
</tr>
<tr>
<td>Pad channels</td>
<td>5.7 x 10⁵</td>
<td>1.25 x 10⁵</td>
<td>1-2 x 10⁶</td>
<td>5.7 x 10⁵</td>
</tr>
<tr>
<td>Readout Chamber</td>
<td>MWPC</td>
<td>MicroMegas</td>
<td>GEM/MicroMegas</td>
<td>GEM</td>
</tr>
<tr>
<td>Analog Front-end</td>
<td>Gain</td>
<td>12 mV/fC</td>
<td>18 mV/fC</td>
<td>12-27 mV/fC</td>
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<tr>
<td></td>
<td>Shaper</td>
<td>CR-(RC)⁴</td>
<td>CR-(RC)²</td>
<td>CR-(RC)⁴</td>
</tr>
<tr>
<td></td>
<td>Peaking time</td>
<td>200 ns</td>
<td>100 ns</td>
<td>30-120 ns</td>
</tr>
<tr>
<td></td>
<td>ENC</td>
<td>385 e</td>
<td>1000 e</td>
<td>520 e</td>
</tr>
<tr>
<td>Waveform Sampler</td>
<td>Method</td>
<td>ADC</td>
<td>SCA</td>
<td>ADC</td>
</tr>
<tr>
<td></td>
<td>Sampling frequency</td>
<td>10MSPS</td>
<td>25MSPS</td>
<td>40MSPS</td>
</tr>
<tr>
<td></td>
<td>Dynamic range</td>
<td>10bit</td>
<td>10bit</td>
<td>10bit</td>
</tr>
<tr>
<td></td>
<td><strong>Power consumption</strong></td>
<td>32mW/ch</td>
<td>6.2-7.5mW/ch</td>
<td>47.3mW/ch</td>
</tr>
<tr>
<td></td>
<td>CMOS Process</td>
<td>250 nm</td>
<td>350 nm</td>
<td>130 nm</td>
</tr>
</tbody>
</table>
ASIC FEE requirements

• Requirement for the front-end electronics
  • Analog front-end, including preamplifier and shaper
  • Waveform sampling ADC in 10b and 20-40MSPS
  • Continuous working, no power pulsing → Low power consumption

<table>
<thead>
<tr>
<th>Total number of channels</th>
<th>~1 Million per endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFE</td>
<td>ENC</td>
</tr>
<tr>
<td>Gain</td>
<td>10 mV/fC</td>
</tr>
<tr>
<td>Peaking time</td>
<td>160 ns</td>
</tr>
<tr>
<td>ADC</td>
<td>Sampling rate</td>
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<tr>
<td></td>
<td>20-40 MSPS</td>
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<tr>
<td></td>
<td>Resolution</td>
</tr>
<tr>
<td></td>
<td>10 bit</td>
</tr>
<tr>
<td>Buffer latency</td>
<td>~50 μs</td>
</tr>
<tr>
<td>Data readout rate</td>
<td>20 Gb per event w.o. zero compression</td>
</tr>
<tr>
<td>Power consumption</td>
<td>&lt;10 mW per channel</td>
</tr>
<tr>
<td>Area</td>
<td>&lt; 6 mm² per channel, incl. cooling</td>
</tr>
</tbody>
</table>
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>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>
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</table>

**SAR ADC test summary**

<table>
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<tr>
<th>Specifications</th>
<th>Test Results</th>
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<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 LSB</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>

1320um x 838um
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 leas 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)

Low power consumption ASIC chip:
- FEE electronics and DAQ collaborated with Tsinghua University
- Less than 5mV per channel
Thanks.