LANZHOU UNIVERSITY
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Physical design and simulation of a fission spectrometer based on the velocity-kinetic energy method

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01. Background

Fission physics

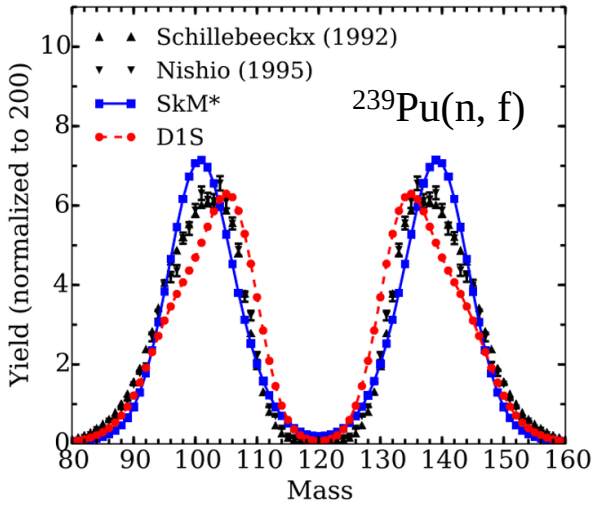


Fig 1. Pre-neutron mass yields for ^{239}Pu(n, f)

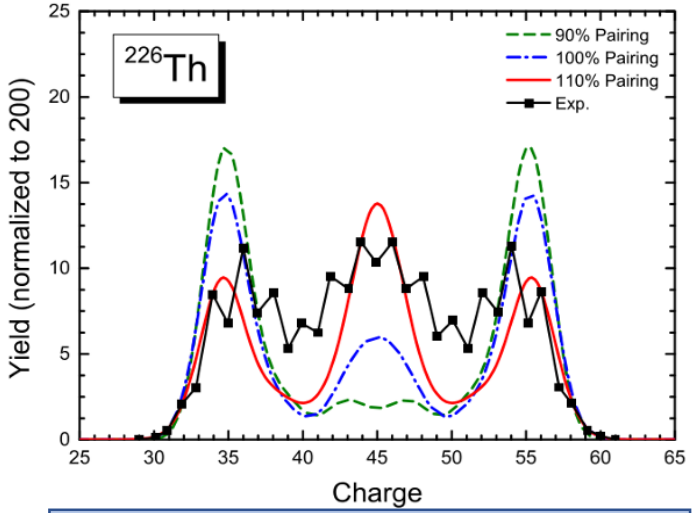


Fig 2. Charge yields for fission of ^{226}Th

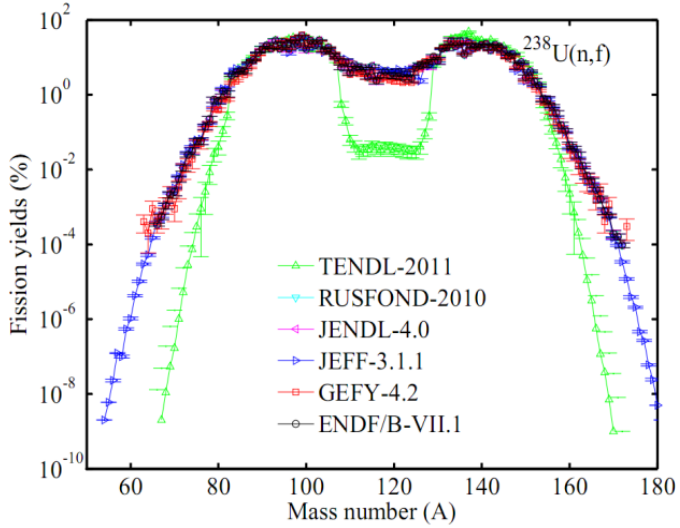


Fig 3. Fission mass yields with different evaluation database

Genera-tion IV

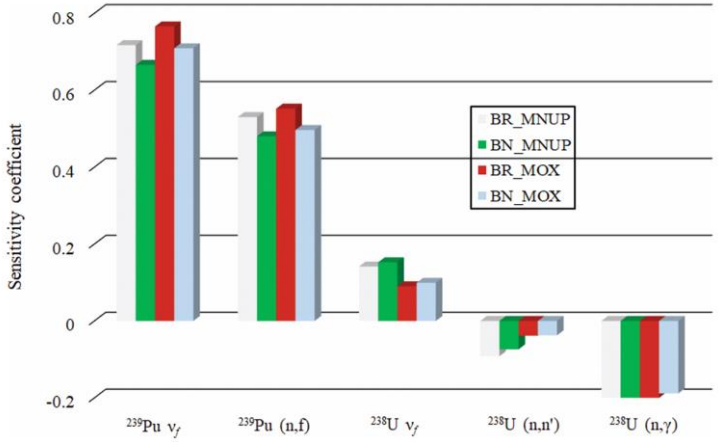


Fig 4. Sensitivity coefficient of k_{eff}

			SG26 - No correlations		
keff			A	B	C
Reaction	EG	Current (%)	Target (%)	Target (%)	Target (%)
240Pu (n,f)	2	8.4	1.2	**1.0**	1.4
240Pu (n,f)	4	25.4	**3.1**	3.6	3.5
238U(n,γ)	4	2.0	0.7	0.7	0.6
240Pu (n,f)	3	14.9	**2.5**	**3.0**	**2.9**
239Pu (n,f)	4	1.0	0.5	0.5	0.5
238U (n.n')	2	7.4	1.3	1.7	2.0
240Pu(n,γ)	4	7.2	1.8	1.4	2.2
239Pu (PFNS)	1	5.5	1.2	1.2	1.1
240Pu (n,f)	1	6.3	2.0	2.2	2.3
239Pu(n,γ)	4	3.1	1.5	1.4	1.4

Fig 5. The difference between target and current uncertainty

New Requirements:

High precision

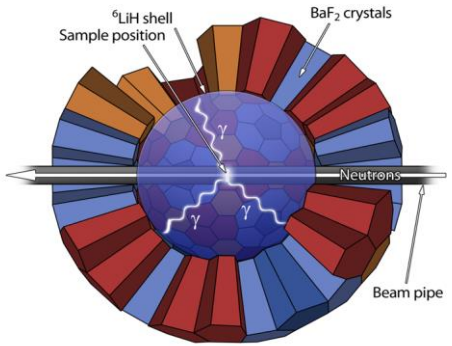
Wide neutron energy range

Multiple fuels

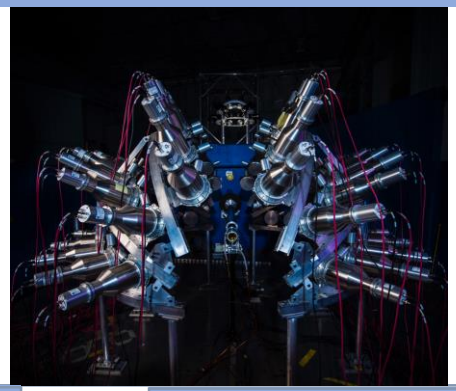
01. Background

- Measurement devices of fission data

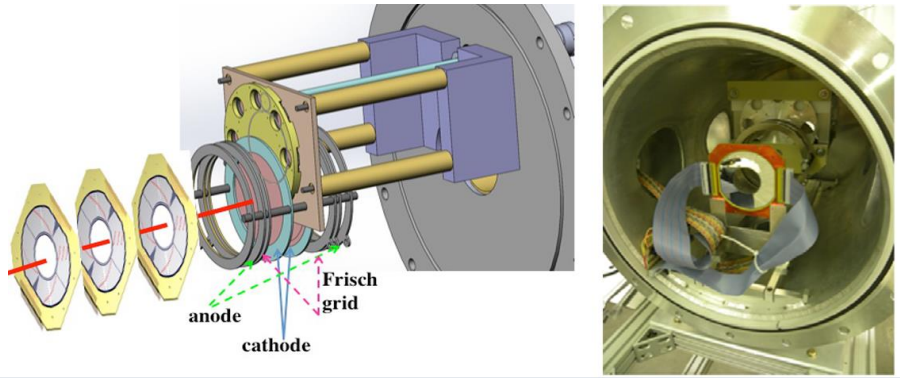
DANCE (n, γ)



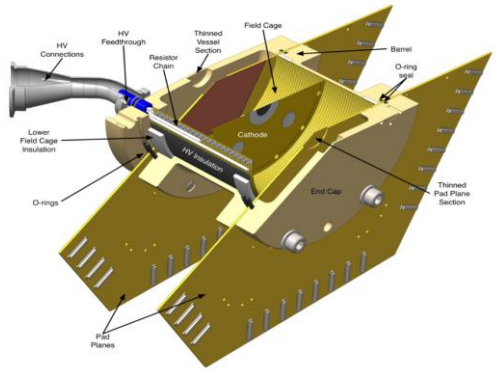
PFNS (n, xn)



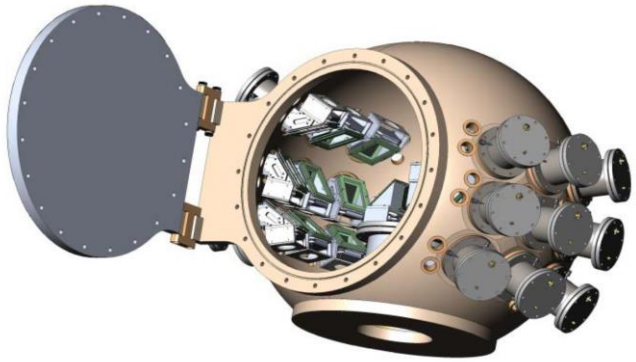
LENZ (angle distribution)



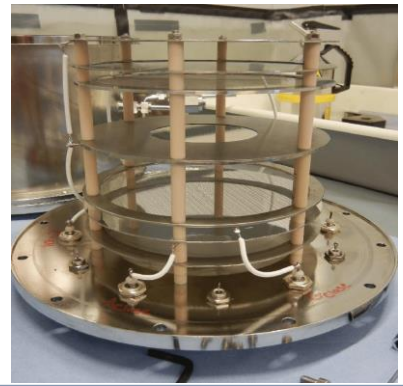
Fission-TPC (n, f)



SPIDER (fission yield)



TFGIC (TKE)



We really need to develop a high-precision, multi-parameters fission yield measurement device.

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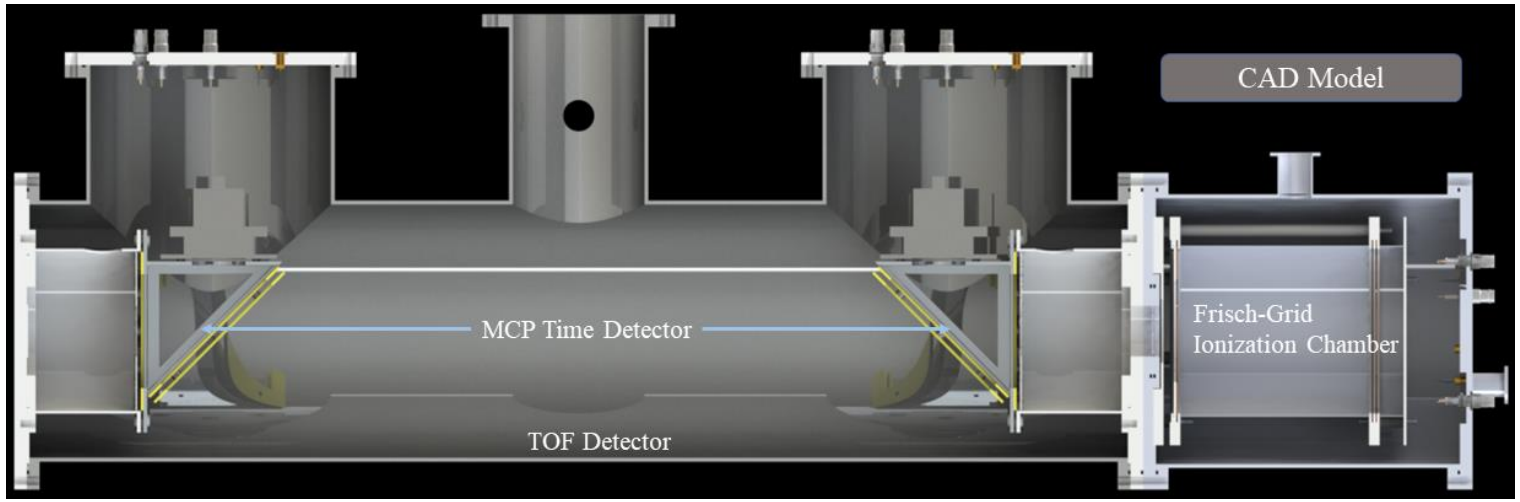
02. Physical design

- Structure and Theory



kinetic energy theorem

$$M = 2\frac{Et^2}{l^2}$$

$$\frac{\delta M}{M} = \sqrt{((\frac{\delta E}{E})^2 + (2\frac{\delta t}{t})^2 + (2\frac{\delta l}{l})^2)}$$

Structure

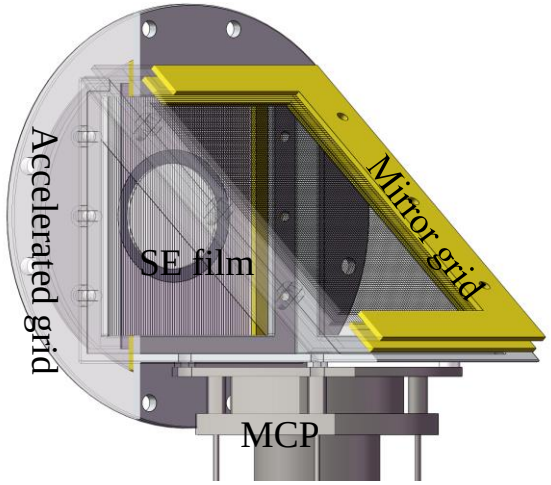
t: Time Of Flight(TOF) detector with two MCP secondary electron time detectors

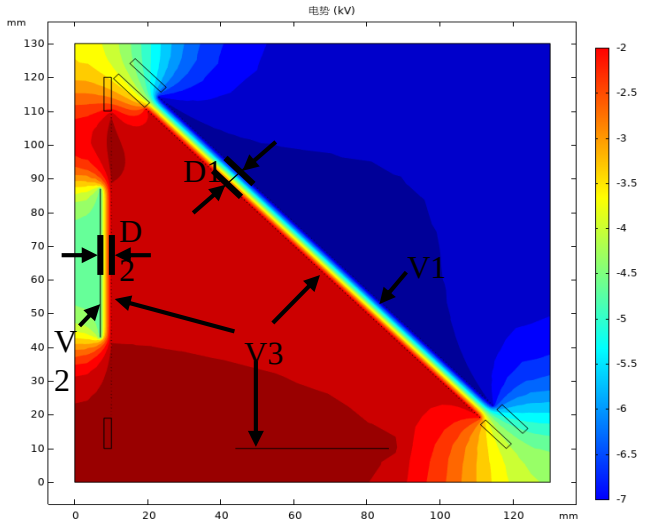
E: Frisch-Grid ionization chamber(FGIC)

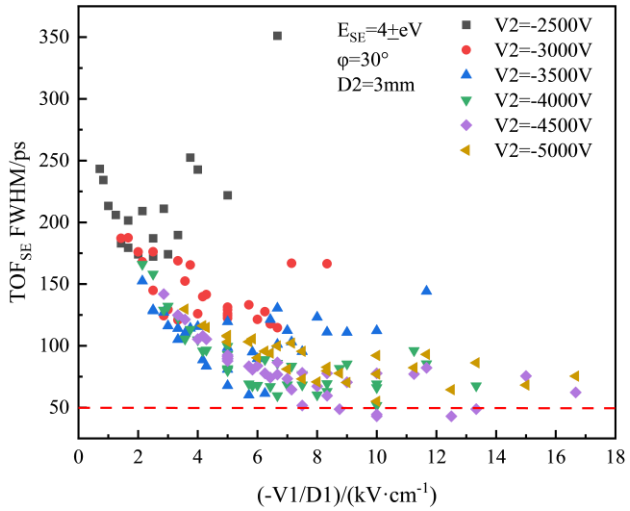
- The mass resolution mainly depends on the time resolution of TOF and energy resolution of FGIC.
- By optimizing the TOF and the FGIC, we can achieve a mass resolution of one atomic mass unit.

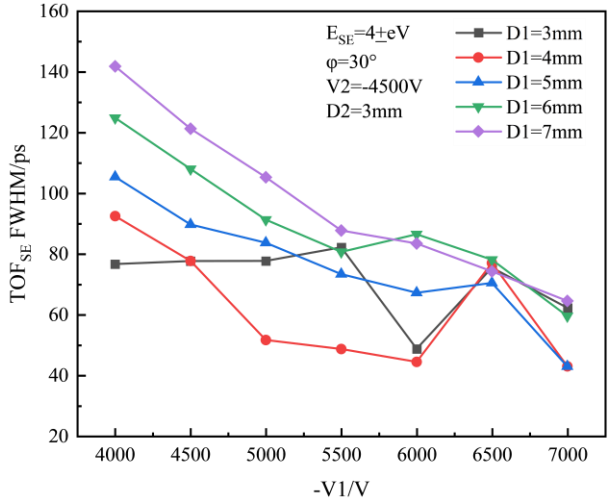
02. Physical design

- MCP secondary electron time detectors

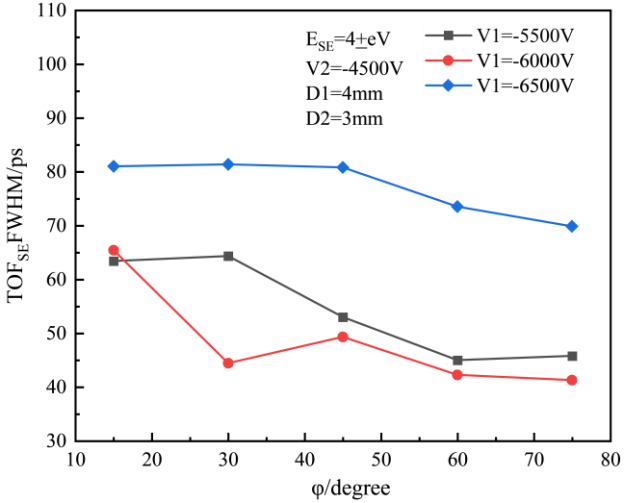


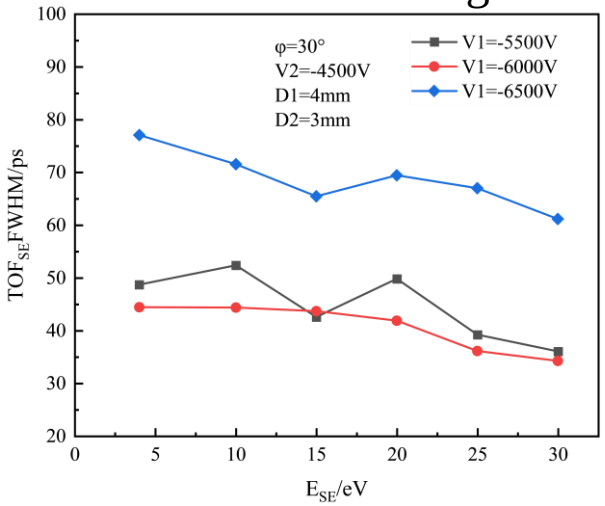






Time unfolding 44.74ps

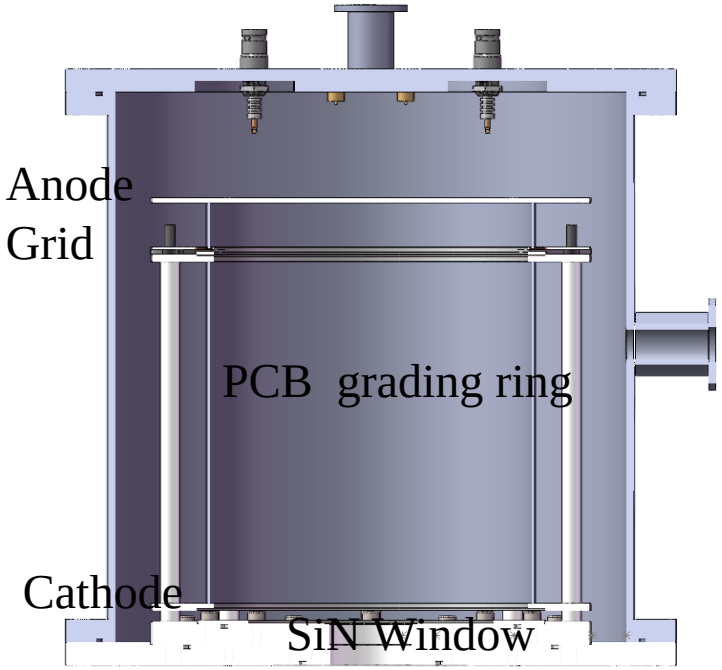




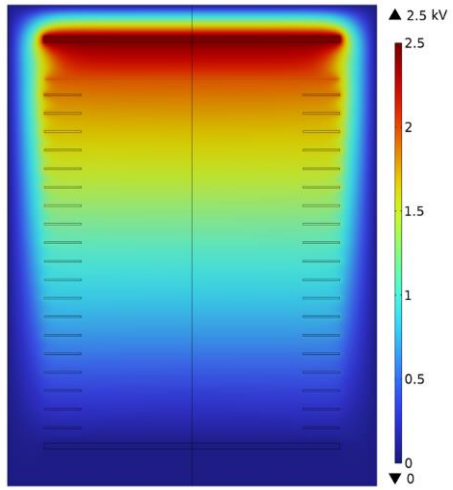
Using distances and voltages as parameters, we calculated the secondary electron time-of-flight unfolding in the time detector using COMSOL software. The optimal time unfolding can reach forty-four picoseconds.

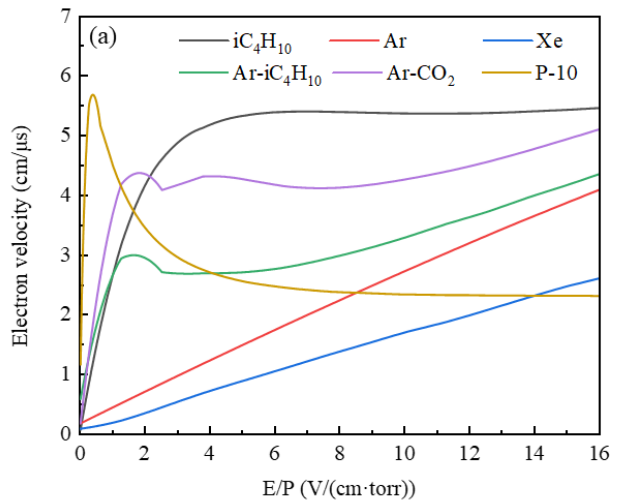
02. Physical design

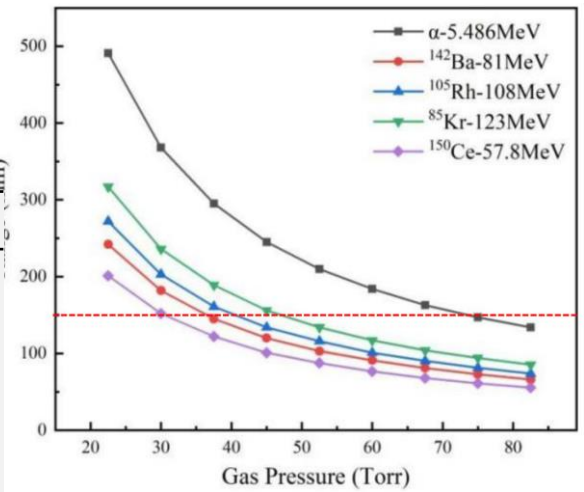
- Frisch-Grid Ionization Chamber

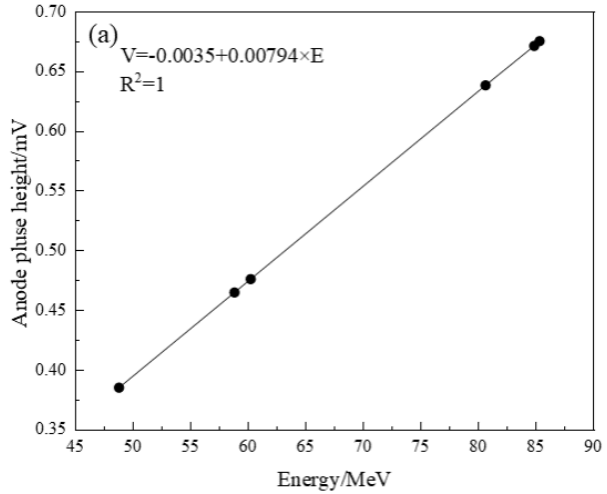


Parameters	Value
Work gas	isobutane
Gas pressure	55Torr(FFs), 75Torr(α)
D_{A-G}	20mm
D_{C-G}	150mm
Optimal E/P	6 V/(cm·Torr)
Grid	r=0.0375mm,d=0.75mm
Grid-inefficiency factor	0.007







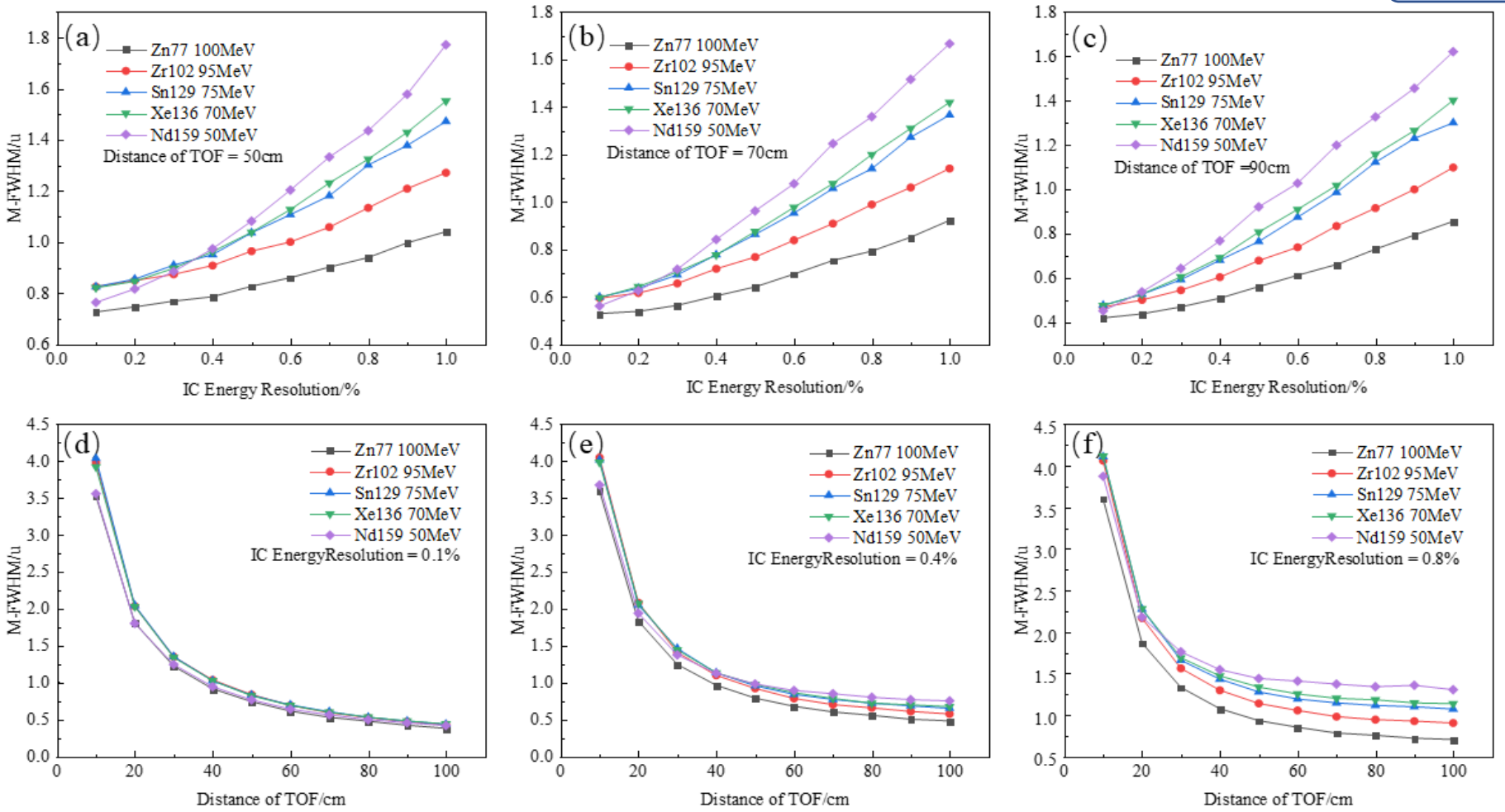


Using COMSOL, Garfield++, and SRIM software, we calculated the optimized parameters, which are shown in the right table.

02. Physical design

- Parameters calculate

The δT is set to 150ps



Distance of TOF: 10~100cm

Energy resolution of FGIC: 0.1%~1%

δM < 1u

TOF flight distance: 70cm

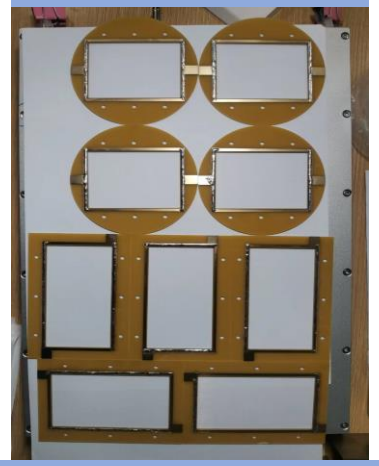
Energy resolution of light fragments: <0.8%

Energy resolution of heavy fragments: <0.6%

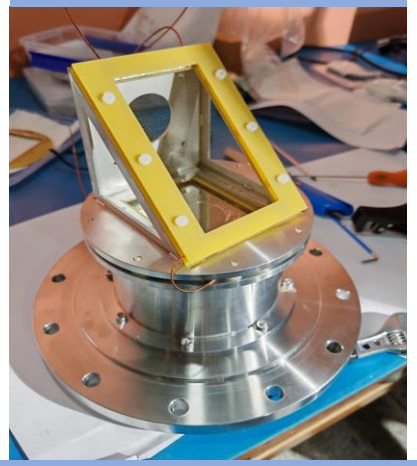
02. Physical design

- Spectrometer design and assembly

Grid Wire

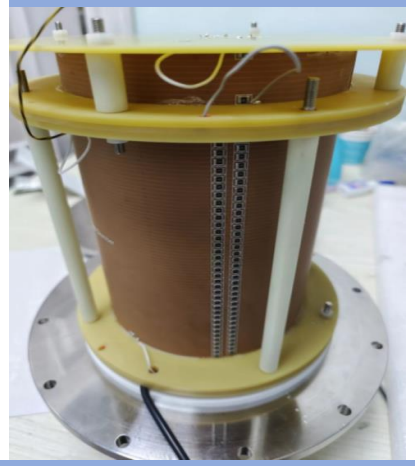


Time detector



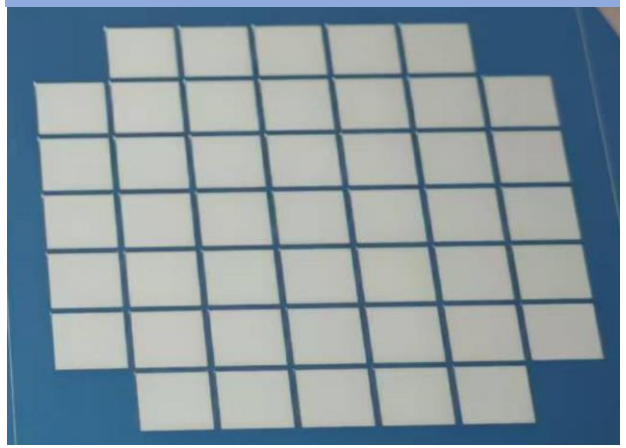
TOF detector

FGIC

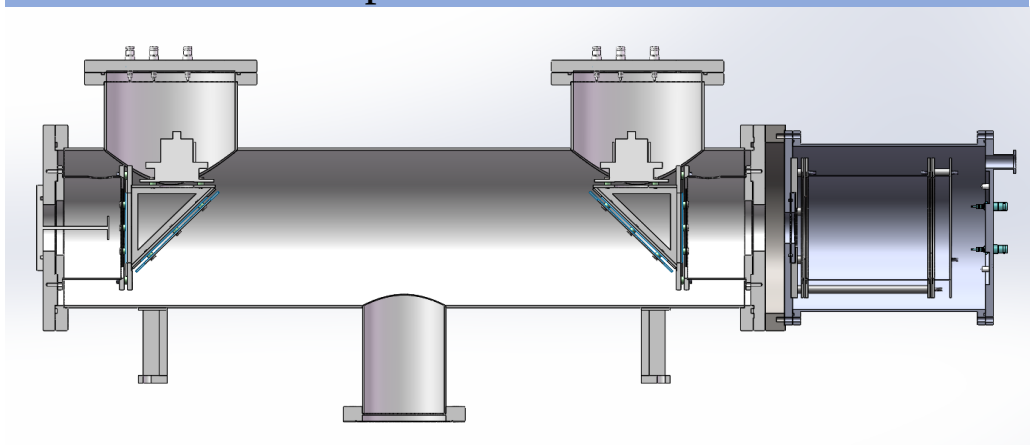


SE film: 200nm C

FGIC window: 100nmSiN



Fission spectrometer CAD model



At present, we have completed the processing and assembly of the fission spectrometer.

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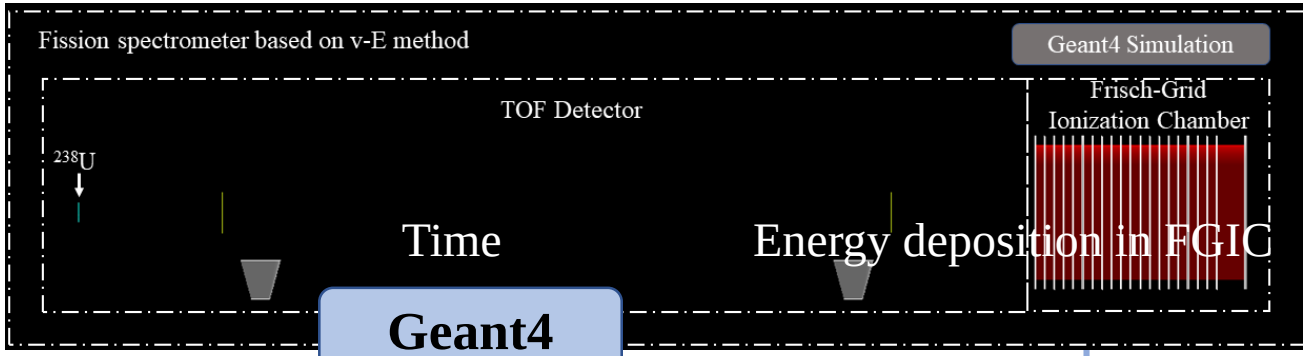
03. Monte-Carlo simulation

- Coupled simulation of 14MeV neutron induced ^{238}U fission



Geant4

t, E

ROOT

$$M = 2\frac{Et^2}{l^2}$$

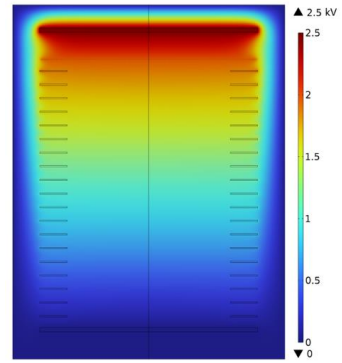
Step information

Garfield++

Anode wave

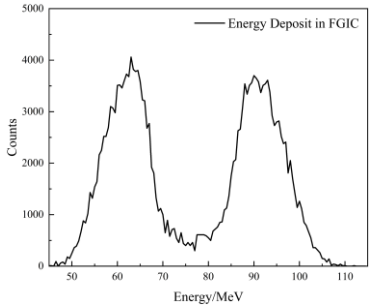
MATLAB

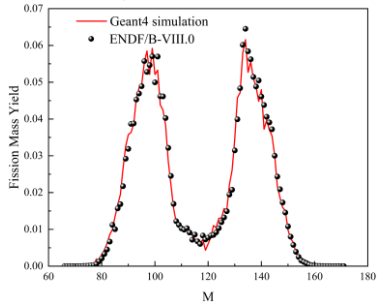
K-means Clustering algorithm

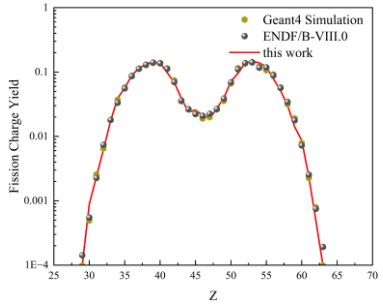


COMSOL

Electric field

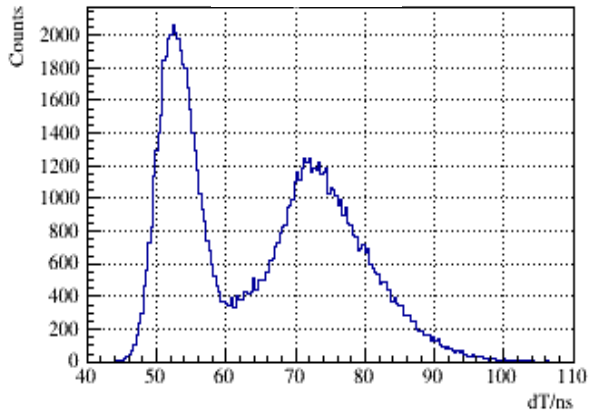


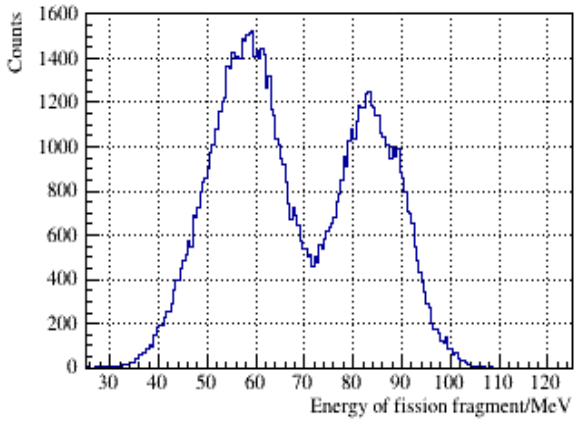


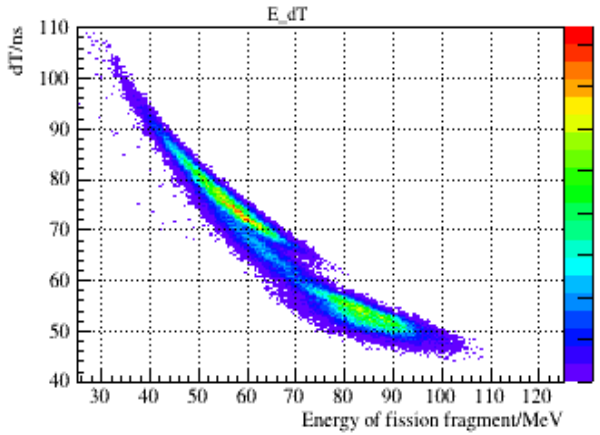


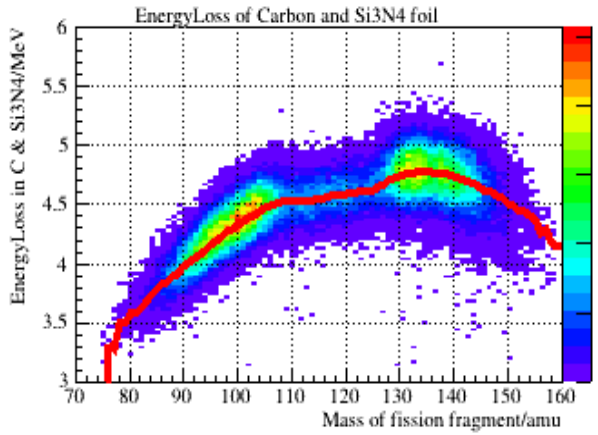
03. Monte-Carlo simulation

- Mass yield distribution







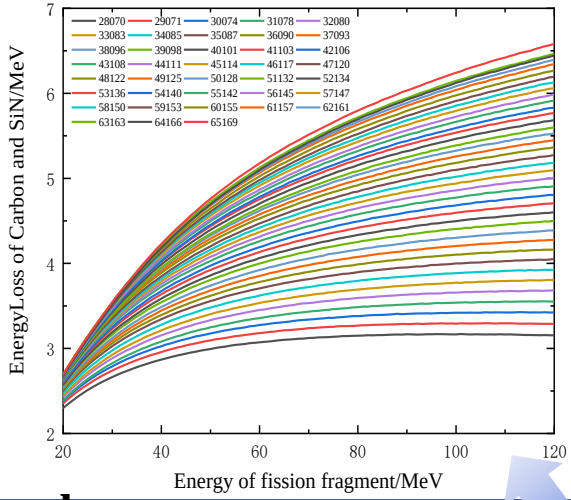


Time~40-110ns

EnergyLoss~3-5.5MeV

Energy in FGIC~30-110MeV

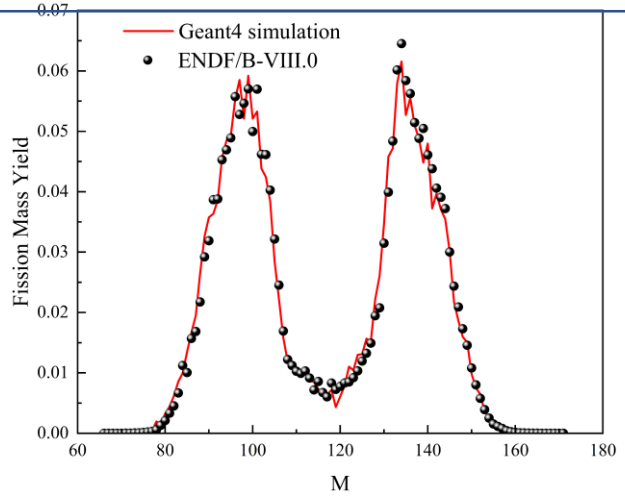
The energy loss matrix calculated by Geant4



kinetic energy theorem

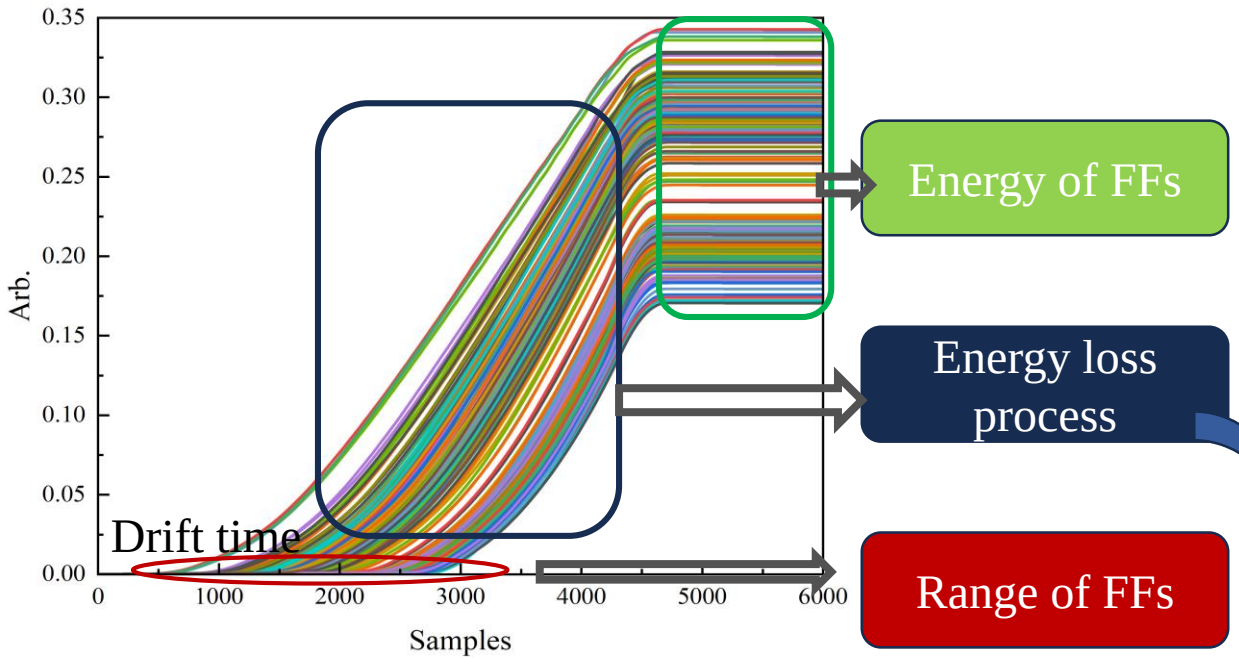
$$M = 2\frac{E^2 t^2}{l^2} \qquad E = E_{FGIC} + E_{SiN,C} \qquad E_{SiN,C} = f(M,E)$$

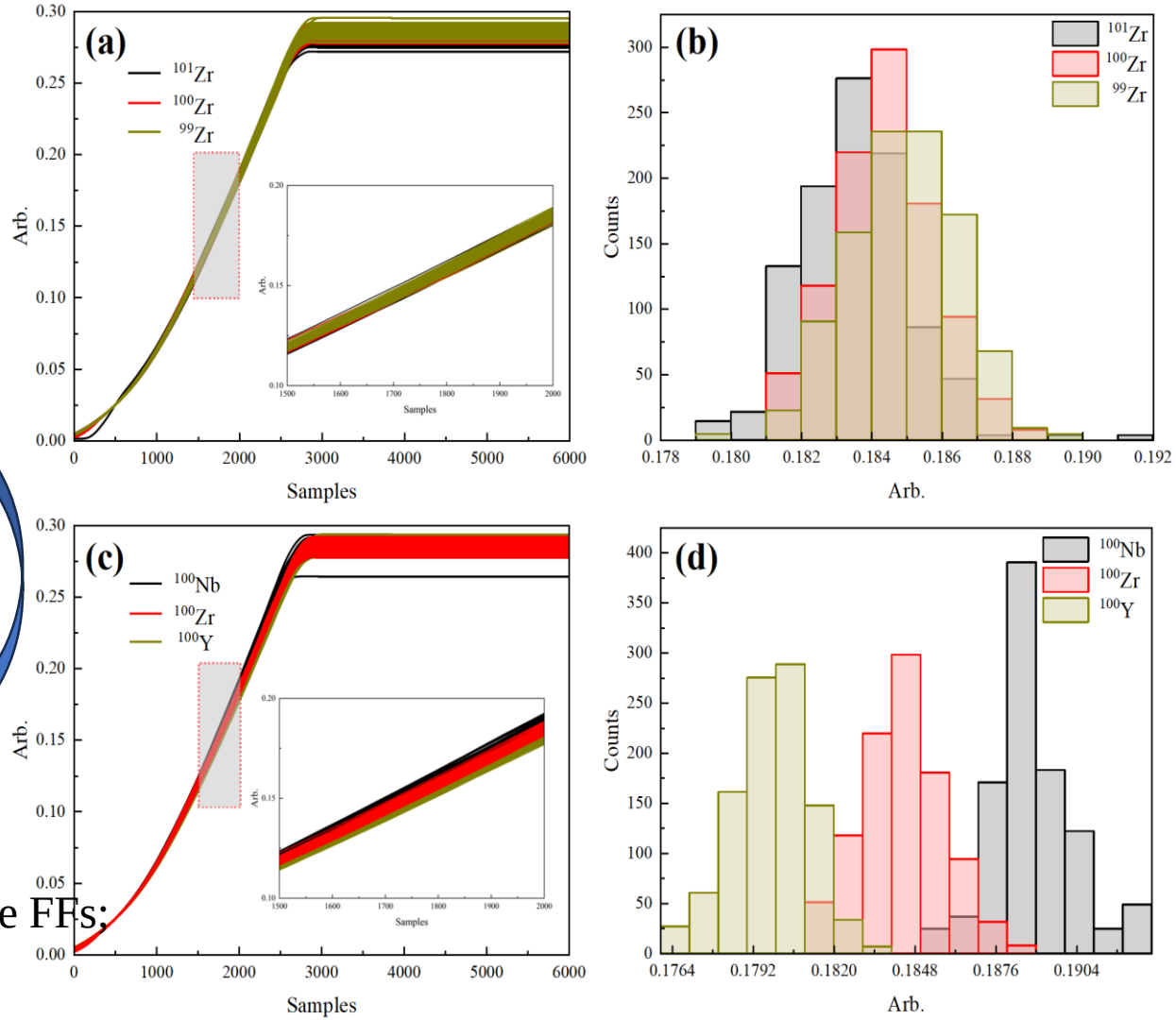
Iteration algorithm



03. Monte-Carlo simulation

- Charge yield distribution





- Bethe-Bloch equation

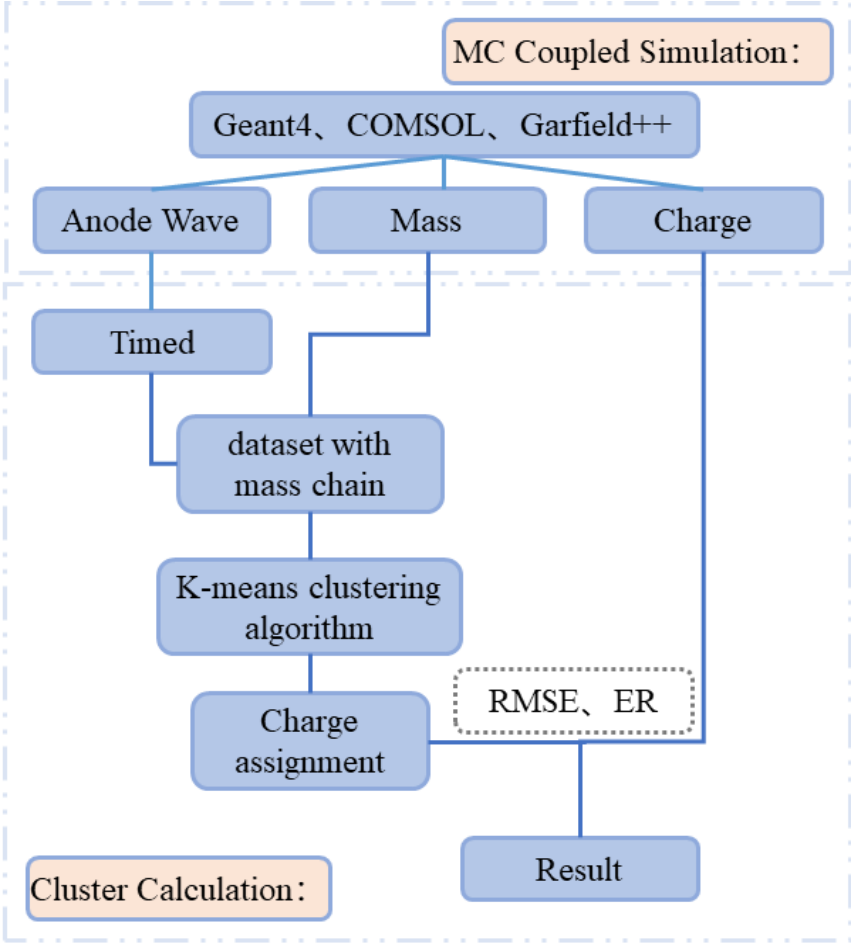
$$-\frac{dE}{dx}=\frac{4\pi z^2 e^4 N_t Z_t}{m_e v^2}\ln\left(\frac{2m_e v^2}{I}\right)$$

z: effective charge of the FFs, correlated with the charge(*Z*) of the FFs;

v: velocity of the FFs, correlated with the energy(*E*) of the FFs;

03. Monte-Carlo simulation

- K-means clustering algorithm



Workflow diagram of K-means clustering algorithm

- K-means clustering algorithm

intra-cluster similarity:

$$SSE = \sum_{i=1}^{k} \sum_{x \in C_i} \| x - u_i \|^2$$

the square of the Euclidean distance

Sum of Squared Errors

cluster separation:

$$ICD = \sum_{i=1}^{k} \sum_{j=1, j \neq i}^{k} \| u_i - u_j \|^2$$

Inter-Cluster Distance

Elbow Rule:

$$Ratio = \frac{SSE}{ICD}$$

- K-means evaluation criterion

global quantification:

$$RMSE = \sqrt{\frac{1}{N_Z} \sum_{i}^{N_Z} (Y_{Cluster,i} - Y_{Geant4,i})^2}$$

Root Mean Square Error

misclassification rate:

$$ER = \frac{N_{errors}}{N_{total}} \times 100\%$$

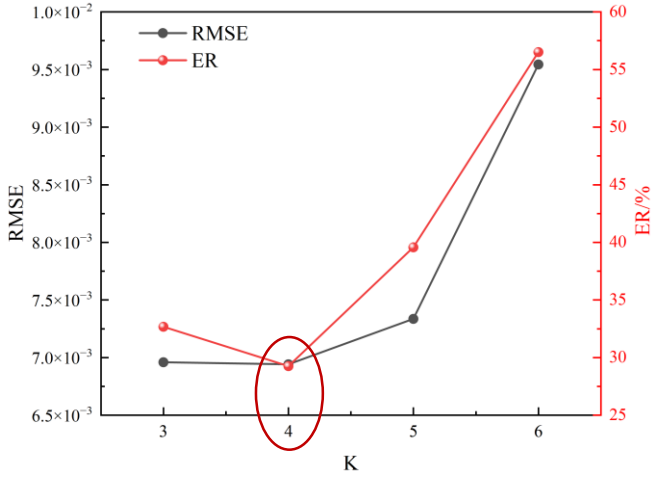
Error Ratio

Dataset:

N_{total}: 203040 $Mass$: 70~159 $Nuclear\ charge$: 29~63

03. Monte-Carlo simulation

- Nuclear charge distribution
  - The fission charge yield distribution can be obtained by counting the charge calculation results of each mass chain.
  - We discussed the clustering results of different clusters and applied the Elbow Rule.
  - When the cluster is equal to four, the best result is obtained.
  - The RMSE of the Elbow Rule is maybe better, but there are subjective factors.
  - In the Elbow Rule, there are forty-four mass chains with cluster four and thirty-four mass chains with cluster five. When only the fission fragments with more than three percent in each mass chain are considered, the charge type four is the largest, accounting for about fifty-seven percent.
  - We choose the cluster number 4 for the charge distribution.

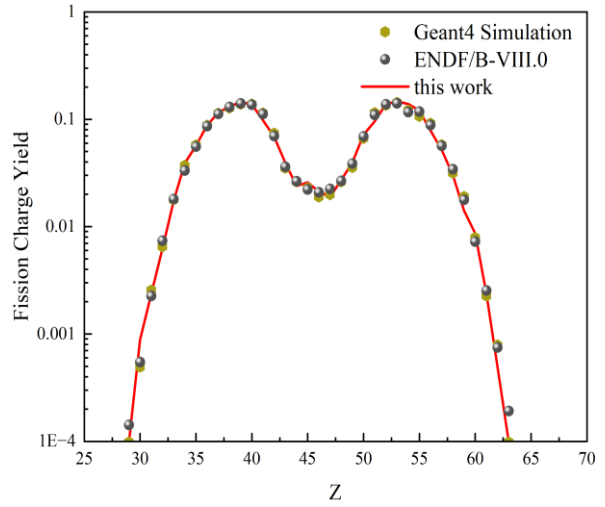


Considering only fragments with >3% yield per mass chain

Number of Z	Counts	Proportion
3	11	11.96%
4	53	57.61%
5	17	18.48%

k	RMSE	ER
3	6.96×10^{-3}	32.68%
4	6.94×10^{-3}	29.26%
5	7.34×10^{-3}	39.56%
6	9.54×10^{-3}	56.51%
Elbow Rule	6.76×10^{-3}	30.48%

K=4, 44 mass chains, 47.83%
K=5, 34 mass chains, 36.96%



04. Summary

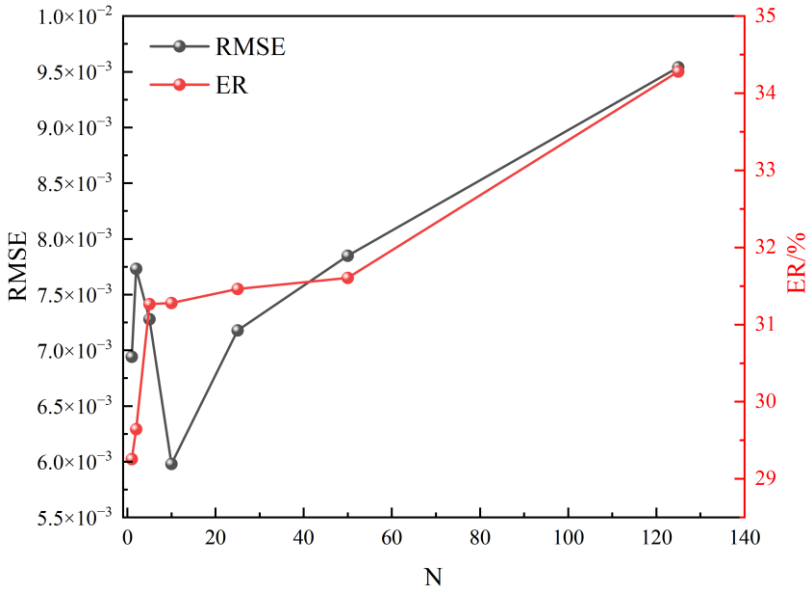
- Sampling rate and signal noise ratio

Considering the applicability of the method to experimental data, the effect of sampling rate and Signal Noise Ratio on clustering results must be discussed.

$$\mathrm{NSR} = \frac{\mathrm{OSR}}{N}$$

- Original Sampling Rate (OSR) in Garfield++: 1GHz
- new sampling rate (NSR) is defined as 1/N of the OSR

As the sampling rate decreases, the clustering effect becomes worse.



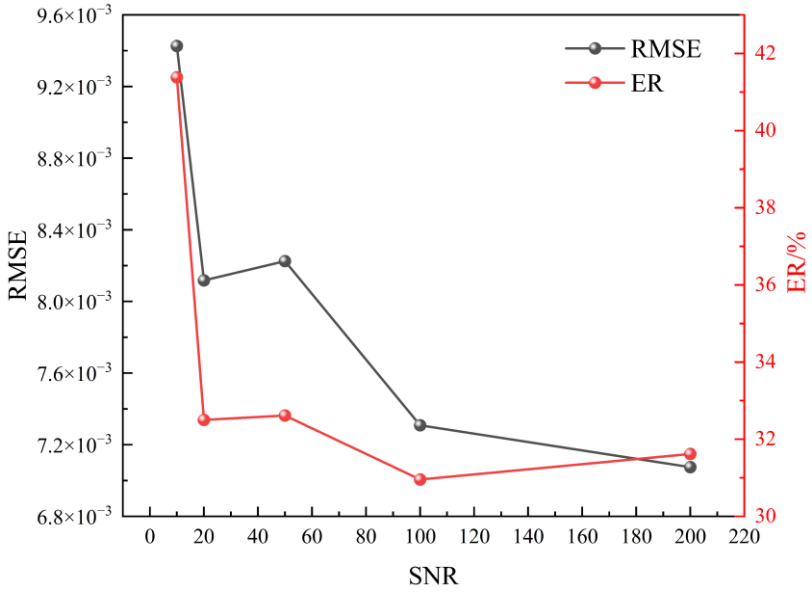
The SNR is defined as the ratio of the maximum value of the wave to the mean value of the noise.

$$\mathrm{SNR} = \frac{V_{\max}}{V_{nosise}}$$

The waveform after adding noise is the sum of the original waveform and noise.

$$W_{Anode,noise} = W_{Anode} + \frac{V_{\max}}{SNR} \cdot \mathrm{gaus}(0,1)$$

As the SNR becomes larger, the clustering effect becomes worse.



CONTENTS:

04. Summary

Physics design

1. MCP secondary electron time detector designed and optimized in COMSOL, achieving TOF_{SE}-FWHM <50ps;
2. Frisch-grid ionization chamber designed with key operating parameters determined;
3. Fission spectrometer parameters requirement finalized, and physical design, manufacturing, and setup accomplished.

Monte-Carlo simulation

1. Simulated 14 MeV n+^{238}U fission using Geant4/COMSOL/Garfield++ coupling, obtaining mass yields through velocity-kinetic energy method;
2. Propose a method for measuring fission charge yield distribution based on K-Means clustering algorithm;
3. Obtain fission charge yield distribution with RMSE 6.95×10^{-3} and ER 29.6%.

Thank you for your attention