TPC-Drum experiment for alpha cluster search at RAON

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KSHEP conference

Chonnam National University, Gwangju, Nov 20, 2025

Forward detector for EIC

Yongsun Kim (Sejong Univ)

KSHEP 2023 가을 학술대회 2023.11.23

임영진 2006, (전남대)

墳周土器를 통해 본 5-6世紀 韓日關係 一面

林永珍*

< 目 次 >

요 약

삼국시대 한국 서남부지역에서는 세가지 유형의 분주토기들이 고분 장엄구로 사용되었다. 당시 서남부지역의 중심권을 이루고 있었던 나주 반남 일대의 대형 고분에서는 筒A形의 분주토기가 사용되었고 나주 반남 일대를 둘러싼 주변지역의 토착계 중형 고분에서는 壺形의 분주토기가 사용되었으며 같은 주변지역이라도 일본과 관련된 장고분에서는 筒B形의 분주토기가 사용되었다.

한국 서남부지역에서 사용되었던 이 세가지 유형의 분주토기는 일본 北九州 지역과의 교류 속에서 壺A形, 筒A形, 筒B形의 순으로 사용되기 시작하였다. 6세기중엽경이 되면 세가지 분주토기 모두 현지에서는 더 이상 지속되지 못하게 되지만 壺形과 筒A形 두가지 분주토기는 일본으로 파급되었는데 이는 현지 마한계 주민들의 일본 이주가 있었음을 의미한다.

마한계 주민의 일본 이주는 그 이전부터 백제의 영역 확장과 관련되어 간헐적으로 이루어져 온 바 있다. 3세기중엽 이후부터 백제에 밀리기 시작하였던 마한에서는 3세기 후엽경 아산만권을 중심으로 일본으로의 이주가 이루어졌으며 4세기중반경에는 충청 내륙지역과 전북지역을 중심으로 일본으로의 이주가 이루어졌다.

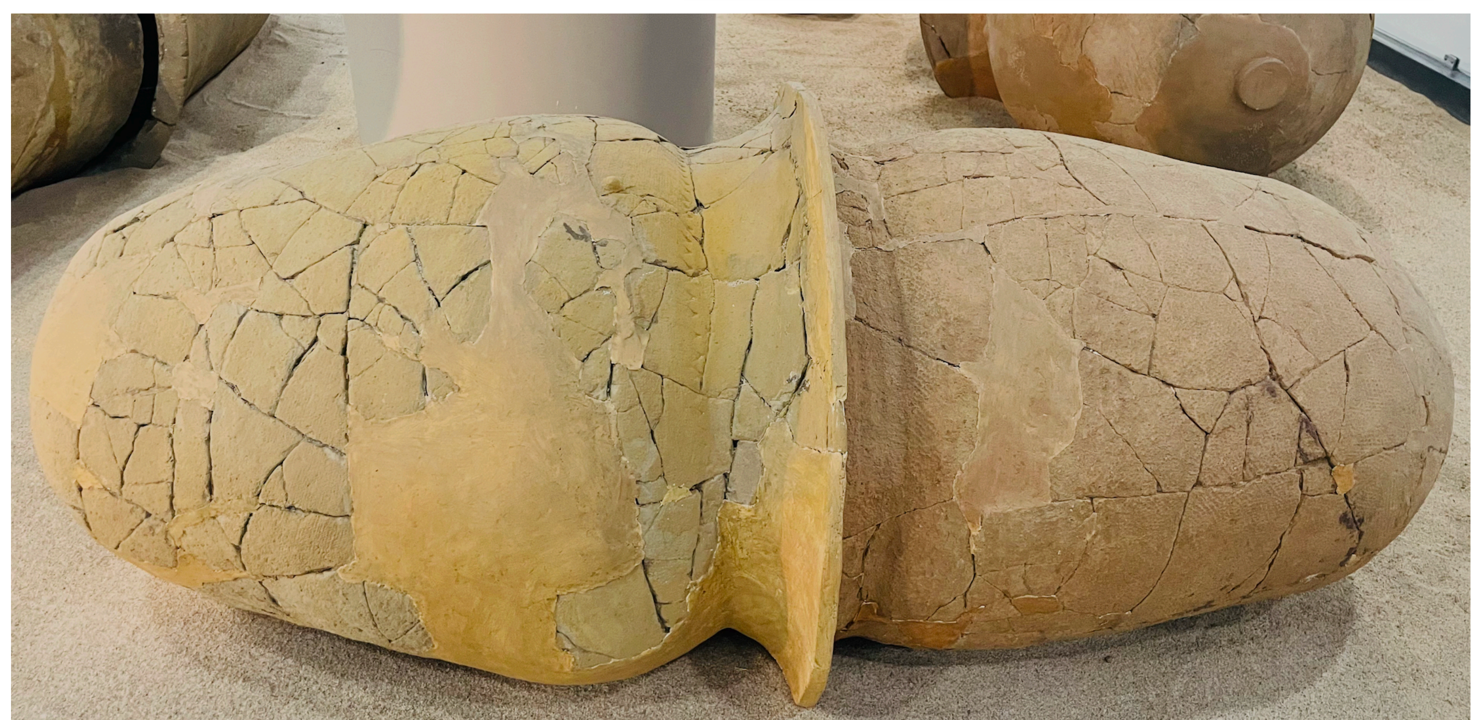
6세기중엽경에 나타나고 있는 壺形, 筒A形 분주토기의 일본 파급이 서남부지역 마한계 주민들의 일본 이주를 의미한다는 것은 일본으로 파급되지 못하고 완전히 단절되는 筒B形 분주토기를 썼던 사람들의 성격을 살펴보면 보다 쉽게 이해된다. 筒B形이 사용되었던 장고분은 거시적으로 보면 大和政權의 일본열도 통합과정에서, 미시적으로 보면 磐井에 의해 北九州 지역이 통합되는 과정에서 밀리게 되었던 北九州 지역의 세력자가 그 주인공인 것으로 보인다. 이들은 자신들의 망명지인 마지막 마한지역이 6세기중엽경 백제에 병합됨에 따라 더 이상 피할 곳이 없어지면서 장고분과 筒B形 분주토기를 쓸 수 없게 되었던 것으로 판단된다.

결론적으로 6세기중엽경 백제의 병합에 따라 서남부지역의 토착 마한세력 일부는 일본으로 망명하였고 나머지 주민들과 일본에서 망명하였던 세력들은 마지막 안식처를 백제에 복속되었다고 본다.

[주제어] 분주토기, 장고분, 6세기중엽, 마한, 백제, 북구주, 망명

* 全南大 敎授

(접수일 : 2006. 4. 27, 심사일 : 2006. 6. 1, 심사완료일 : 2006. 6. 9)



전남대 박물관 마한관

장고분

장고

장고분

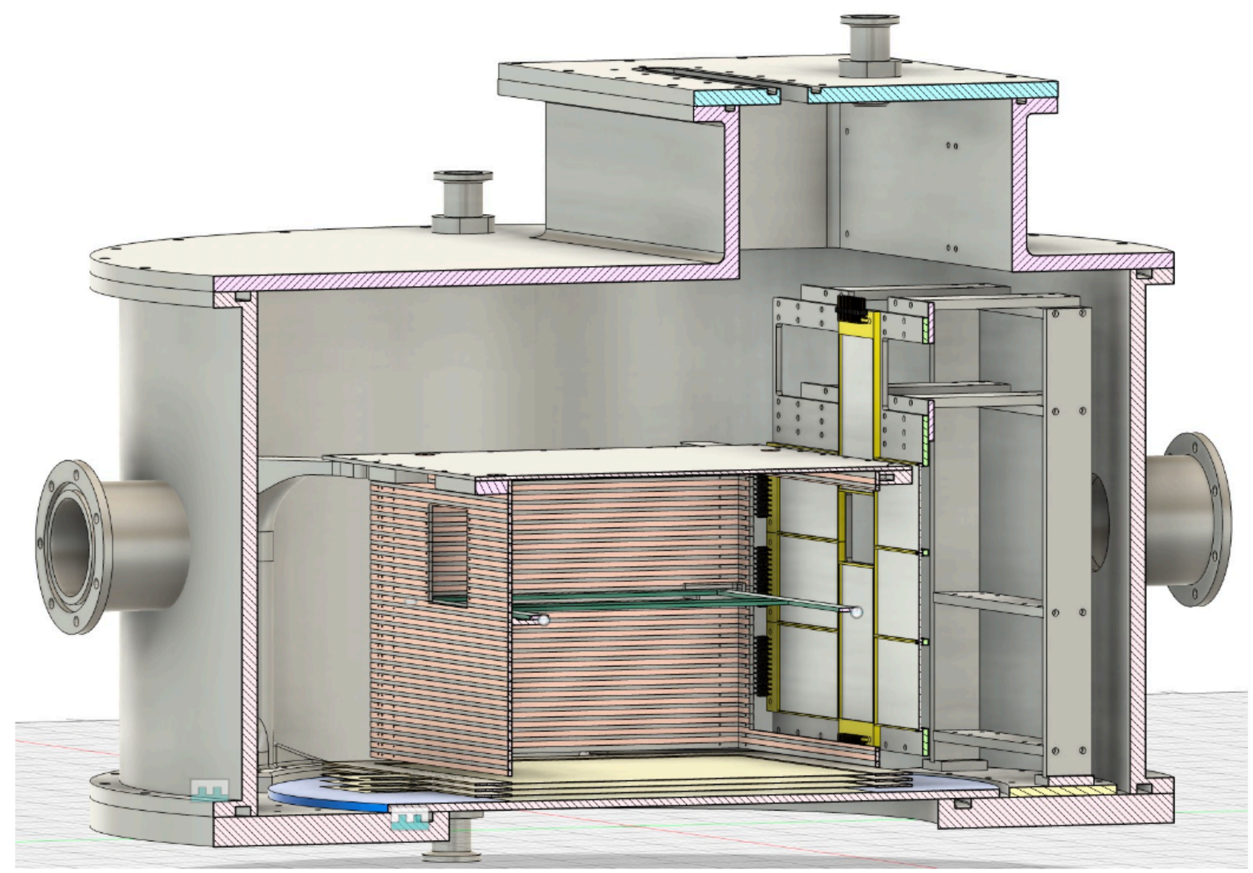
장고

Drum

장고분

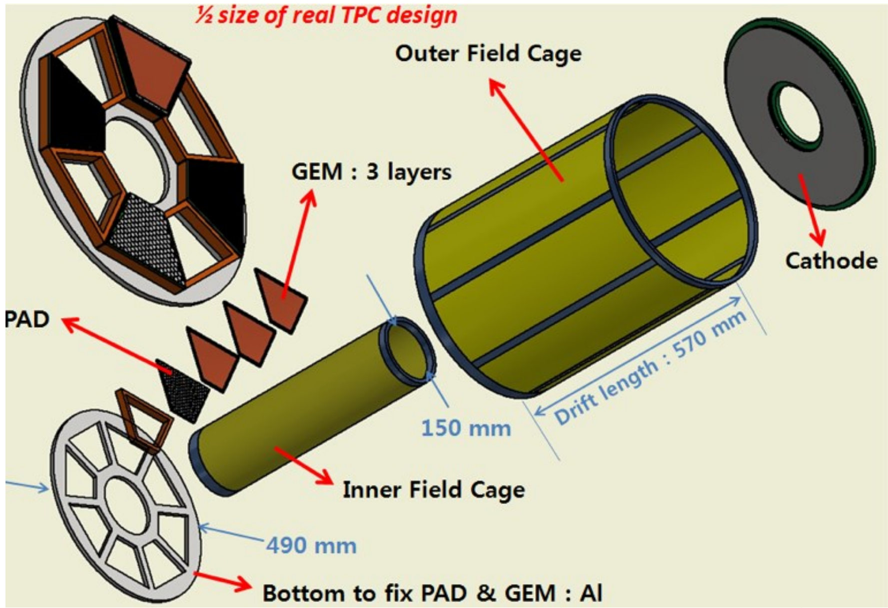
장고

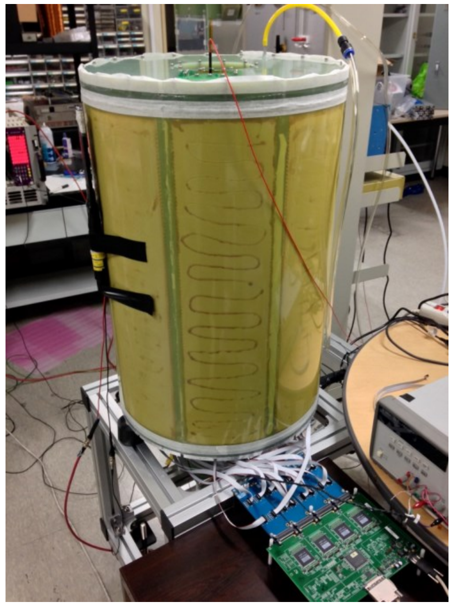
Drum

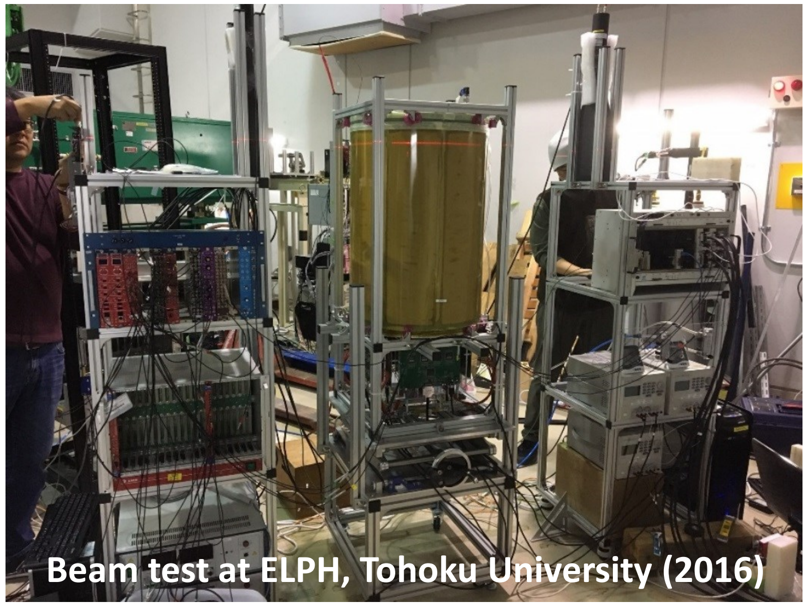


TPC-Drum

High Energy LAMPS experiment

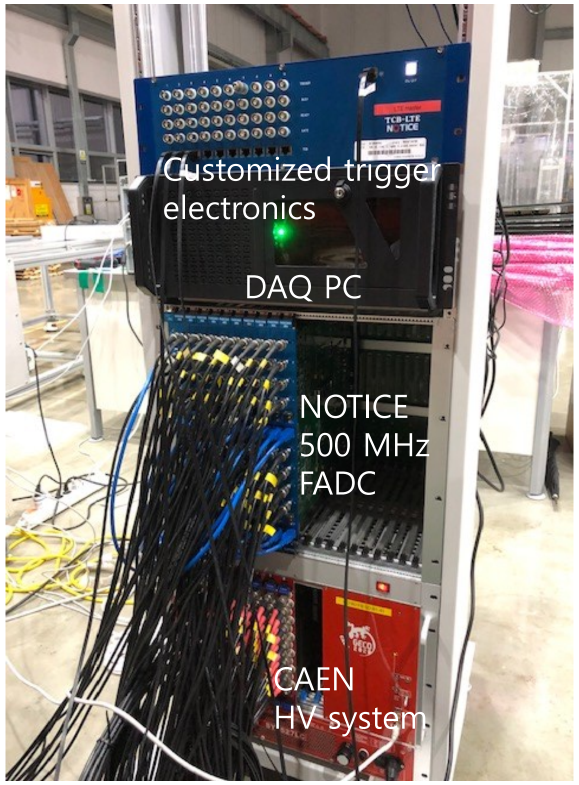






Beam test at ELPH, Tohoku University (2016)

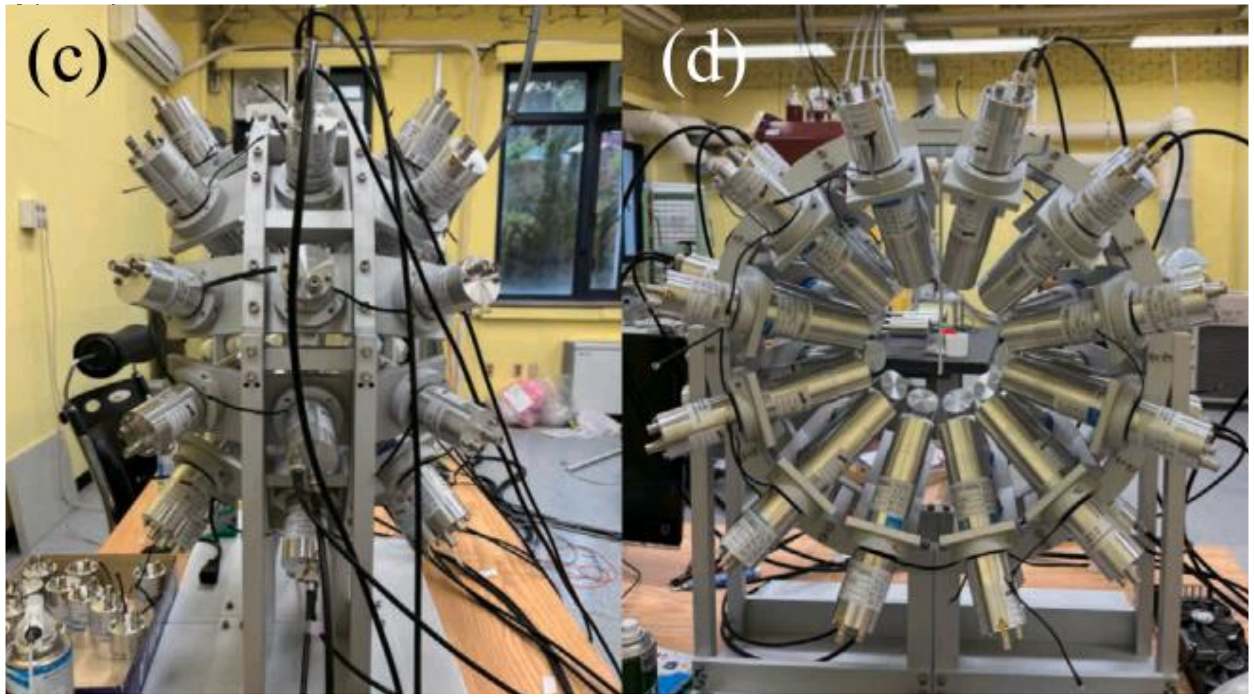
Assembled detector system at the Sejong Campus of Korea Univ.



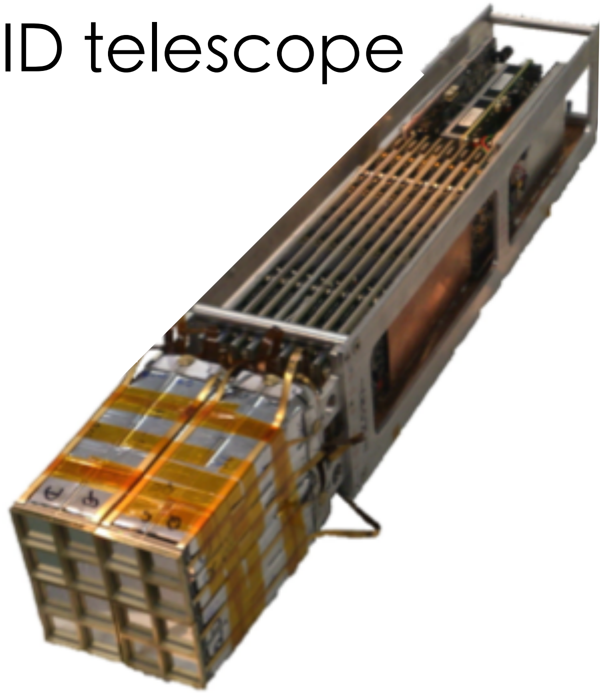
First station assembled at the high-energy experimental hall of the RAON site

Low-Energy LAMPS experiment

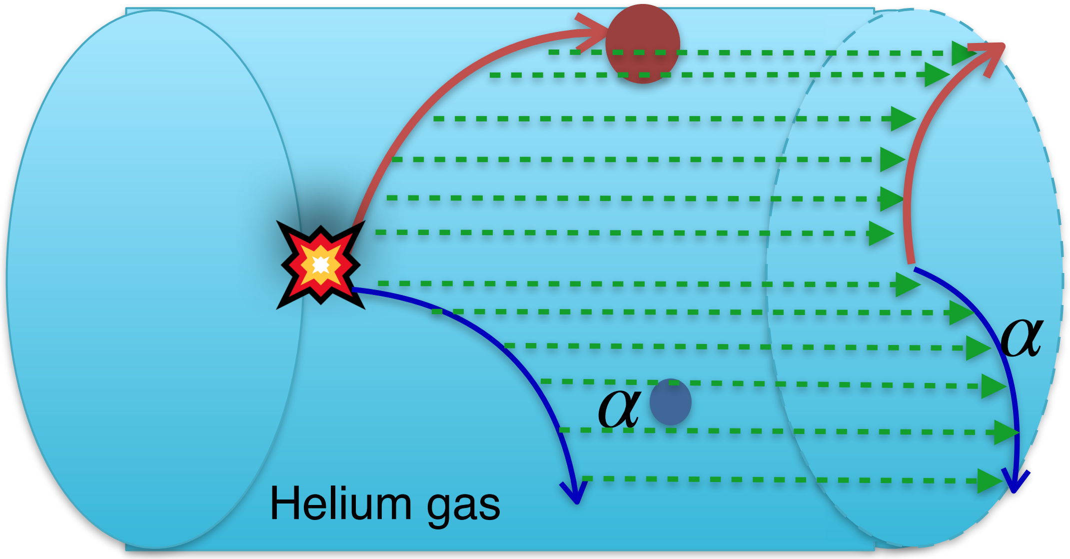
LaBr3 gamma detector w/ precise



Silicon CsI PID telescope



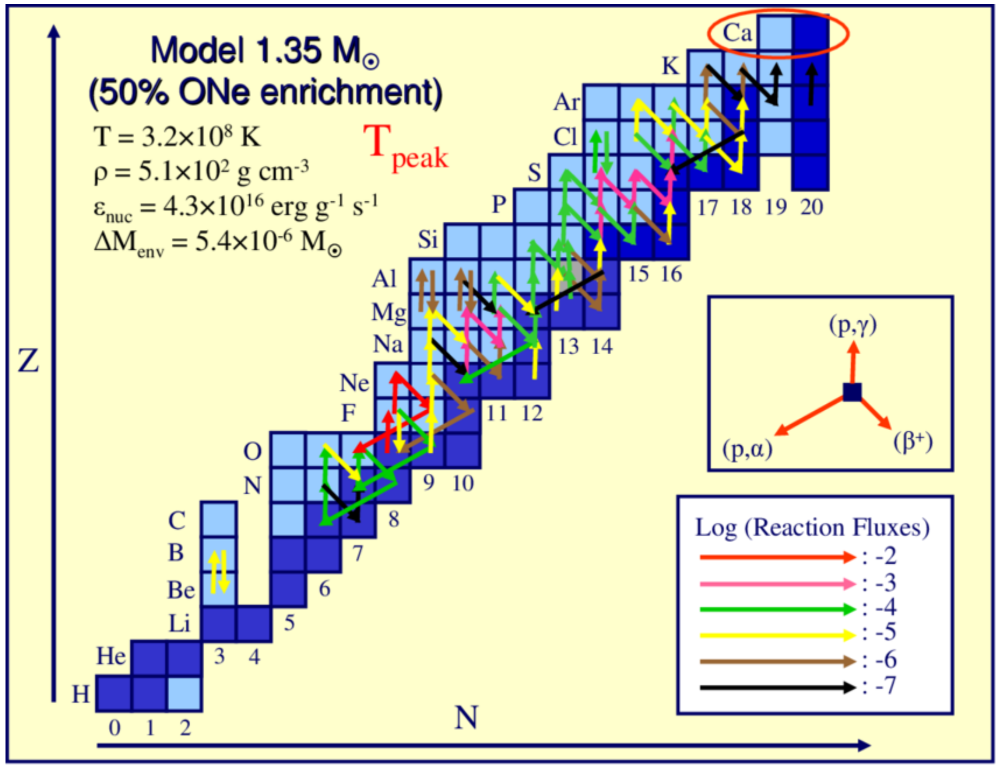
1.5 T SC magnet



Active target time projection chamber

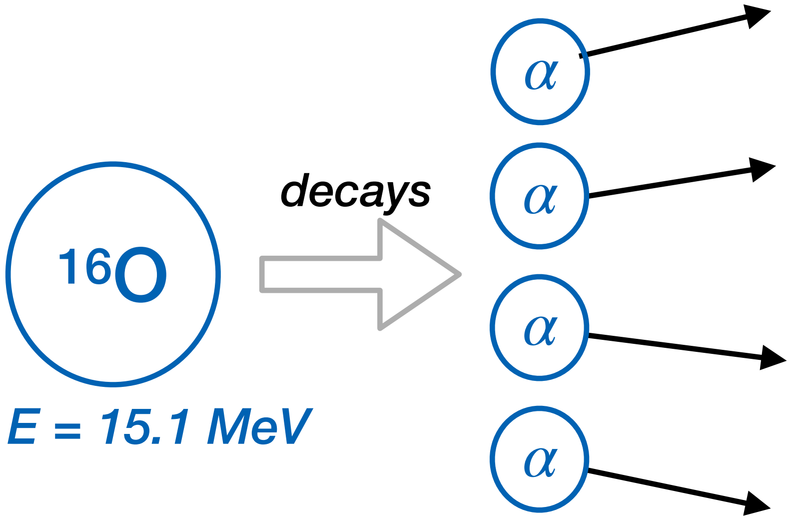
Alpha-involved channels

- Astrophysical channels in Nova models
  - $^{14}O(\alpha, \gamma)^{18}Ne$, $^{15}O(\alpha, \gamma)^{19}Ne$, $^{18}Ne(\alpha, \gamma)^{22}Mg$
  - $^{14}O(\alpha, p)^{17}F$, $^{15}O(\alpha, p)^{18}F$, $^{18}Ne(\alpha, p)^{21}Na$, $^{22}Mg(\alpha, p)^{25}Al$, $^{16}O(\alpha, pn)^{18}F$
  - $^{18}F(p, \gamma)^{19}Ne$, $^{65}As(p, \gamma)^{66}Se$
  - $^{29}P(d,\alpha)^{30}P$
  - Requires good energy resolution and PID

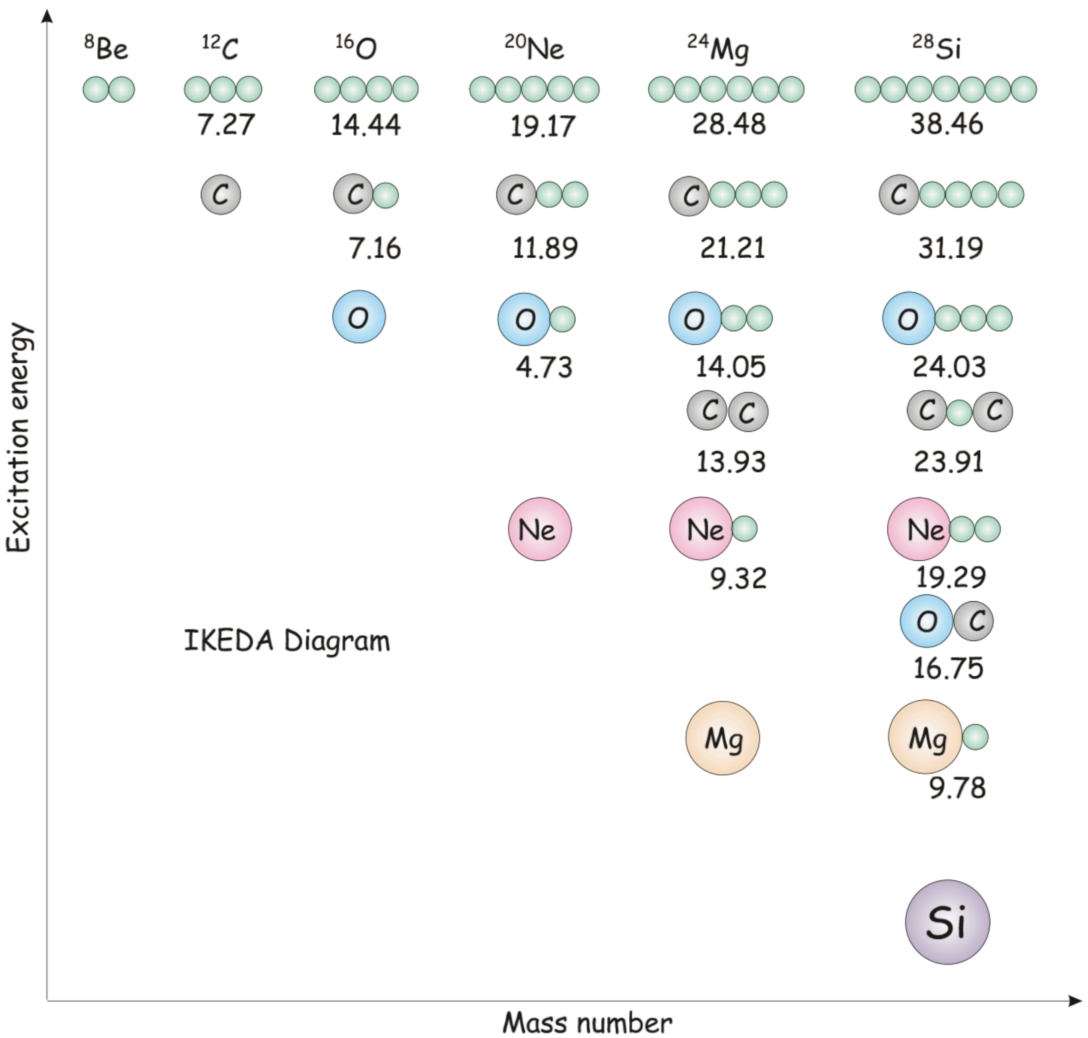


J. Jose, NIC 2010

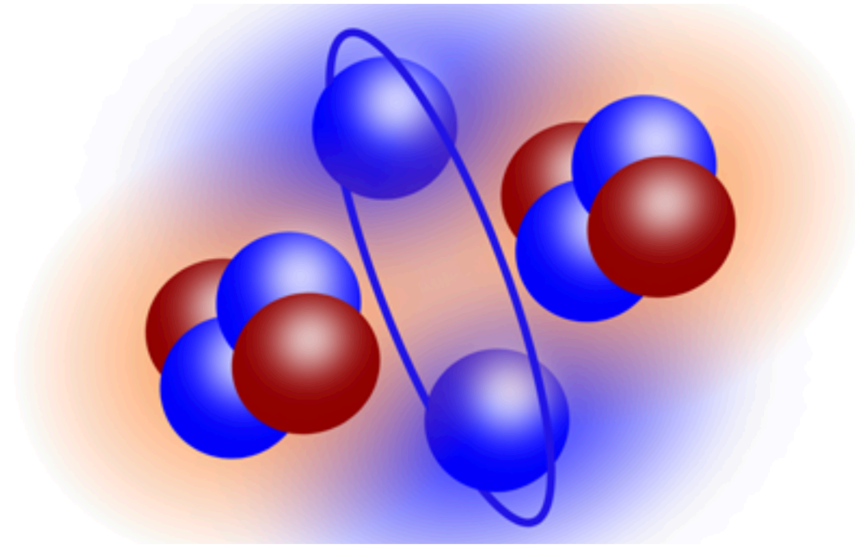
- Clustering phenomena in alpha-conjugate nucleus
  - Linear chain, Alpha molecular states
  - Search for direct 3α decays of Hoyle state
  - Search for Hoyle-like states in ^{16}O, ^{20}Ne, ^{24}Mg, …
  - Requires good angular and energy resolution with side acceptance for protons and ^{4}He



Alpha clusters in nuclei



Physics SYNOPSIS P. J. Li et al., published in PRL on Nov 2023



Nuclear Ground State Has Molecule-Like Structure

Published 21 November 2023

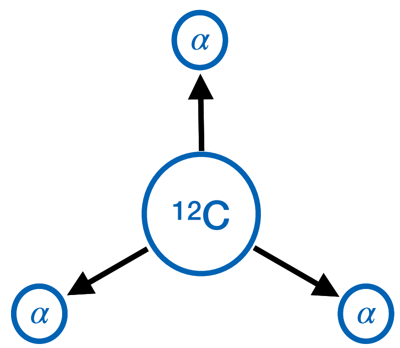
The protons and neutrons in a nucleus can form clusters analogous to atoms in a molecule, even in the nuclear ground state.

- Clustering phenomena in alpha-conjugate nucleus and molecular states with alpha cores are of interest for low-E LAMPS experiment
- Search for linear chain and exotic geometry of alpha clusters will be studied as well
- LMAPS AT-TPC is designed to measure alpha tracks all the way down to the collision vertex

Observables

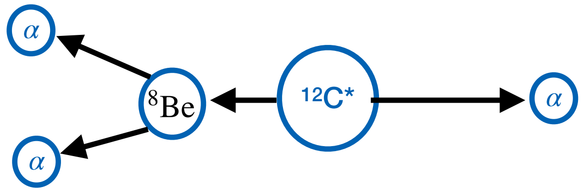
Search for Direct 3α decay

$$^{12}\mathrm{C}_{\mathrm{Hoyle}} \to \alpha + \alpha + \alpha$$



- Signature of BEC-like alpha condensate
- Never observed with significant statistics
- Major background is sequential decay

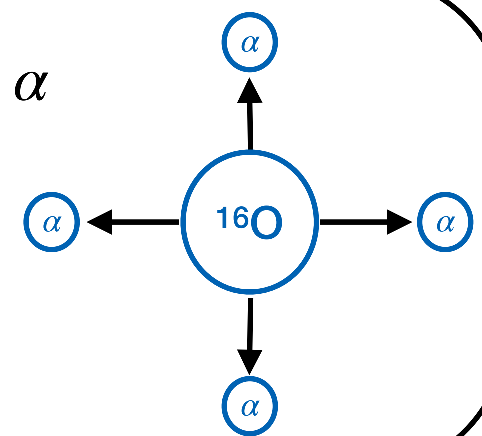
$$^{12}\mathrm{C}_{\mathrm{Hoyle}} \to {}^{8}\mathrm{Be} + \alpha \to \alpha + \alpha + \alpha$$



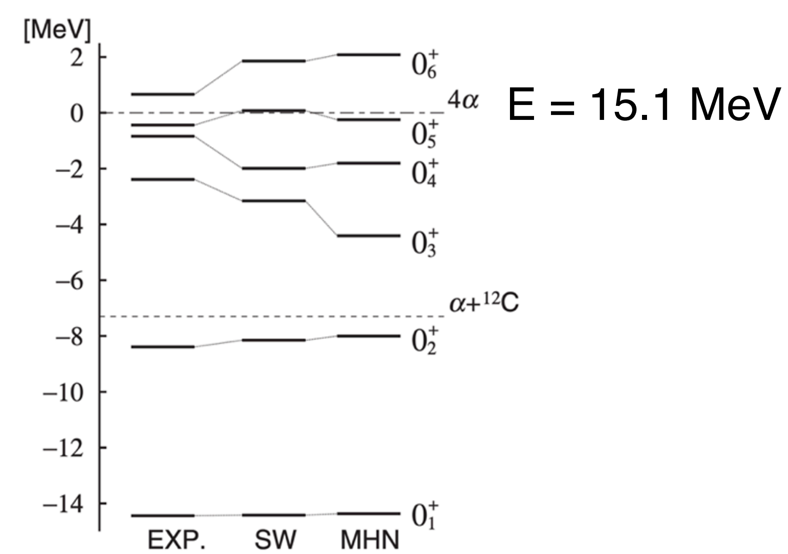
A.Tohsaki et al., Phys. Rev. Let. 87 (2001) 192501

Search for Hoyle-like state in ^{16}O

$$^{16}\mathrm{O}* \to \alpha + \alpha + \alpha + \alpha$$



- Strong candidate for α-cluster of in ^{16}O
- If exists, 4α decay must be observed
- 4α threshold E = 15.1 MeV



Y. Funaki et al., J. Phys. G: Nucl Part. Phys. 37 (2010) 064012

Observables

nature communications

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Article | Open access | Published: 11 December 2023

The 5α condensate state in ^{20}Ne

Bo Zhou, Yasuro Funaki, Hisashi Horiuchi, Yu-Gang Ma, Gerd Röpke, Peter Schuck, Akihiro Tohsaki & Taiichi Yamada

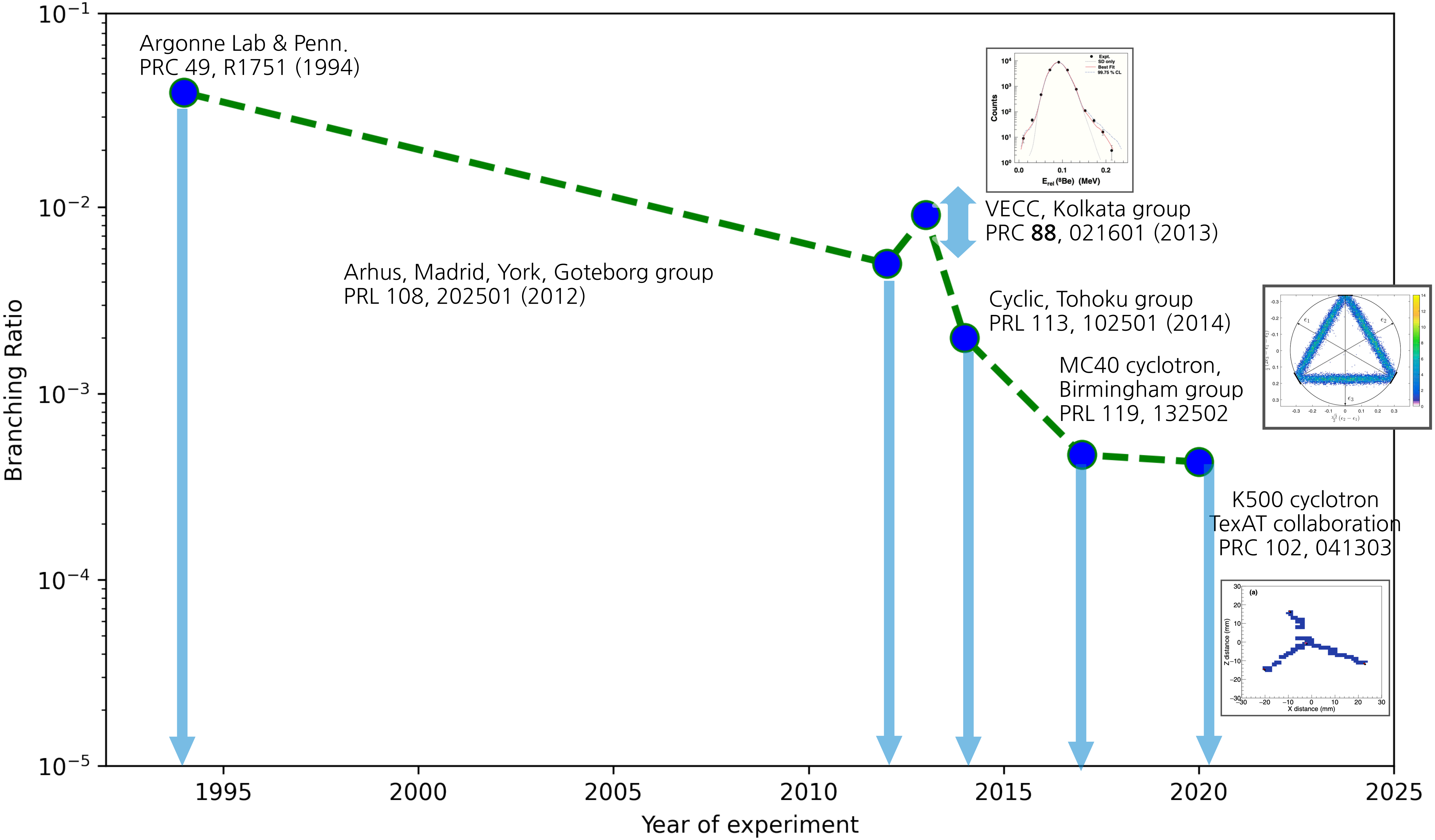
Nature Communications **14**, Article number: 8206 (2023) | Cite this article

5496 Accesses | **50** Citations | **64** Altmetric | Metrics

Abstract

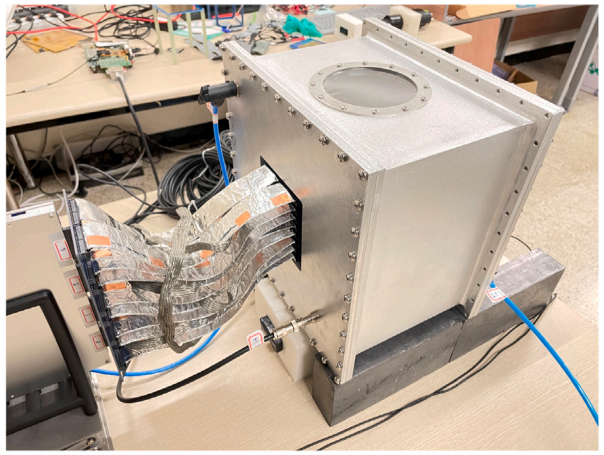
The formed ^{4}He (α) clusters consisting of two neutrons and two protons can be a building block in light nuclear systems. Intriguingly, these alpha clusters could potentially form alpha condensate states within the nuclear system. The Hoyle state at 7.65 MeV in ^{12}C, which plays an essential role in stellar nucleosynthesis, is now considered to be a phase transition, namely the 3α Bose-Einstein condensate. Confirming the existence of Hoyle-analog states in $N\alpha$ nuclei ($N > 3$) remains a major challenge. Here we show microscopic five-body calculations for the ^{20}Ne nucleus. We find that one excited 0^+ state has a distinct gas-like characteristic and represents the condensate state. Identifying the 5α condensate state is an important step in establishing the concept of α condensation in nuclear fermion systems.

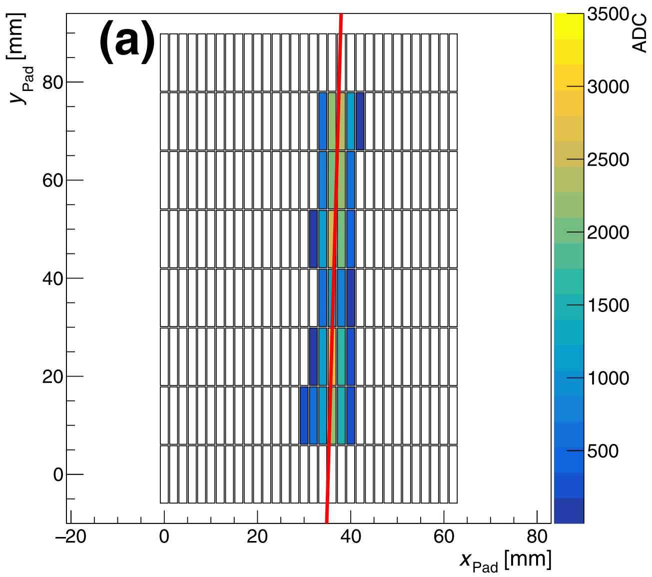
Branching Ratio of direct decay in Hoyle state

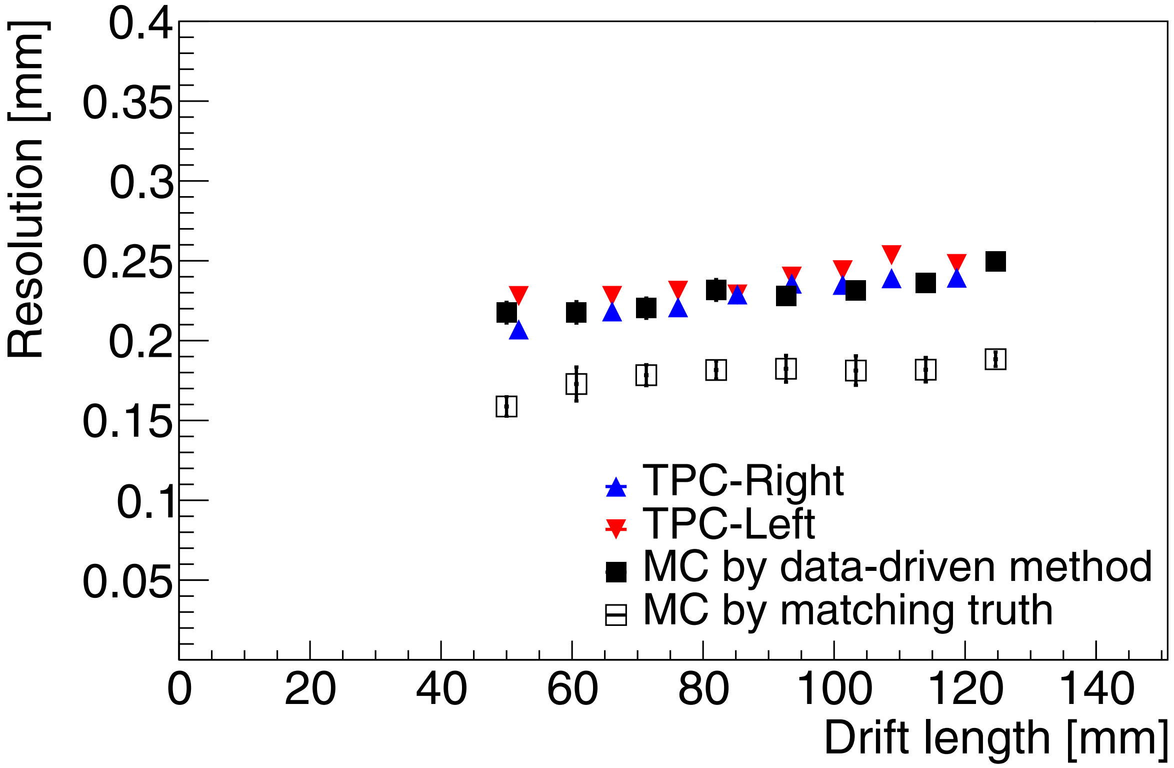


Prototype TPC

We made two cubic TPC's were to measure the quasi-free elastic scattering in ^{12}C + p at HIMAC







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Full Length Article

Characteristics of the prototype LAMPS TPC for low-energy nuclear collisions at RAON

Yechan Cheon [a,b], Seunghwan Lee [a,b], Deuk Soon Ahn [c], Jung Keun Ahn [d,b], Joonsuk Bae [g], Yunseul Bae [h], Jeongsu Bok [e], Sung Wook Choi [d,b], Seungkyung Do [d,b], Cheong Heo [h], Byungsik Hong [d,b], Jangyong Huh [c], Jaein Hwang [d,b], Seonggeun Hwang [a,b], Youngseub Jang [d,b], Byungmin Kang [d,b], Aram Kim [d,b], Beomkyu Kim [g], Chong Kim [e], Eun-Joo Kim [j], Giyeong Kim [f,b], Hyunchul Kim [h], Jiseok Kim [d,b], Jiyoung Kim [f,d,b], Shin Hyung Kim [k], Yongsun Kim [a,b,*], Young Jin Kim [i], Yongjun Kim [e], MinJung Kweon [f,b], Cheong Soo Lee [i], Hyo Sang Lee [i], Jaehwan Lee [d,b], Jong-Won Lee [d,b], Jung Woo Lee [c], Junseok Lee [d,b], Haein Lee [d,b], Hyungjun Lee [g], Seoung Hun Lee [f,b], Sungjune Lee [d,b], Sanghoon Lim [e], Dong Ho Moon [h], Seon Ho Nam [d,b], Jeonghyeok Park [d,b], (The LAMPS Collaboration)

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ABSTRACT

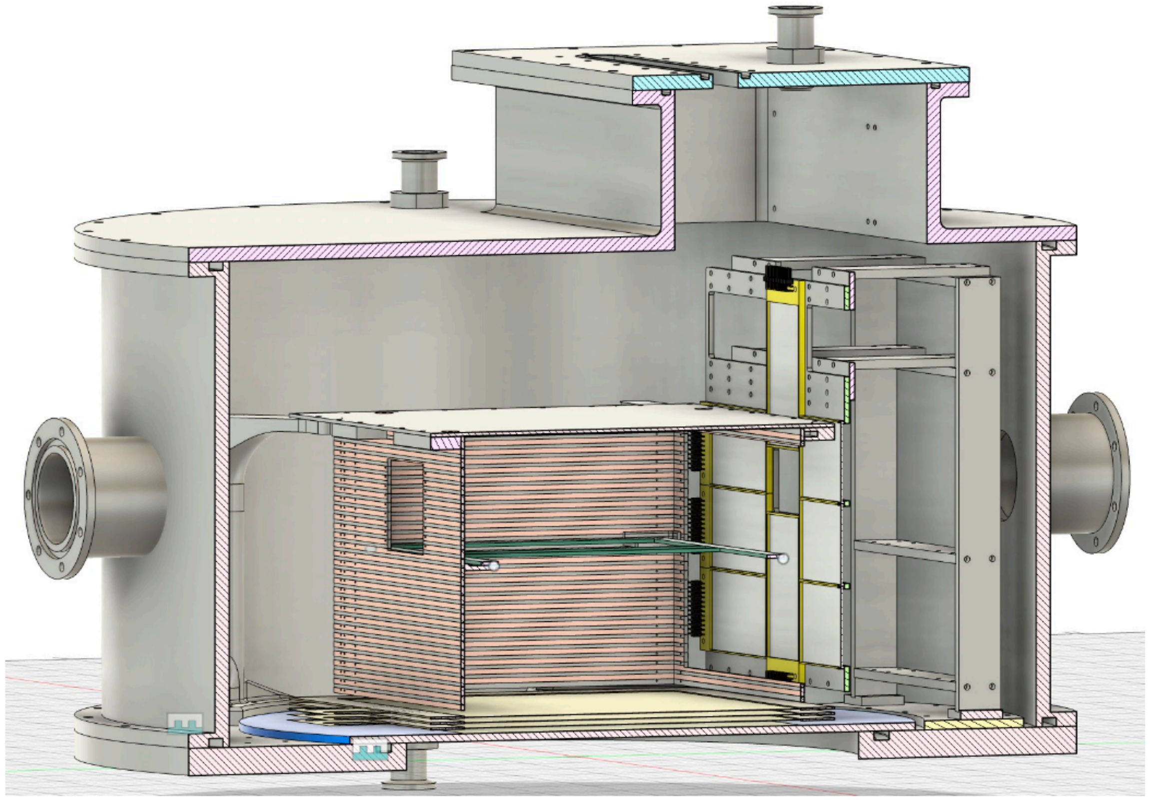
The time projection chambers (TPCs) with triple GEM amplifiers are tested at HIMAC using ^{12}C beams to investigate their nucleus track reconstruction capability. The two identical TPCs, each having an active volume of 96 × 64 × 144 mm^3 and rectangular pixel pads, have been developed as prototypes of the LAMPS collaboration's low-energy active target TPC (AT-TPC). The responses to light nuclei, such as particle identification and spatial resolution, have been investigated. The Si-CsI detectors located next to the TPCs further facilitate the identification of incident particles, as well as the matching tracks. This paper presents the technical details of the experimental setup, pulse shape analysis, tracking algorithm, and spatial resolution measurement. Comparisons of the experimental data with the calculations by the Monte Carlo (MC) simulation are also discussed.

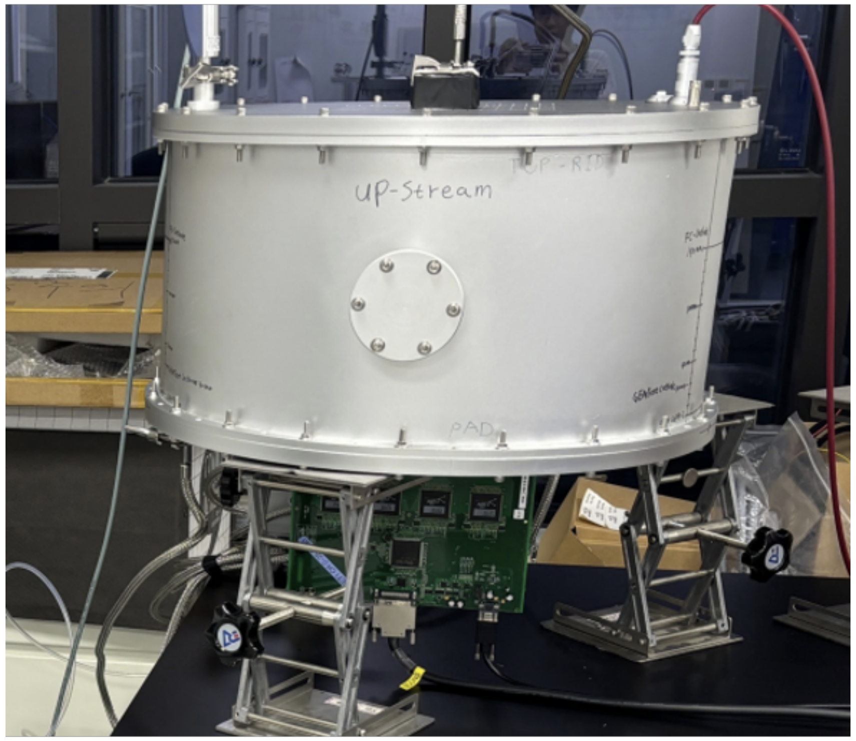
- Tracking and vertex finding are very successful
- Position resolution — 150 μm
- Great PID performance of Si-CsI array
- Our MC framework well agrees with data in terms of electron diffusion and position resolution over a wide range of drift length

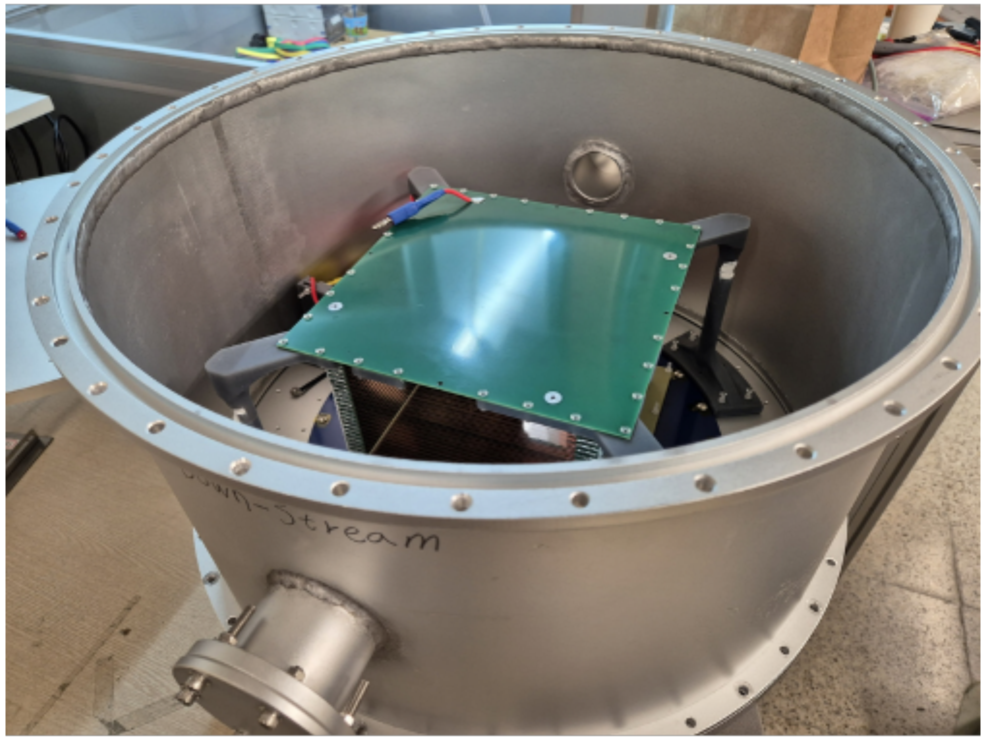
Dedicated detector

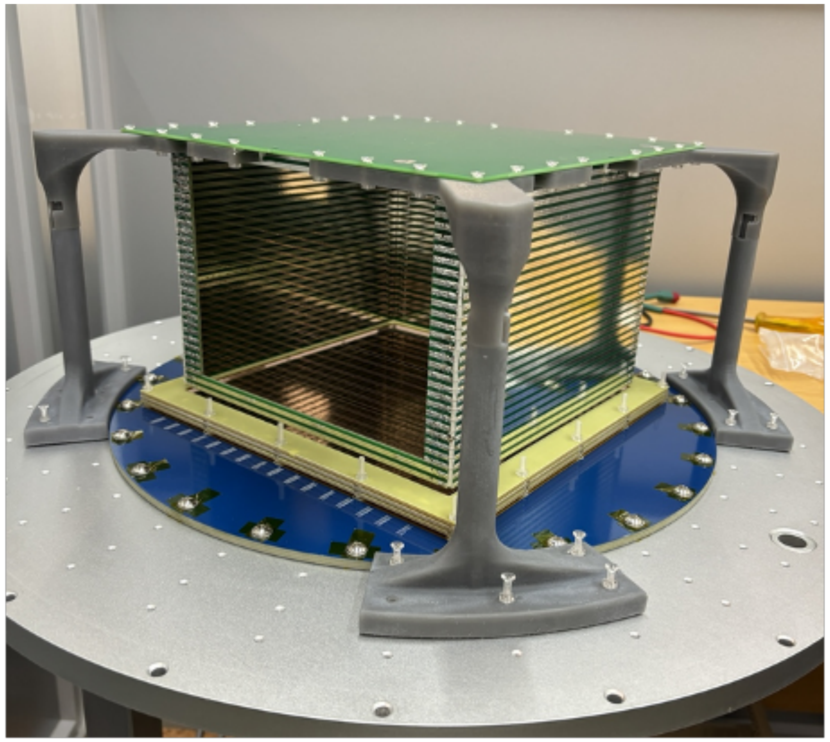
TPC-Drum

- Active target TPC (768 ch)
- 8 Si-CsI array (176 ch)
- He (90%) + CO_2 (10%) gas
- GET electronics (4 AsAd + 1 CoBo)
- The last prototype for the low-energy LAMPS AT-TPC

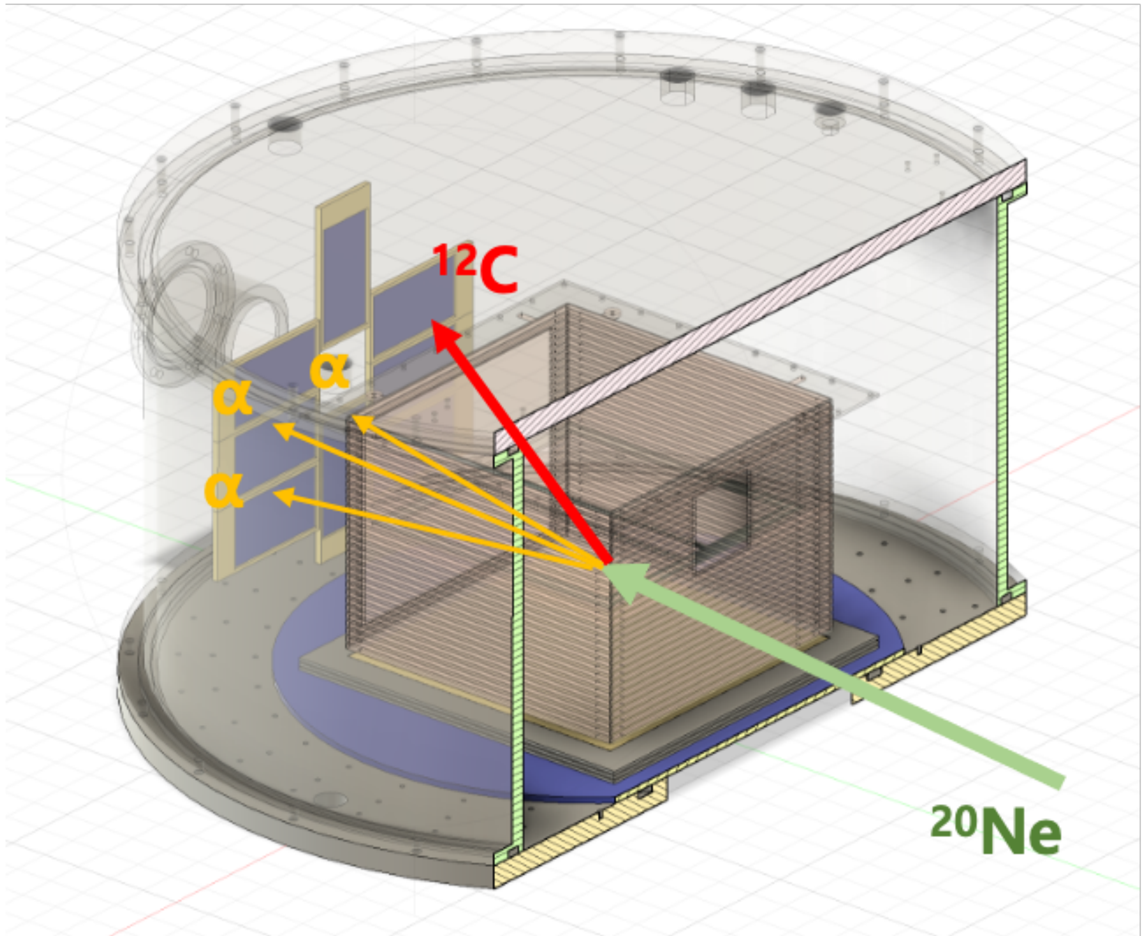


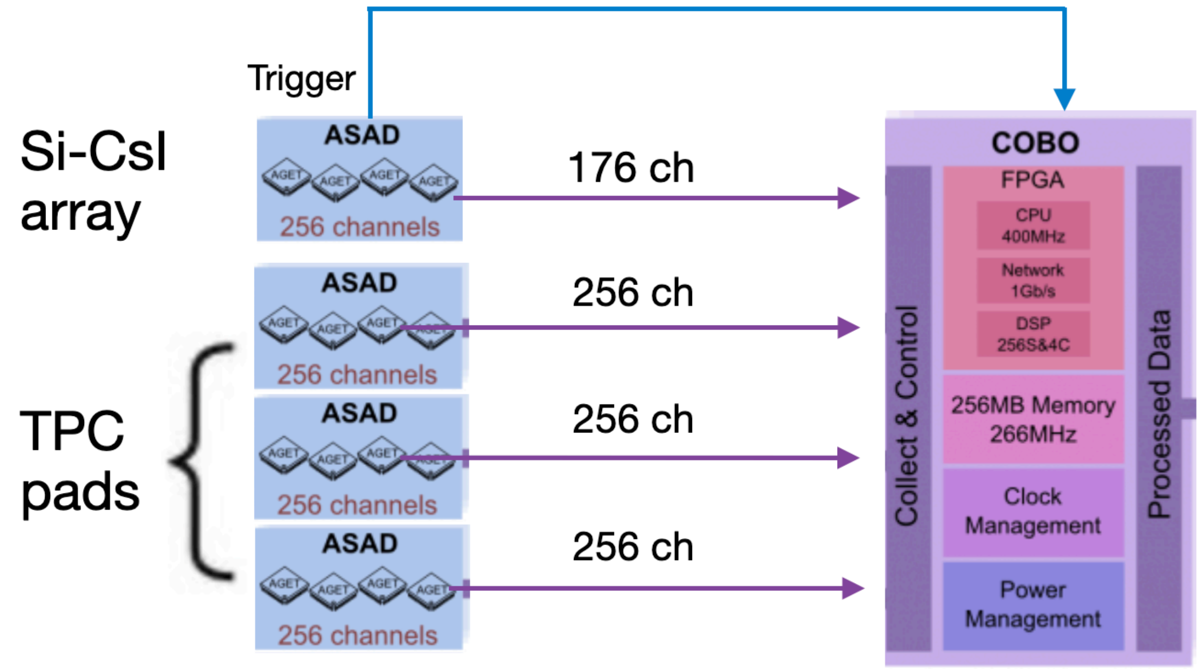






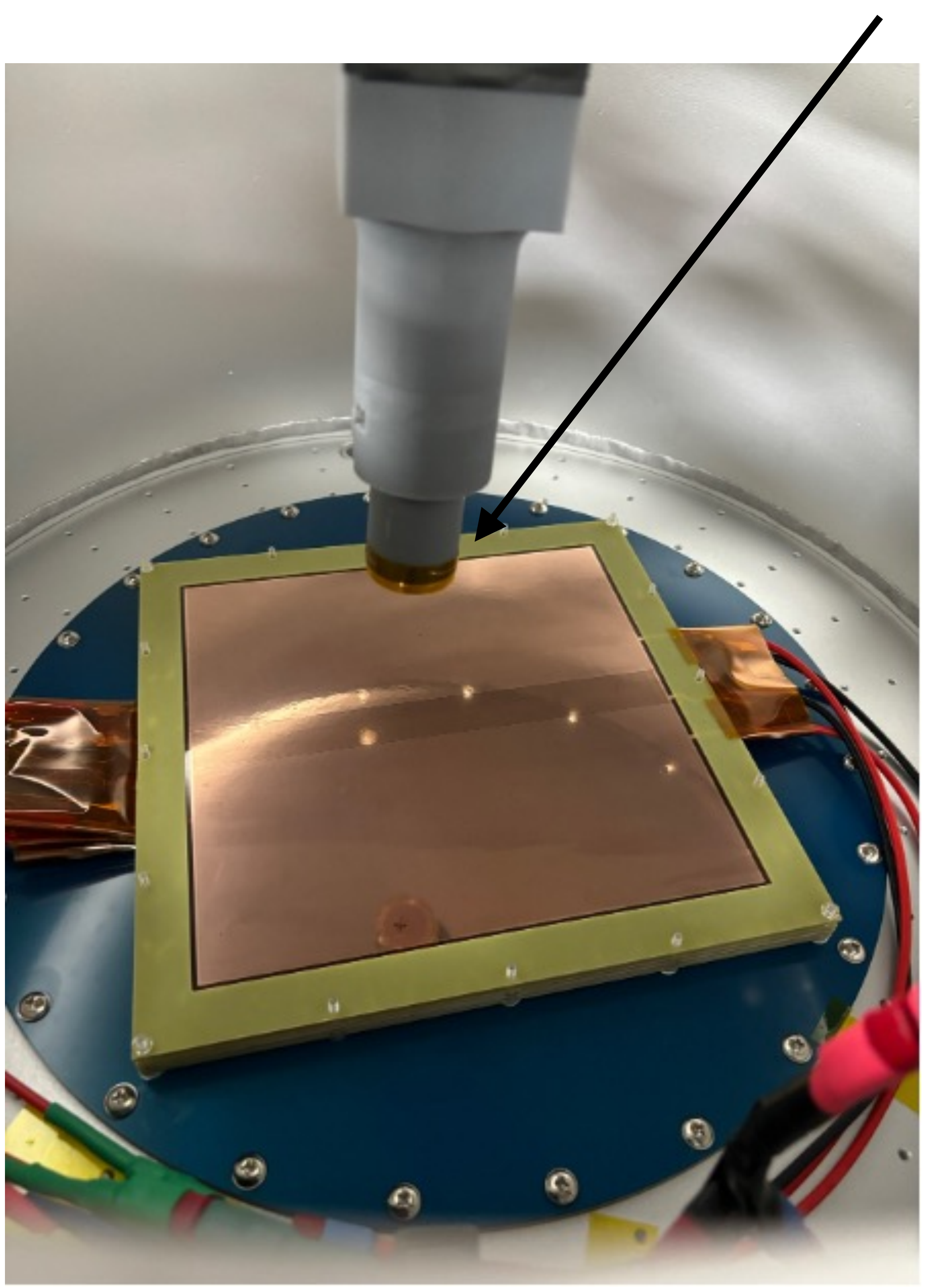
Dedicated detector

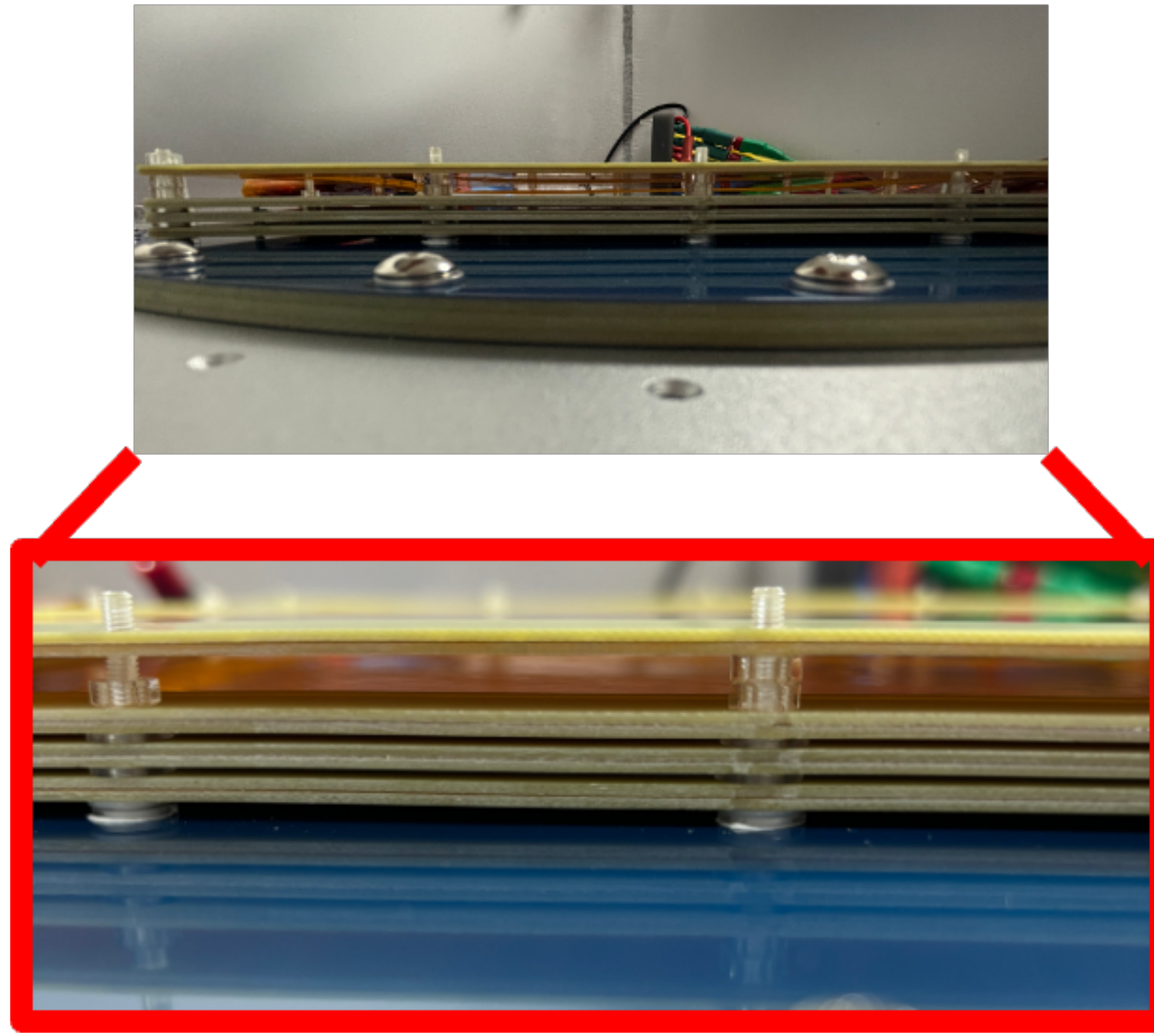




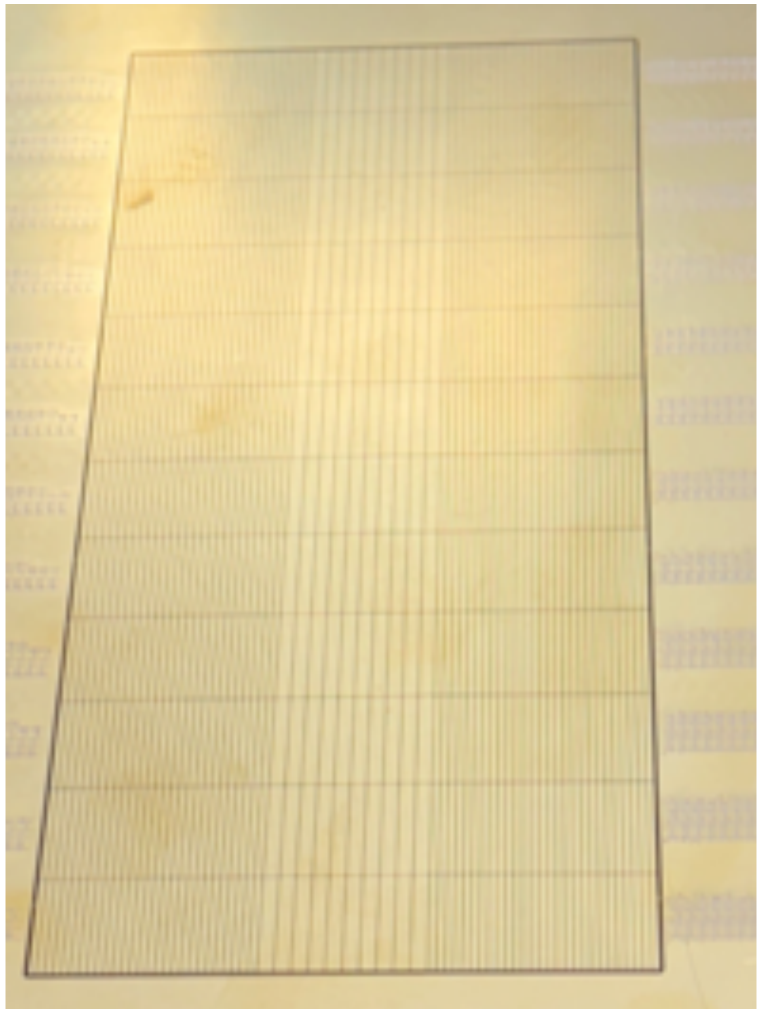
- Collision system : ^{20}Ne + α at 10 MeV/u
- The detector must measure multiple α's with high precision
- Energy will be measured using Si (thickness = 1 mm)
  - Resolution for α is 40 - 50 keV
- Momentum vector will be determined by TPC part
  - A spatial resolution ~150 μm translates to an angular resolution of ~0.004 $mrad$
- By correlation of E (Si) and dE (TPC), α can be isolated from other nuclei

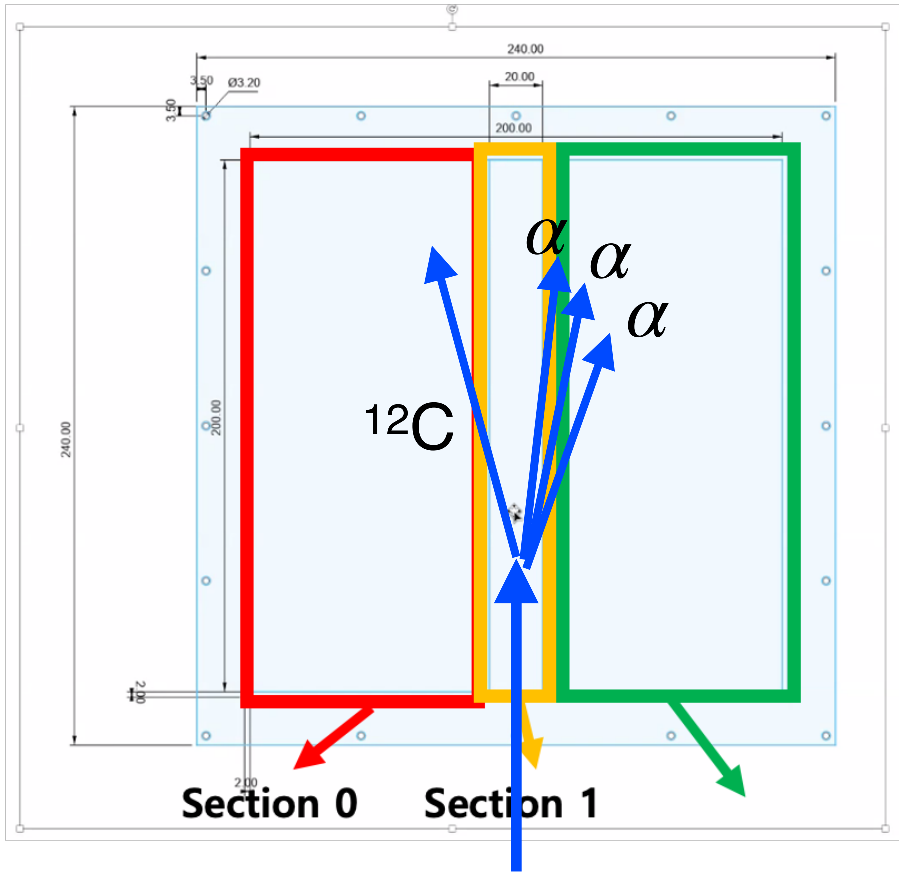
Performance test for triple GEM



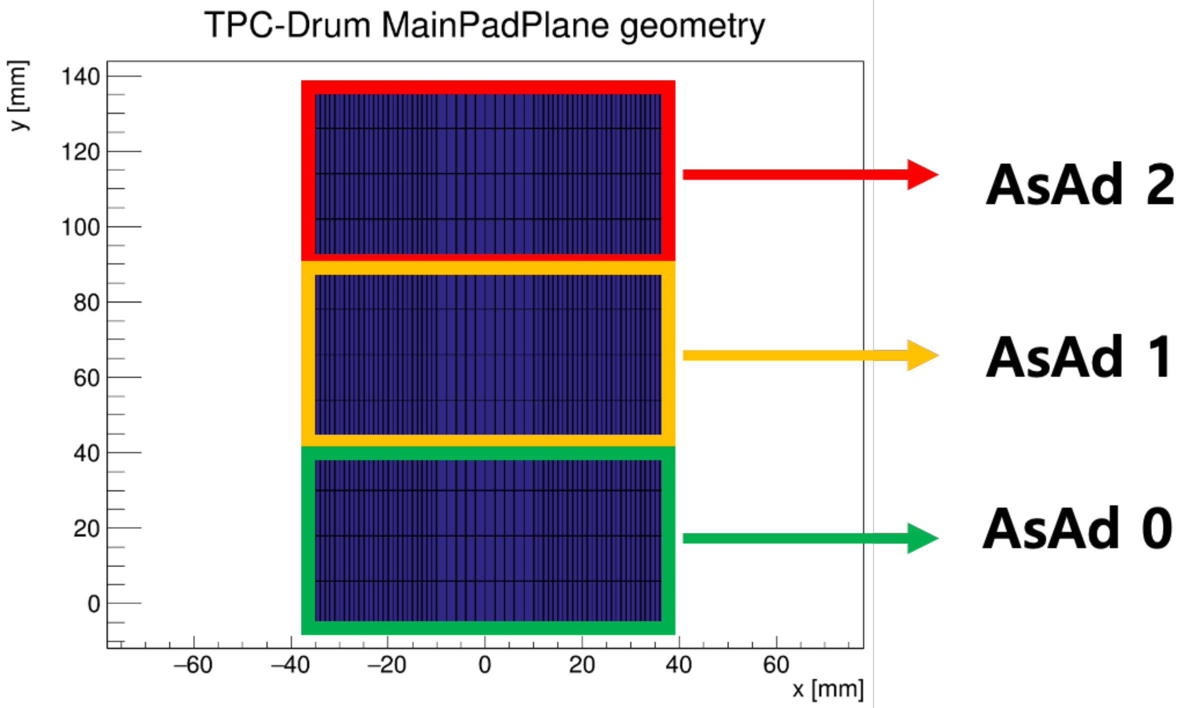


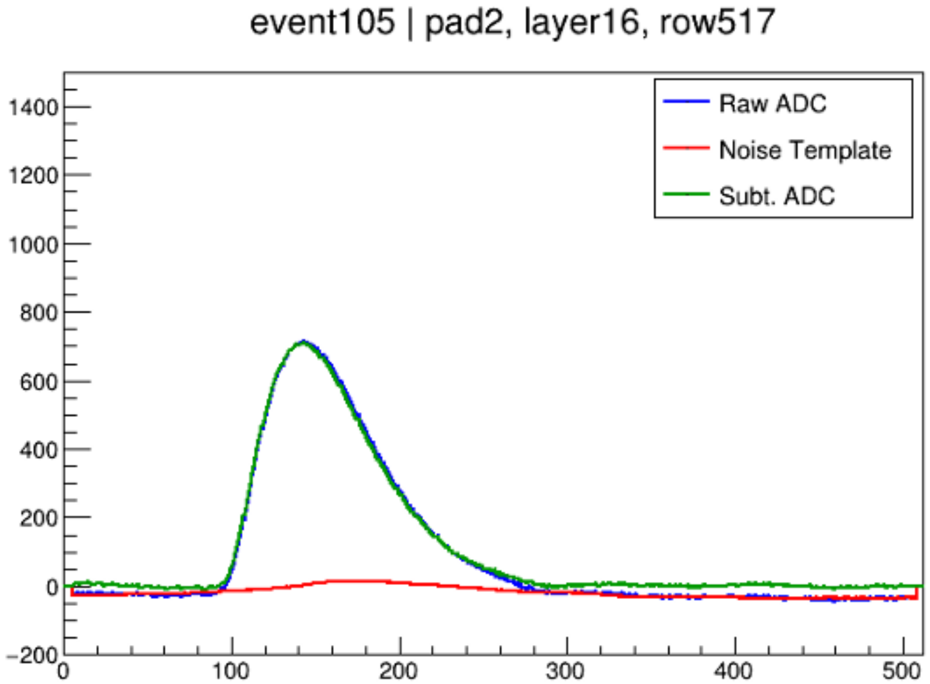
768 ch Readout pad



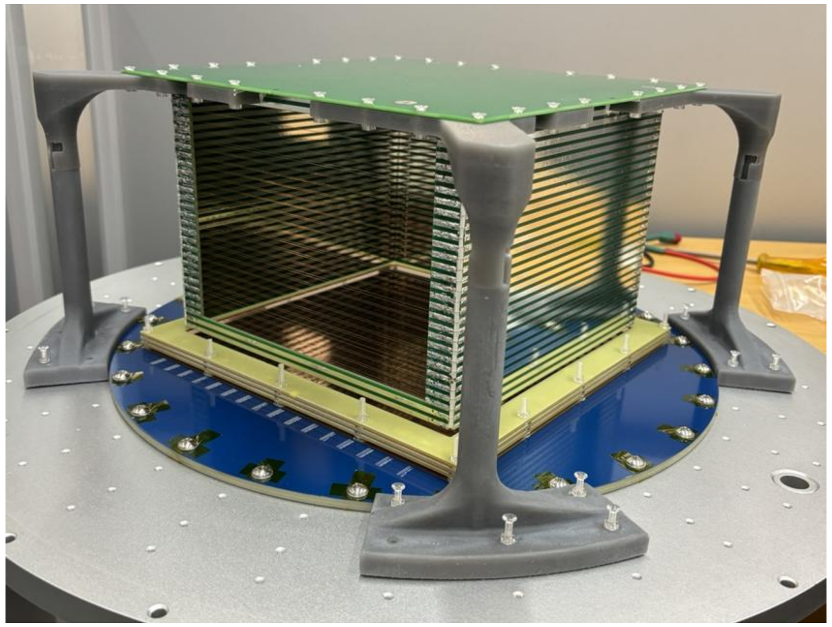


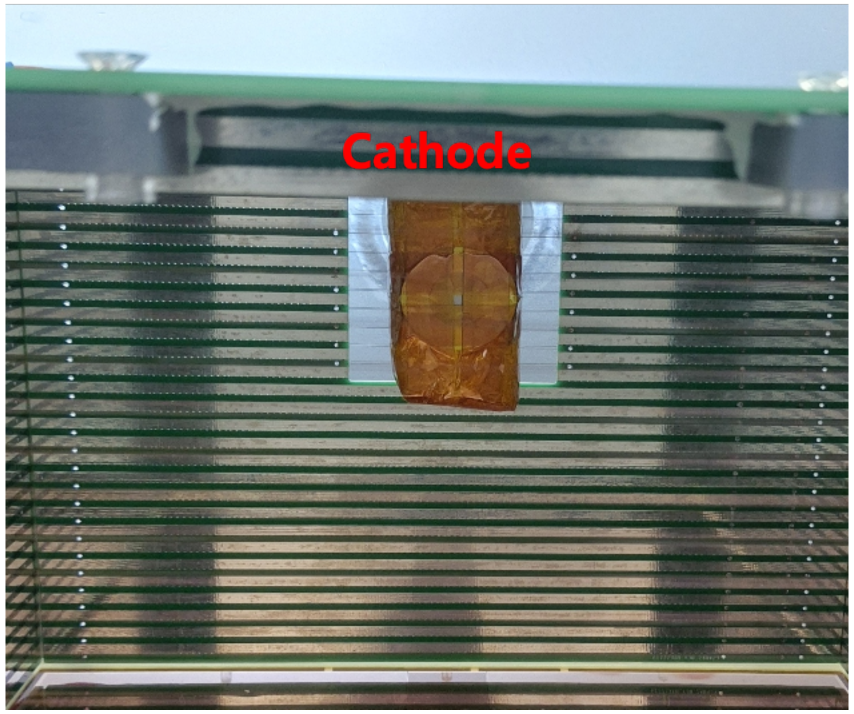
- Different GEM hole sizes
- Different pad sizes correspondingly

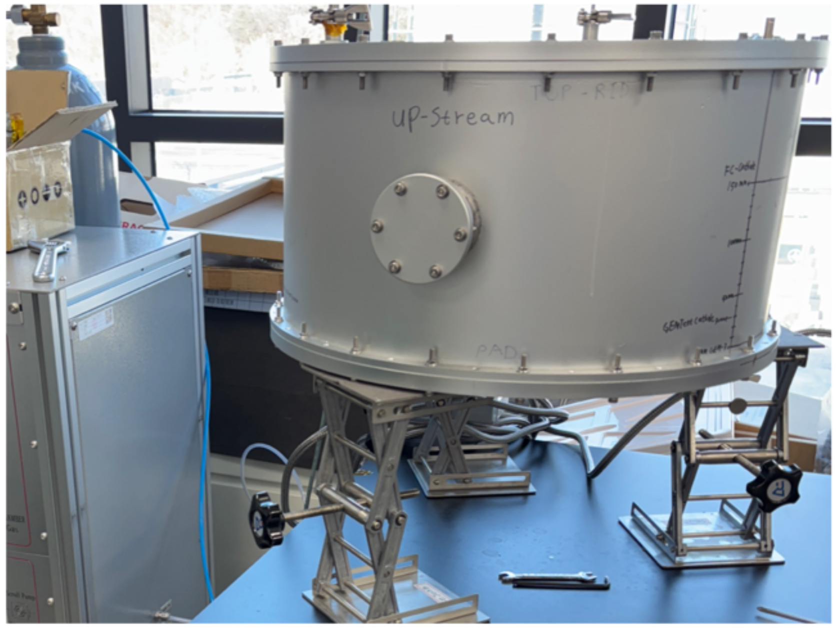




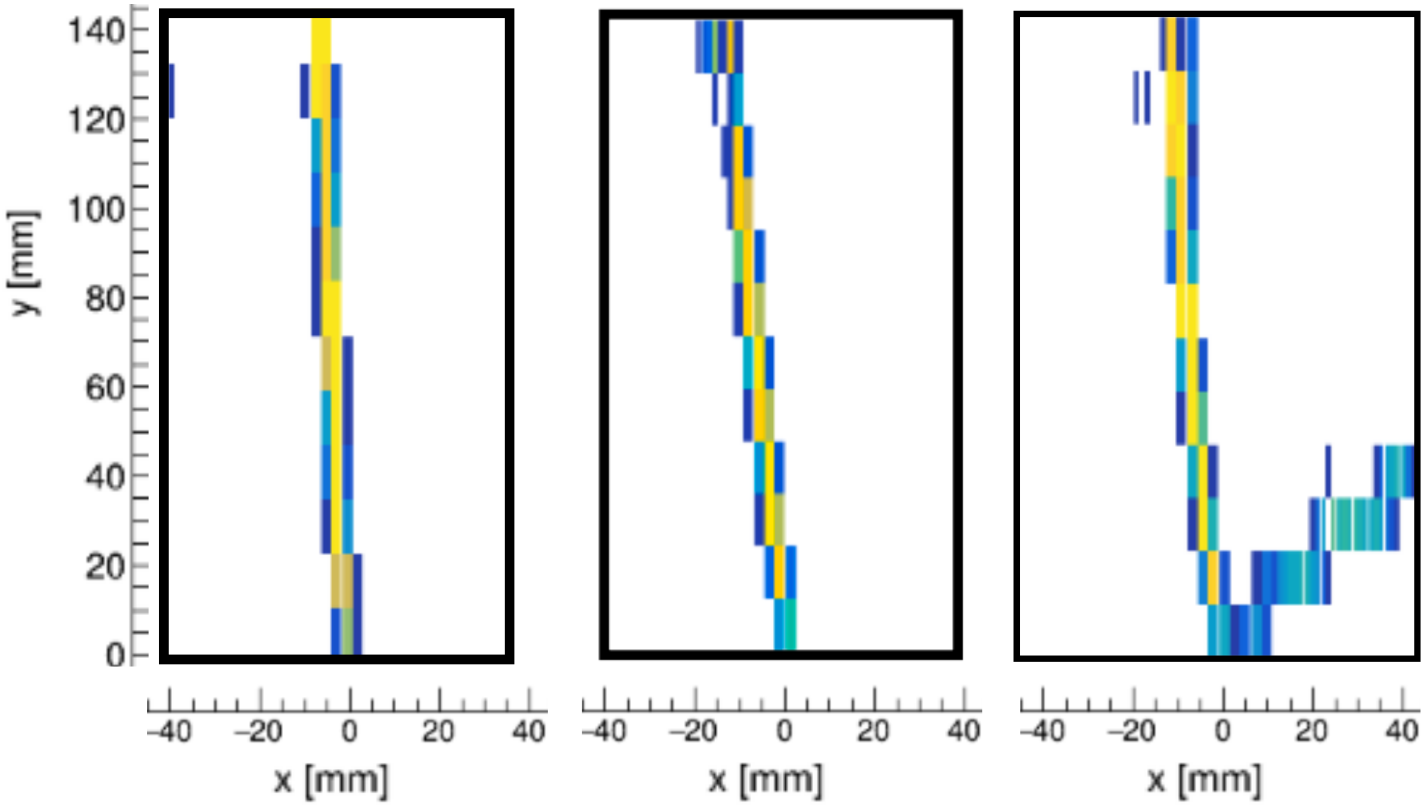
Detector status





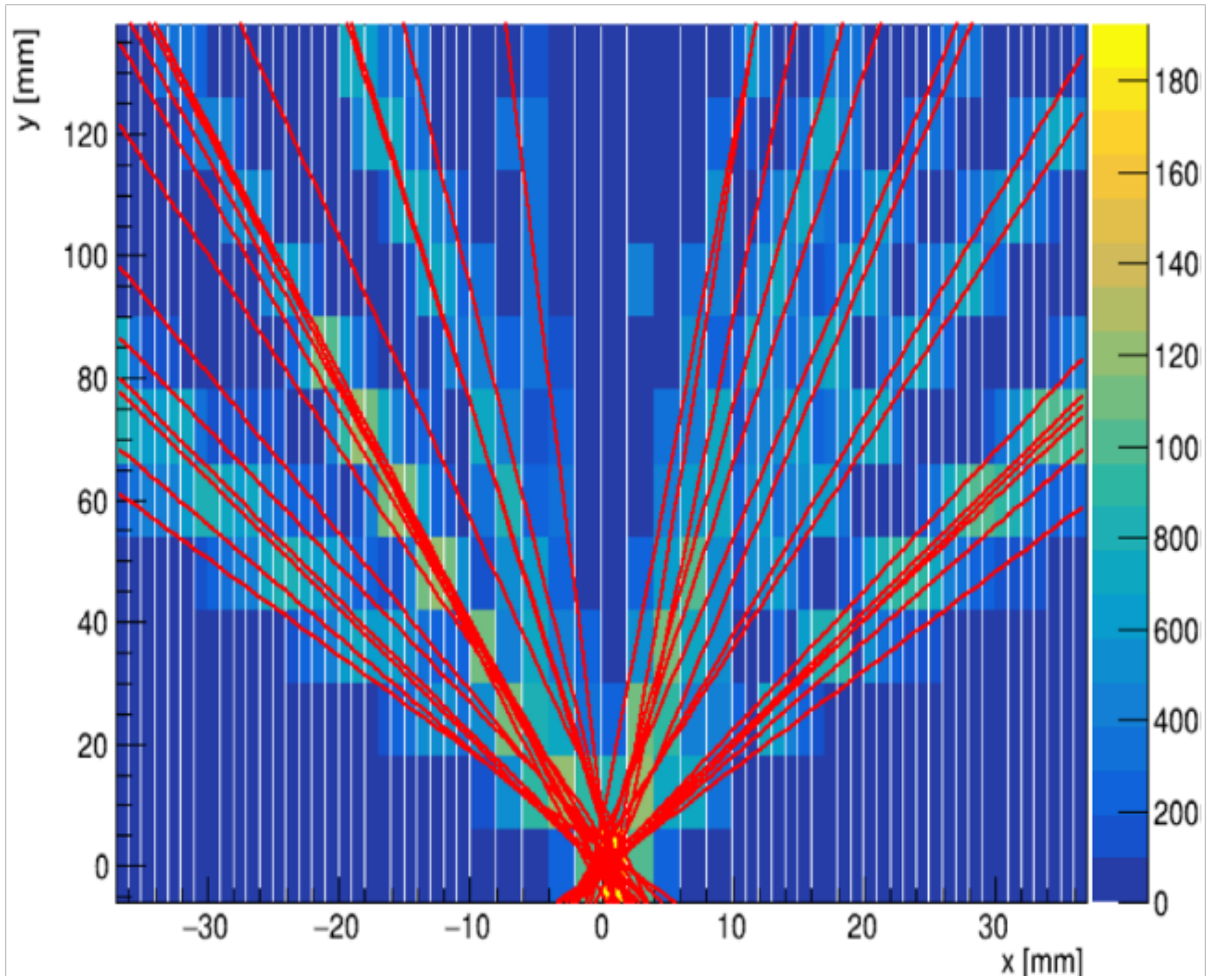


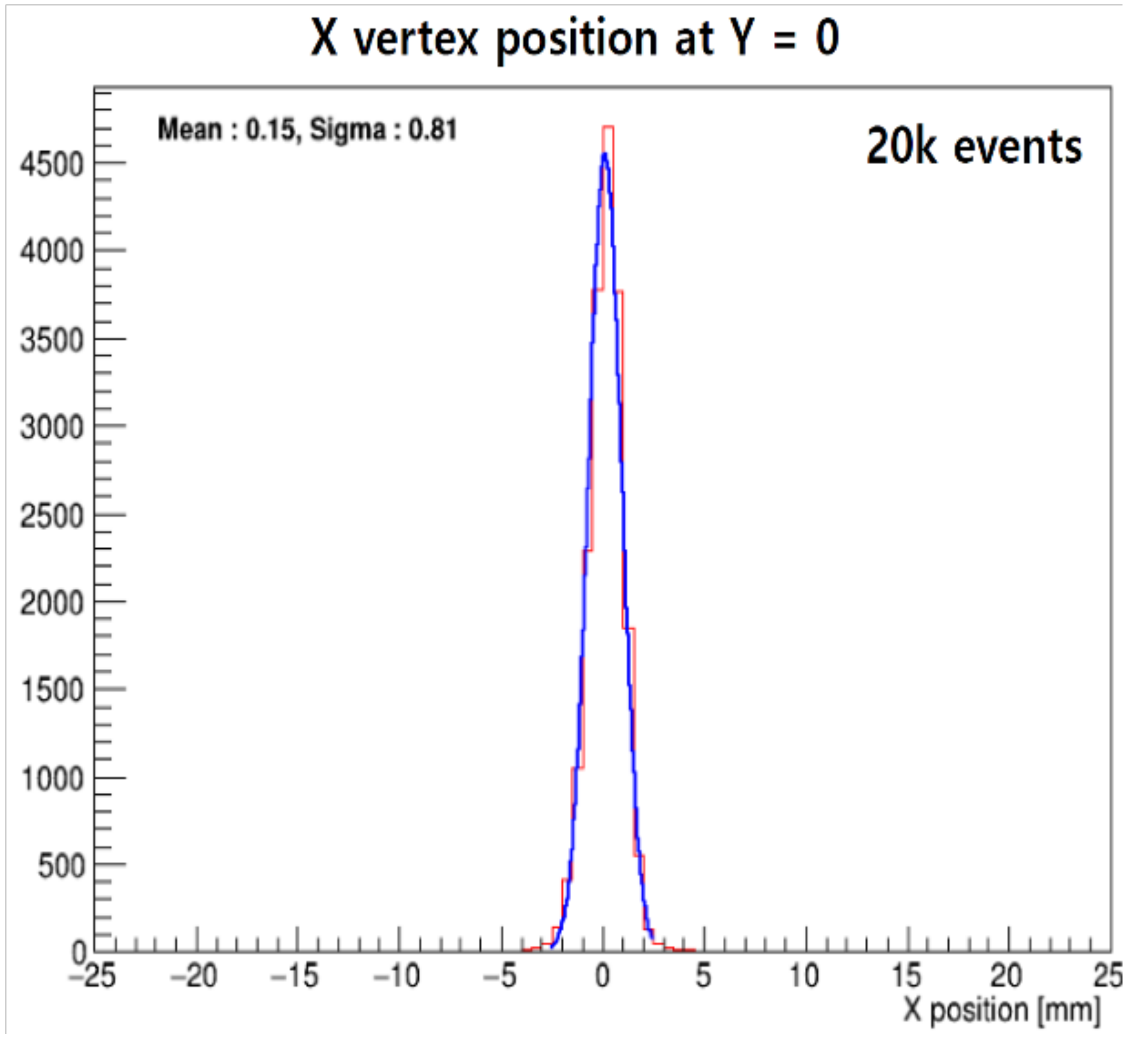
- Ready for experiment
  - Tested with cosmic ray and Am-241
  - Position-dependent calibration for triple-GEM gain using Fe-55
- Alpha track measurement
  - Am-241 (E = 5.44 MeV, 5.49 MeV)
  - Average track length is 11.5 cm, consistent with SRIM simulation
  - Cluster size in data is close to that of MC
    - Good grip for resolution!



Event displays for measured one- and two-α tracks using Am-241 source

Commissioning

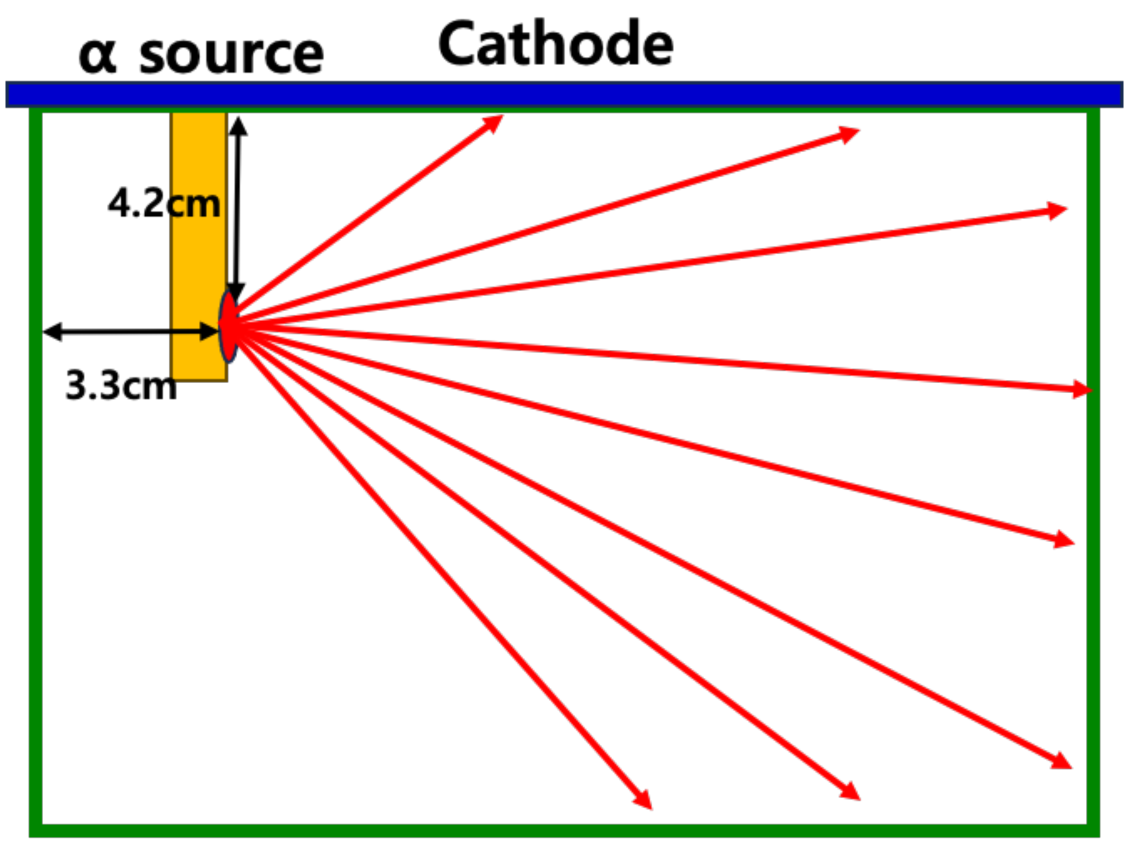




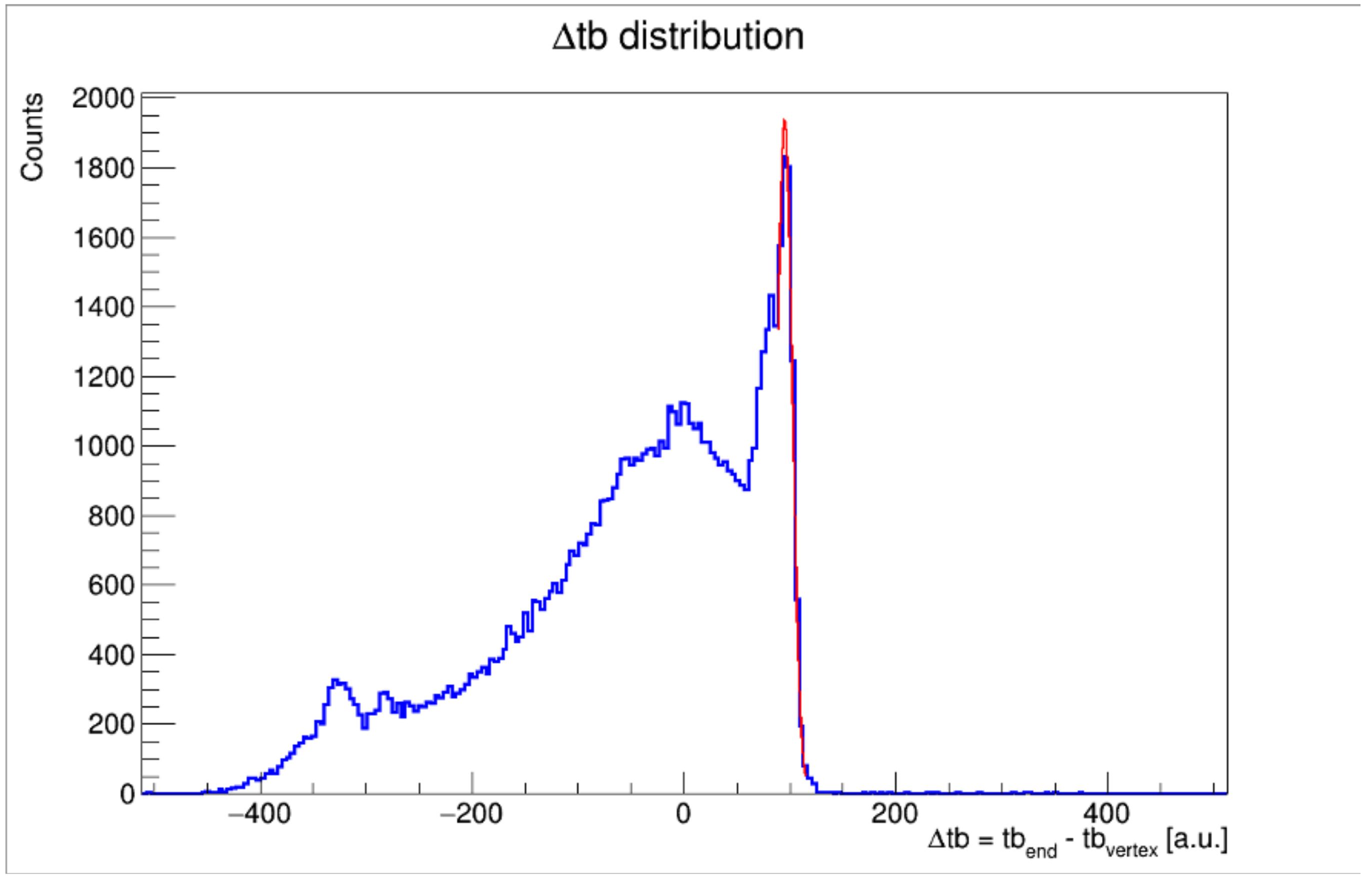
Clustering fitted track (sum of 30 events)

A simple straight line fitting algorithm shows a very good vertex reconstruction resolution σ = 0.81 mm

Drift velocity



Schematic side view

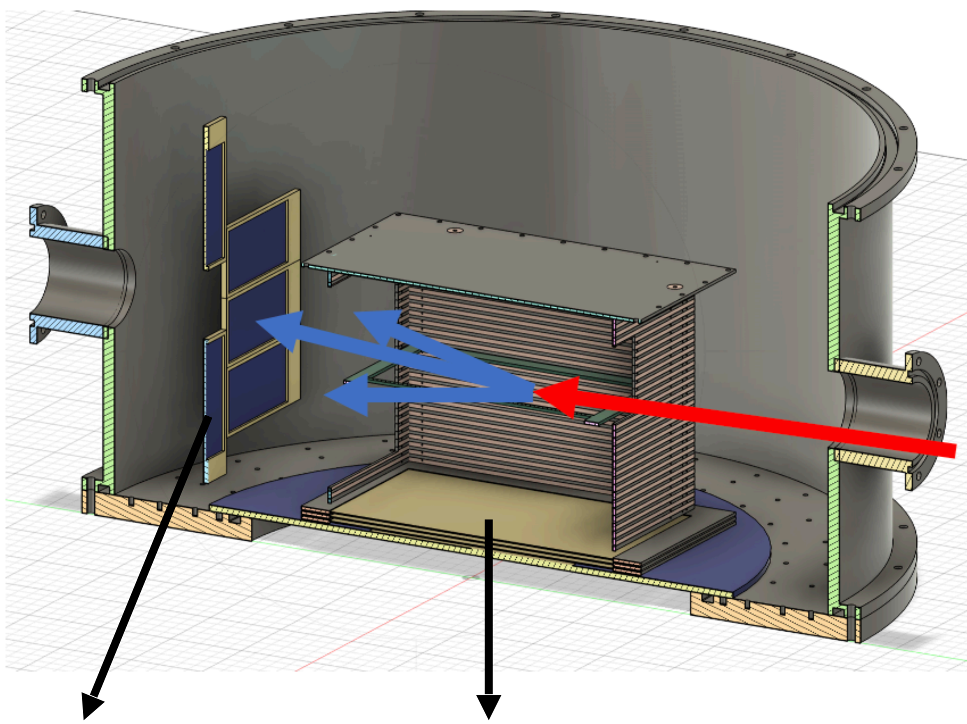


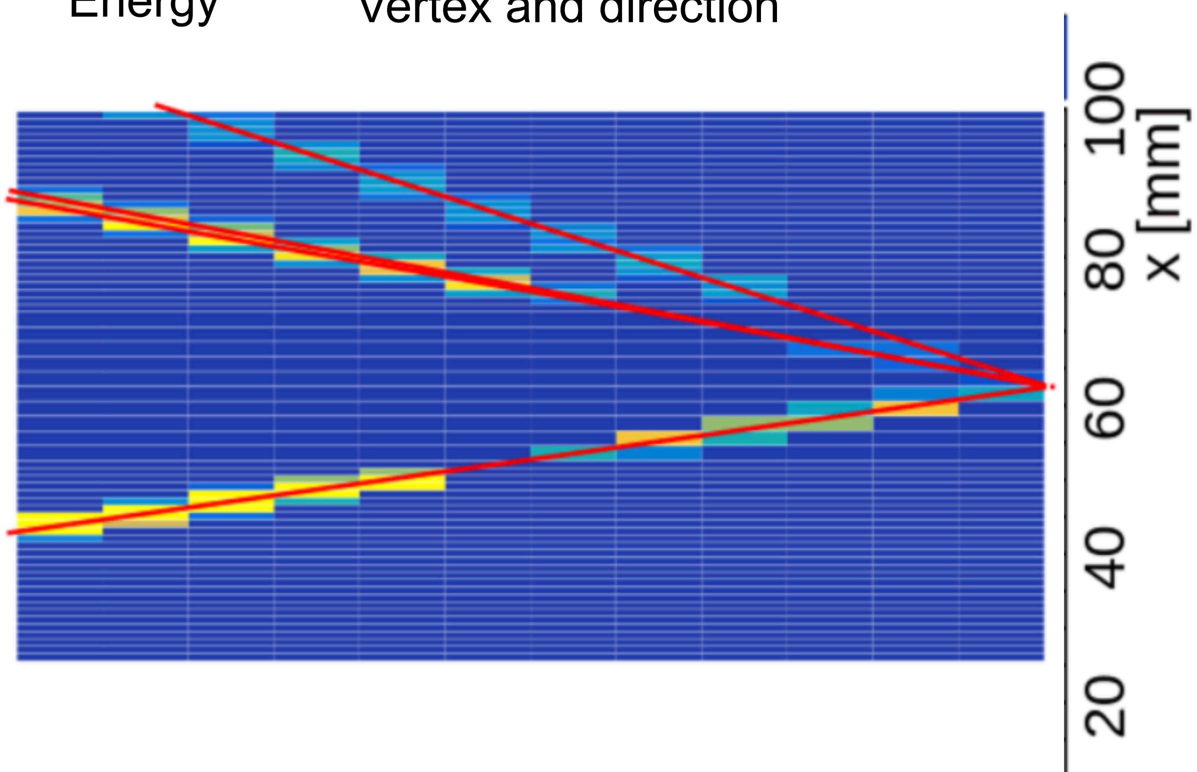
- Used 40 *ns* configuration for a time bucket
- Drift velocity is measured to be **1.1** *cm/μs* which is consistent with GARFIELD++ simulation

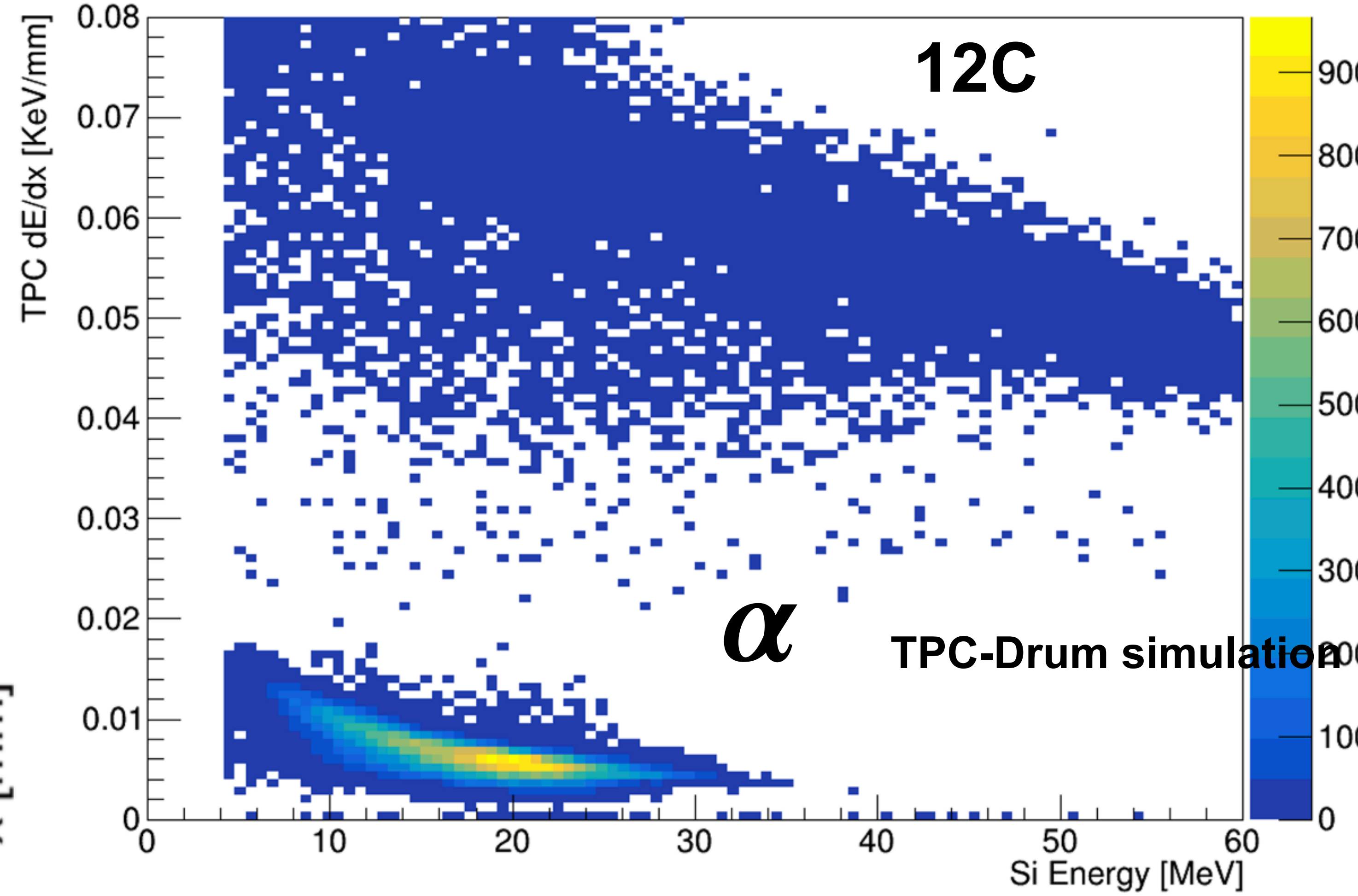
- GEM voltage : 1850V
- Fieldcage voltage : 4850V (250 V/cm)
- Gas : He(90%) + CO2(10%) pre-mixed gas
- Drift velocity ~ 1 cm/us (Garfield++)
- Pressure : 650 Torr
- Alpha track length ~ 13.5 cm (SRIM)

Simulation of collision events

- Simulation of ^{20}Ne + $\alpha \rightarrow$ ^{12}C + ^{12}C$_{\mathrm{Hoyle}}$ $\rightarrow$ ^{12}C + 3α



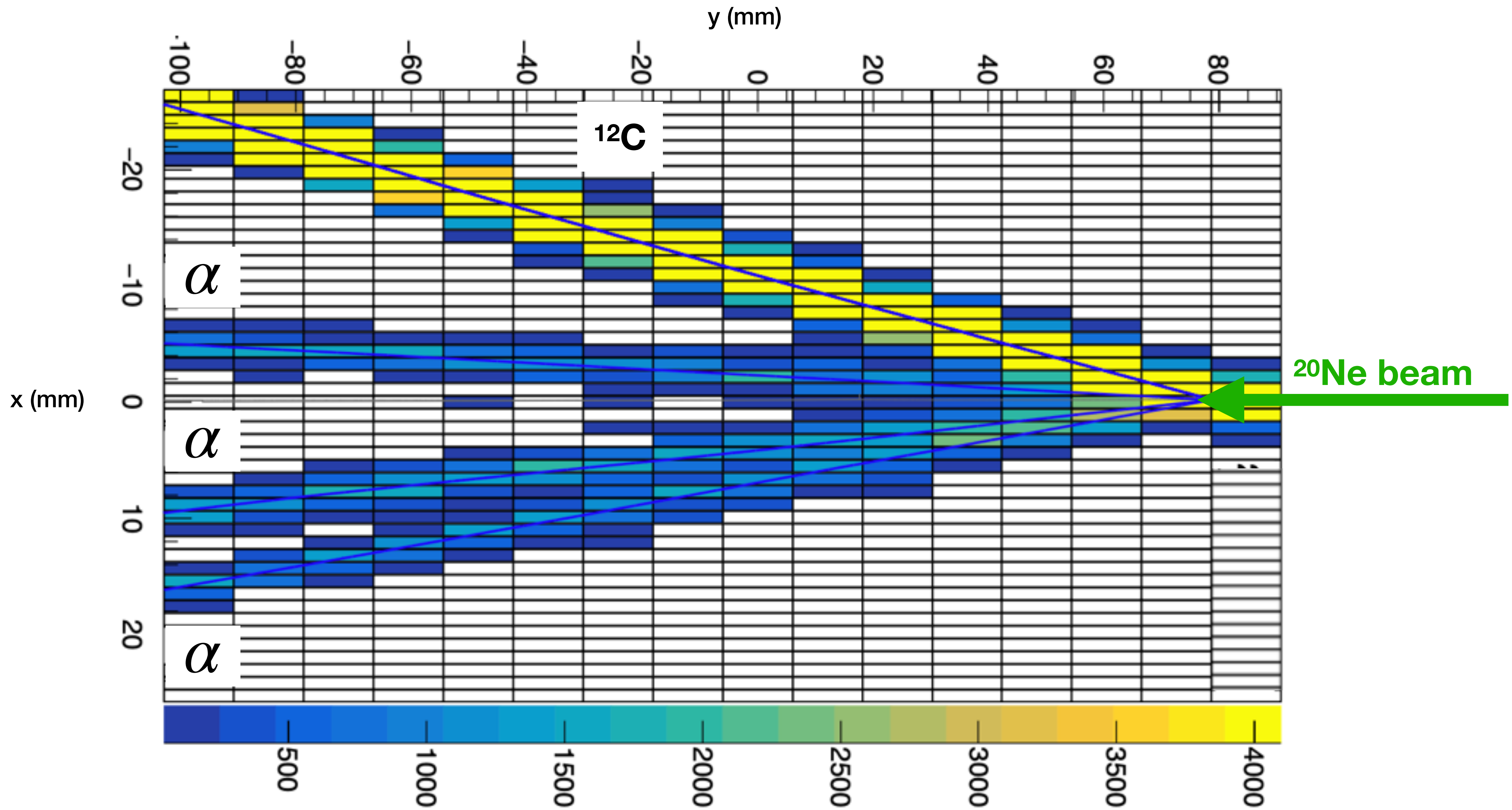




- Four-momentum can be calculated using TPC ($\vec{p}$/p) and Si (E)
- α particles are distinguishable

Simulation of collision events

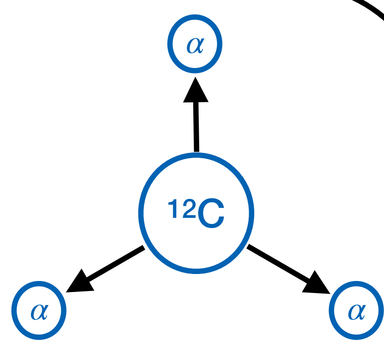
- Simulation of $^{20}Ne + \alpha \rightarrow {}^{12}C + {}^{12}C_{Hoyle} \rightarrow {}^{12}C + 3\alpha$



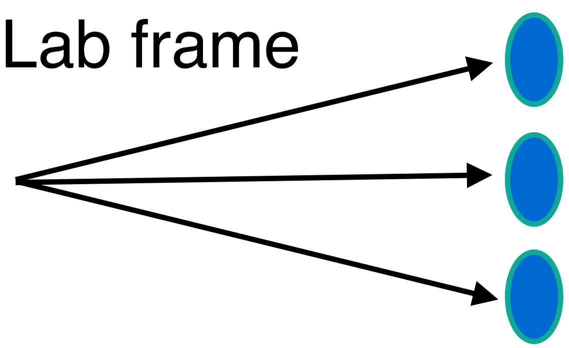
Reconstruction of invariant mass

Hoyle state

$$^{12}\mathrm{C}_{\mathrm{Hoyle}} \rightarrow \alpha + \alpha + \alpha$$



Lab frame

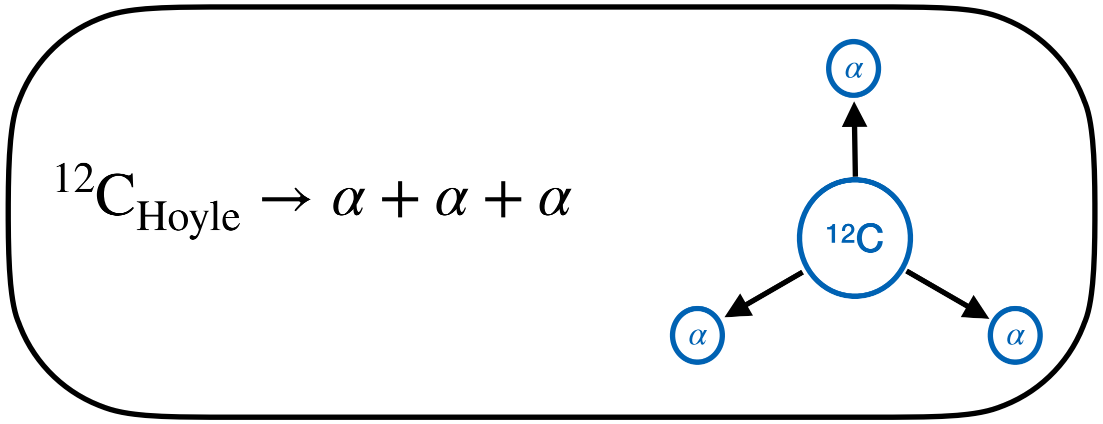


4-vector of α particles are obtained

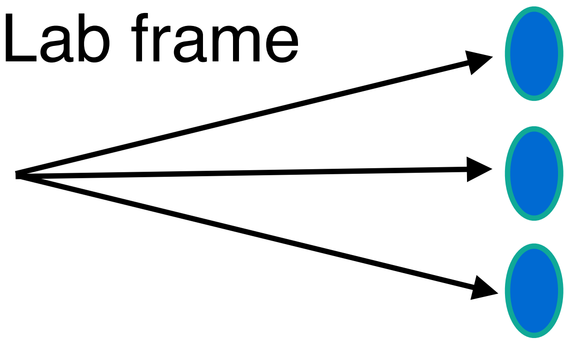
- E measured by Si part
- $\vec{p}/|\vec{p}|$ measured by TPC part
- $|\vec{p}|$ calculated using α mass

Reconstruction of Hoyle state

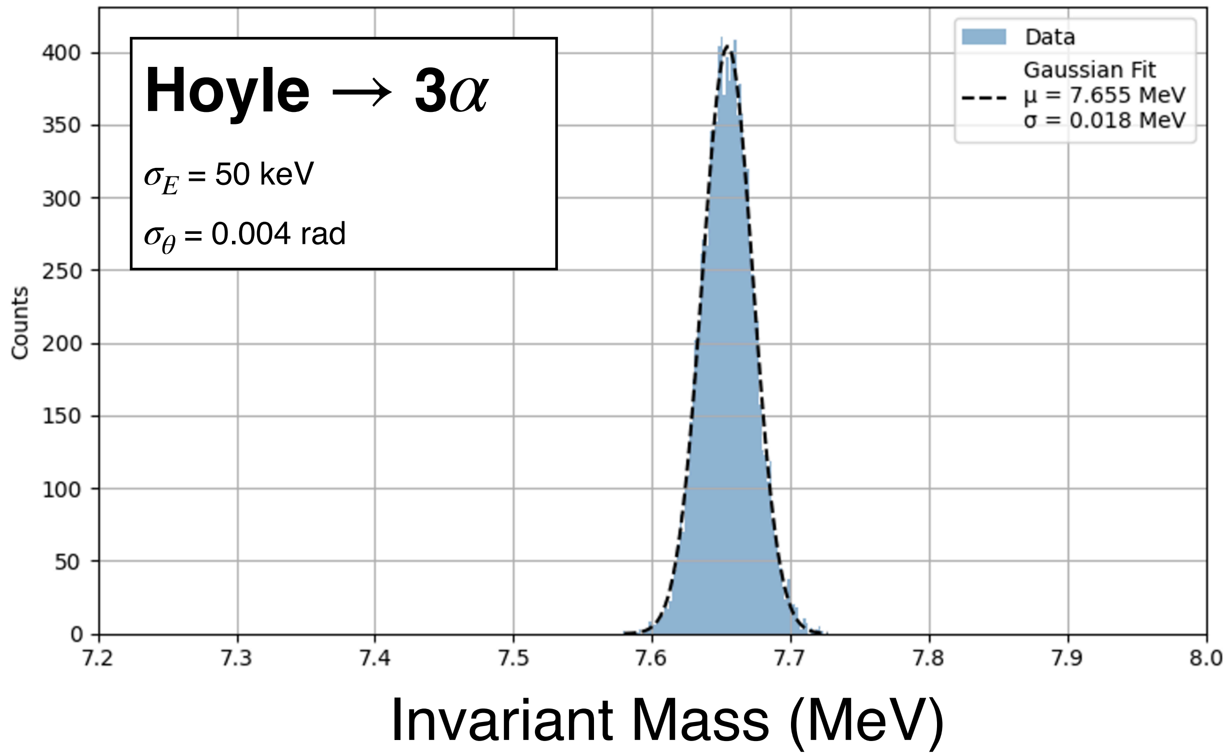
Hoyle state



Lab frame



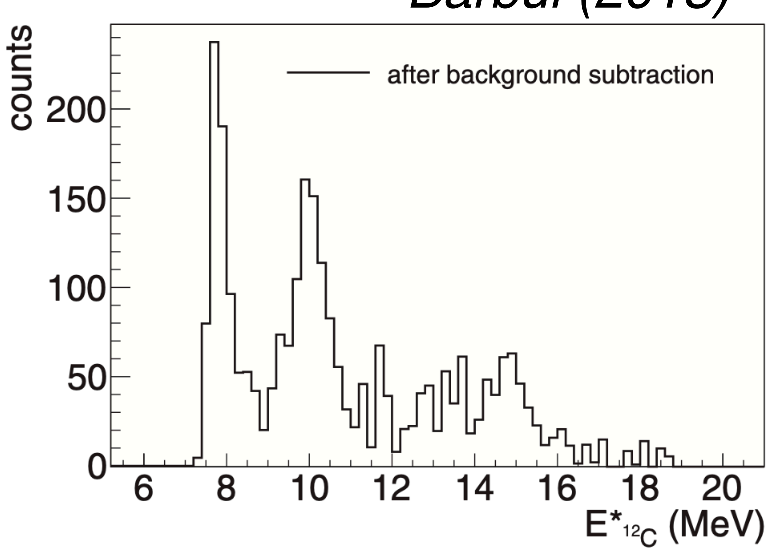
TPC-Drum (Toy MC simulation)



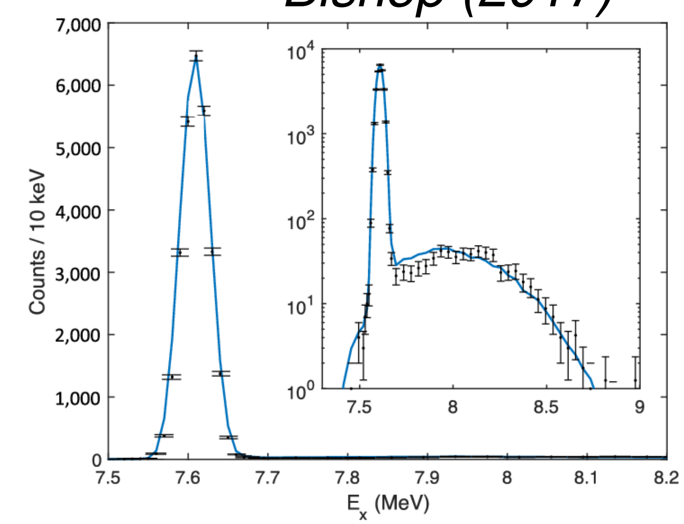
4-vector of α particles are obtained

- E — measured by Si part
- $\vec{p}/|\vec{p}|$ — measured by TPC part
- $|\vec{p}|$ — calculated using α mass

Barbui (2018)



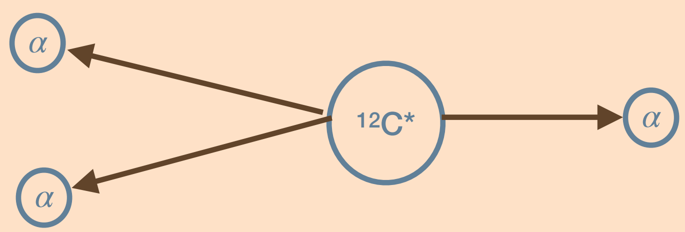
Bishop (2017)



Separation of Signal to Background

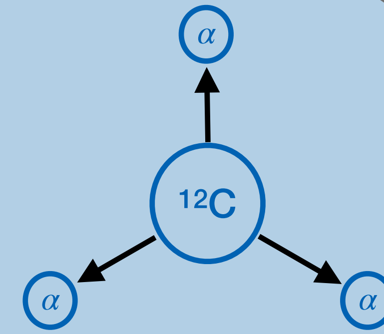
Background: Sequential decay

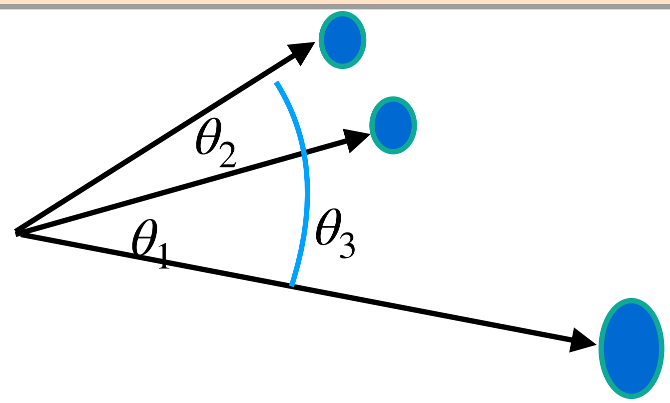
$$^{12}\mathrm{C}_{\mathrm{Hoyle}} \rightarrow \; ^{8}\mathrm{Be} + \alpha \; \rightarrow \; \alpha + \alpha + \alpha$$



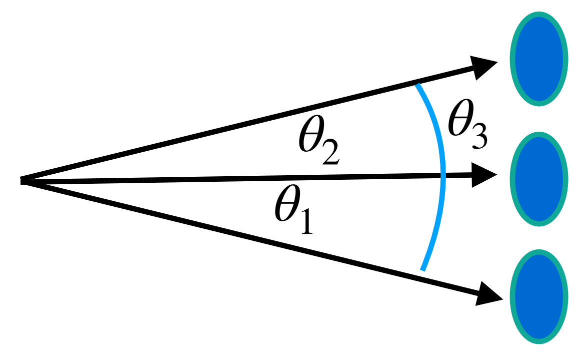
Signal: Direct decay

$$^{12}\mathrm{C}_{\mathrm{Hoyle}} \rightarrow \alpha + \alpha + \alpha$$





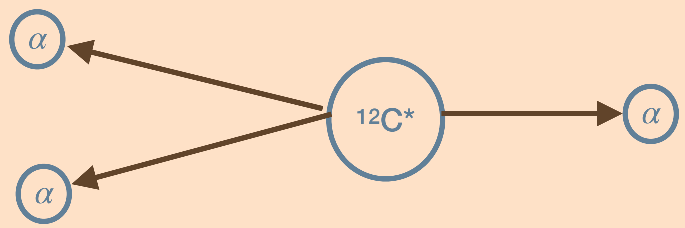
Lab frame



Separation of Signal to Background

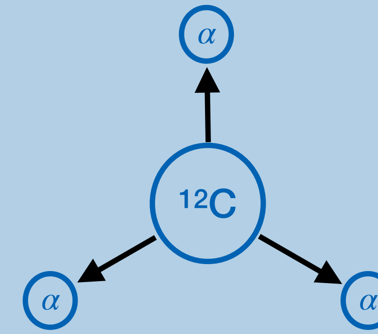
Background: Sequential decay

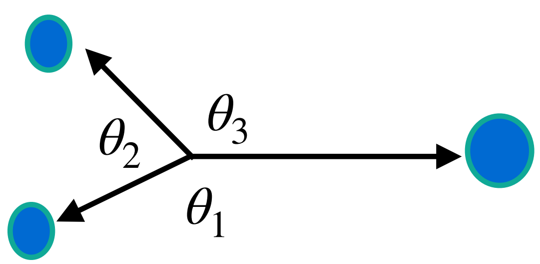
$$^{12}\mathrm{C}_{\mathrm{Hoyle}} \rightarrow \ ^{8}\mathrm{Be} + \alpha \ \rightarrow \ \alpha + \alpha + \alpha$$



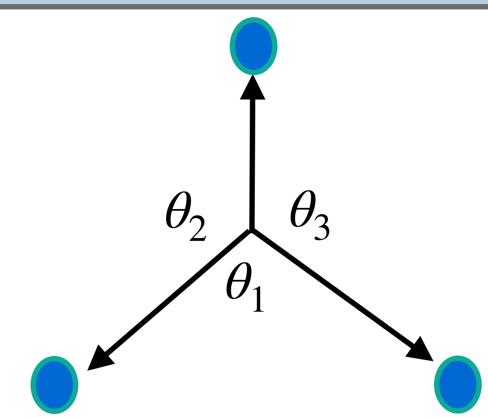
Signal: Direct decay

$$^{12}\mathrm{C}_{\mathrm{Hoyle}} \rightarrow \alpha + \alpha + \alpha$$





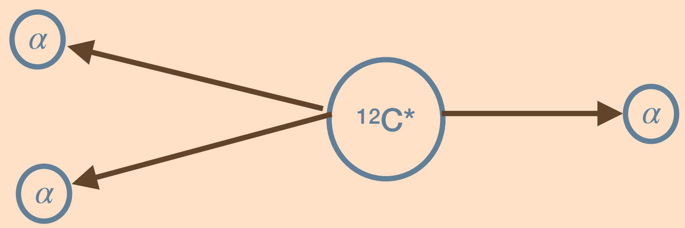
Reconstructed in ^{12}C* frame



Separation of Signal to Background

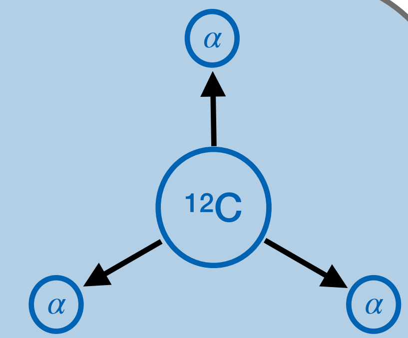
Background: Sequential decay

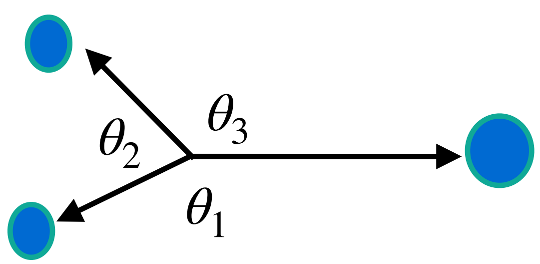
$^{12}\mathrm{C}_{\mathrm{Hoyle}} \rightarrow\ ^{8}\mathrm{Be} + \alpha \rightarrow \alpha + \alpha + \alpha$



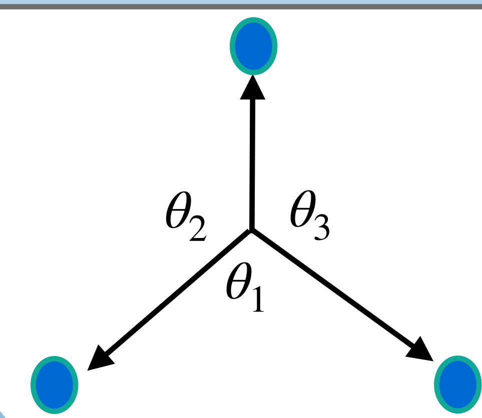
Signal: Direct decay

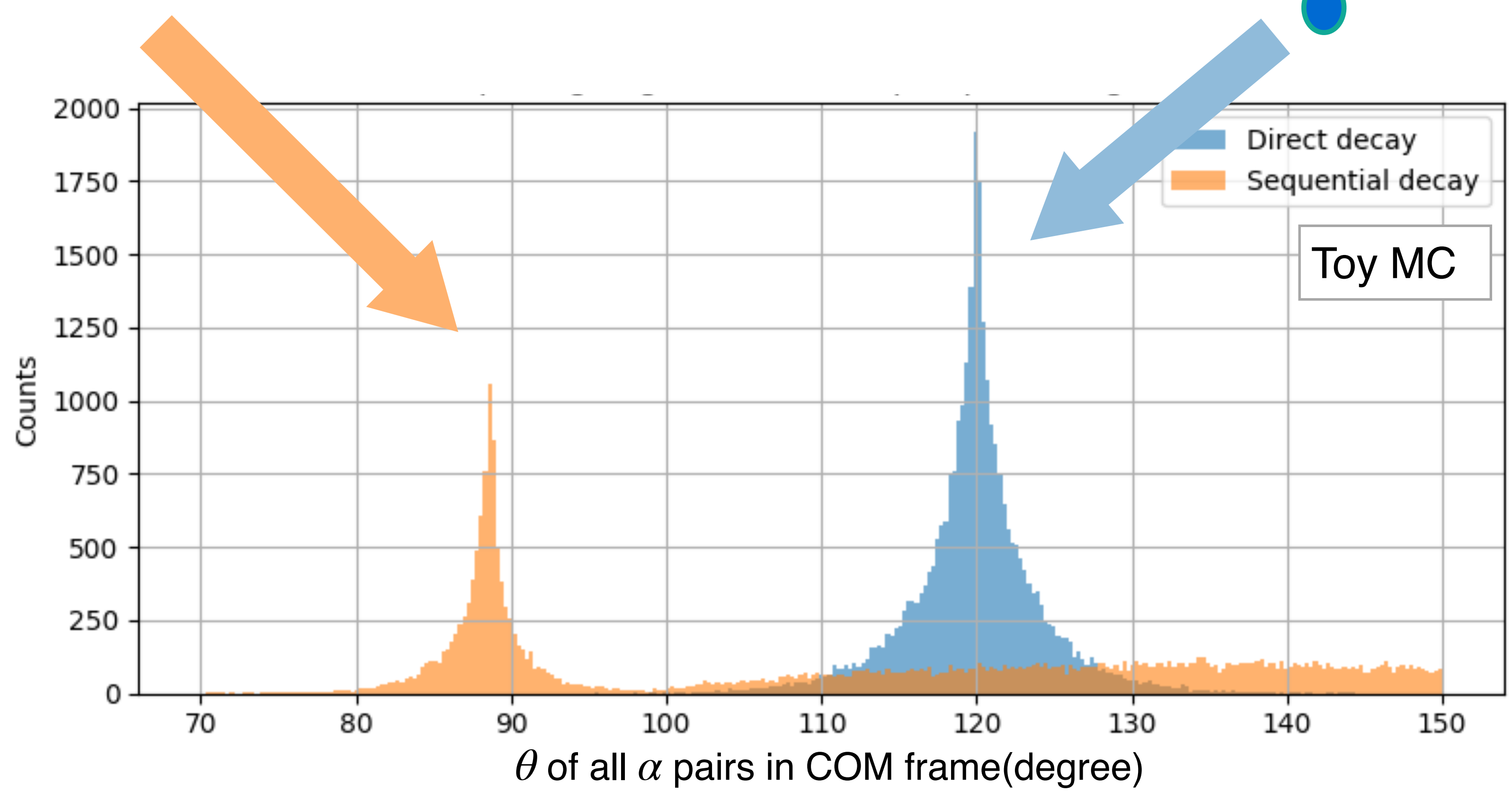
$^{12}\mathrm{C}_{\mathrm{Hoyle}} \rightarrow \alpha + \alpha + \alpha$





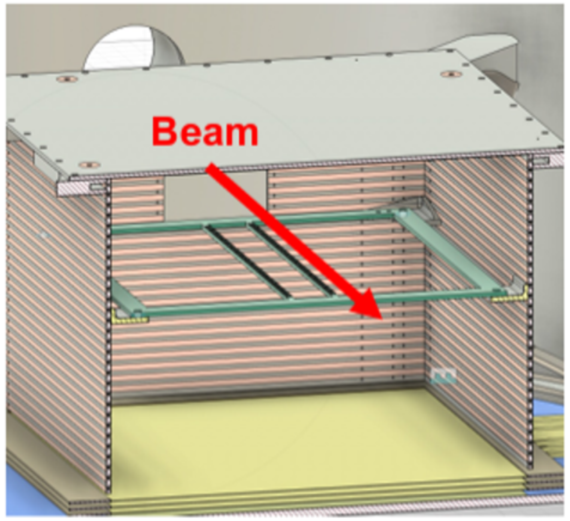
Reconstructed in ^{12}C* frame

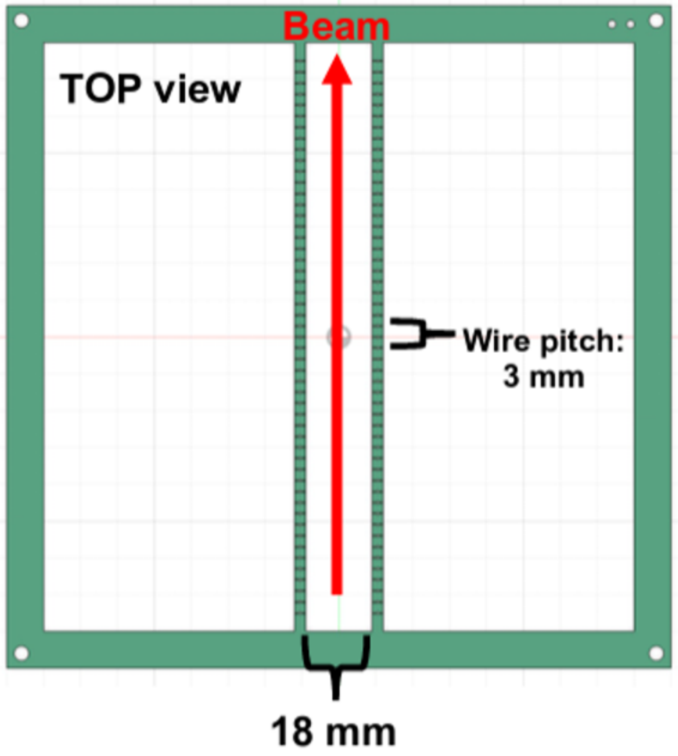


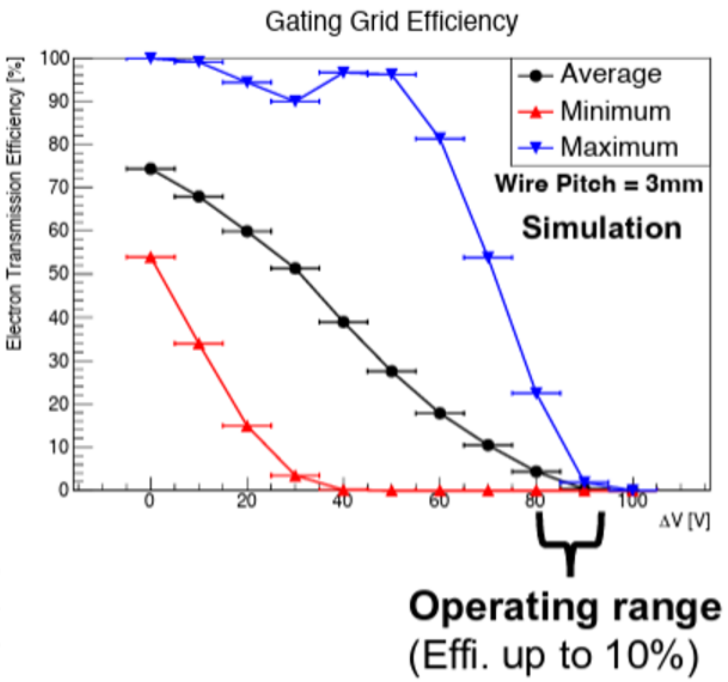


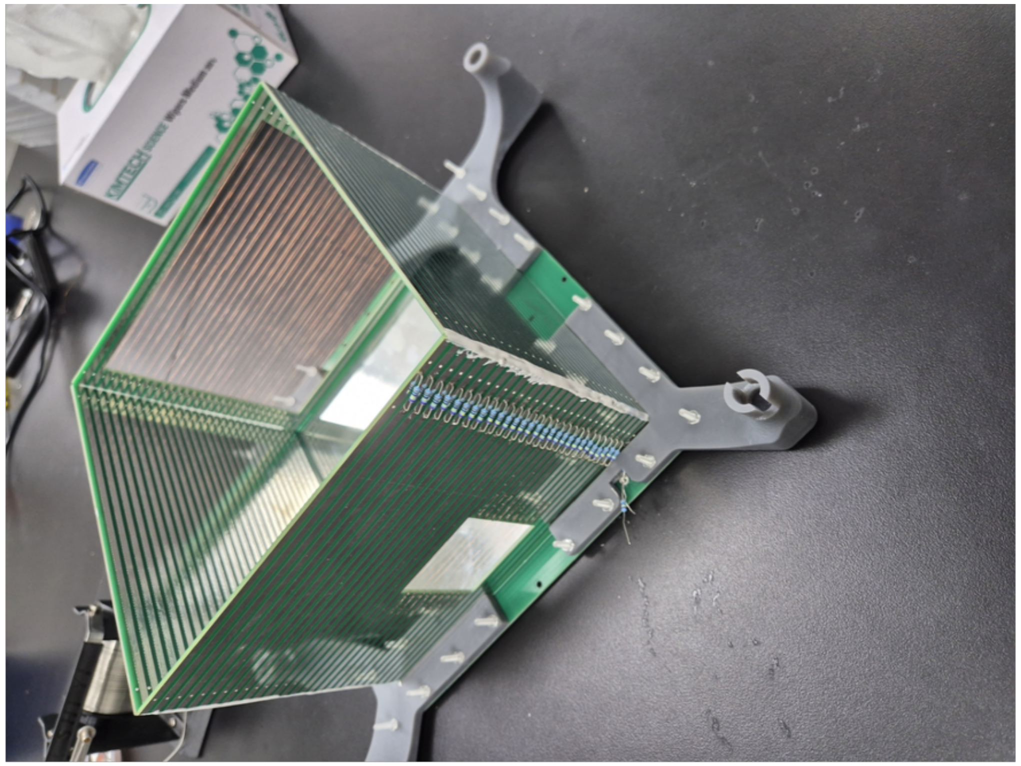
Caveat - signals and backgrounds are generated by same numbers

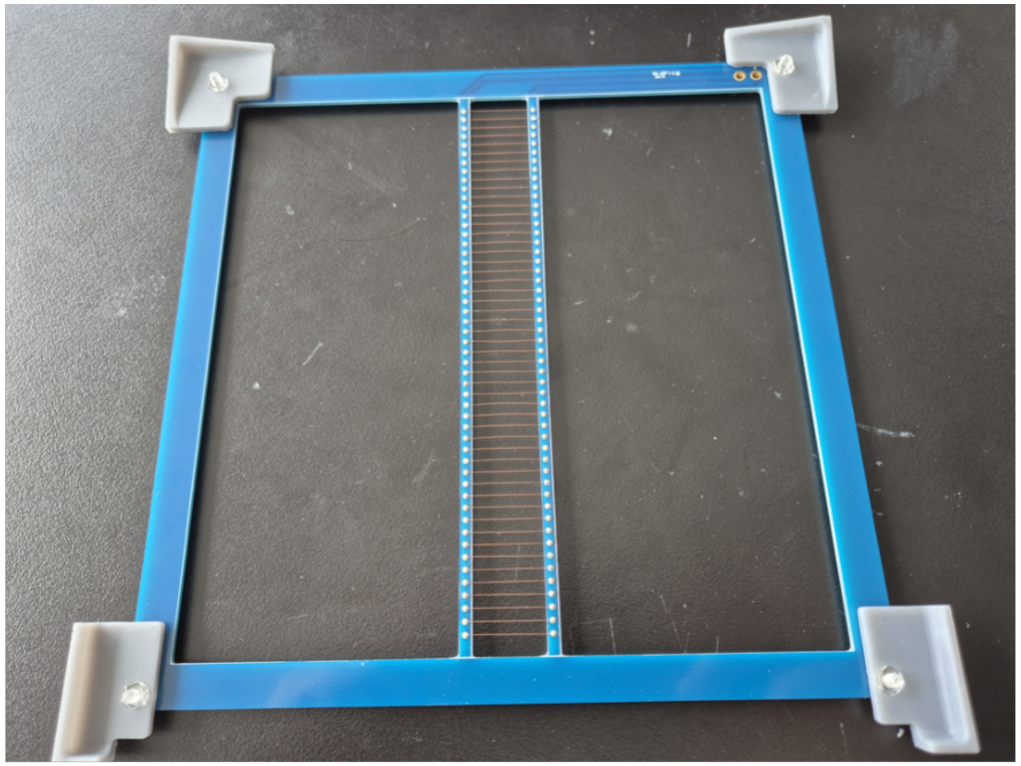
Ongoing works - gating grid





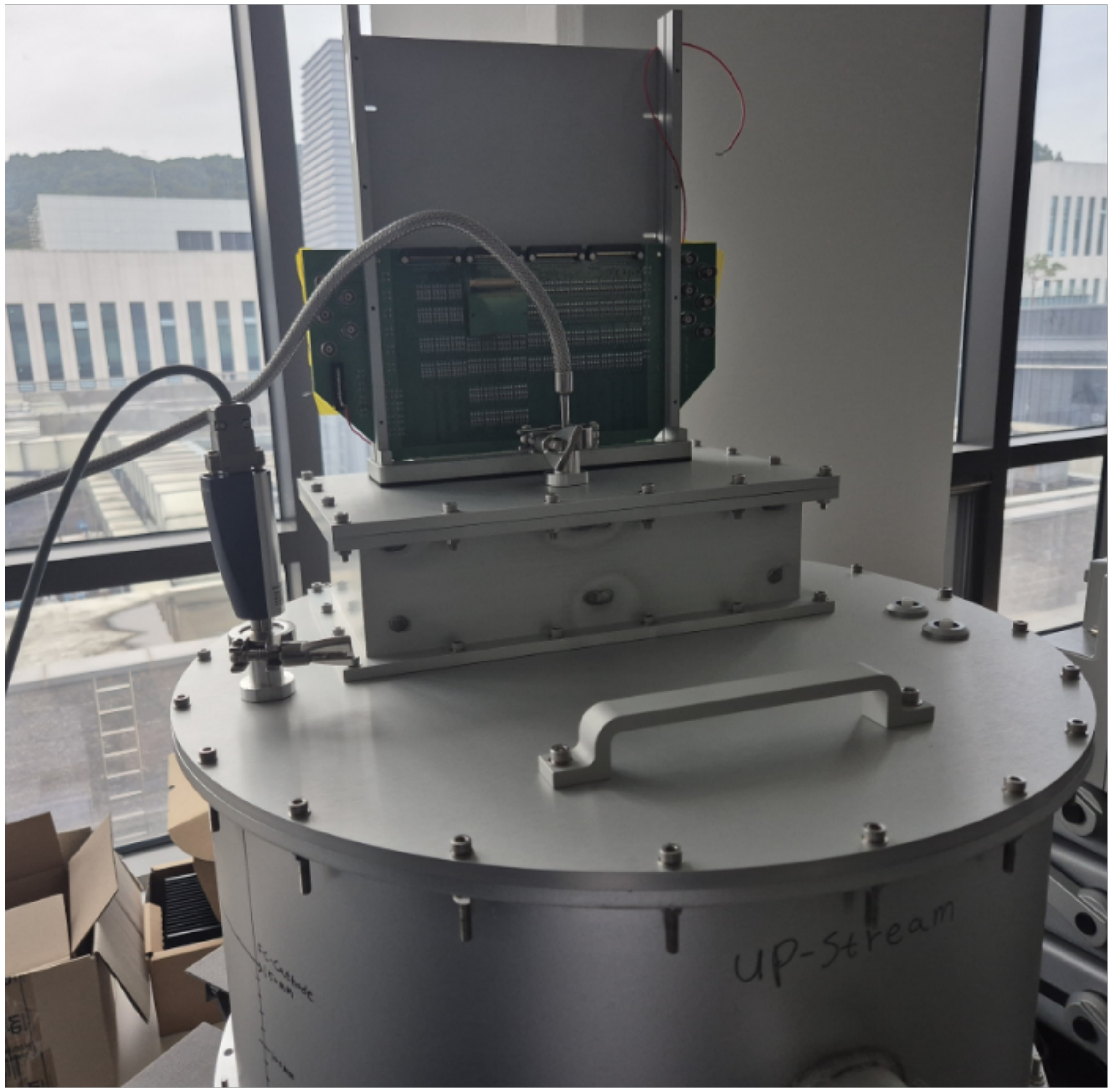




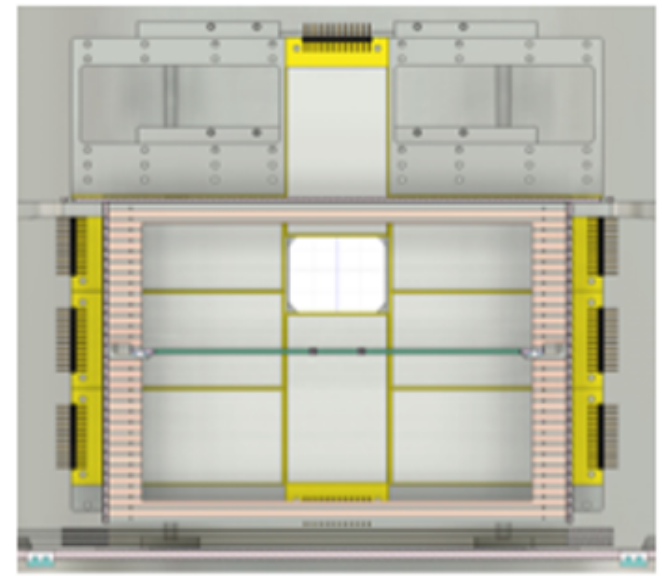


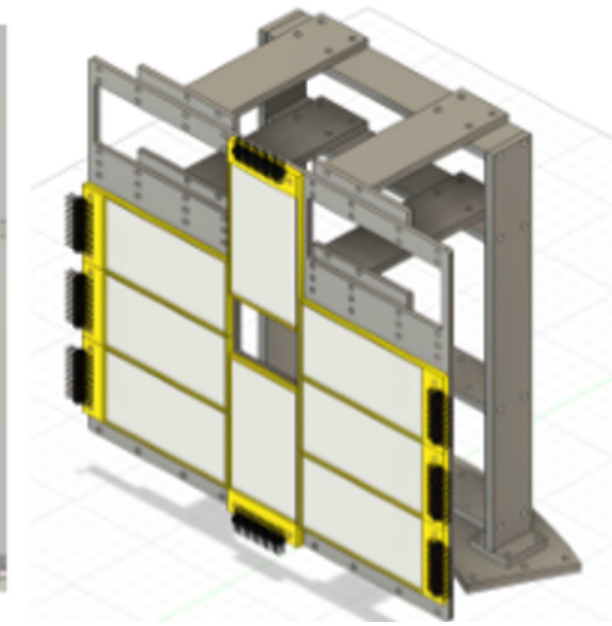
Ongoing works - Si detector installation

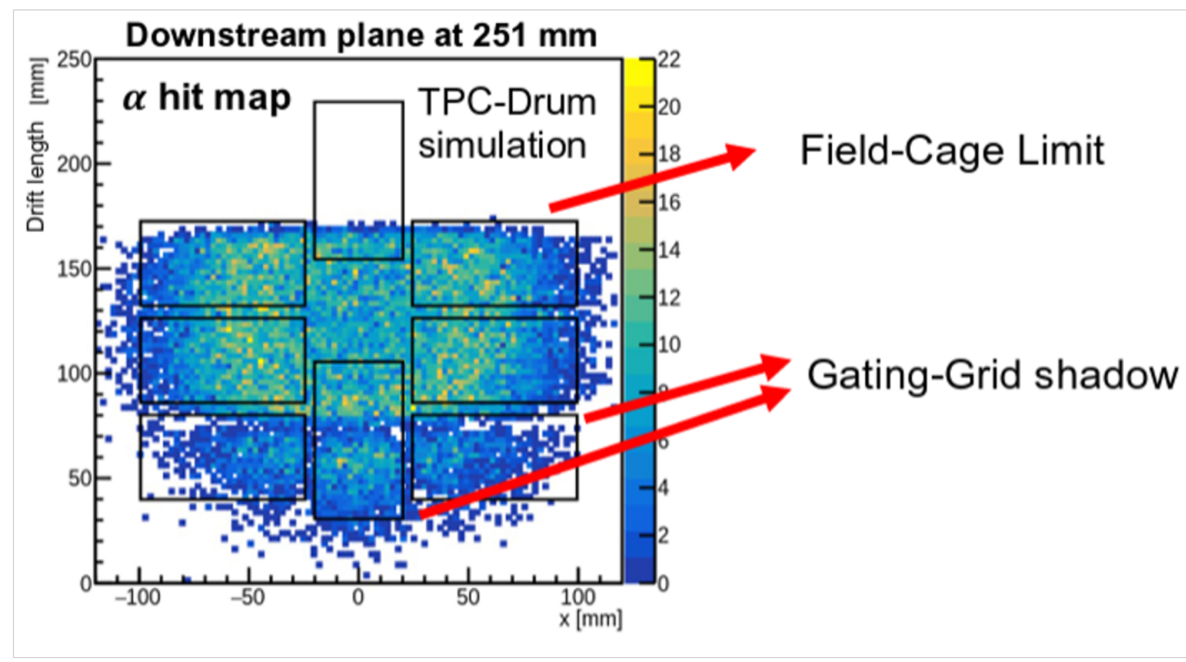
Si ZAP board



(inside)Si merging board







- Si detector positions were determined to maximize the acceptance for 3-alpha decay of the Hoyle state

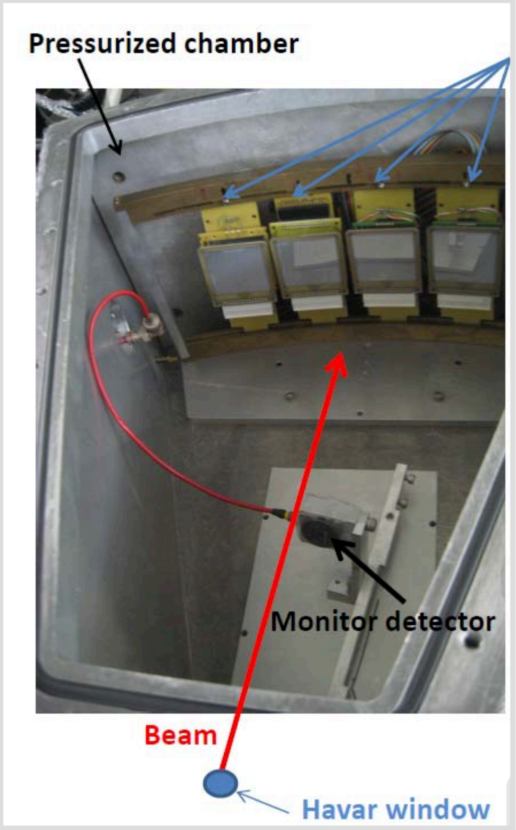
Experiment at RAON

- **Extrapolation from Barbui (2018) [1]**
  - ^{20}Ne, E = 9.7, 12 MeV/u
  - ^{4}He gas as the active target
  - Obtained ~1,000 Hoyle states from 3.82×10^{10} Ne particles
  - Si telescope located at the similar position with TPC-Drum

- **Beam time at RAON**
  - We got 5 days (= 40 hours) of beam time at RAON in Spring 2026
  - We proposed to take 10^5 pps Ne beam at 10 MeV/u
  - Expect to get ~10k Hoyle states and ~200 16O $\rightarrow 4\alpha$ events

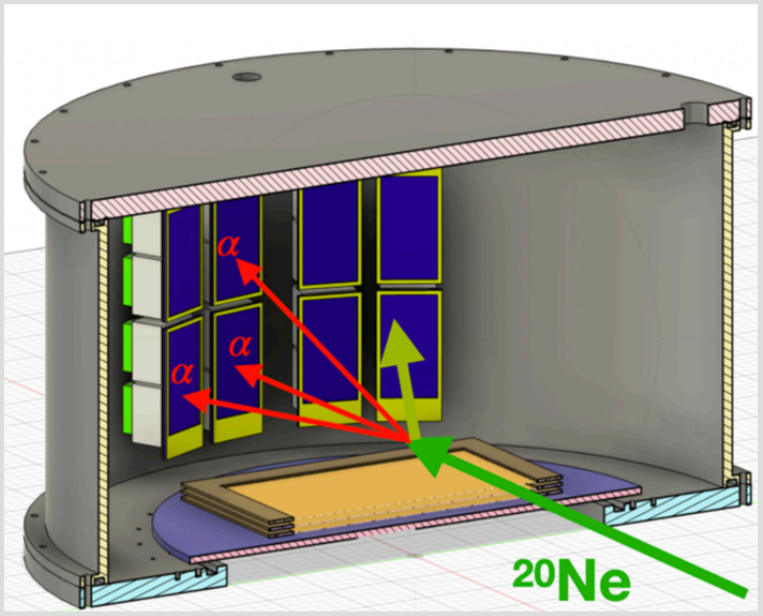
	Barbui (2018)	For this experiment
^{20}Ne + ^{4}He collisions	3.82 x 10^{10}	2.7 x 10^{10}
Collected Hoyle state	~1000	~10,000
Collected ^{16}O (15.1 MeV)	~20	~200

[1] *Phys.Rev.C 98 (2018) 4, 044601*



PRC 98, 044601 (2018)

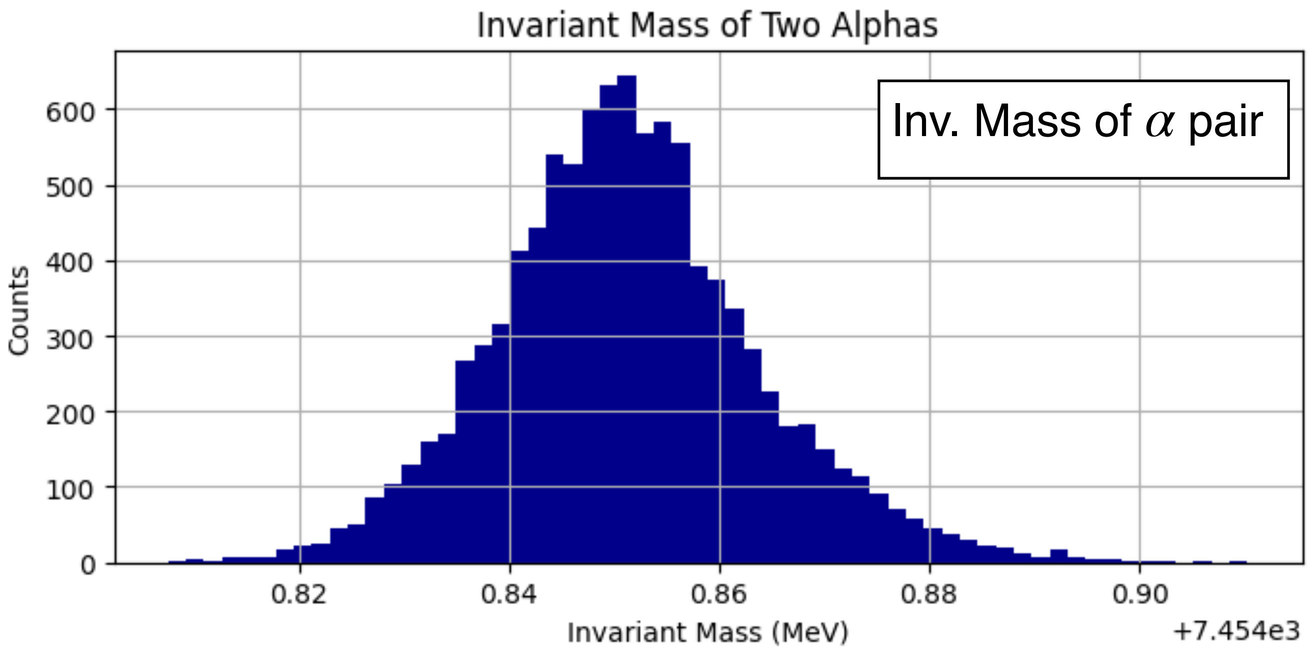
extrapolate

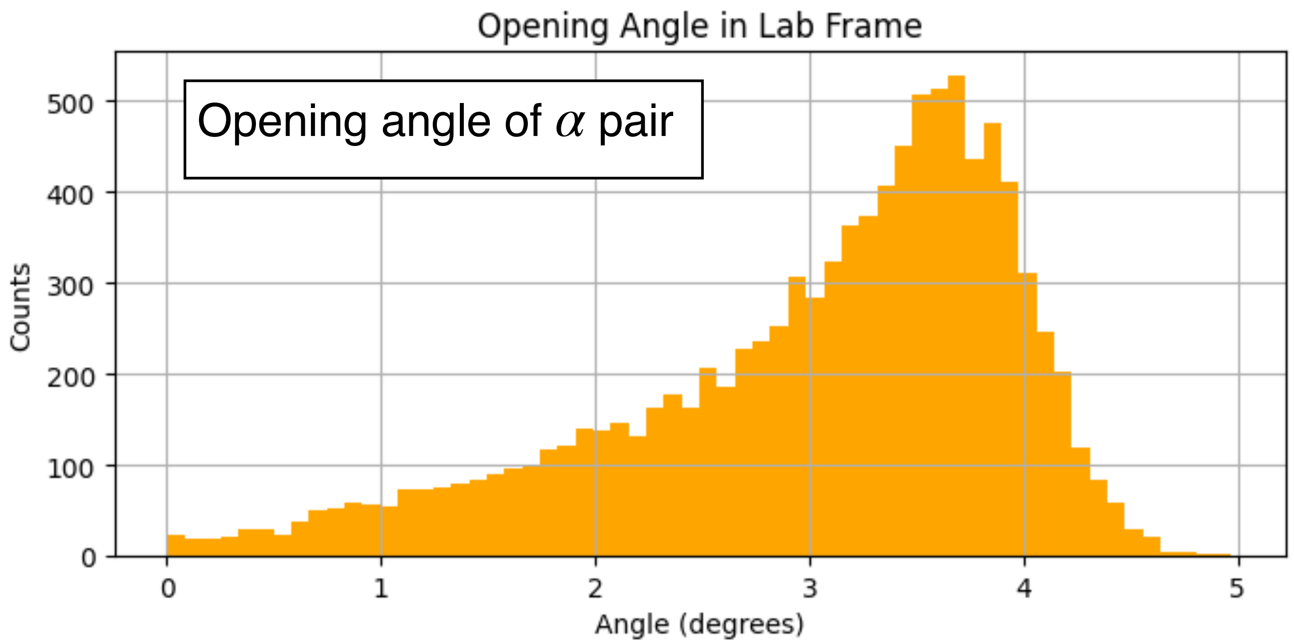


Calibration channel

- 8Be $\rightarrow \alpha + \alpha$ to be used for the detector validation
  - Well know peak position
  - Width provides the data-driven energy and angular resolution information

- Spectra of single α emission from ^{24}Mg* can also be compared with models (PACE4, HIPSe)

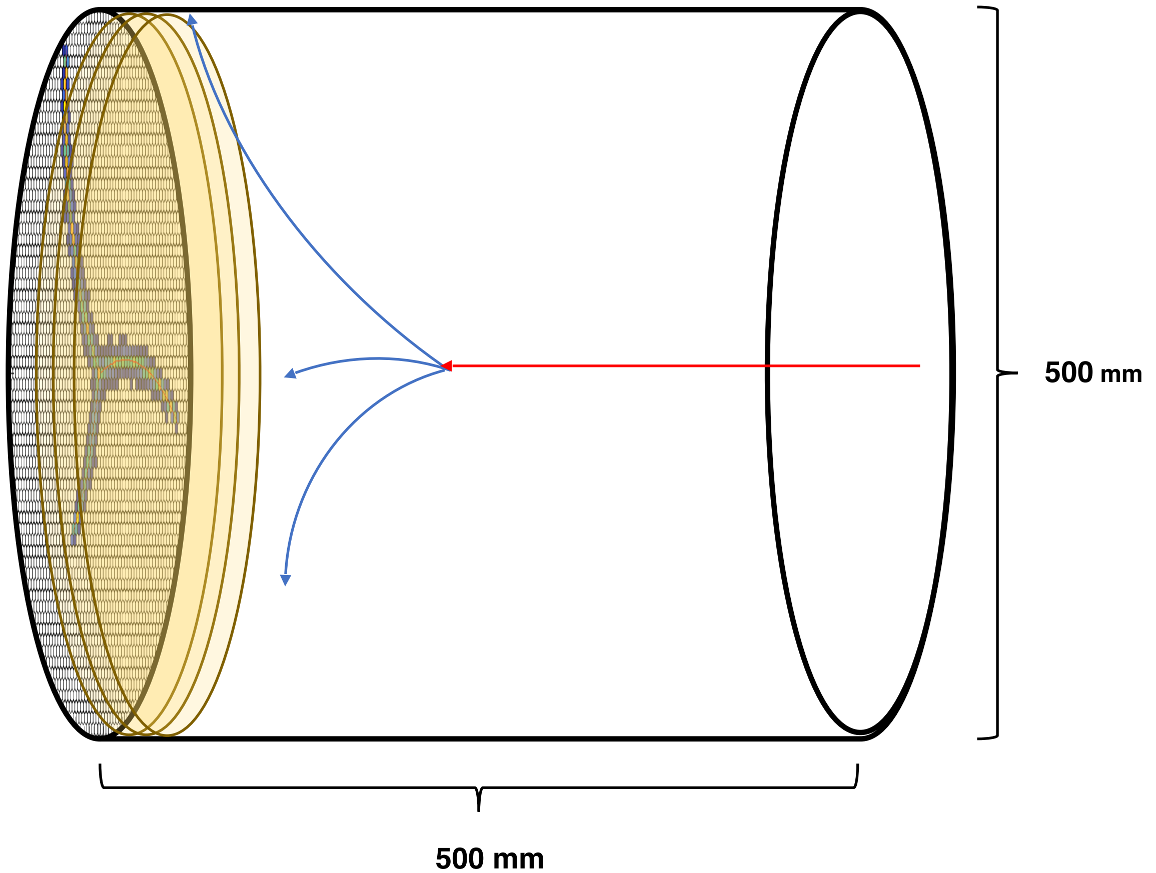


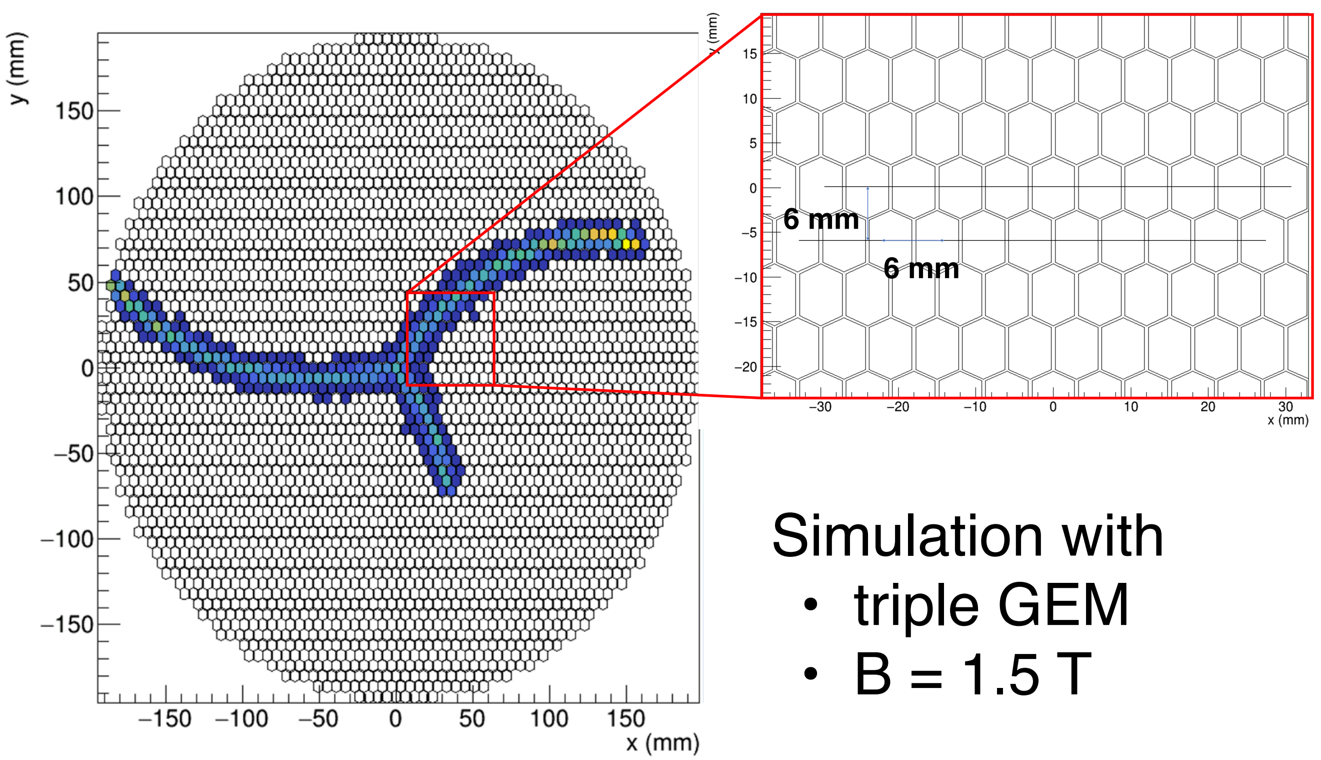


Next generation LAMPS AT-TPC

LAMPS active target TPC

- Cylindrical shape with readout at downstream with GEM-based gain
- To be used inside the SC magnet, 3k - 4k pad channels
- Operational for high collision rate for rare probe search
  - Streaming readout is very suitable
  - Studies are ongoing for electrons - GET? SAMPA-based board?
- Manufacturing planned in 2026





Simulation with
- triple GEM
- B = 1.5 T

OO collision at LHC

Chinese Physics C Vol. 47, No. 2 (2023) 024105

Signals of α clusters in $^{16}O+^{16}O$ collisions at the LHC from relativistic hydrodynamic simulations*

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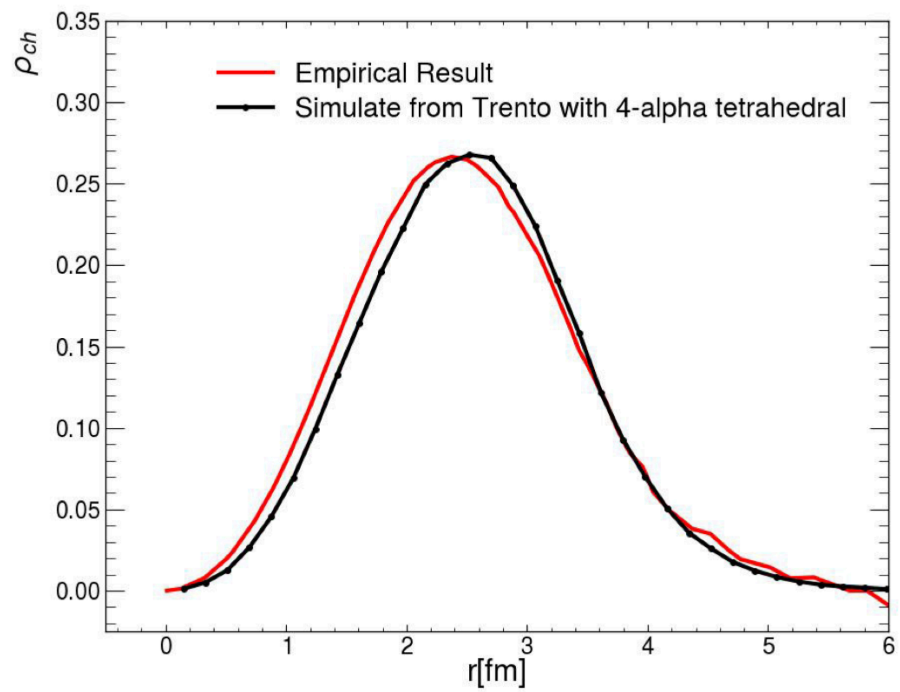
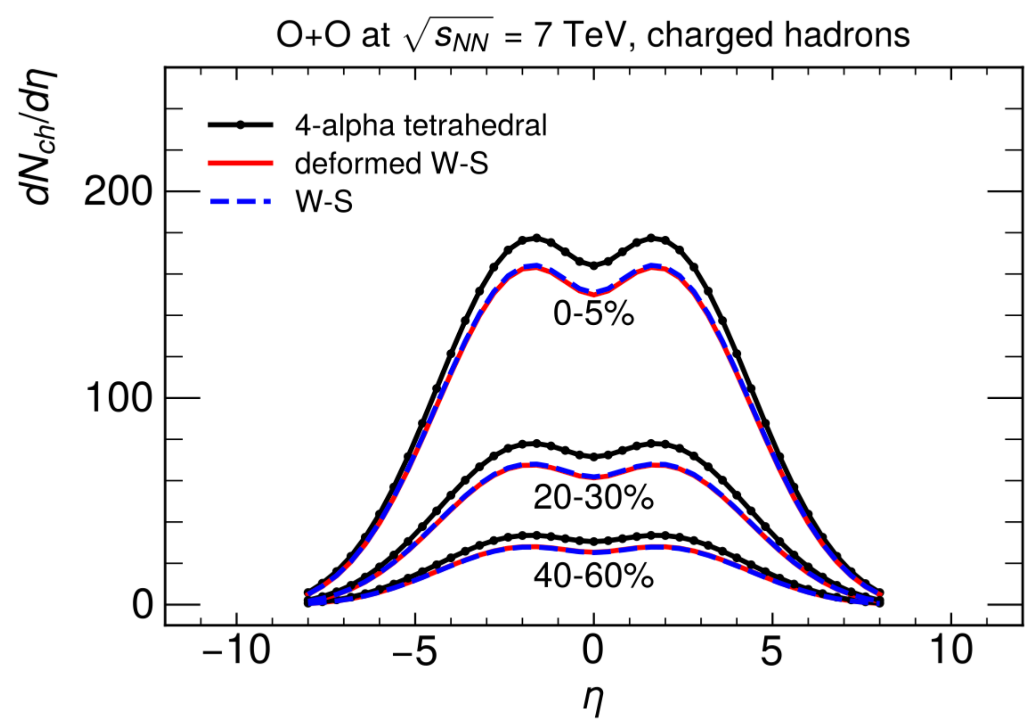
[1]Key Laboratory of Quark & Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China
[2]Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China
[3]Shanghai Research Center for Theoretical Nuclear Physics NSFC and Fudan University, Shanghai 200438, China



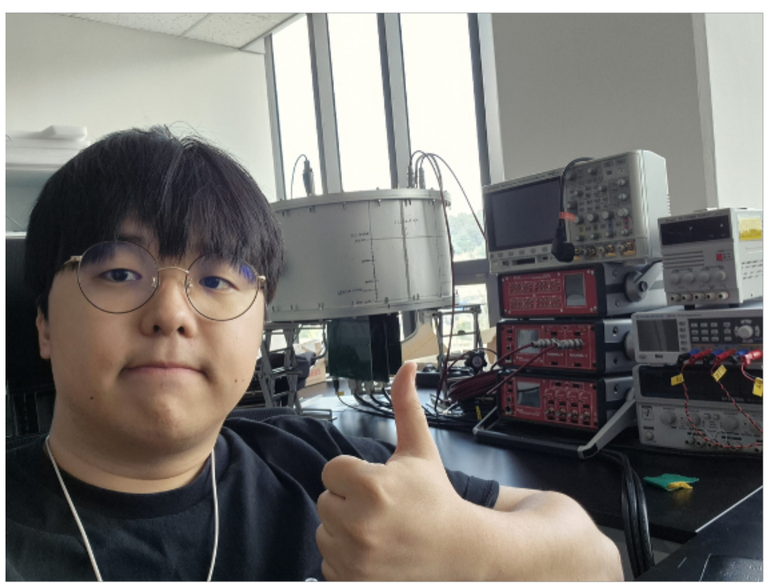


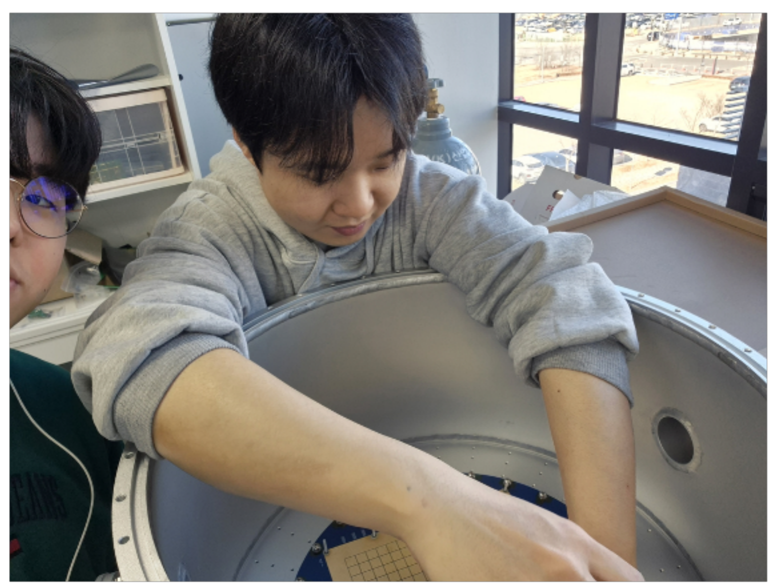
$$\rho(r) = \rho_0\left(1 + w\frac{r^2}{R^2}\right)\left[1 + \exp\left(\frac{r-R}{a}\right)\right]^{-1}$$

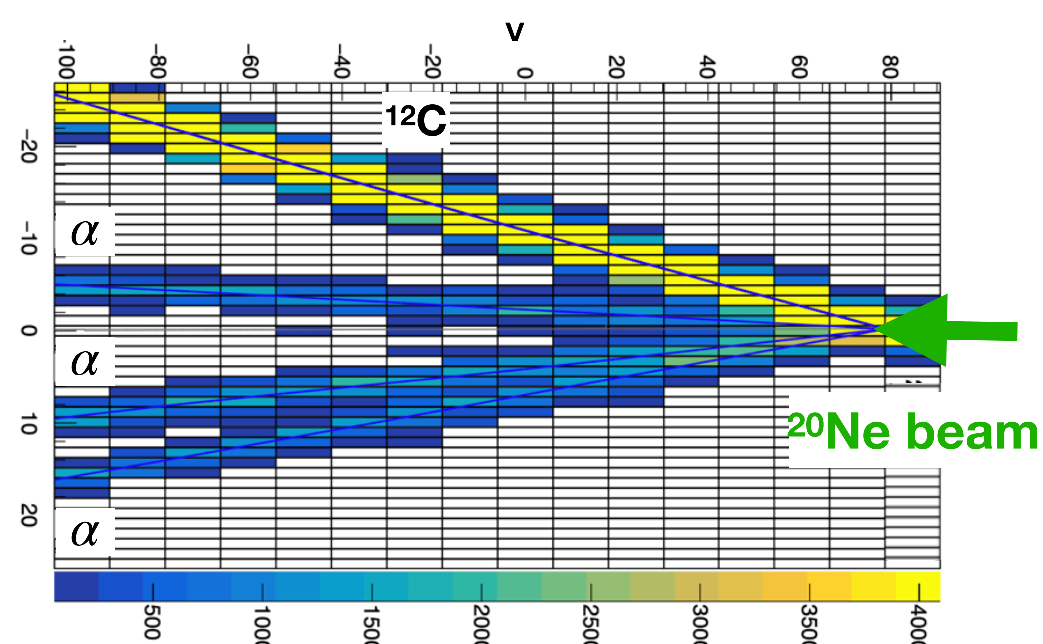
- Simulation study shows the deformation signal of ^{16}O can be observed from the multiplicity distribution in OO collision at LHC energy
- Clustering structure is of interest for two energy extremum (10 MeV and 10 TeV), providing unique complementarity

Summary

- With the goal of exploring exotic alpha-cluster structures, we aim to measure the direct decay of Hoyle states and the 4α decay of ^{16}O states, which are phenomena of increasing interest in the nuclear physics community.
- The TPC-Drum is ready for precision measurement
  - Good energy resolution of Si ⊗ Good angular resolution of TPC
- ***Stay tuned for the first result to be released very soon!***







BACKUP