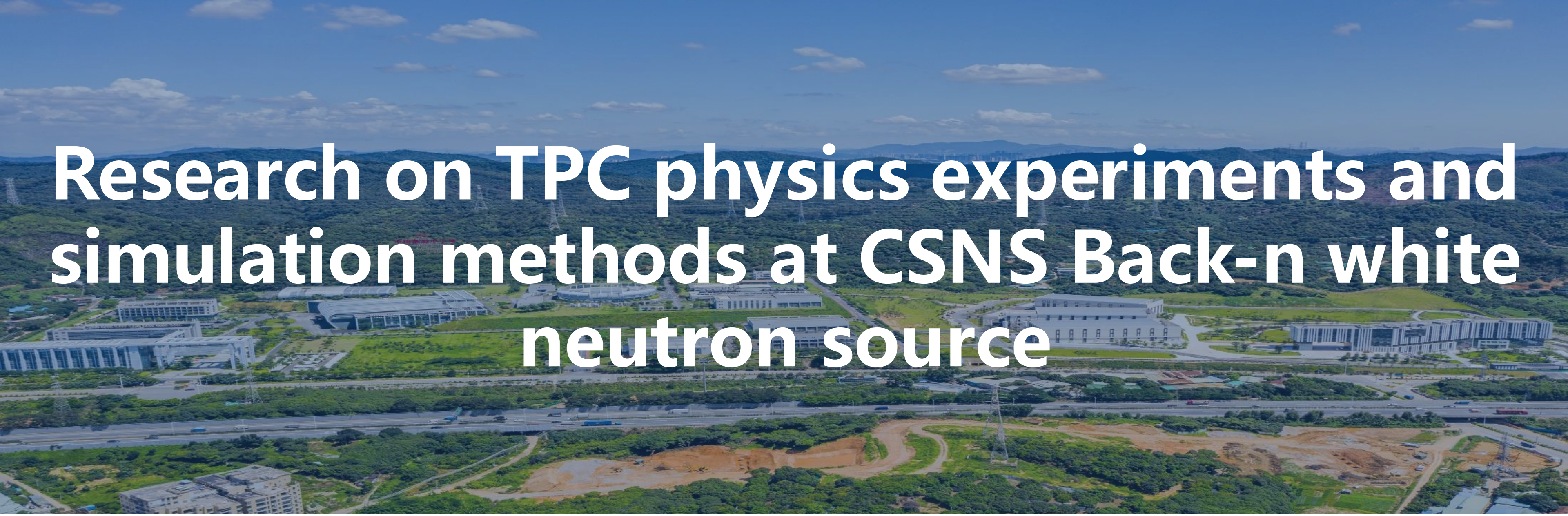

Research on TPC physics experiments and simulation methods at CSNS Back-n white neutron source

Haizheng Chen (陈海铮) on behalf of MTPC collaboration

China Spallation Neutron Source (CSNS)

Institute of High Energy Physics, Chinese Academy of Sciences (CAS)

Xi’an Jiaotong University

The 8th International Conference on Micro-Pattern Gaseous Detectors, Hefei, China

MTPC
Multi-purpose TPC

MTPC System

MTPC
Multi-purpose TPC

- **Introduction**
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  - Detector testing methods:, Data processing
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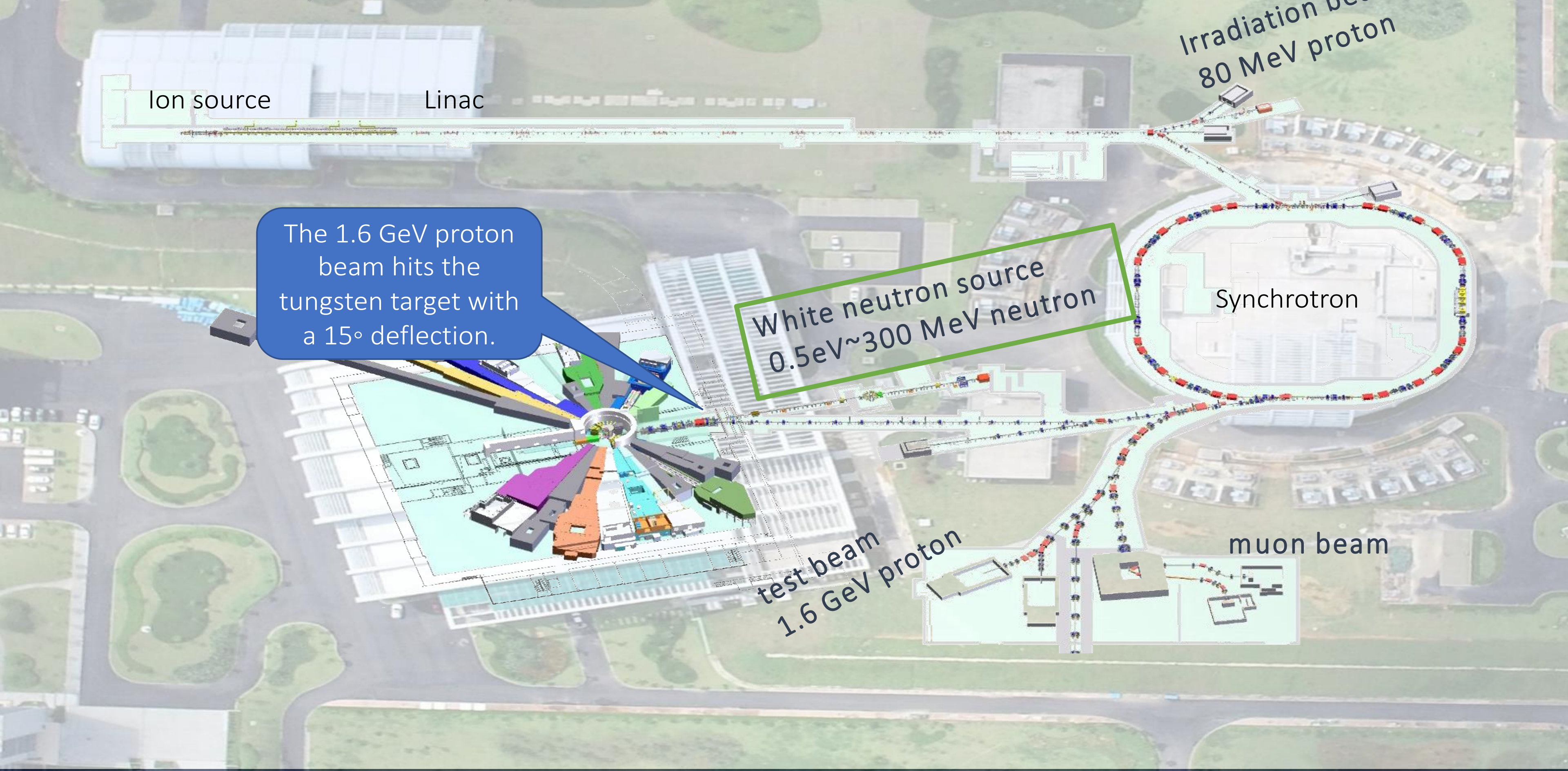
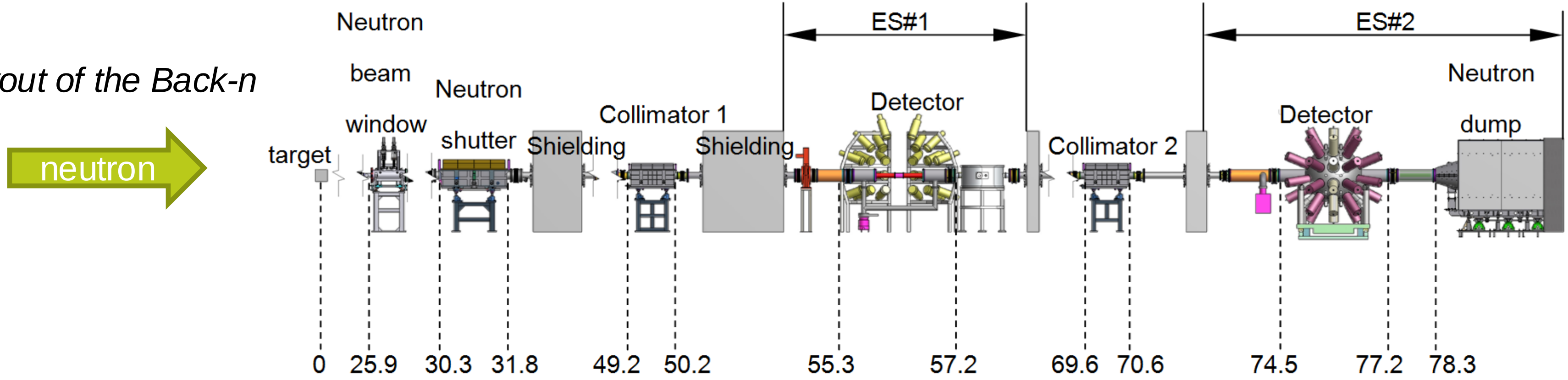
  - Standard cross section measurement, Nuclear physics frontier challenges, Focusing on the needs of nuclear data

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

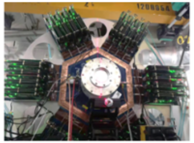
MTPC
Multi-purpose TPC

2019.8:
TPC design and processing

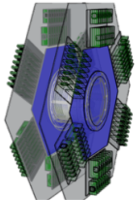
2019.12:
Build v1 detector and develop DAQ

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

MTPC System

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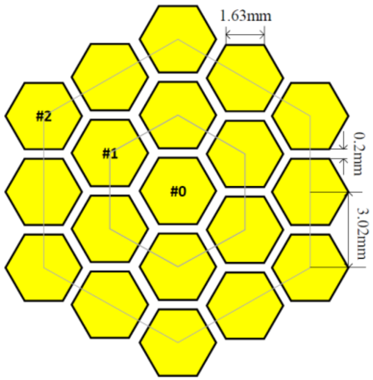
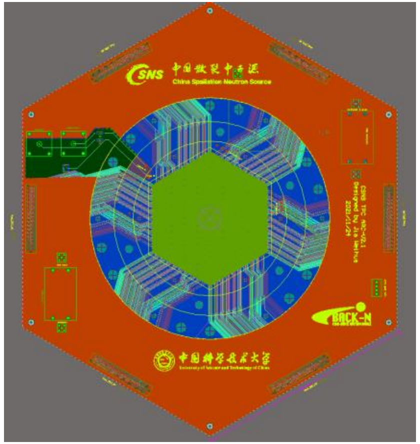
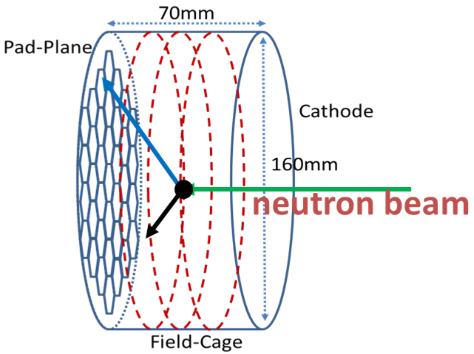
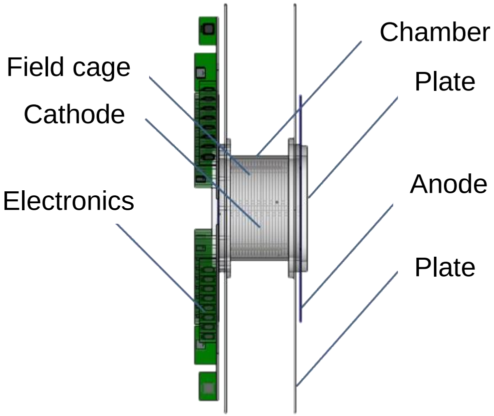
Detector Structure

- 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



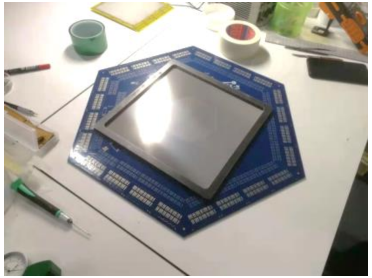




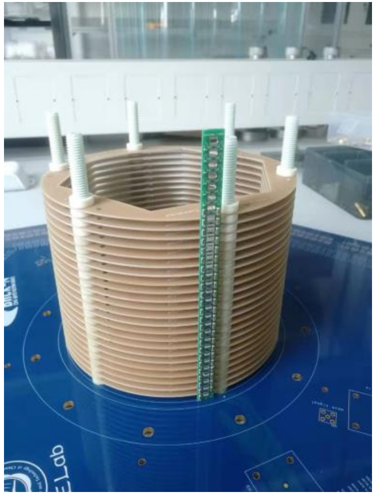


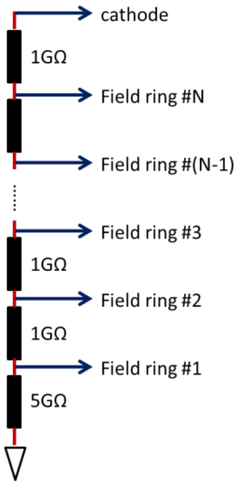
[1] Weihua Jia, You Lv, Zhiyong Zhang et al. Gap uniformity study of a resistive Micromegas for the Multi-purpose Time Projection Chamber (MTPC) at Back-n white neutron source. NIMA, 1039, 2022.

Detector Structure



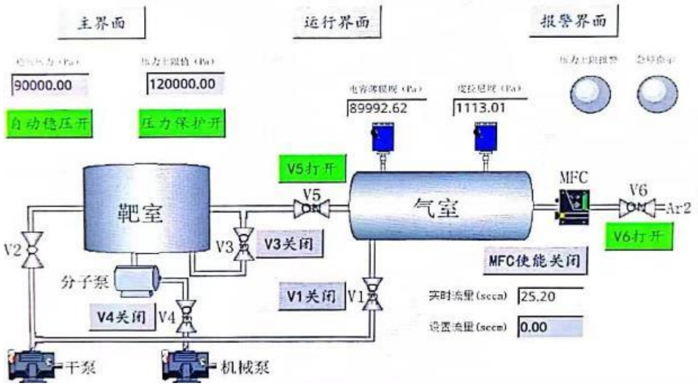
- Micromegas structure is made by hot pressing technology
- The gap between Mesh and Anode is 100μm
- The surface of the anode plate is plated with a 400nm high-resistance germanium layer to increase stability under high voltage
- Mesh parameters: stainless steel wire diameter 16μm, thickness 25μm, LPI-400
- The grading rings is used to uniform the electric field
- Design divider resistor welding PCB, used for connection between grading rings





Gas Supply System

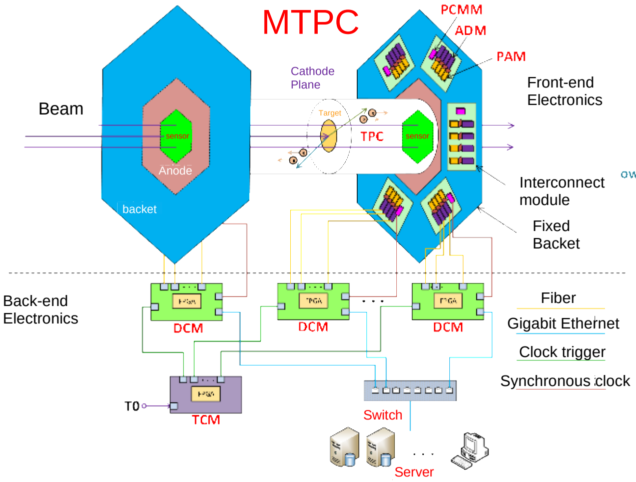
Pressure Control System (In Chinese)



Gas Mixer

- The gas pressure (0~5 bar) can be set
- The pressure can be automatically stabilized by the Pressure Control System
- The gas mixer can control the proportion of working gases of different components according to the flow rate
- The detector gas flow is adjusted by the needle valve
- The Gas Supply System is connected to the control system, and the pressure can be adjusted online

Readout Electronics[2]



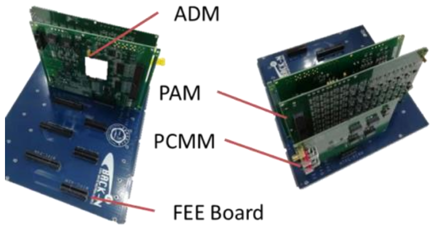
PAM
Pre-Amplifier Module

ADM
Analog-to-Digital Module

PCMM
ower Clock Management Module

DCM
Data Concentrator Module

TCM
Trigger Clock Module



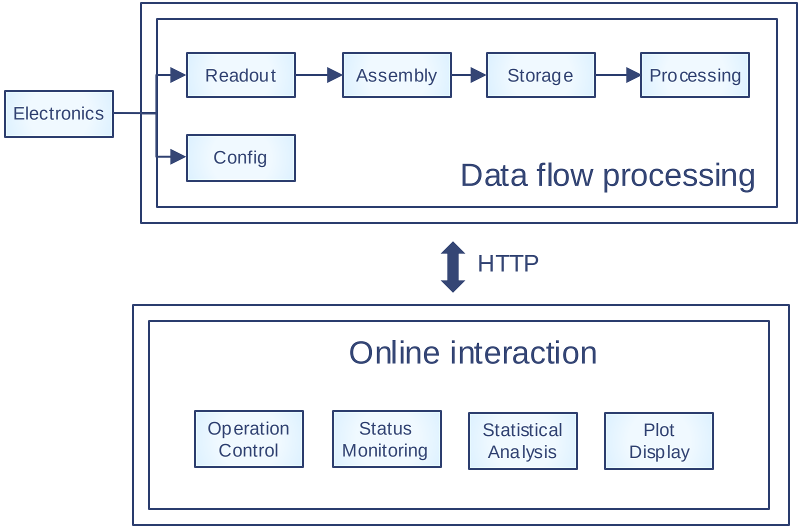
DCM

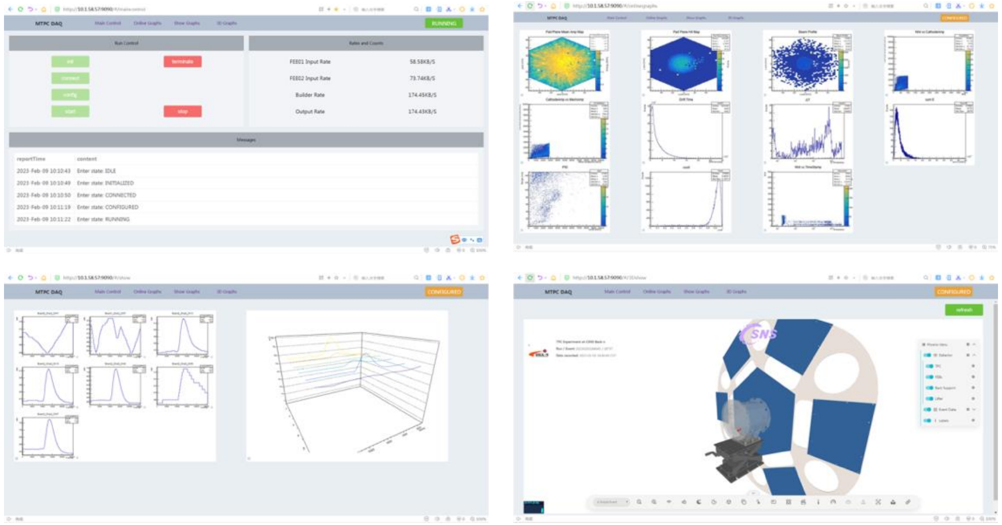
TCM

- Main parameters of the electronic system:
  - Total 1536 channels (MTPC uses 1521 channels)
  - Sampling frequency: 40MHz
  - Sampling window width: 1024 sampling points (each point with 25ns)
  - ADC bit number: 12bit

[2] Z. Chen, C. Feng, H. Chen et al. Readout system for a prototype multi-purpose time projection chamber at CSNS Back-n. Journal of Instrumentation. 17, 2022.

DAQ Program & Online Display





Data Acquisition Program (DAQ core)

Responsible for collecting data:

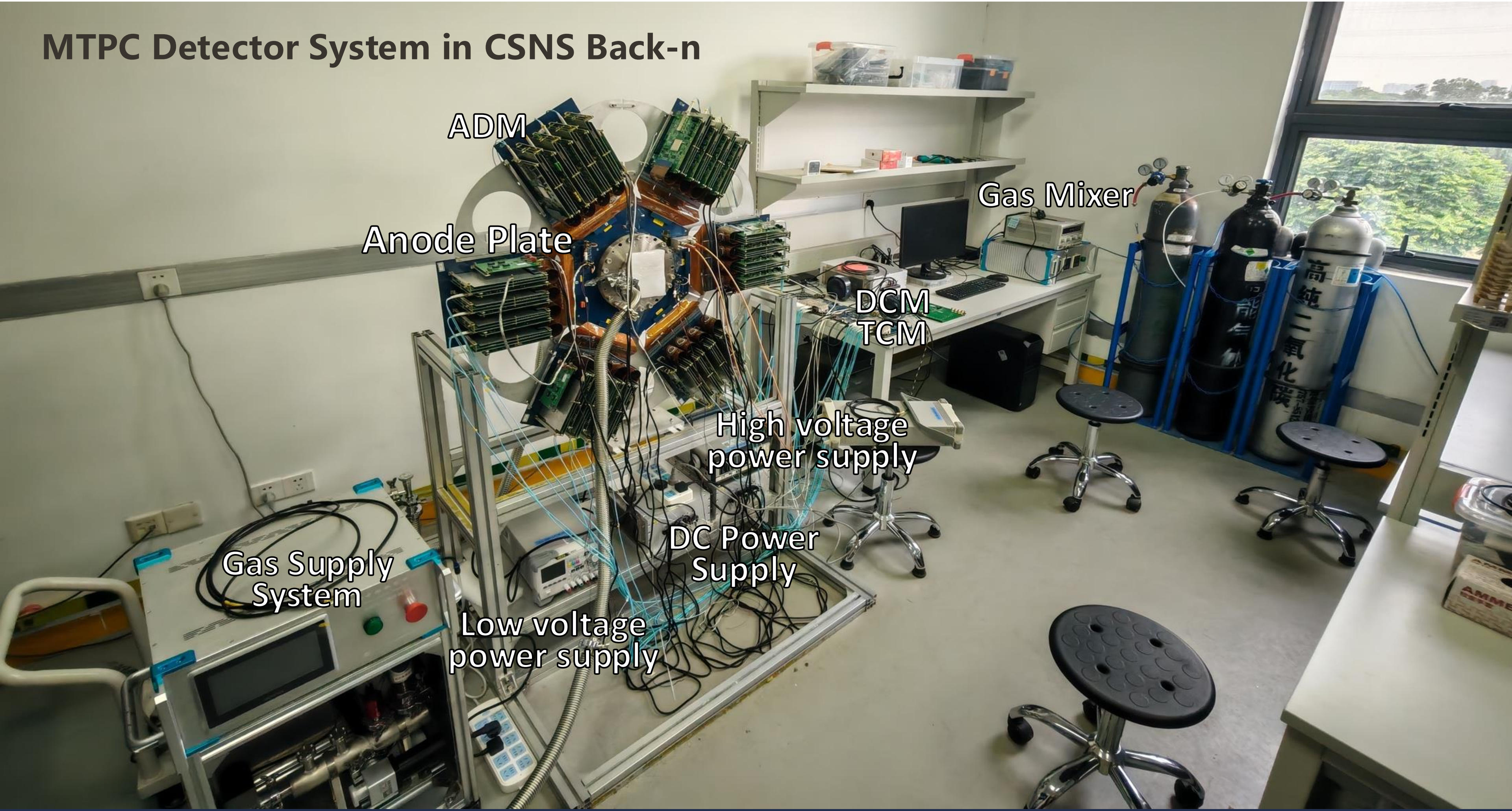
Data receiving, assembly, storage and processing

Online interactive interface

Provide user services upward: execution, feedback

Transfer information downward with the data flow subsystem

MTPC Detector System in CSNS Back-n



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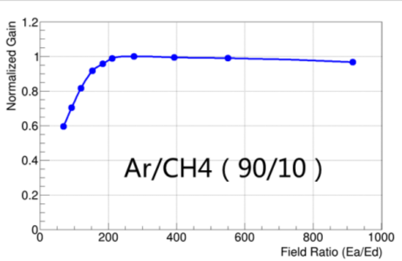
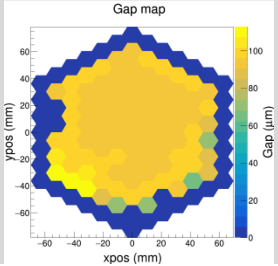
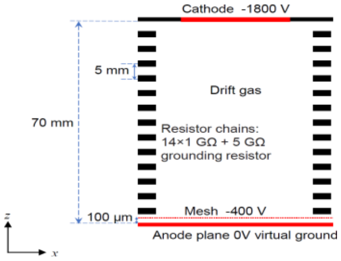
Detector Testing

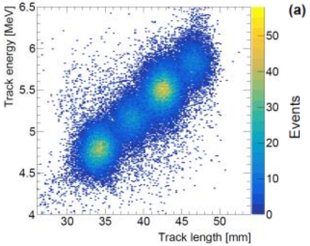
- X-ray test:
  - Electron transmission rate
  - Gain curve
  - Gap uniformity

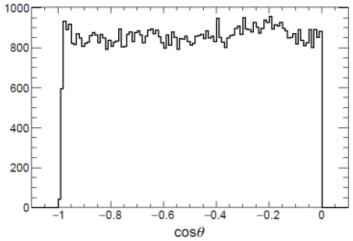




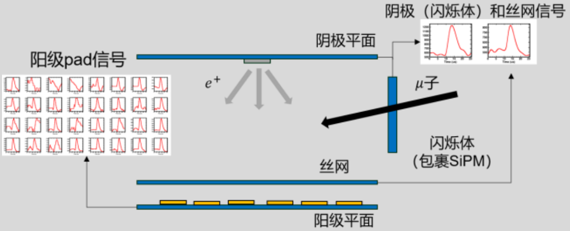
- α radiation source test:
  - Energy resolution
  - Drift velocity
  - Angular distribution

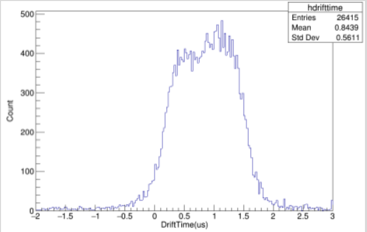






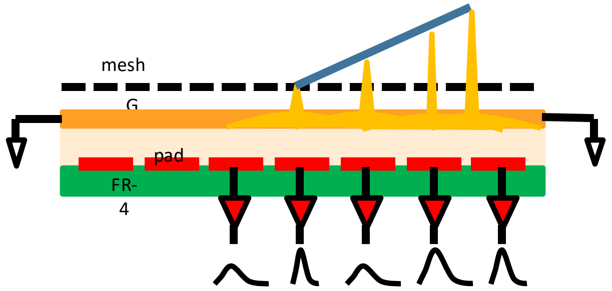
- Cosmic ray test:
  - Drift time distribution
  - Spatial resolution
  - Electric field uniformity

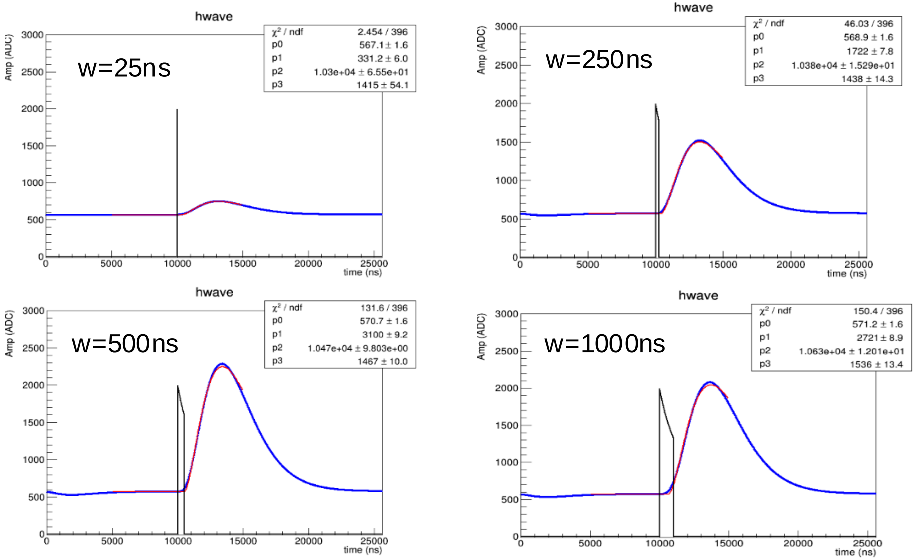




Waveform Fitting Algorithm

- Electronic Transfer Function: $f(t) = B + A\left(\frac{t-t_0}{\tau}\right)^n e^{-(t-t_0)/\tau}$
- The original signal widths of different angle tracks are inconsistent, and the actual waveform differs from the function form.
- Set n=2 for fitting. As the original waveform width w increases, the starting timing of the fitting will be delayed.
- Improve the timing accuracy through waveform inversion

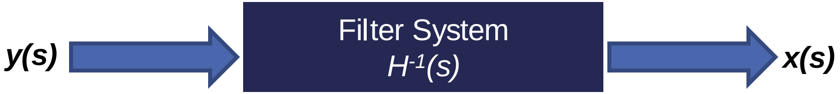




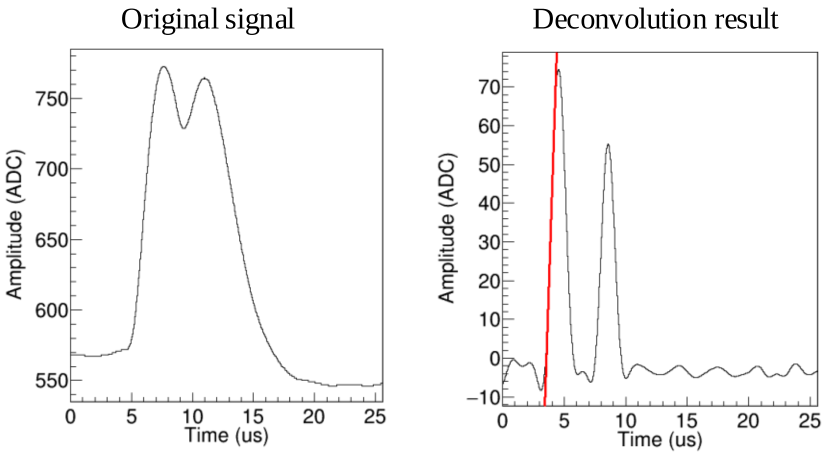
w(ns)	25	250	500	1000
t0(ns)	10300	10380	10470	10630

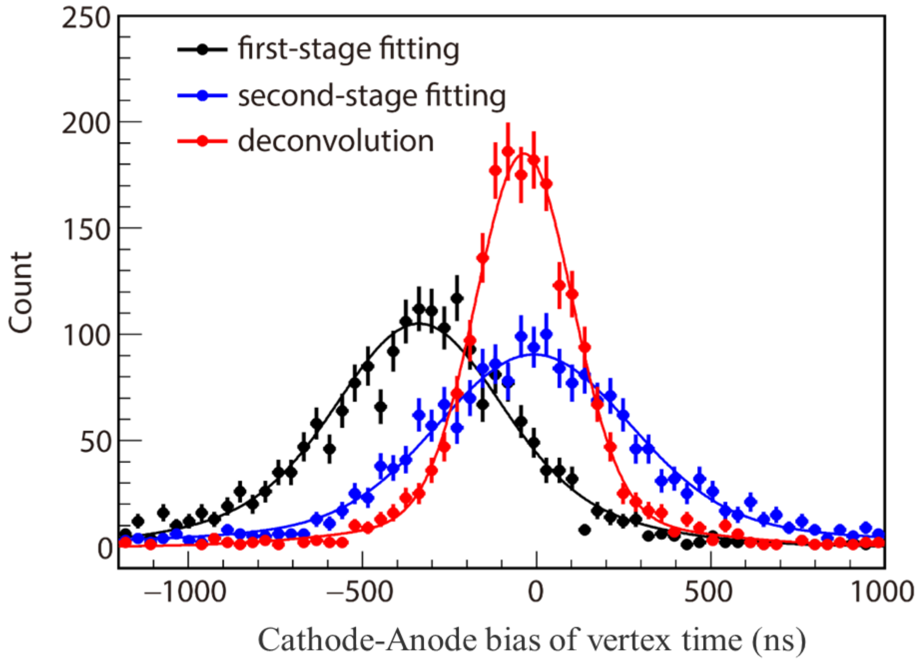
Waveform Deconvolution Algorithm

- To improve the time resolution and multi-event resolution capabilities, deconvolution is used here to get the original current signal.
- Starting time is determined by fitting the rising edge.



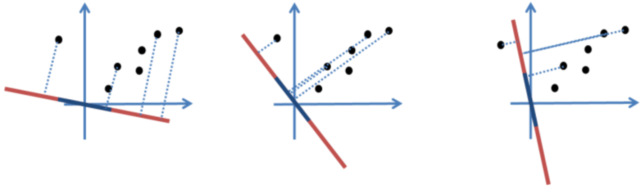
$$x(s) = H^{-1}(s)y(s)$$

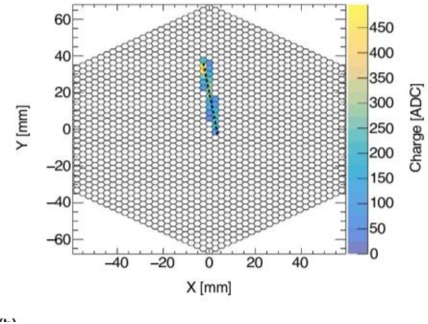




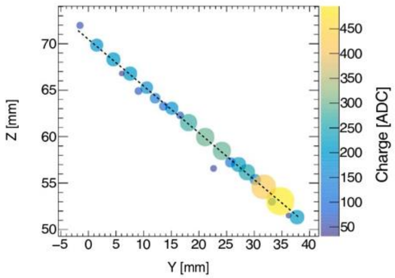
Track Reconstruction

- 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

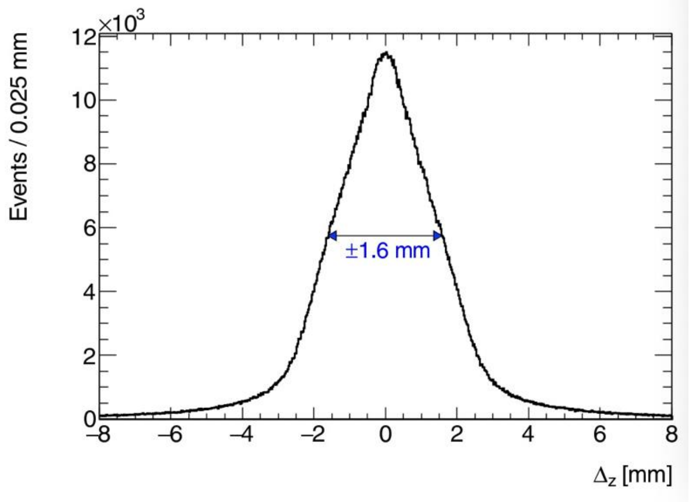




X-Y Track reconstruction



X-Z Track reconstruction



Track reconstruction resolution

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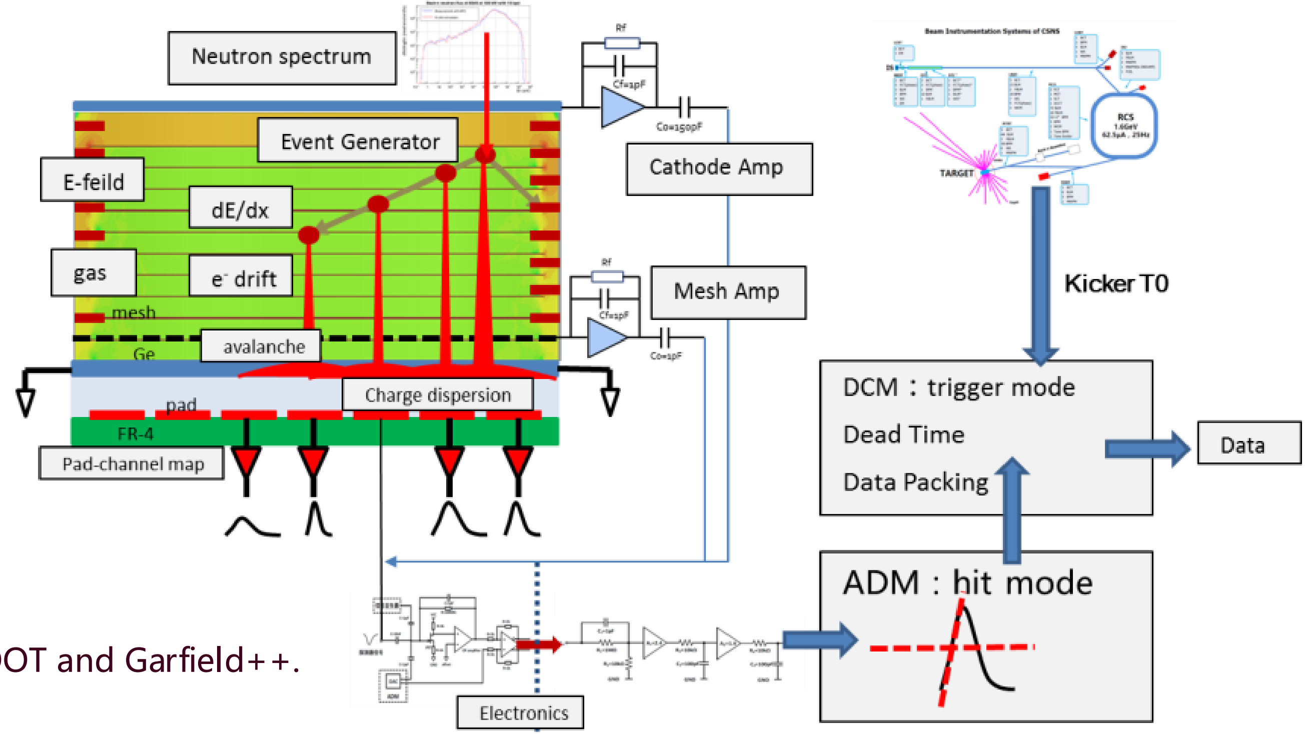
Simulation framework

- The simulation framework includes all physical processes
  - Gas parameters
  - Neutron spectrum
  - Event generator
  - Ionization process
  - Electron drift
  - Electron avalanche
  - Charge diffusion
  - Electronics model
  - Cathode waveform
  - Mesh waveform
  - Hit and trigger

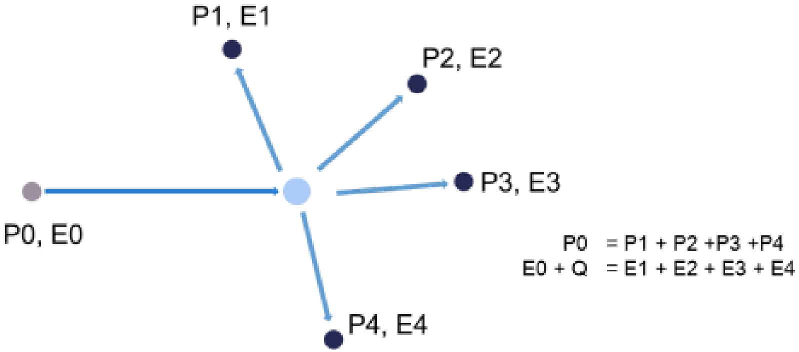


- Combined with Geant4, ROOT and Garfield++.

Physics model: Event generator

For nuclear reaction mode:

- Use TGenPhaseSpace (ROOT) to determine the parameters of primary particles.
- Set the initial state particles and final state particles, randomly generate the particle phase space parameters according to the uniform distribution of the center of mass system, and the physical quantity is expressed as the Lorentz four-vector
- Input parameters to Geant4: Particle type, energy, direction and position.

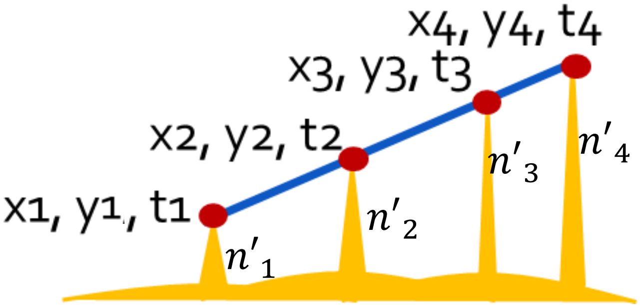


Particle ionization process

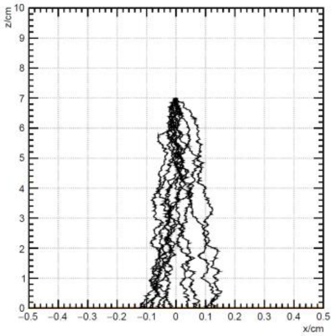
- Geant4 is used here to get the distribution of energy deposition

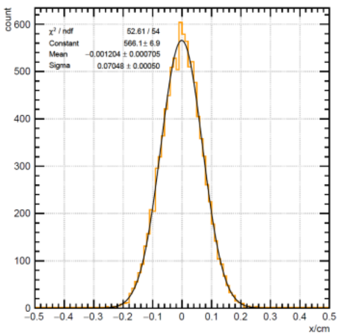
> G4double edep = step->GetTotalEnergyDeposit() - step->GetNonIonizingEnergyDeposit()

- 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: $\sigma'_L = \sigma_L / v = \sqrt{d_l z} / v$

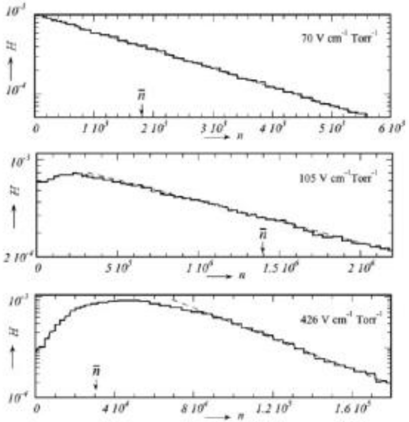
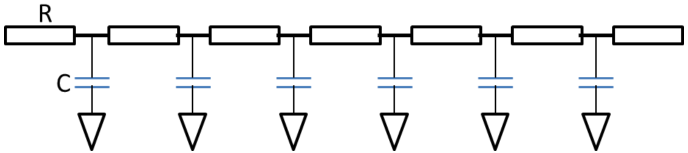


Figure 5.30 Evolution of the avalanche size from exponential to a Polya distribution at increasing values of field (Schlumbohm, 1958). By kind permission of Springer Science+Business Media.

- According to the gas avalanche theory, the number of electrons after the avalanche at low gain: $P(n) = e^{-n/G}$
- Assume that there is no spatial diffusion after the electron avalanche, and the coordinates are the same as the original electrons.
- At high gain, the single electron gain conforms to the Polya distribution (to be implemented)

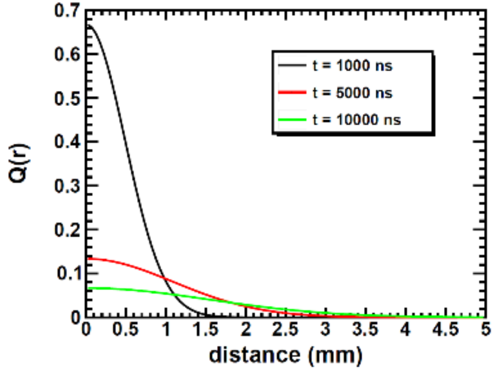
Charge dispersion in the resistive Ge-layer

- 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.

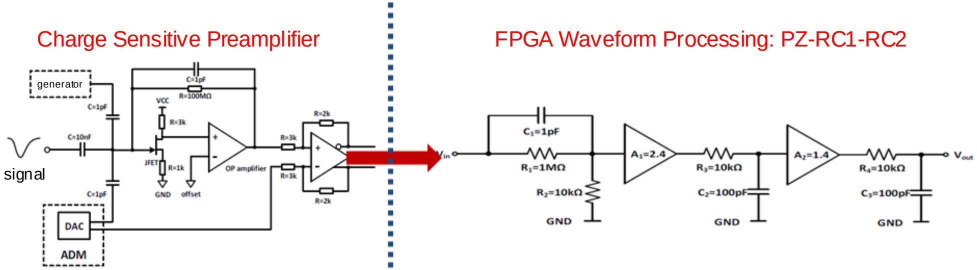


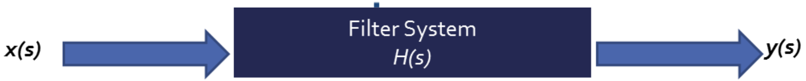
$$\rho(x,y,t) = \left(\frac{1}{2\sqrt{\pi tRC}}\right)^2 exp[-(x^2+y^2)/4tRC]$$

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



Electronics Signal Convolution

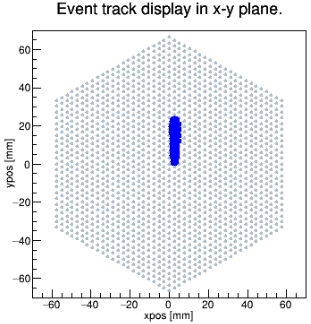


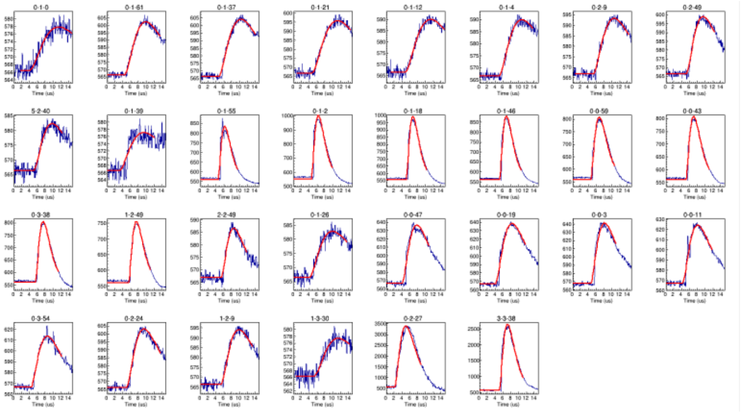


$$y(s) = H(s)x(s)$$

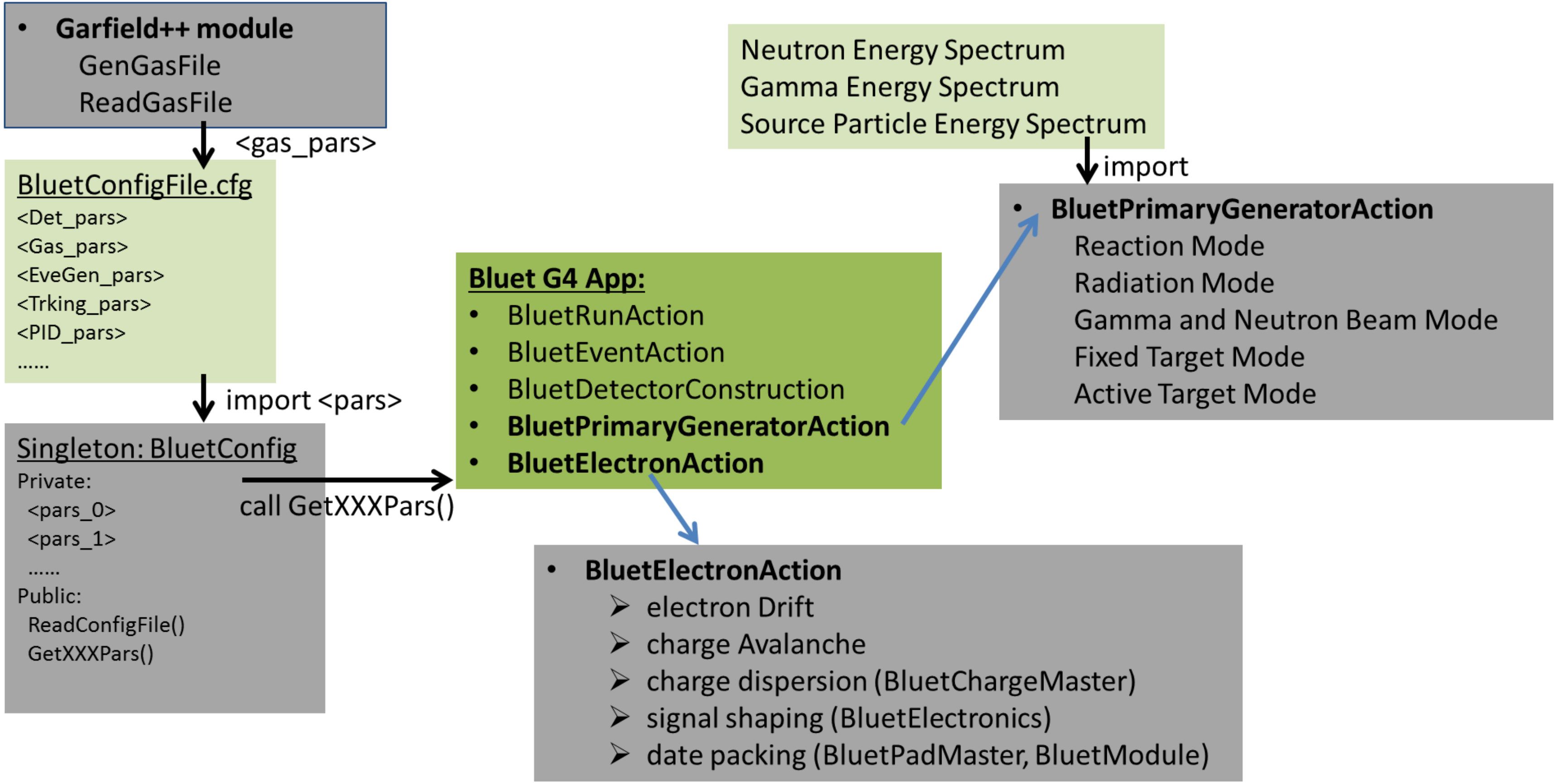
- **Q(t) is used as input signal：**
- Pre-amplifier: $H(t) = 1/C_0(-\frac{e^{-\frac{t}{\tau_0}}}{\tau_0} + \frac{e^{-\frac{t}{\tau_r}}}{\tau_r})$
  - $\tau_0 = RC$, integration time; τ_r signal rising time.
- PZ: $H(t) = \delta(t) + 1/\tau_0(1 - \frac{\tau_0}{\tau_1})e^{-t/\tau_1}$
  - $\tau_1 = R_2C_1$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

Simulated alpha particle events and waveforms

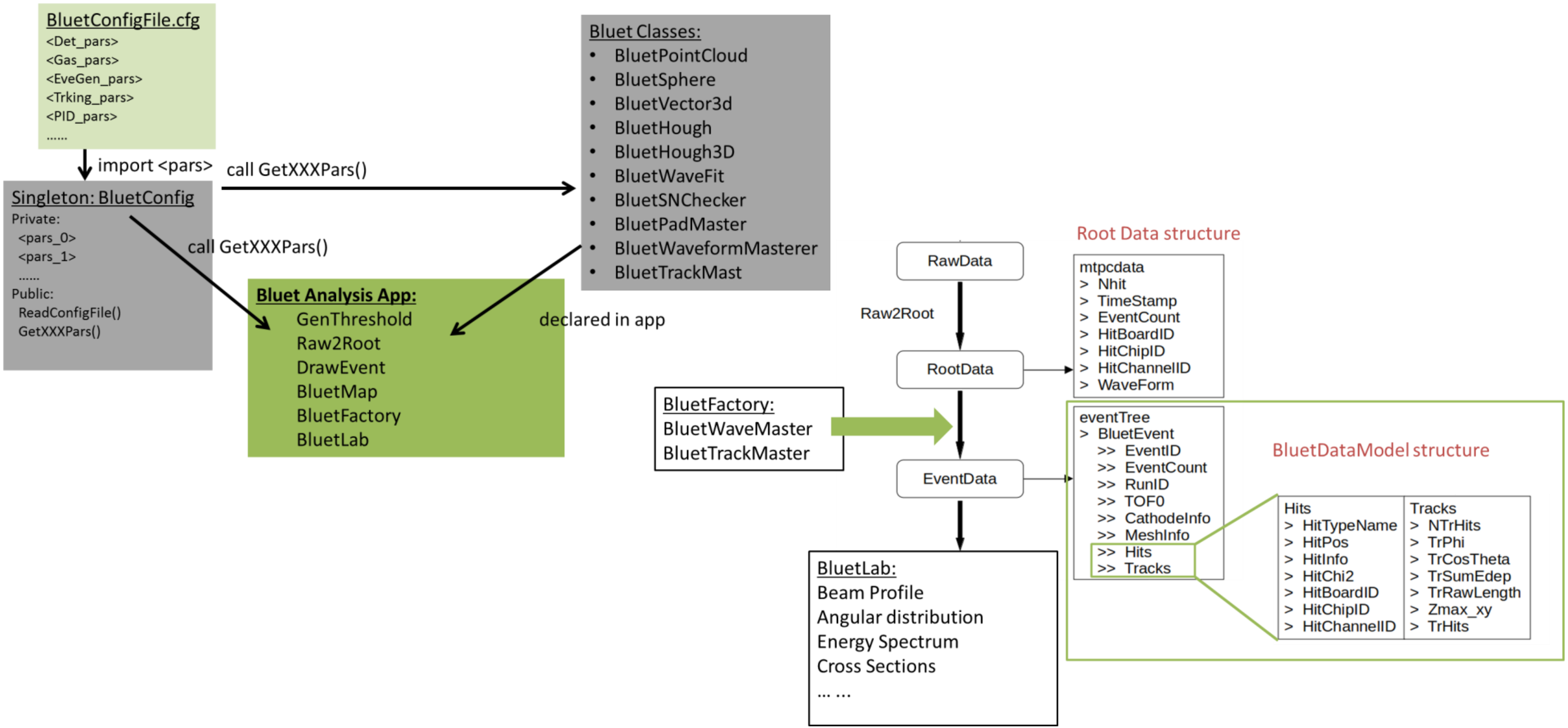




Simulation framework

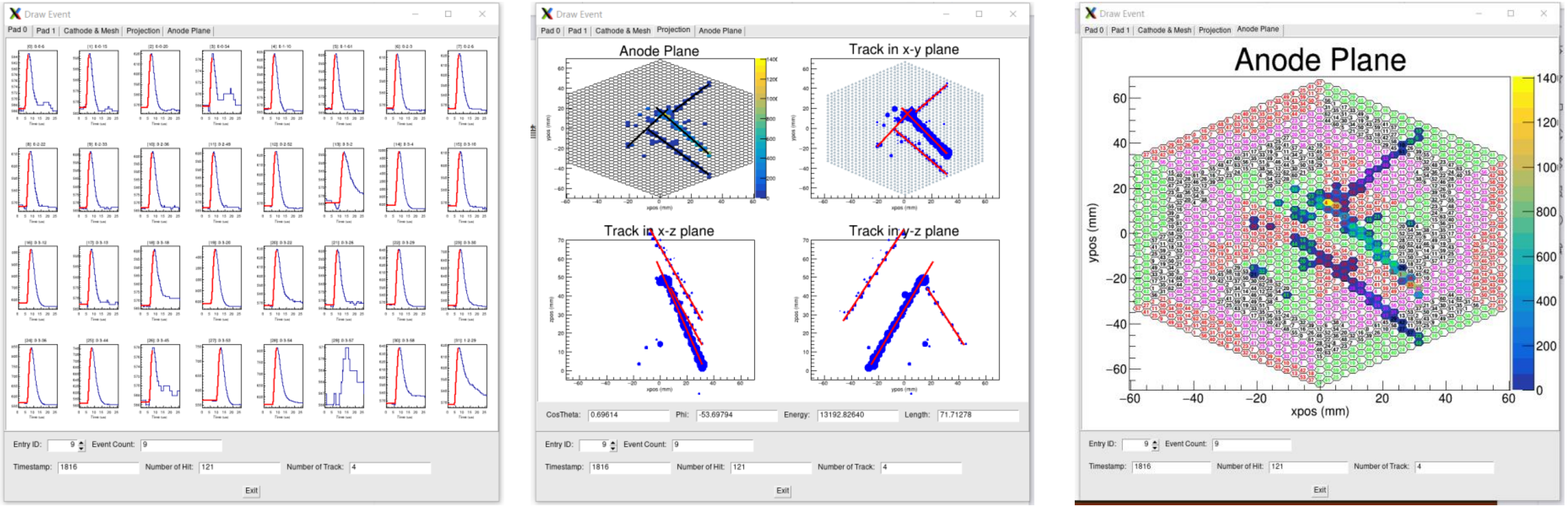


Analysis framework



User interface

- User-friendly UI for data display and algorithm testing
- Includes: waveform display, tracks, pad array

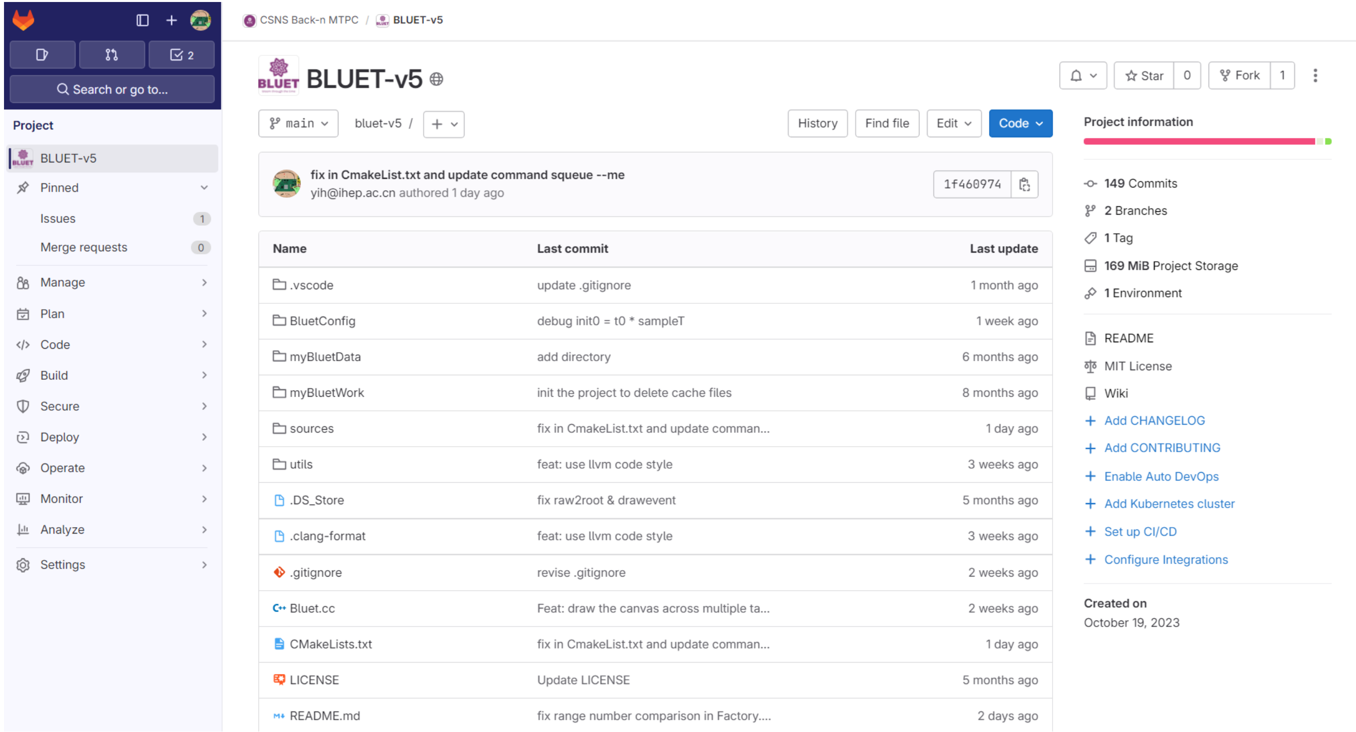


BLUET: A simulation and analysis library

- Open-source

> https://code.ihep.ac.cn/csns-backn-tpc/bluet-v5

BLUET
bloom through the time



MTPC System

MTPC
Multi-purpose TPC

- **Introduction**
  - CSNS, Back-n white neutron source, Project history
- **Detector system**
  - Detector structure, Gas supply system, Readout electronics, Data acquisition
- **Detector testing and analysis methods**
  - Detector testing methods:, Data processing
- **Simulation and analysis framework**
  - Simulation framework、Physical model、Analysis framework、Data structure
- **Experimental Plans**
  - Standard cross section measurement, Nuclear physics frontier challenges, Focusing on the needs of nuclear data

Experimental Plans

- Three types of physical experiments

MTPC

Multi-purpose TPC

Standard cross-section measurement

Nuclear physics frontier challenges

Focusing on the needs of nuclear data

Standard cross-section measurement

- Neutron standard cross section data is the basic of cross section measurement.
- In the energy range below 10MeV, it is suitable to use MTPC for measurement.
- It is of great significance to independently carry out systematic standard cross section experimental measurement and data evaluation.

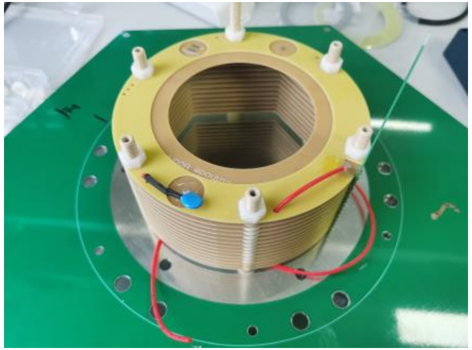
TABLE I. Cross section standards and reference data, release 2017.

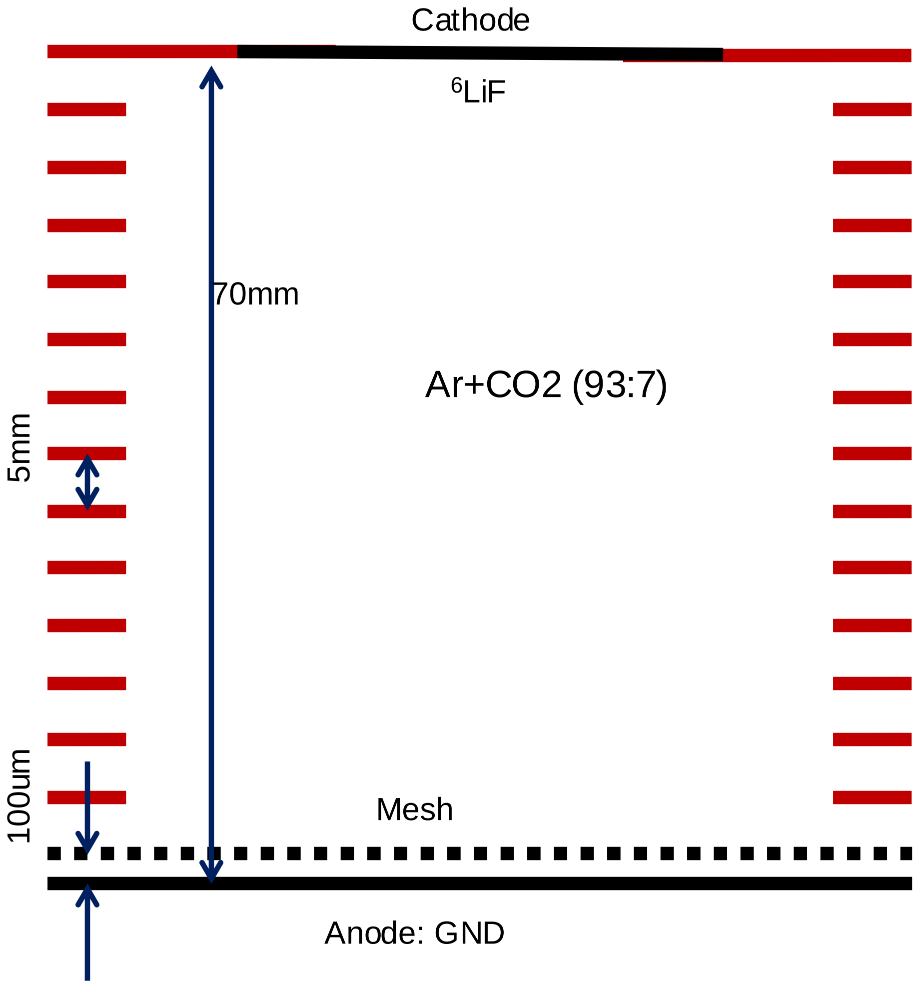
Neutron cross section standards	
Reaction	Standards incident neutron energy range
H(n,n)	1 keV to 20 MeV
^{3}He(n,p)	0.0253 eV to 50 keV
^{6}Li(n,t)	0.0253 eV to 1 MeV
^{10}B(n,α)	0.0253 eV to 1 MeV
^{10}B(n,$\alpha_1\gamma$)	0.0253 eV to 1 MeV
C(n,n)	10 eV to 1.8 MeV
Au(n,γ)	0.0253 eV, 0.2 to 2.5 MeV, 30 keV MACS
^{235}U(n,f)	0.0253 eV, 7.8-11 eV, 0.15 MeV to 200 MeV
^{238}U(n,f)	2 MeV to 200 MeV

Reaction	Time
^{6}Li(n,t)	Feb. 2023
H(n,n)	Oct. 2024 (in progress)
^{235}U(n,f)	Oct. 2024 (in progress)
^{10}B(n,α)	2025-2027

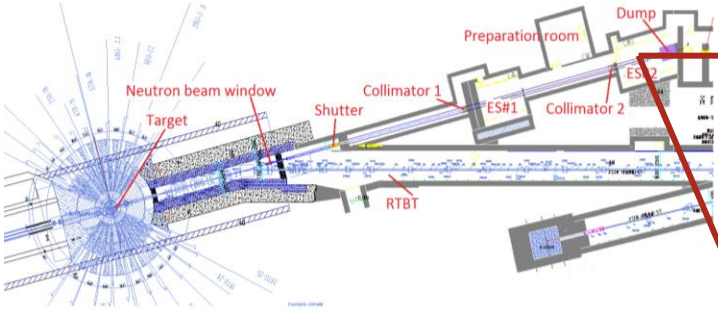
$^6Li(n,t)^4He$ (Feb. 2023)

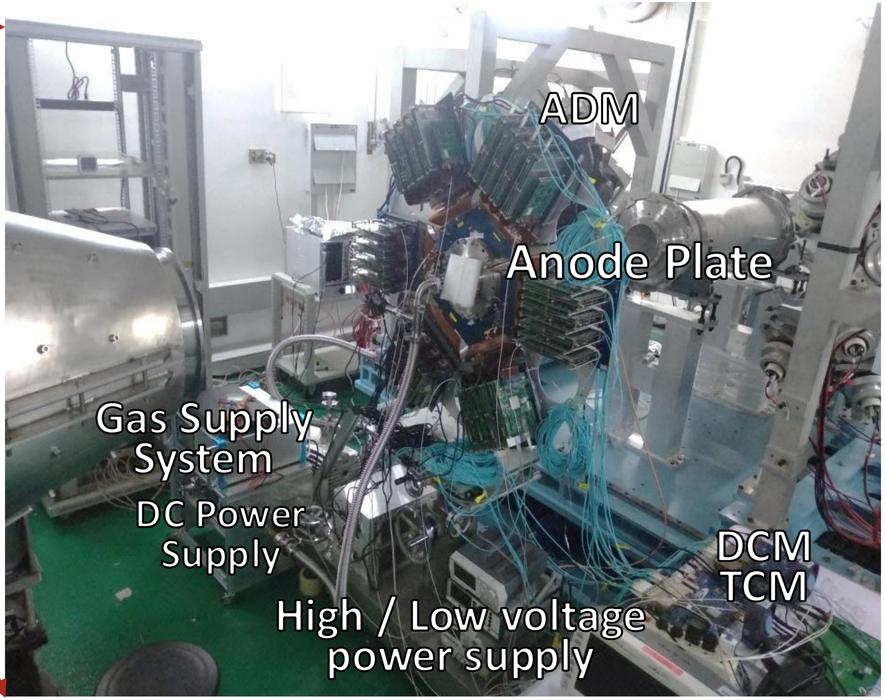
- Neutron energy range: 1eV-500keV
- Drift distance is 70mm, ^6LiF sample placed in the cathode center
- Sample parameters:
  - Thickness 560nm, ^6Li abundance 95%, ^6LiF surface density 148ug/cm^2, diameter 66mm
  - Al plate diameter 89mm, thickness 10.8um





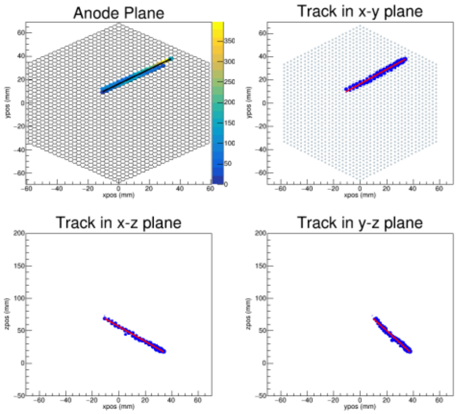
$^6Li(n,t)^4He$ (Feb. 2023)

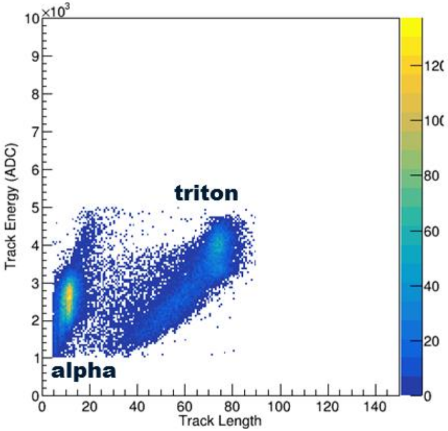


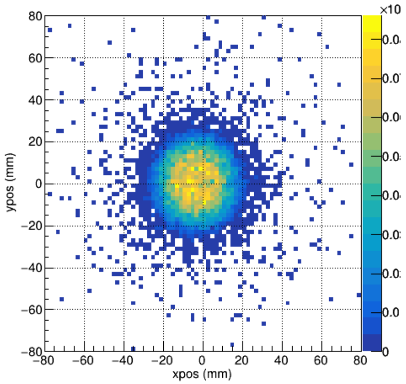


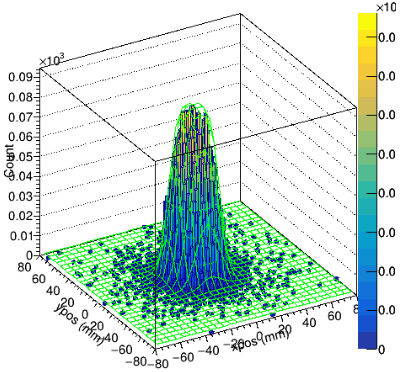
- TPC was located in End-Station 2, with the anode plate 77m away from the center of the spallation target
- Beam spot：Φ30 (with 1mm Gd-6cm Pb-Φ12-Φ15-Φ40 combination)
- 0.9 bar pressure: measure triton particles (133h)
- 0.5 bar pressure: measure alpha particles (143h)

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









- Select the triton events to analyze the beam spot
- Fit the beam spot center and radius through a two-dimensional function
- $\boldsymbol{Erf}$: error function
- $\boldsymbol{r_0}$: radius at 50% amplitude
- $\boldsymbol{\sigma}$: distribution variance

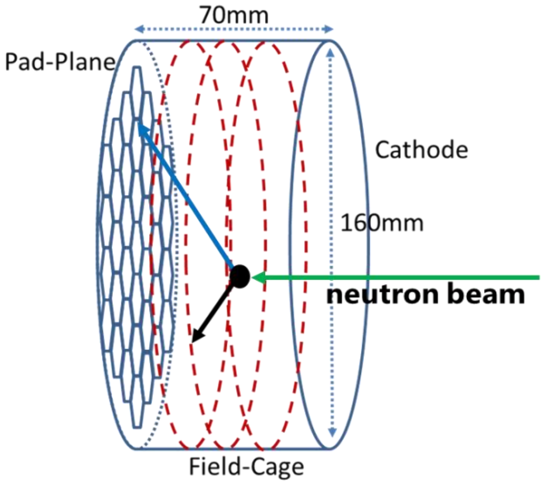
$$f(x,y) = B + \frac{A}{2}\left[Erf\left(\frac{r(x,y) - r_0}{\sqrt{2}\sigma}\right) - Erf\left(\frac{r(r,y) + r_0}{\sqrt{2}\sigma}\right)\right],$$

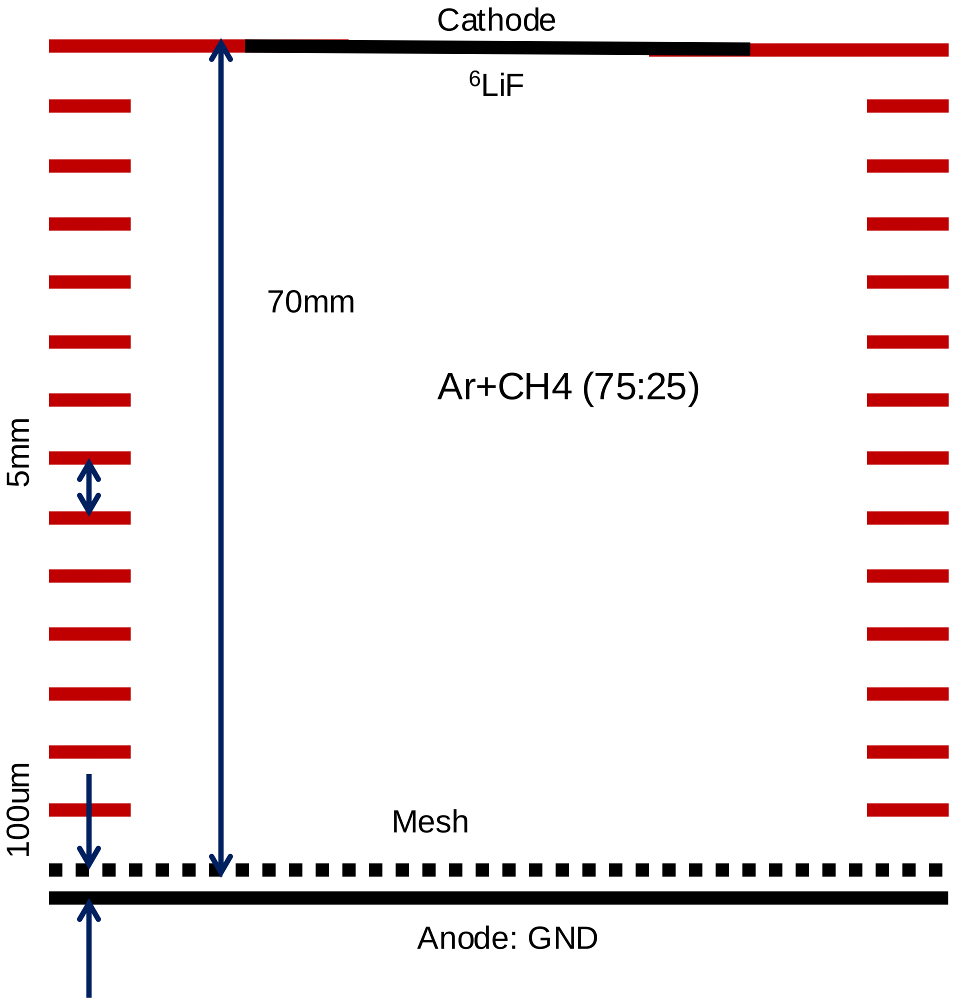
$$r(x,y) = \sqrt{(x - x_0\ )^2 + (y - y_0\ )^2}$$

- Fitting result:
  - center(x_0, y_0): (-3.1mm, 0.6mm)
  - $\boldsymbol{r_0}$: 17.7±0.1mm
  - $\boldsymbol{\sigma}$: 6mm

H(n,n) (Oct. 2024, in progress)

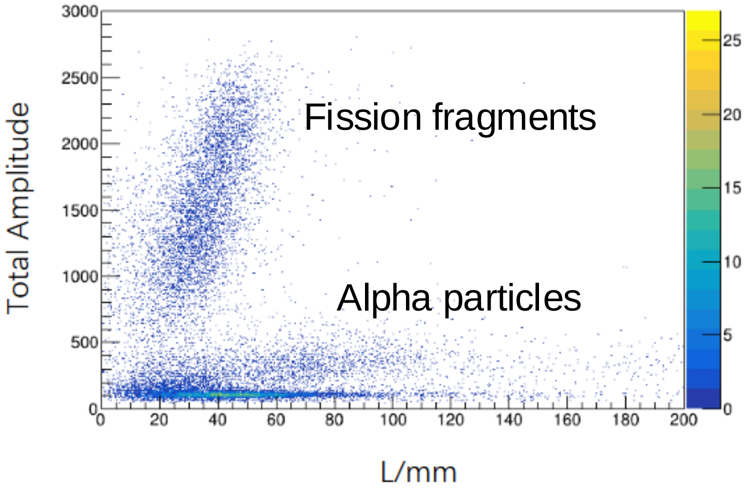
- Neutron energy range: 100keV-500keV
- Drift length: 70mm
- Working gas is 75% Ar + 25% CH_4 mixed gas, with H as the target nucleus
- A ^{6}LiF sample is placed in the center of the cathode as a standard sample for detector parameter inspection

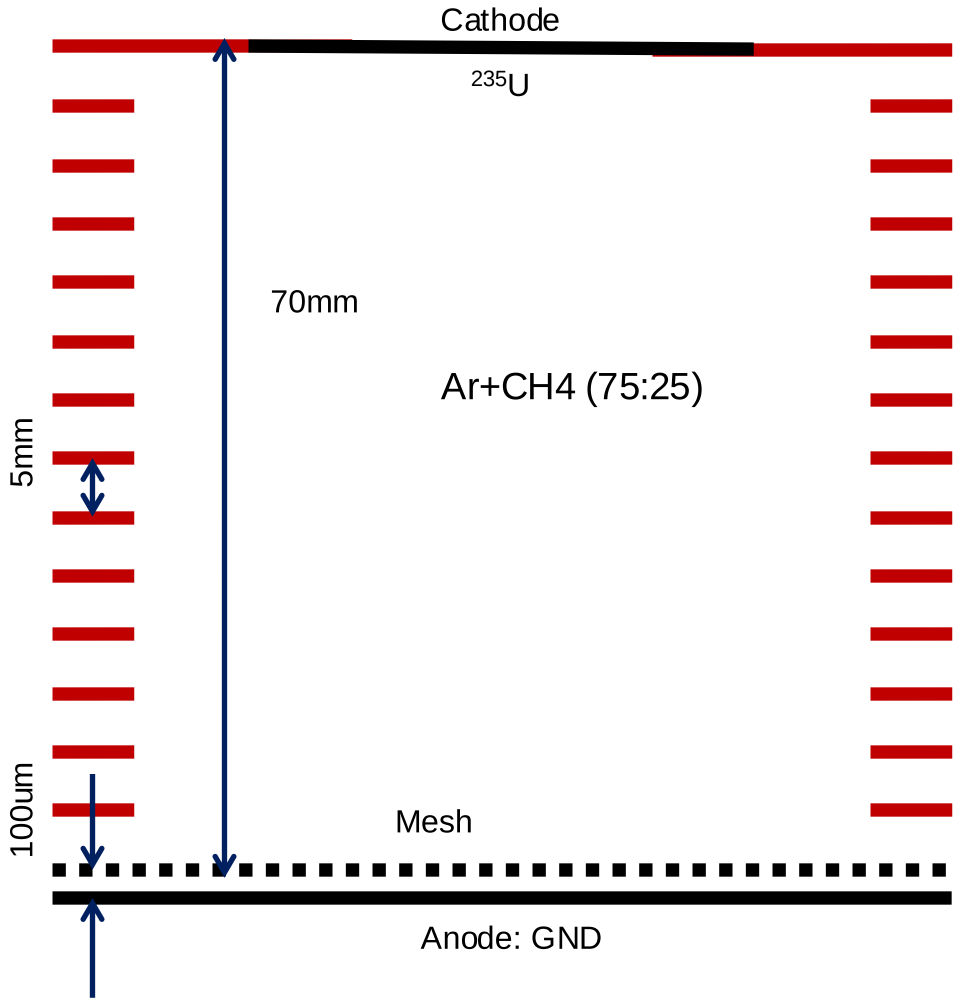




$^{235}U(n,f)$ (Oct. 2024, in progress)

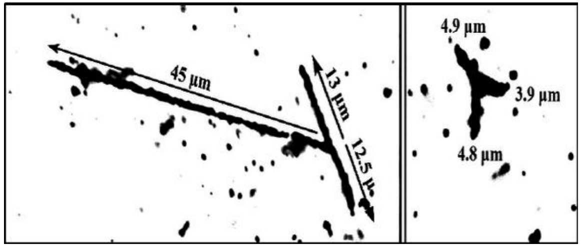
- Use 0.6 bar and low voltage on Mesh to reduce avalanche gain to reduce alpha particle interference and achieve high-precision measurement

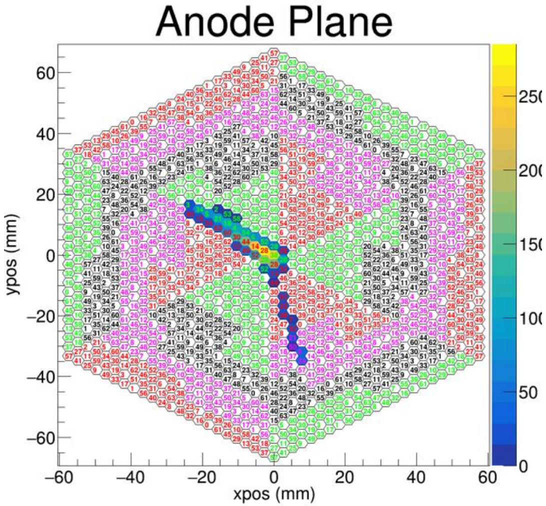


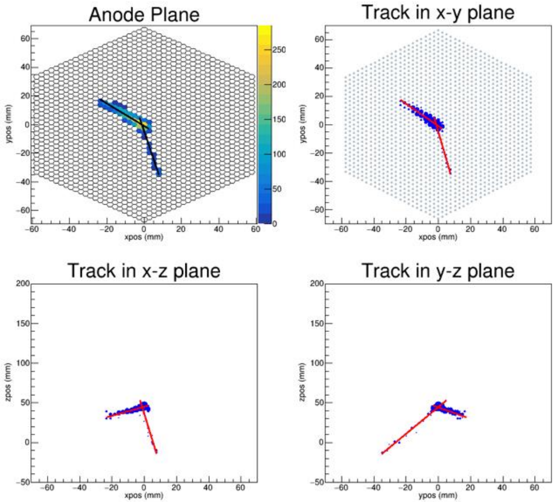


Date 2024-09-29: ^{252}Cf ternary fission measurement in laboratory

- Drift length: 70mm
- Working gas is 75% Ar + 25% CH_4 mixed gas
- High voltage setting: Mesh 270V, Cathode 800V.

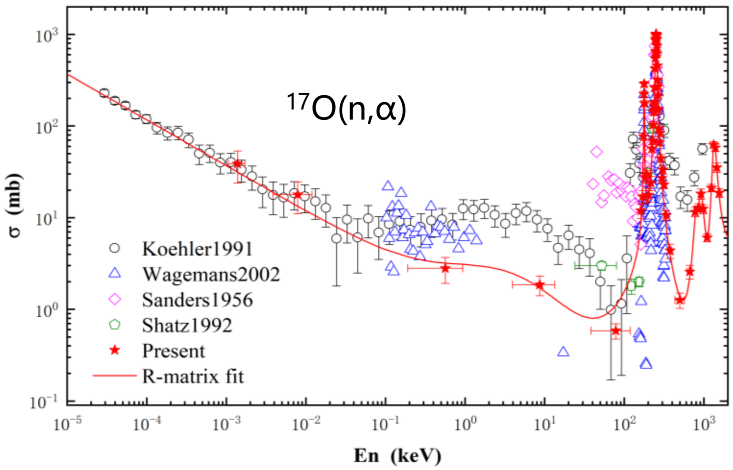






Nuclear physics frontier challenges

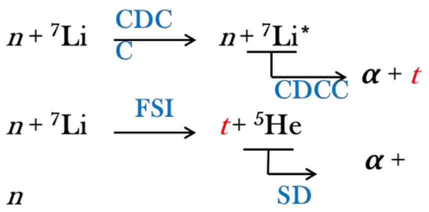
- **$^{17}O(n,\alpha)$**
- Existing experiments: $W^{17}O_3$ target + Si/SiC detector array
- Experimental shortcomings: SiC detector has a small receiving solid angle
- The cross section of the key energy region is about an order of magnitude lower than the predicted results
- The cross section measurement is expected to use TPC to solve this problem
- Further attempt to measure the reaction of $^{25}Mg(n,\alpha)$

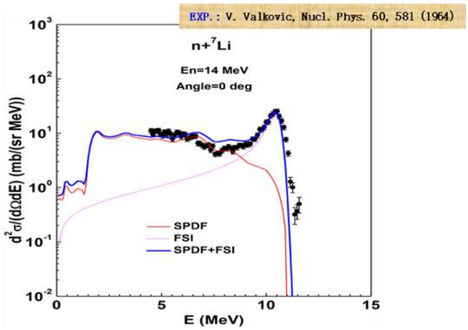


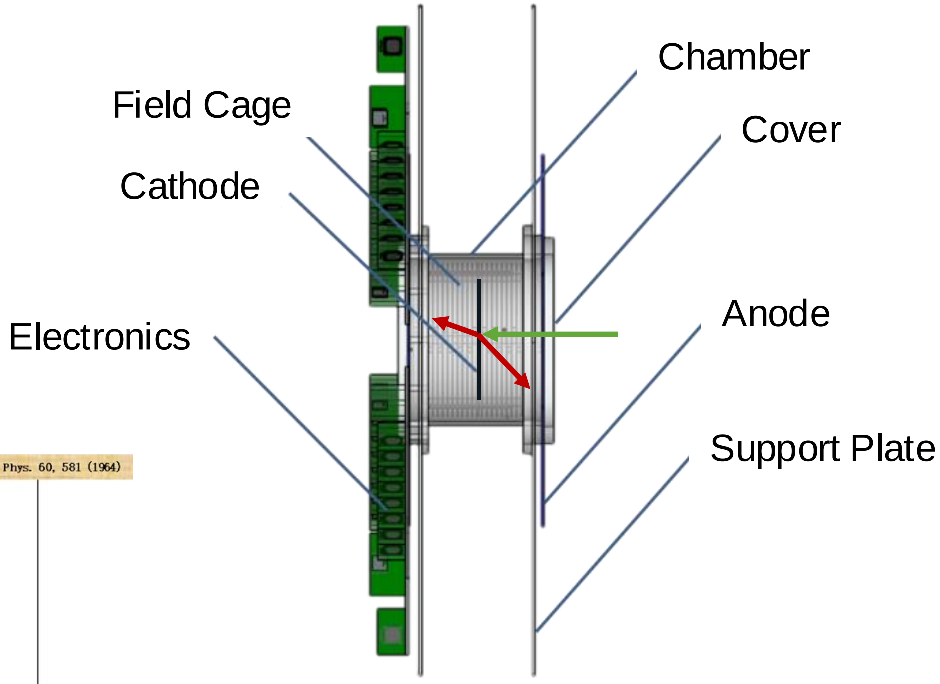
Reaction	Time
$^{17}O(n,\alpha)$	Oct. 2024 (in progress)
$^{25}Mg(n,\alpha)$	2025-2027

Focusing on the needs of nuclear data

- $n+^7Li \rightarrow \alpha + t + n$
- Energy region: 0-20MeV
- Measurement is performed using the MTPC with the target in the middle between Cathode and Mesh to achieve coincidence measurement of two charged particles







Reaction	time
$n+^7Li \rightarrow \alpha + t + n$	2027~

Summary

The completed works:

- Completed the development of the v2 MTPC system
- Completed the construction of the simulation and analysis framework
- Completed the MTPC system test and Li-6 experiment at Back-n
- The cross-section measurements of $^{1}H(n,n)$, $^{17}O(n,\alpha)$, $^{235}U(n,f)$ are in process
- Upgrade plans in the future: use double-sided target, replace electronics with an SCA ASIC-based multi-channel readout system, add magnetic field to better identify charged particles

Comments:

- Advanced cross-section measurement experiments can be carried out at Back-n white neutron source with MTPC.
- The MTPC has a wider range of application and can replace other charged particle measurement detectors in Back-n.

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Thank you!