Progress and Developments on the IDEA Drift Chamber

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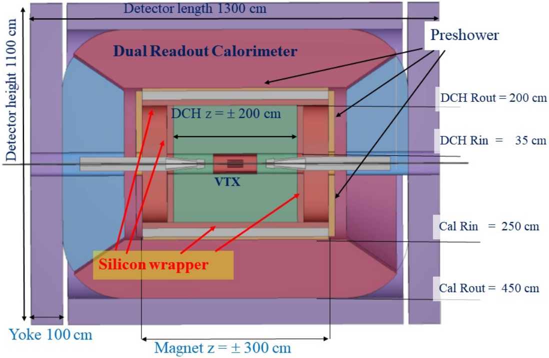
The IDEA Detector

- Vertex (VTX)
  - 1 cm around the beam pipe
  - Si-pixel detector for impact parameter determination
- *Central Drift Chamber (DCH)*
  - 4m long, $R = 35 - 200$ cm
  - He:iC_4H_{10} (90:10)
  - Fully stereo
  - Cluster Counting (CC) technique
- Silicon wrapper
  - Si micro-strip tracker
- Preshower
  - μ-RWELL technology, 2 layers
- Magnet
  - Solenoid, 5m: 2T B-field
  - Inside calorimeters
- Calorimeters (*Alessandro's talk*)
  - EM (crystal) + Hadronic dual readout
- Muon chambers:
  - μ-RWELL, 3 stations

Innovative **D**etector for **E**lectron-positron **A**ccelerator



Tracking requirements

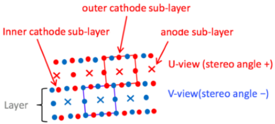
- High precision measurements of $Z/W/H$ boson and *top* quark decays
- Physics rates up to 100 kHz (at Z pole)
- High efficiency for low transverse momenta
- Target requirements for low-momenta muons, for precise measurements of Higgs boson properties:
  - $\sigma(1/p_T) \lesssim 3 \cdot 10^{-5}\ (GeV/c)^{-1}$
  - $\sigma(\theta, \phi) \sim 0.1$ mrad
  - High transparency
- Large angular coverage and large tracking radius
- Particle IDentification (PID) high efficiency to distinguish between final state with same signatures, e.g. flavour physics

Why a drift chamber instead of other detector technologies, e.g., silicon detectors?

- Multiple Scattering highly reduced $\Rightarrow$ Good resolution for low-momenta (charged) tracks
- PID at tracking level
- High capabilities in reconstruction of kinks and vees

The IDEA Drift Chamber

- Unique volume, low-mass chamber: 4 m long, inner (outer) radius of 0.35 (2) m
- High transparency due to the total amount of material:
  - Radial directions, i.e. barrel calorimeter: $\sim 1.6\% \; X_0$
  - Forward directions, i.e. end-cap calorimeter: $\sim 5\% \; X_0$
- Operating gas mixture: $He{:}iC_4H_{10}$ (90:10)
  - Average drift velocity of $\sim 2 \; cm/\mu s$, corresponding to drift time $t_D < 400 \; ns$
  - Number of cluster (per m.i.p.) $\sim 12.5 \; cm^{-1}$ (with ~ 1.6 electrons/cluster)
- Fully stereo chamber: 112 layers ranging from 50 to 250 mrad
- Wires:
  - Sense (anode): 20 μm W(Au) $\rightarrow$ 56448 total
  - Field (cathode): 40 μm Al(Ag) $\rightarrow$ 285504 total
  - Guard (cathode): 50 μm Al(Ag) $\rightarrow$ 2016 total
    To equalize gain of innermost and outermost layers
- Active volume: 56448 almost squared drift cells ($12 \div 14.5$ mm), with a 5 : 1 field-to-sense wire ratio for simpler time-to-distance relations



5 : 1 field-to-sense wire ratio

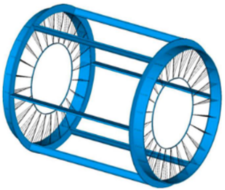
Overall expected resolution: $\sigma_{xy} \lesssim 100 \; \mu m$ and $\sigma_z \lesssim 1 \; mm$

Drift Chamber: Ongoing Mechanical Design (1)

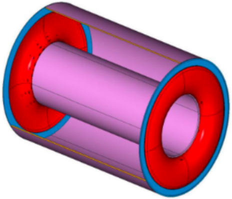
Change Of Paradigm

Traditional DCH: anchoring wires to a solid end-plate, to sustain the load due to the wires tension
⇒ Heavy end-plates!

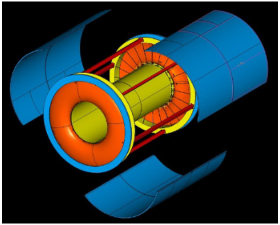
IDEA DCH: separating wire support, by counterbalancing the wire tension (external stays) from the gas containment
⇒ Ultra-light structure!



Wire support cage: light (no differential pressure on it) and feed-through-less structure



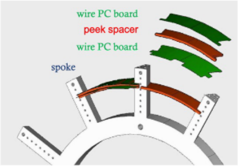
Gas containment: vessel free to deform without impacting on the wire position and mechanical tension

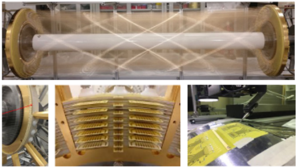


Final layout: higher granularity and reduction of material

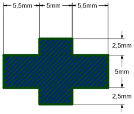
Drift Chamber: Ongoing Mechanical Design (2)

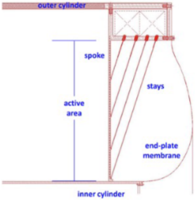
- New wiring strategy: inner and outer cylinder connected to 48 spokes, forming 24 identical sectors
- Spokes, 48: 165 cm lenght
- Each spoke supported by 15 stays
- Materials:
  - Spokes: epoxy carbon
  - Stays: 3 mm structural steel (plan to use carbon/polymers)
- FEA: vary dimensions of each component, e.g. height/thickness of the cage (inner/outer), spoke dimensions, etc., to evaluate responses

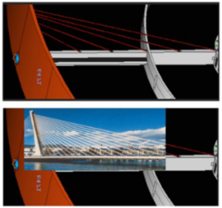




MEG-II chamber







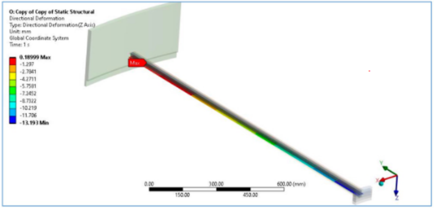
Structure like a harp cable-stayed bridge

Finite Element Analysis (FEA):
Total deformation allowed of the order of $\sim 200\ \mu m$
(Mechanical and electrostatic stability)

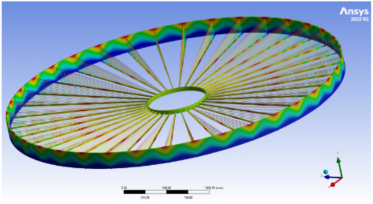
Drift Chamber: Ongoing Mechanical Design (3)

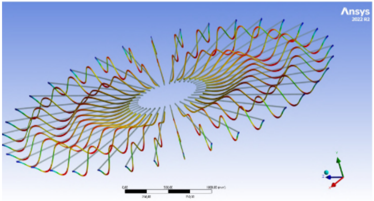
- FEA: single end-cap simulation, to evaluate spoke and stays behaviour under wires mechanical tension
- Goal: minimize spokes deformation by using prestressing force in stays. Deformation upper limit at $\sim 200\ \mu m$, while ensuring the structural integrity

Ongoing spoke layout optimization from *ENGINSOFT* gives a maximum deformation along the chamber axis of $\sim 190\ \mu m$

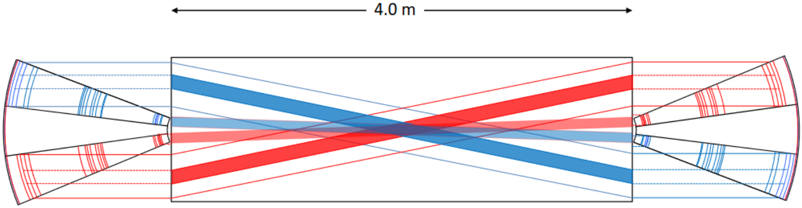


In parallel, the choice of gas envelope shape profile and materials will be addressed soon





Drift Chamber: Ongoing Mechanical Design (4)



Ongoing work in model definition(s):

- *ENGINSOFT*: complete model, mechanically accurate (spacers location, connecting cables/wire definition...)
- *CETMA*: mold design and construction for spokes and inner ring

Full-length prototype as final aim:

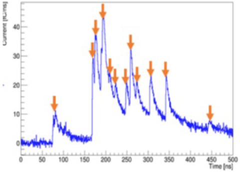
- ✔ Latest design, once ready from *ENGINSOFT*
- ✔ Materials and construction techniques
- ✔ Electrostatic stability
- ✔ Electronics and readout

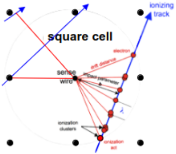
Specifications

- Total layers: 10
- Total wires: 1397
- Total PCB wire layers: 42
- Total readout channels: 112

Type	Wires	Wire Boards
Sense	168	8
Field	965	22
Guard	264	12
Total	1397	42

Particle Identification (1)





Counting dN_{cl}/dx to identify particles with a better resolution than dE/dx

- Collect signals and identifying peaks
- Record electron arrival times per ionisation act

➥ dE/dx

- Needed high stability on HV and gas parameters
- Calibration for electronics (all channels)
- Reduced amount of information due to truncated mean cut (70-80%)

$$\frac{\sigma_{dE/dx}}{(dE/dx)} \propto 0.41 N^{-0.43} (pL_{track})^{-0.32}$$

$N = 112,\ L_{track} = 2\ m,\ p = 1\ atm$

$\sigma \sim 4.3\%$ (*empirical parametrization*)

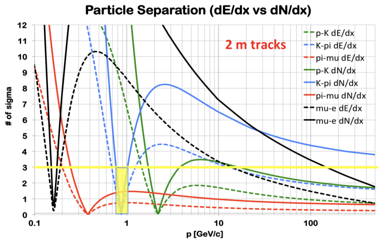
➥ dN_{cl}/dx

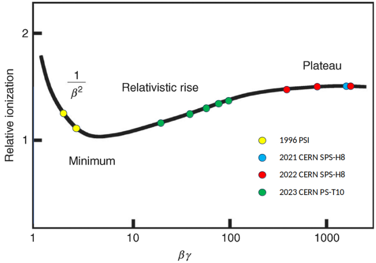
- Digital measurement, not related to electronics gain
- Needed fast electronics and efficient algorithms
- Poisson statistics

$$\frac{\sigma_{dN_{cl}/dx}}{(dN_{cl}/dx)} \propto (\delta_{cl} L_{track})^{-\frac{1}{2}} = N_{cl}^{-\frac{1}{2}}$$

$L_{track} = 2\ m,\ \delta_{cl} = 12\ cm^{-1}$ for He:iC_4H_{10} (90:10) $\longrightarrow \sigma \sim 2.0\%$

Particle Identification (2)





- Predicted excellent K/π separation over the full momentum spectrum, but $p \in [0.85, 1.05]$ GeV/c
- $\sigma_{dE/dx}/(dE/dx) \sim 4.3\%$
- $\sigma_{dN/dx}/(dN/dx) \sim 2.3\%$
- Simulation with GARFIELD++ and GEANT4, after importing the GARFIELD++ model
- Simulations to be cross-checked with test beam data

Test beam campaings:

- 2021, November and 2022, July: two tests at *CERN-H8*, using 40-180 GeV/c muon beams
- 2023: test at *CERN PS*, using a 2-10 GeV/c muon beam
- Evaluating the possibility for a test beam at *FNAL-MT6* with π and/or K in the range $\beta\gamma \in [10, 140]$, particularly important to fully exploit the relativistic rise

Particle Identification (3)

Several experimental setup configurations:

- Sense wire diameter: 10, 15, 20, 25, 40 μm
- Outer (inner) drift tube size: 1.0 (0.8), 1.5 (1.2), 2.0 (1.8), 3.0 (2.8) cm
- Gas gain: $1 \div 4 \cdot 10^5$
- Track angle: 0°, 15°, 30°, 45°, 60°
- $He{:}iC_4H_{10}$ mix: (90:10), (85:15) and (80:20)
- Readout sampling rate: 1, 1.5, 2 GS/s at 12 bits

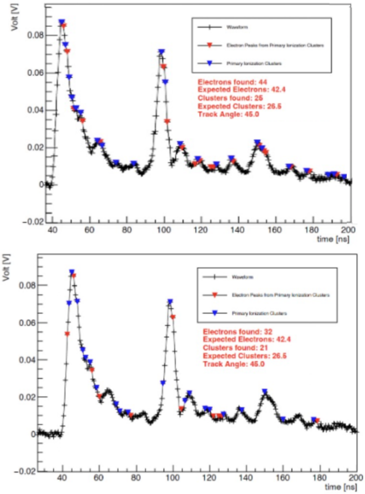
Algorithms for electron peak finding:

- *First and Second Derivative* (DERIV)
- *Running Template Algorithm* (RTA)
- *ML-based*, with RNN techniques

Clusterization:

- Based on drift times (DERIV, RTA)
- *ML-based*, with CNN/GNN techniques

See *Guang's talk* for details about the ML approach

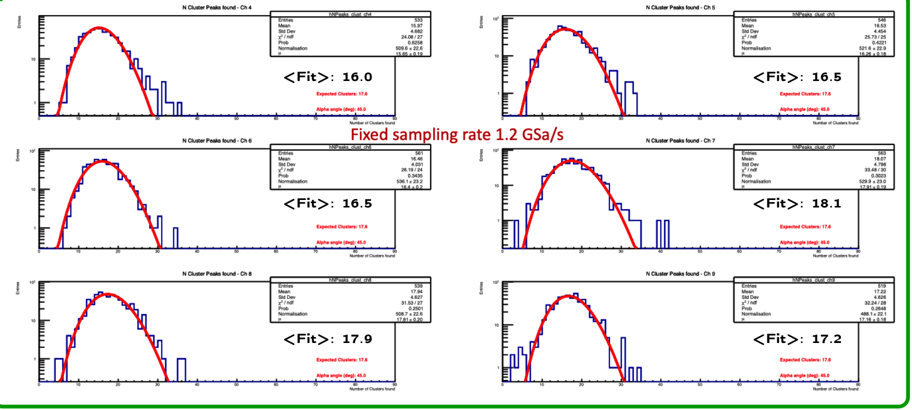


Applied corrections for space charge effect, attachment, recombination

Particle Identification (4)

Poissonian distributions for the number of clusters, independently of the different sense wire diameter

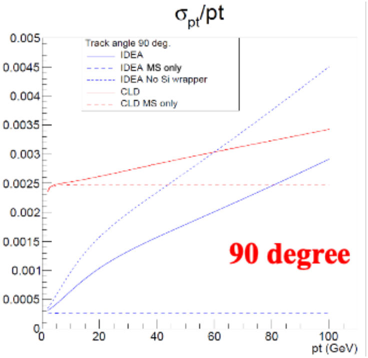
Drift tube size: 1.0 cm – Gas gain: $2 \cdot 10^5$ – Gas mix: He:iC_4H_{10} (90:10) – Track angle: 45° – Sampling rate: 1.2 GS/s



Results in agreement with expectations: $\delta_{cl/cm} \cdot L_{tube} \cdot 1.3(rel.\ rise) \cdot (1/\cos\theta) = 17.6$

Simulation (1)

- IDEA geometry: GEANT4 and DD4HEP
- IDEA full simulation: KEY4HEP
- Good status of the full chain: good level of geometry details, including end-caps. Hits and digits available
- High momentum resolution $\sigma_{pt}/pt \sim 10^{-3}$ (*studies ongoing for new results*)



Simulation (2)

A reliable simulation of the ionisation clusters generation is needed to exploit potentiality of CC on real physics events:

- Starting from energy deposit information, provided by GEANT4
- Evaluate cluster kinetic energy, always from GEANT4
- Import model derived from GARFIELD++ to reproduce cluster number and cluster size distributions
- To be implemented in the IDEA full simulation

Results for cluster size distribution (~ 1.61), in reasonable agreement overall:

- GARFIELD++: ~ 1.56
- Test beam analysis: ~ 1.67
- He experimental measurements: ~ 1.6

Readout electronics and data reduction

IDEA DCH operating conditions:

- 56448 drift cells in 112 layers with ~ 130 hits/track
- 500 ns drift time with a cluster density of 20 cluster/cm
- 12 bits signal digitization at 2 GS/s
- Trigger rate ~ 100 kHz at Z-pole (~ 20 charged tracks) + background, noise, $\gamma\gamma$, Bhabha scattering for additional ~ 100 kHz
- Reading both ends of the wires

$$\Downarrow$$

Data transfer rate $\gtrsim 1$ TB/s

Proposed solution:

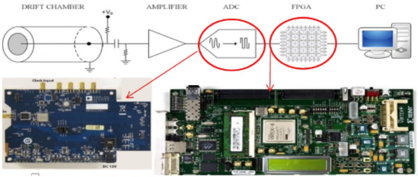
- Sending minimal information, instead of the full waveform, to reduce data transfer
- Minimal information: amplitude and arrival time of each peak associated with individual ionisations
- Implement on FPGAs a real time analysis (peak finding algorithms) of drift chamber data and digitized by ADCs

$$\Downarrow$$

Data transfer rate ~ 25 GB/s

Readout electronics and data reduction (2)

- Single channel solution successfully verified: details *here* and *here*



- Extension to a 4-channel board (WIP)
- Completed benchmark tests with the ASoCv3 chip (4 CHs) from *NALU SCIENTIFIC*
- Received the HDSoC test board (32 CHs) from *NALU SCIENTIFIC*. Starting preliminary tests with drift tubes and cosmic rays
- Now available the VX2740 digitizer from *CAEN* (a lower performance version of the VX2751, suitable for CC)
  $\longrightarrow$ Becoming acquainted with *OpenFPGA SCICompiler* software package

Conclusions

A lot of work is ongoing for the IDEA Drift Chamber in different areas:

- Mechanical structure under definition: design, materials, component optimization
- Simulation:
  - Potentially good results from simulation tools
  - Full chain in good status
- Cluster Counting technique:
  - Analysis of already taken data (2023) ongoing: efficiency, electron peaks and cluster density as a function of gas mixture, gas gain, wires diameter. Single cell size and track angle as function of track length
- Electronics: testing different components for a multi-channel implementation
- Test Beams: planning future data-taking campaign(s) to study relativistic rise region (momenta $p \lesssim 30\ GeV/c$)

Stay Tuned!

Backup

Clusterization algorithm

- Merging of electron peaks in consecutive bins in a single electron (peak) to reduce fake electrons counting
- Contiguous electron peaks being compatible with the electrons' diffusion time (different for each gas mixture) must be considered belonging to the same ionisation cluster. In this case, a counter for electrons per each cluster is incremented
- Position and amplitude of the clusters corresponds to the position and height of the electron having the maximum amplitude in the cluster
- Result: Poissonian distribution for the number of clusters

Algorithms

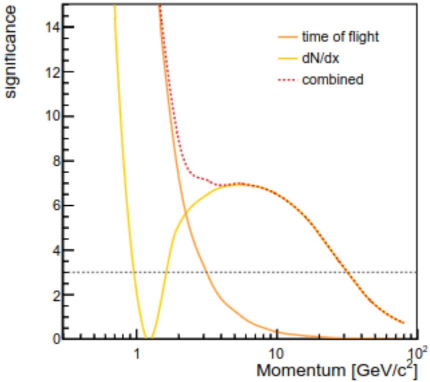
First and Second Derivative

- Compute the first and second derivative from the amplitude average over two times the timing resolution
- At the peak candidate position, require they are less than a r.m.s. signal-related small quantity
- Require they increase (decrease) before (after) the peak candidate position of a r.m.s. signal-related small quantity
- At the peak candidate position, require the amplitude is greater than a r.m.s. signal-related small quantity
- At the peak candidate position, require the previous (next) signal amplitude to be greater (less) than a r.m.s. signal-related small quantity
- r.m.s. is a measurement of the noise level in the analog signals from first bins

Running Template Algorithm

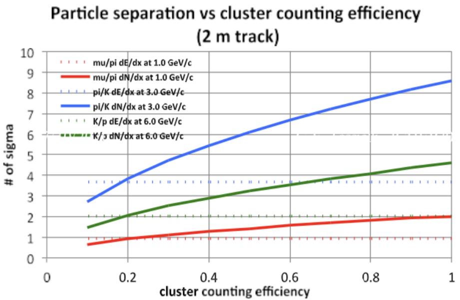
- Define an electron pulse template based on experimental data
- Raising and falling exponential over a fixed number N of bins
- Digitize it according to the data sampling rate
- The algorithm svan the waveform and run over N bins by comparing it to the subtracted and normalized data (to build something similar as a χ^2)
- Define a cut on the aforementioned variable
- Subtract the found peak to the signal spectrum
- Iterate the search and stop when no new peak is found

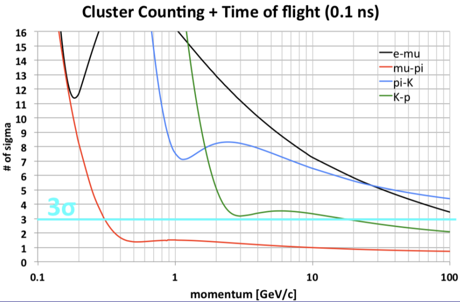
PID resolution



Efficient ($\gtrsim 3\sigma$) level of π/K separation for momenta $p < 30$ GeV/c *from Delphes*
(*studies ongoing for new results*)

Particle separation vs Cluster Counting efficiency

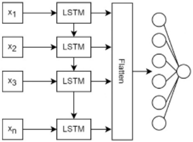




Cluster Counting with ML

Peak finding with LSTM

Why LSTM? Waveforms are time series

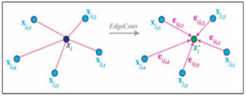


- Architecture: LSTM (RNN-based)
- Method: Binary classification of signals and noises on slide windows of peak candidates

LSTM: Long Short-Term Memory

Clusterization with DGCNN

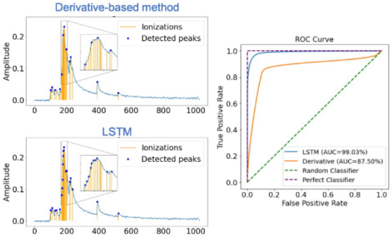
Why DGCNN? Locality of the electrons in the same primary cluster, perform massage passing through neighbour nodes in GNN



arXiv: 1801.07829

- Architecture: DGCNN (GNN-based)
- Method: Binary classification of primary and secondary electrons

DGCNN: Dynamic Graph Convolutional neural networks



LSTM model is better classifier compared to derivative-based model

Why 200 μm deformation as main goal?

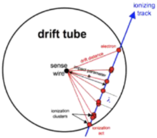
- A wire tensioned at 30g stretches by 3mm/m, on 4m we have **12mm** of tension length on the wire.

- If we assume 2% error -> 240 µm
- If the spokes deform by 240 µm it means that the tension of the wire changes by 2% (0.6gr) and we are wrong by 2% on the sagitta therefore by **8um**. This added in quadrature to the 50 µm gives us an acceptable value.

- For **600 µm** as we currently have, there are **25 µm** of error on the sagitta which becomes comparable with the precision error of the wire.

Cluster timing

Cluster Timing

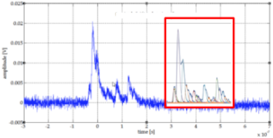


Determine, in the signal, the ordered sequence of the electrons arrival times:

$$\{t_j^{el}\} \quad j = 1, n_{el}$$

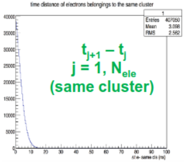
Based on the dependence of **the average time separation between consecutive clusters** and on the **time spread due to diffusion**, as a function of the drift time, **define** the **probability function**, that the j^{th} **electron** belongs to the i^{th} **cluster**:

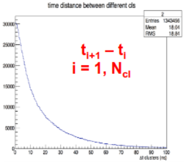
$$P(j,i) \quad j = 1, n_{el}, \quad i = 1, n_{cl}$$



from this **derive** the most probable **time ordered sequence of the original ionization clusters:**

$$\{t_i^{cl}\} \quad i = 1, n_{cl}$$





For any given first cluster (**FC**) drift time **t_1**, the **cluster timing technique** exploits the drift time distribution of all successive clusters to statistically (**MPS**) or using **ML techniques**, determine, hit by hit, the most probable **impact parameter**, thus reducing the **bias** and improving the average **spatial resolution** with respect to that obtainable with the FC method alone:

over a 1 cm drift cell, **spatial resolution** may improve by ≳ 20% **down to ≲ 80 μm**.

Fringe benefits of the cluster timing technique are:

- **event time stamping (at the level of ≈ 1 ns);**
- **improvements on charge division;**
- **Improvements on left-right time difference.**