Multi-purpose Time Projection Chamber (MTPC) Signal Simulation Method and Experimental Verification

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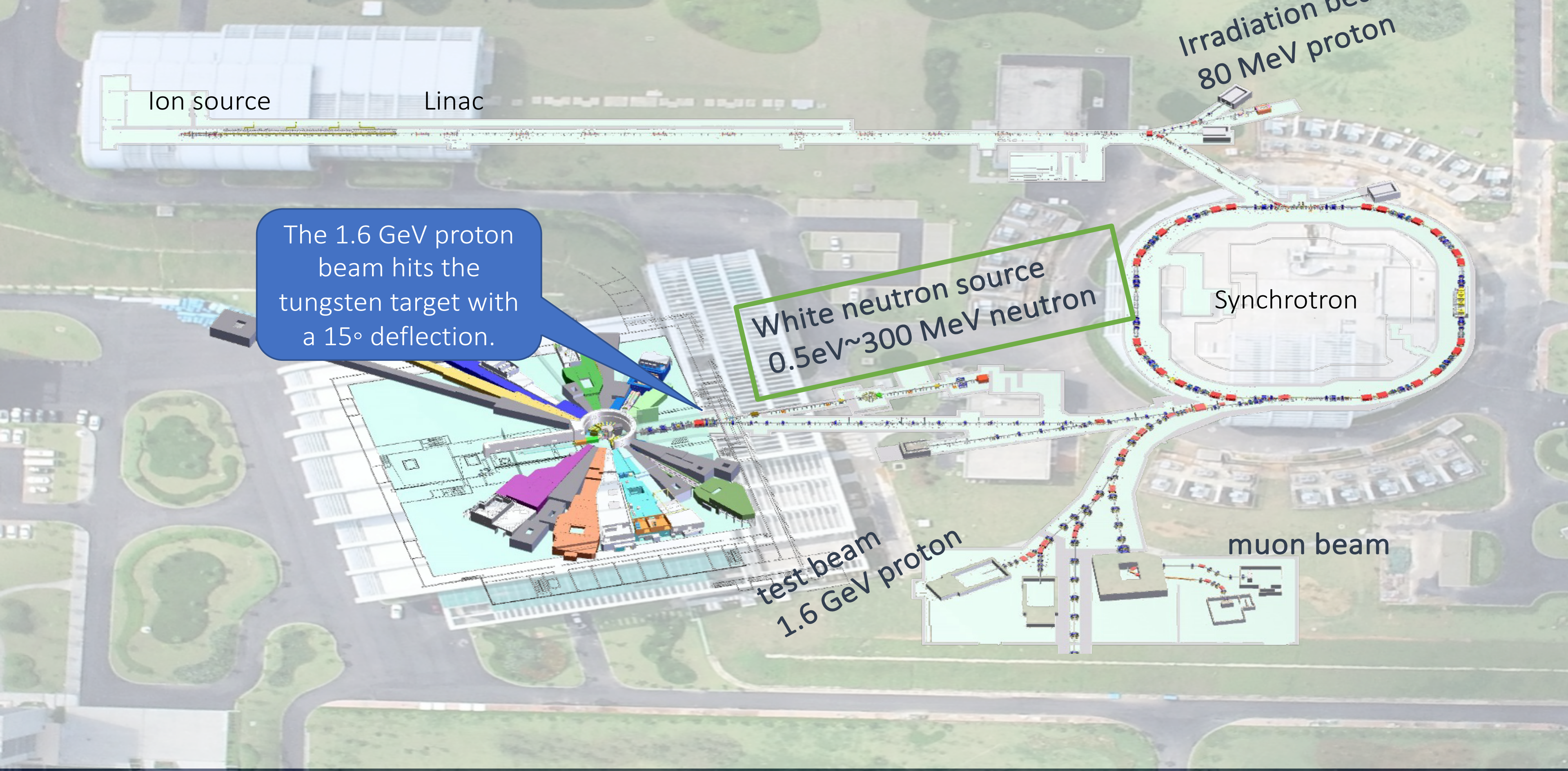
The 31st International Seminar on Interaction of Neutrons with Nuclei (ISINN), Dongguan, China

MTPC System

MTPC
Multi-purpose TPC

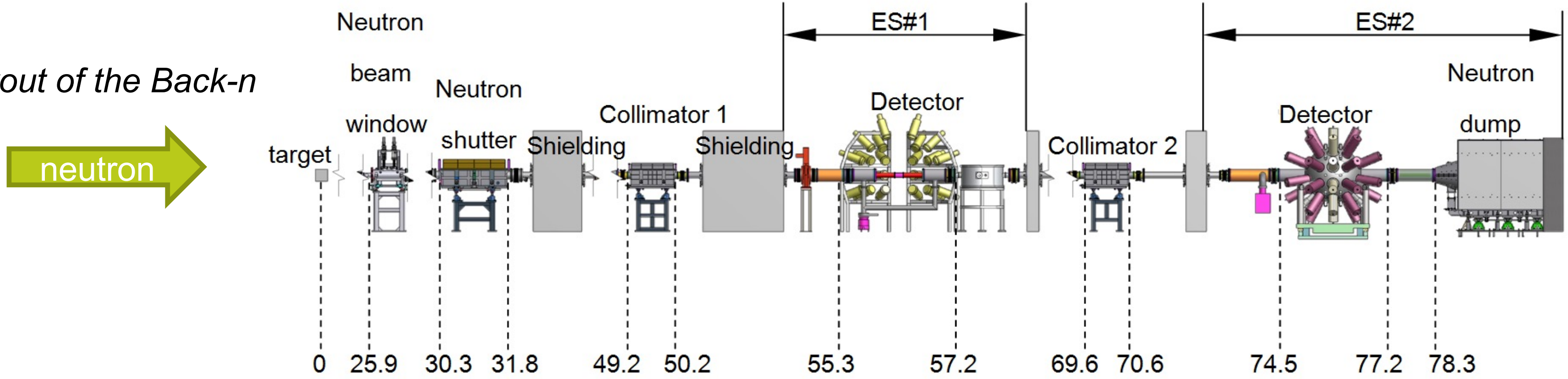
- **Introduction**
  - CSNS, Back-n white neutron source, Project history, Software framework
- **Simulation method**
  - Detector construction, Ionization, Electron drift and avalanche, Electronics response
- **Experimental verification**
  - Experimental setup, Timing verification, Energy response verification
- **Summary**

CSNS beam expansion application



Back-n white neutron source

Layout of the Back-n



Shutter (mm)	Coll#1 (mm)	Coll#2 (mm)	ES#1 spot (mm)	ES#1 flux ($n/cm^2/s$)	ES#2 spot (mm)	ES#2 flux ($n/cm^2/s$)
Φ3	Φ15	Φ40	Φ15	1.27E5	Φ20	4.58E4
Φ12	Φ15	Φ40	Φ20	2.20E6	Φ30	7.81E5
Φ50	Φ50	Φ58	Φ50	4.33E7	Φ60	1.36E7
78×62	76×76	90×90	75×50	5.98E7	90×90	2.18E7

Now the power increases to 170kW

- Back-n is the first white neutron beamline with wide energy range and high flux intensity in China
- Energy range: thermal neutron-300MeV
- Flux intensity: $10^7/cm^2/s$
- Research on neutron nuclear data measurement:
  - Total cross section
  - Fission cross section
  - Neutron capture cross section

Project history

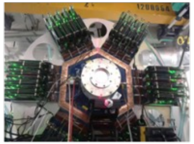
MTPC
Multi-purpose TPC

2019.8:
TPC design and processing

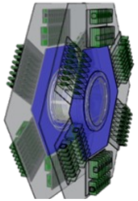
2019.12:
Build v1 detector and develop DAQ

2021.1:
Build dedicated electronics

2021.02:
Conduct beamline test

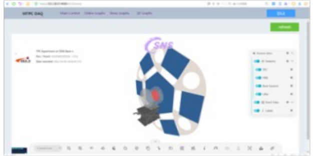


2021.4:
Release simulation and analysis program



2021.8:
Build v2 detector structure

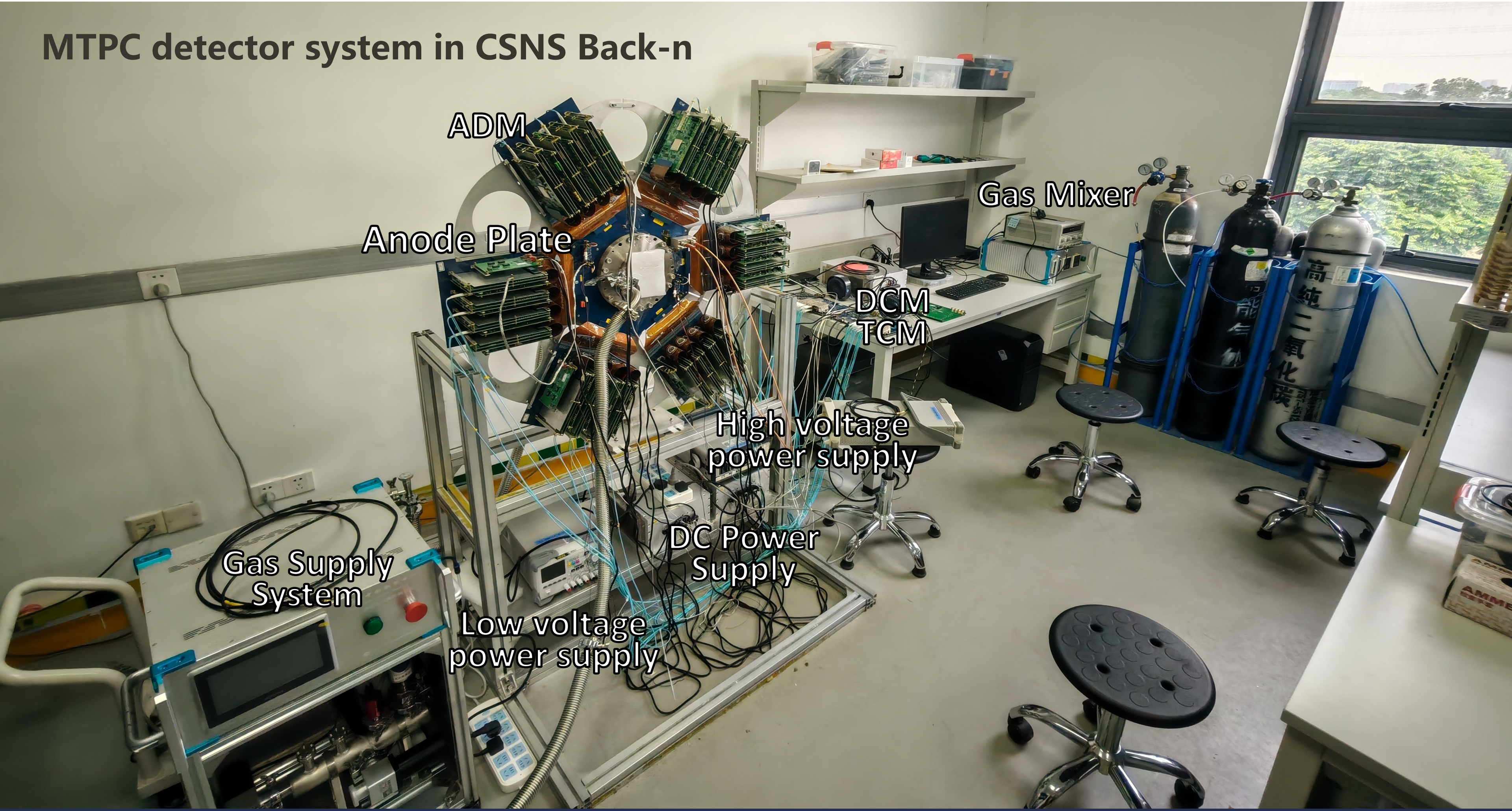
2022.3:
Develop v2 DAQ and online display



2023.2:
Start the first experiment

2025.4:
Complete the simulation and analysis framework

MTPC detector system in CSNS Back-n



BLUET: A simulation and analysis library

BluetConfigFile.xml

- Run mode
- Simulation
  - Gas
  - Detector
  - Sample
  - Electronics
  - Event Generator
  - Others
- Analysis
  - Binary conversion
  - Cut Parameters
  - Wave Fit
  - Track
  - Event Reconstruct

temp_env.xml

- <bluet_config>
- <bluet_rawdata>
- <bluet_eventdata>
- <bluet_rootdata>
- <bluet_simdata>

Bluet Core:

- Environment config
- RunningMode config
- ConfigFile reading
- Modules loading

config:

- BluetConfig.hh
- BluetDataModel.hh
- BluetDeconvolution.hh
- BluetFourierFilter.hh
- BluetHough.hh
- BluetHough3D.hh
- BluetPointCloud.hh
- BluetSNChecker.hh
- BluetSphere.hh
- BluetVector.hh
- BluetVector3d.hh
- BluetWaveFit.hh
- BluetWaveformMaster.hh

custom:

- BluetCustom.hh

modules:

- BluetDrawLinkDef.hh
- BluetLab.hh
- BluetMap.hh
- BluetProgram.hh
- DrawEvent.hh
- DrawWave.hh
- Factory.hh
- GenGasFile.hh
- Raw2RootMTPC.hh
- ReadGasFile.hh

utils:

- BluetModule.hh
- clipp.h
- pugiconfig.hpp
- pugixml.hpp
- stringhandle.hh
- xmlparse.hh

runner:

- BluetActionInitialization.hh
- BluetChamberHit.hh
- BluetChamberSD.hh
- BluetChargeMaster.hh
- BluetDetectorConstruction.hh
- BluetElectronDriftAction.hh
- BluetElectronics.hh
- BluetEventAction.hh
- BluetNoise.hh
- BluetOutput.hh
- BluetPadMaster.hh
- BluetPhysicsList.hh
- BluetPrimaryGeneratorAction.hh
- BluetRunAction.hh
- BluetTrackMaster.hh

BLUET
bloom through the time

Prerequisites:

- C++ compiler; Fortran compiler; ROOT 6; GSL; Geant4; Garfield++; fmt; eigen3.

> https://code.ihep.ac.cn/csns-backn-tpc/bluet-v5 (Open Source)

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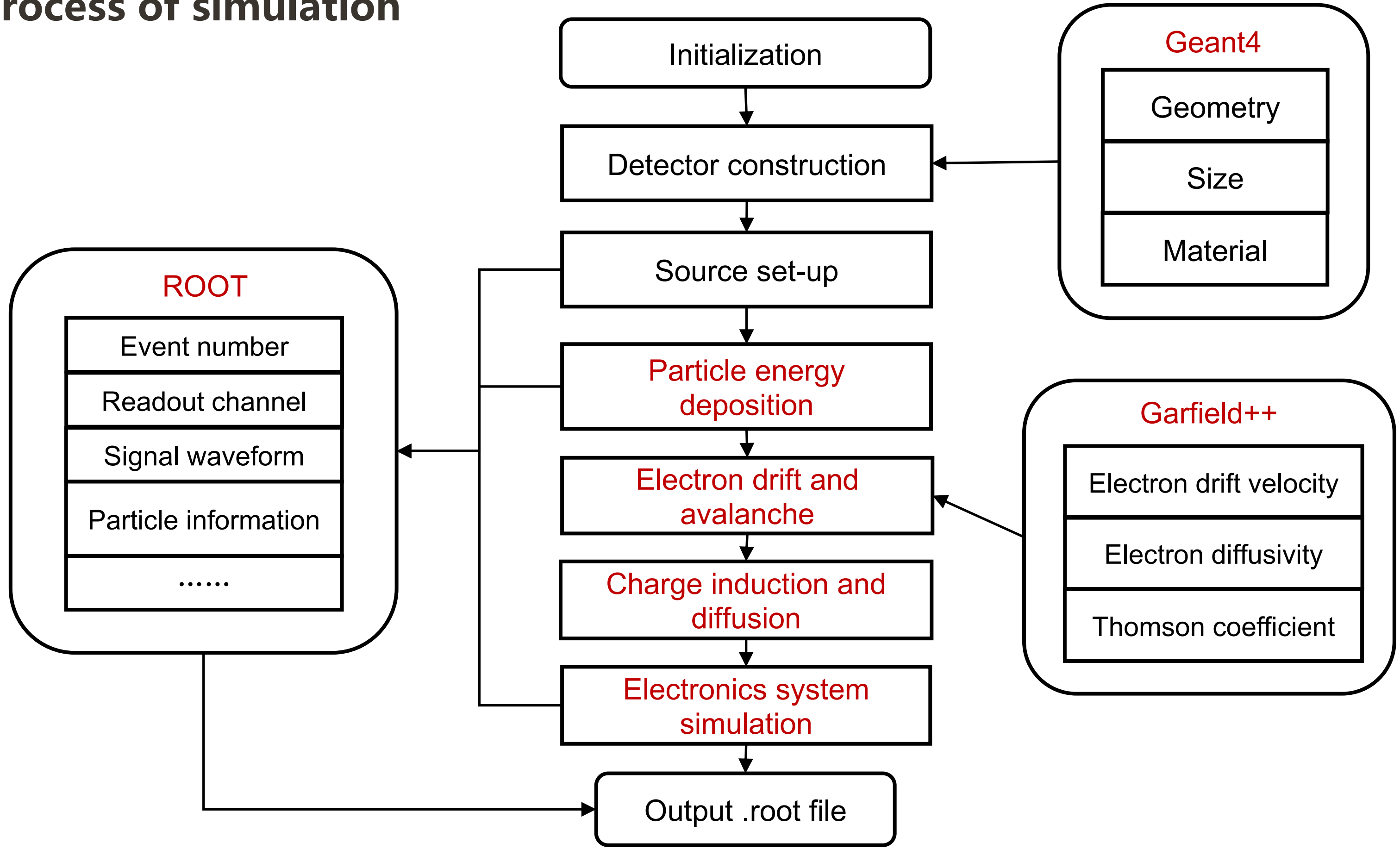
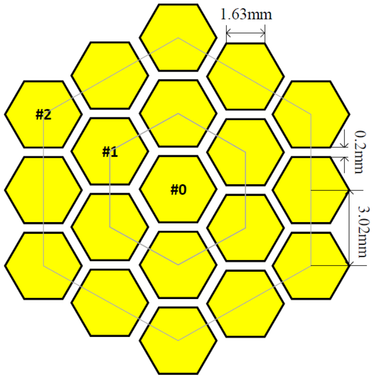
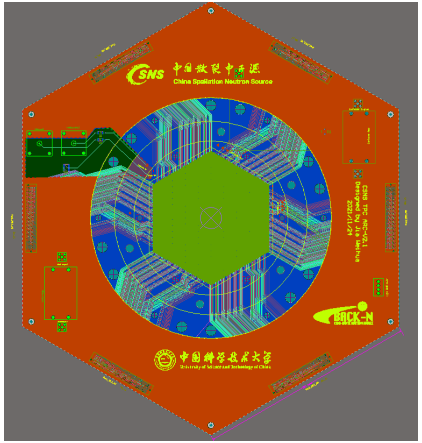
The process of simulation

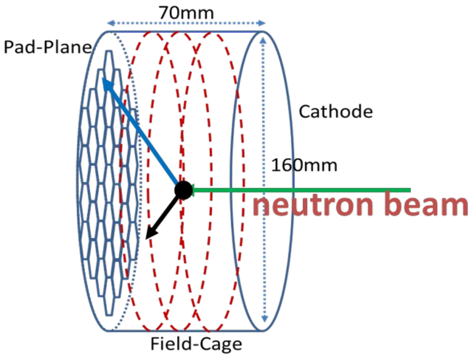


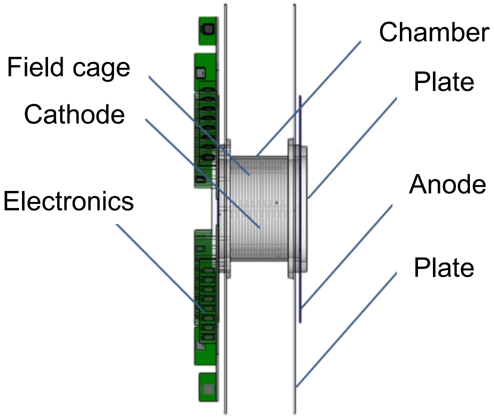
Detector structure

- The shape of chamber is cylinder
- The drift distance is adjustable to meet different experimental requirements
- The Micromegas structure[1] is used between Mesh and Anode to amplify signals
- The readout array uses a hexagonal dense stacking structure
- There are 1519 anode pads, each with a side length of 64 mil
- The anode area is a hexagon with a side length of 68 mm



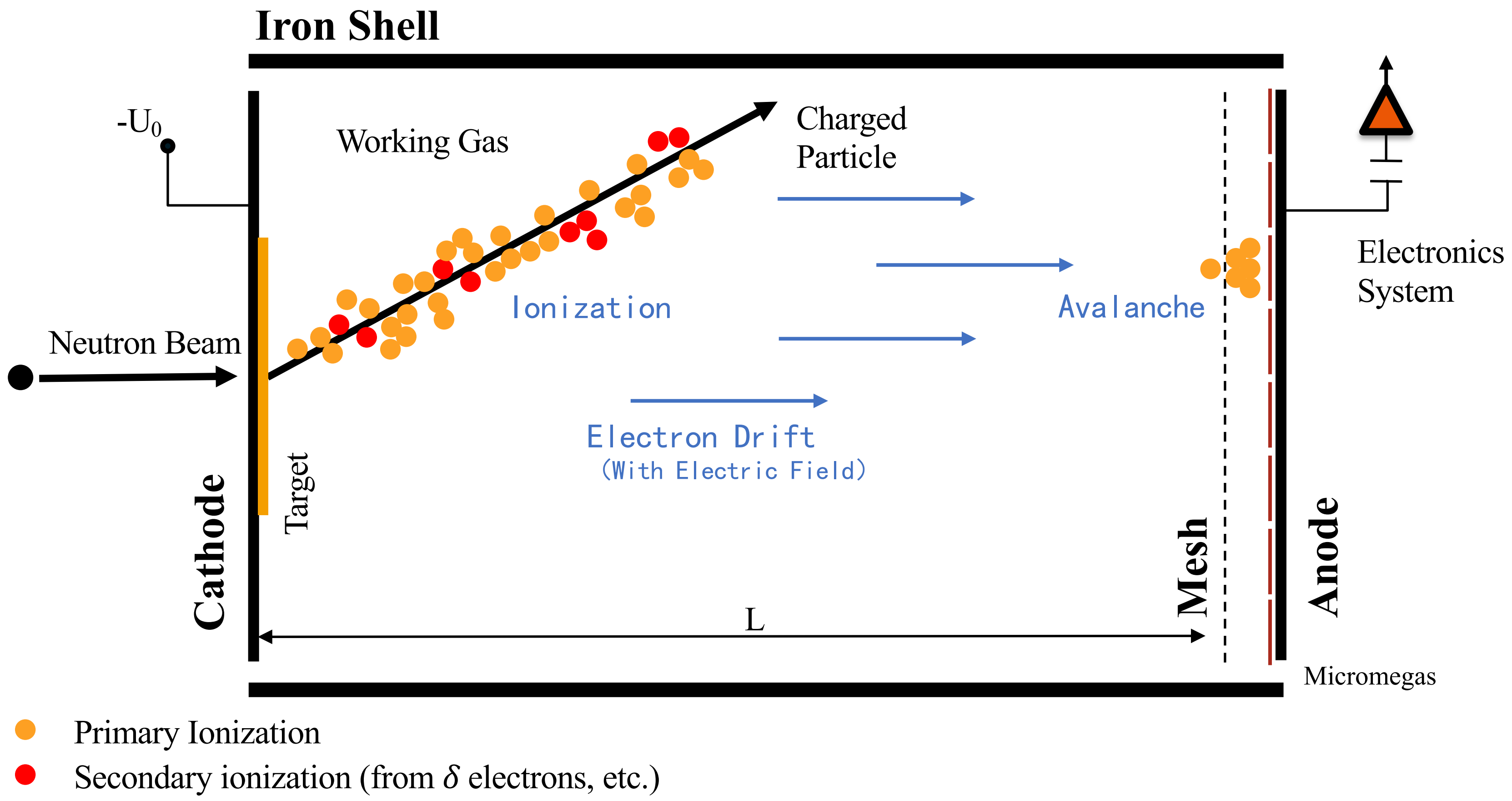






[1] Weihua Jia, You Lv, Zhiyong Zhang et al. Gap uniformity study of a resistive Micromegas for the Multi-purpose Time Projection Chamber (MTPC) at Back-n white neutron source. NIMA, 1039, 2022.

Ionization, electron drift and avalanche

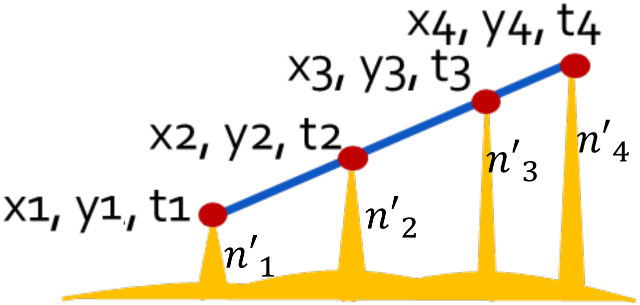


Particle ionization process

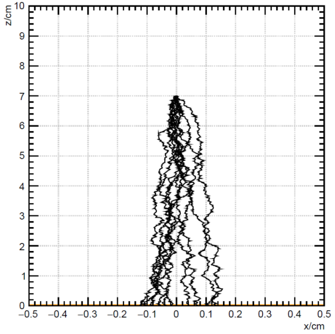
- Geant4 is used here to get the distribution of energy deposition

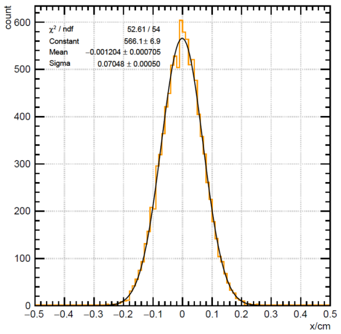
> G4double edep = step->GetTotalEnergyDeposit() - step->GetNonIonizingEnergyDeposit()

- The number of ionized electrons generated by each hit $n = E_{dep}/I$
- The actual number of ionized electrons for each hit is obtained by approximate random sampling according to the Poisson distribution with a mean of n, $n' = P(n)$
- For n' electrons, diffuse sampling is performed on each electron separately to obtain the final drift position and drift time of each electron

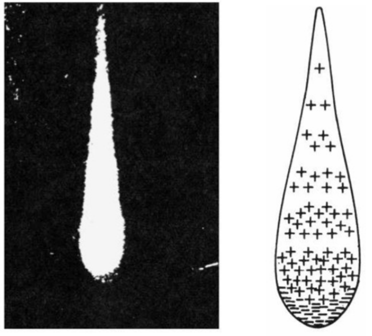


Electron drift and avalanche





- Garfield++ is used to simulate transport parameters.
- Horizontal diffusion: $\sigma_T = \sqrt{d_t z}$
- Vertical diffusion: $\sigma'_L = \sigma_L / v = \sqrt{d_l z} / v$



Thomson avalanche model

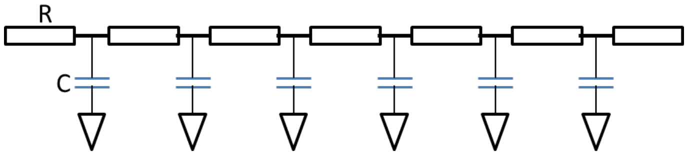
- According to the gas avalanche theory, the number of electrons after the avalanche at low gain:

$$G = \frac{n}{n_0} = e^{\alpha x}$$

- Assume that there is no spatial diffusion after the electron avalanche, and the coordinates are the same as the original electrons.

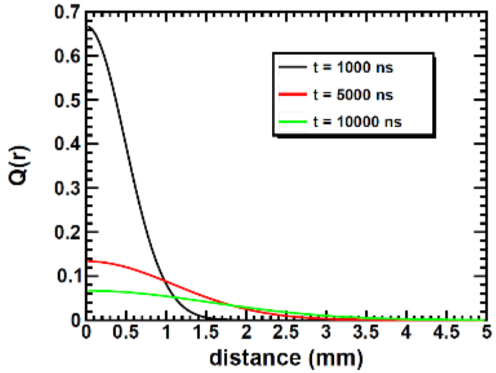
Charge dispersion in the resistive Ge-layer

- The charges generated by the avalanche are deposited on the resistive germanium layer and disperses to the surrounding area.
- The signals with small amplitude and shorter rising time are also generated on the pad near the center of the avalanche.
- The signals generated by the charge diffusion depend on the surface resistance of the resistive layer and the coupling capacitance between the resistive layer and the pad layer.



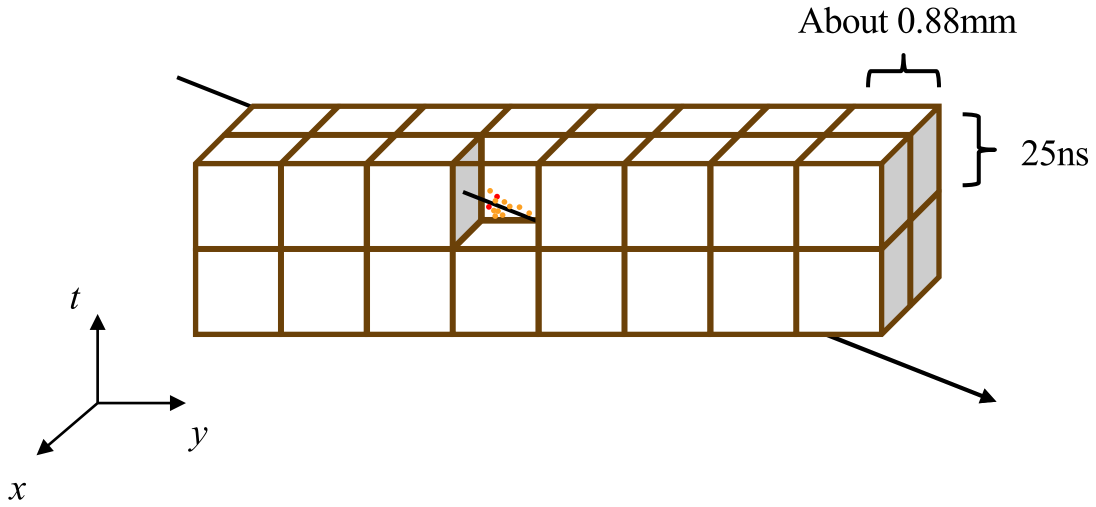
$$\rho(x,y,t) = \frac{RC}{4\pi t} e^{-RC(x^2+y^2)/4t}$$

- Charge dispersion is Gaussian, $\sigma = \sqrt{\frac{2t}{RC}}$
- As time increases, σ increases



Charge unit division

- The time required for electrons to reach the anode is called "Drift time t";
- The coordinates of the electrons reaching the anode after drift diffusion are (x, y);
- (x, y, t) is divided into units, and the center of each unit is taken to calculate.



Dispersion integral algorithm

- X and y are independent of each other in the dispersion function:

$$f(x,y,t)=\frac{\tau}{4\pi t}e^{-\tau(x^2+y^2)/4t}$$

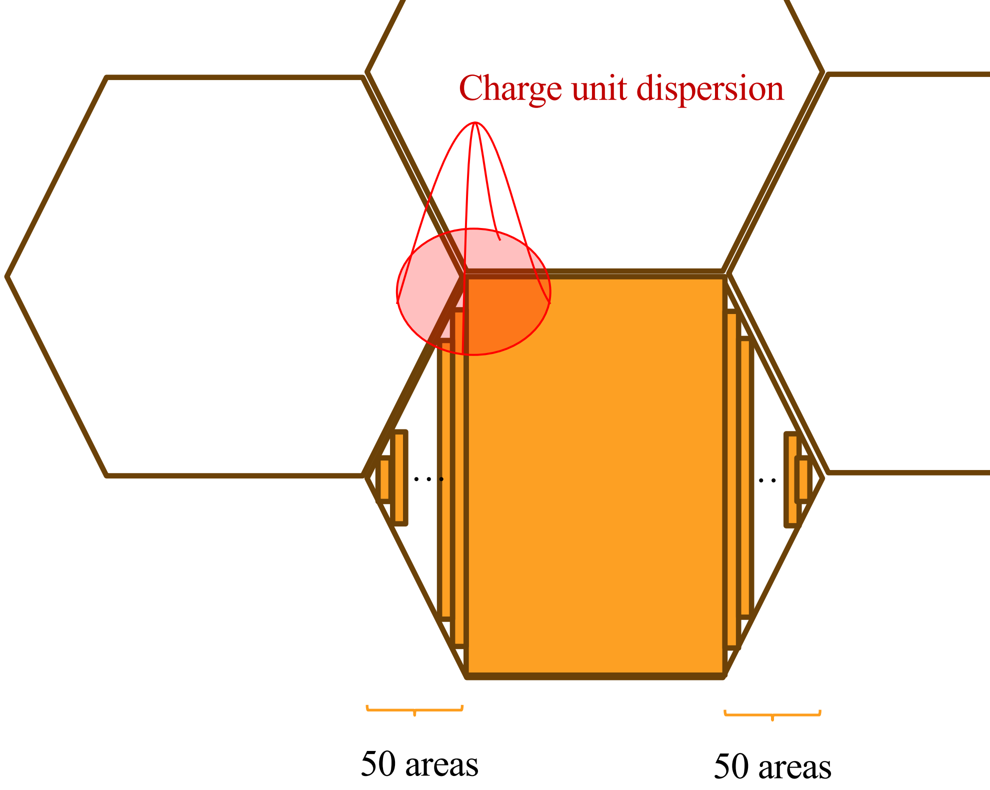
- The one-dimensional distribution after coordinate translation and splitting is:

$$f(x,t)=\sqrt{\frac{\tau}{4\pi t}}e^{-\tau(x-\mu)^2/4t}$$

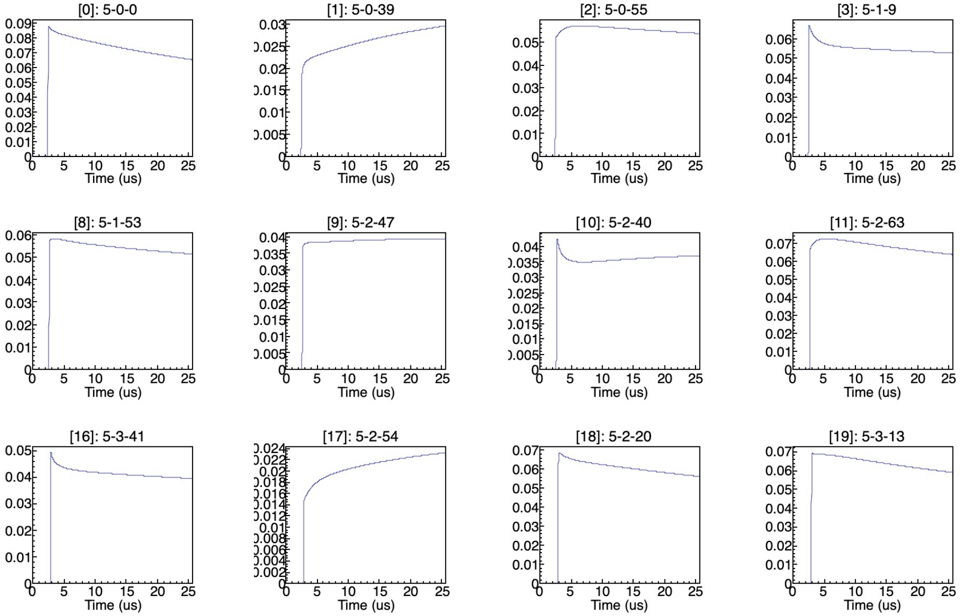
- The integral of any interval [a, b) is

$$F(b)-F(a)=\frac{1}{2}\left(\operatorname{erf}\frac{b-x_0}{2\sqrt{t/\tau}}-\operatorname{erf}\frac{a-x_0}{2\sqrt{t/\tau}}\right)$$

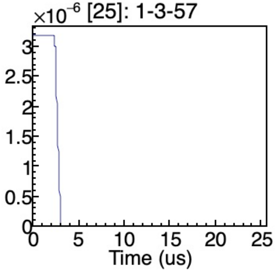
- Divide a Pad into (100+1) intervals for integration, as shown in the right figure.



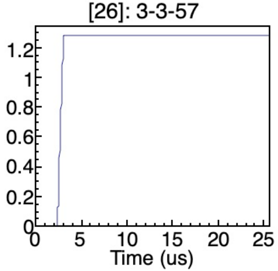
Original signals



Pad

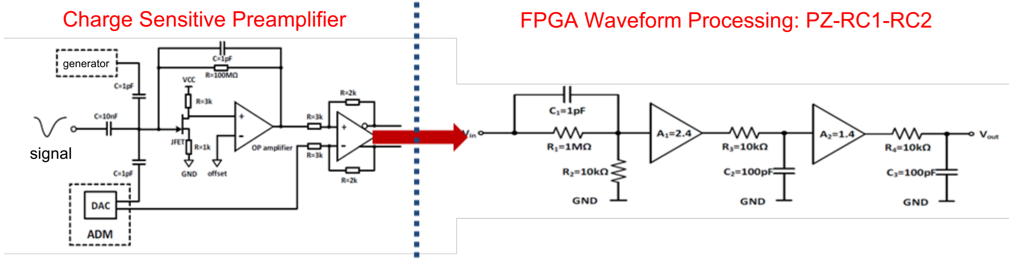


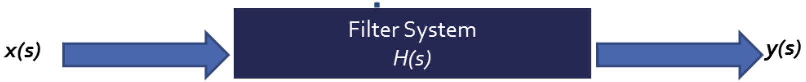
Cathode



Mesh

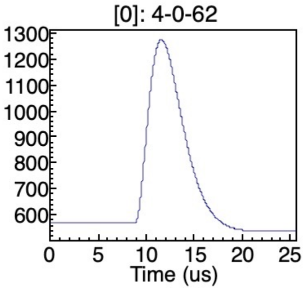
Electronics signal convolution

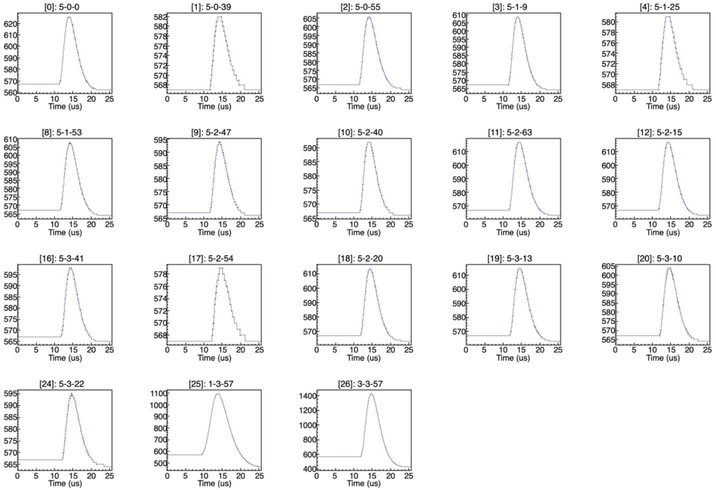




$$\boldsymbol{y(s) = H(s)x(s)}$$

The electronic system's response function was characterized under controlled laboratory conditions.





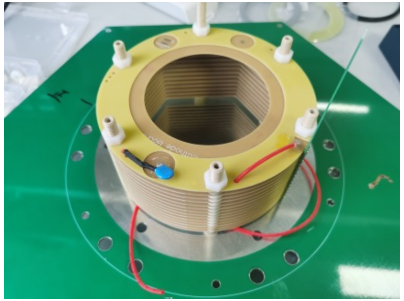
- **Q(t) is used as input signal：**
- Pre-amplifier： $H(t) = 1/C_0(-\frac{e^{-\frac{t}{\tau_0}}}{\tau_0} + \frac{e^{-\frac{t}{\tau_r}}}{\tau_r})$
  - $\tau_0 = RC$， integration time； τ_r signal rising time.
- PZ： $H(t) = \delta(t) + 1/\tau_0(1 - \frac{\tau_0}{\tau_1})e^{-t/\tau_1}$
  - $\tau_1 = R_2C_1$
- RC： $H(t) = 1/\tau_1 e^{-1/\tau_1}$

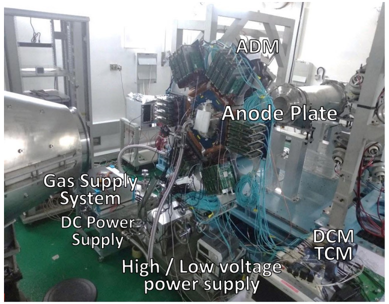
MTPC System

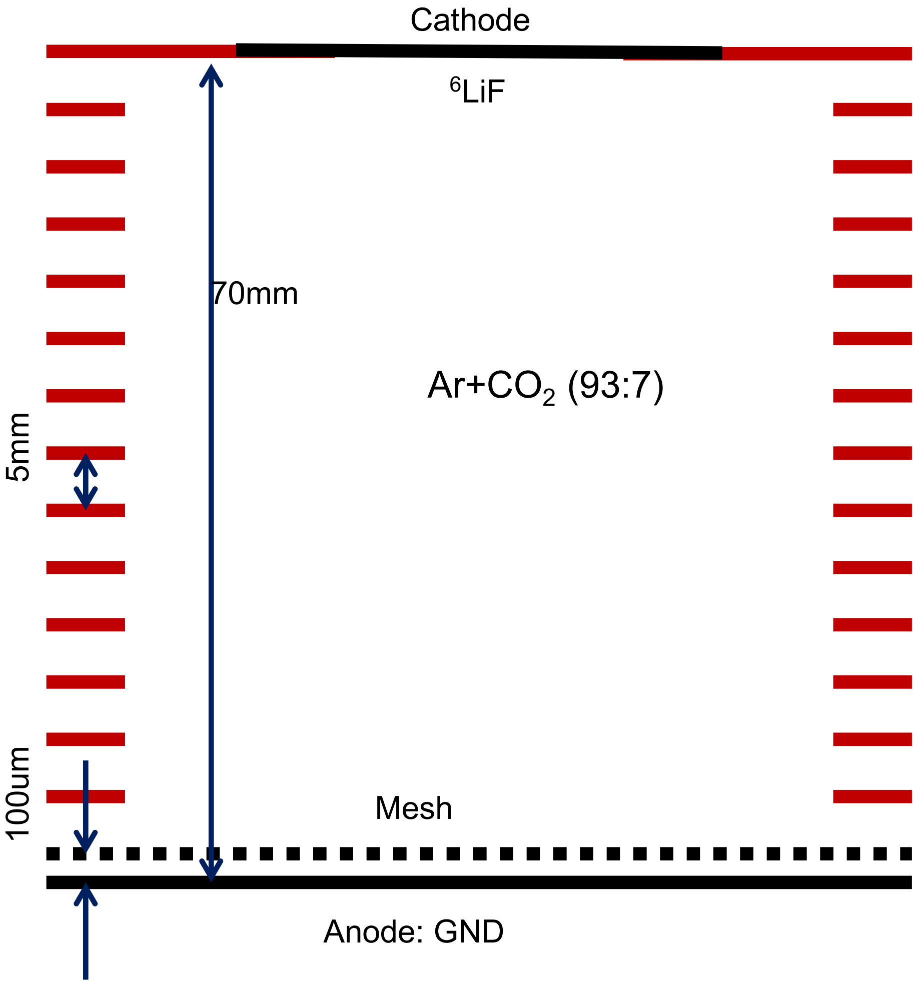
MTPC
Multi-purpose TPC

$^{6}Li(n,t)^{4}He$ (Feb. 2023)

- Neutron energy range: 1eV-500keV
  - 0.9 bar pressure: measure triton particles (133h)
  - 0.5 bar pressure: measure alpha particles (143h)
- Drift distance is 70mm, ^{6}LiF sample placed in the cathode center
- Sample parameters:
  - Thickness 560nm, ^{6}Li abundance 95%, ^{6}LiF surface density 148ug/cm^2, diameter 66mm
  - Al plate diameter 89mm, thickness 10.8um







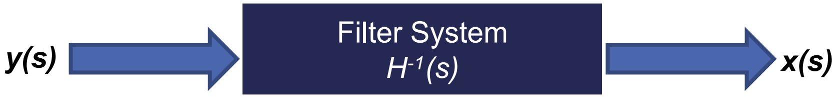
Waveform timing algorithm

The starting time of signal can be used to get the particle z-position and neutron energy.

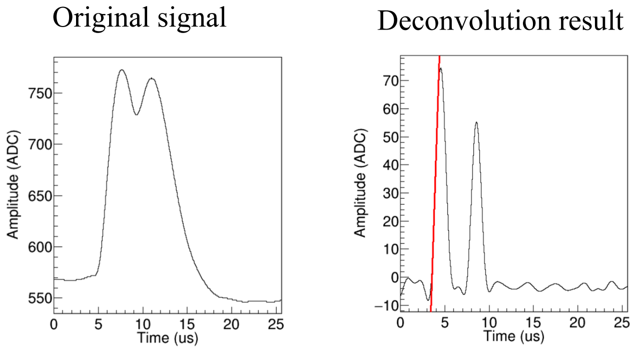
Method 1: Waveform Fitting Algorithm

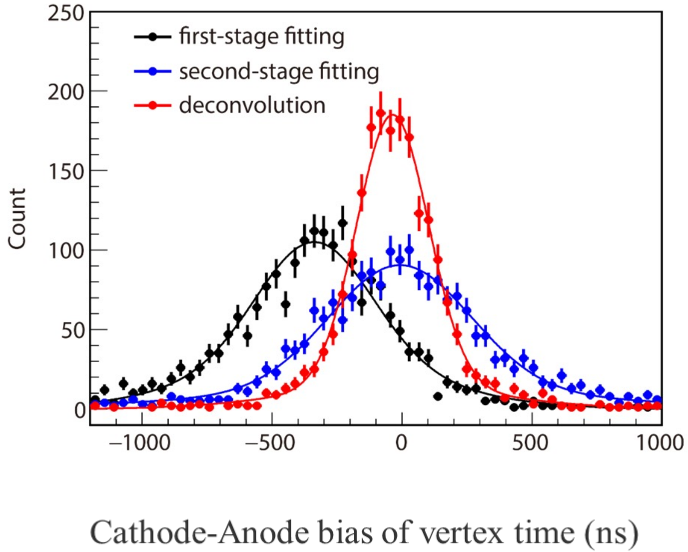
- Electronic Transfer Function: $f(t) = B + A\left(\frac{t-t_0}{\tau}\right)^n e^{-(t-t_0)/\tau}$
- Set n=2 for fitting. As the original waveform width w increases, the starting timing of the fitting will be delayed.

Method 2: Waveform Deconvolution Algorithm



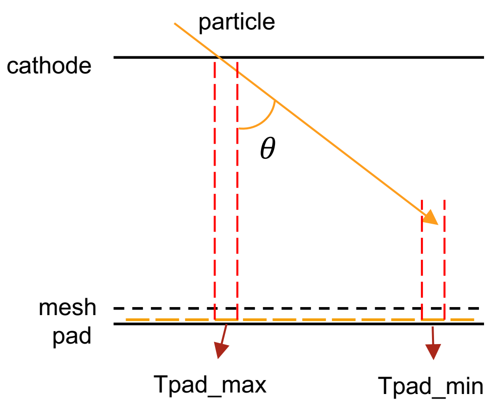
$$\boldsymbol{x}(s) = \boldsymbol{H}^{-1}(s)\boldsymbol{y}(s)$$

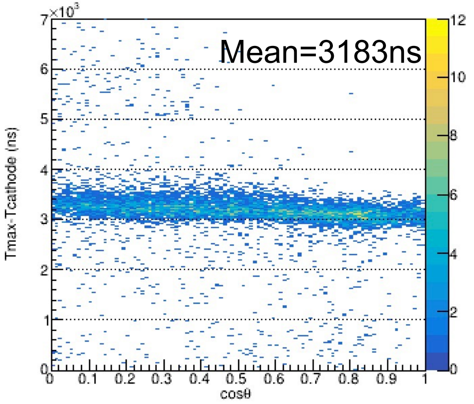




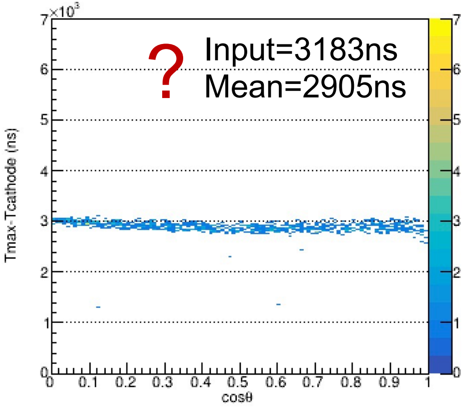
Waveform timing verification

- (Tpad_max-Tcath) is used to get the maximum value of drift time
  - Tpad_max is the maximum drift time for the farthest electron cloud (from cathode) to reach the anode mesh
  - Tcath represents the time instant of charged particle incidence on the cathode.
- Garfield++ simulation result is 3083ns, less than the experimental result.
- The simulation timing result is smaller than the input, which is not as expected.



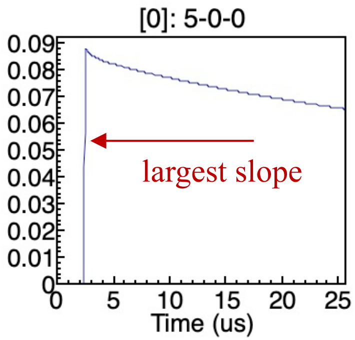


Experimental result



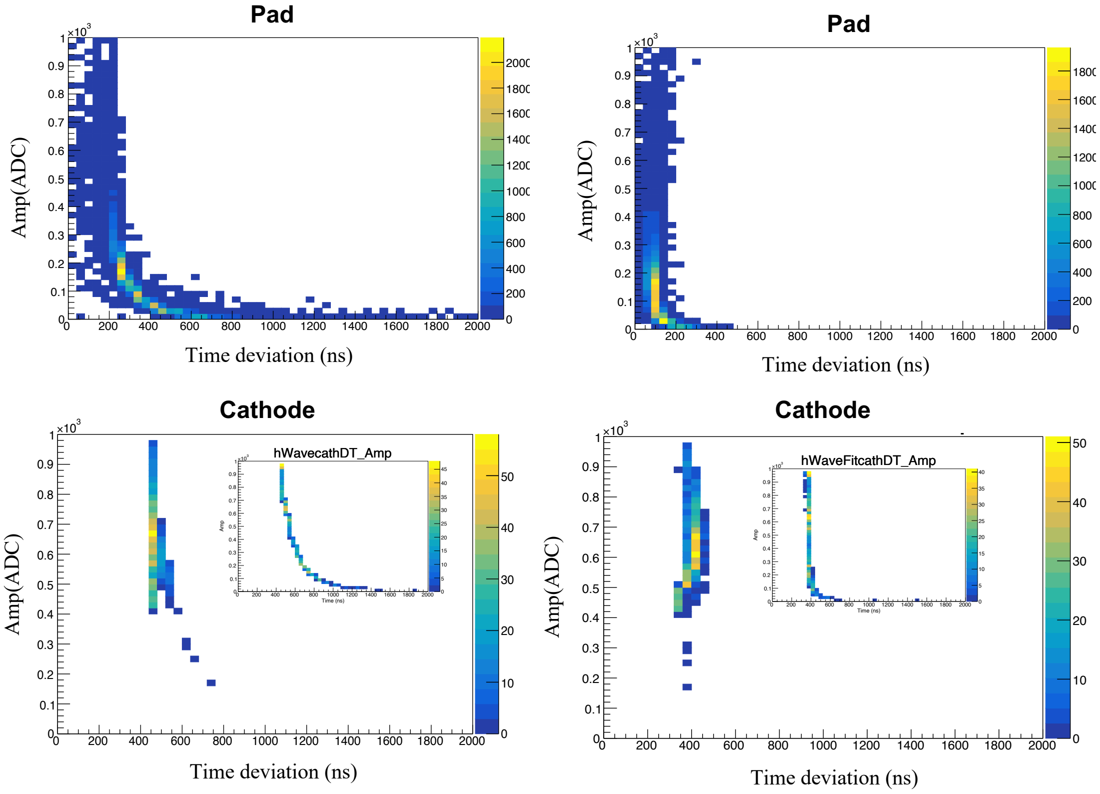
Simulation result

Relationship between time deviation and amplitude



Original signal

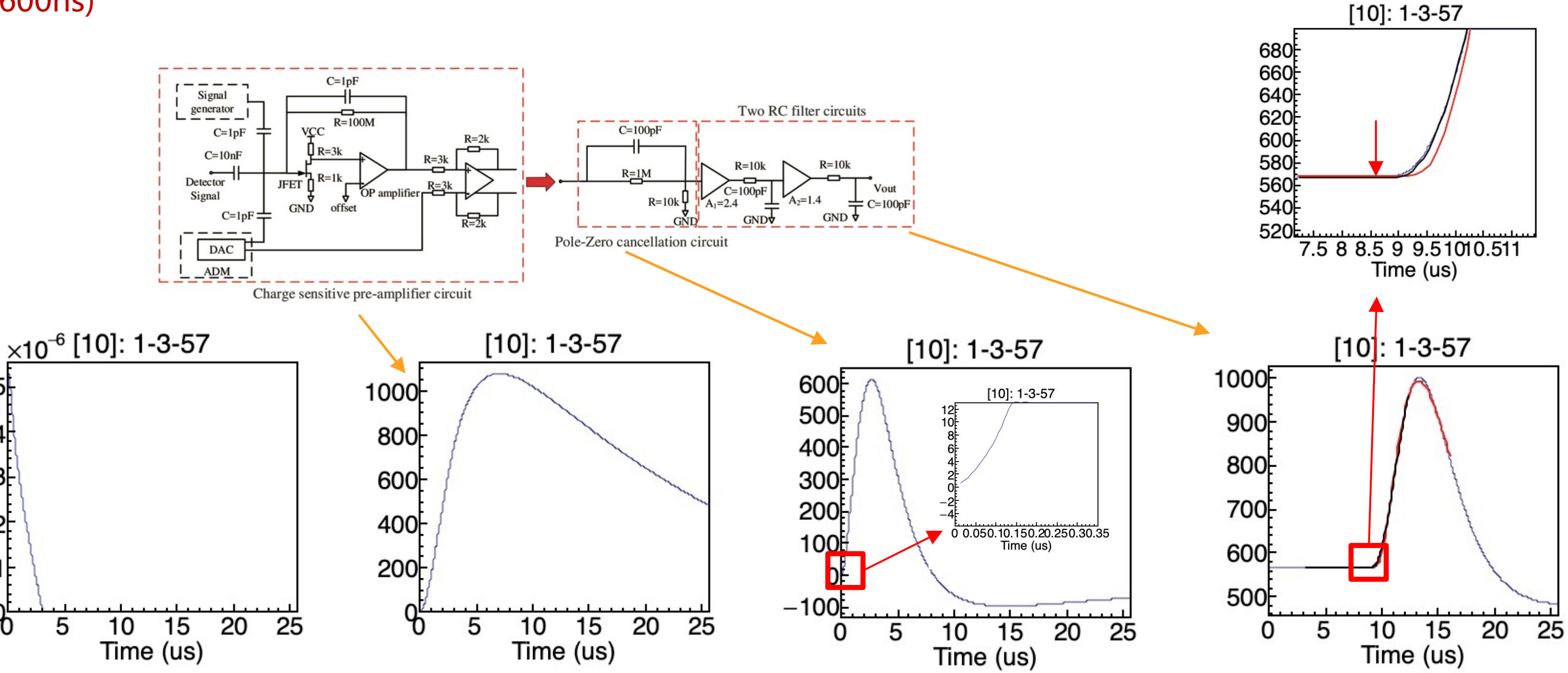
- Use the maximum slope of the original charge signal as the time comparison.
- The smaller the amplitude, the greater the deviation.
- Fitting can reduce the deviation.
- The results show that the information on the rising edge of the signal is lost.



Timing with amp > 0 **Timing with fitting algorithm**

Electronics system deviation

- It is found that the main factor of timing deviation lies in the two RC filter circuits (The theoretical result is 8600ns)



Current Signal

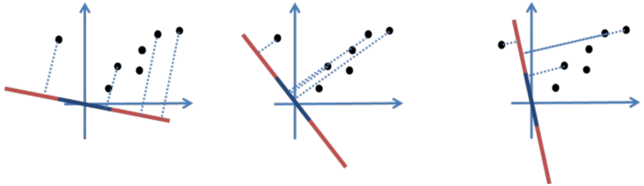
Preamplifier signal

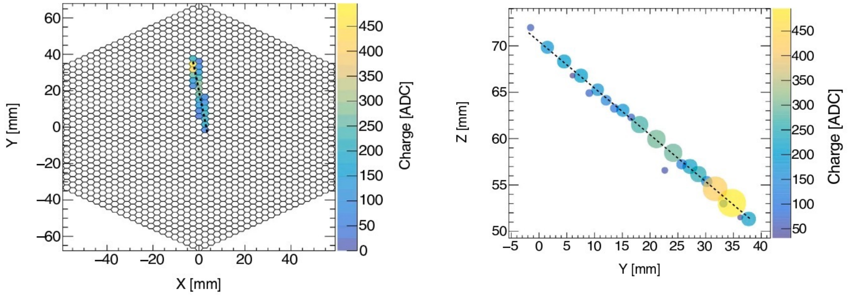
Pole-Zero signal

Output signal

Range-amplitude verification

- Track search:
  - Find the maximum value in Hough space, and the points falling in the maximum value bin are considered to belong to a straight line;
- Track length:
  - Project the reconstructed track to the track direction to obtain the dE/dx distribution
  - Use the KDE algorithm to smooth the dE/dx distribution
  - Take the particle range from the starting point of the track to the point corresponding to Qmax/λ, λ=2

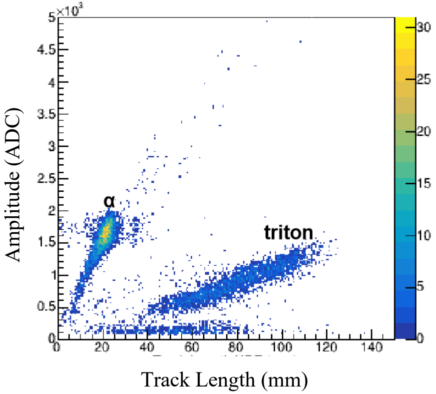




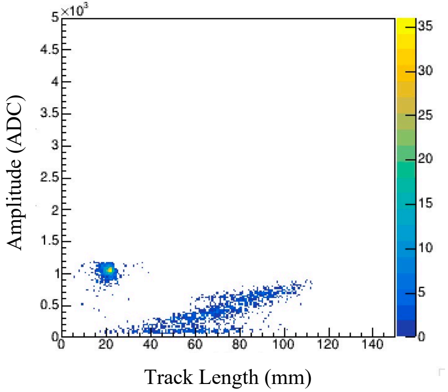
X-Y Track reconstruction

X-Z Track reconstruction

Tracks are similar in length but have half the amplitude



Experimental result



Simulation result

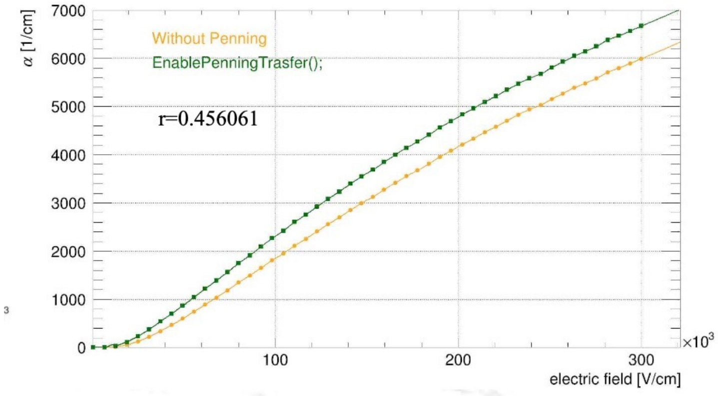
Gain correction

Penning Energy Transfer (Garfield++):

- $A^* + B \to A + B^+ + e^-$: collisional ionization,
- $A^* + A \to A_2^+ + e^-$: homonuclear associative ionization,
- $A^* \to A + \gamma$: radiative decay
  - $\gamma + \mathrm{B} \to B^+ + e^-$: photo-ionization

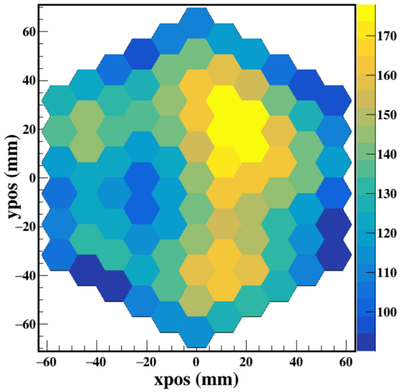
(A : noble gas (Ar, Xe, Ne, He ...))

(B : mostly a molecular gas (CO_2, CH_4, C_2H_6, C_3H_8, iC_4H_{10} ...))

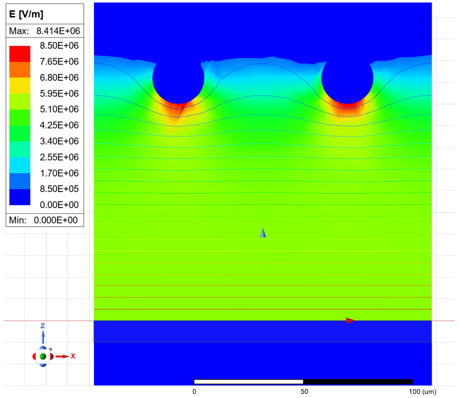


Townsend coefficient with and without Penning Transfer using Garfield++(cite from Ibrahim A.M. ALASAMAK)

The corrected gain after simulation with Garfield++ is 146, close to the measurement.



Experimental gain distribution



Simulated electric field distribution (non-uniform field)

MTPC System

MTPC
Multi-purpose TPC

- **Introduction**
  - CSNS, Back-n white neutron source, Project history, Software framework
- **Simulation method**
  - Detector construction, Ionization, Electron drift and avalanche, Electronics response
- **Experimental verification**
  - Experimental setup, Timing verification, Energy response verification
- **Summary**

Summary

The completed works:

- The development of the v2 MTPC system is completed.
- The construction of the simulation and analysis framework is completed.
- The MTPC system test and Li-6 experiment at Back-n are completed.

Comments:

- There are many inconsistencies in the comparison between simulation results and experimental results, but they are all reasonably explained.
- The electronics system needs to be upgraded to reduce timing deviations.
- The gain of the detector is affected by penning transfer and actual electric field distribution.
- Consider applying simulation methods to experimental predictions.


Thank you !