CEPC漂移室粒子鉴别的模拟研究

赵光[1]，辛水艇[1]，董明义[1]，伍灵慧[1]，孙胜森[1]
zhaog@ihep.ac.cn

[1] 中国科学院高能物理研究所

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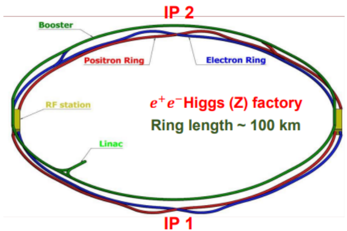
Outline

- **Introduction**
  - Drift chamber in CEPC
  - Principles: dE/dx vs. dN/dx
- **Simulation**
  - Full simulation: waveform + electronics + cluster counting
  - Preliminary PID performance
- **Prototype experiment**
- **Summary**

Introduction: Physics Programs of CEPC

- The CEPC aims to start operation in 2030's, as a Higgs (Z) factory in China. The plan is to operate
  - Above **ZH** threshold ($\sqrt{s}$ ~ 240 GeV) for 7 years.
  - Around and at the **Z** pole for 2 years.
  - Around and above **W^+W^-** threshold for 1 year.
  - It is upgradeable to run at the $t\bar{t}$ threshold.
- Possible *pp* collider (SppC) of $\sqrt{s}$ ~ 50–100 TeV in the future.

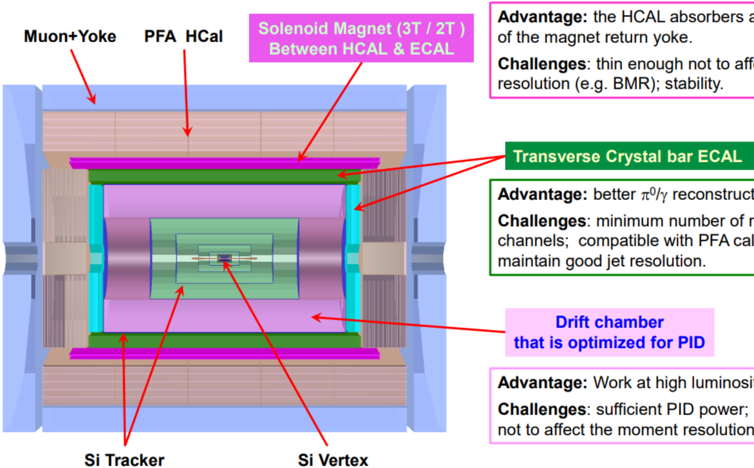


Operation mode		ZH	Z	W^+W^-
$\sqrt{s}$ [GeV]		~240	~91.2	158-172
Run time [years]		7	2	1
CDR	L / IP [10^{34} cm^{-2}s^{-1}]	3	32	10
	$\int L\,dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6
	Event yields [2 IPs]	1×10^6	7×10^{11}	2×10^7
Latest	L / IP [10^{34} cm^{-2}s^{-1}]	5	105.5	18.7

- The large samples from 2 IPs: **10^6** Higgs, **10^{12}** Z, **10^8** W bosons, provide a unique opportunity for
  - High precision Higgs, EW measurements,
  - Study of flavor physics (b, c, tau) and QCD,
  - Probe physics beyond the standard model.
  - …

From Jianchun Wang's talk

Introduction: The 4th Conceptual Detector Design



Advantage: the HCAL absorbers act as part of the magnet return yoke.

Challenges: thin enough not to affect the jet resolution (e.g. BMR); stability.

Advantage: better π^0/γ reconstruction.

Challenges: minimum number of readout channels; compatible with PFA calorimeter; maintain good jet resolution.

Advantage: Work at high luminosity Z runs

Challenges: sufficient PID power; thin enough not to affect the moment resolution.

From Jianchun Wang's talk

Introduction: PID in Drift Chamber

- **Particle identification (PID) is essential for flavor physics**
  - Kaon/pion separation up to 20 GeV/c is necessary ➔

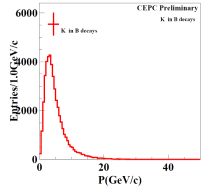
- **Ionization measurement with a gaseous detector can provide powerful K/π separation up to dozens of GeV/c within an acceptable detector size**

  ➔ Drift chamber (DC) for PID is proposed

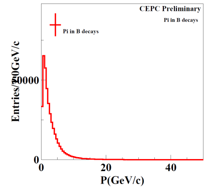
- **Comparing to the energy loss measurement, the cluster counting technique is expected to improve the ionization measurement with small fluctuations**

- **To study the PID capability of DC with cluster counting, a full simulation is performed**

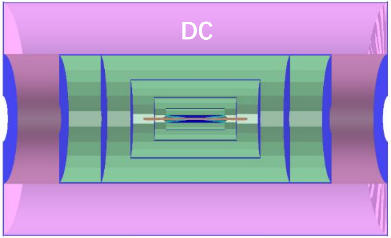
K in B decays



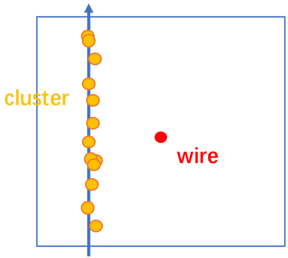
π in B decays



CEPC 4th Conceptual Detector



Principle of Ionization (I)



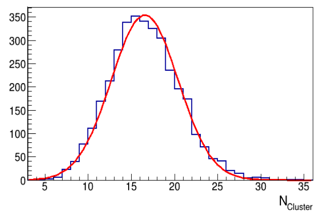
(for demonstration)

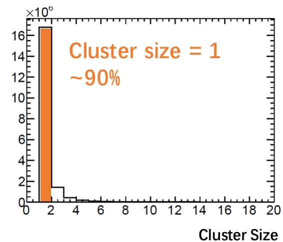
- **A charged particle losses energy when traversing a medium**

- **A sequence of primary interactions (clusters) along the track**
  - The # of clusters can be described by the Poisson distribution

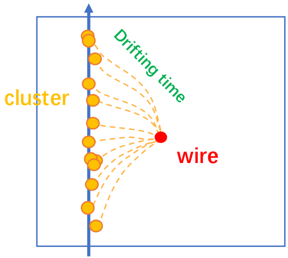
$$P\left(\bar{N}_p, k\right) = \frac{\bar{N}_p^{\,k}}{k!} e^{-\bar{N}_p}$$

- **For each cluster, one or more electrons are released**
  - Secondaries usually localized to the primaries
  - **Cluster size**: # of electrons for each cluster





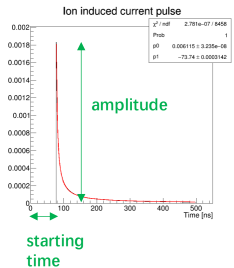
Principle of Ionization (II)



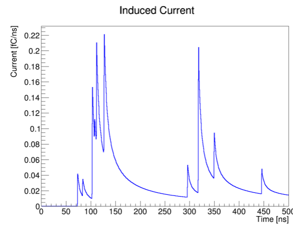
(for demonstration)

- **Electrons/ions drift in the fields**
- **Avalanche happens near the wire and signal is induced**
  - Each electron/ion pair produces a current pulse
    - The **amplitude** is proportional to the # of avalanche electrons
    - The **starting time** is almost determined by the **drifting time**
  - Induced current is further fed to the electronics system

Single Pulse



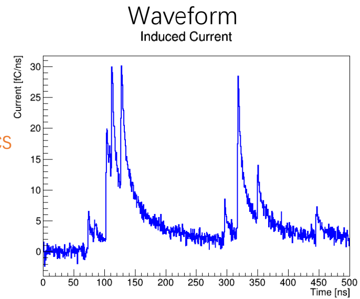
Full waveform of a cell

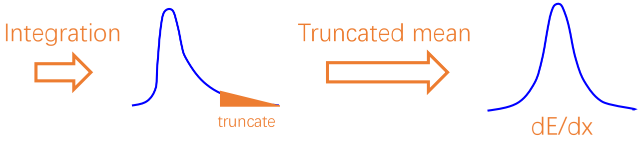


Electronics

Ionization Measurement: dE/dx

Electronics





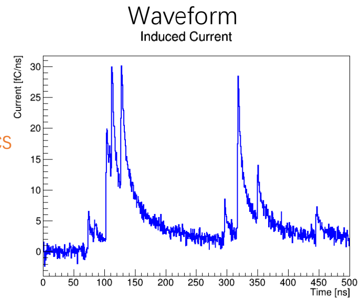
dE/dx measurement: integration of the waveform

- **Large fluctuation** from
  - Energy loss from all the processes (primary, secondary)
  - Amplification (avalanche)
- **Long tail** due to secondary electrons, usually use truncated mean for a better resolution
- A reference resolution (truth)*: **~3%** (20 GeV/c, pions, det. size=120 cm)

* https://indico.ihep.ac.cn/event/13181/session/0/contribution/7/material/slides/0.pdf

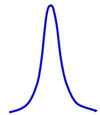
Ionization Measurement: dN/dx

Electronics



Cluster counting

dN/dx

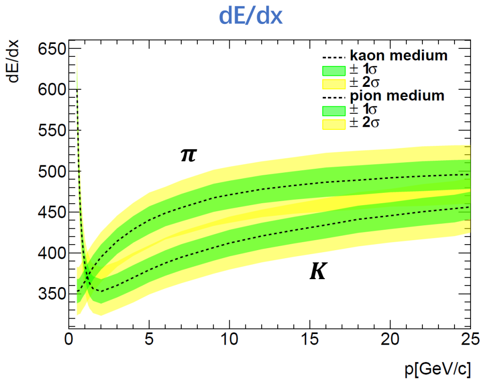


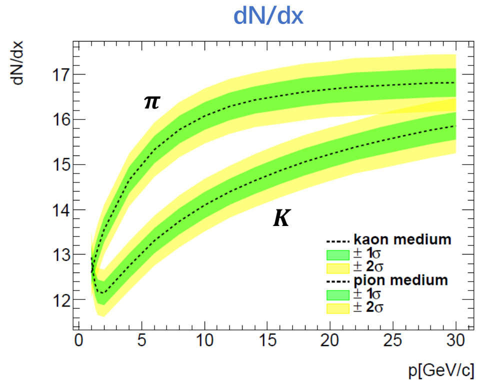
dN/dx measurement: counting the # of primaries

- **Small fluctuation** (only from the Poisson behavior of the primary ionizations)
- Easy to reach the **Gaussian** limit
- A reference resolution (truth)*: **<2%** (20 GeV/c, pions, det. size=120 cm)

* https://indico.ihep.ac.cn/event/13181/session/0/contribution/7/material/slides/0.pdf

dE/dx vs. dN/dx (MC truth)





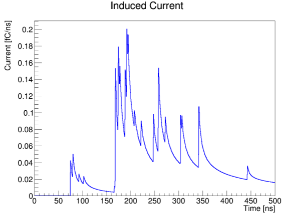
dN/dx measurement:

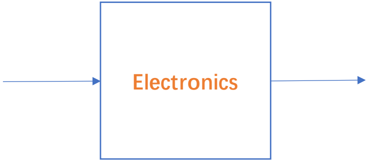
- More powerful for K/pi separation
- Technically challenging

Simulation

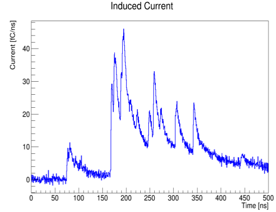
Simulation

Induced current





Realistic waveform



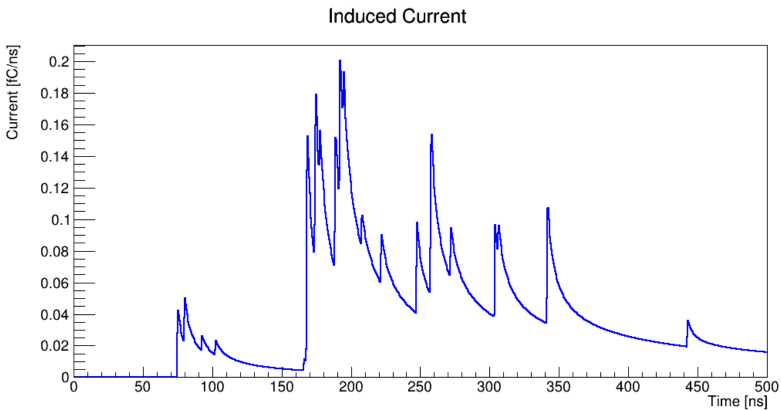
Counting

- **Garfield++**
  - Heed: ionization process
  - Magboltz: gas properties (drift/diffusion)
  - Signal generation

- **Preamplifier**
  - Impulse response
- **Noises**
  - Amplitude
- **ADC**
  - Sampling rate

Essential to simulate the distortion and interference of the signals

Induced Current Waveform



Gas composition: He 90% + iC_4H_{10} 10%

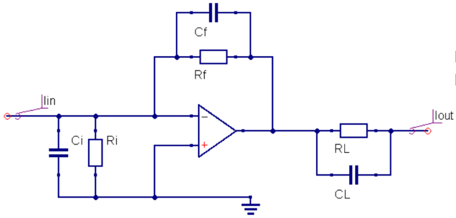
Cell size: 1x1 cm

Particle: 10 GeV/c pions, θ = 90 deg

Average N_{cl}: ~16.5

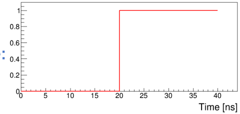
Electronics (I): Preamplifier

A simple current-sensitive preamplifier

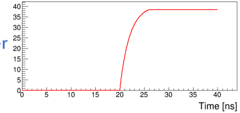


Time constants (τ) and risetime:

Step response:



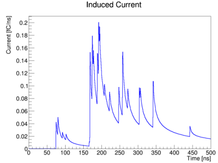
Response after preamplifier:



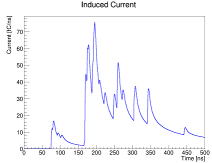
Time Constant (ns)	Risetime (ns)
0.5	0.95
1.0	1.85
2.0	3.70
3.0	5.50
4.0	7.35
5.0	9.20

Broaden of the waveforms with different time constants:

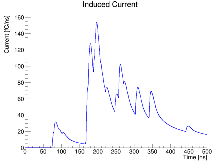
$\tau = 0\ ns$



$\tau = 2\ ns$

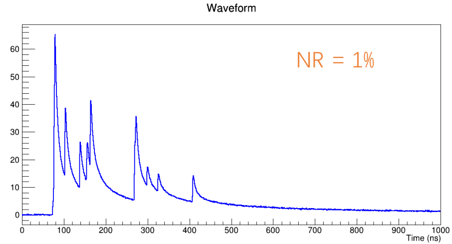


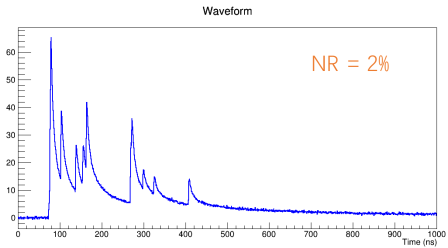
$\tau = 5\ ns$

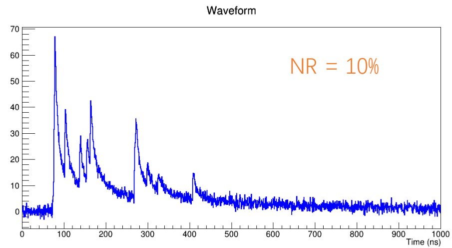


Electronics (II): Noises

- **Add white noises to the raw current signal**
- **Relative noise ratio (NR):** $\frac{\sigma_n}{S}$
  - σ_n: Standard deviation of noises
  - S: Average single pulse amplitude



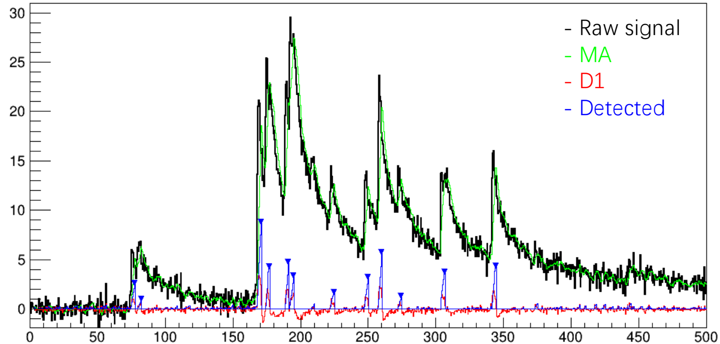




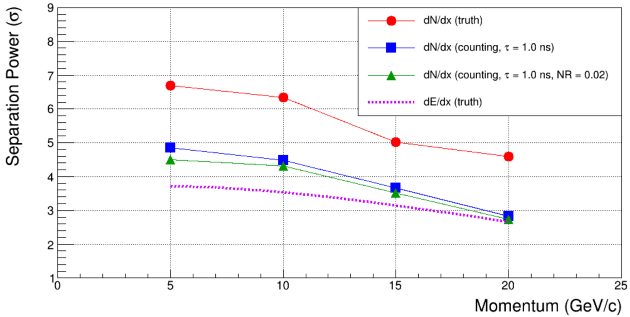
Cluster Counting Algorithm: MA + D1

- Moving average (MA) filter: $\mathbf{MA[i]} = \frac{1}{M} \times \sum_{k=0}^{K<M} S[i-k]$ (smoothing)
- First difference (D1) filter: D1[i] = MA[i] – MA[i – 1]

Induced Current



K/pi Separation Power (det. size = 150 cm)



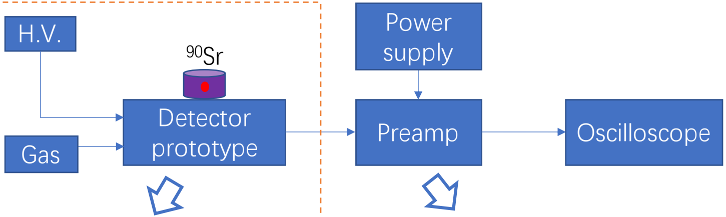
Separation power

$$\frac{\left|\left(\frac{dN}{dx}\right)_{\pi}-\left(\frac{dN}{dx}\right)_{K}\right|}{(\sigma_{\pi}+\sigma_{K})/2}$$

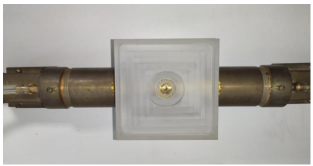
Can achieve ~3.5(2.5)σ K/pi separation power for p < 15(20) GeV/c

Prototype Experiment

Prototype Experiment Setup



Sr Source

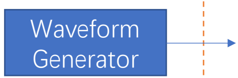


- ✓ Proportional tube (φ32mm)
- ✓ Gas: 80% He + 20% iC_4H_{10}

OR

Generator

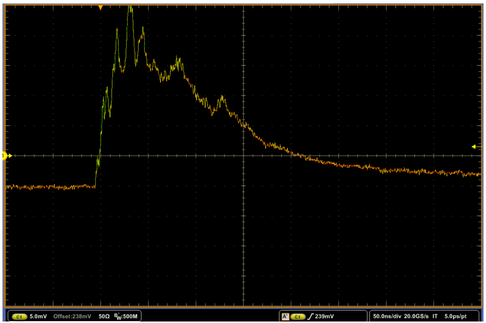
Pulse or rectangular waveform



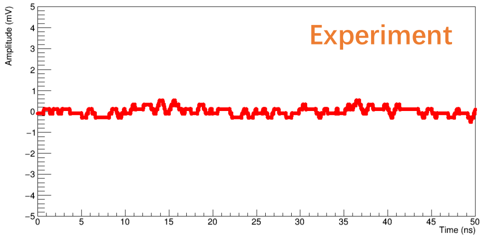
- ✓ **Pre-amplifier: LMH5401 evaluation module**
- ✓ Gain bandwidth product (GBP): 8 GHz
- ✓ Gain : 12 dB (4 V-V)
- ✓ R_f: 127 Ω

Waveform Examples (Sr Source)

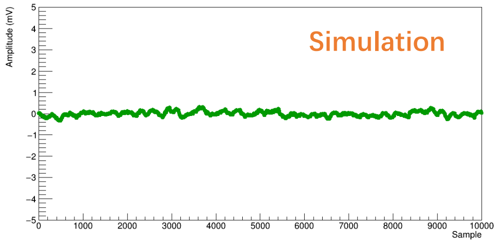
- **Can observe peaks with fast rising edges in the waveforms**
- **Small-gain signal and low noise**
  - Signal amplitude: ~10^{1} mV (max. peak)
  - Noise amplitude: ~10^{-1} mV (sigma)



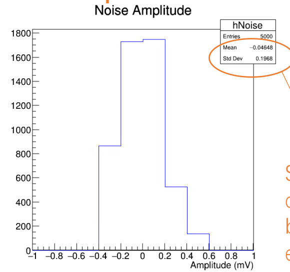
Noise generation



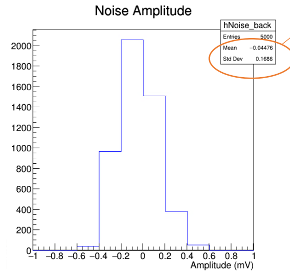
FFT Analysis



Experiment



Simulation

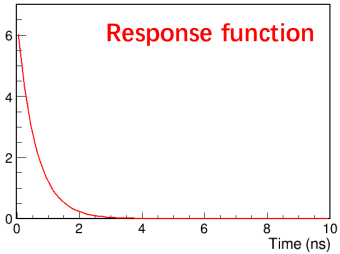


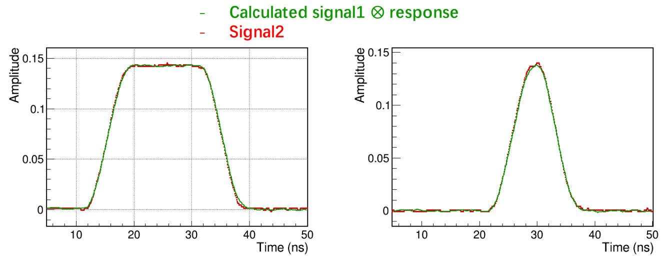
Similar distribution between experiment and simulation

(Bin size is limited by the measurement precision)

Response function extraction (preliminary)

$$\text{Signal1} \otimes \text{Response} = \text{Signal2}$$





Extracted pre-amplifier response:

- Time constant ~0.6 ns (assume an exponential form)
- Risetime ~ 1ns: comparable with our previous simulation

Checks:

- Check the response function by convoluting to the signal w/o pre-amp.
- Show good consistency for different signal types

Summary

- **A simulation framework for cluster counting is ready**

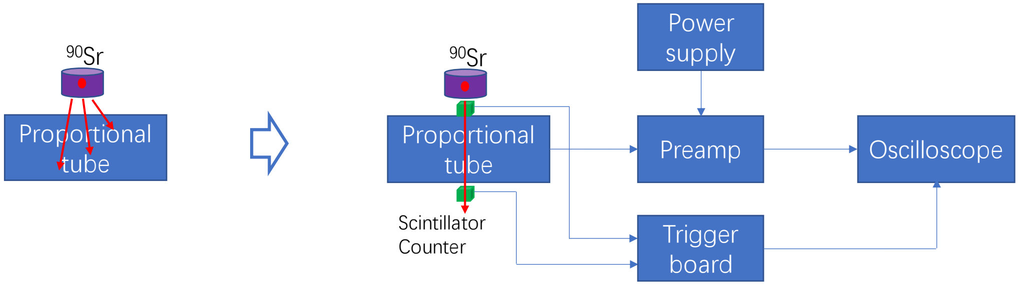
- **Preliminary PID performance with baseline configuration is obtained**
  - det. size = 150 cm: ~3.5(2.5)σ K/pi separation is achievable for $p < 15$ (20) GeV/c

- **Initial prototype experiments are setup. The following information is extracted:**
  - Electronics noises
  - Response of the preamplifier (preliminary)

- **Next to do**
  - Optimizations
    - Detector design: layout, cell, gas, …
    - Electronics: tuning parameters based on experiments
    - Reconstruction: counting algorithm, corrections/calibrations
  - Experiment with trigger

Thank you!

Plan: Prototype experiment with collimation



- **Constrain the entrance angle and track length of the emitted electrons from the Sr source**
  - Two scintillator counters with small active area will be used to provide trigger signals
- **Tune the gain of the preamplifier**