A Time Projection Chamber for the International Linear Collider.

Dimitra Tsionou
On behalf of the LPTPC Collaboration
HEP 2017, Ioannina 9 April 2017
The International Linear Collider (ILC)

- $e^+e^-$ collisions with energy 250 GeV – 1 TeV
- Superconducting acceleration cavities (proven technology - XFEL)
- High luminosity ($2 \times 10^{34}$ cm$^{-2}$s$^{-1}$)
- ~30 km long (500 GeV)
- Beam polarisation ($\pm 80\%$ for $e^-$, $\pm 30\%$ for $e^+$)
Green ILC

- Power consumption
- ILC designed with self-imposed limits on total site power
  - <200 MW at 500 GeV
  - 300 MW at 1TeV
Detectors at the ILC

- Two multiple purpose detectors planned that will operate through push-pull scheme
  - One interaction point

- Imaging calorimeters with extreme granularity
- High power tracking and vertexing
Detectors at the ILC

- Two multiple purpose detectors planned that will operate through push-pull scheme
  - One interaction point

SiD

ILD

- Imaging calorimeters with extreme granularity
- High power tracking and vertexing
Physics Motivation

- ILC can do high precision measurements
  - eg Higgs measurements in a model independent way, top mass measurements
- ILC can do direct searches of New Physics complimentary to the LHC

Higgs coupling measurements at the percent level
International Large Detector – Tracking Requirements

- **Momentum resolution:**
  - \( \sigma(\Delta p_T/p_T^2) = 2 \cdot 10^{-5} \text{ GeV}^{-1} \)
  - TPC alone: \( 10^{-4} \text{ GeV}^{-1} \)

- **Tracking efficiency**
  - close to 100% down to low momenta for Particle Flow

- **Minimum material**

- **Full angular coverage and high hermeticity**
International Large Detector – TPC Requirements

TPC provides:

- ~200 space points along the track
- $\sigma \approx 100 \, \mu m$ in the $r\varphi$ plane (full drift)
- $\sigma \approx 400 \, \mu m$ in the $z$ direction at zero drift and 1.4mm at full drift
- 5% $X_0$ for barrel & 25% $X_0$ for endcaps (including field cage and readout)

`tTh event`
Time Projection Chamber – Working Principle

- Magnetic field parallel to the electric field
- Anode equipped with Micro Pattern Gas Detectors for the ILD
Large Prototype TPC and Current Infrastructure

- Test beam area T24/1 at DESY (1-6 GeV e⁻ beams)
- Large Prototype TPC built and installed

- Infrastructure includes a large bore 1T magnet
  - 25% $X_0$ material budget

- LP field cage parameters:
  - Length: 61 cm, Diameter: 72 cm
  - Up tp 25 kV $\rightarrow E_{\text{drift}}$ up to 350 V/cm
  - Wall material budget: 1.3% $X_0$

- The endplate is able to host 7 readout modules (dimensions ~22x17 cm²)
LP Modules

- GEM modules
  - Asian: 2 GEM stack, no side support
  - DESY: 3 GEM stack, ceramic frame support
  - \( \approx 1 \times 6 \text{ mm}^2 \) pad size (\( \approx 5K \) channels per module)

- Micromegas
  - Resistive foil used for charge spreading
  - \( \approx 3 \times 7 \text{ mm}^2 \) pad size (\( \approx 2K \) channels per module)

- GridPix (Micromegas+Timepix)

- Pixel TPC. 96 Timepix chips per module. \( \approx 7M \) channels per module
LP Modules

- GEM modules
  - Asian: 2 GEM stack, no side support
  - DESY: 3 GEM stack, ceramic frame support
  - ~1x6 mm² pad size (~5K channels per module)

- Micromegas
  - Resistive foil used for charge spreading
  - ~3x7 mm² pad size (~2K channels per module)

- GridPix (Micromegas+Timepix)

- Pixel TPC. 96 Timepix chips per module.
  ~7M channels per module
GEM detectors

- Strong fields inside GEM holes lead to high amplification of ionisation electrons
- Gain depends on potential difference between the GEM electrodes
DESY GEM module

 Goals

- Maximum active area
- Minimum material budget
- Field and high gain homogeneity
  → Flatness of GEMs
- Stable operation
- Minimal field distortions (field shaping wire/strips)

 GEM design and characteristics

- Thin ceramic mounting grid
- Anode divided into 4 sectors
- No division on cathode side
- Triple GEM stack (→ stable operation at high gain and flexibility)
- Field shaping wire
- Pad size 1.26 x 5.85 mm² (~5k pads per module)
During the last two years, all different MPDG technologies for the ILC TPC have had test beams at DESY

Experimental setup

- 1-7 readout modules equipped with readout electronics
- Default drift field 240 V/cm (maximum drift velocity) or 130 V/cm (minimal diffusion)
- T2K gas mixture: 95% Ar, 3% CF4, 2% iC4H10

Aim

- Validation of module design and performance understanding
Resolution

> Single point resolution

\[
\sigma_{r\phi/z}(z) = \sqrt{\sigma_{0r\phi,z}^2 + \frac{D_{t/l}^2}{N_{\text{eff}} \cdot e^{-A z}} z}
\]

> z resolution \(\sim 300 \, \mu m\) at zero drift distance (ILD TPC requirement)

<table>
<thead>
<tr>
<th>(\sigma)</th>
<th>(\sigma_{0r\phi,z} [\mu m])</th>
<th>(N_{\text{eff}})</th>
<th>(A [m^{-1}])</th>
<th>(D_{t/l} [mm/\sqrt{cm}]) (fixed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(r\phi)</td>
<td>71.0 ± 1.2</td>
<td>39.8 ± 2.0</td>
<td>0.495 ± 0.097</td>
<td>0.103</td>
</tr>
<tr>
<td>(z)</td>
<td>306.3 ± 0.8</td>
<td>39.5 ± 1.6</td>
<td>0.529 ± 0.084</td>
<td>0.226</td>
</tr>
</tbody>
</table>

> The ILD TPC requirement of \(r\phi\) resolution <100 \(\mu m\) for full drift distance at 4T corresponds to an \(r\phi\) resolution <150 \(\mu m\) for the large prototype TPC at 1T.
Extrapolation to ILD scale

- From test beams, the point resolution was measured and extrapolated to the ILD scale.

- Meets the requirement for the ILD detector $\sigma_z < 1.4\text{mm}$.

- The $\sigma_{r\phi} < 100\ \mu\text{m}$ resolution can be achieved if the gas quality is tightly controlled and therefore the electron attachment is insignificant.
From the gas amplification, ion disks are formed and drift in the TPC volume (low drift velocity). These ion disks can cause field distortions and impact the resolution.

- 3 ion disks can form in the TPC volume corresponding to 3 bunch trains (5Hz running)

MPGDs have an inherent ability of ion absorption but it's not perfect. Therefore, there is a need of a dedicated device to prevent amplification ions from drifting back in the TPC sensitive volume.

First test beam with ion gating GEM in Nov 2016
Test beam with gating

Gating GEM provides high transparency for drift electrons (~85%) and should provide high blocking power for positive ions ($10^{-4}$)

Electron transmission rate measurements and simulations

Gating GEM to be integrated in the DESY GEM module
Mechanic structures

- Current mechanical projects: new field cage, designs for gating GEM module integration

- New lightweight endplate for the LP (Cornel) to be tested

- Goal: Same stability with half material budget (ILD requirements)

- New field cage production

- Difficult to simulate mechanical deformation due to composite materials

Deflection $O(150 \text{ um})$ at 3mbar
Momentum resolution measurements

- Determination of the momentum resolution in a tracking detector (Gluckstern formula)

\[
\sigma_{p_T} = \sqrt{\frac{720}{n+4} \cdot \frac{\sigma \cdot p_T^2}{0.3 B L^2}}
\]

- In the Large Prototype TPC case, there is a broad energy spectra due to the energy loss in the magnet

- In addition, field inhomogenities can cause distortions
  - Hits appear to be displaced especially at module edges
  - This has an impact on the momentum determination
Silicon Telescope

> In order to correct for field distortions and measure the momentum resolution of the LPTPC, we need an external reference tracker

- Build and install a silicon telescope in the T24/1 test beam area at DESY

> Challenge: The external tracker needs to fit in the available space between the magnet and the LPTPC (~3.5 cm)

> This puts very stringent requirements on the spatial resolution of the sensors (better than 10 μm)

<table>
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<tr>
<th></th>
<th>ILC</th>
<th>ATLAS</th>
<th>CMS</th>
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<tbody>
<tr>
<td>&lt;10 μm</td>
<td>12 μm (pixels)</td>
<td>10 m (pixels)</td>
<td>20-30 μm (strips)</td>
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<tr>
<td>16μm (strips)</td>
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Coverage area

- Hit positions on front and back sensors for 5 GeV e beam

   ![yz position of hit on 2nd Si layer](image)

   ![yz position of hit on 4th Si layer](image)

   90-95% of events

- For lower energy beams, the hit distribution on the back sensors is more spread and shifted to lower y values

- Minimum coverage area: ~2x2 cm² for front and 4x10cm² for back sensors

- Larger coverage area is beneficial eg 10x10 cm² (less moving and alignment of the system)
**Silicon module**

- Si strip sensors of 25 μm pitch → spatial resolution 7-8 μm
  - sensor to be used for SiD strip tracker

- Read out by two KPiX chips bump bonded onto the sensor

- Control of sensor and KPiX through wire bonding

- Kapton cable to read out the data from KPiX and control the KPiX and sensor
Mechanical Support for Silicon Telescope

The mechanical support of the system will be split in two parts

- 1 big cylindrical support that will go inside the magnet
- 1 cassette-like support that will accommodate the sensors

Sketch showing the concept of the silicon tracker being able to move in different directions as required for a versatile system

Design of a support structure that can host the silicon tracker inside the magnet installed in test beam area T24/1
Summary & Outlook

- The ILD is a planned detector for the ILC providing high precision tracking.

- Different technologies are being pursued for the ILD TPC and it has been demonstrated they can achieve the requirements for the ILD TPC:
  - GEMs, MM, GridPix

- Further tests with gating GEM and integration with the DESY GEM module.

- Future TPC test beams will be performed with a silicon reference tracker leading also to momentum resolution measurements.
Back-Up
Present

- LHC is currently the only existing collider at the energy frontier
- $3000 \text{ fb}^{-1}$ until $\sim 2035$
- Plenty of results to come!
- What comes afterwards?
- New colliders take $>10-15$ years of preparation and construction time
Future Colliders

**ILC:** $e^+e^- @ 200-500$ GeV ($\sim$1 TeV)  
TDR in 2012  
under review by Japan

**CLIC:** $e^+e^- @ 0.38, 1.4, 3$ TeV  
Conceptual Design 2013  
TDR in 2017

**CEPC:** $e^+e^- @ 250$ GeV  
Pre-CDR in 2014  
Engineering design by 2020

**SppC:** $pp @ 50-70$ TeV  
Engineering design by 2035

**FCC:** $pp @ \sim 100$ TeV  
& initially $e^+e^- @ 90-350$ GeV  
Conceptual design in 2017
Higgs: What do we want?

- Goal of the ILC program: Comprehensive study of the Higgs couplings
- We will need excellent jet energy resolution for high precision
Higgs Recoil Measurement

- Measure recoil mass against measured Z
- Requires no specific H decay (ie including also invisible modes)
- Model independent measurement of
  - ZH cross section
  - Absolute normalisation of branching ratios
  - Extraction of $g_Z$
Higgs couplings precision

Projected precision of Higgs coupling and width (model-independent fit)

Projected Higgs coupling precision (7-parameter fit)

ILC 500 GeV, 500 fb$^{-1}$ @ 350 GeV, 200 fb$^{-1}$ @ 250 GeV, 500 fb$^{-1}$
ILC 500 GeV, 4000 fb$^{-1}$ @ 350 GeV, 200 fb$^{-1}$ @ 250 GeV, 2000 fb$^{-1}$
ILC @ HL-LHC 3000 fb$^{-1}$ combination

ILC 500 GeV, 500 fb$^{-1}$ @ 350 GeV, 200 fb$^{-1}$ @ 250 GeV, 500 fb$^{-1}$
ILC 500 GeV, 4000 fb$^{-1}$ @ 350 GeV, 200 fb$^{-1}$ @ 250 GeV, 2000 fb$^{-1}$
ILC @ HL-LHC 3000 fb$^{-1}$ combination
ILC precision on H coupling measurements can differentiate between theory models
Top EW couplings

- Top pair production threshold scan is a central measurement in the ILC program (no QCD uncertainties ~GeV currently present)
- Access to top mass and electroweak couplings
- Sensitivity to New Physics

Expected precision for $t$ couplings will allow to distinguish between different BSM models

*Expected precision for $t$ couplings will allow to distinguish between different BSM models*
H20 Running Scenario

- 500(550) GeV → General purpose – Higgs & top physics, Higgs self-coupling, top-Yukawa coupling, BSM
- 350 GeV → top threshold scan, Higgs width
- 250 GeV → Higgs measurements (mass, branching ratios, invisible Higgs,...)

**Total Integrated Luminosities**

<table>
<thead>
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<th>√s</th>
<th>∫Ldt</th>
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<tr>
<td>250 GeV</td>
<td>2 ab⁻¹</td>
</tr>
<tr>
<td>350 GeV</td>
<td>200 fb⁻¹</td>
</tr>
<tr>
<td>500 GeV</td>
<td>4 ab⁻¹</td>
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Cost & Staging

> Detailed value estimation cost for ILC TDR in 2012 (~8 billion)

> R&D and detectors not included

> Cost estimation has been reviewed and approved by independent review panel

> International cost sharing expected (~50% to be covered by host country)
Higgs measurements and energy reach

\[ \sigma(e^+e^- \rightarrow HX) \text{ [fb]} \]

- \( H \nu_e \overline{\nu}_e \)
- \( H e^+e^- \)
- \( t \bar{t}H \)
- \( HH \nu_e \overline{\nu}_e \)
- \( HHZ \)

- Mass: \( \geq 250 \text{ GeV} \)
- BR's: \( \geq 350 \text{ GeV} \)
- BR's (LHC)-invisible: \( \geq 500 \text{ GeV} \)
- \( \Gamma_{\text{tot}} \)
- \( g_t \)
- \( g_{HHH} \)
- \( \geq 1 \text{ TeV} \)
Particle Flow Concept

> Idea: Use the sub-detector with the best resolution for the energy measurement

- Charged particles: tracking system
- Photons: ECAL
- Neutral hadrons: HCal

> Need to avoid double counting

> Granularity and pattern recognition are very important
External Si tracker for Large Prototype TPC

- Solution: Build an external Si tracker (Si telescope) to provide reference tracks (entry and exit hits)

- Prototype for ILD TPC exists at DESY

- Goal: Combined test beam with LPTPC → track reference, field distortion corrections, momentum resolution measurements

- The Silicon tracker should be versatile and simple to be used as a telescope by other groups during test beams

- Challenge: The Silicon system needs to fit in the existing infrastructure (available space is ~3.5 cm)
GEM detectors

- Strong fields inside GEM holes lead to high amplification of ionisation electrons
- Gain depends on potential difference between the GEM electrodes
Micromegas

- Compact and integrated electronics
- 2-phase CO$_2$ cooling
- Last test beam used modules with either carbon loaded kapton or diamond-like carbon as resistive layer
Field distortions in TPC

- Inhomogenities in Electric fields can cause distortions
- Magnetic field parallel to the electric field
  - ExB terms pronounced at module edges
- E and B field present
- A curved fit (helix) is used for the track (distortions can be partially absorbed in the track curvature)
- Distortion effects more pronounced on module edges
GridPix

- Micromegas with pixel readout (Timepix)
- Using smaller pads to improve resolution
- Demonstrated using 96 timepix chips per module

- Timepix pixel size: 55x55 μm², ~65K channels

- Integrated readout electronics. ~7M channels per module

Bump bond pads used as charge collection pads