



International Workshop “Unlocking the QCD Phase Diagram”
Georg-Christoph-Lichtenberg-Haus, Darmstadt, Germany, September 7–9, 2026

Plan to Study EoS with **LAMPS** at **RAON**

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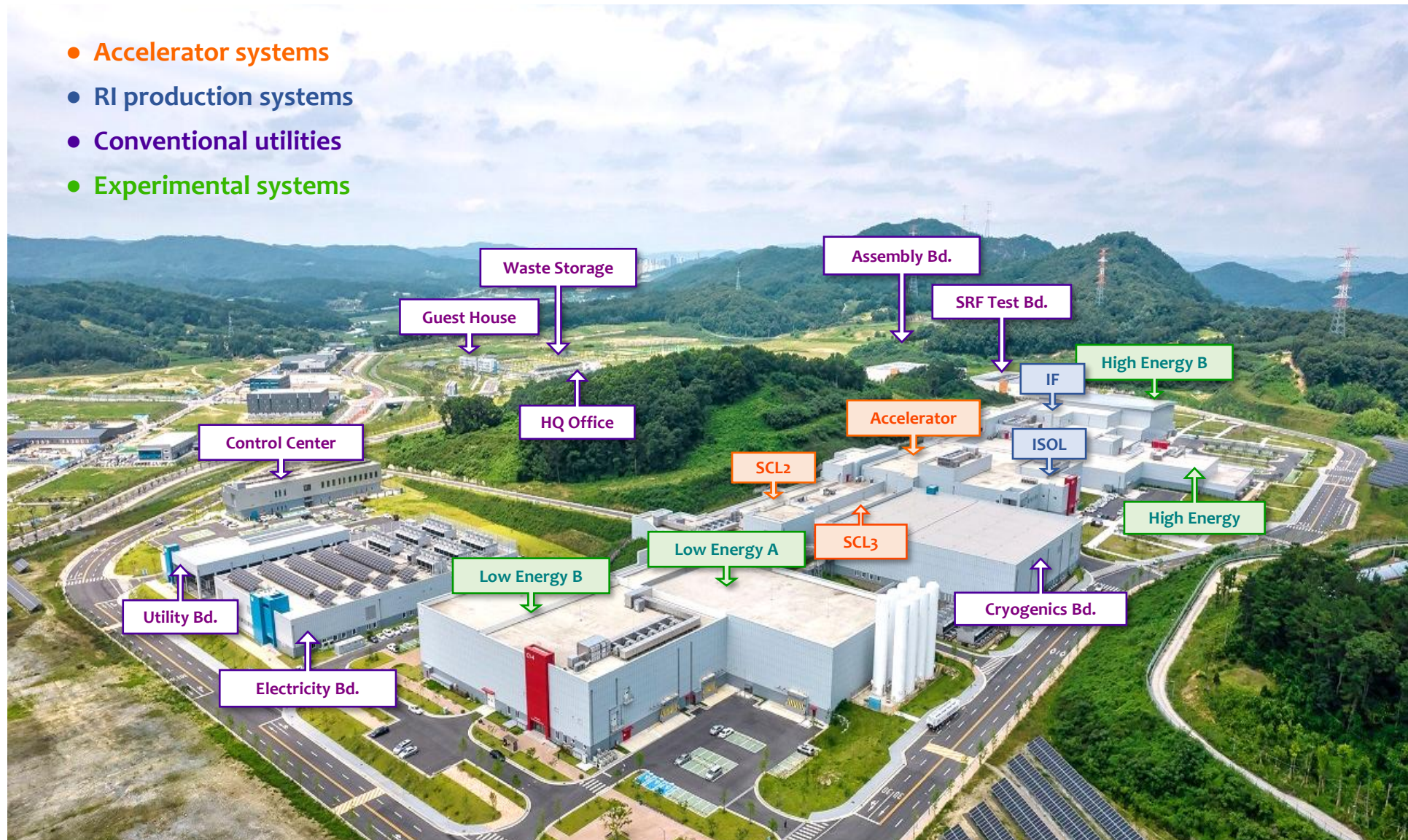
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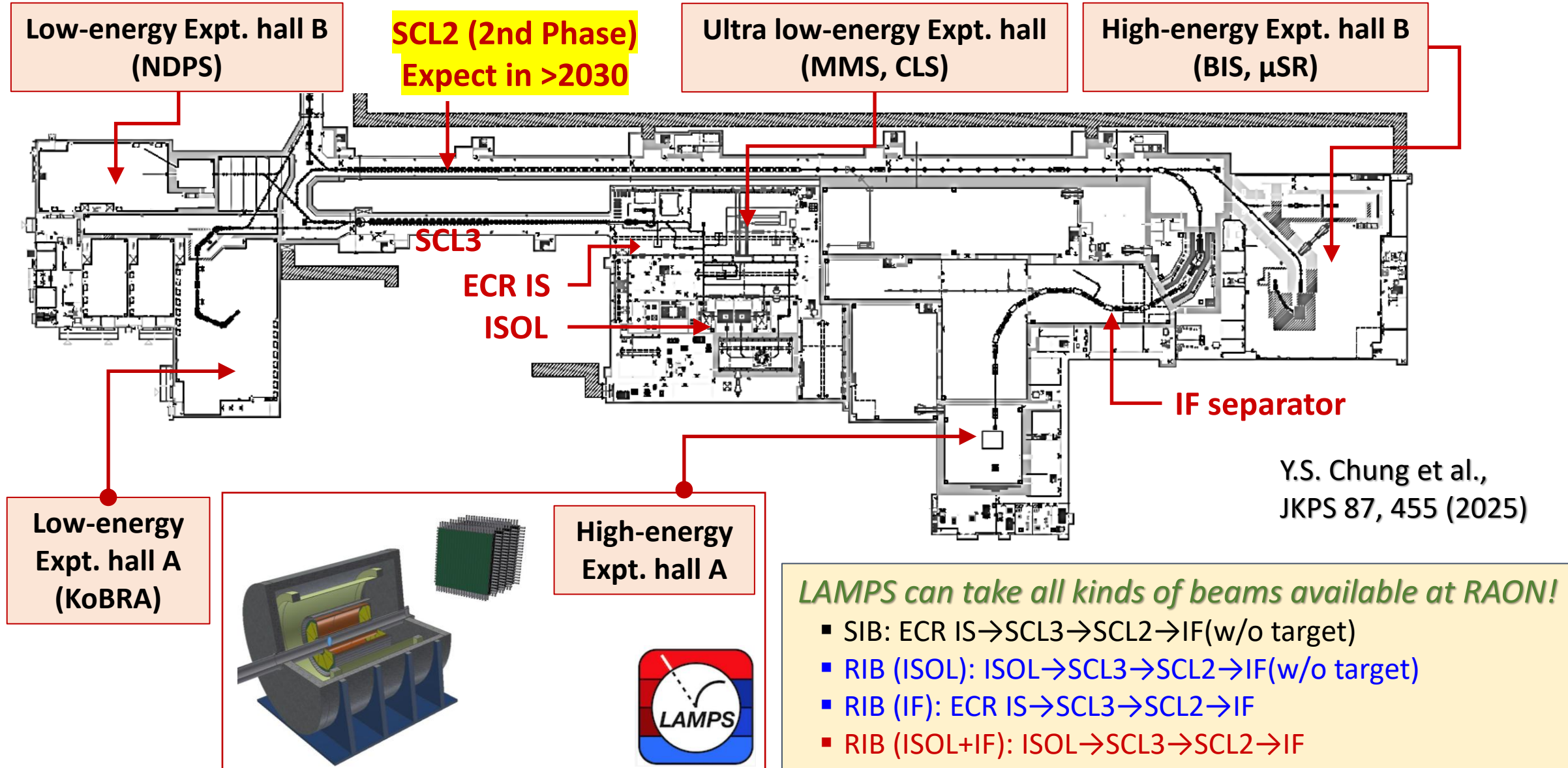
LAMPS: Large Acceptance Multi-Purpose Spectrometer

RAON: Rare isotope Accelerator complex for ON-line experiments

Bird's-eye view of RAON in Korea



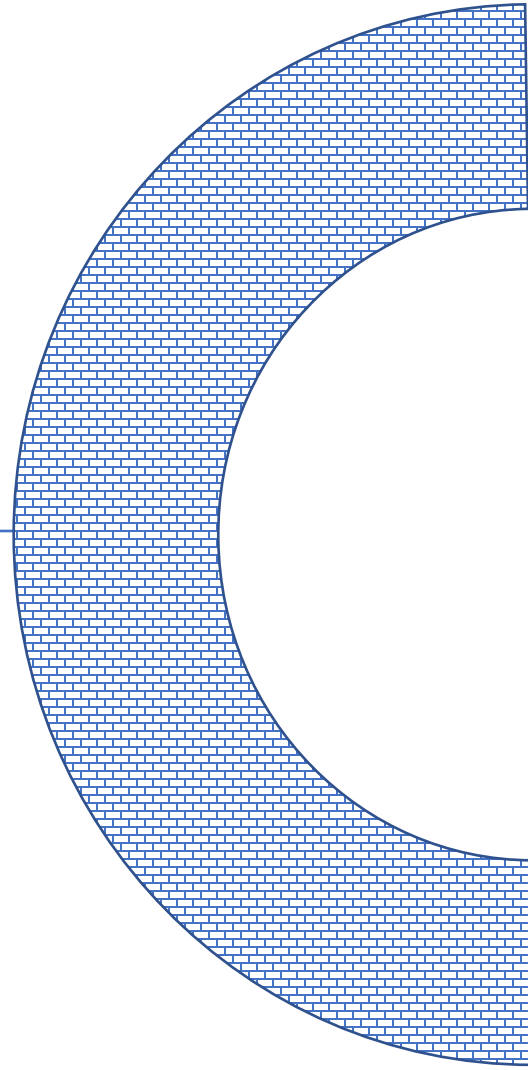
LAMPS @ RAON





Part 1.

Physics goal of LAMPS



Main physics goal of LAMPS

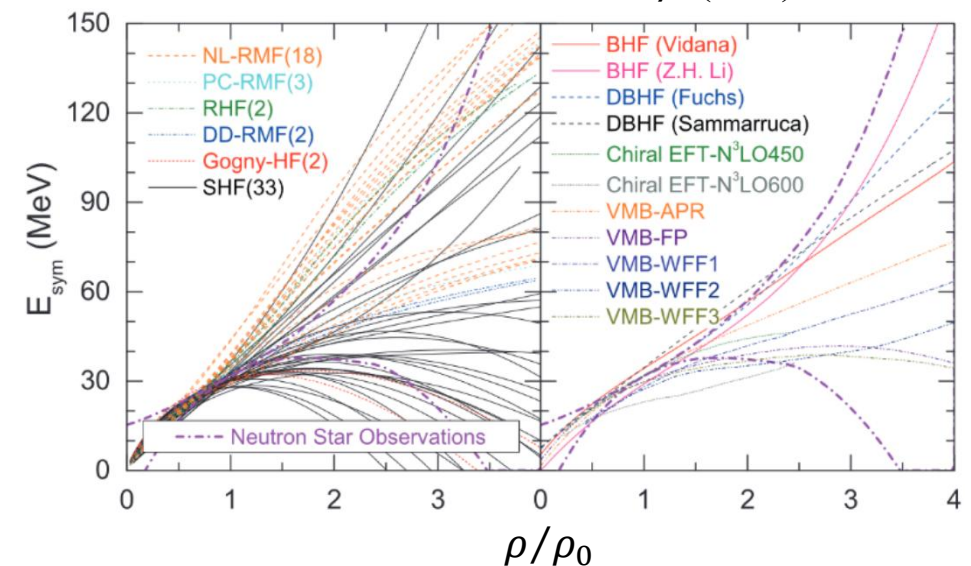
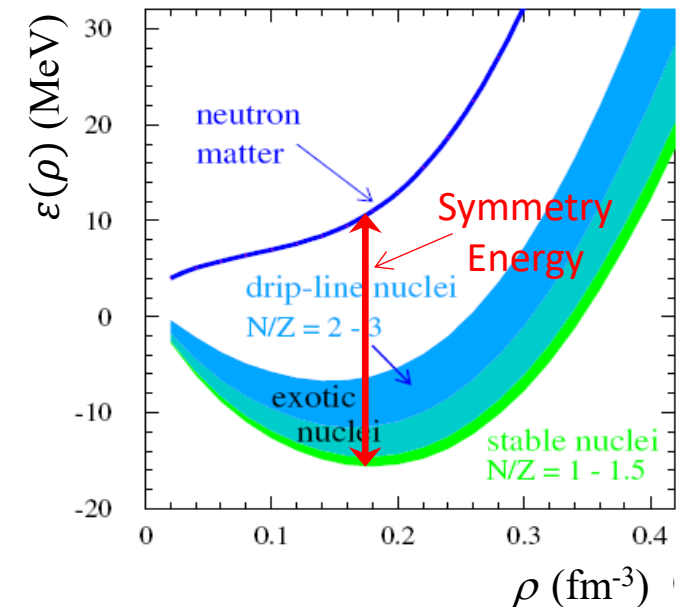
- Equation of state (EoS) & symmetry energy E_{sym} of nuclear matter [$\delta = (N - Z)/(N + Z)$]:

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

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

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

- 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.

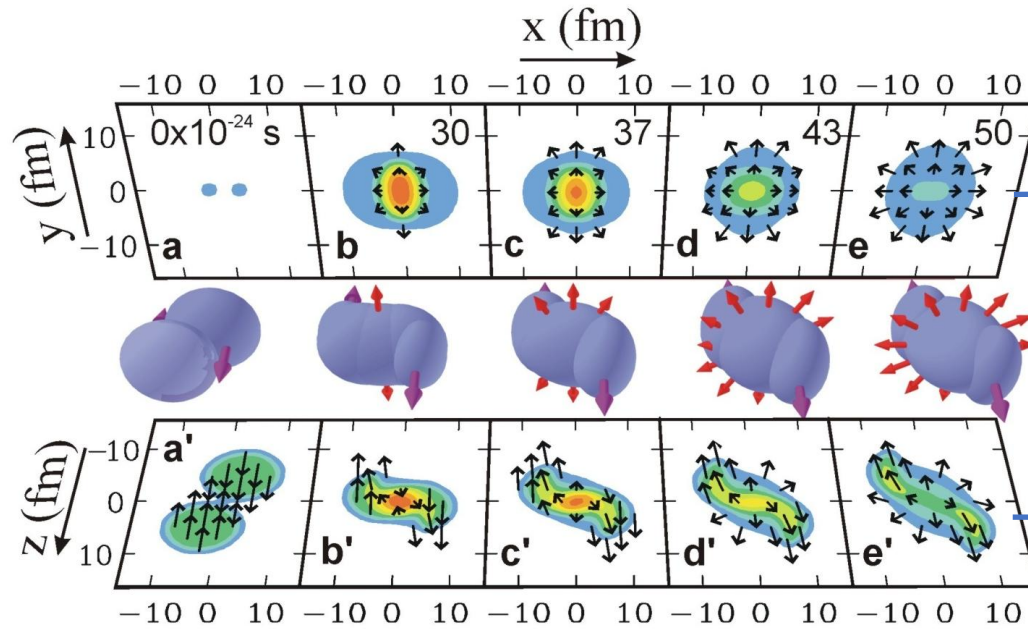


L-W. Chen, Nucl. Phys. Rev. 34, 20 (2017)

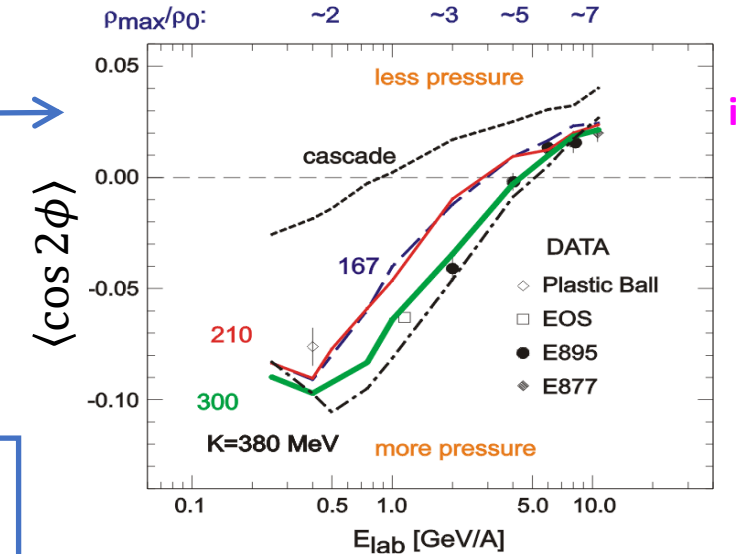
N.B. Zhang & B.-A. Li, Eur. Phys. J. A 55, 39 (2019)

Status of EoS & symmetry energy

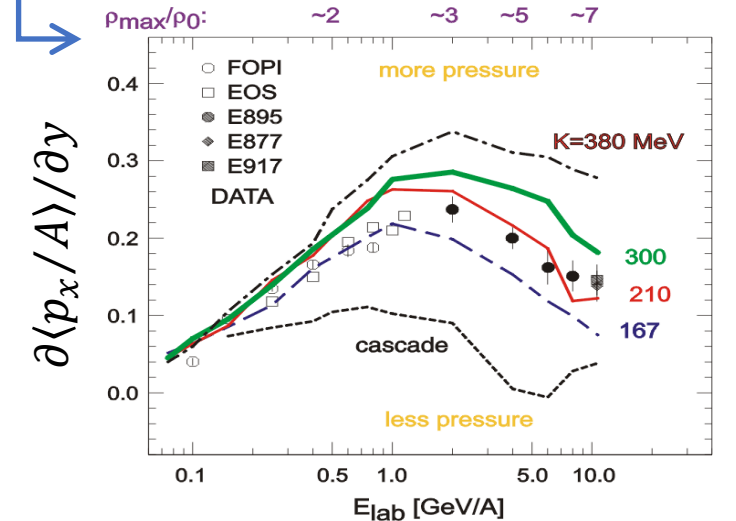
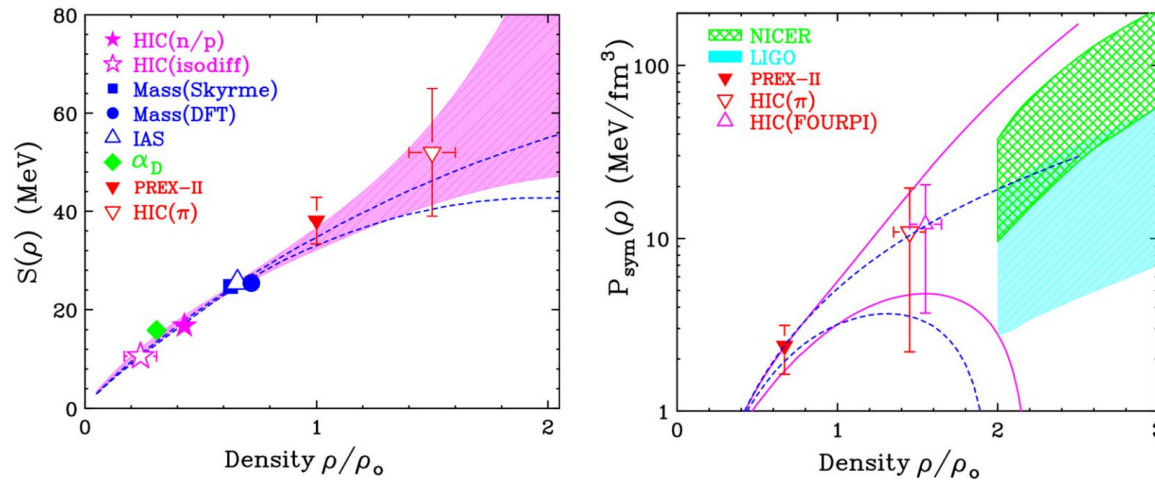
Figure adopted from
Danielewicz et al.,
Science 298,1592 (2002)



Symmetric matter



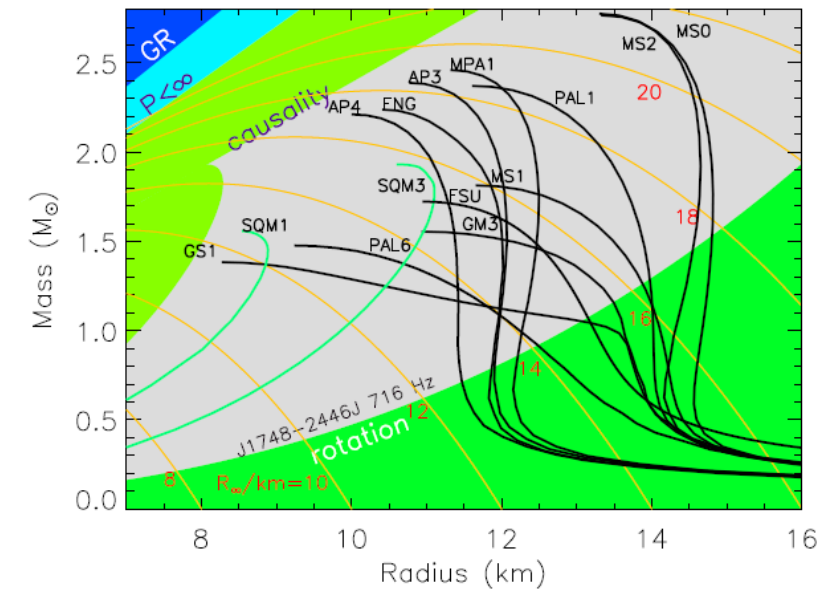
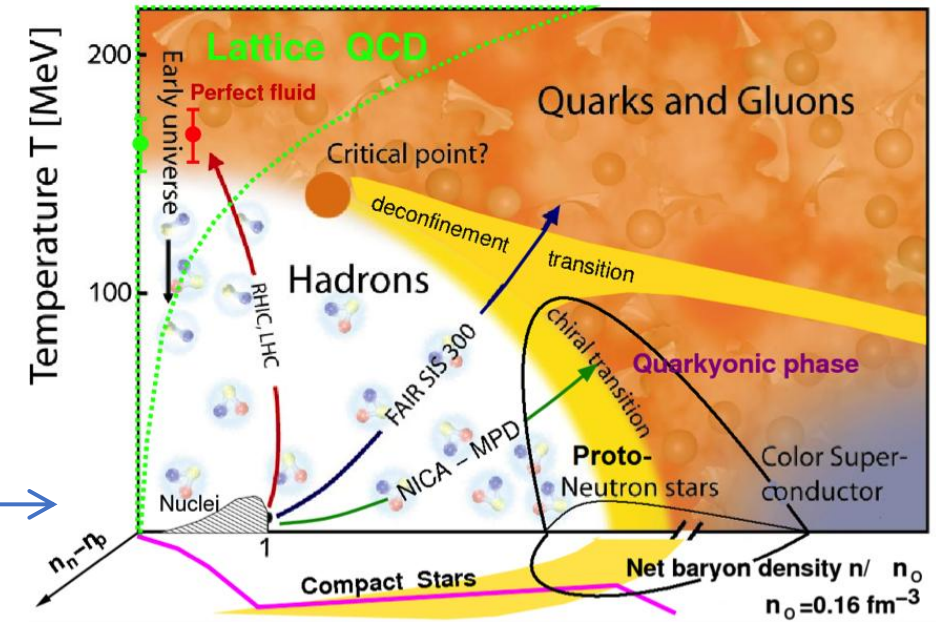
Recent constraint of the symmetry energy



Lynch & Tsang,
PLB 830, 137098 (2022)

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 Radioactive Ion Beam (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



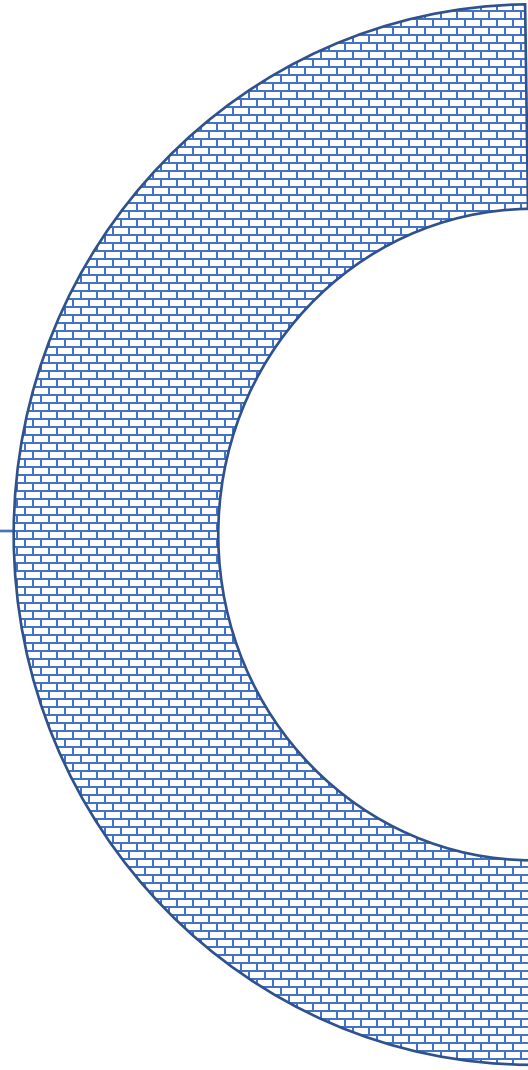
Observables

- 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 , ${}^3\text{H}/{}^3\text{He}$, ${}^7\text{Li}/{}^7\text{Be}$, 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.

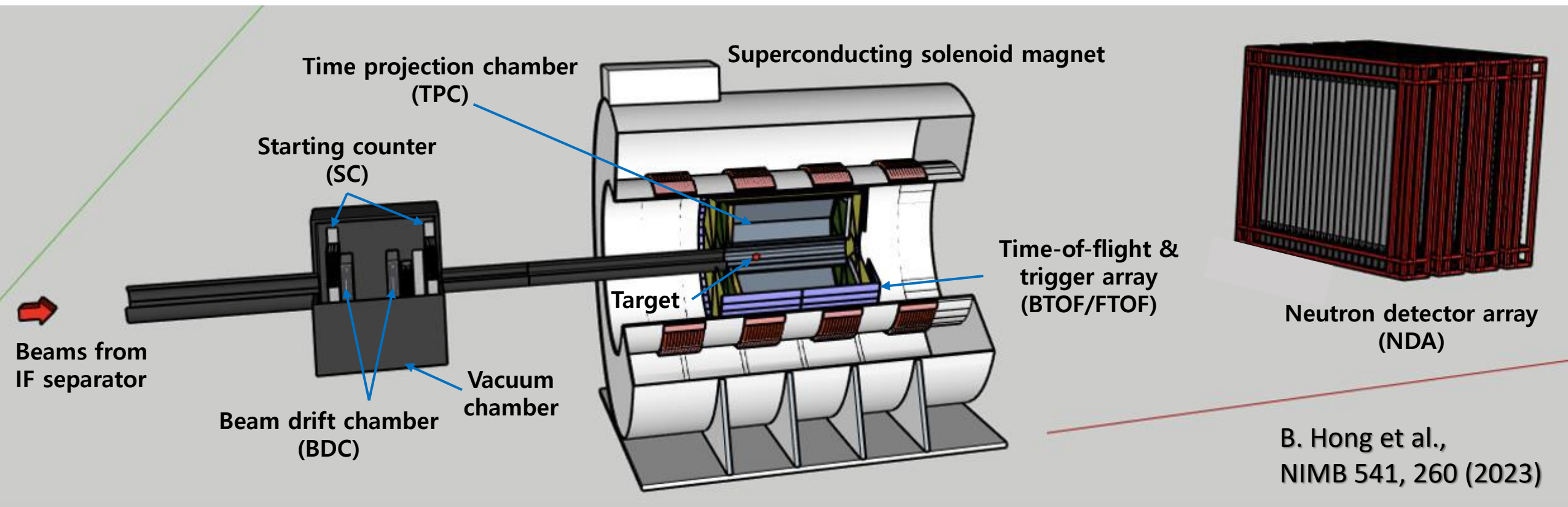
LAMPS detection system @ RAON





Overall design of LAMPS

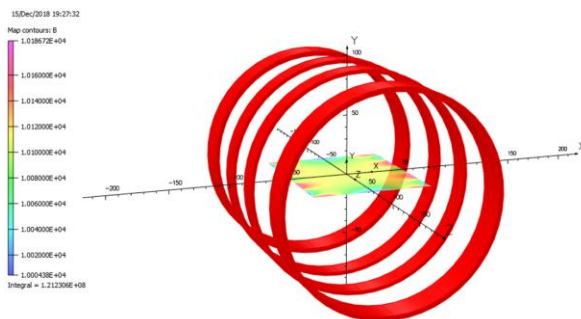
- **LAMPS: Large Acceptance Multi-Purpose Spectrometer**
 - TPC with $\sim 3\pi$ sr acceptance for tracking light charged particles ($Z=1,2,3$)
 - Beam energy up to 250 MeV/u for ^{132}Sn ; Intensity up to 10^8 pps (TPC can take only $\sim 10^{4-5}$ pps)
 - *Useful system not only for nuclear EoS, but also for nuclear structure & dynamics*



Superconducting magnet

● Design parameters

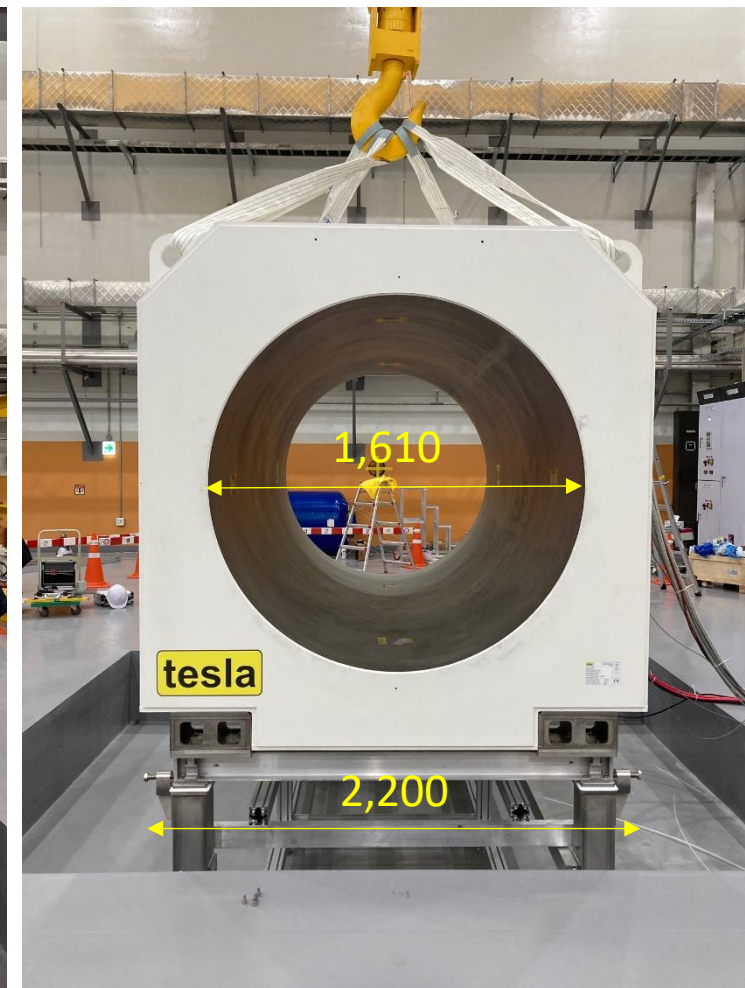
- Superconducting solenoid magnet
- Dim.: 3,000(L) X 2,200(W) X 2,250(H) mm³
- Diameter of bore: 1,610 mm
- Max. field: 1 Tesla
- Variation of B field over TPC volume:
 - (Simulation) $\pm 0.94\%$
 - (Measurement) $-0.86 \sim 0.67\%$



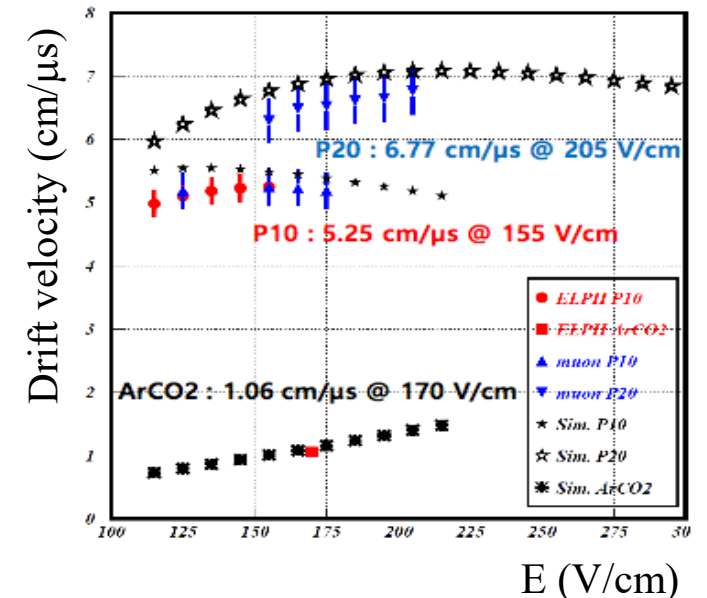
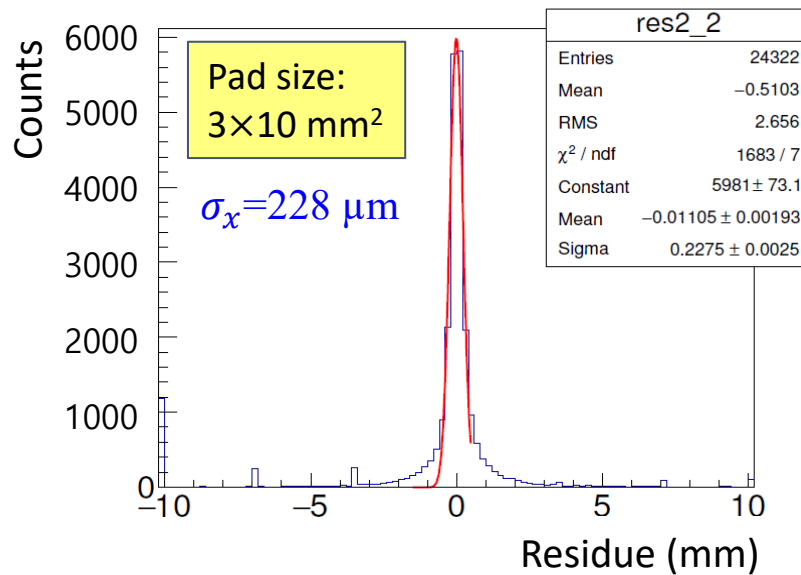
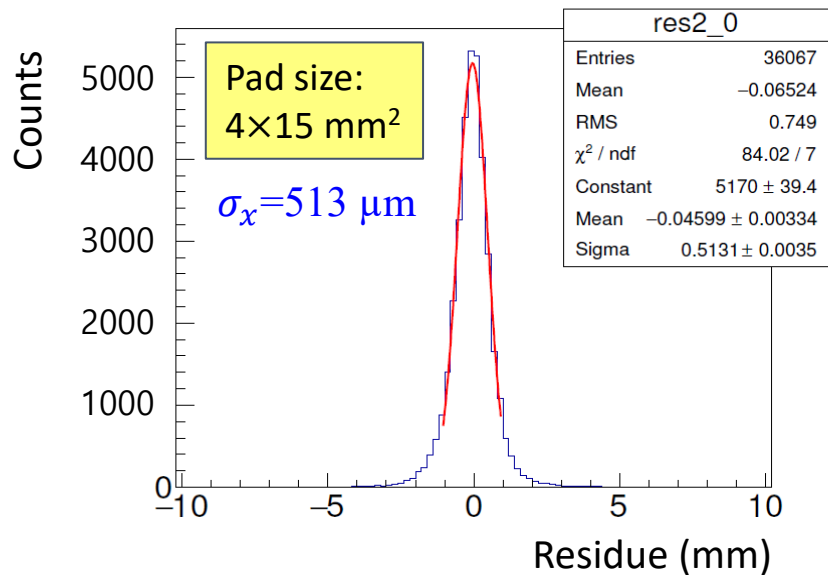
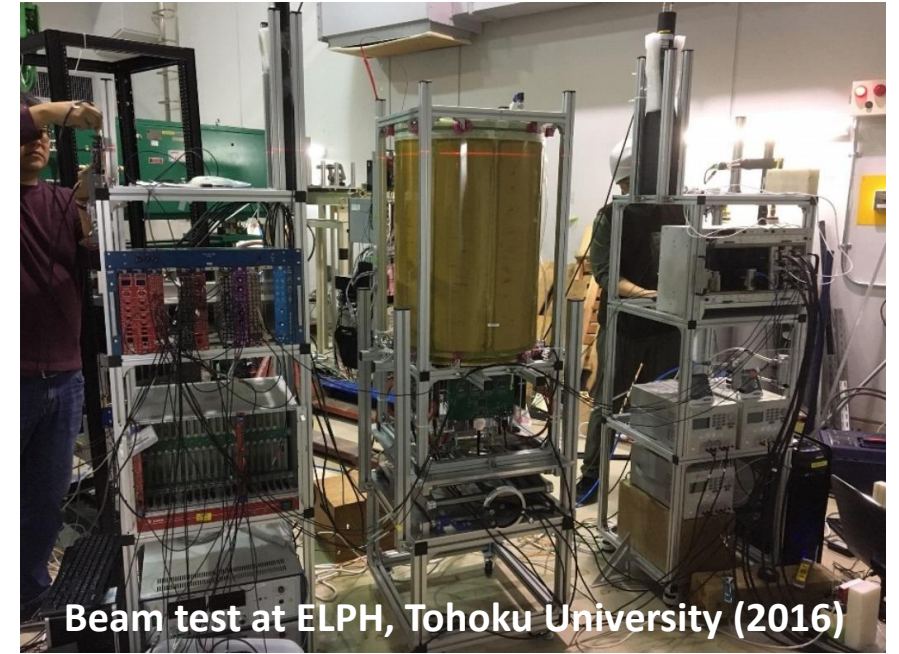
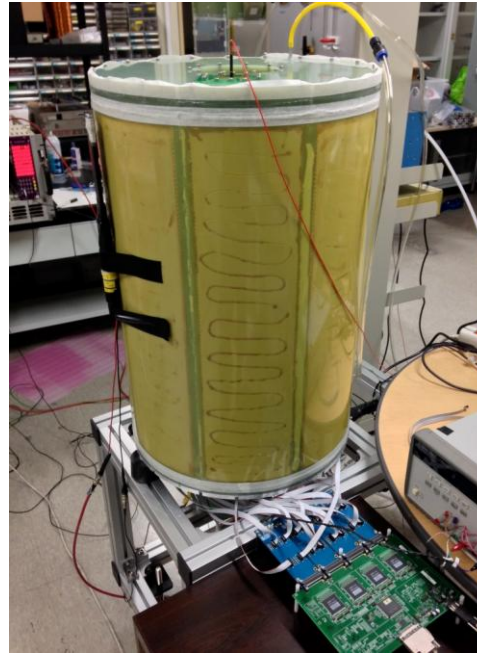
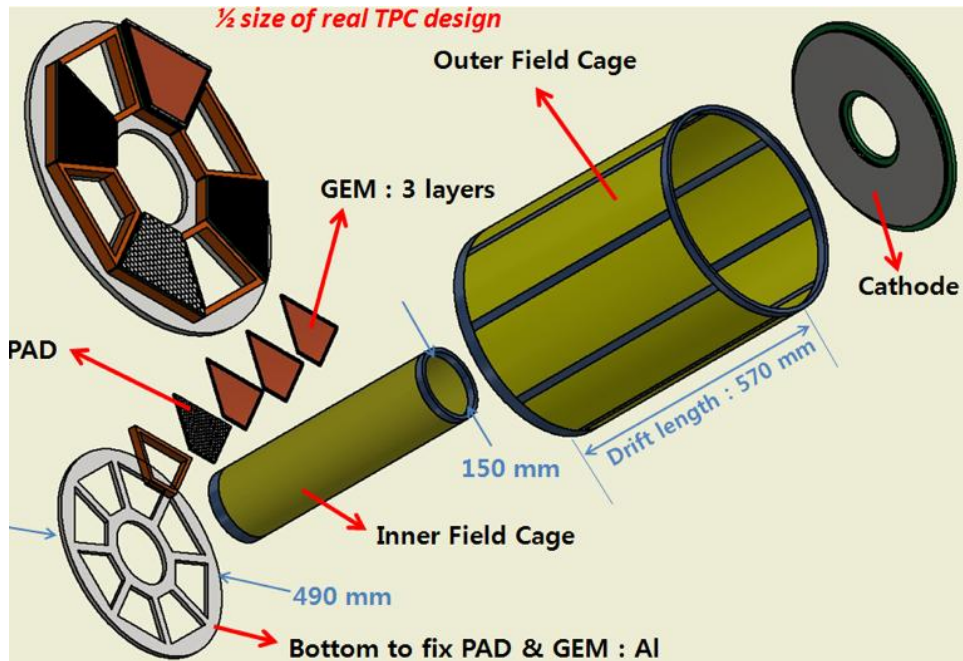
- Passive quench protection
- Conduction cooling with 4 K vessel thermal shield and vacuum vessel

● Construction

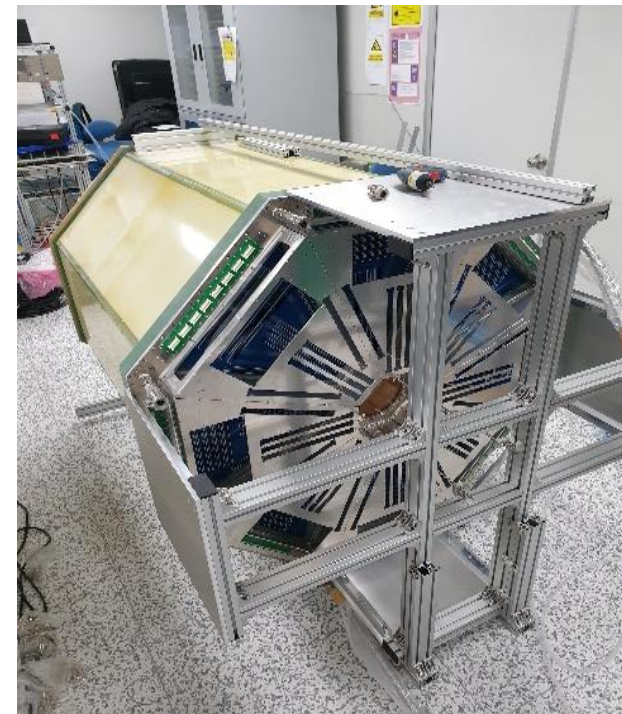
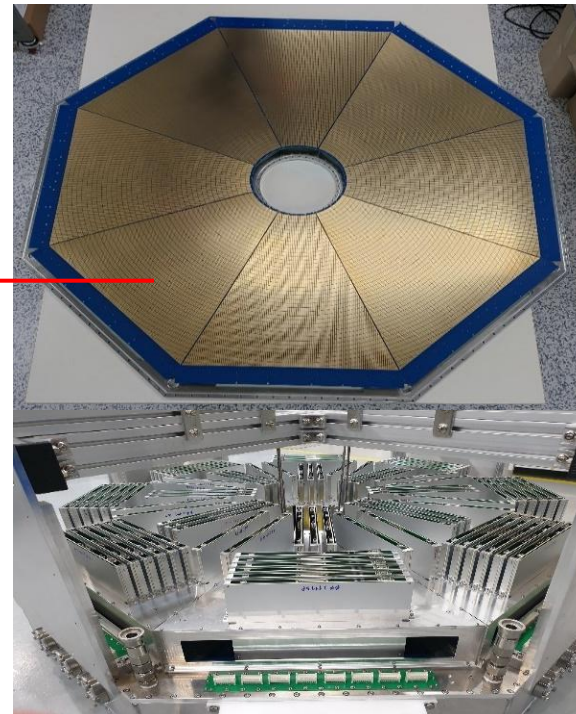
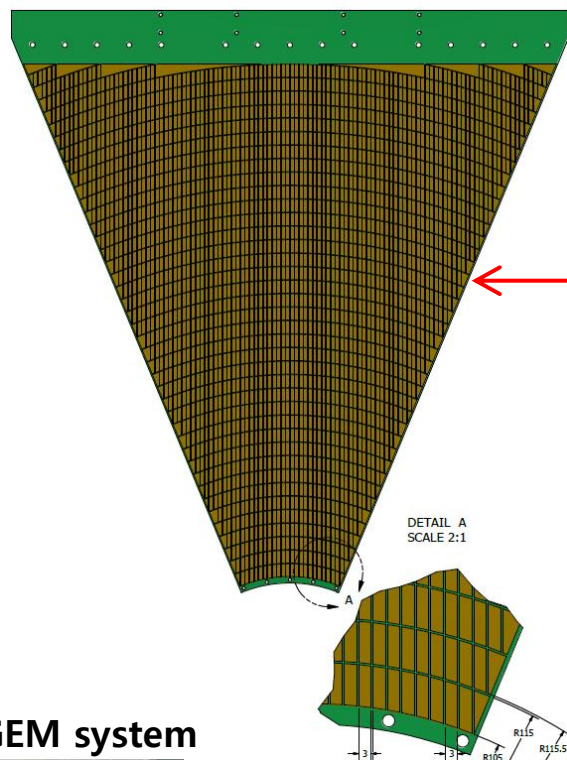
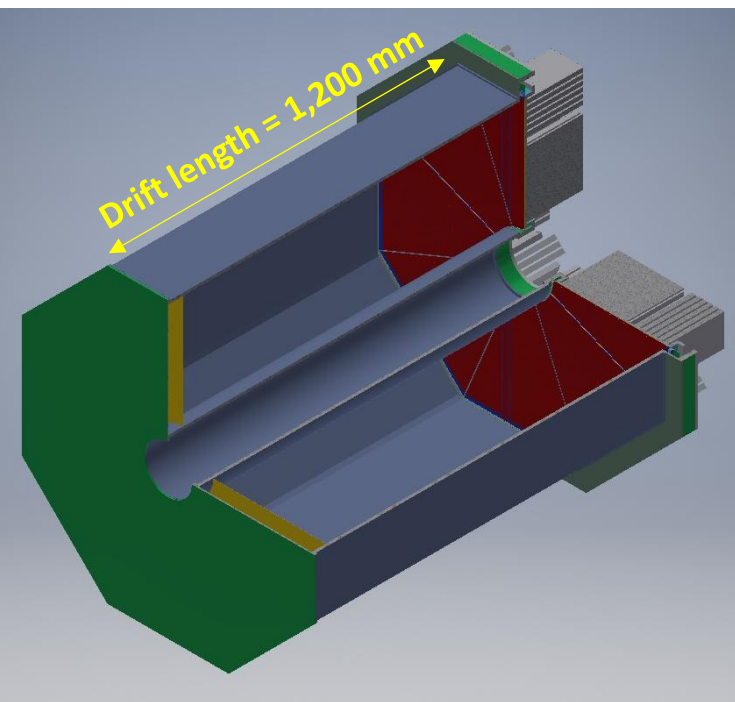
- Manufactured by tesla Engineering Ltd., UK
- Installation completed at RAON in 2021



TPC: Performance test with prototype

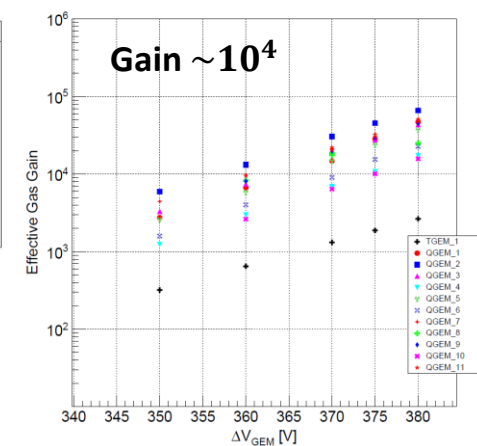
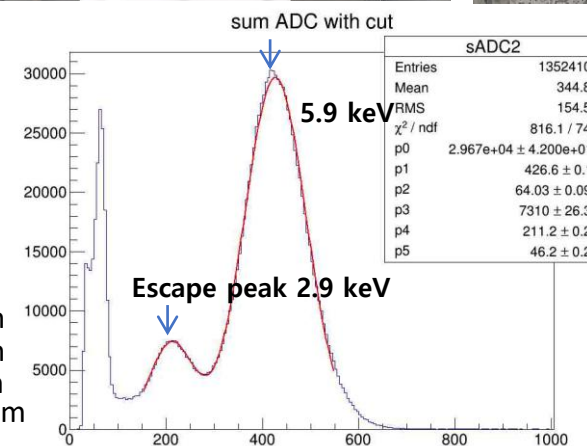
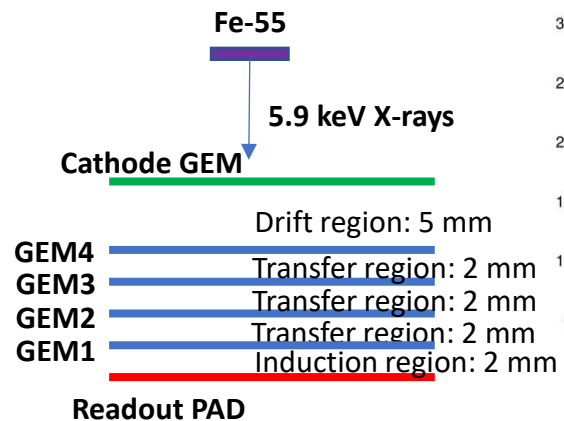
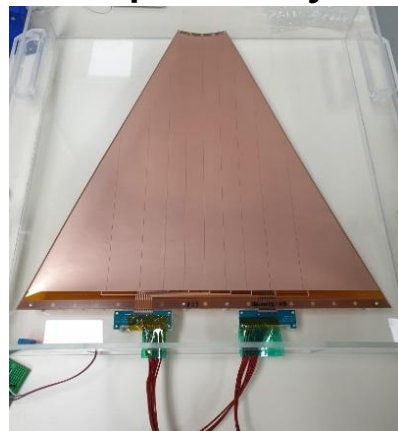


TPC: Construction of real detector



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

Quadruple GEM system

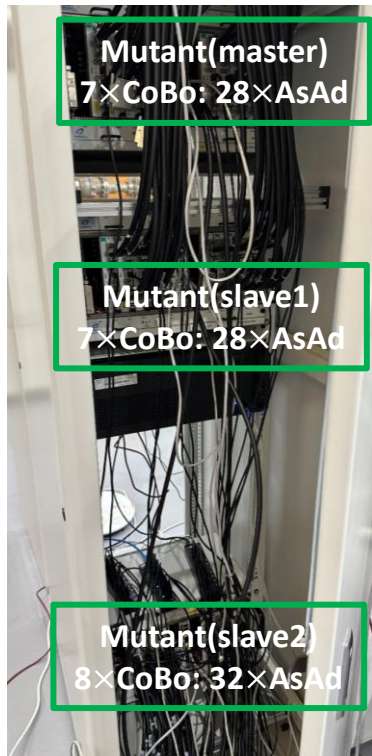


TPC: Drift velocity measurement

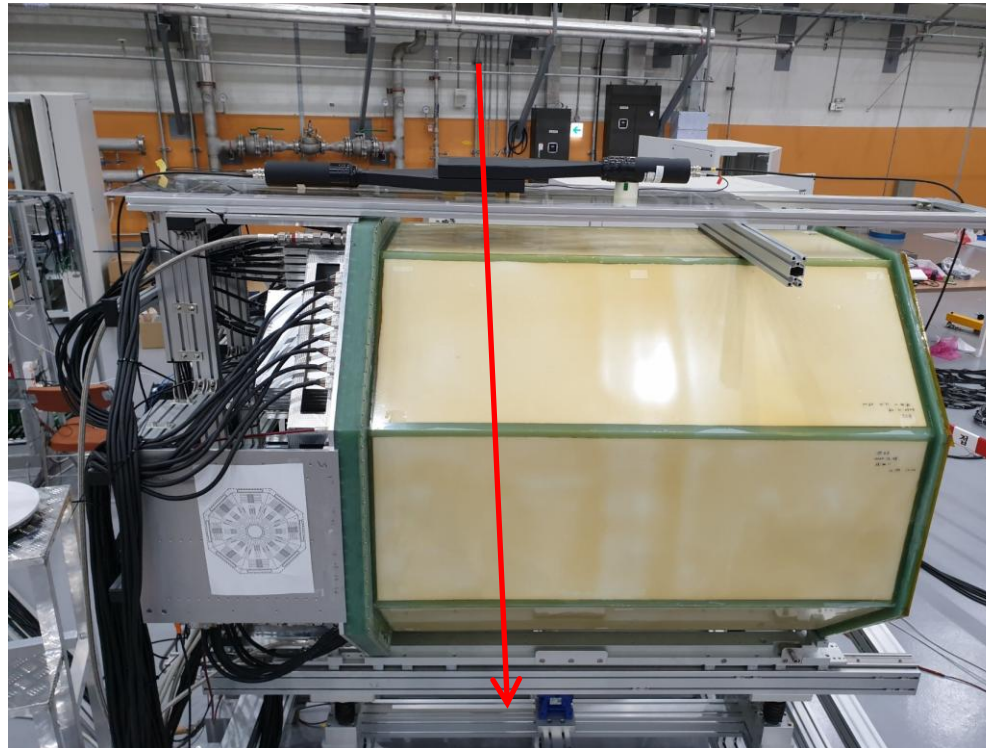
Y.J. Kim et al.,
JKPS 87, 670 (2024)

- Cosmic muon trigger
 - Coincidence of two scintillators (scintillator size: 20 x 20 cm² each)
 - Trigger positions at 30, 60 and 90 cm with the drift fields of 115, 125 and 135 V/cm

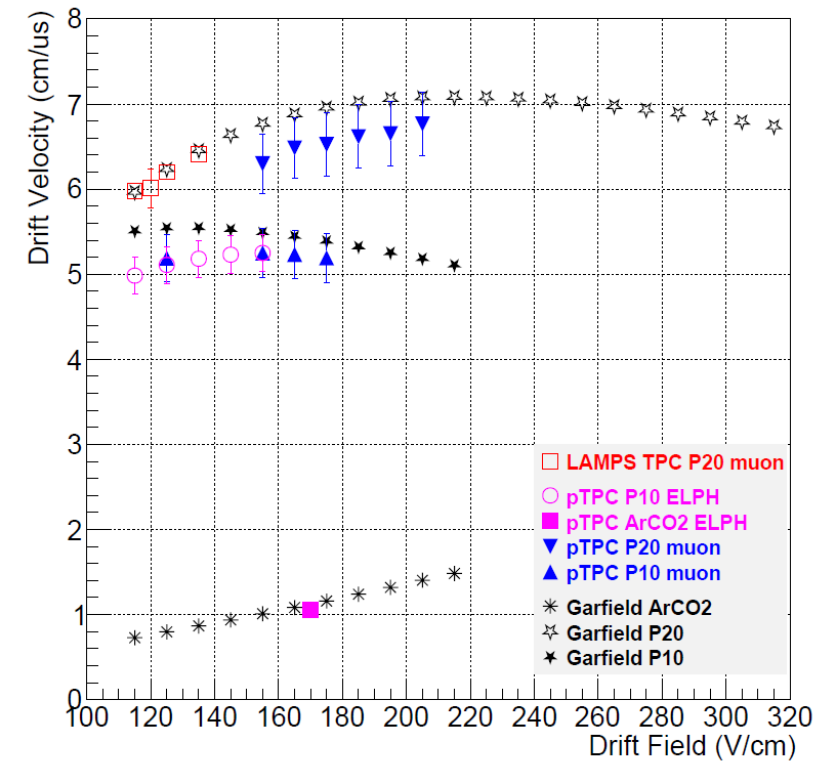
GET



Cosmic muon test

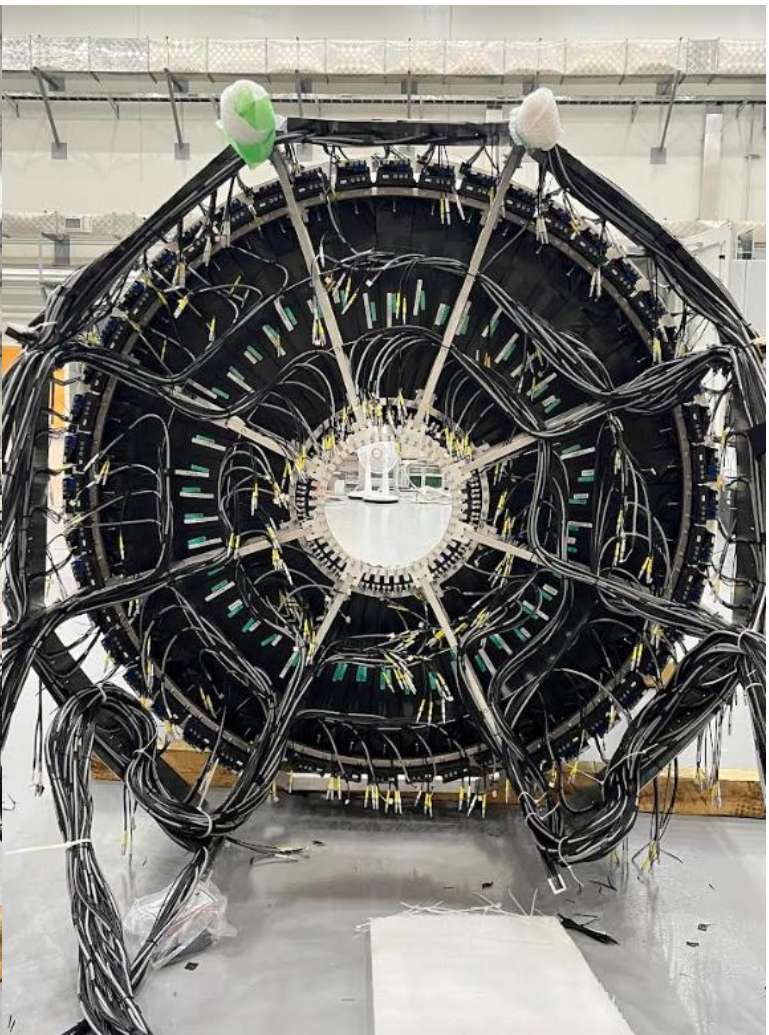
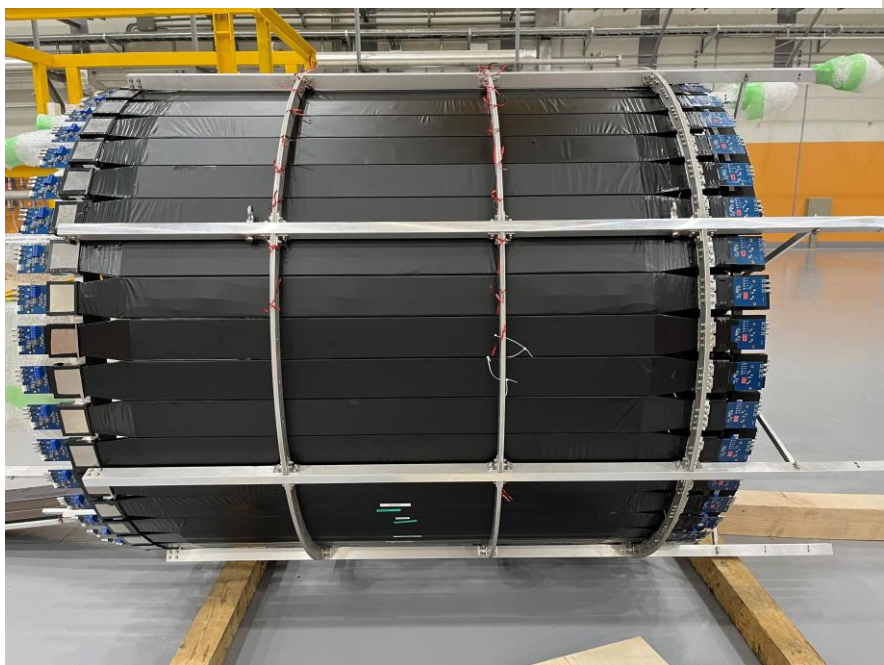


Drift velocity data



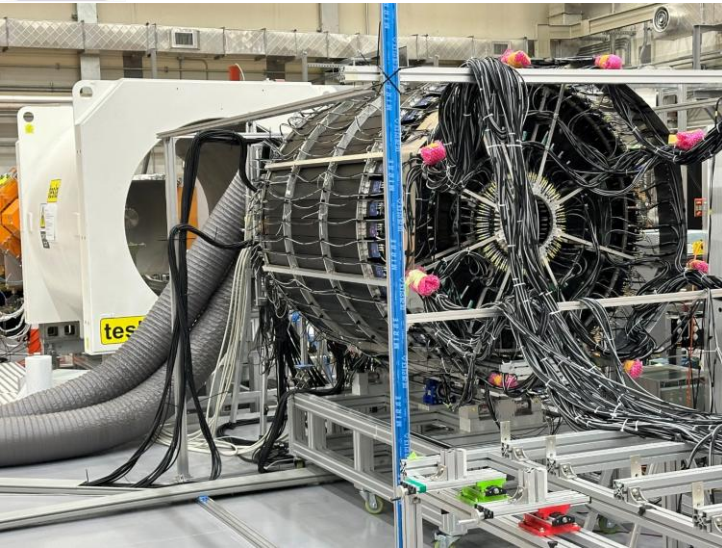
BTOF/FTOF

- Surrounding TPC for measuring the time-of-flight and providing trigger
- Number of scintillators & dimensions:
 - BTOF: (48) 1500 X 90 X 10 mm³ each
 - FTOF: (48) 500 X (90, 24) X 5 mm³ each
- MPPC readout from both ends
- Installation completed in 2022

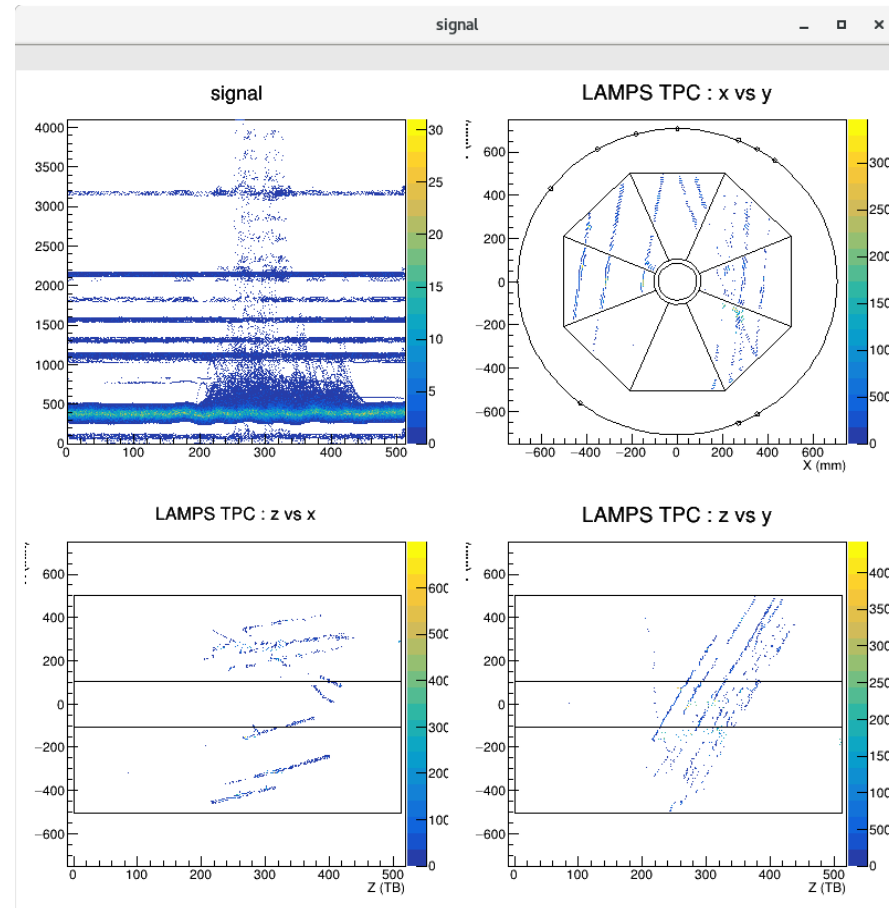
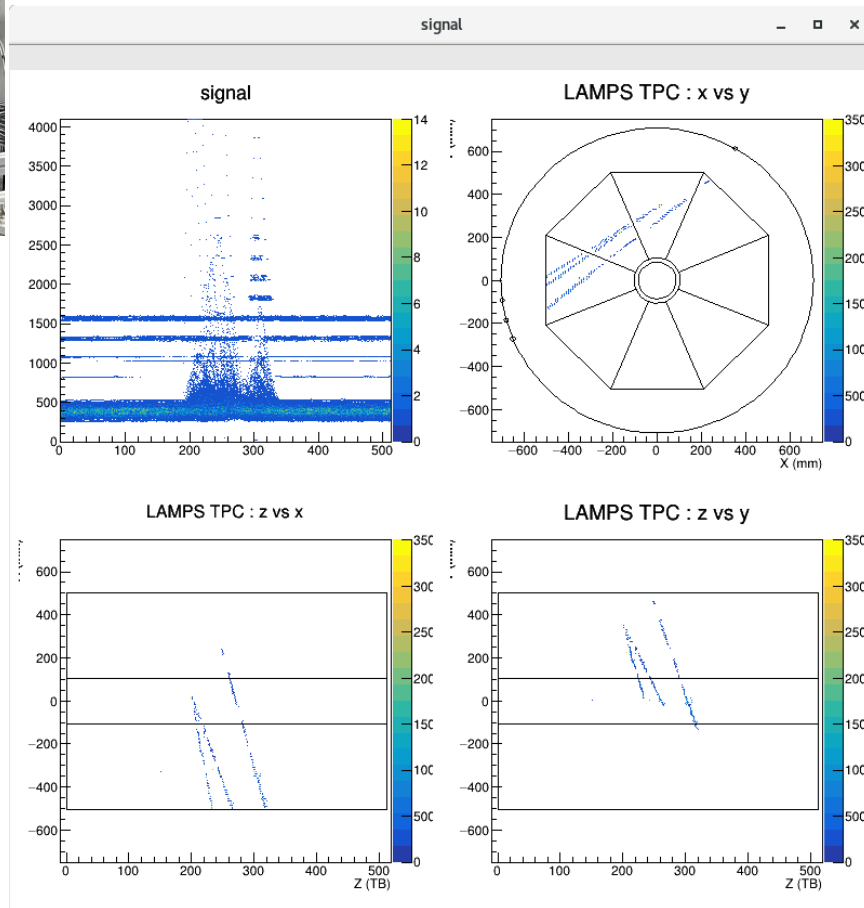
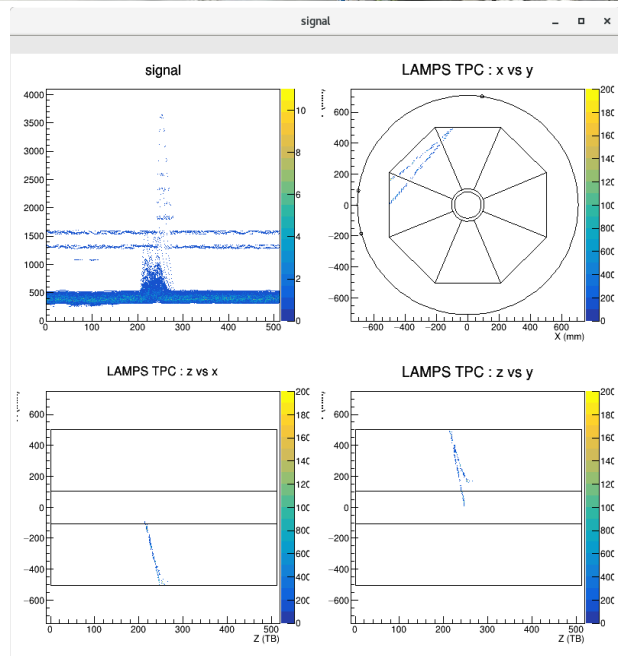




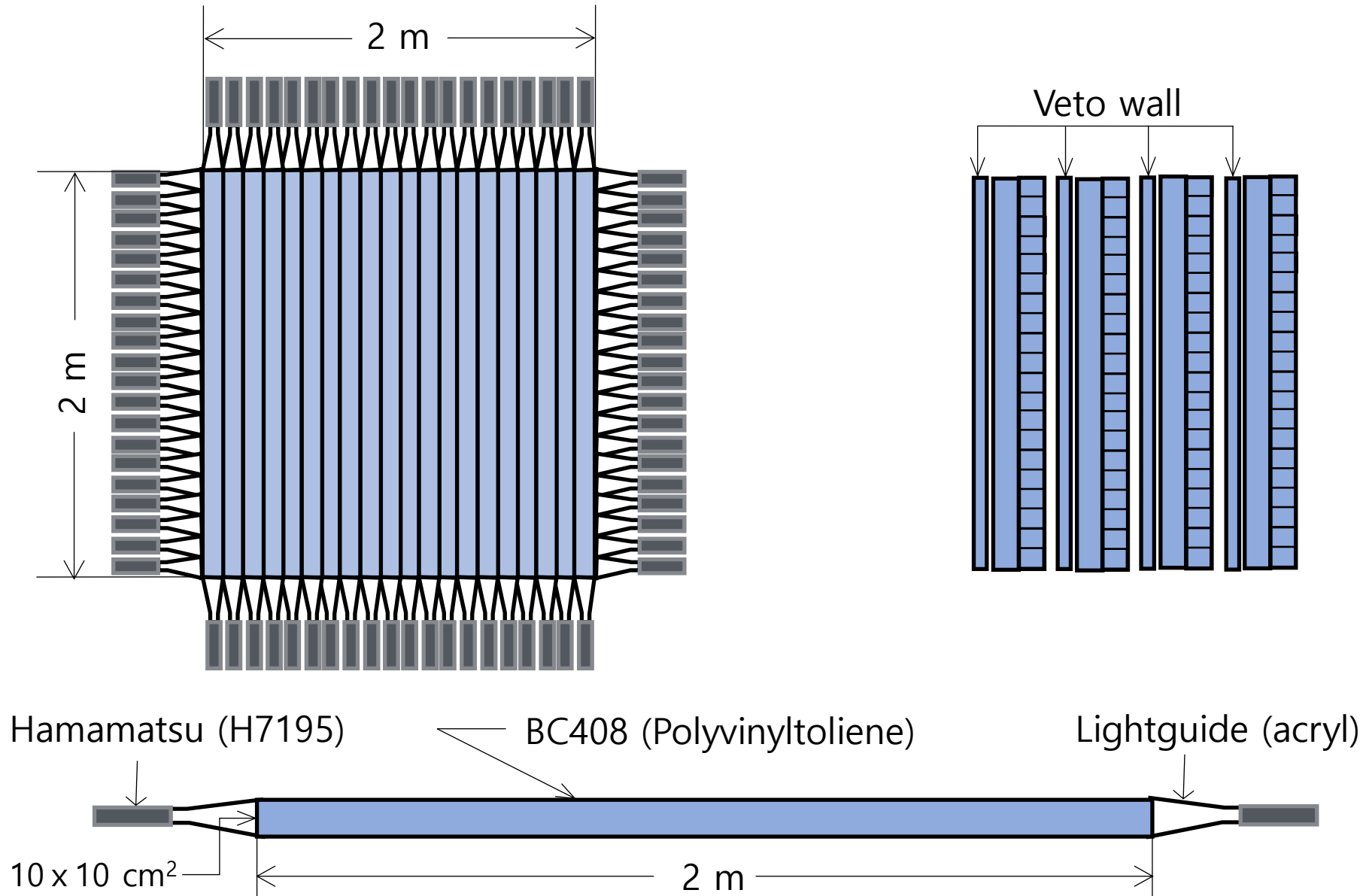
TPC+BTOF/FTOF: Cosmic test



- 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

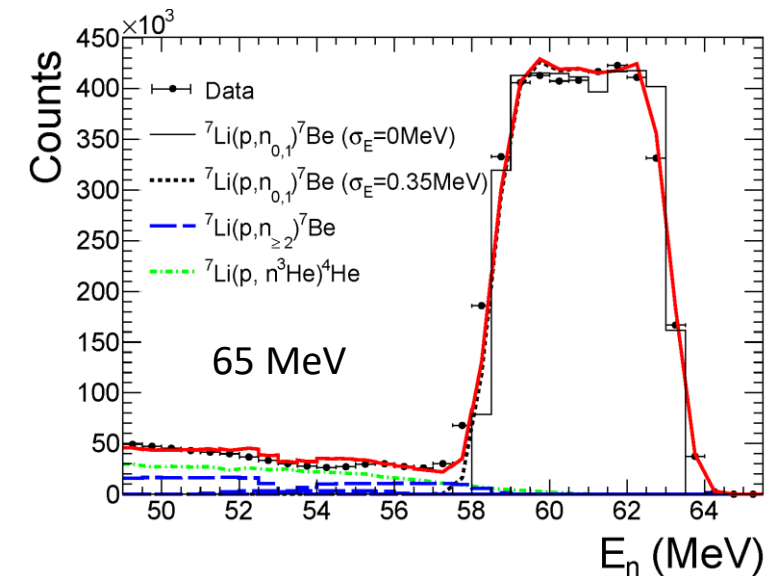
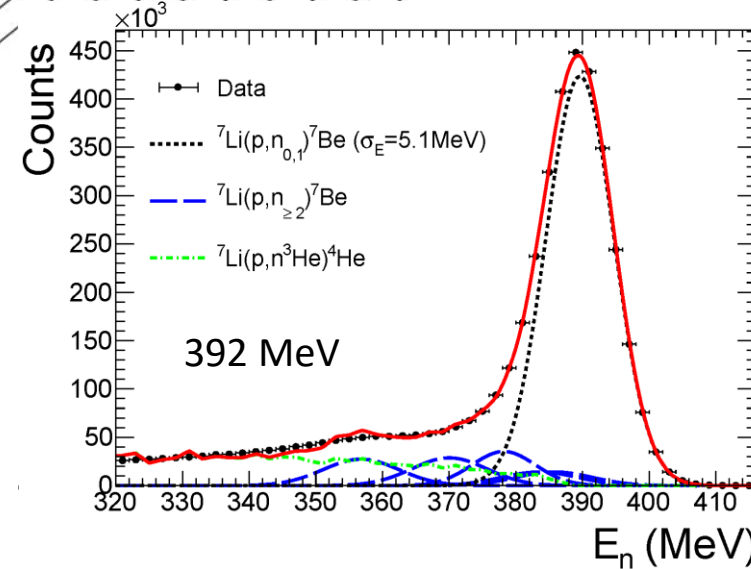
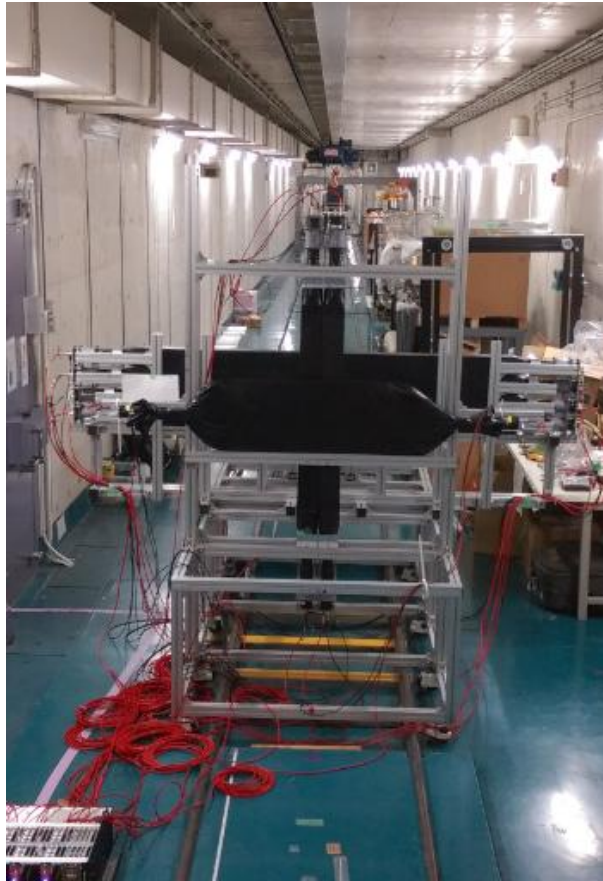
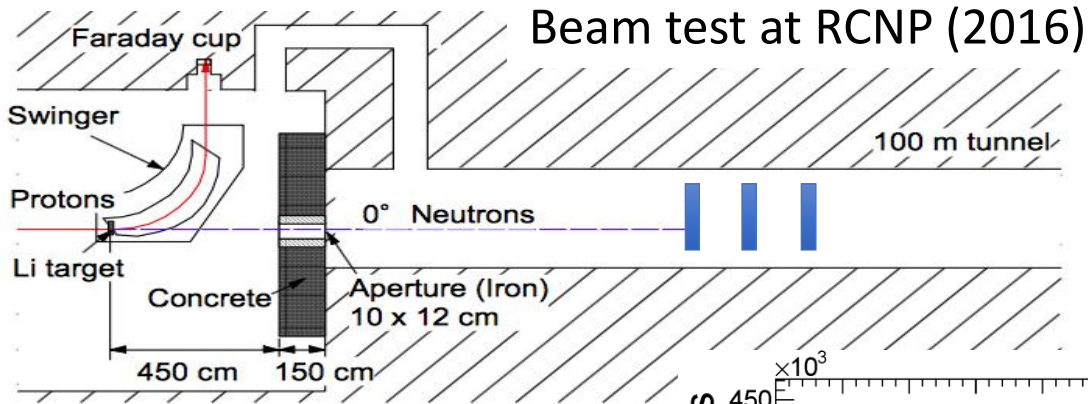


NDA: Performance test with prototype

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

● Beam specifications

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



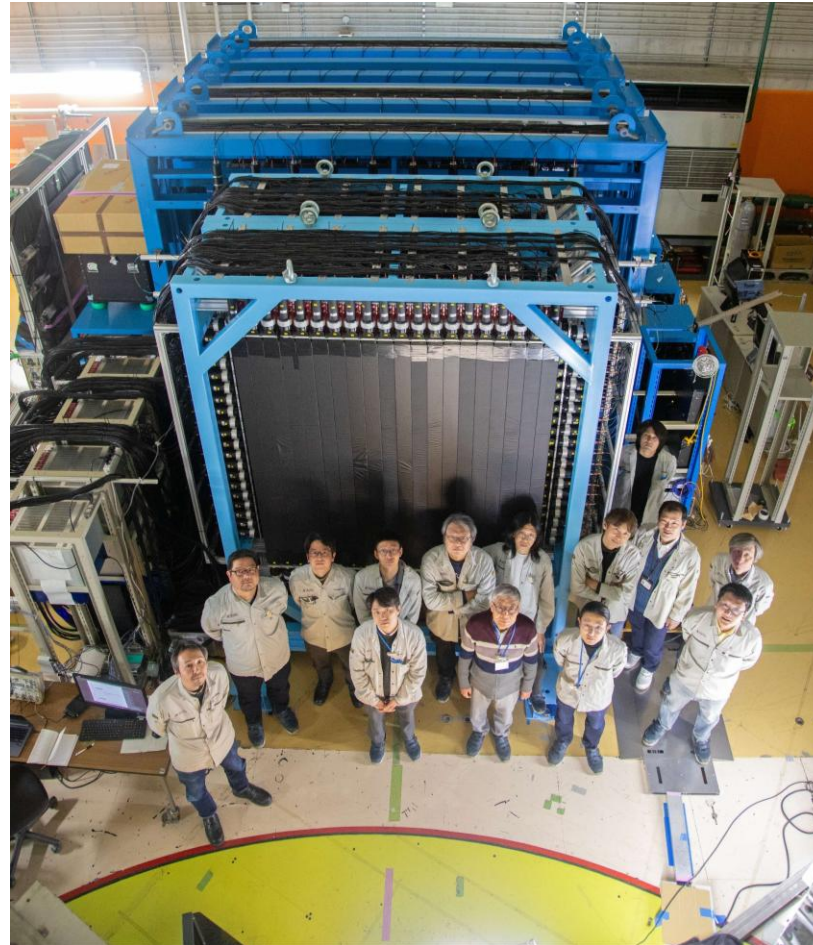
- Significant energy-loss effect in the Li production target at 65 MeV
- Energy resolution (FWHM): 3.1% @ 392 MeV, 1.3% @ 65 MeV
- (Cosmic-ray test) Time resolution(FWHM): 309 ps, Position resolution(FWHM): 4.8 cm

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 was moved to the SAMURAI spectrometer at RIBF in the end of 2025.*



↑ Assembled detector system
at the Korea Univ. Lab.



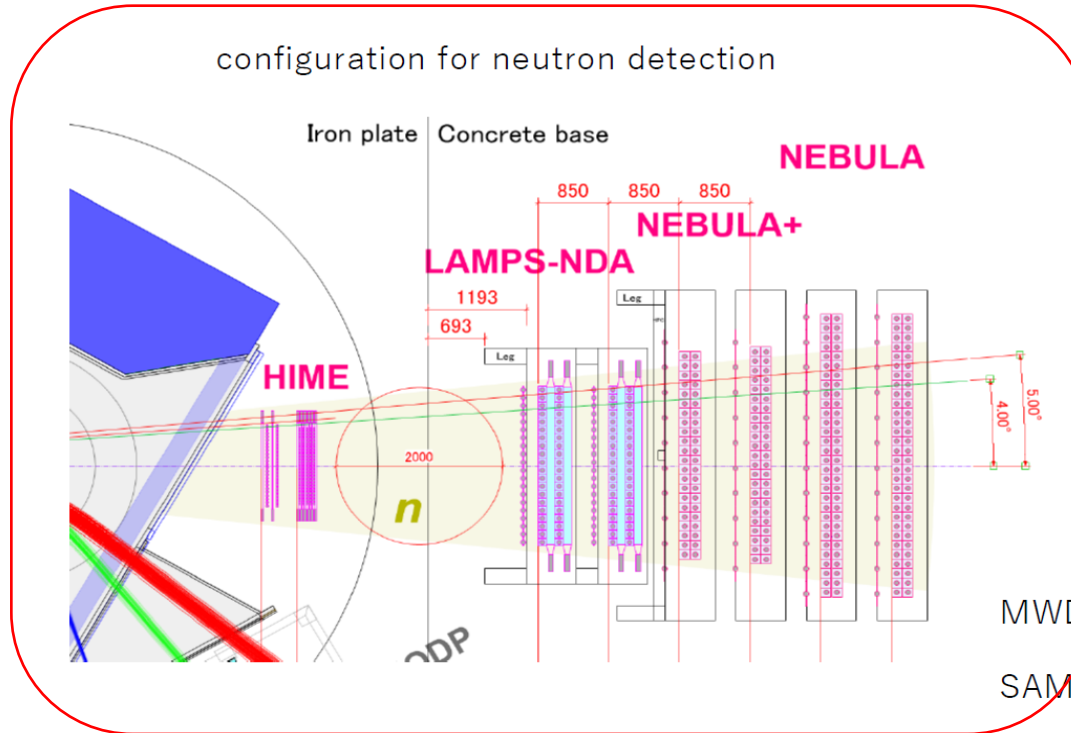
QCD Phase Diagram @ Darmstadt



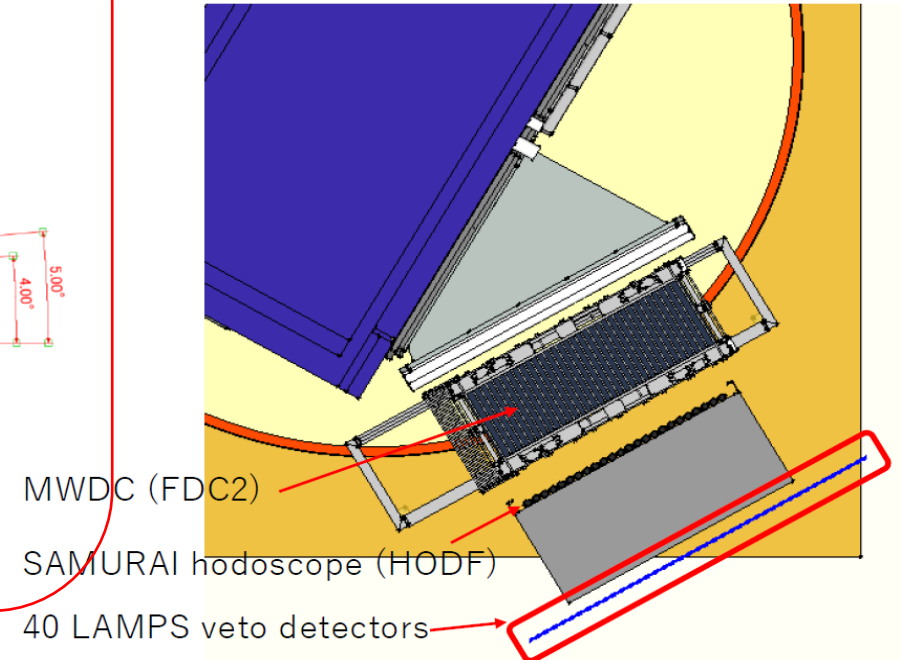
← ↑ NDA installed in the
SAMURAI spectrometer
at RIBF, RIKEN

Two possible setup at SAMURAI

Y. Kondo



configuration for charged particles
(under discussion)

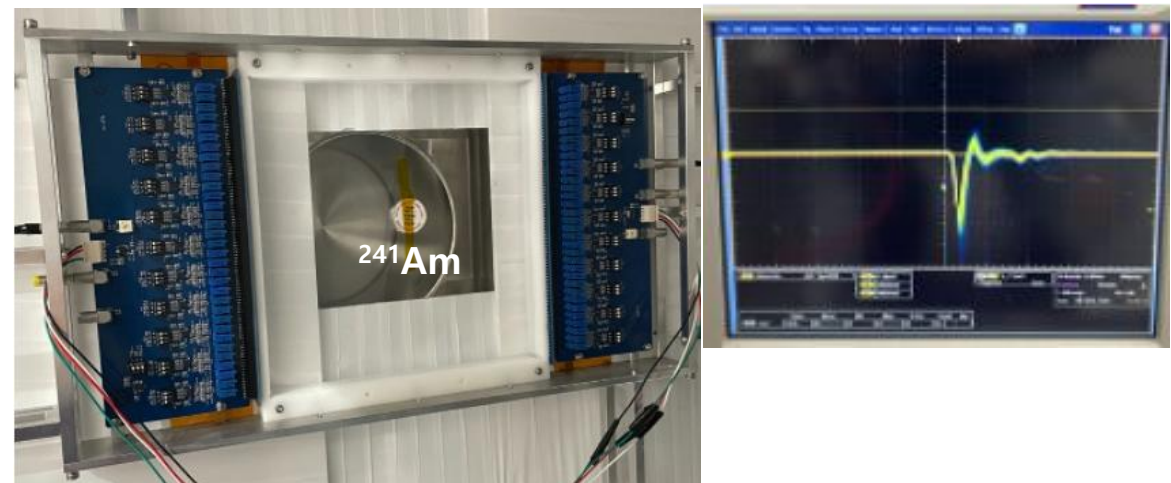
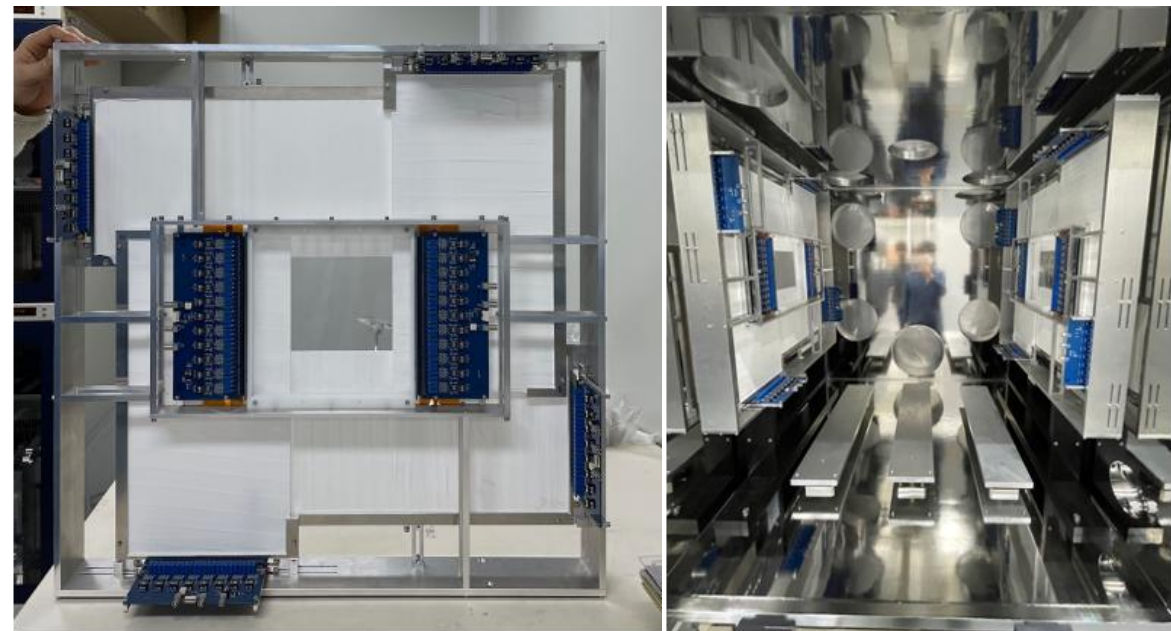


- NDA took the first physics data in May & June 2026.
 - S74: Multi-neutron correlations (K. Miki, M. Duer)
 - S55: nn scattering length (T. Aumann)
 - NDA data looks good: Detailed calibration is in progress

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: $210 \times 210 \times 0.2$ mm³ (Active area: 200×200 mm²)
 - Veto: $410 \times 210 \times 5$ mm³ (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 (²⁴¹Am) test
 - Full system installed in the vacuum chamber
 - $\sigma_t \sim 92$ ps

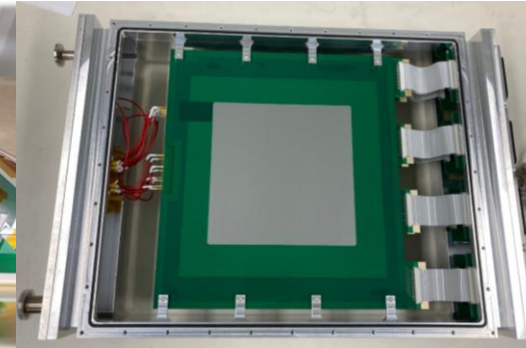
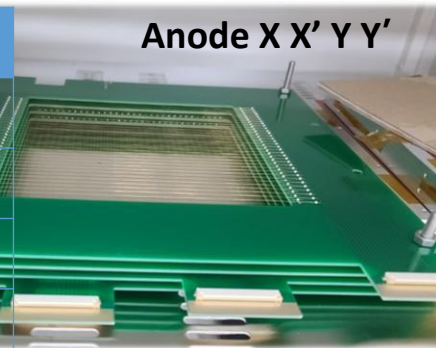


BDC (Beam drift chamber)

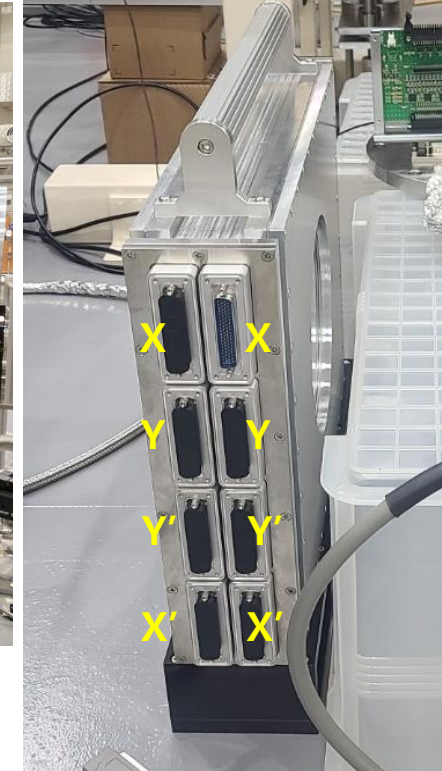
H. Kim et al., JINST 19, P12008 (2024)

Parameter	Value
Anode wire	ϕ 20 μ m Au-W
Potential wire	ϕ 80 μ m Cu-Be or Au-W
Cathode	2 μ m-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 ₄ H 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 μ m Al-mylar (up to 20 kPa) 50 μ m Al-mylar (up to 50 kPa)

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



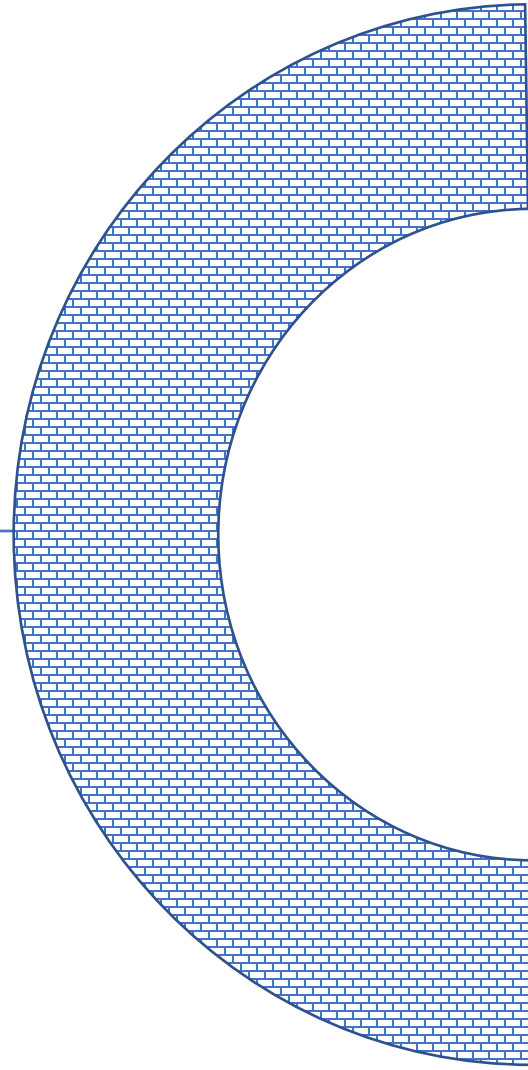
BDCs in the beam diagnostic vacuum chamber





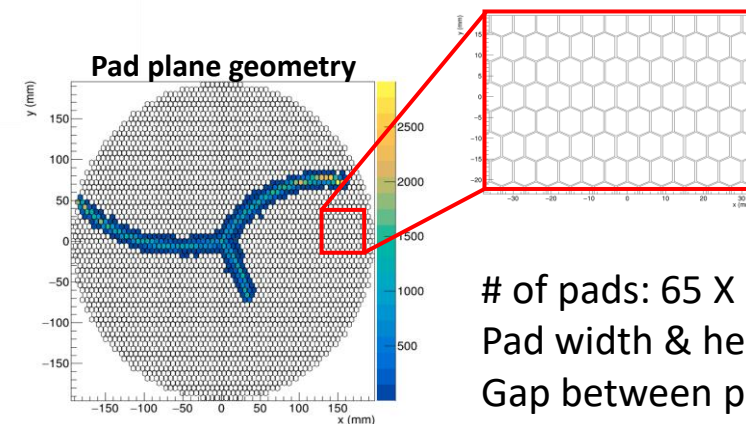
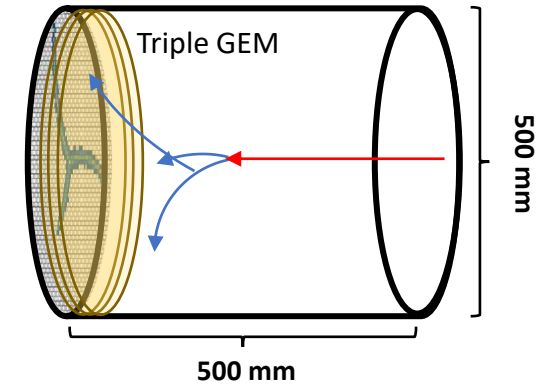
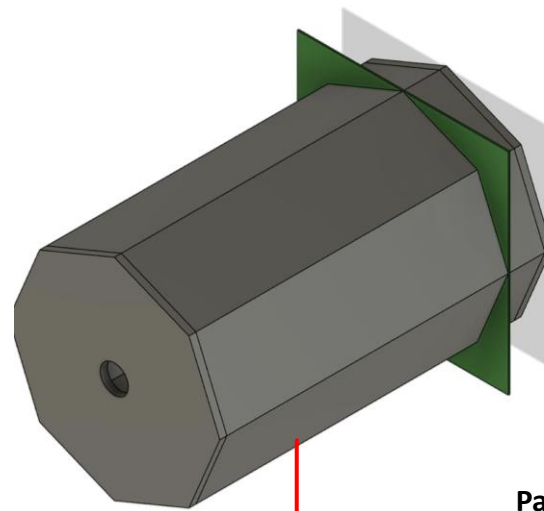
Part 3.

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: $65 \times 65 = 3,300$
 Pad width & height: 6 mm each
 Gap between pads: 0.5 mm

AT-TPC: Beam test with prototype

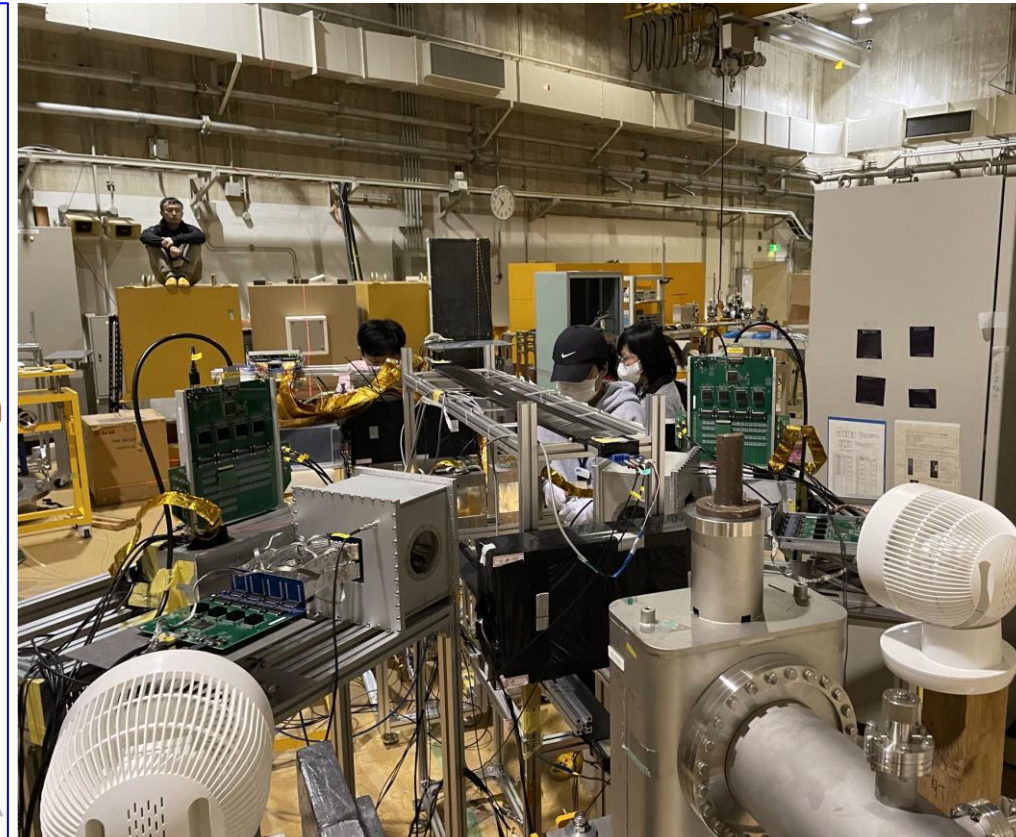
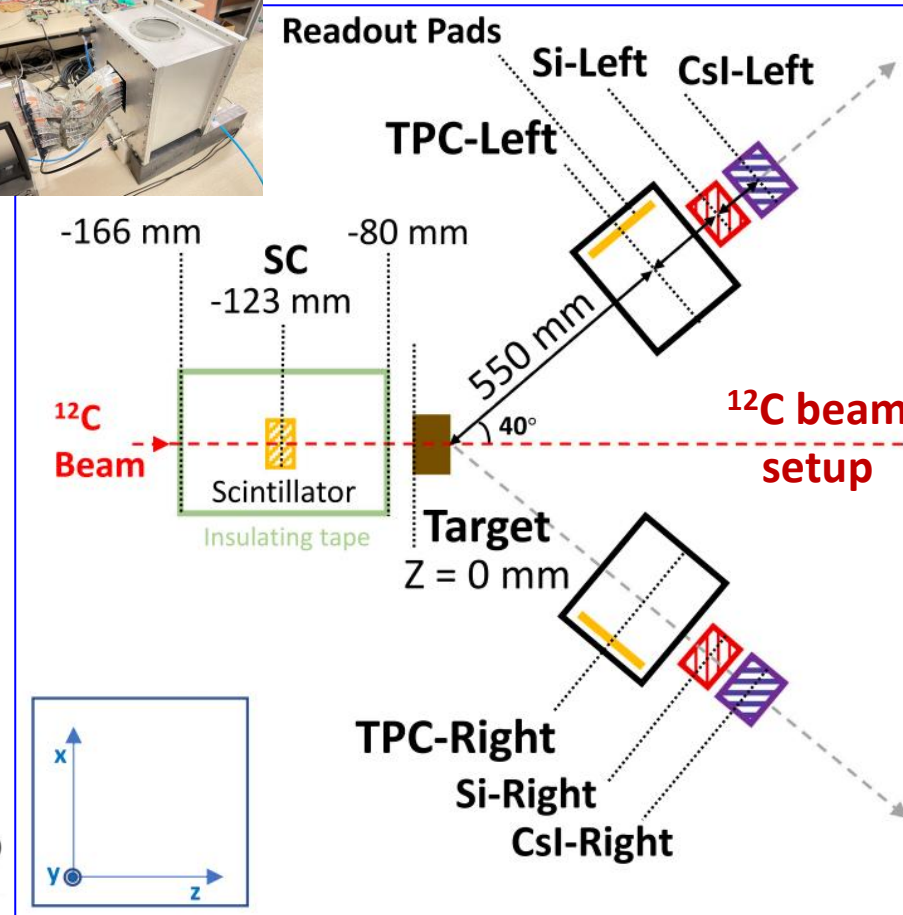
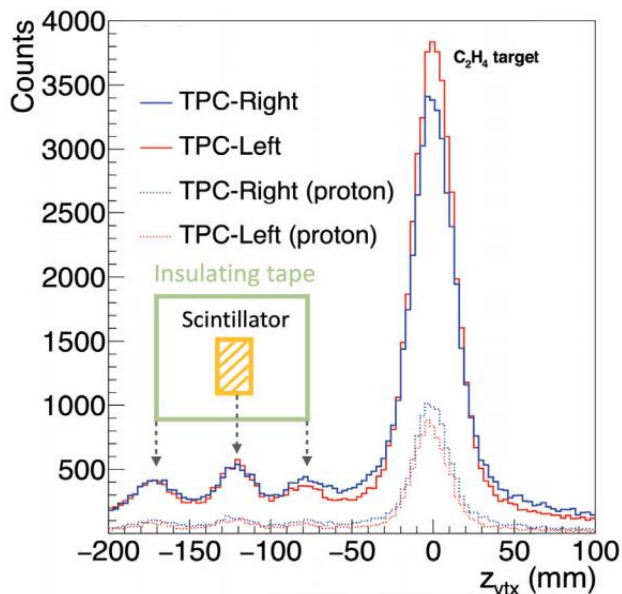
- Beam test of two prototypes at HIMAC in Japan in Feb. 2023
 - Beams: p @ 100 MeV, ^{12}C @ 200 MeV/u, 10^6 ppp
 - Performance test for LAMPS detectors including AT-TPC
 - Analyzing $^{12}\text{C}(p,2p)$ Quasi-Free Scattering (QFS) events

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

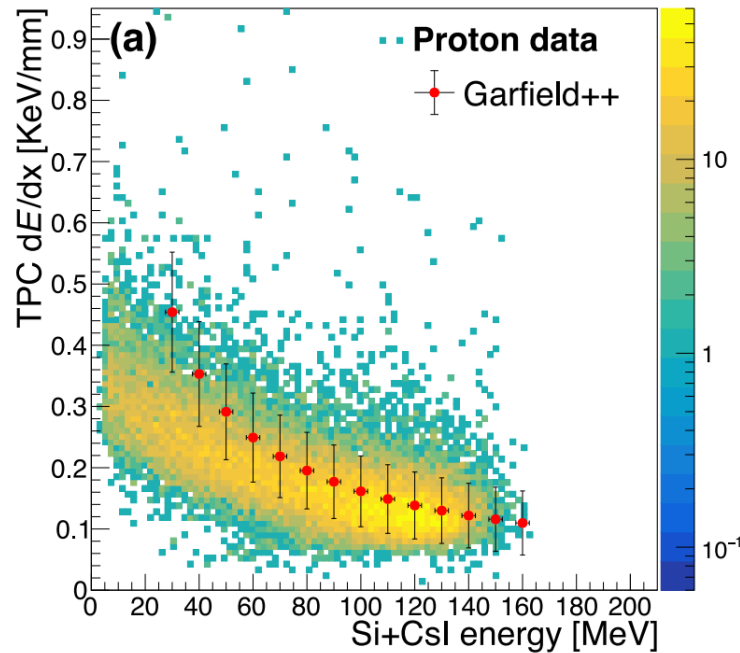
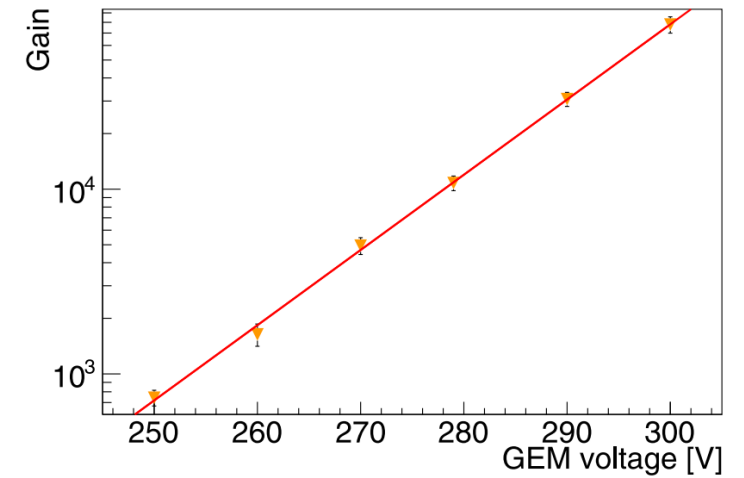
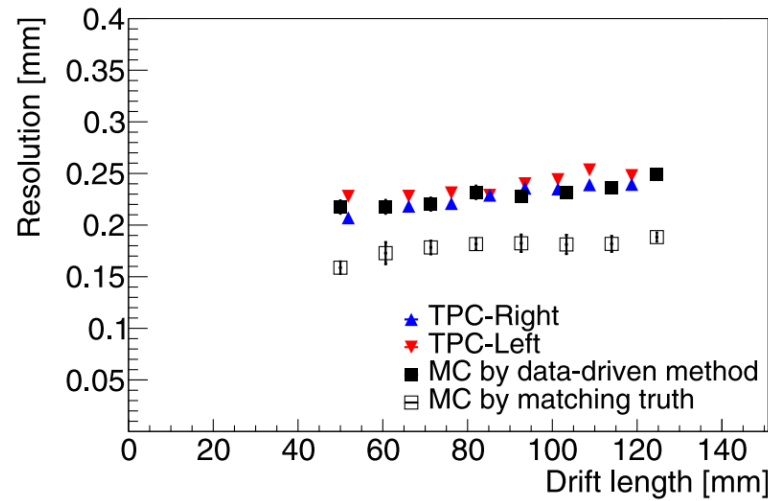
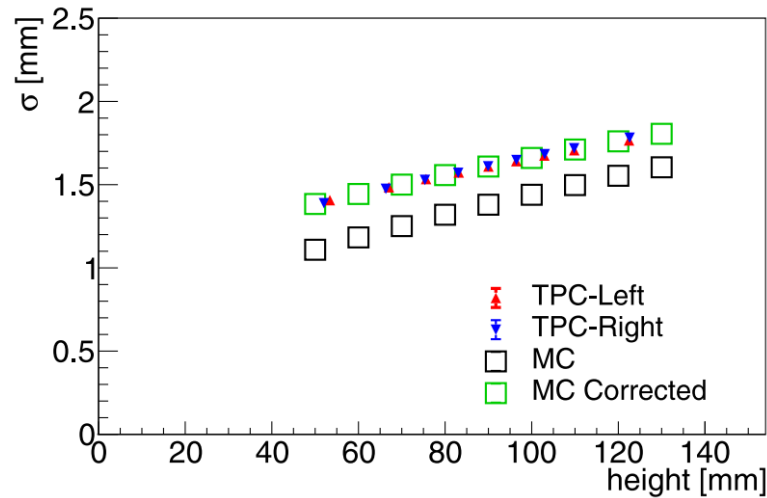
Prototype AT-TPC →



↓ Reconstructed vertex distribution by AT-TPC

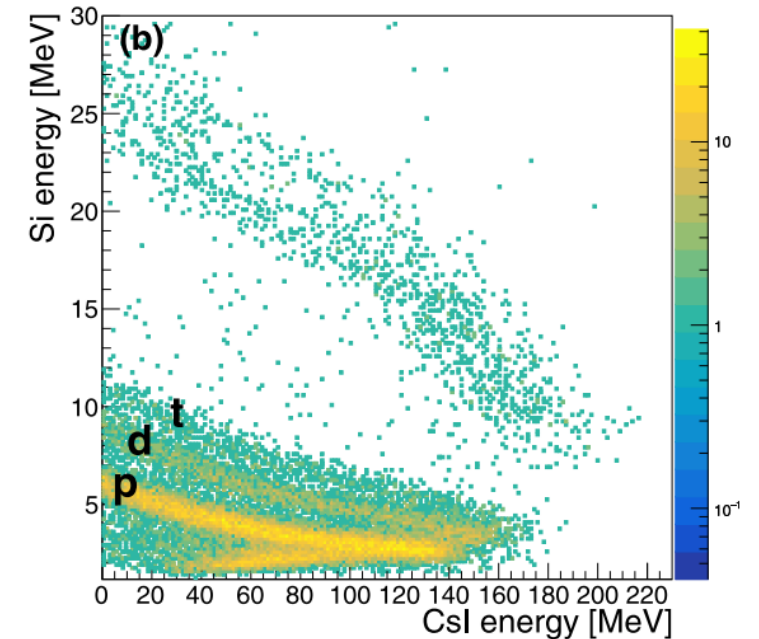


AT-TPC: Characteristics



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

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

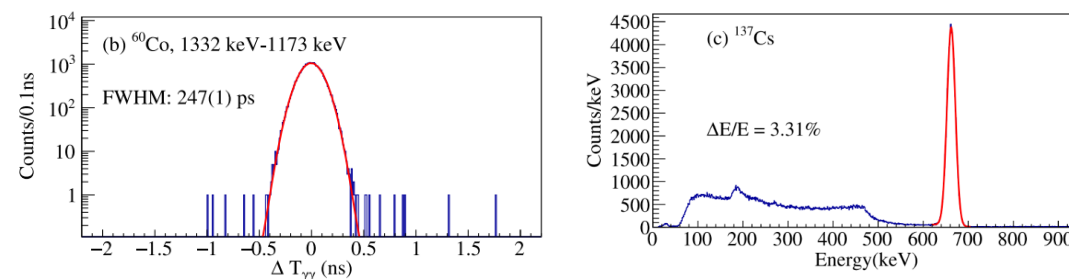


KHALA: Korea high-resolution array of LaBr_3

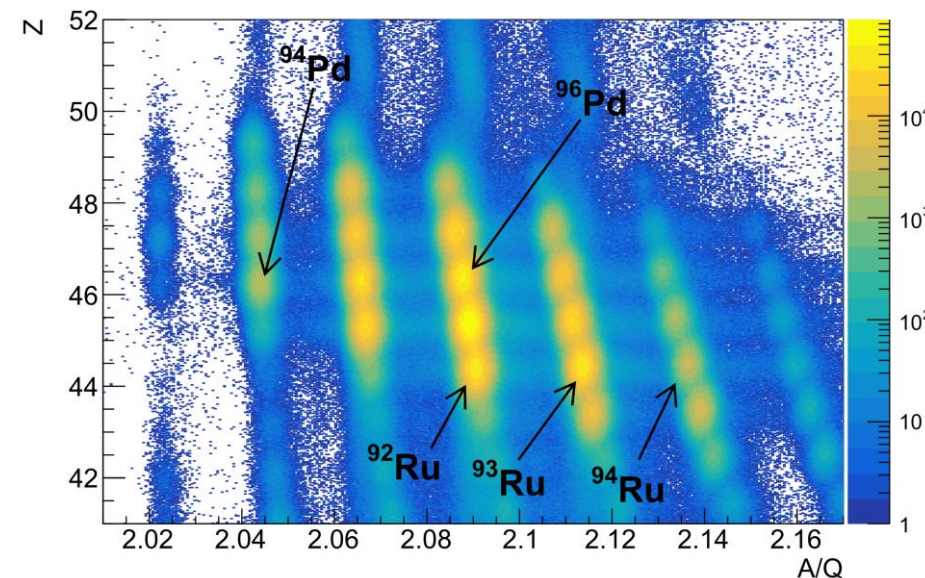
- $\text{LaBr}_3(\text{Ce})$ fast-timing γ -detector array
 - Total 36 $\text{LaBr}_3(\text{Ce})$ modules
 - $R_t < 250$ ps, $R_E < 3.5\%$ (FWHM)
- **IDATEN = KHALA (Korea) + FATIMA (Europe)**
 - The largest acceptance fast-timing γ -detector array
 - Commissioning experiment at RIBF in June 2024
 - The first U-beam campaign is foreseen in December 2026.



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



ZDS PID (preliminary)

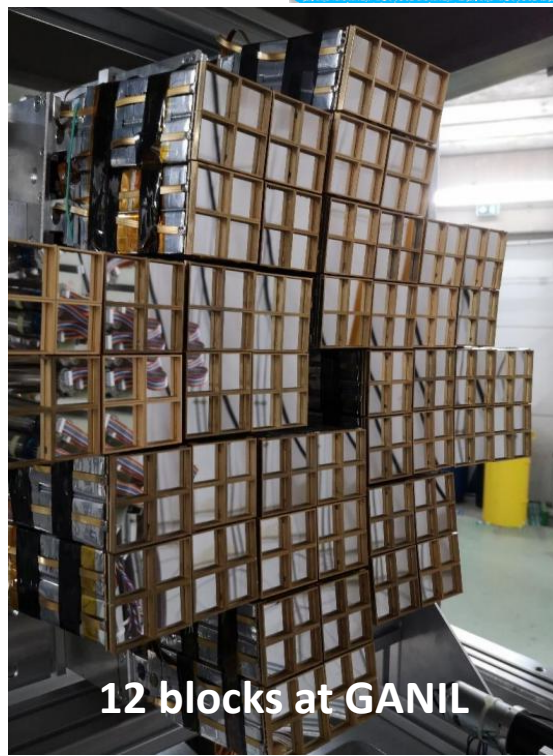
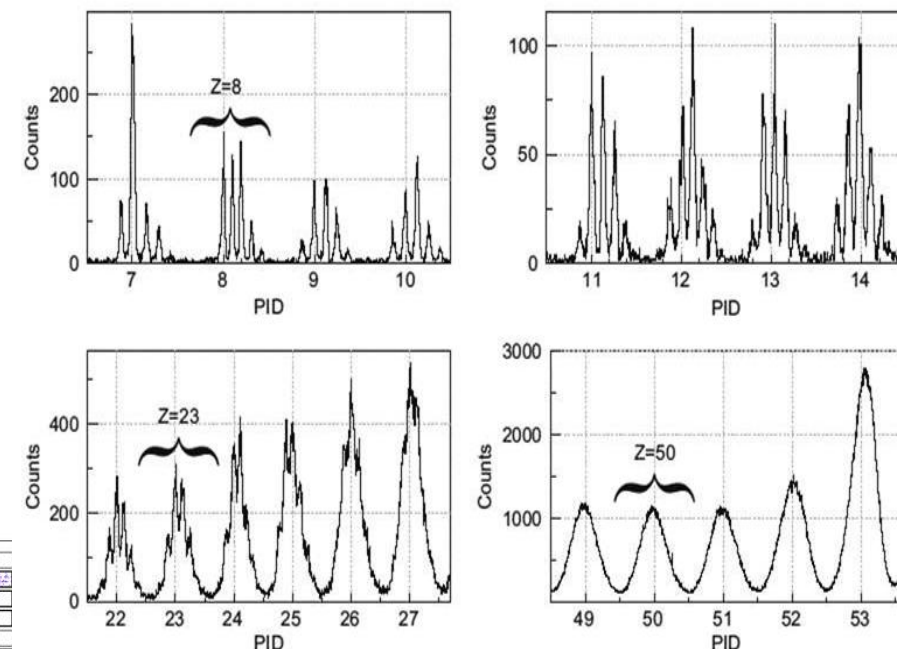
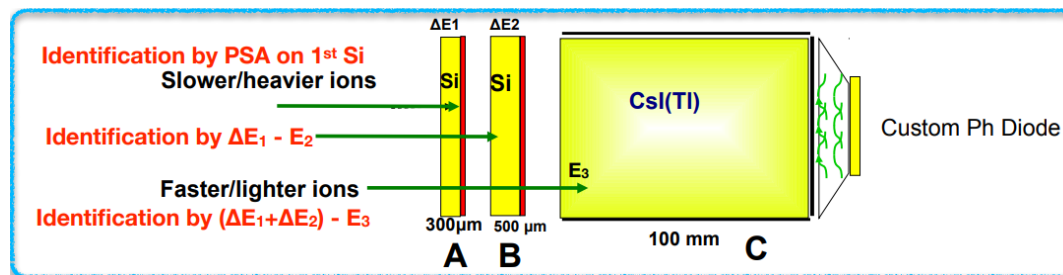


- The first physics paper was published!
 - Youngseub Jang et al. (Ph.D. thesis, Korea Univ.), “Yrast-state lifetimes in ^{94}Pd at the transition between the isoscalar and isovector coupling regimes”, PRC 114, 024342 (2026)

Si+Csl charged particle detector

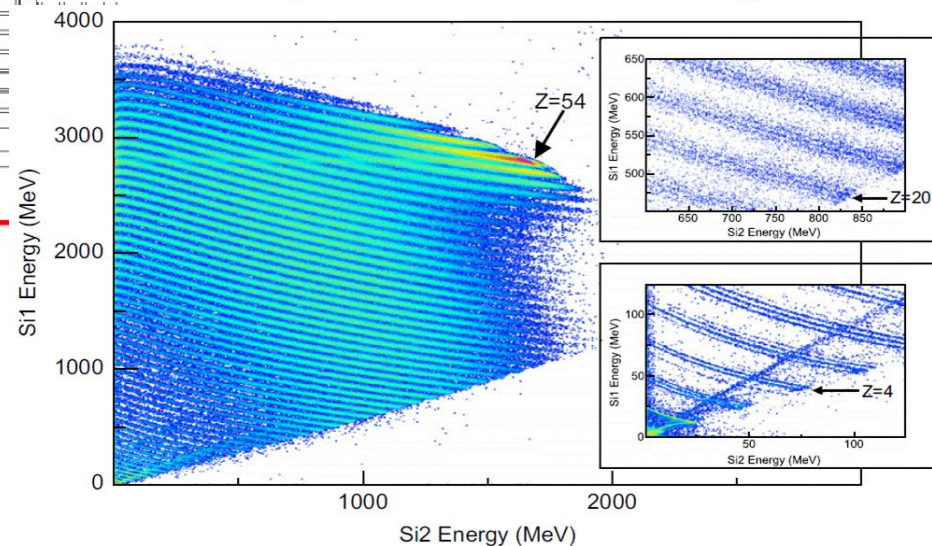
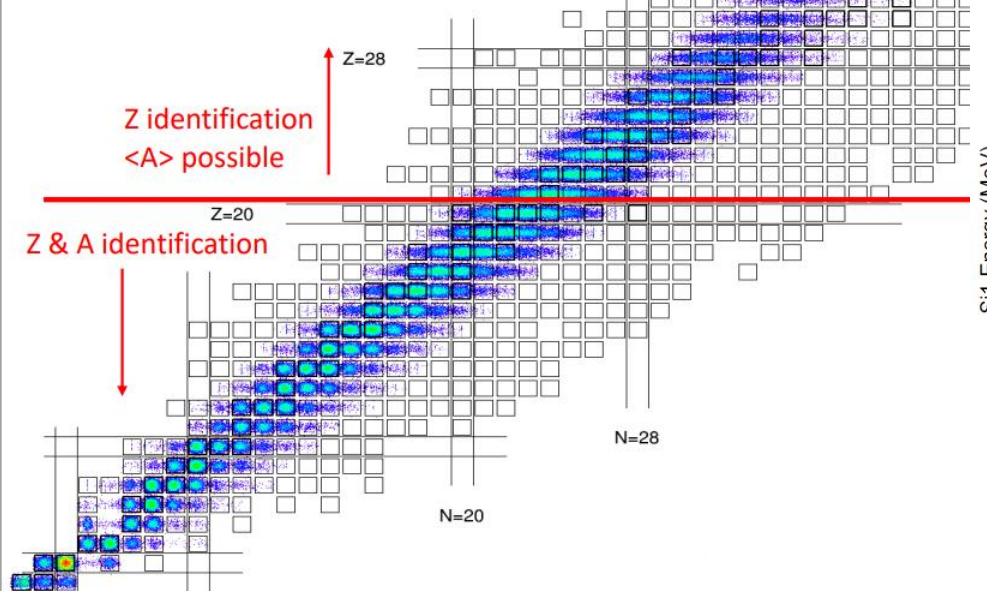
FAZIA, EPJA 50, 47 (2014)

- FAZIA: One block consists of 16 Si₁+Si₂+Csl telescopes with a cross-section of 2 × 2 cm².
 - New Si chips are being developed in Korea.
 - New FEB electronics with modern components are manufactured in Korea.

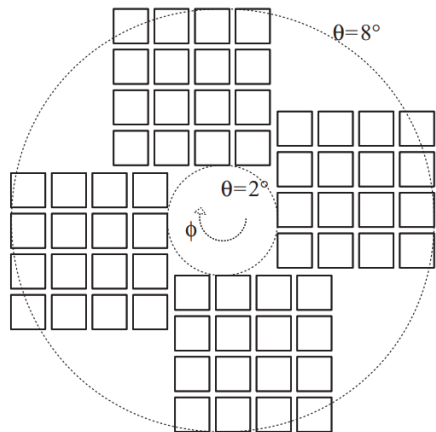
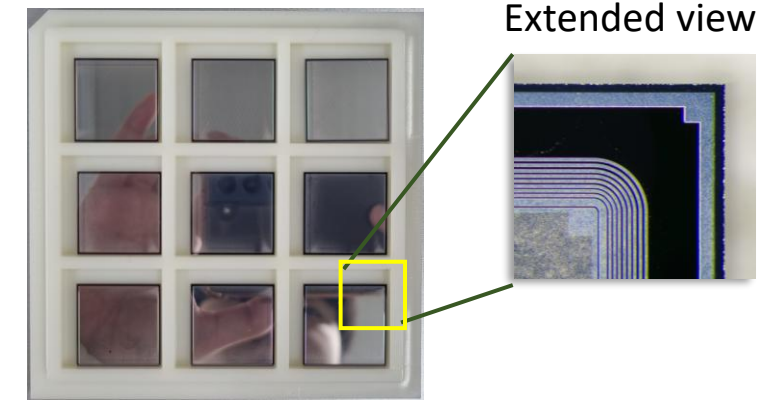
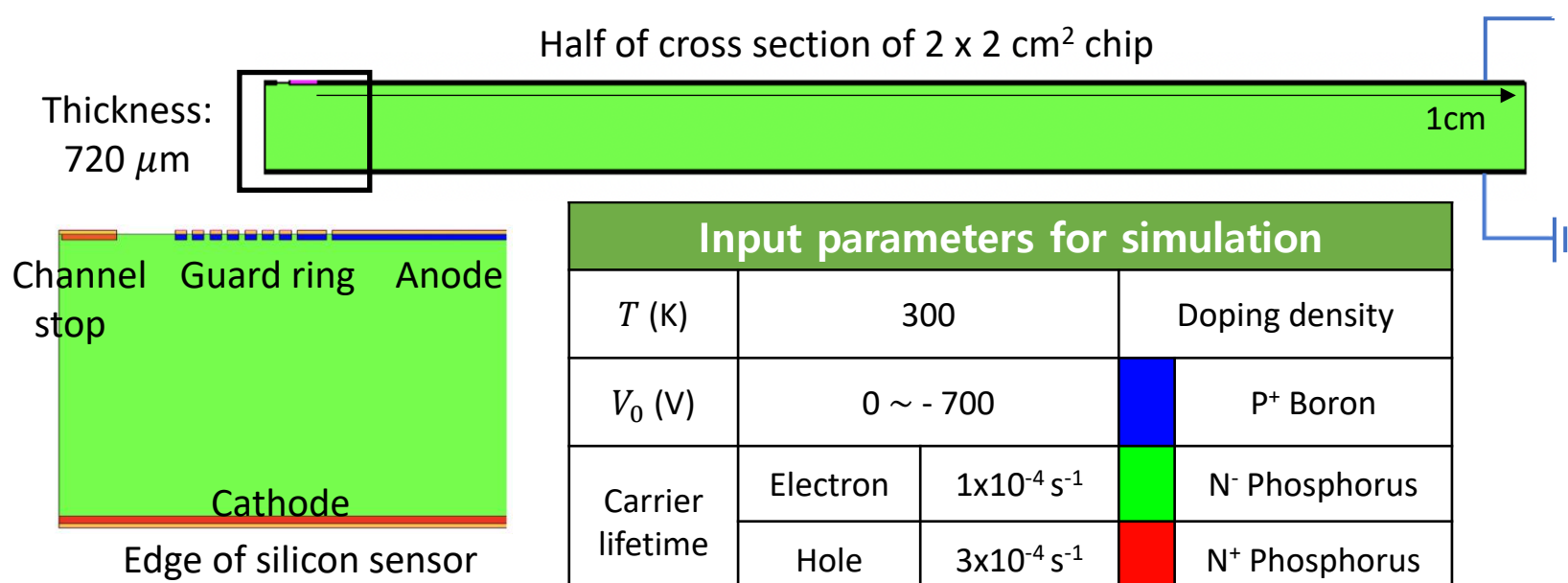


12 blocks at GANIL

$^{80}\text{Kr} + ^{40-48}\text{Ca}$ at 35 AMeV in the IsoFAZIA Expt. @ LNS in 2015



● Design of PiN sensor using TCAD: Simulation setup

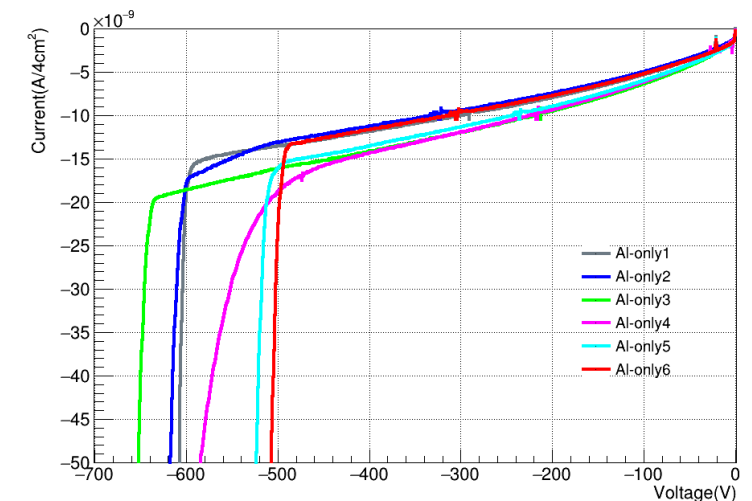


→ Results

- 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 middle of September 2026.





Summary

- Purpose of LAMPS
 - Detailed investigation of *nuclear equation of state (EoS) and symmetry energy*
 - We will also use LAMPS for the new features of nuclear structure and dynamics.
- 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 was done.
 - 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 SAMURAI experiments at RIBF.
 - Exploring the opportunity to use LAMPS TPC for the EoS experiment at FRIB or other Labs.
 - KHALA LaBr3 system is being used for the IDATEN experiment at RIBF.
- Any idea using the LAMPS detector elements are welcome!

피터의 80세 생신을 축하 드립니다!

*My sincere congratulations to Peter
on his 80th birthday!*