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NuSYM 2024

Status of LAMPS for Nuclear Symmetry Energy at RAON

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Contents

Part 1.

Physics goal of LAMPS:
Nuclear equation of state & symmetry energy

Main physics objective of LAMPS

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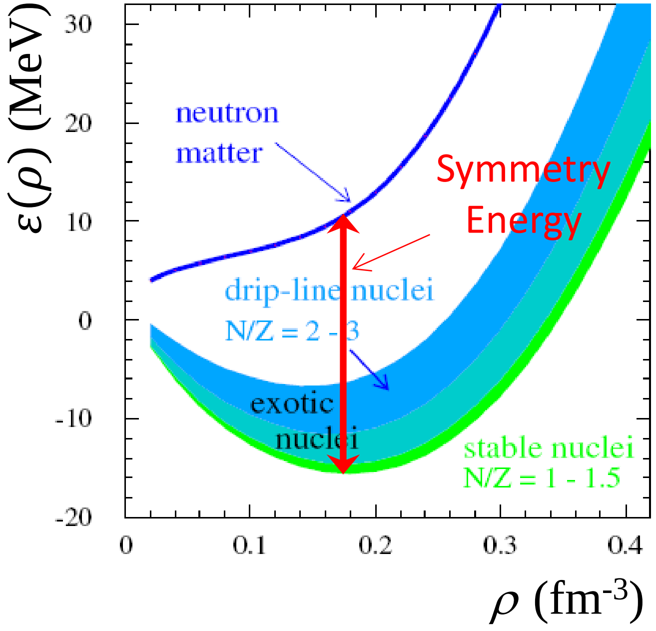
- Equation of state (EoS) & symmetry energy E_{sym} of nuclear matter $[\delta = (N-Z)/(N+Z)]$:

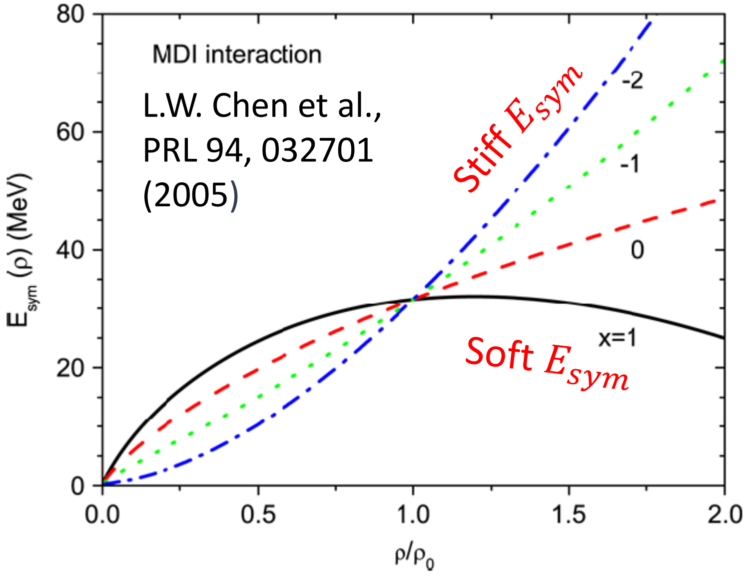
$$E/A = \varepsilon(\rho,\delta) = \varepsilon(\rho,\delta=0) + E_{sym}(\rho)\delta^2 + \mathcal{O}(\delta^4) + \cdots$$

$$E_{sym}(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$$

$$L = \frac{3}{\rho_0}P_{sym} = 3\rho_0 \left.\frac{\partial E_{sym}(\rho)}{\partial\rho}\right|_{\rho=\rho_0}, K_{sym} = 9{\rho_0}^2 \left.\frac{\partial^2 E_{sym}(\rho)}{\partial\rho^2}\right|_{\rho=\rho_0}$$



- Theoretical approach
  - Estimate of $\varepsilon(\rho,\delta)$ by using some density functionals or variational calculations
- Experimental approach
  - Constrain EoS & E_{sym} with the controlled laboratory experiments at specific densities (determined largely by the beam energy and less effectively by the system size)



Status of EoS & symmetry energy

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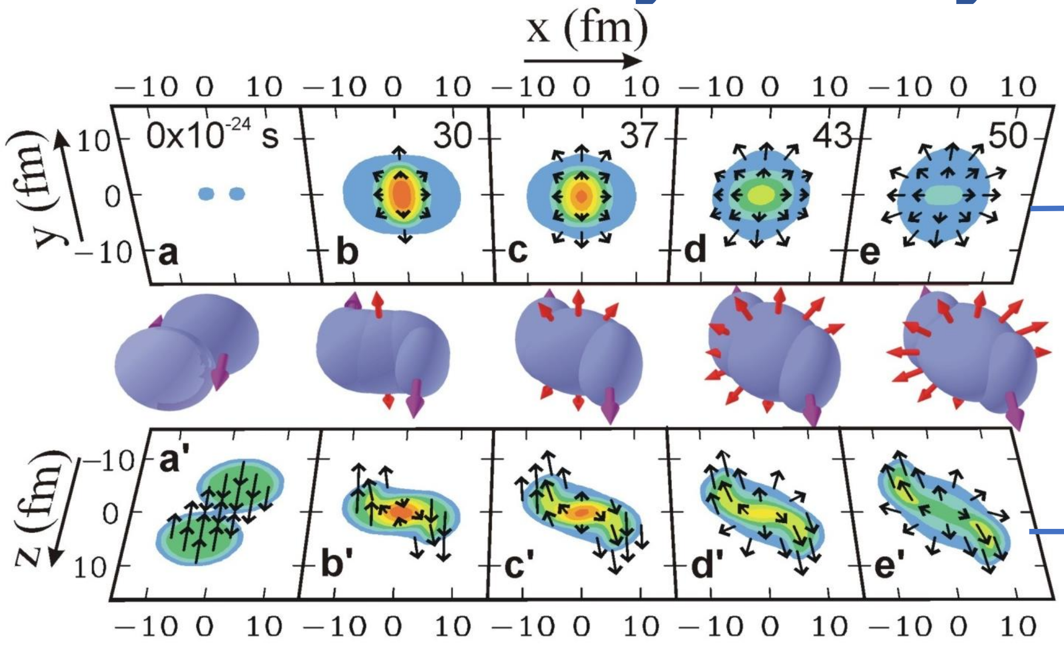
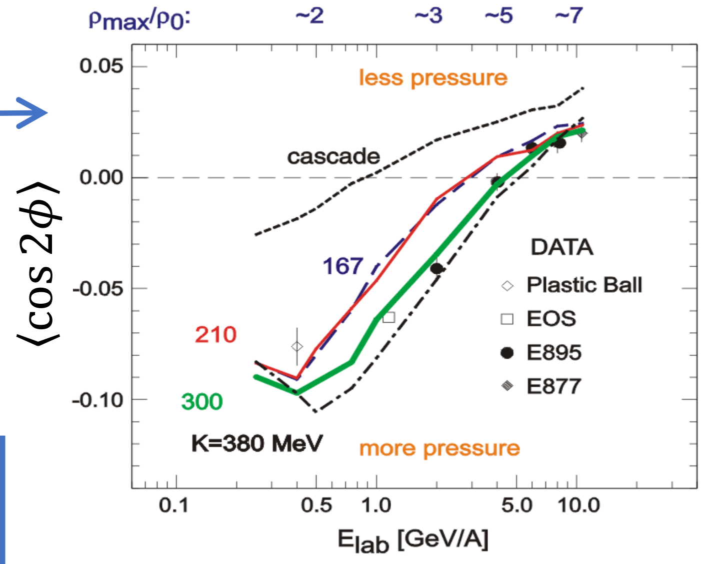
Figure adopted from Danielewicz et al., Science 298,1592 (2002)



elliptic flow or squeeze out

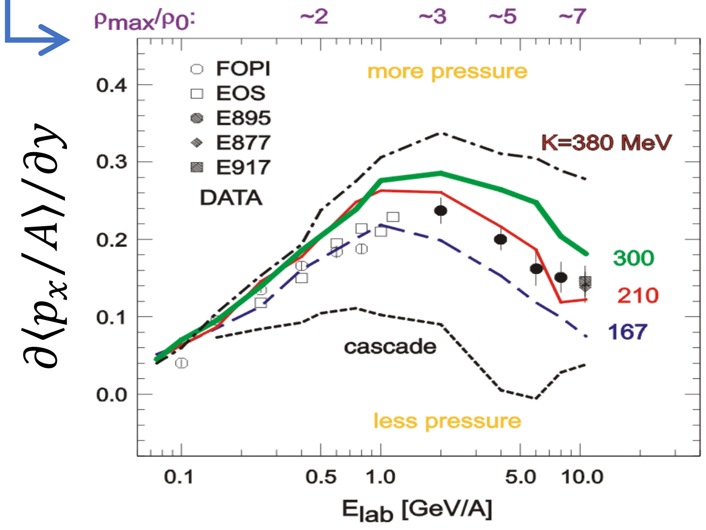
directed flow

Symmetric matter



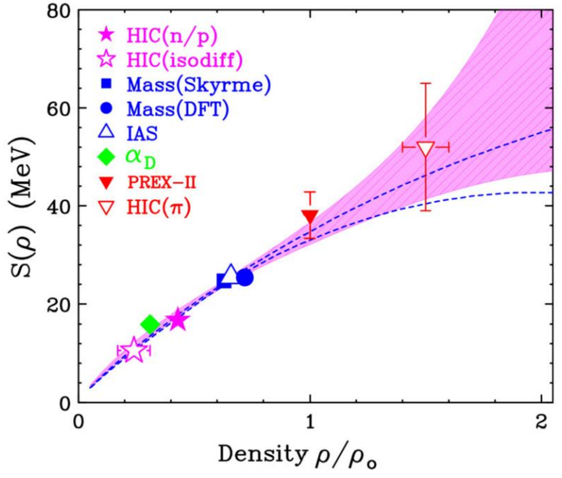
in plane

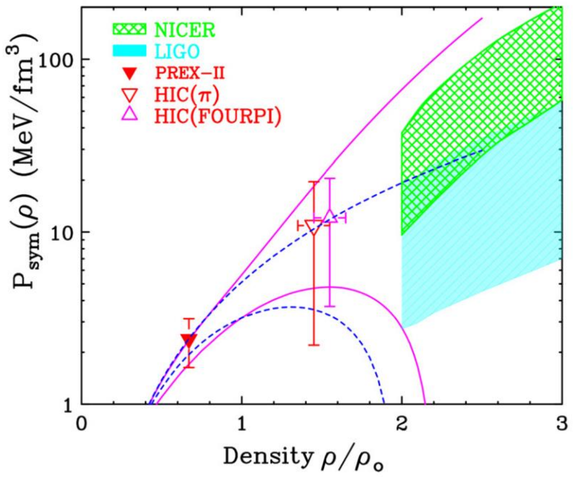
out of plane



Recent constraint of the symmetry energy

Lynch & Tsang, PLB 830, 137098 (2022)





Observables

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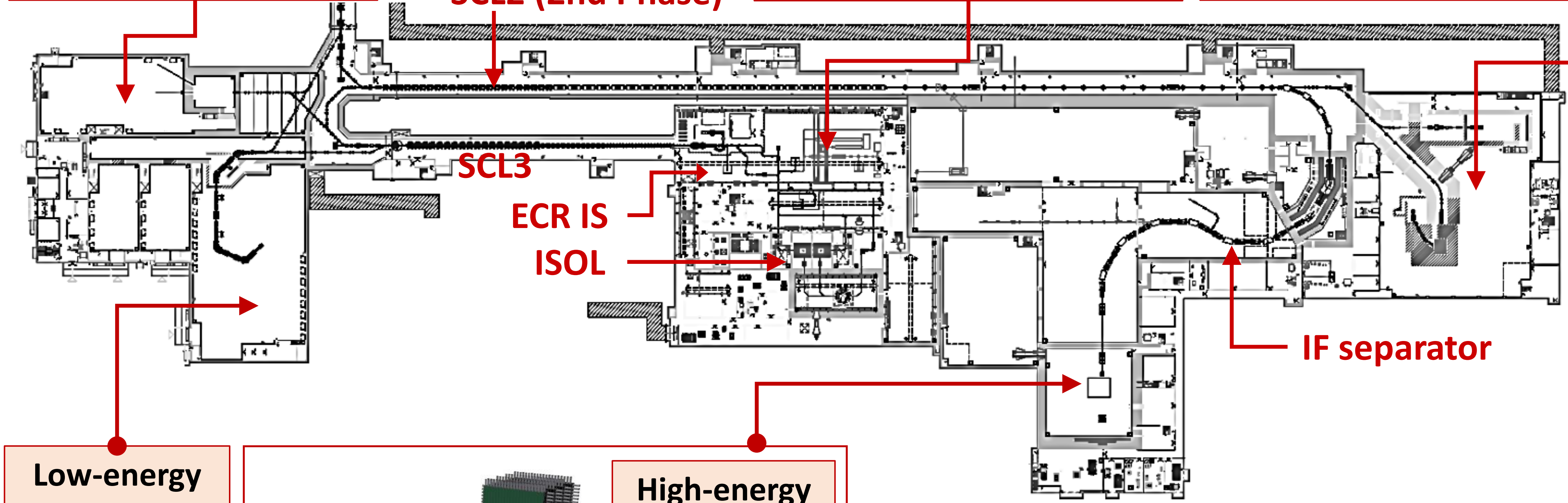
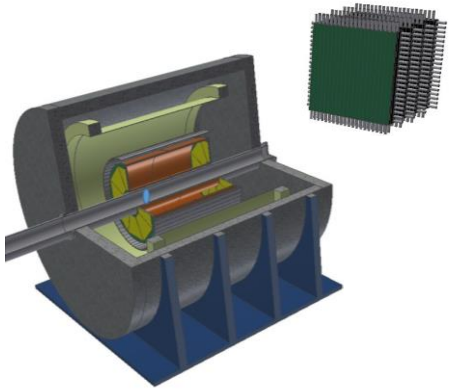
- Requirements for EoS experiments
  - Systematic change of the system size and N/Z of the collision system
  - Systematic change of the beam energy to cover a wide range of ρ/ρ_0
  - Analysis of diverse observables as functions of the collision centrality and momentum
  - Better to preserve the symmetric configuration of the detection system
- Representative observables
  - Particle spectra and yield ratios of isospin mirror particles, such as *n/p*, $^3H/^3He$, $^7Li/^7Be$, π^-/π^+, etc.
  - Collective flow: v_1 & v_2 of *n*, *p*, and fragments
  - Azimuthal angle dependence of *n/p* ratio relative to the reaction plane
  - Isoscaling phenomenon in nuclear multi-fragmentation process
  - Isospin transportation: isospin diffusion and drift
  - $E1$ transitions (giant and pygmy dipole resonances): peak position and magnitude
    (Some theories suggest that PDR is sensitive to the radius of the neutron skin for unstable nuclei.)
  - Angular dependence of the gamma emission
- Detectors
  - Large acceptance charged particle tracking (from pions to fragments)
  - Neutron (and gamma) detector
  - Event characterization detector for centrality and the reaction plane

Part 2.

LAMPS detection system @ RAON

LAMPS @ RAON



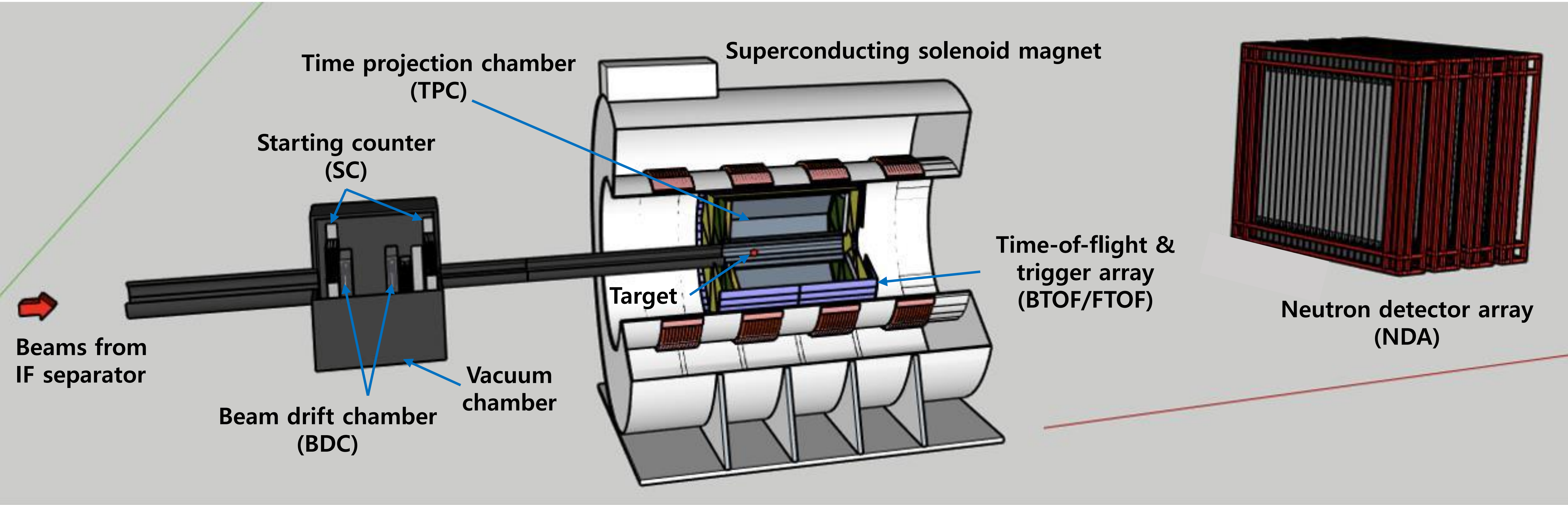


LAMPS can take all kinds of beams available at RAON!

- SIB: ECR IS→SCL3→SCL2→IF(w/o target)
- RIB (ISOL): ISOL→SCL3→SCL2→IF(w/o target)
- RIB (IF): ECR IS→SCL3→SCL2→IF
- RIB (ISOL+IF): ISOL→SCL3→SCL2→IF

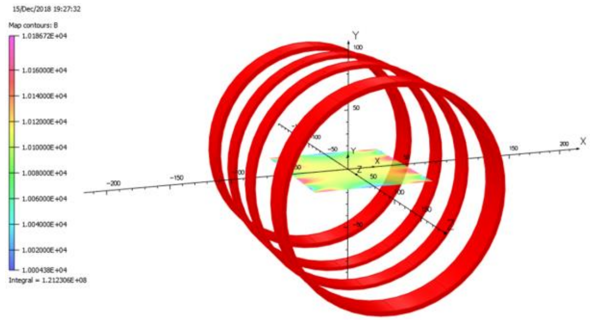
Overall design of LAMPS

- **LAMPS**: **L**arge **A**cceptance **M**ulti-**P**urpose **S**pectrometer
  - TPC with $\sim 3\pi$ sr acceptance for tracking light charged particles (Z=1,2,3)
  - Beam energy up to 250 MeV/u for ^{132}Sn; Intensity up to 10^8 pps (TPC can take only $\sim 10^{4-5}$ pps)
  - *Useful system not only for nuclear EoS, but also for nuclear structure*

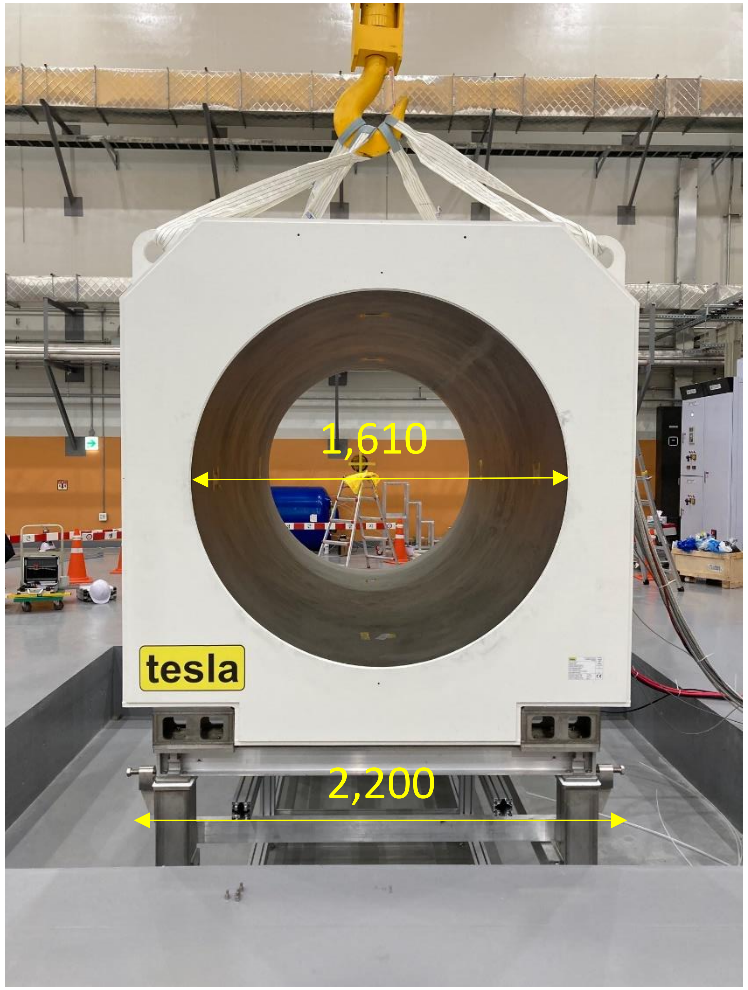


SC magnet

- Design parameters
  - Superconducting solenoid magnet
  - Dim.: 3,000(L) X 2,200(W) X 2,250(H) mm^3
  - Diameter of bore: 1,610 mm
  - Max. field: 1 Tesla
  - Variation of B field over TPC volume:
    - (Simulation) $\pm 0.94\%$
    - (Measurement) $-0.86 \sim 0.67\%$



  - Passive quench protection
  - Conduction cooling with 4 K vessel thermal shield and vacuum vessel
- Construction
  - Mfr. by Tesla Engineering Ltd., UK
  - Installation completed at RAON in 2021



TPC: Performance test with prototype

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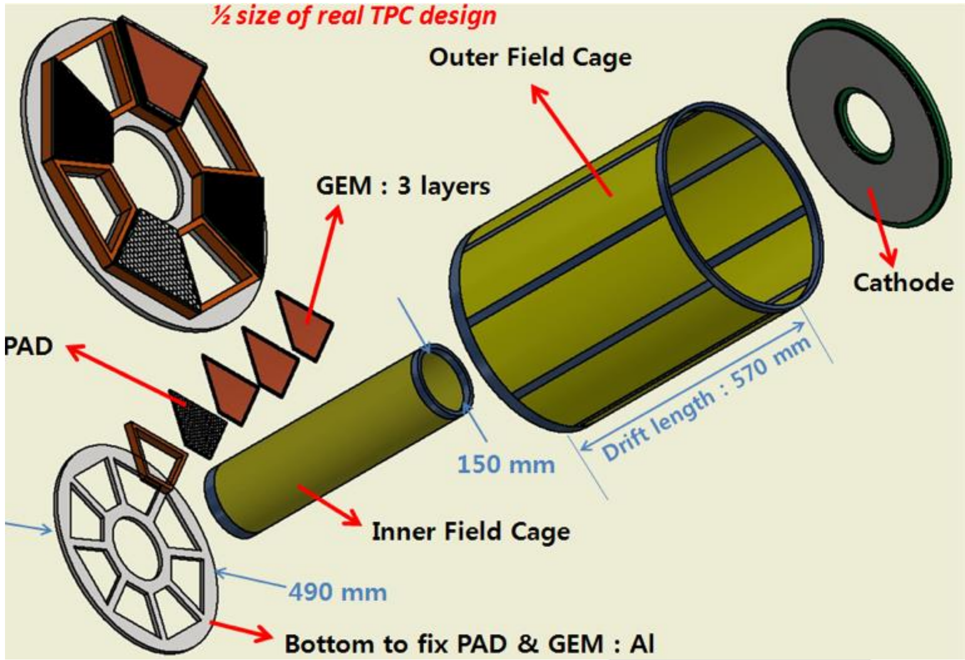
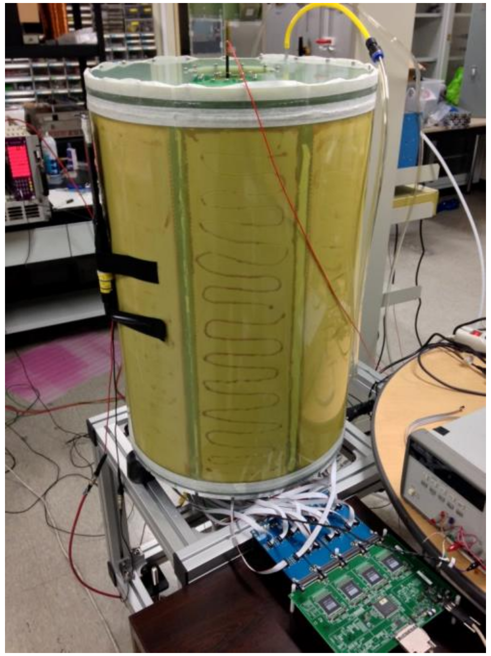
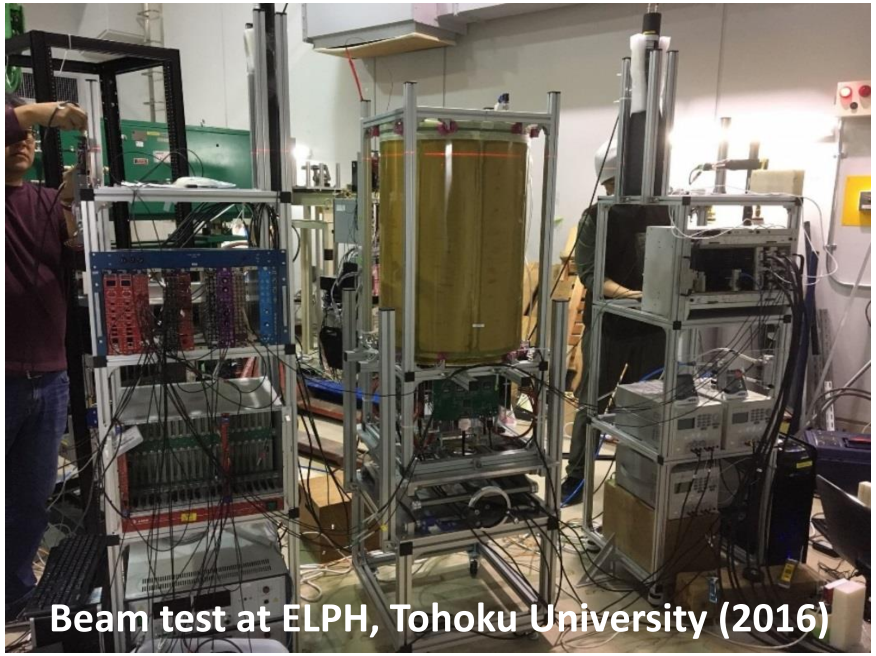
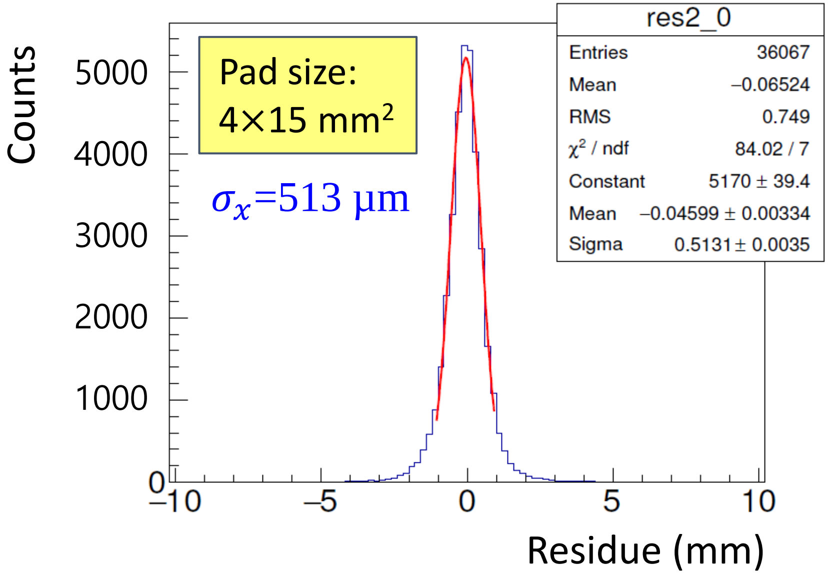
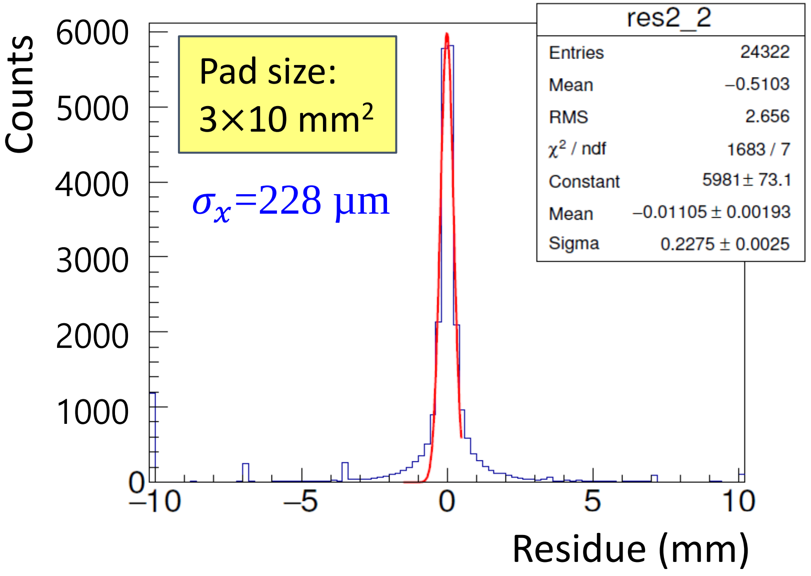
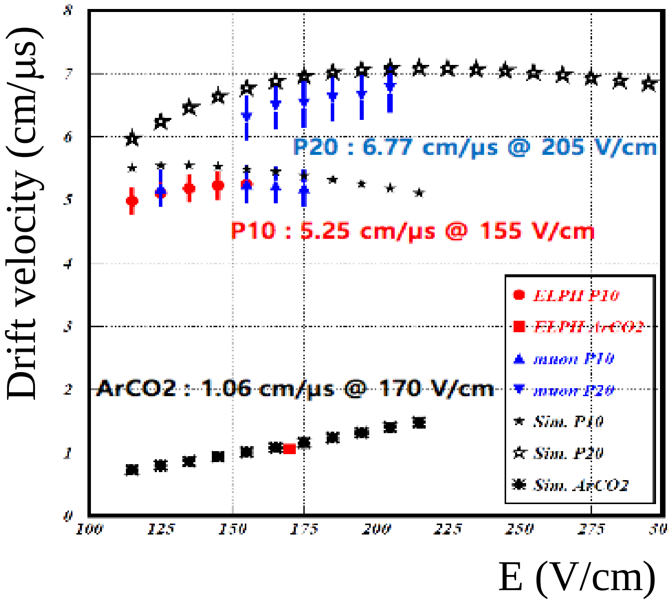




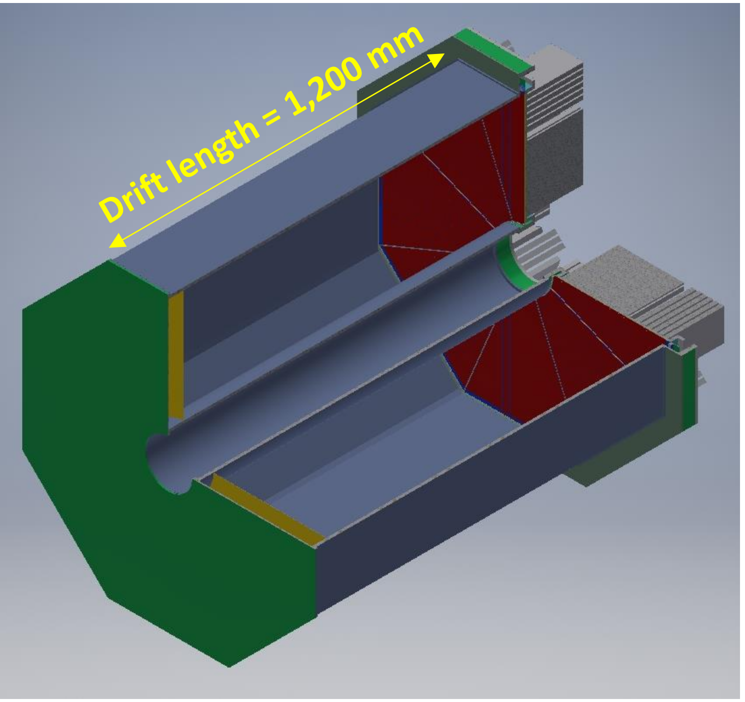


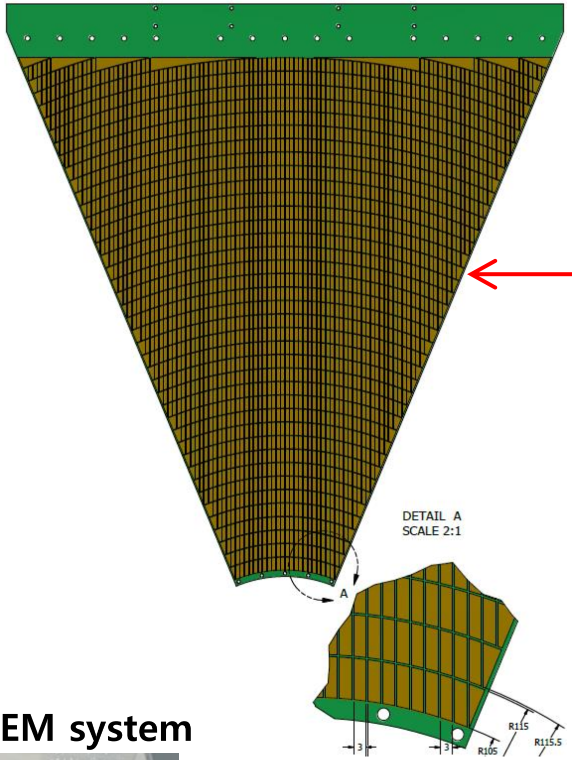


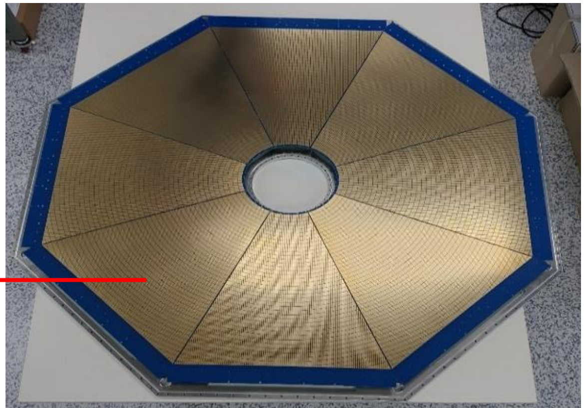


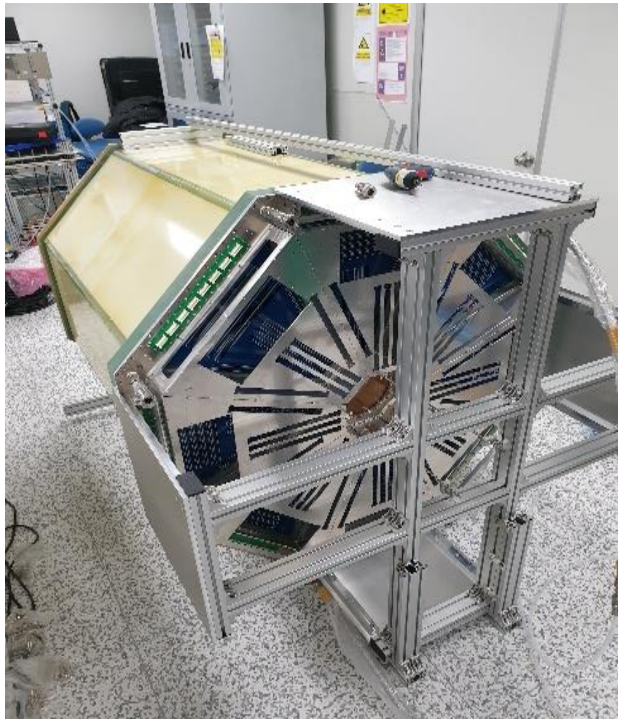


TPC: Construction of real detector



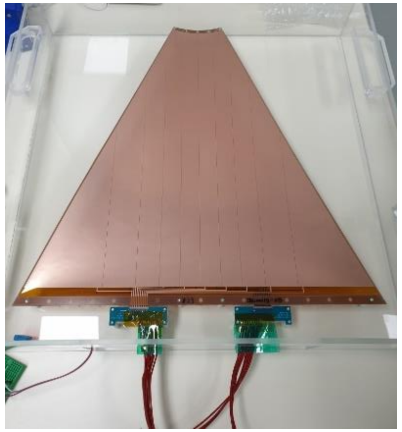






- Gas vessel (Rohacell + G10): $X/X_0 \sim 1.45\%$
- Pad Dim.: 3×10 mm^2
- Ch. #: 21,584
- FEE (GET electronics): 11 AsAD/sector × 8 sectors = 88 AsAD (22 CoBo, 3 μTCA)

Quadruple GEM system



Fe-55

5.9 keV X-rays

Cathode GEM

Drift region: 5 mm

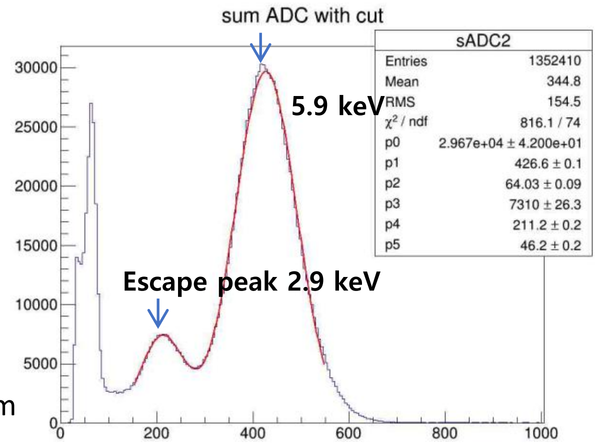
GEM4 Transfer region: 2 mm

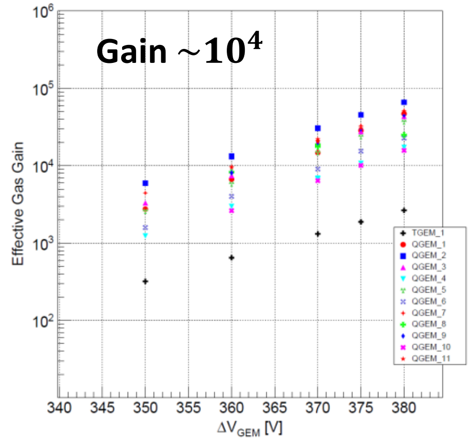
GEM3 Transfer region: 2 mm

GEM2 Transfer region: 2 mm

GEM1 Induction region: 2 mm

Readout PAD





TPC: Drift velocity measurement

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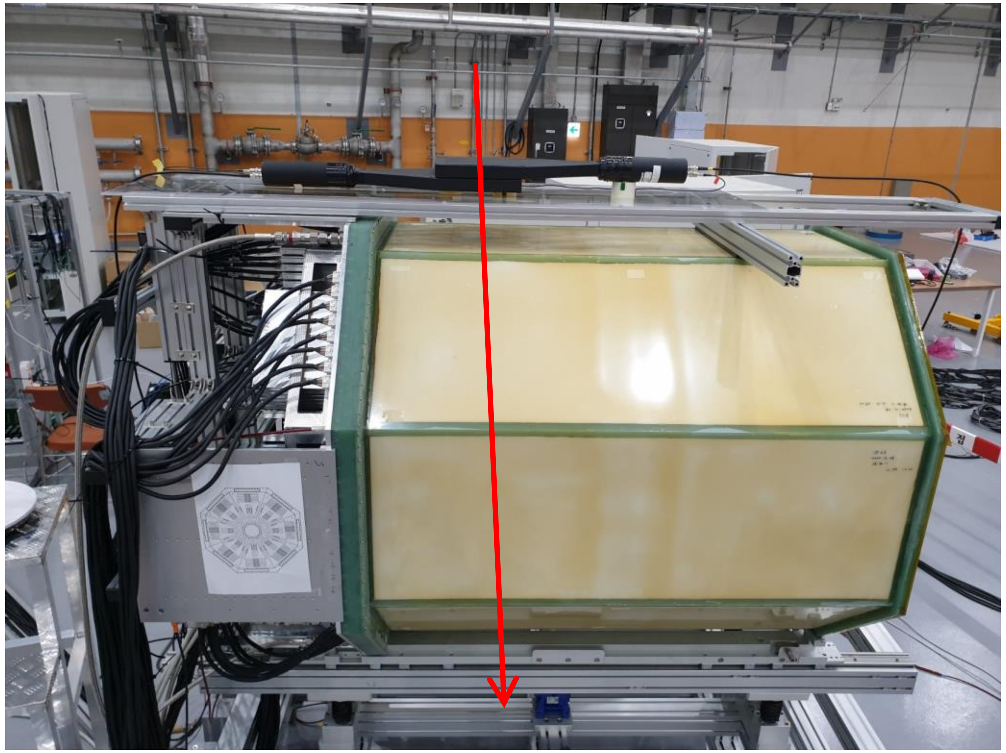
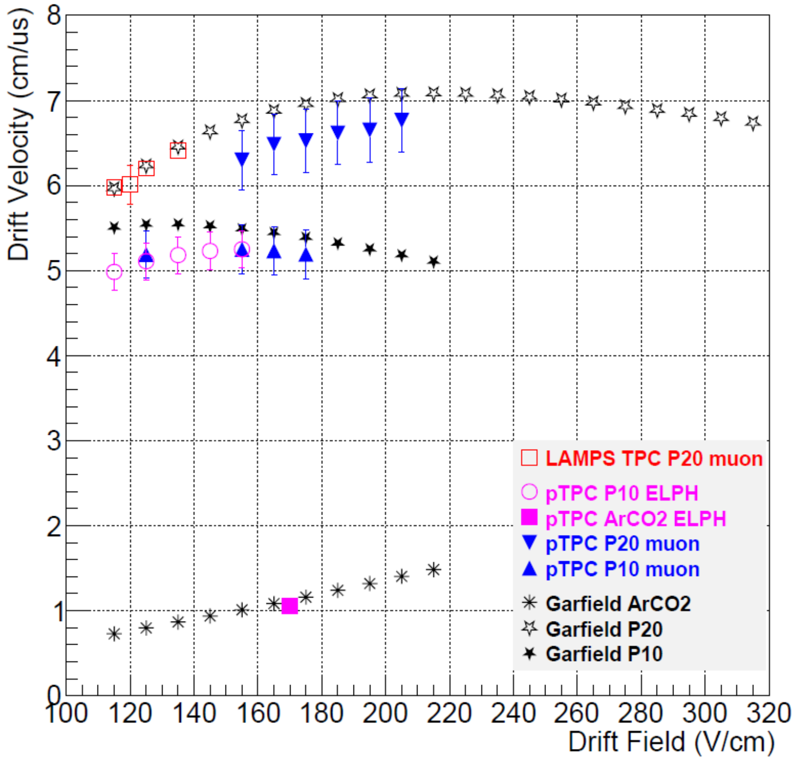
- Cosmic muon trigger
  - Coincidence of two scintillators (scintillator size: 20 x 20 cm^2 each)
  - Trigger positions at 30, 60 and 90 cm with the drift fields of 115, 125 and 135 V/cm

GET

Cosmic muon test

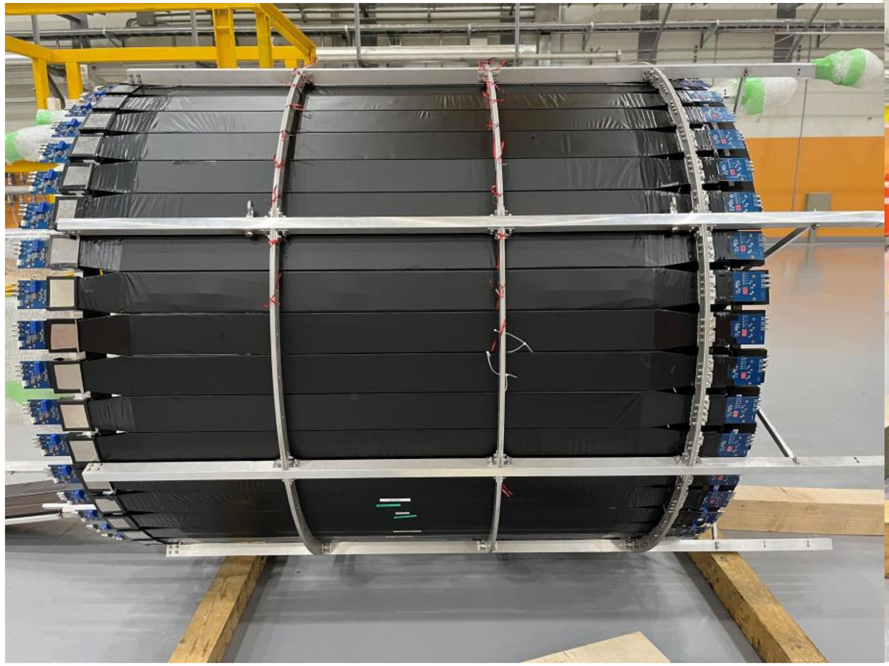


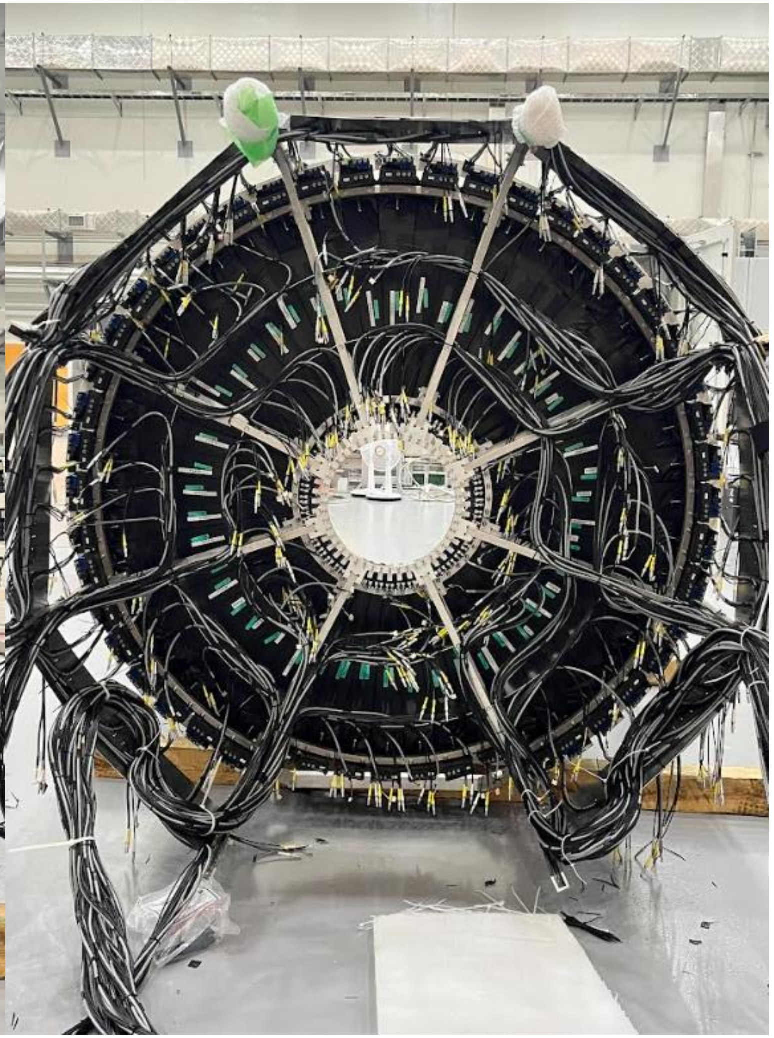
Drift velocity data



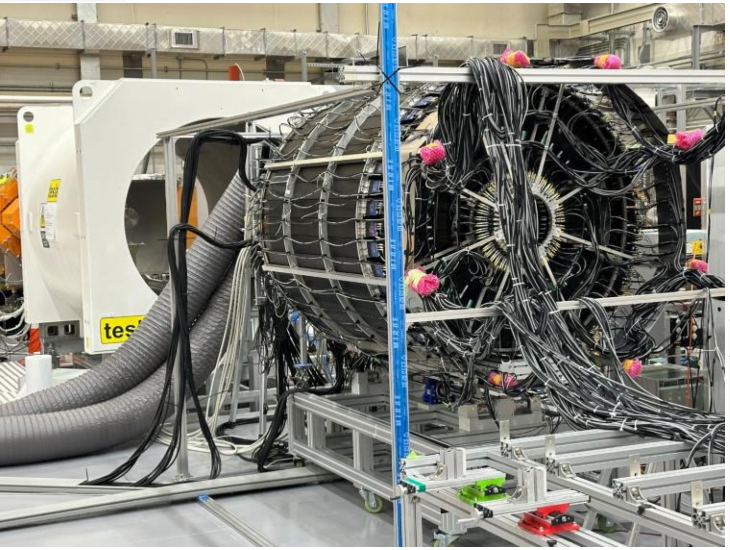
BTOF/FTOF

- Surrounding TPC for measuring the time-of-flight and providing trigger
- Number of scintillators & dimensions:
  - BTOF: (48) 1500 X 90 X 10 mm^3 each
  - FTOF: (48) 500 X (90, 24) X 5 mm^3 each
- MPPC readout from both ends
- Installation completed in 2022

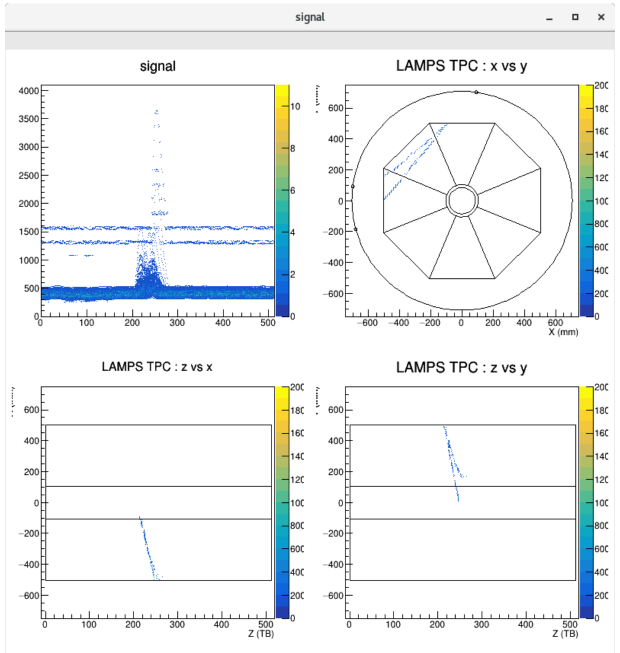


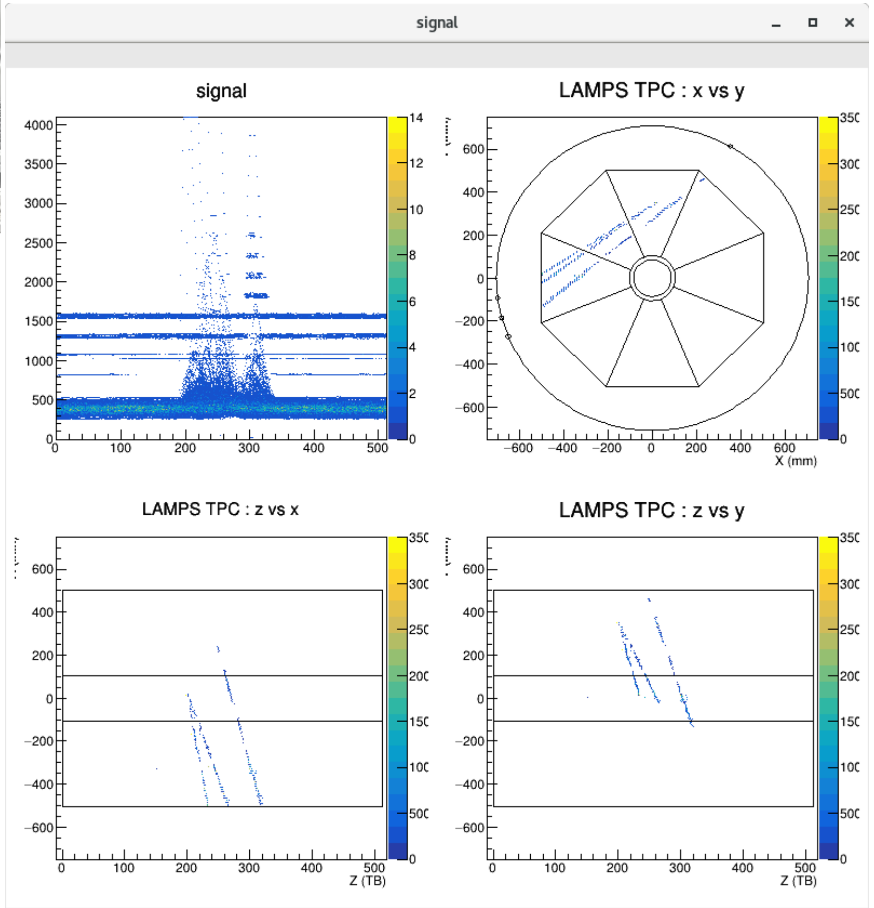


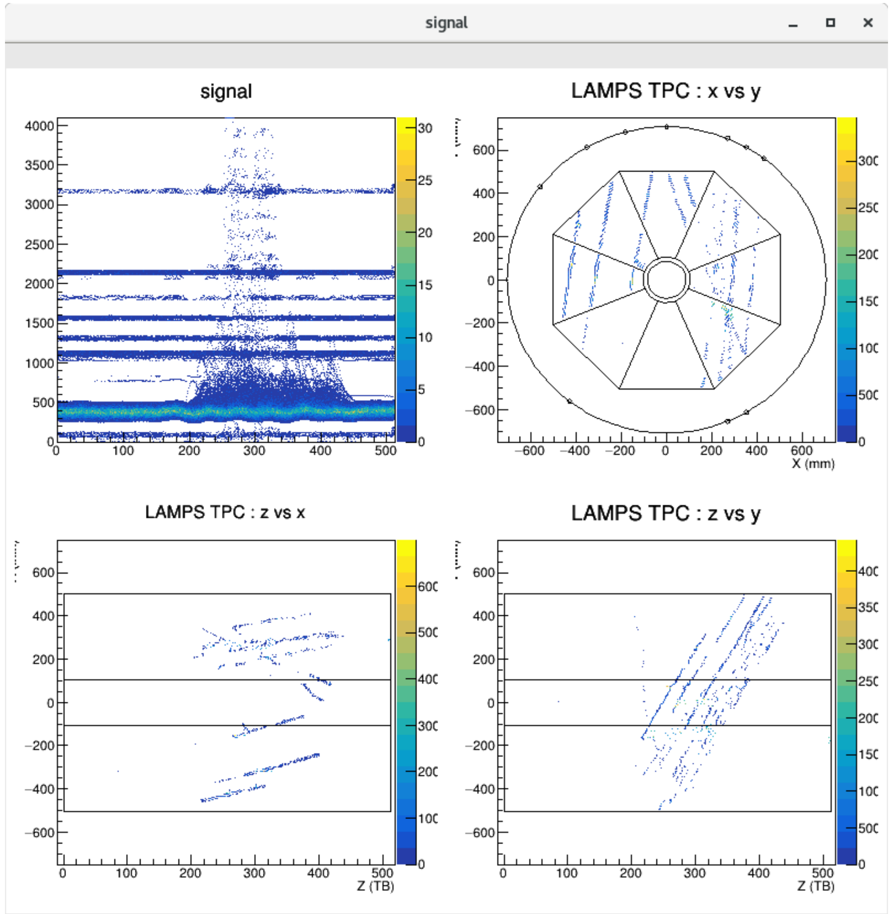
TPC+BTOF/FTOF: Cosmic test



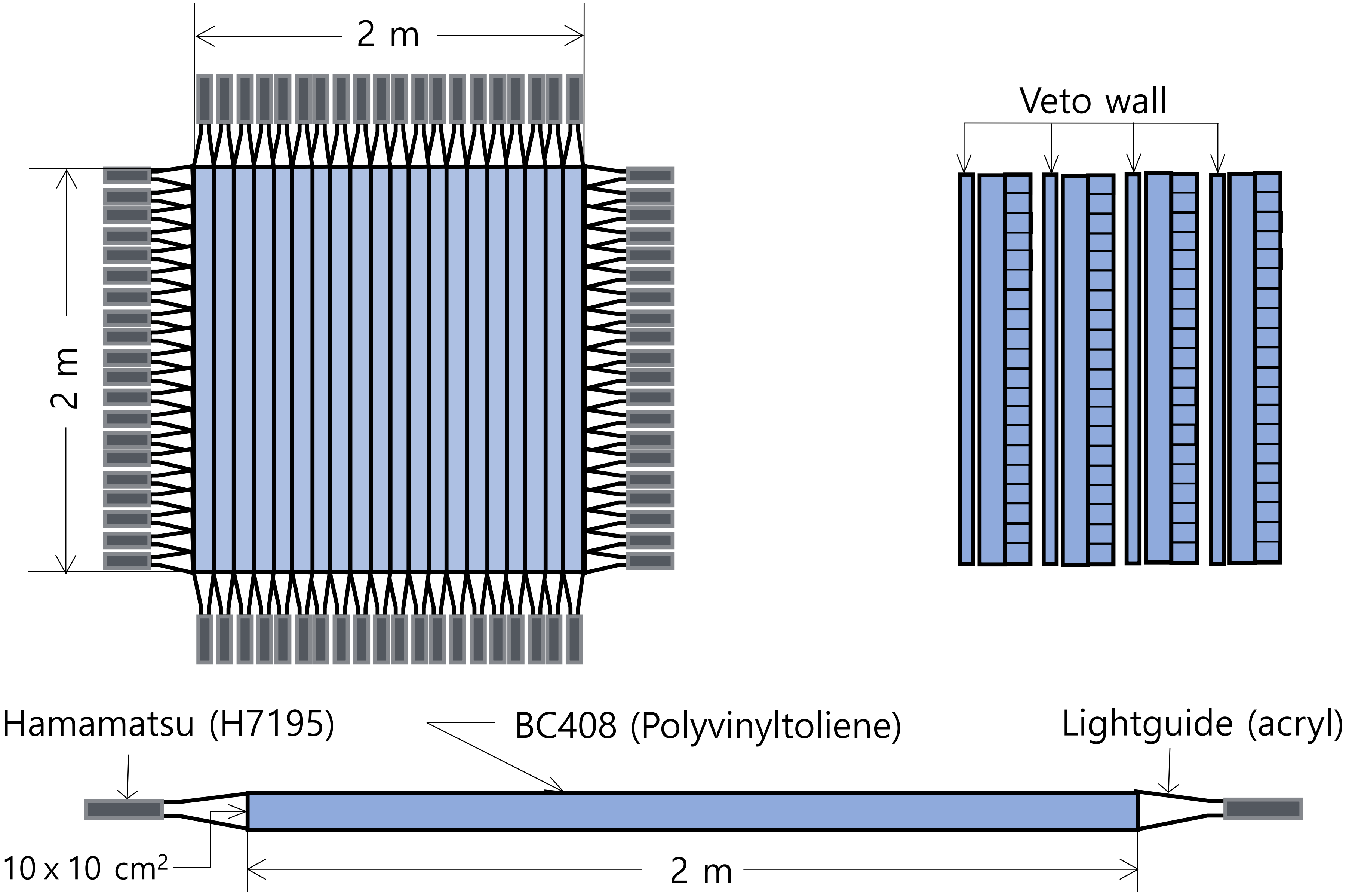
- We have developed the LAMPS trigger electronics system (LTE).
- The integrated system (TPC+BTOF/FTOF+SC) is continuously taking the cosmic data using LTE.
- Some examples of the cosmic events triggered by TOF are displayed below:





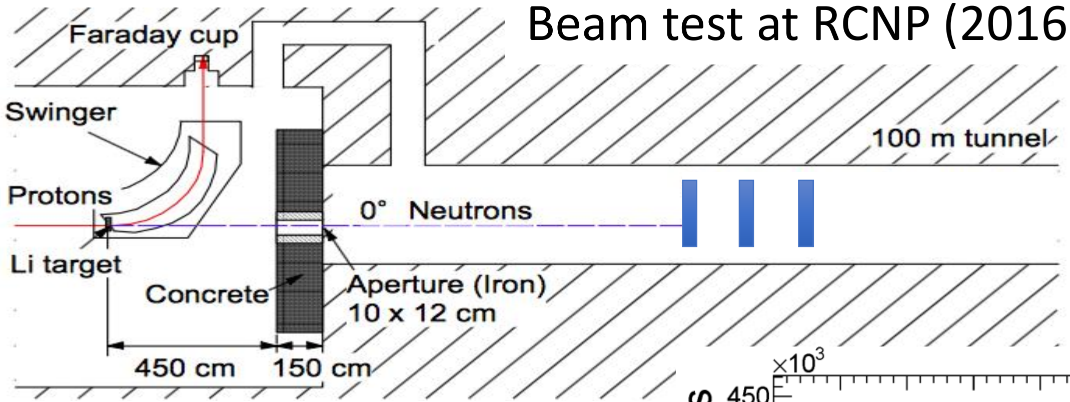


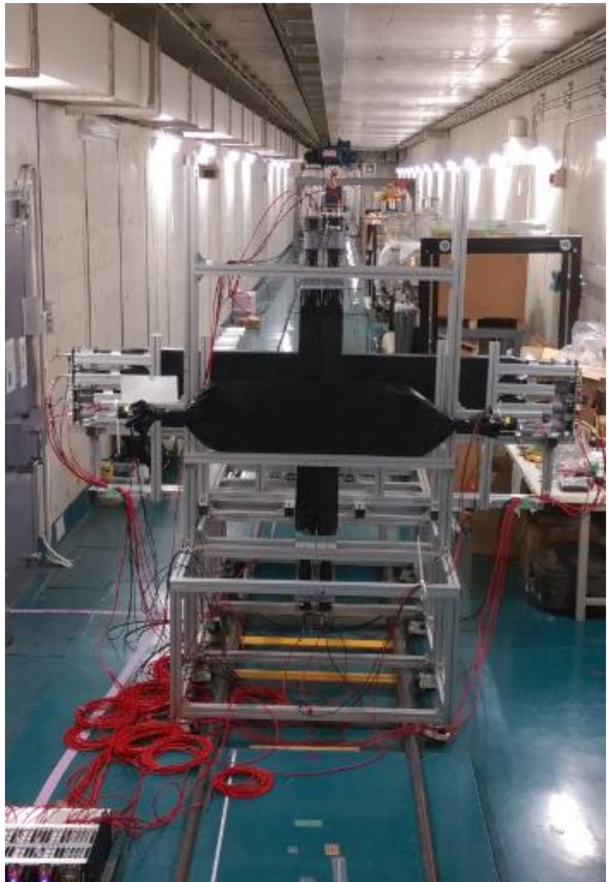
NDA (Neutron detector array): Structure



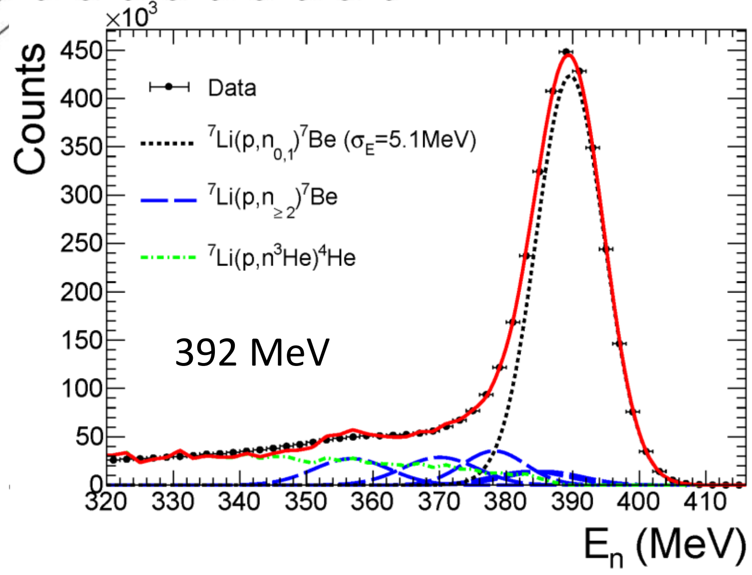
NDA: Performance test with prototype

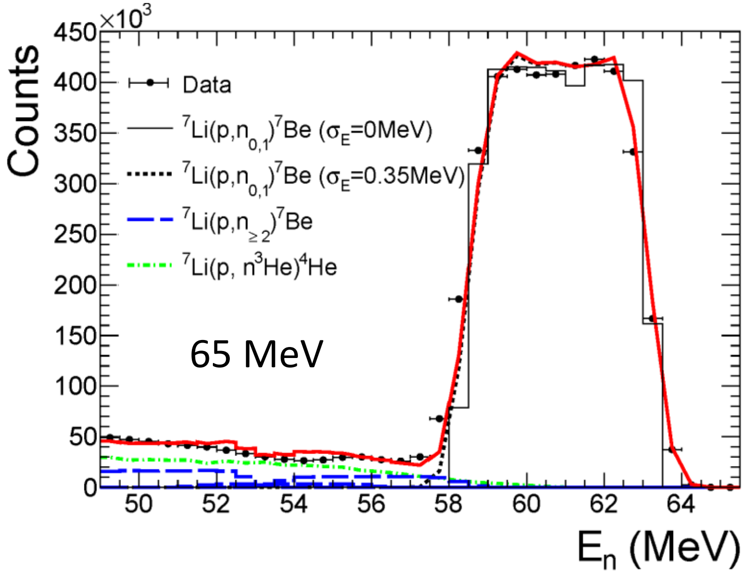
Beam test at RCNP (2016)





- Beam specifications
  - Production reaction: p+^{7}Li → n + ^{7}Be
  - Neutron beam: 1×10^{10} n/sr/μC @ 65 and 392 MeV
  - Background neutrons above 3 MeV is < 1% [NIMA 629, 43 (2011)]





- Significant energy-loss effect in the Li production target at 65 MeV
- Energy resolution (FWHM): 3.1% @ 392 MeV, 1.3% @ 65 MeV
- (Cosmic-ray test) Time resolution(FWHM): 309 ps, Position resolution(FWHM): 4.8 cm [H. Shim et al., NIMA 927, 280 (2019)]

NDA: Construction

- The complete detector system was developed, built, and tested using cosmic rays.
- Custom-made FADC were developed, produced, and tested.
- *We will bring LAMPS NDA to RIBF/RIKEN in early 2025 and use it for the cluster structure Expt.*

Assembled detector system at the Sejong Campus of Korea Univ.

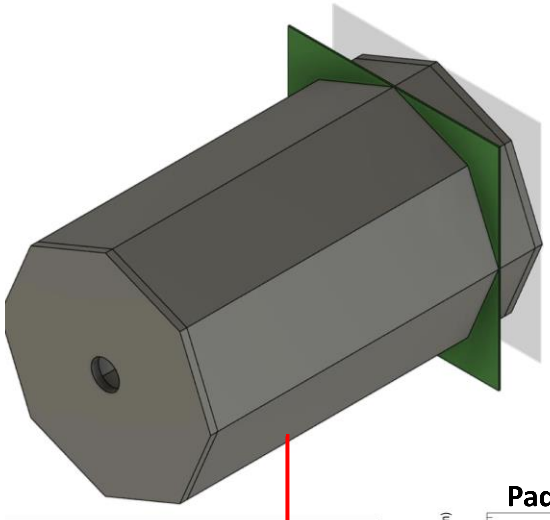
First station assembled at the high-energy experimental hall of the RAON facility

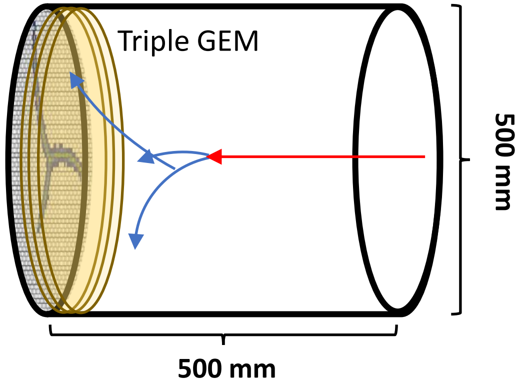
Part 3.

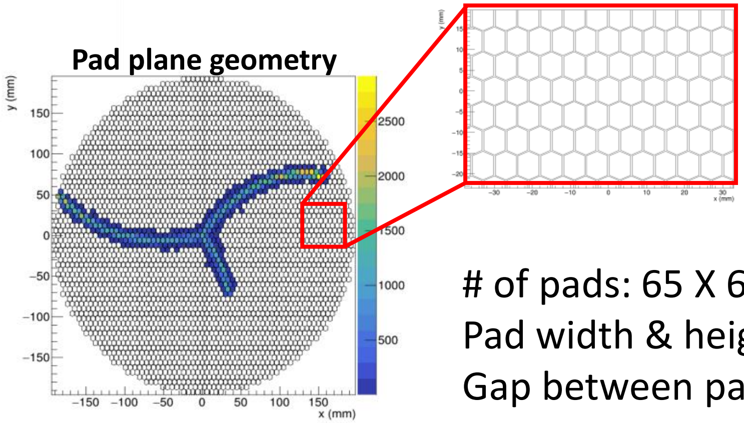
Detectors for the low-energy experiments

SC magnet & Active-Target TPC (AT-TPC)

- Superconducting solenoid magnet
  - B_{max} = 1.5 T
  - Diameter & length of the detector installation space = 60 cm each
  - Commissioning successfully done in 2019
- Design of AT-TPC (Sejong Univ.)
  - Number of channels: > 3,000
  - $\phi \simeq$ 40 cm
  - Cylindrical shape similar to the LAMPS TPC







# of pads: 65 X 65 = 3,300
Pad width & height: 6 mm each
Gap between pads: 0.5 mm

AT-TPC: Beam test with prototype

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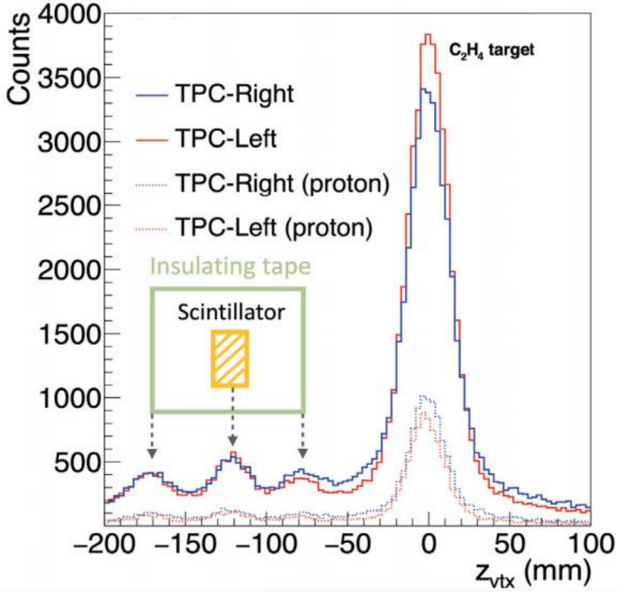
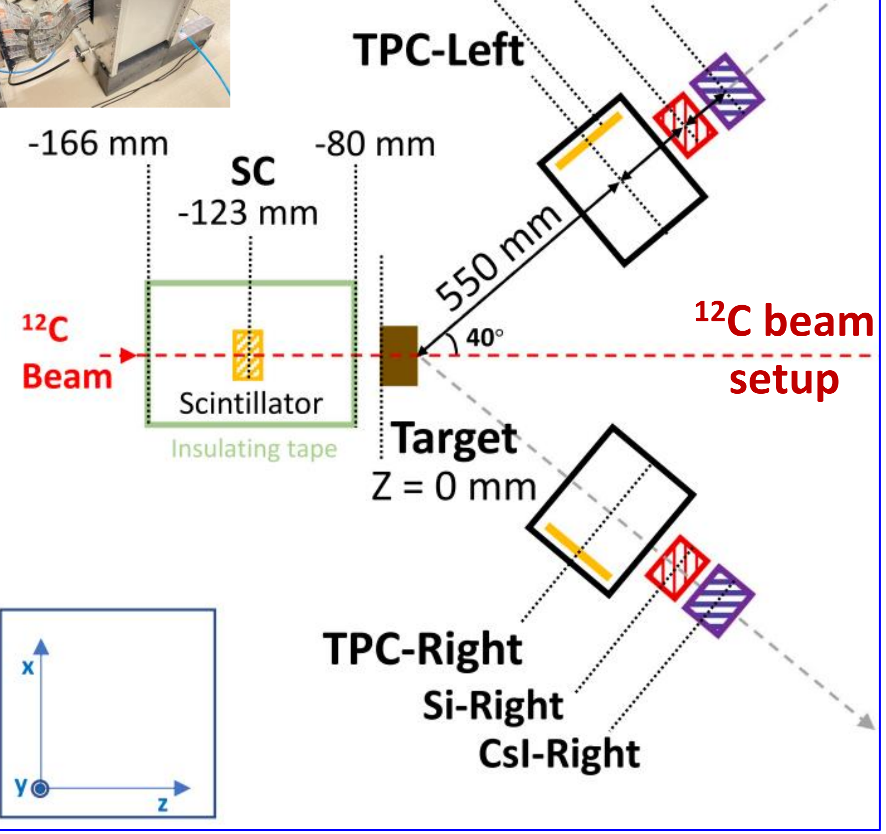
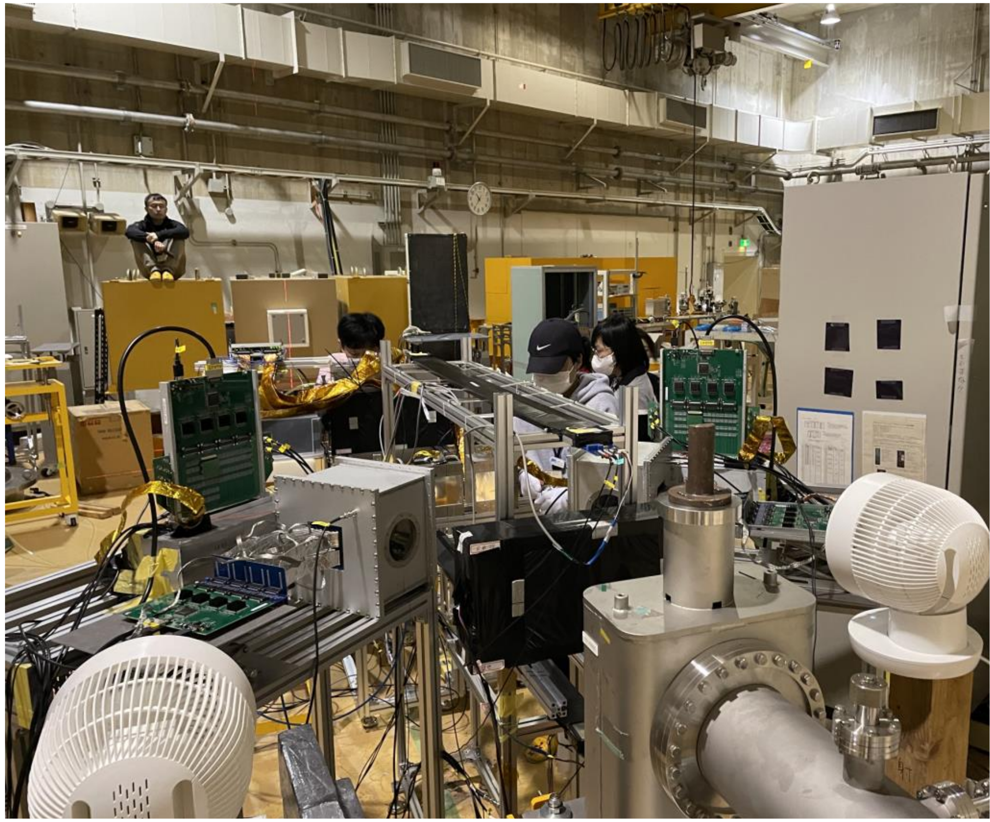
- Beam test of two prototypes at HIMAC in Japan in Feb. 2023
  - – Beams: p @ 100 MeV, ^{12}C @ 200 MeV/u, 10^6 ppp
  - – Performance test for LAMPS detectors including AT-TPC [Y. Cheon et al., NIMA 1066, 169610 (2024)]
  - – Analyzing $^{12}C(p,2p)$ Quasi-Free Scattering (QFS) events

Prototype AT-TPC →

↓ Reconstructed vertex distribution by AT-TPC







AT-TPC: Some characteristics

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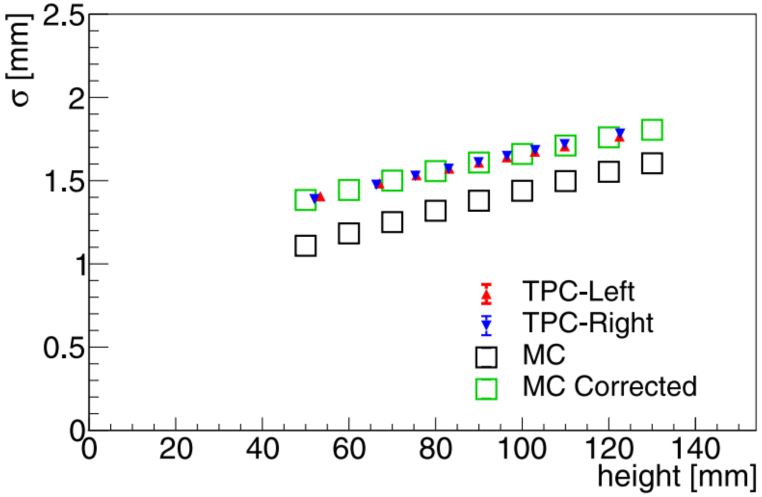
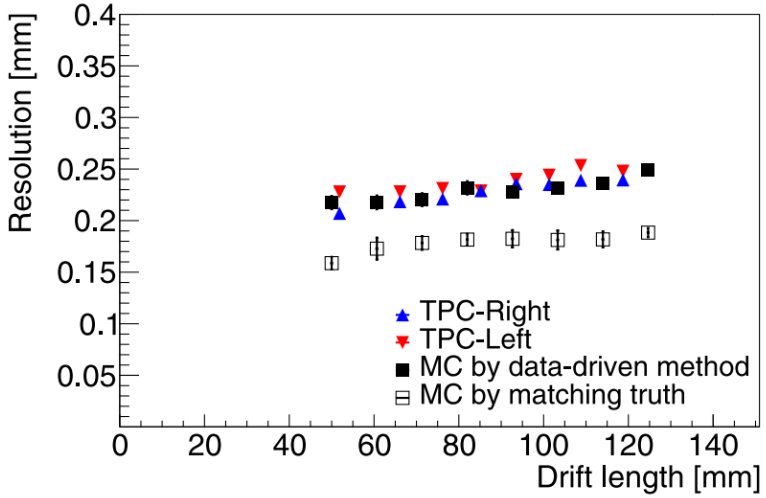
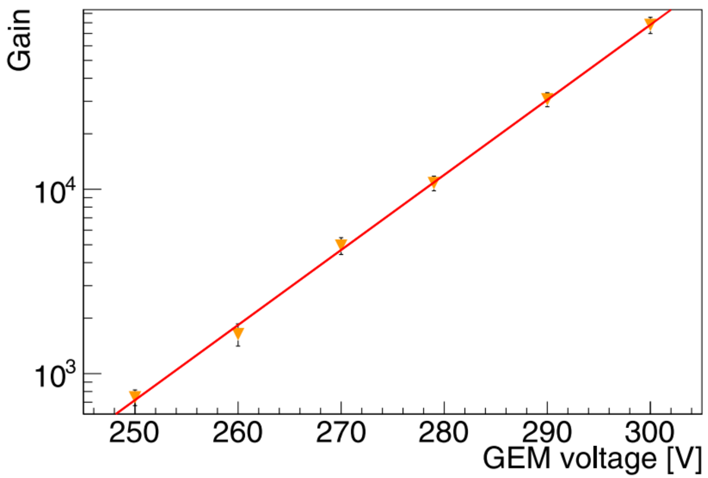
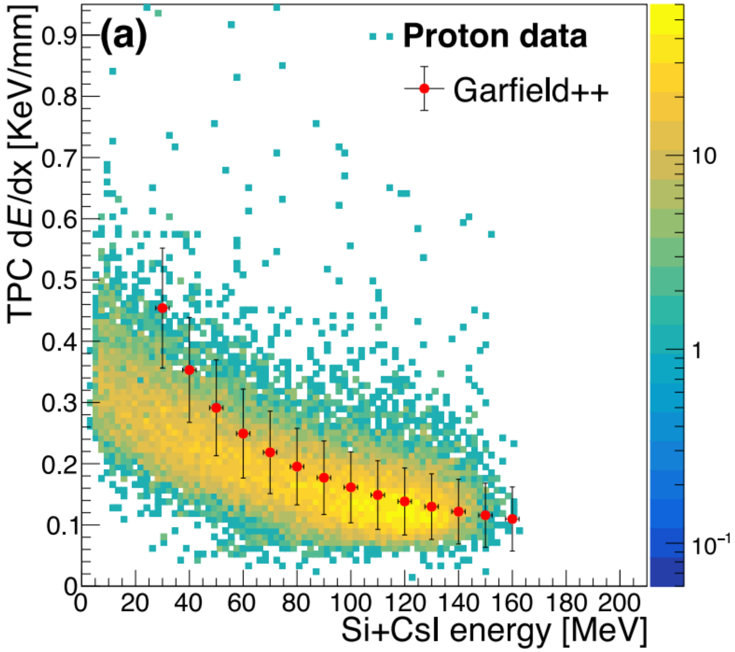


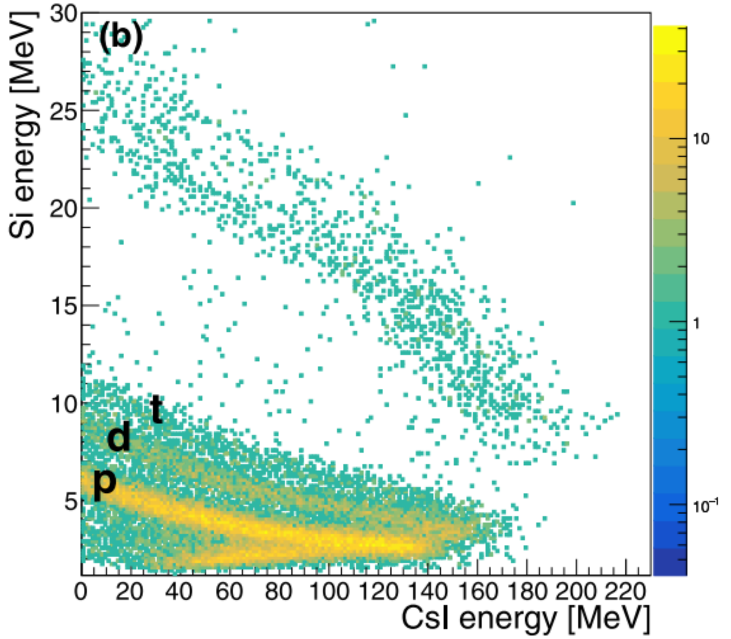






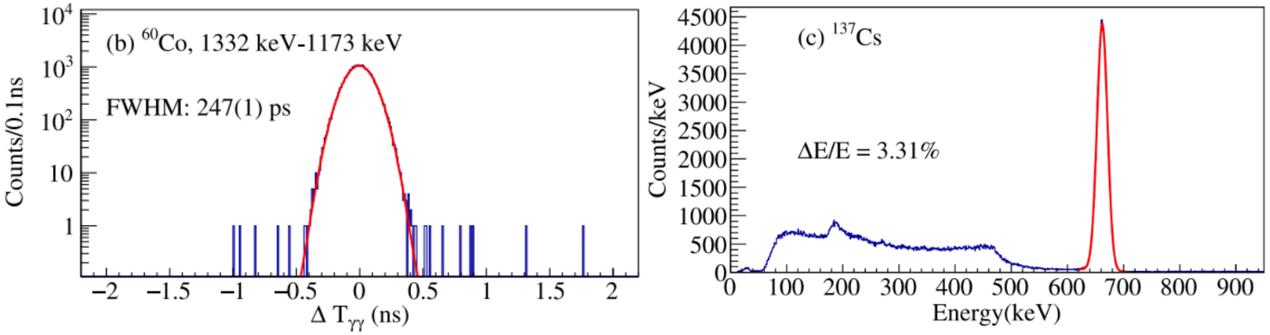
- ↖ Transverse diffusion of electrons vs. drift length
- ↑ Spatial resolution vs. drift length
- ↗ Gain vs. GEM bias voltage
- → ΔE vs. E for Si+CsI (PID)
- ← Correlation of dE/dx(TPC) vs. $\Delta E + E$(Si+CsI) for protons

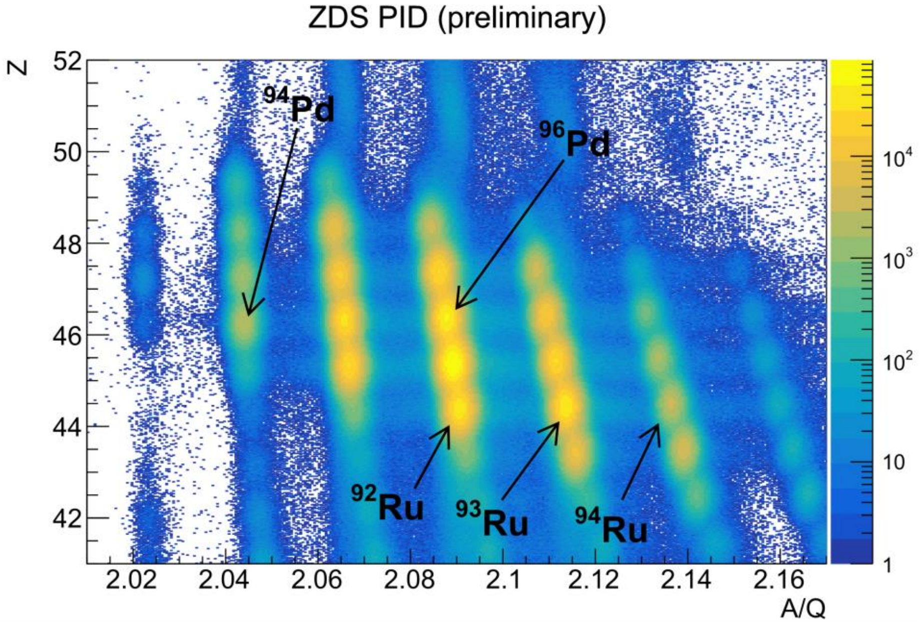
[NIMA 1066, 169610 (2024)]



KHALA: Korea high–resolution array of $LaBr_3$

- $LaBr_3$(Ce) fast-timing γ-detector array
  - Total 36 $LaBr_3$(Ce) modules
  - Characteristics: R_t < 250 ps, R_E< 3.5%
- *Formed **IDATEN** Collaboration = KHALA + FATIMA*
  - The largest acceptance fast-timing γ-detector array
  - Commissioning experiment at RIBF in June 2024

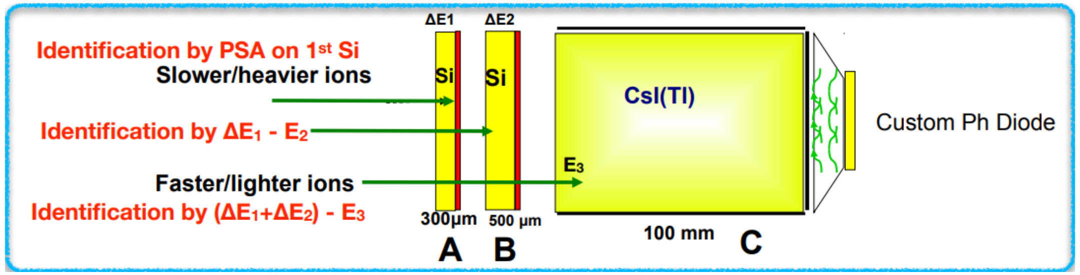


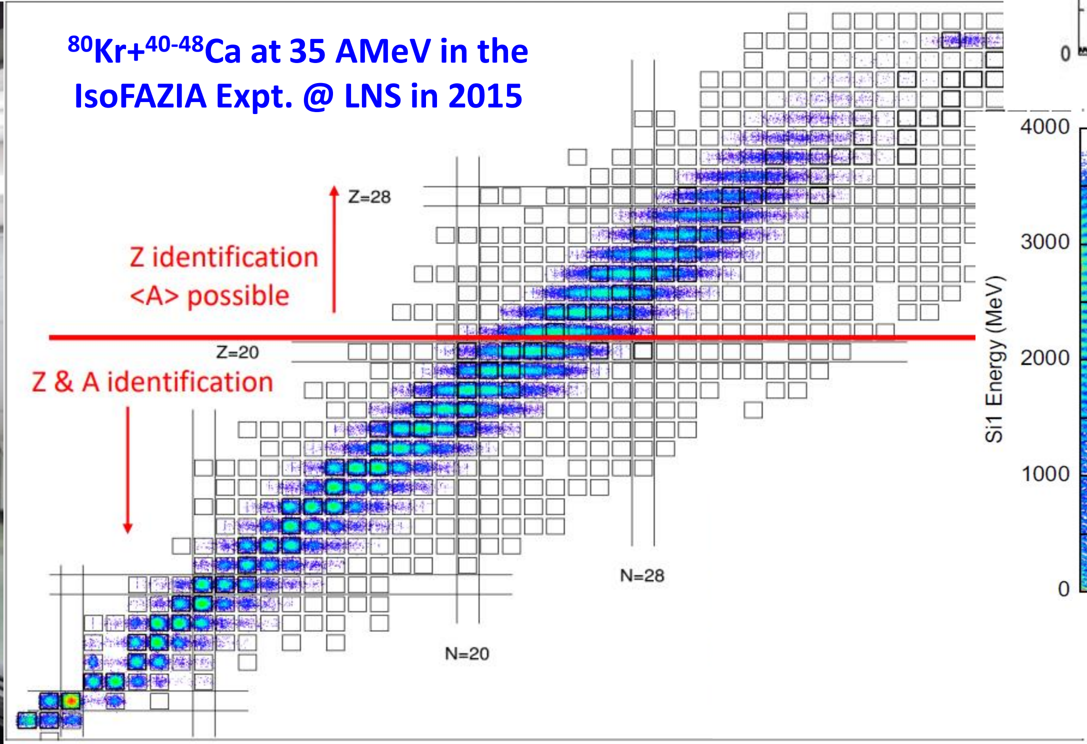


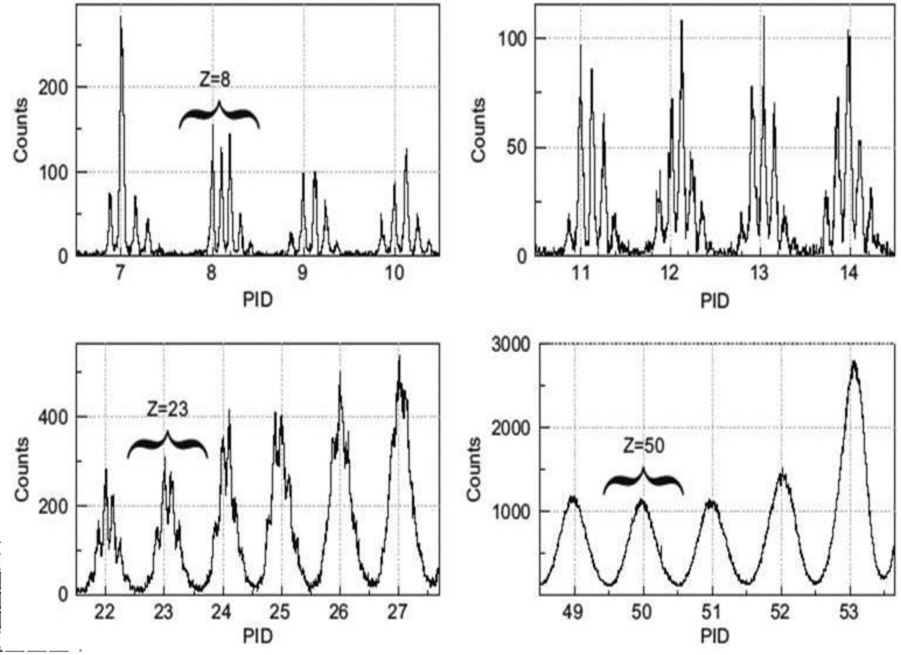
- Some of isotopes, e.g., ^{94}Pd, ^{96}Pd, ^{94}Ru, have not yet been studied.

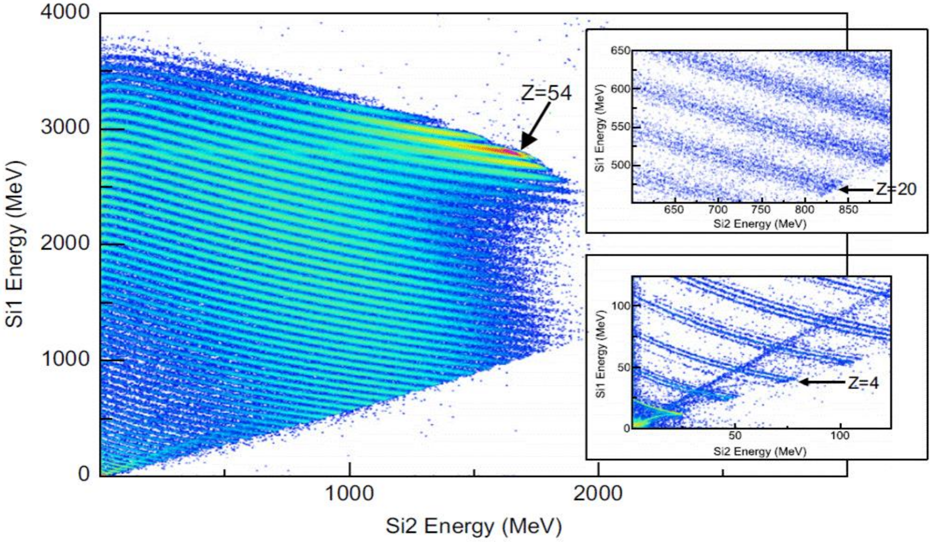
Si+CsI charged particle detector

- FAZIA: One block consists of 16 Si_1+Si_2+CsI telescopes with a cross-section of 2×2 cm^2.
  - New Si chips are being developed in Korea.
  - New FEB electronics with modern components are manufactured in Korea.









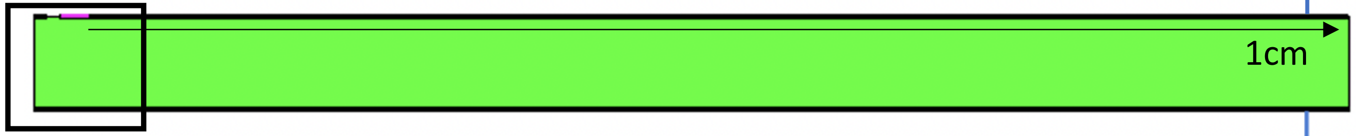
R&D of Si sensors

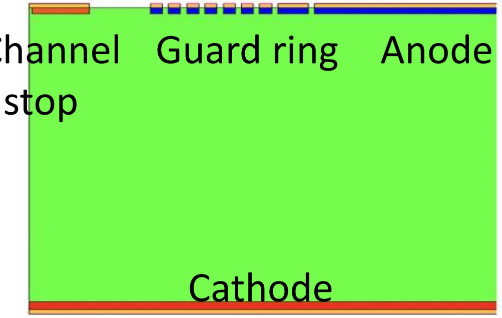
- Design of PiN sensor using TCAD: Simulation setup

Half of cross section of 2 x 2 cm^2 chip

V_0 (reverse bias voltage)

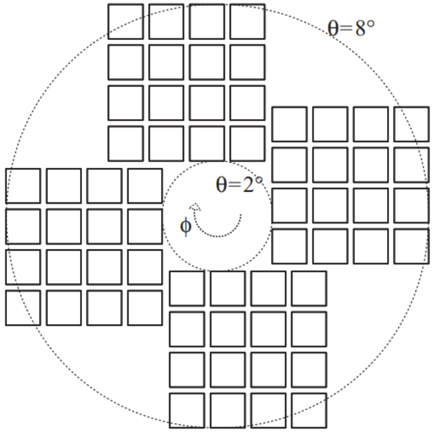
Thickness: 720 μm





Edge of silicon sensor

Input parameters for simulation				
T (K)	300		Doping density	
V_0 (V)	0 ~ - 700		(blue)	P^+ Boron
Carrier lifetime	Electron	1×10^{-4} s^{-1}	(green)	N^- Phosphorus
	Hole	3×10^{-4} s^{-1}	(red)	N^+ Phosphorus



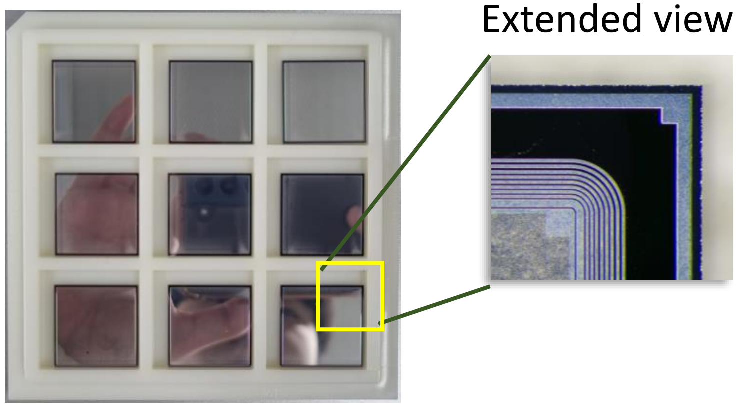
→ Results

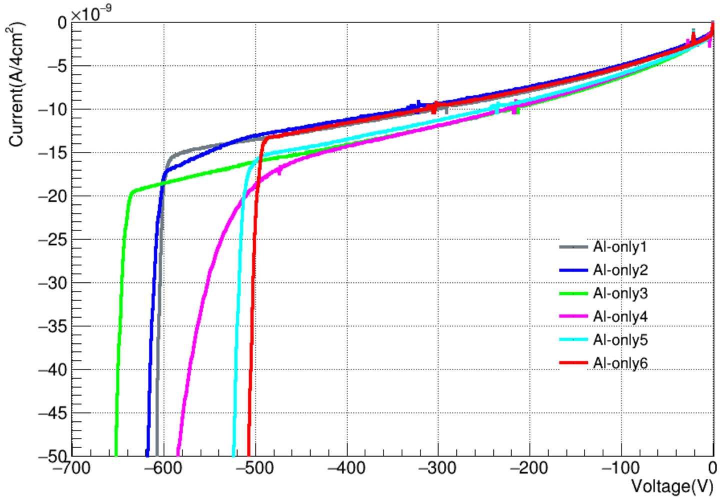
- Breakdown voltage point is close to -600 V
- Enough to reach full depleted voltage (400 V)

— We are also developing 150 μm-thick chips.

← We plan to build 4 FAZIA blocks by the end of 2025 for the experiments at RAON.

Extended view





Summary

- Purpose of LAMPS
  - Detailed investigation of *nuclear equation of state (EoS) and symmetry energy*
  - We are also exploring the possibility to use LAMPS for the nuclear structure.
- Status of the LAMPS detector system
  - All detector elements were developed, manufactured, and assembled.
  - Performance test with cosmic muons using LTE for the integrated system is in progress.
  - The high-energy beams from SCL2 at RAON will be available in ~2030 or later.
  - Thus, we are exploring the possibility to utilize the LAMPS detector elements for other experiments until the SCL2 is ready.

    → *The neutron detector array will be used for the cluster structure Expt. at RIBF/RIKEN.*

    → *LAMPS TPC can be used for the EOS experiment at other Labs. (e.g., FRIB).*

    → *KHALA LaBr3 system is being used for the IDATEN experiment at RIBF.*
- *Any idea using the LAMPS detector elements are welcome!*

LAMPS

NuSYM 2024