HALO-40

International Symposium Commemorating
the 40th Anniversary of the Halo Nuclei (HALO-40)
Beijing, China, October 12 – 18, 2025

Status of LAMPS at RAON

(Large Acceptance Multi-Purpose Spectrometer)

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Korea University

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Part 1.

Physics goal of LAMPS

Main physics objective of LAMPS

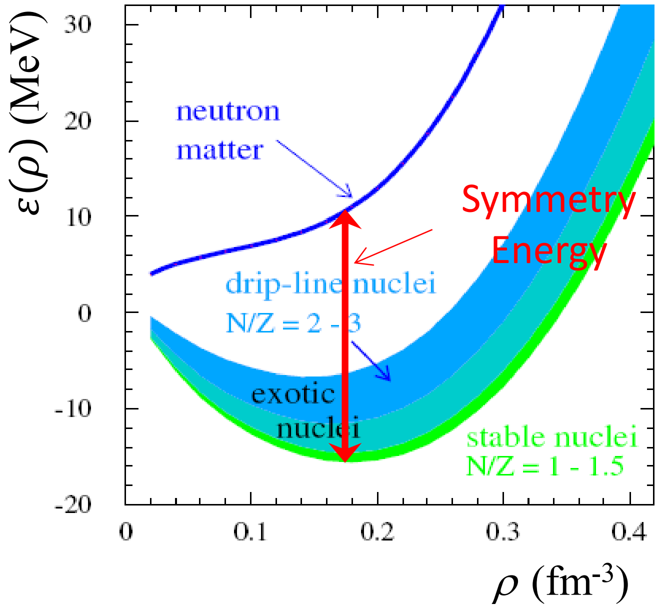
- Equation of state (EoS) & symmetry energy E_{sym} of nuclear matter $[\delta = (N-Z)/(N+Z)]$:

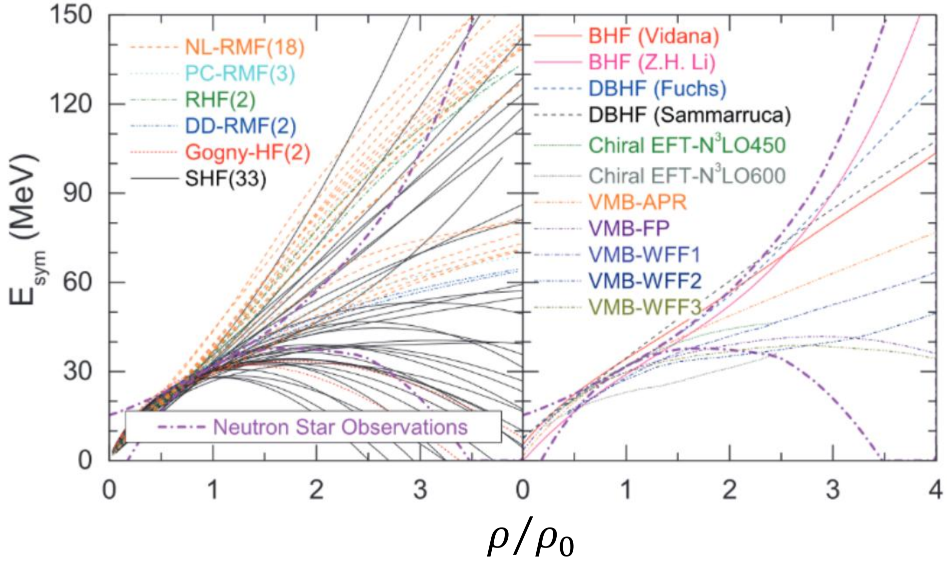
$$E/A = \varepsilon(\rho,\delta) = \varepsilon(\rho,\delta=0) + E_{sym}(\rho)\delta^2 + \mathcal{O}(\delta^4) + \cdots$$

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

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

- 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)
- *The halo structure of nuclei can be also sensitive to the symmetry energy.*





L-W. Chen, Nucl. Phys. Rev. 34, 20 (2017)
N.B. Zhang & B.-A. Li, Eur. Phys. J. A 55, 39 (2019)

Status of EoS & symmetry energy

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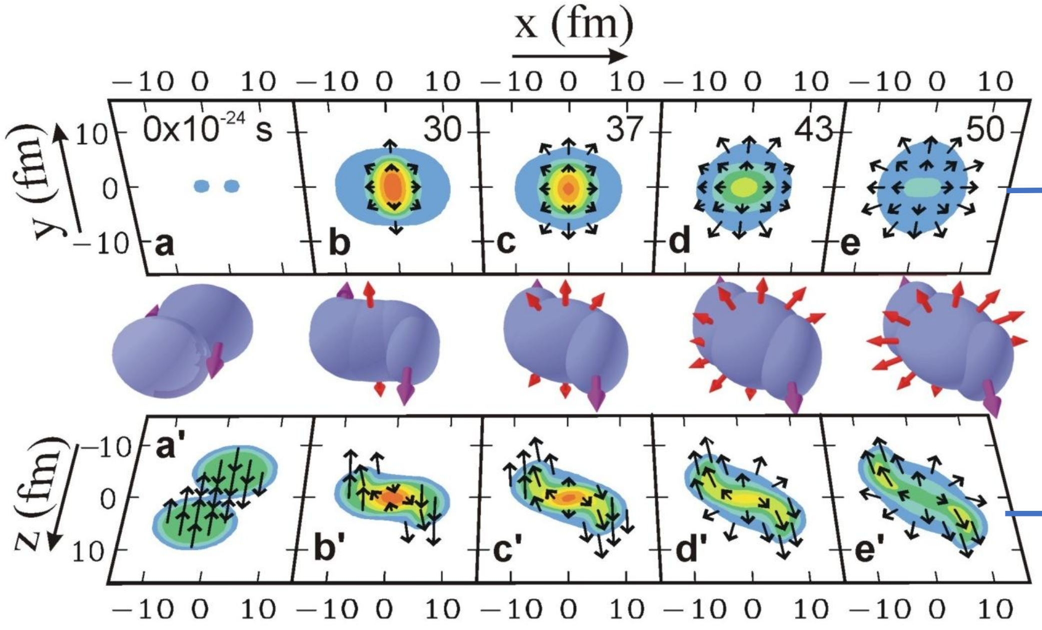
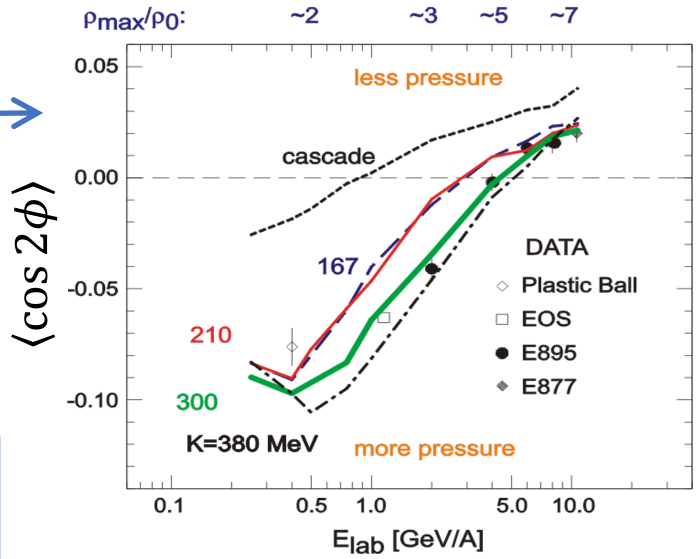
Figure adopted from Danielewicz et al., Science 298,1592 (2002)



elliptic flow or squeeze out

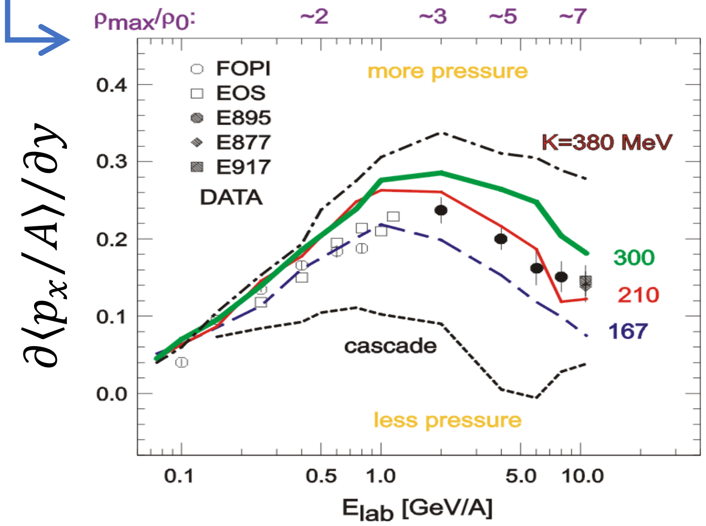
directed flow

Symmetric matter



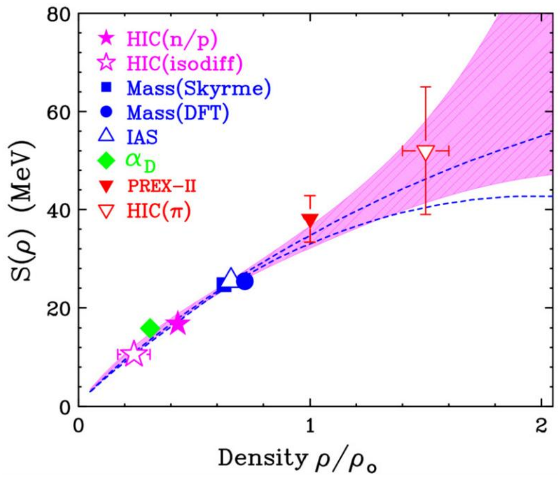
in plane

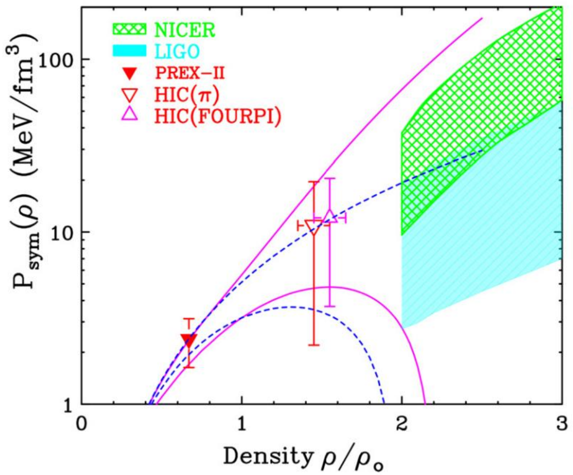
out of plane



Recent constraint of the symmetry energy

Lynch & Tsang, PLB 830, 137098 (2022)





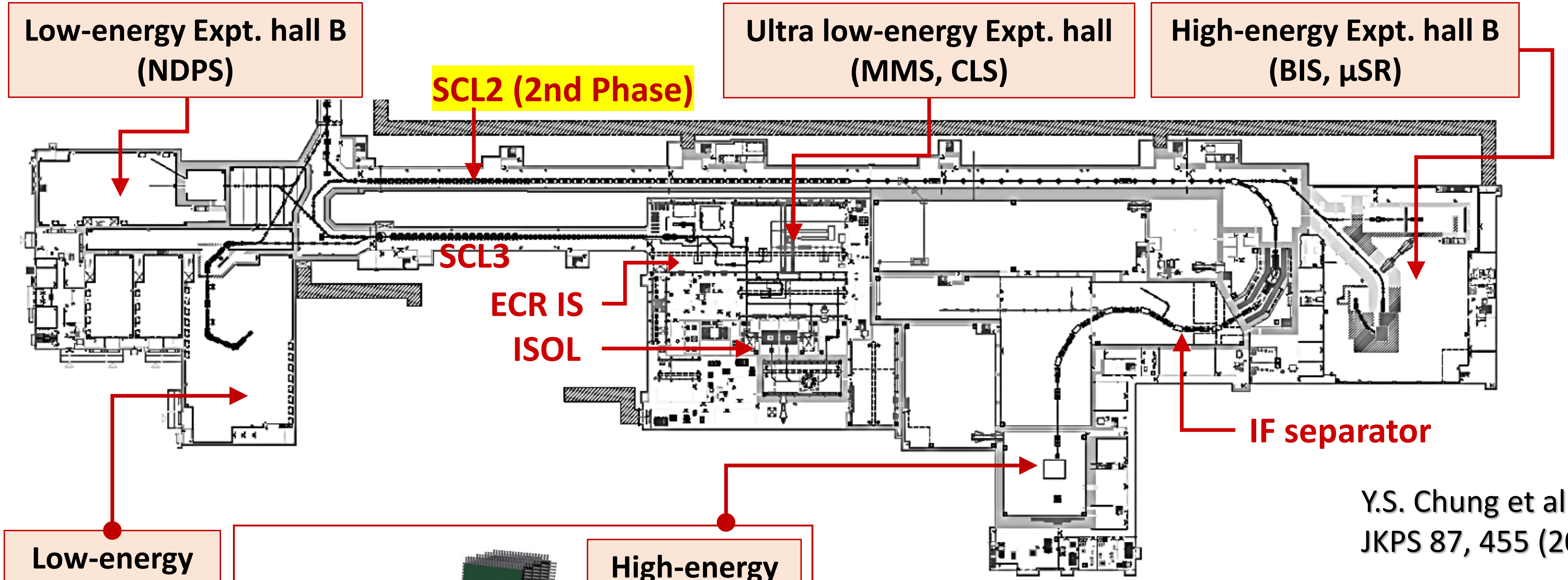
Observables

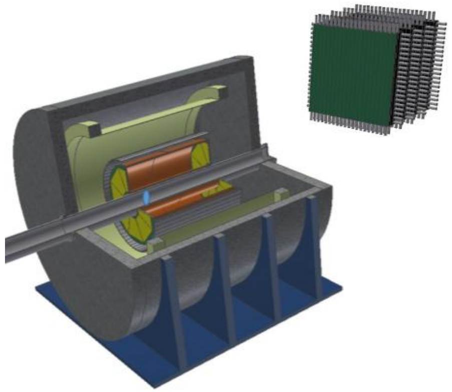
- Requirements for EoS experiments
  - Systematic change of the system size and N/Z of the collision system
  - Systematic change of the beam energy to cover a wide range of ρ/ρ_0
  - Analysis of diverse observables as functions of the collision centrality and momentum
  - Better to preserve the symmetric configuration of the detection system
- Representative observables
  - Particle spectra and yield ratios of isospin mirror particles, such as *n/p*, ^{3}H/^{3}He, ^{7}Li/^{7}Be, 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





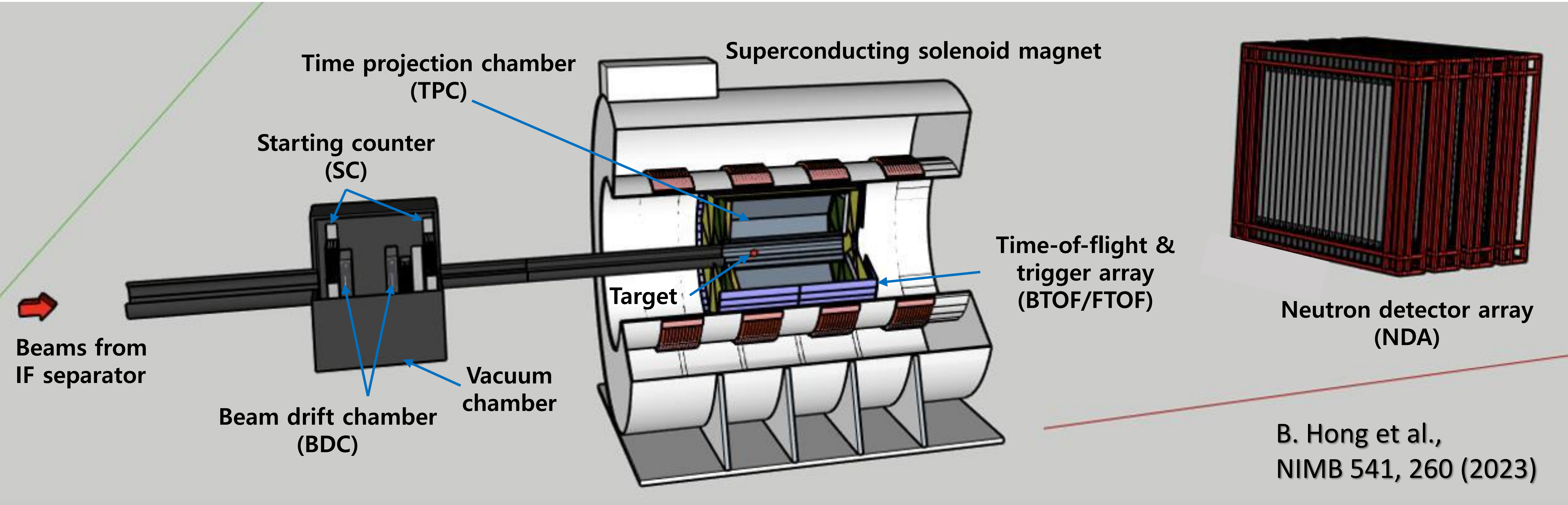
Y.S. Chung et al.,
JKPS 87, 455 (2025)

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

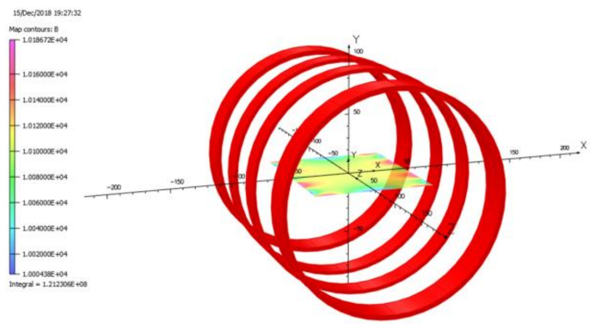
- **LAMPS**: **L**arge **A**cceptance **M**ulti-**P**urpose **S**pectrometer
  - TPC with $\sim 3\pi$ sr acceptance for tracking light charged particles (Z=1,2,3)
  - Beam energy up to 250 MeV/u for ^{132}Sn; Intensity up to 10^8 pps (TPC can take only $\sim 10^{4-5}$ pps)
  - *Useful system not only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



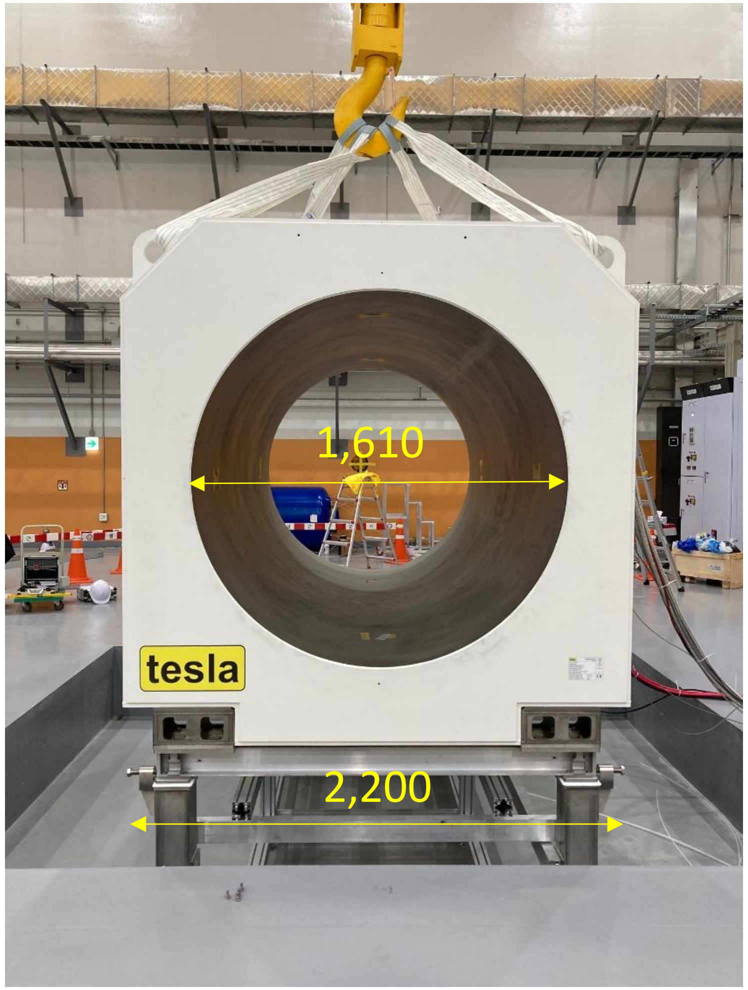
B. Hong et al.,
NIMB 541, 260 (2023)

SC magnet

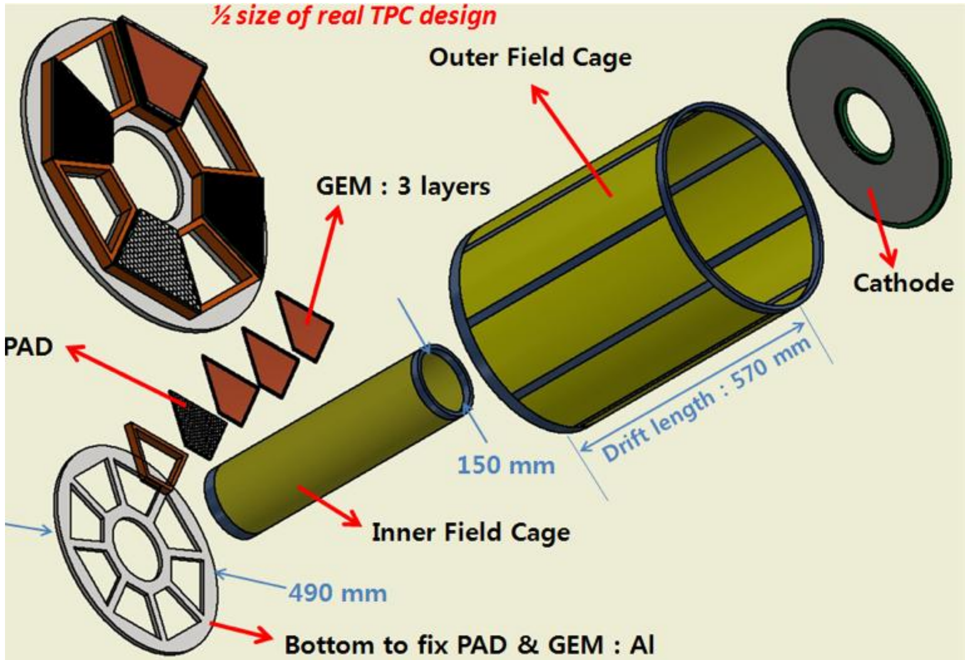
- Design parameters
  - Superconducting solenoid magnet
  - Dim.: 3,000(L) X 2,200(W) X 2,250(H) mm^3
  - Diameter of bore: 1,610 mm
  - Max. field: 1 Tesla
  - Variation of B field over TPC volume:
    - (Simulation) $\pm 0.94\%$
    - (Measurement) $-0.86 \sim 0.67\%$

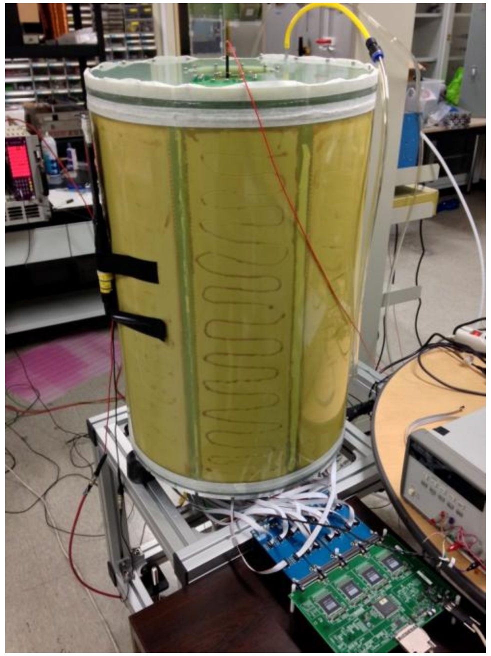


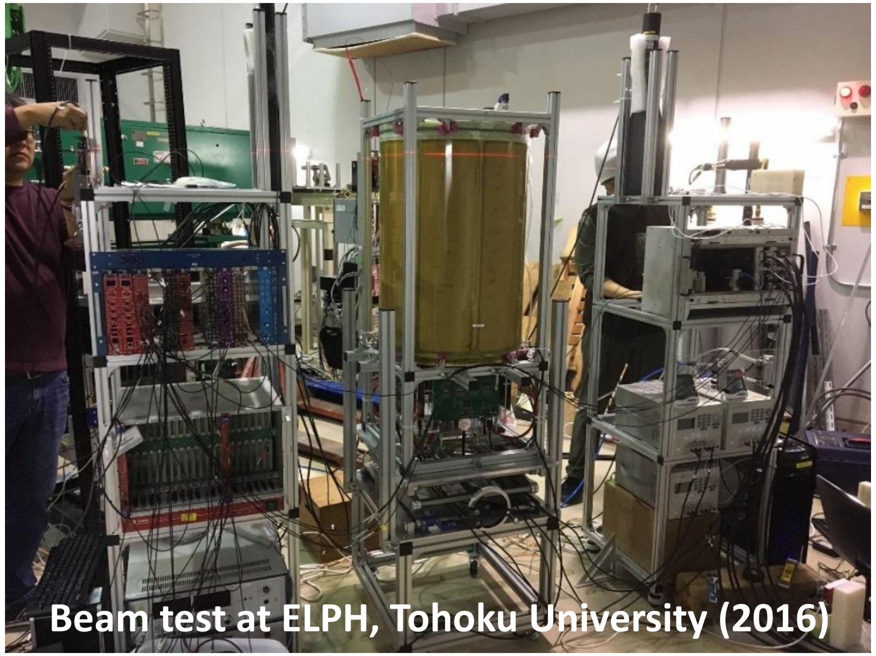
  - Passive quench protection
  - Conduction cooling with 4 K vessel thermal shield and vacuum vessel
- Construction
  - Manufactured by Tesla Engineering Ltd., UK
  - Installation completed at RAON in 2021

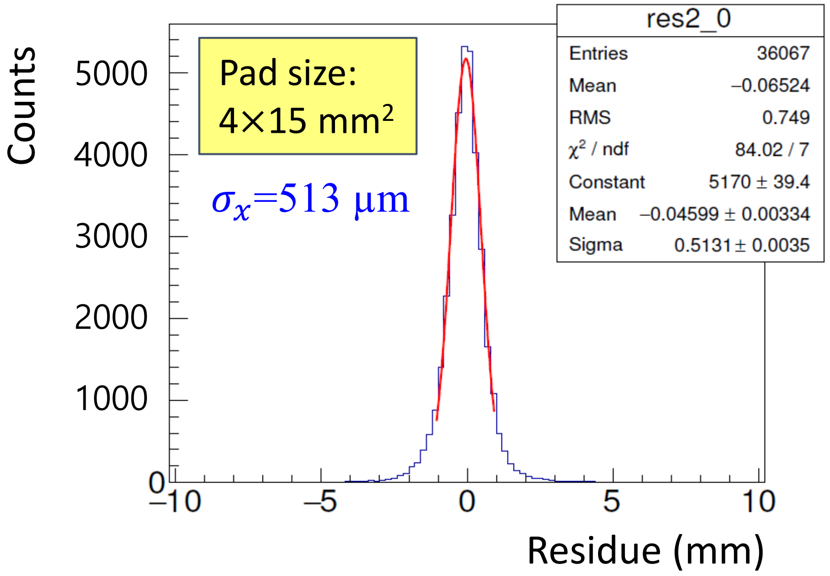


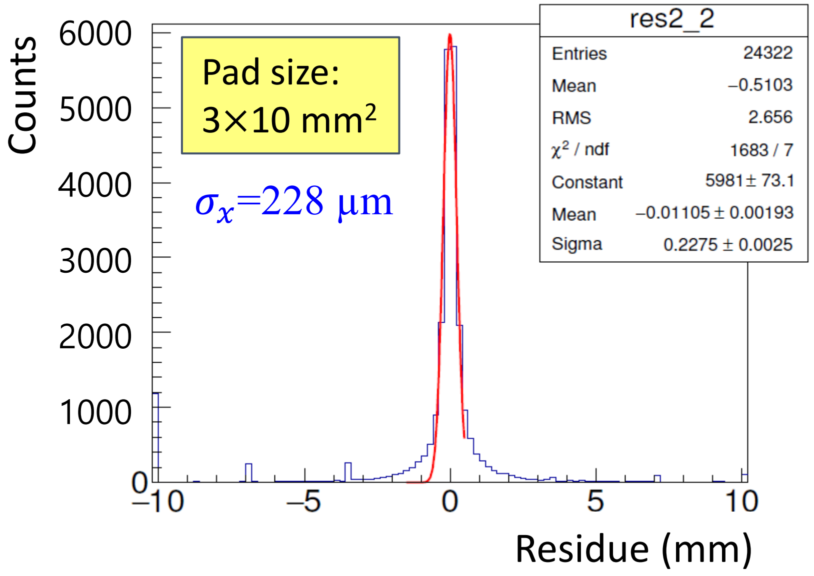
TPC: Performance test with prototype

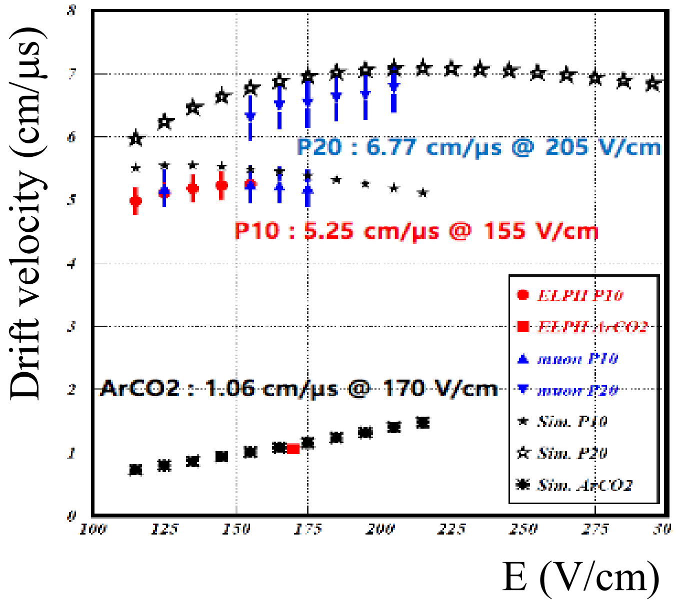




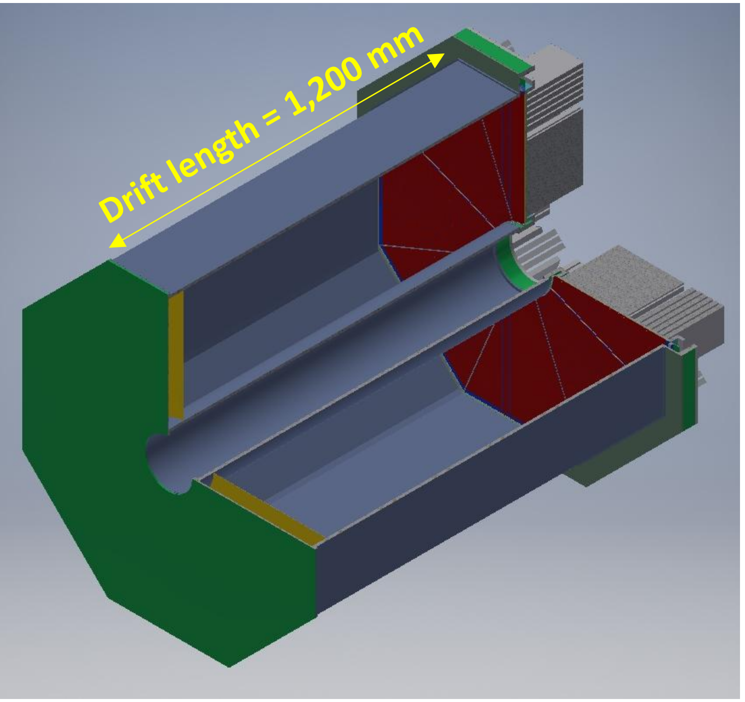


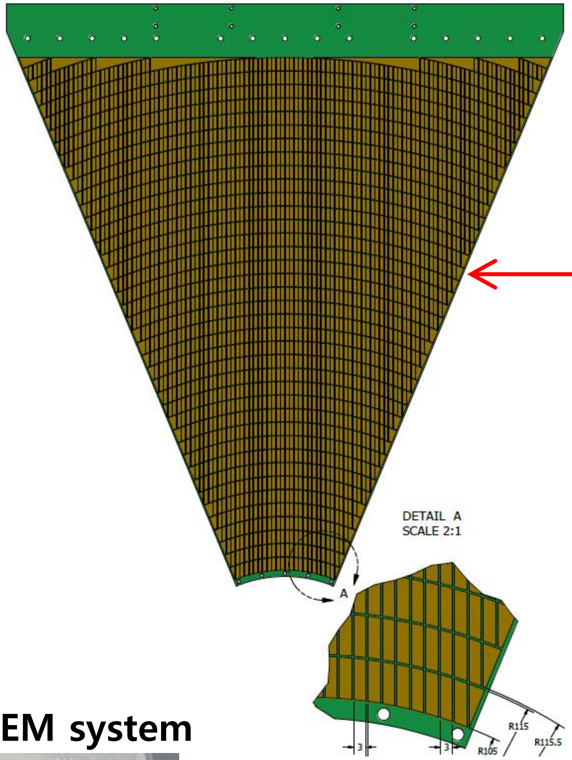


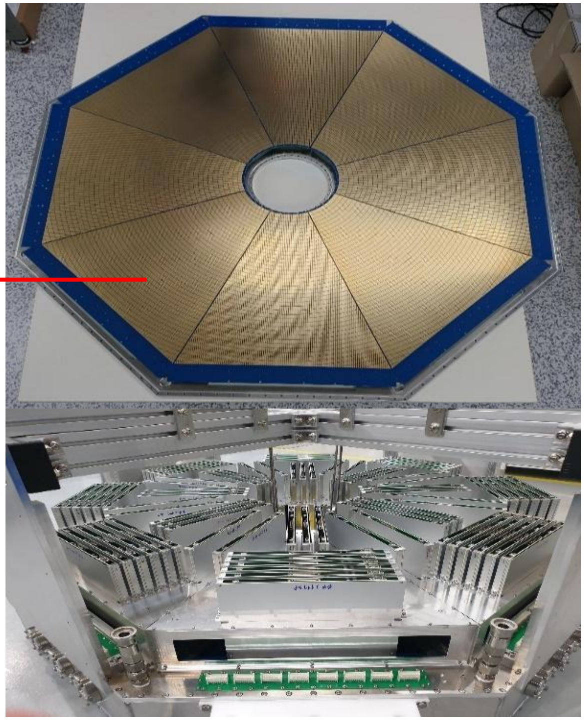


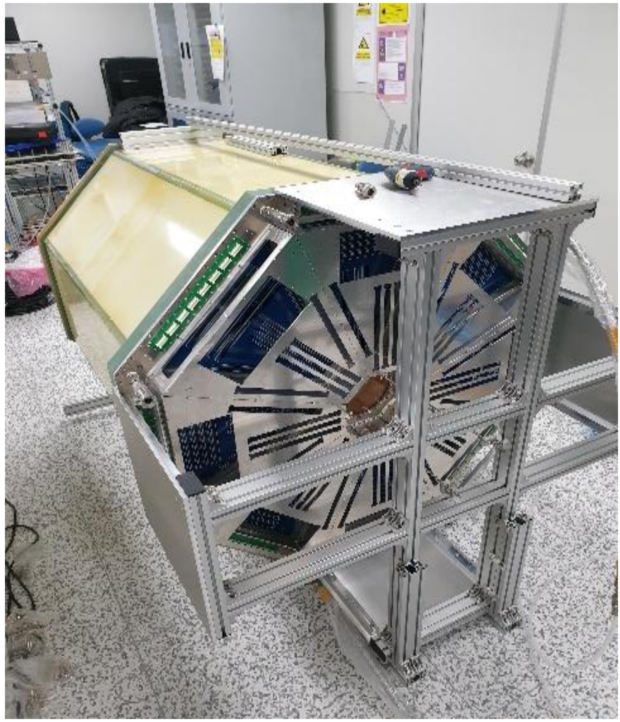


TPC: Construction of real detector



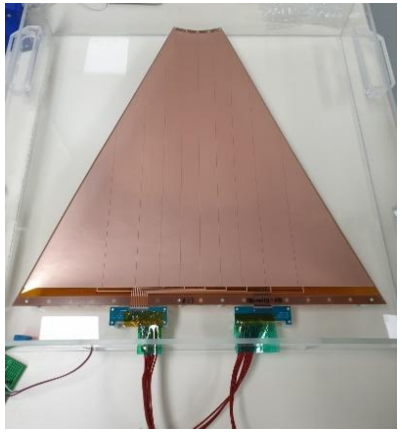


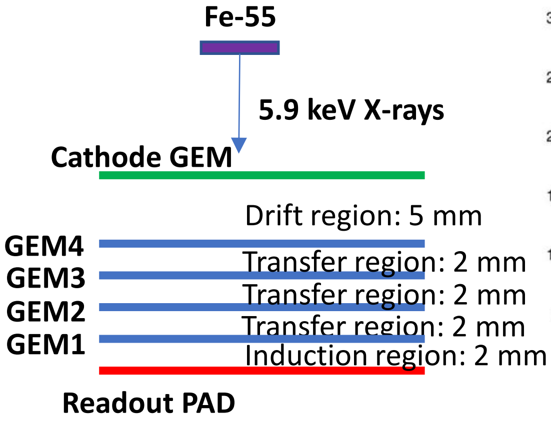


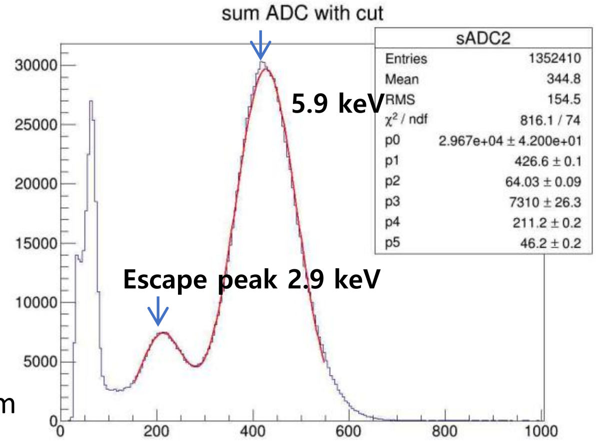


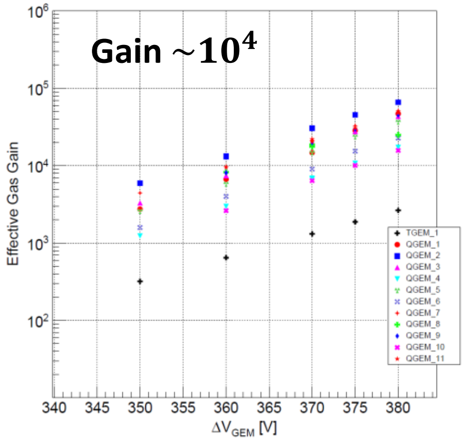
- Gas vessel (Rohacell + G10): $X/X_0 \sim 1.45\%$
- Pad Dim.: 3×10 mm^2
- Ch. #: 21,584
- FEE (GET electronics): 11 AsAD/sector $\times$ 8 sectors = 88 AsAD (22 CoBo, 3 μTCA)

Quadruple GEM system







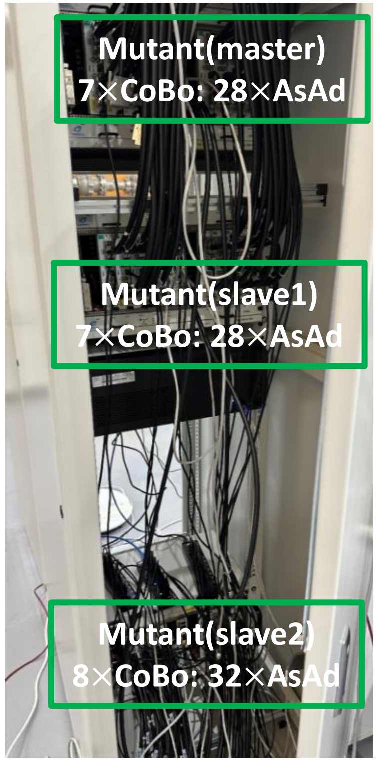


TPC: Drift velocity measurement

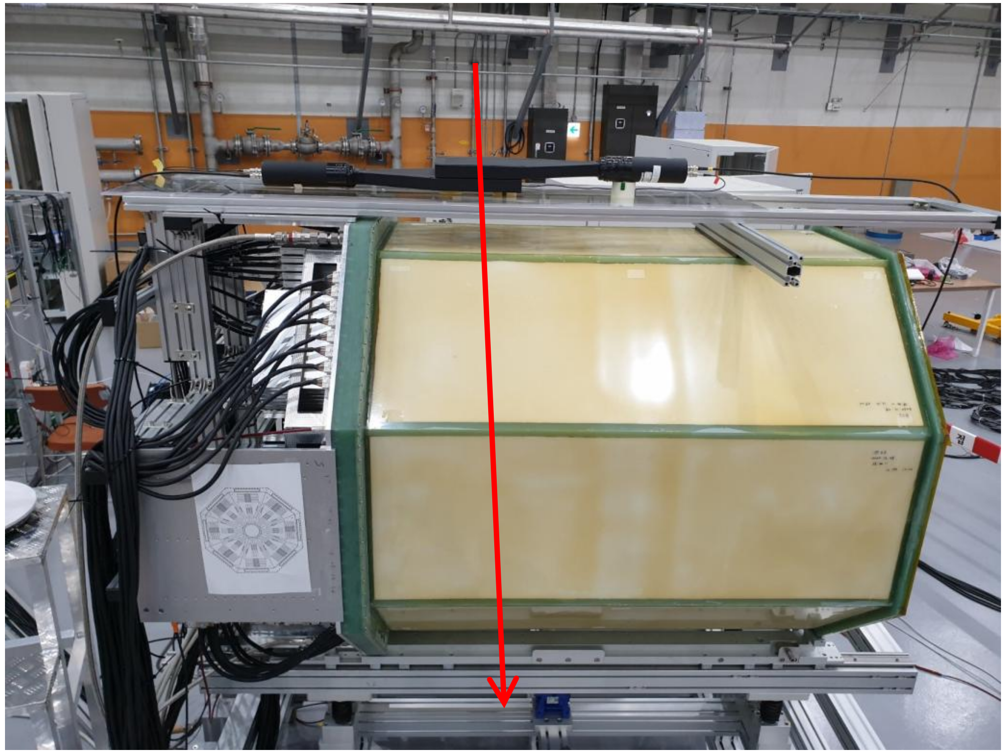
Y.J. Kim et al.,
JKPS 87, 670 (2024)

- 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

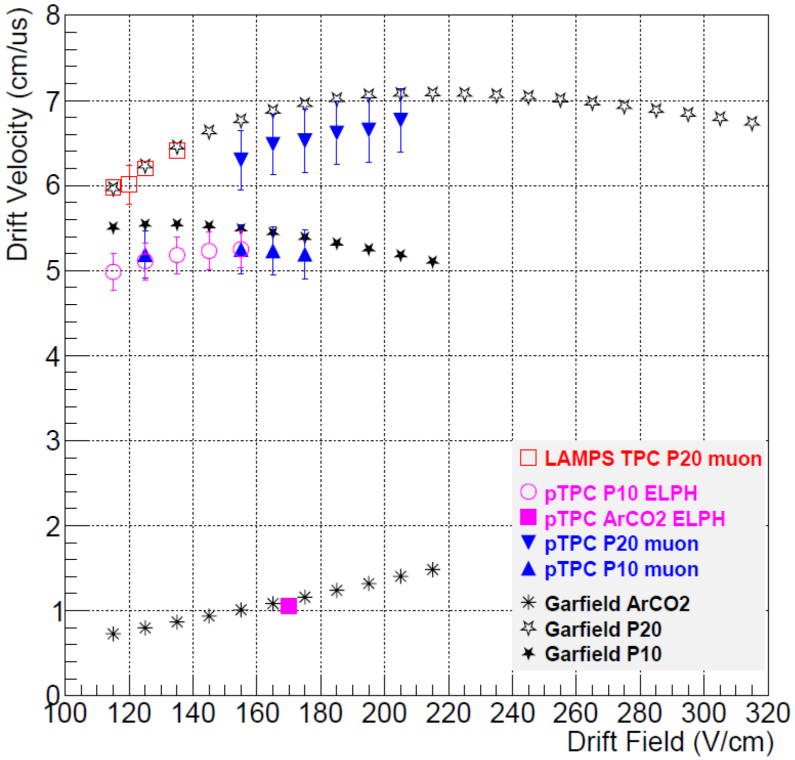
GET



Cosmic muon test

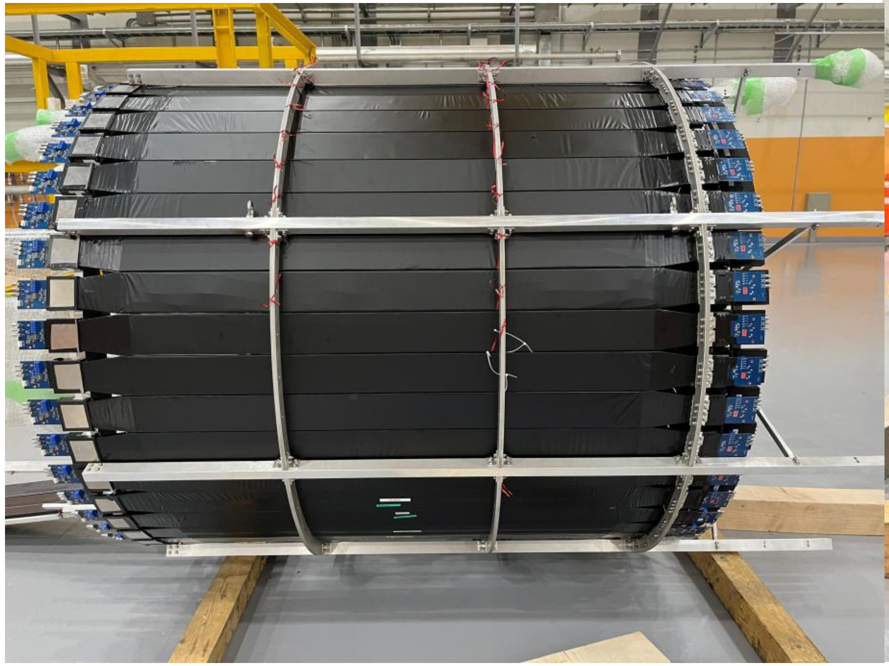


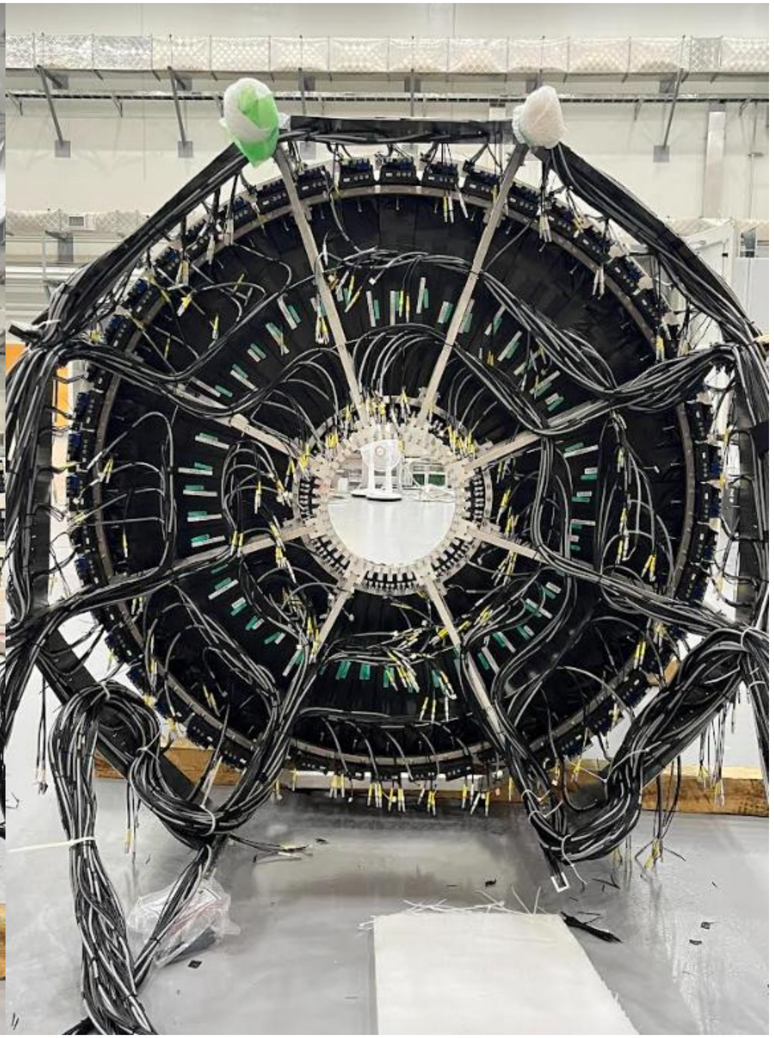
Drift velocity data



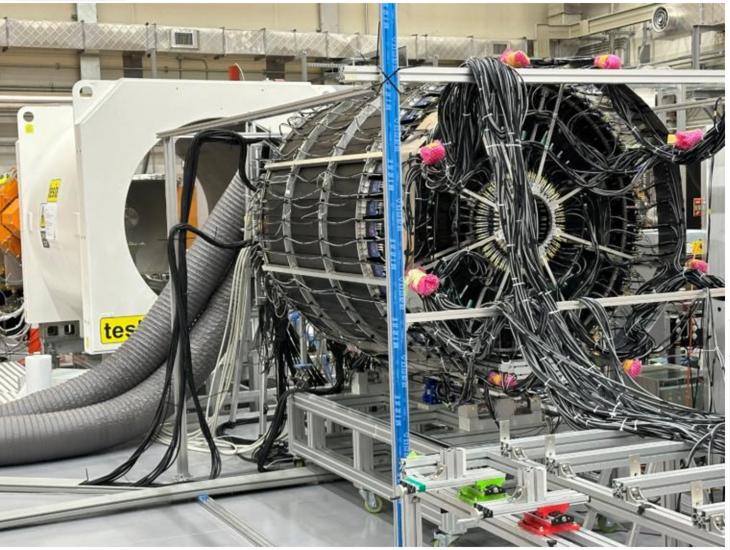
BTOF/FTOF

- 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

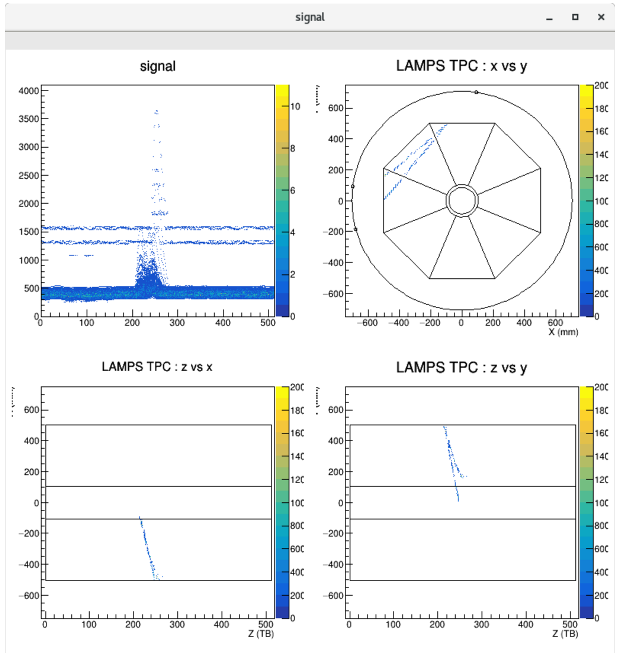


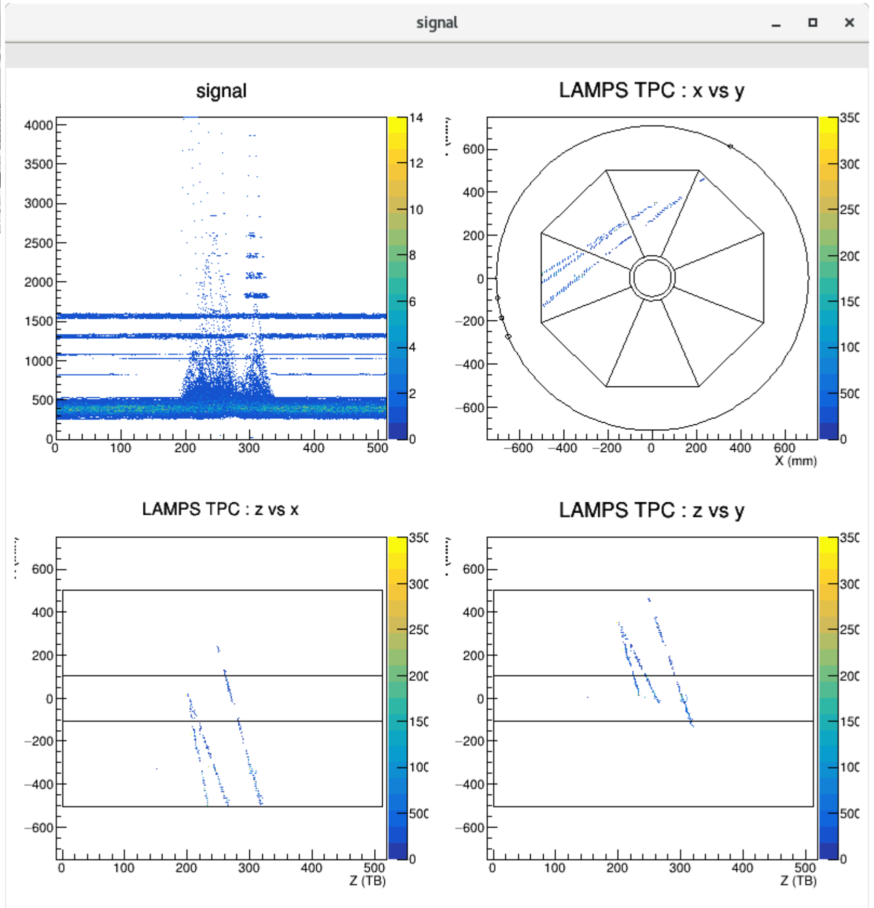


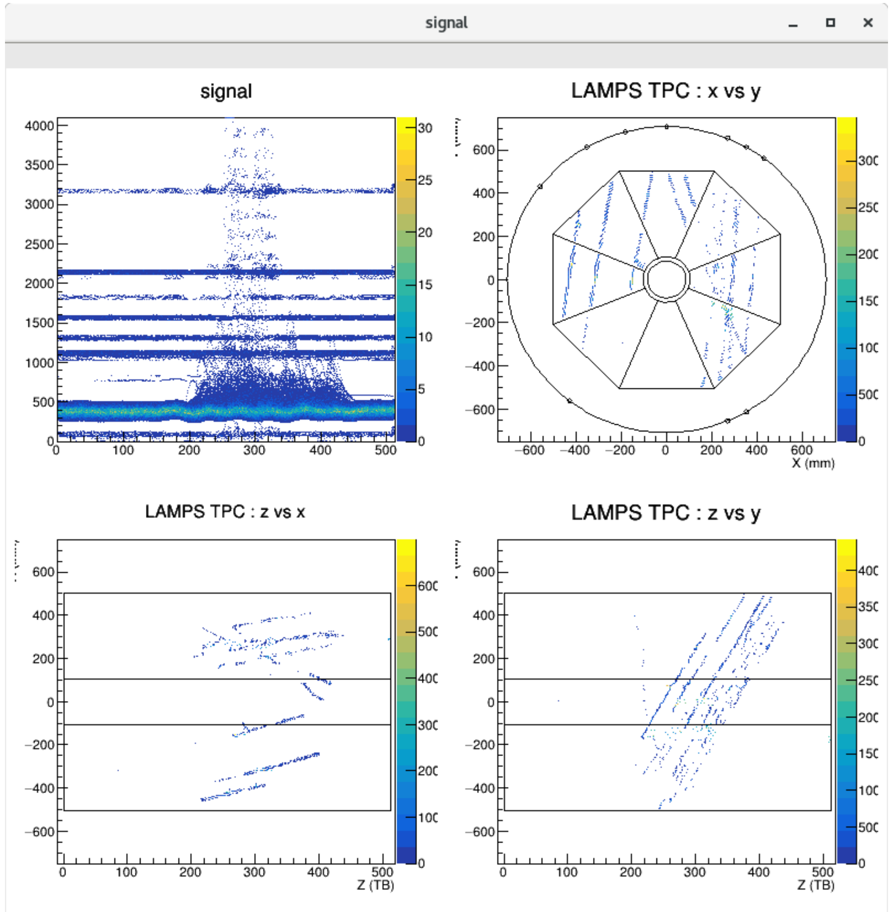
TPC+BTOF/FTOF: Cosmic test



- 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

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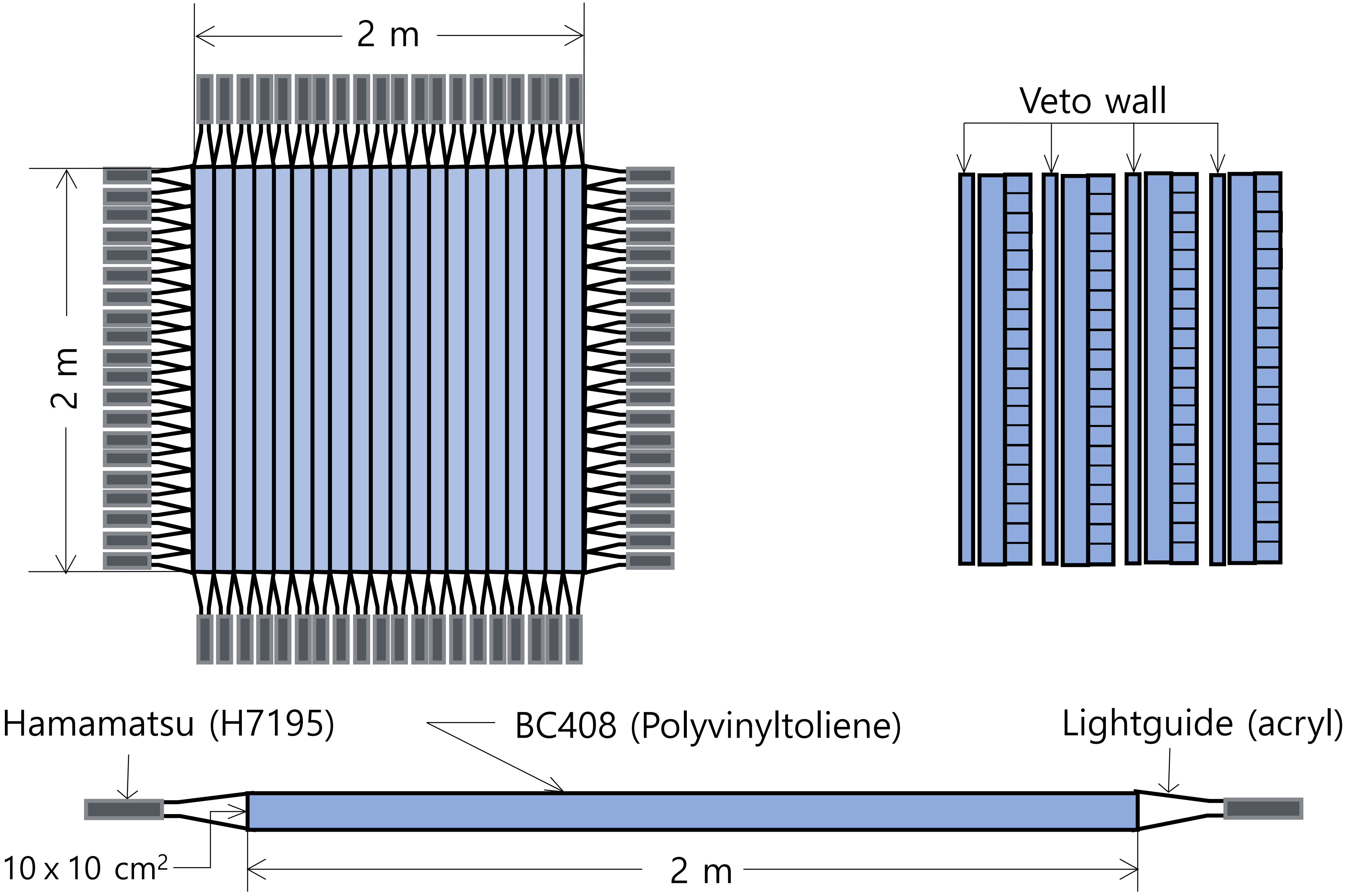
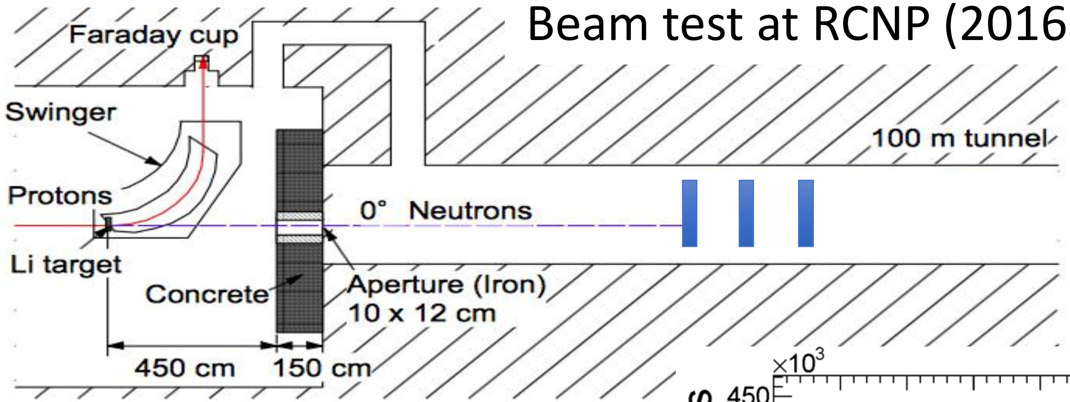
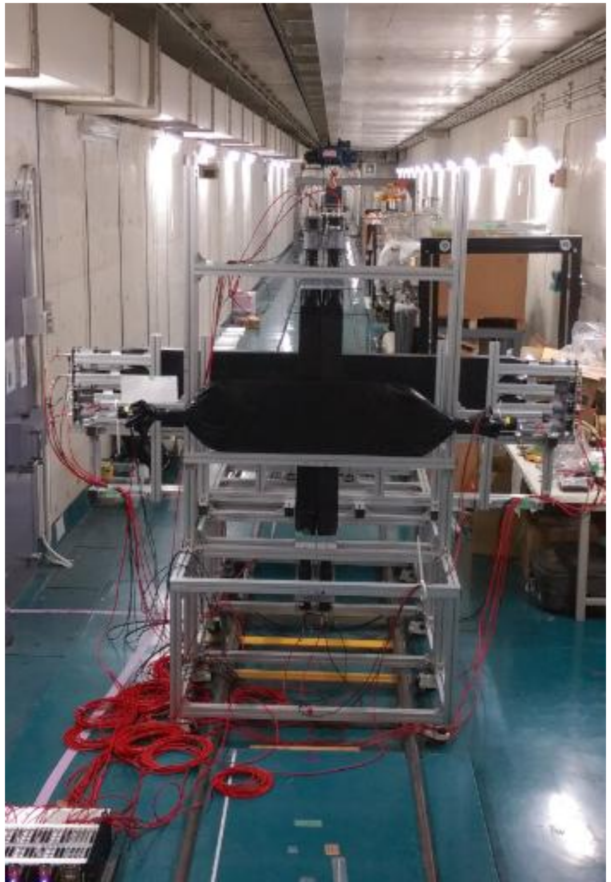


NDA: Performance test with prototype

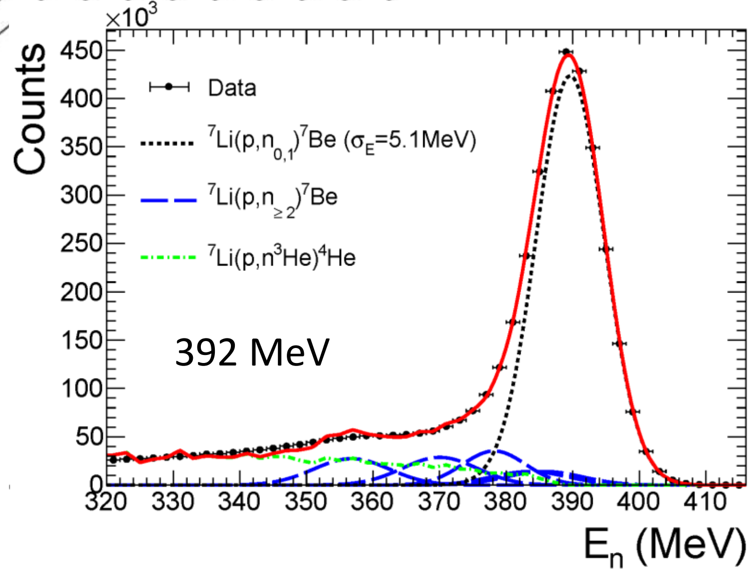
H. Shim et al., NIMA 927, 280 (2019)

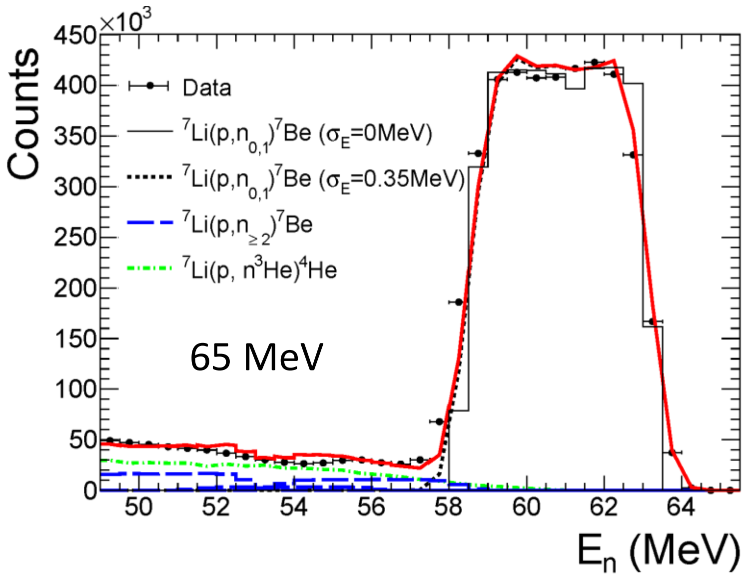
Beam test at RCNP (2016)





- Beam specifications
  - Production reaction: p+^{7}Li → n + ^{7}Be
  - Neutron beam: $1 \times 10^{10}\ \mathrm{n/sr}/\mu\mathrm{C}$ @ 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

NDA: Construction

- The complete detector system was developed, built, and tested using cosmic rays.
- Custom-made FADC were developed, produced, and tested.
- *The LAMPS NDA will be transported to RIKEN by the end of 2025 and used for the ONOKORO project.*

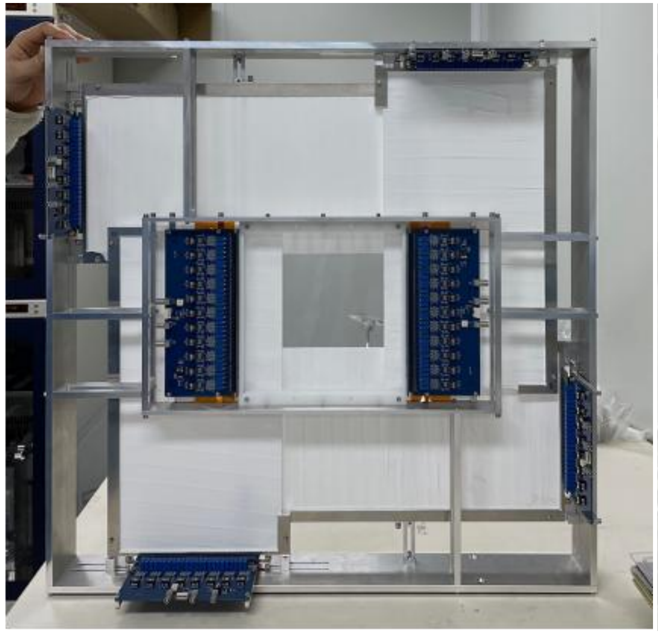
Assembled detector system at the Sejong Campus of Korea Univ.

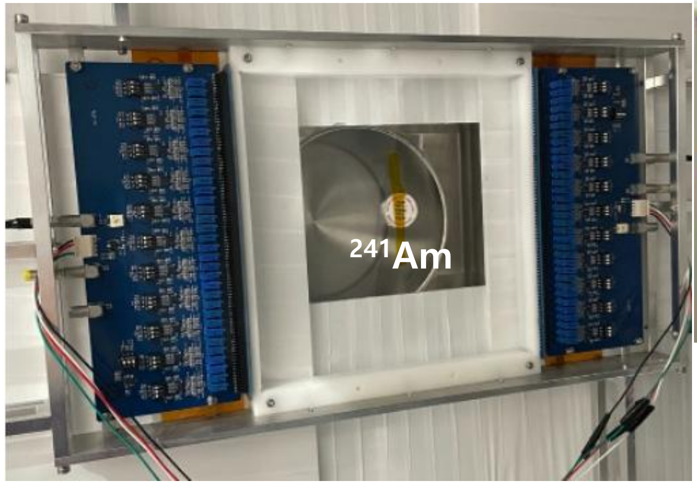
First station assembled at the high-energy experimental hall of the RAON facility

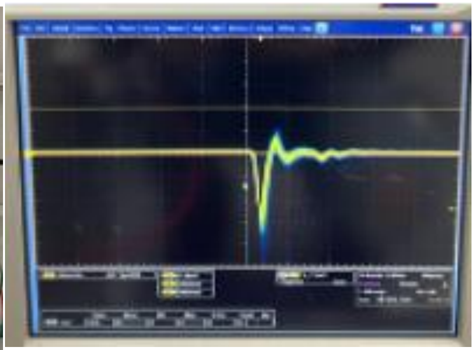
SC (Starting counter)

J.-W. Lee et al., NIMA 1081, 170827 (2026)

- **Primary function**
  - Providing an accurate reference time ($\sigma_t \lesssim 100$ ps) for entire experiment when actual beams arrive.
- **Structure & dimensions**
  - Two sets of (1 SC + 4 Veto counters)
  - SC: 210 X 210 X 0.2 mm^3 (Active area: 200 X 200 mm^2)
  - Veto: 410 X 210 X 5 mm^3 (Adjustable area)
- **Material**
  - SC & Veto: EJ-230 polytoluene-based scintillator
  - Lights collected by MPPC on a sensor board
    - 2 sensor boards on a SC scintillator & 1 board for Veto
    - 33 MPPCs on a sensor board for SC & 24 MPPCs for Veto
- **Electronics**
  - Conventional CAEN TDC, QDC for the time and charge information
- **Installation & α source (^{241}Am) test**
  - Full system installed in the vacuum chamber
  - $\sigma_t \sim 92$ ps







BDC (Beam drift chamber)

H. Kim et al., JINST 19, P12008 (2024)

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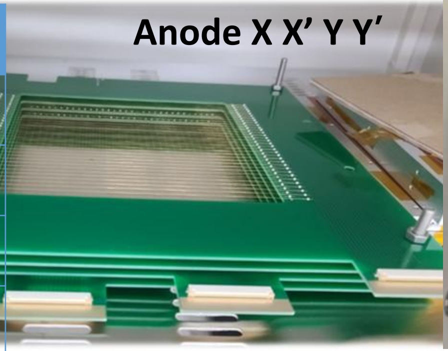
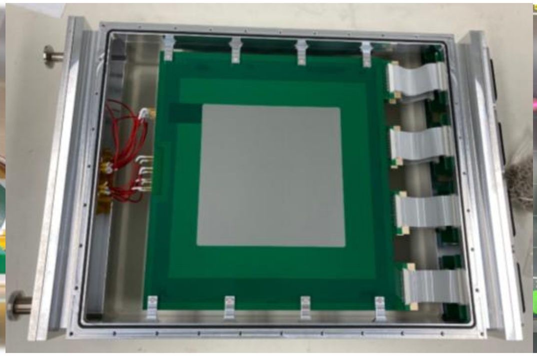
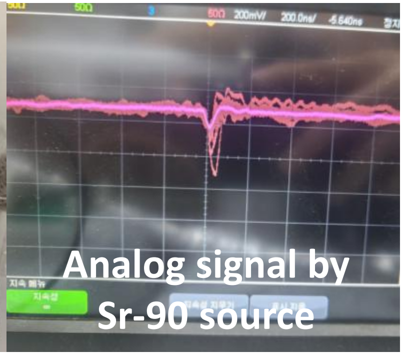
Parameter	Value
Anode wire	ϕ 20 μm Au-W
Potential wire	ϕ 80 μm Cu-Be or Au-W
Cathode	2 μm-thick Al-mylar, 9 layers
Cell size	5 mm (max. drift length 2.5 mm)
Active area	170 x 170 mm^2
Anode configuration	XX'YY'XX'YY', 8 layers
Number of channel	256 (32 wires/plane, 8 planes)
Operation gas	i-C_4H_{10} below 1 atm P10 (Ar 90% + CH_4 10%) at 1 atm
High voltage	2 channels for cathode & potential wires
Readout	ASD(RP-2125)+TDC(V1190A)+QDC(V792)
Body dimension	490(L) x 360(H) x 100(W) mm^3
Beam window (variable)	12 μm Al-mylar (up to 20 kPa) 50 μm Al-mylar (up to 50 kPa)

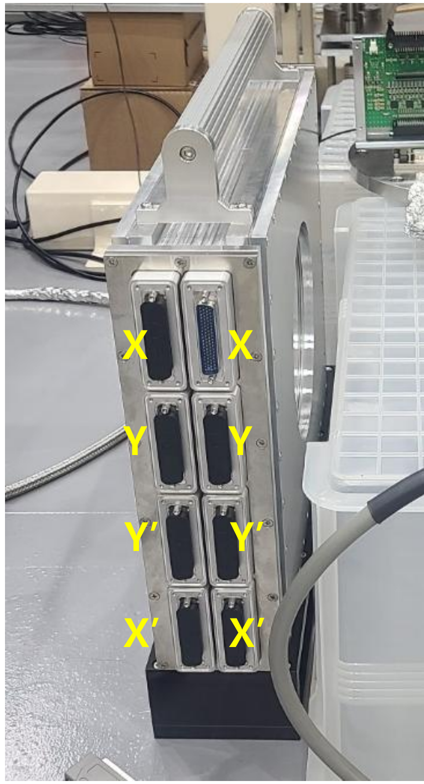






- HV & vacuum tests completed
- Source test shows $\sigma_x \approx 80\ \mu$m.

BDCs in the beam diagnostic vacuum chamber



Part 3.

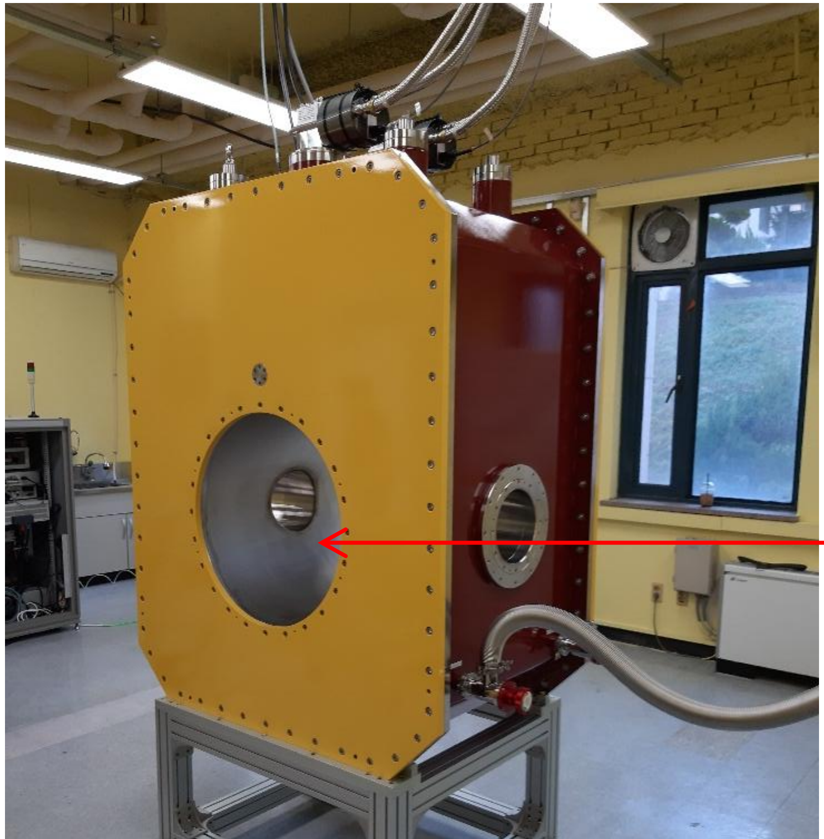
Detectors for the low-energy experiments

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

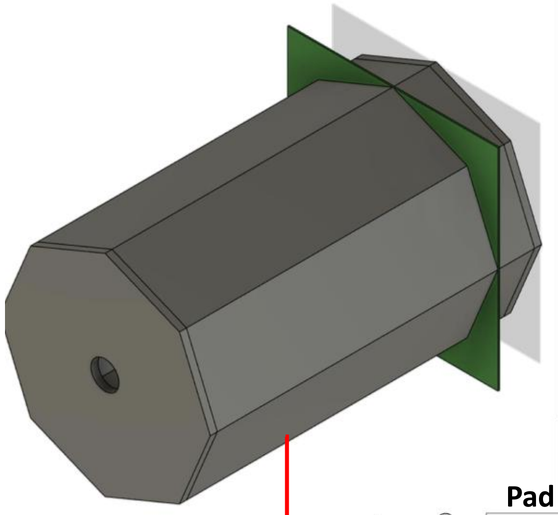
HALO-40

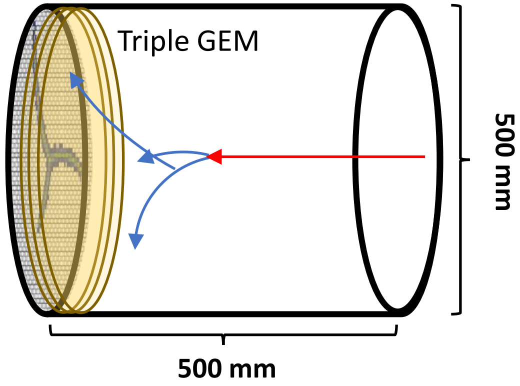
- Superconducting solenoid magnet
  - B_{max} = 1.5 T
  - Diameter & length of the detector installation space = 60 cm each
  - Commissioning successfully done in 2019

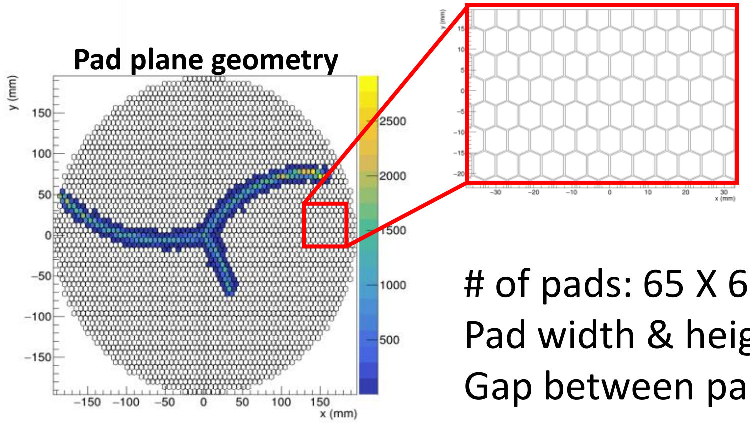
- Design of AT-TPC (Sejong Univ.)
  - Number of channels: > 3,000
  - $\phi \simeq$ 40 cm
  - Cylindrical shape similar to the LAMPS TPC



S.H. Kim & J. Ahn, IEEE Transactions on Applied Superconductivity 31, 4500107 (2020)







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

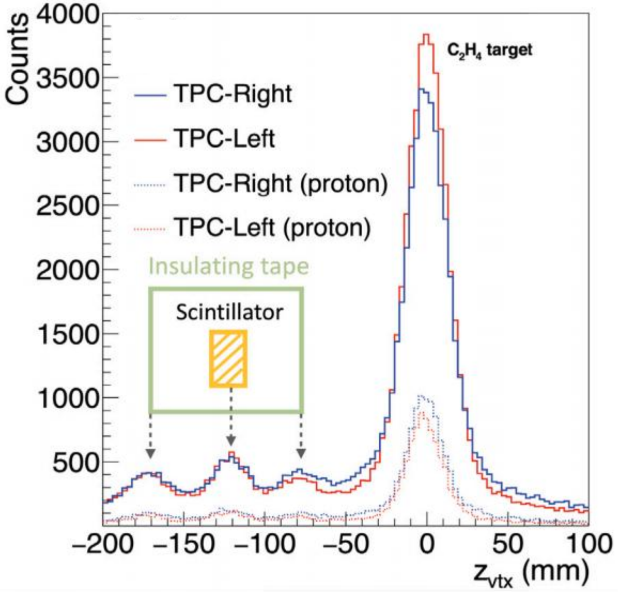
AT-TPC: Beam test with prototype

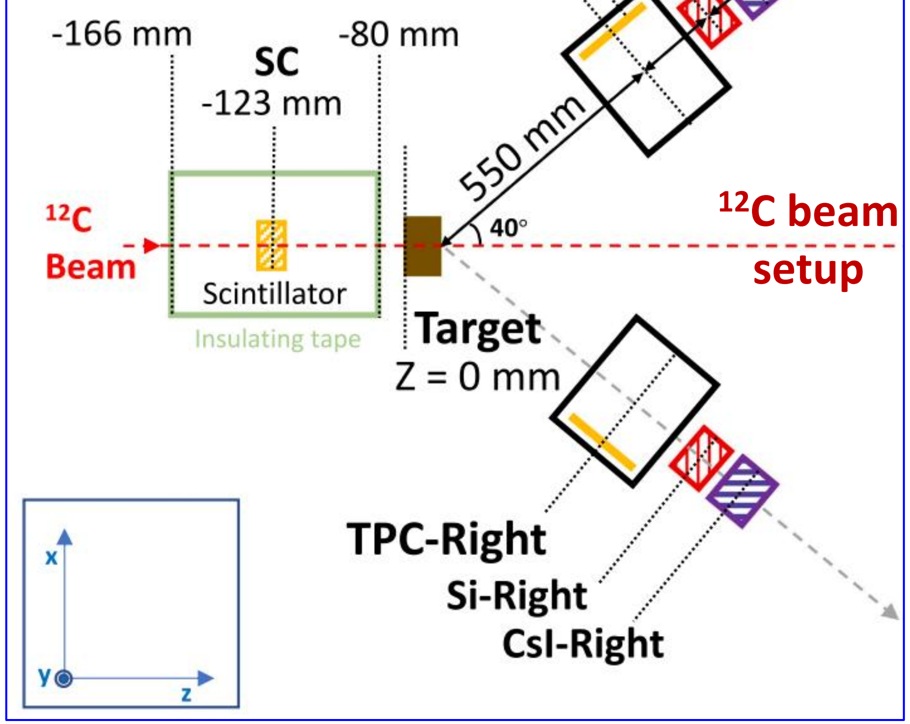
- Beam test of two prototypes at HIMAC in Japan in Feb. 2023
  - Beams: p @ 100 MeV, ^{12}C @ 200 MeV/u, 10^6 ppp
  - Performance test for LAMPS detectors including AT-TPC
  - Analyzing ^{12}C(p,2p) Quasi-Free Scattering (QFS) events

Y. Cheon et al., NIMA 1066, 169610 (2024)

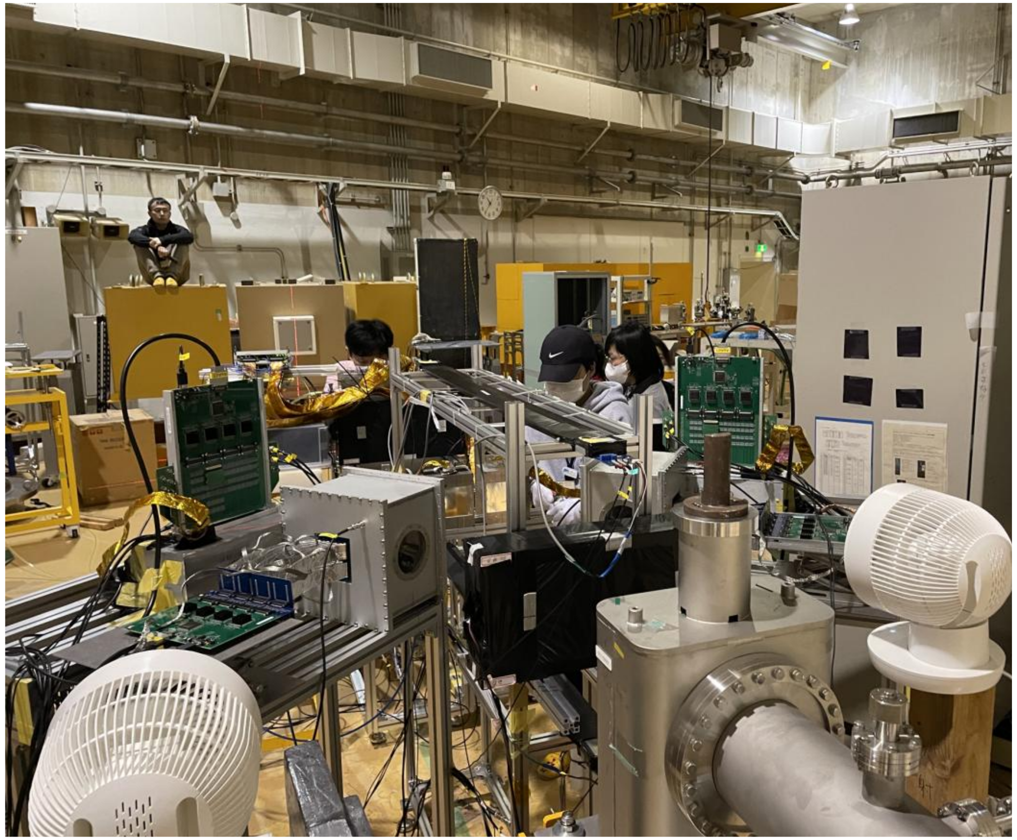
Prototype AT-TPC →

↓ Reconstructed vertex distribution by AT-TPC

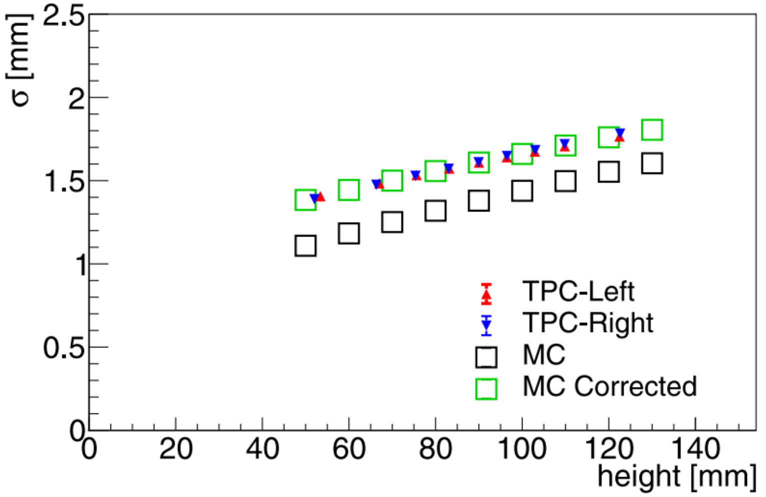


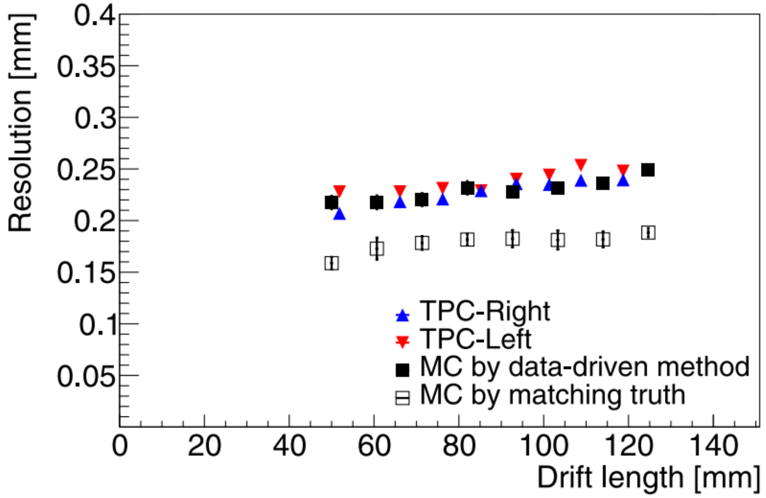


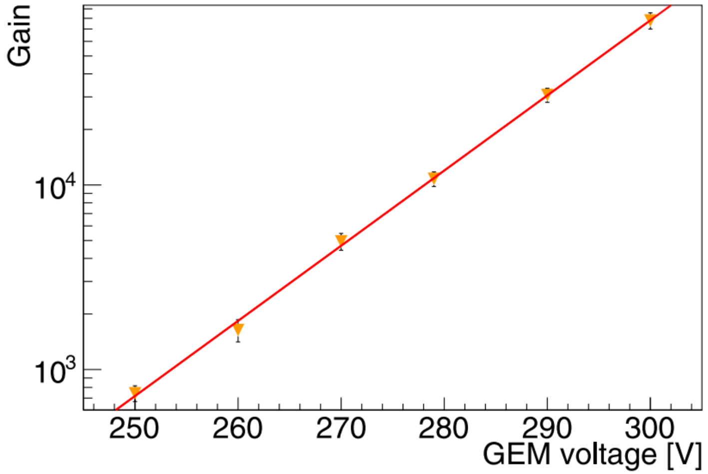
^{12}C beam setup

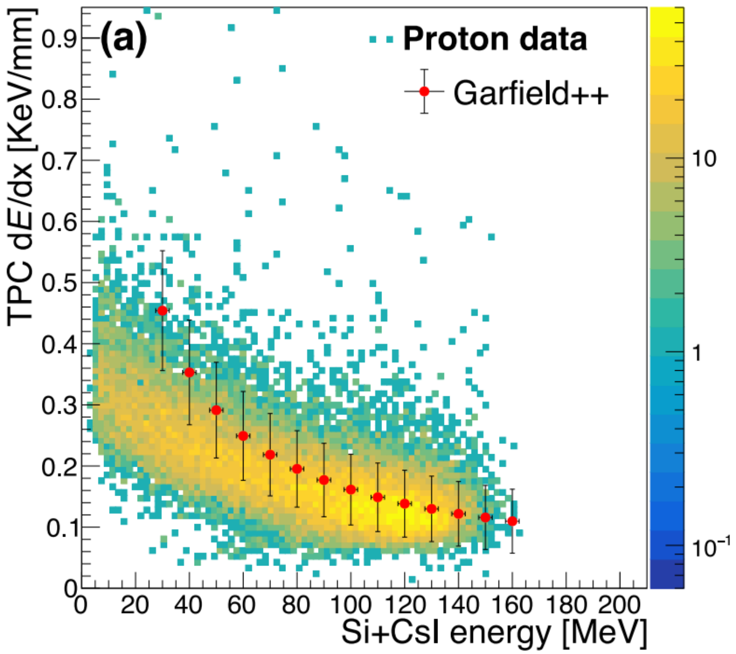


AT-TPC: Characteristics









↖ Transverse diffusion of electrons vs. drift length

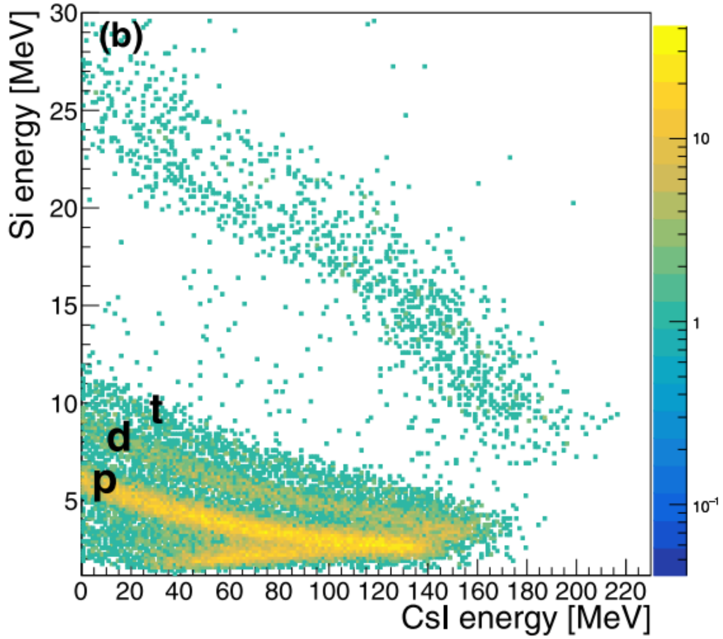
↑ Spatial resolution vs. drift length

↗ 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

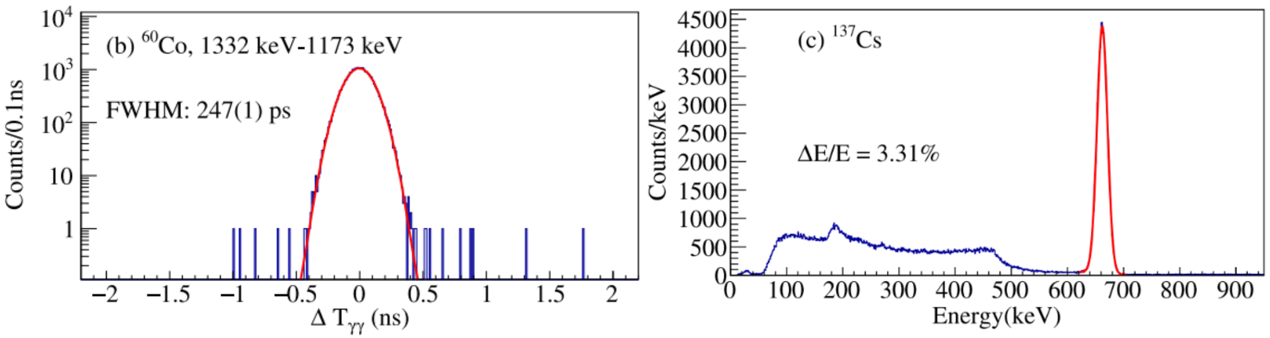
Y. Cheon et al.,
NIMA 1066, 169610 (2024)

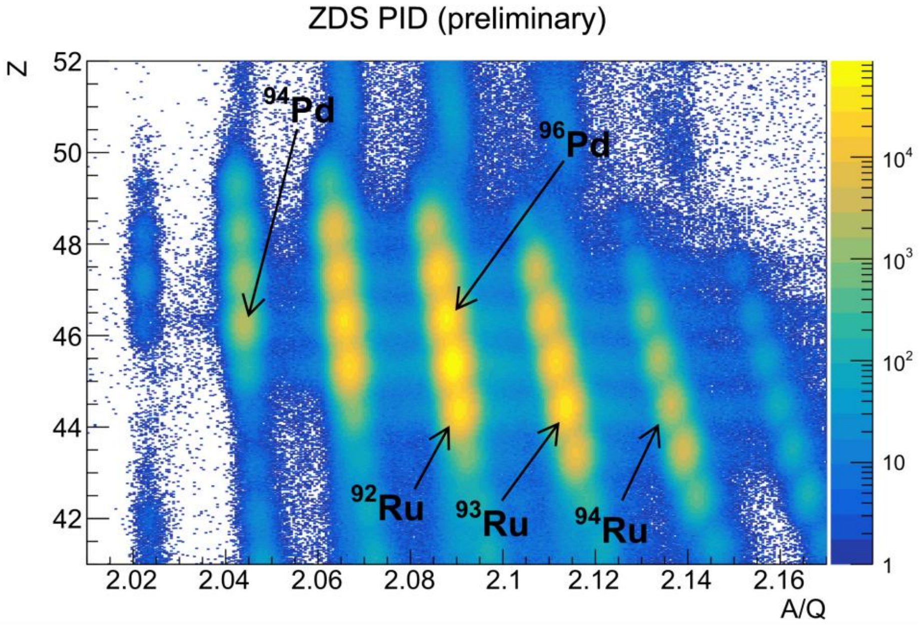


KHALA: Korea high–resolution array of $LaBr_3$

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

B. Moon et al., NIMB 541, 253 (2023)





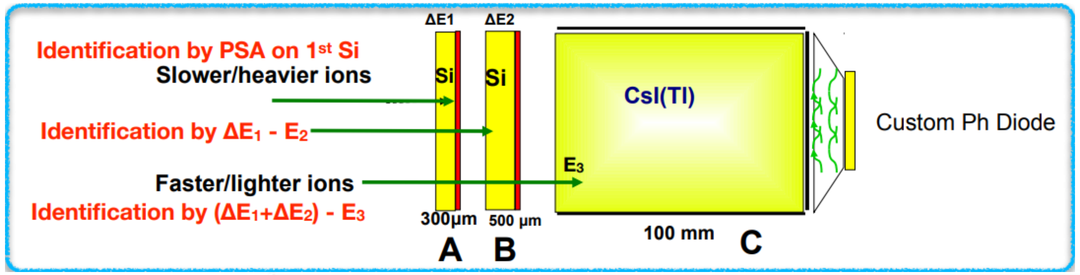
- Some of isotopes, e.g., ^{94}Pd, ^{96}Pd, ^{94}Ru, have not yet been studied.

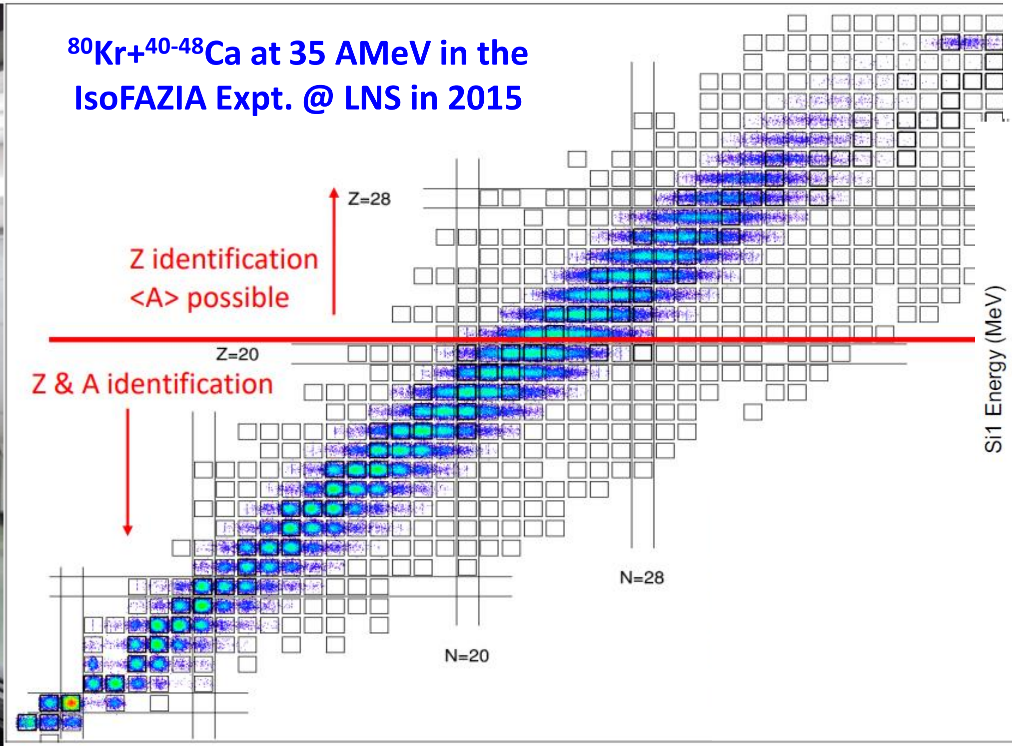
Si+CsI charged particle detector

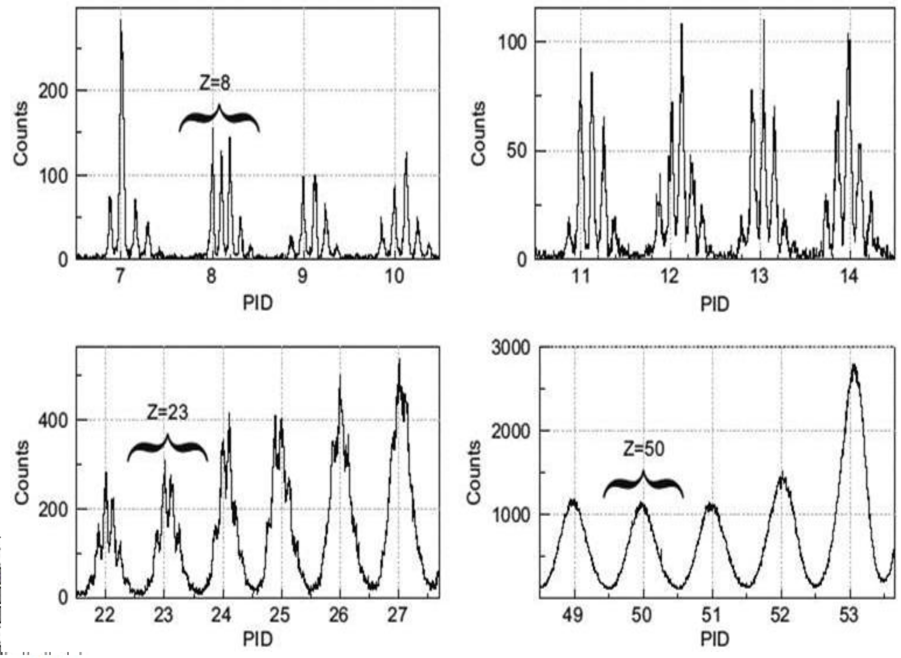
HALO-40

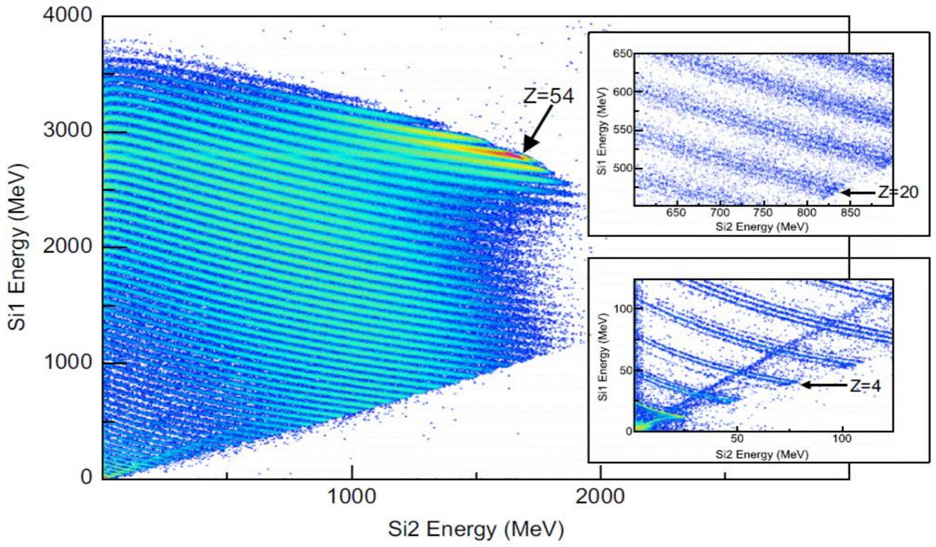
FAZIA, EPJA 50, 47 (2014)

- 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.









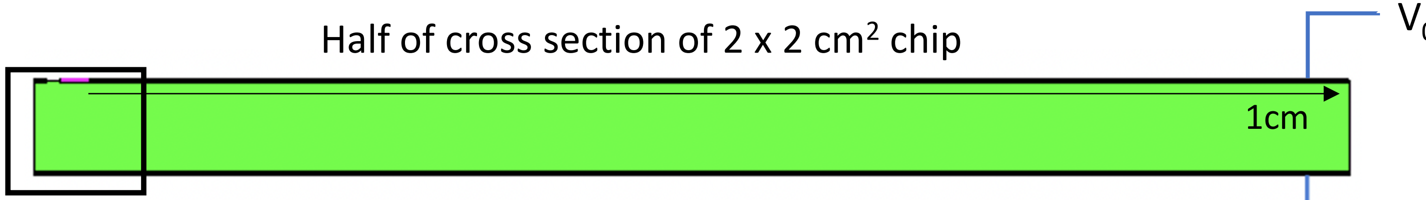
R&D of Si sensors

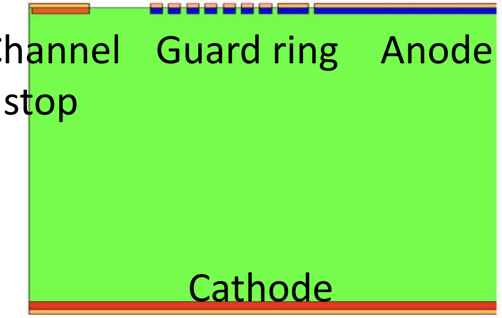
M. Kweon et al., NIMB 541, 310 (2023)

- Design of PiN sensor using TCAD: Simulation setup

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

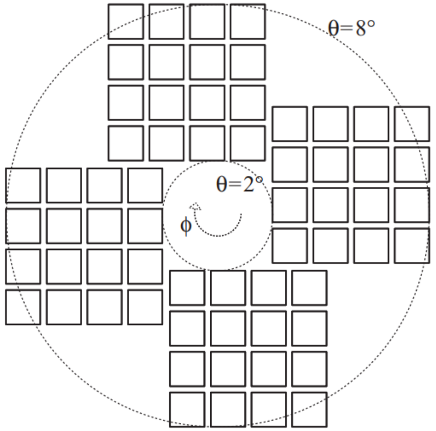
Thickness: 720 μm





Edge of silicon sensor

Input parameters for simulation				
T (K)	300		Doping density	
V_0 (V)	0 ~ - 700		Blue	P^+ Boron
Carrier lifetime	Electron	$1\times10^{-4}\ s^{-1}$	Green	N^- Phosphorus
	Hole	$3\times10^{-4}\ s^{-1}$	Red	N^+ Phosphorus



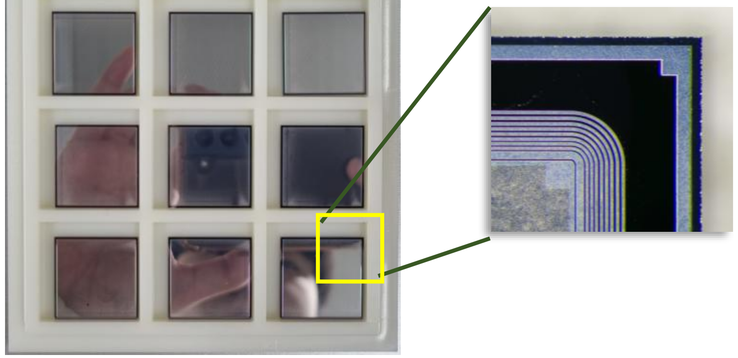
→ Results

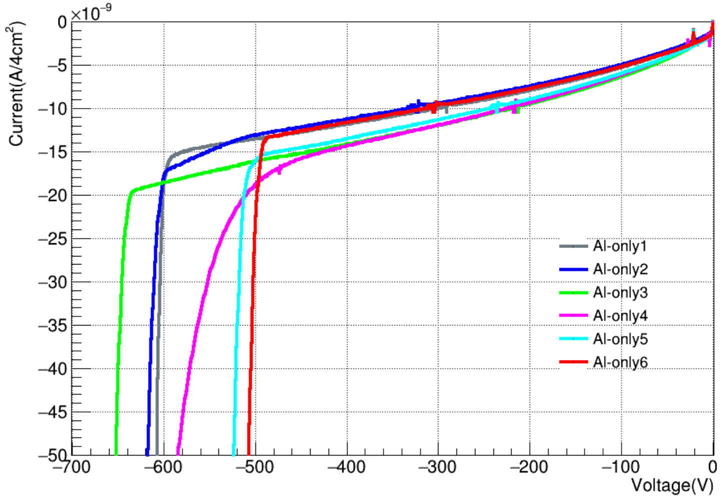
- Breakdown voltage point is close to -600 V
- Enough to reach full depleted voltage (400 V)

— We are also developing 150 μm-thick chips.

← We plan to build 4 FAZIA blocks for the experiments at RAON.

Extended view





Summary

- Purpose of LAMPS
  - Detailed investigation of *nuclear equation of state (EoS) and symmetry energy*
  - We plan to use LAMPS for the new features of nuclear structure, including halo.

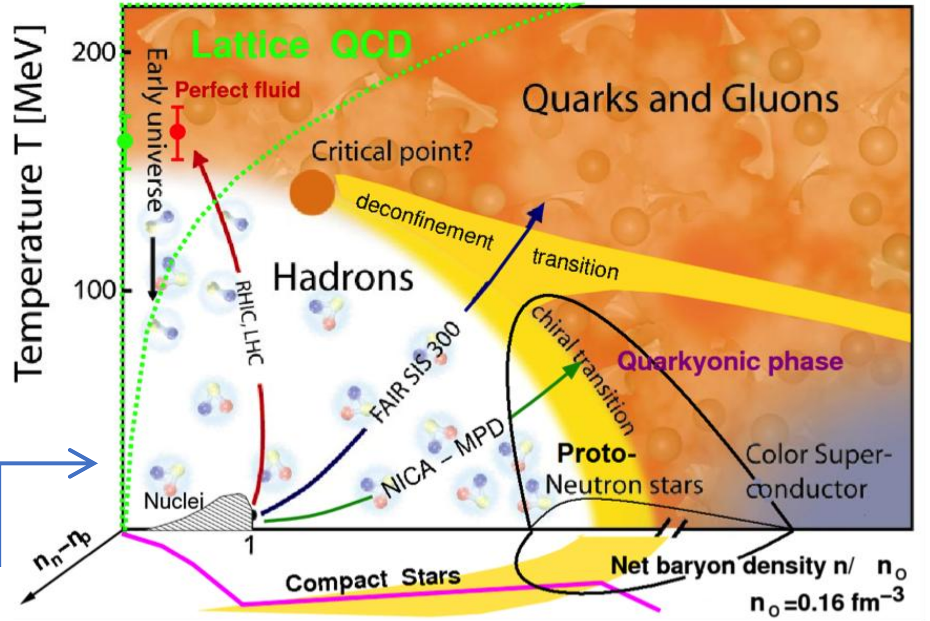
- Status of the LAMPS detector system
  - All detector elements were developed, manufactured, and assembled.
  - Performance test with cosmic muons using LTE for the integrated system is in progress.
  - The high-energy beams from SCL2 at RAON will be available in ~2030 or later.
  - Thus, we are exploring 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 ONOKORO project at RIBF.*
    - → *LAMPS TPC can be used for the EOS experiment at other Labs.*
    - → *KHALA LaBr3 system is being used for the IDATEN experiment at RIBF.*

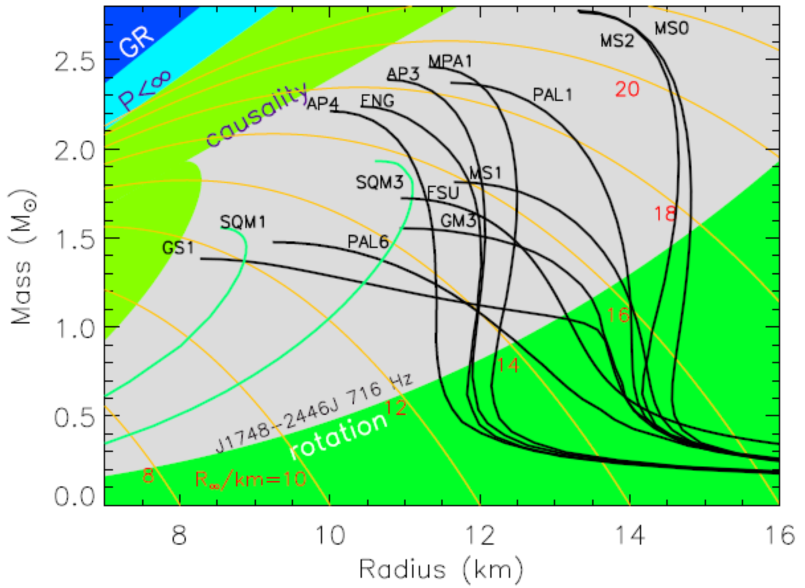
- *Any idea using the LAMPS detector elements are welcome!*

Backup slides

Physics objectives

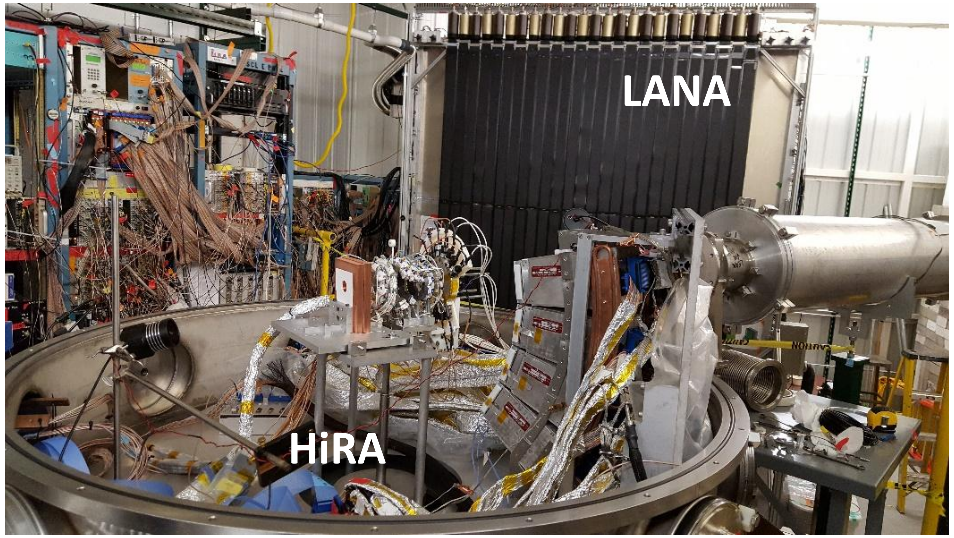
- Why do we need heavy-ion collisions?
  - It is the only way to create dense nuclear matter in the laboratories.
- Why do we need RIB?
  - RIB enables us to access a wide range of the isospin axis ($n_n - n_p$ or N/Z).
- EoS and E_{sym} are essential to understand
  - Phase structure of the nuclear matter including the isospin degree of freedom
  - Stability of neutron stars against the gravitational collapse
  - Relation between mass & radius of neutron stars
  - Determination of the stella density profile and internal structure
  - Cooling rate of proto-neutron stars
  - Stella masses, radii, and moments of inertia from temperatures and luminosities of the X-ray bursters

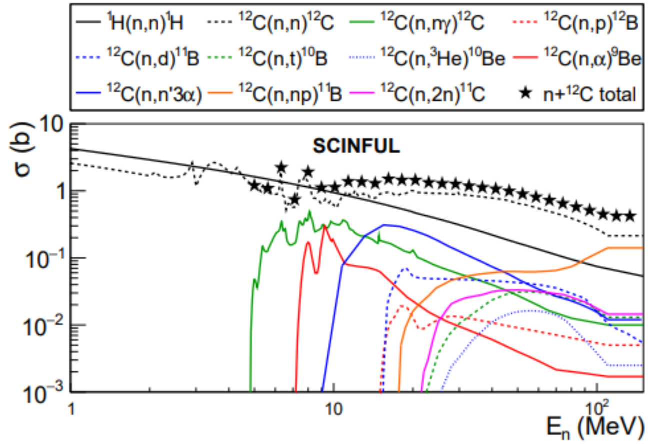


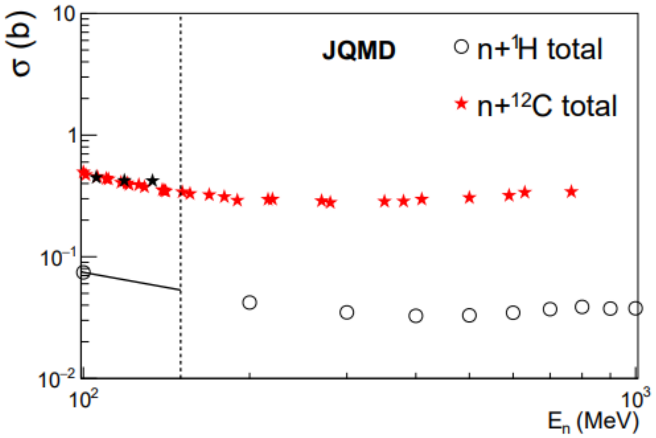


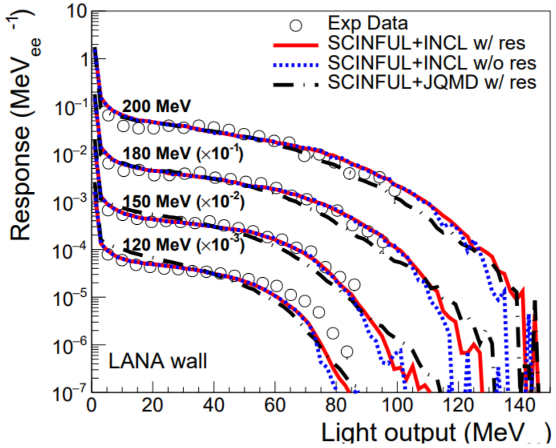
Neutron analysis framework: neuSIM4

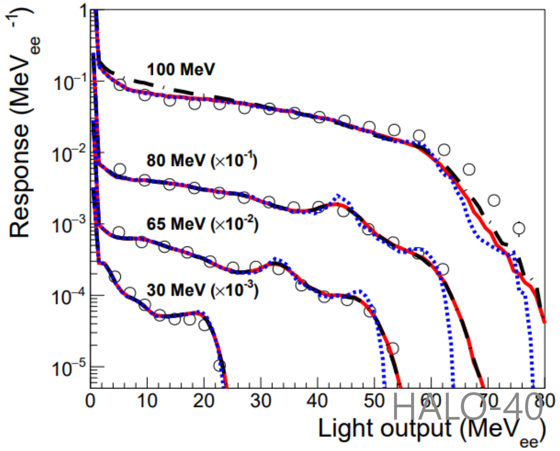
- Framework originally developed for LANA @ NSCL
  - GEANT4 based neutron analysis & simulation framework
  - It will be used for the data analysis of the nucleon's effective mass (m_N^*) experiment at NSCL (^{48}Ca+ ^{64}Ni @ 140 AMeV).
  - But the software framework is applicable to all neutron detectors including the LAMPS neutron detector array.

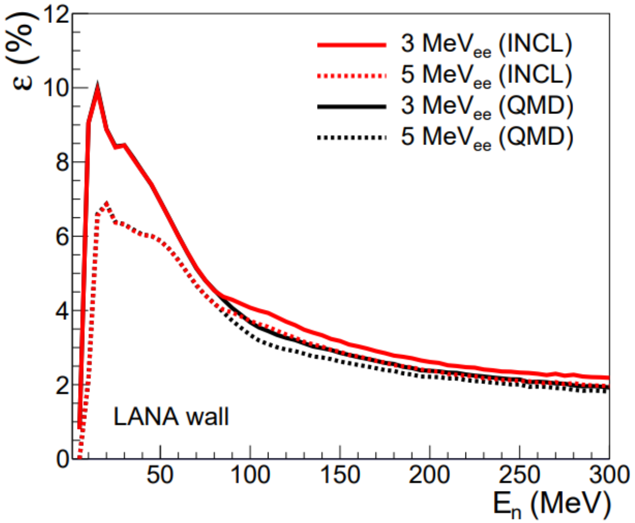












J. Park et al., NIMA 1065, 169475 (2024)