2025 Korea-China Joint Workshop For Rare Isotope Physics

CsI Array Test for SUPER at RARiS

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- CsI(Tl) Introduction
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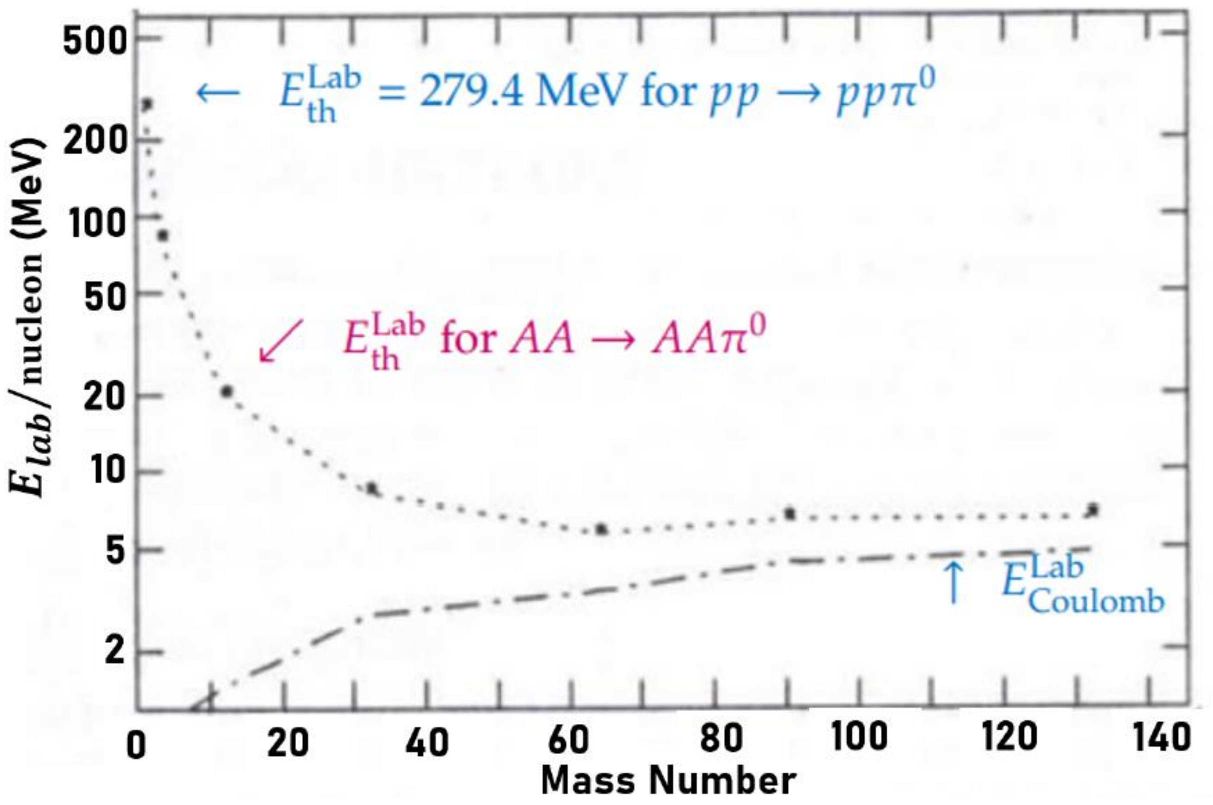
Pion production at Subthreshold Energy

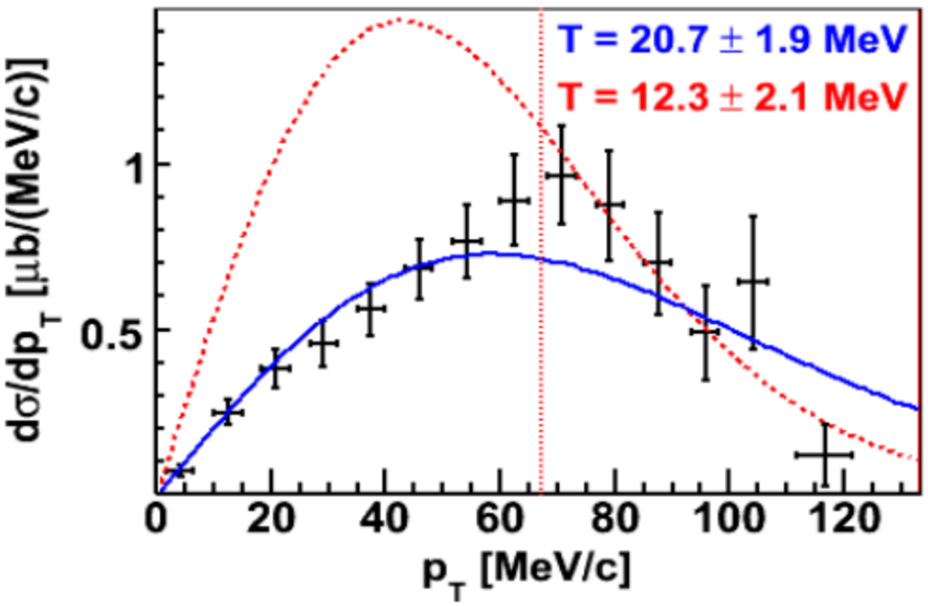
SUPER (**SU**bthreshold **P**ion production **E**xperiment at **R**CNP)



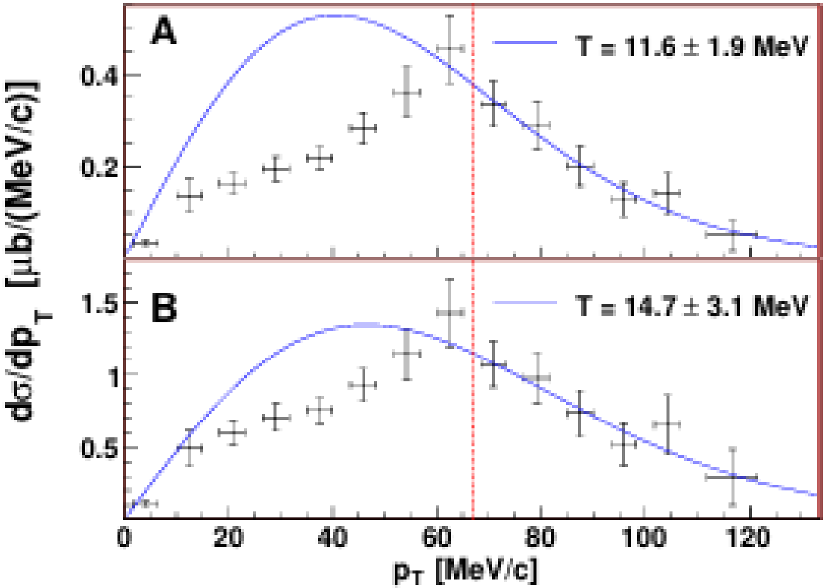
- According to the single NN collision model, π^0 production's threshold collision energy is at around **50 AMeV**.
- Below this threshold, π^0 creation relies on **cooperative motion** to convert sufficient energy into the π^0 mass.

Temperature and Transverse Momentum

^{181}Ta + ^{197}Au at 40 AMeV TAPS (GANIL)



K. Piasecki and T. Matulewicz, Acta Phys. Polonica B 41, 393 (2010)



Y. Schutz et al., Nucl. Phys. A622, 405 (1997)

$$\frac{d\sigma}{dP_T} \propto P_T\sqrt{E_T}\,\exp\left(-\frac{E_T}{T_0}\right)$$

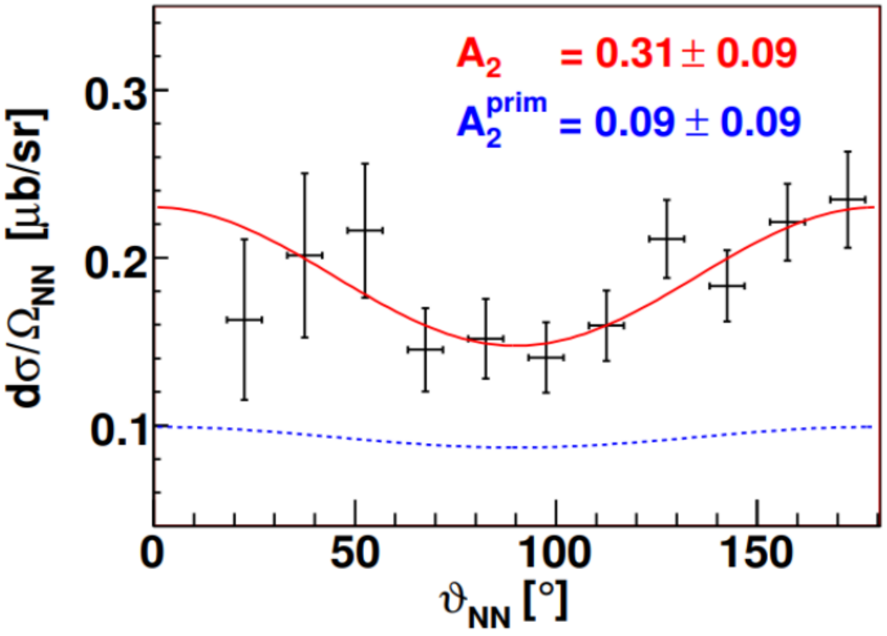
$$E_T = \sqrt{m_{\pi^0}^2 + P_T^2}$$

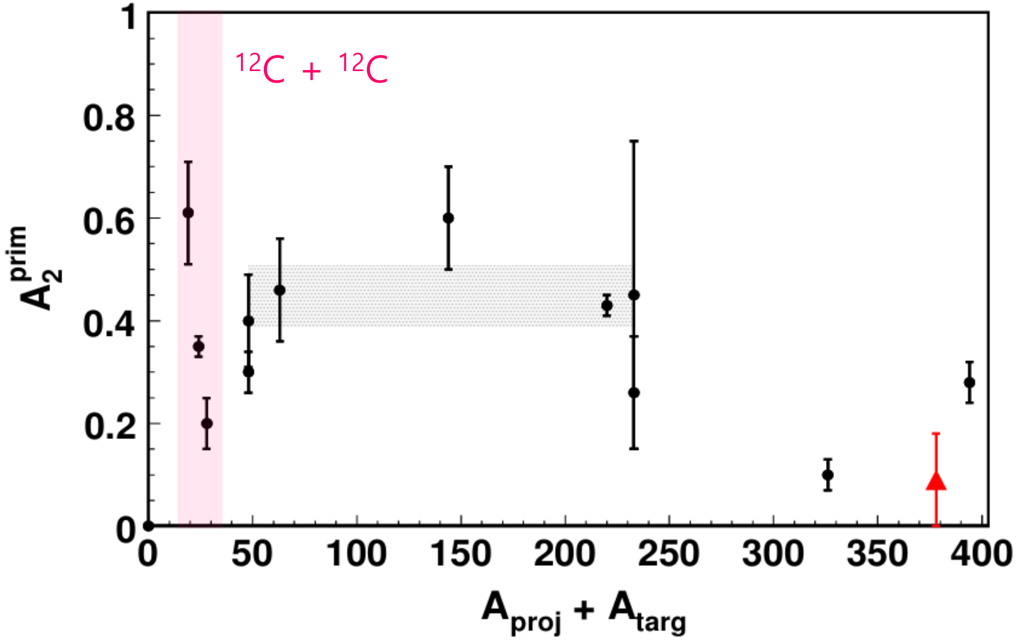
- Assuming a source in **thermal equilibrium**, the transverse momentum of π^0 should exhibit a **Boltzmann distribution**, where a slope parameter (T0 [MeV]) related to apparent temperature of the source.
- After accounting for reabsorption, the primordial π^0 transverse momentum spectrum still deviates from a Boltzmann distribution across its entire range.

Polar Anisotropy and Pion Absorption

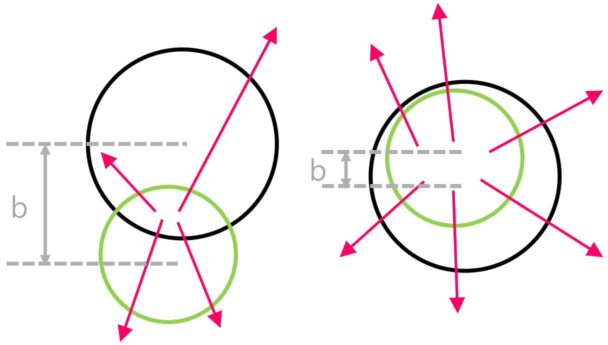
K. Piasecki and T. Matulewicz, Acta Phys. Polonica B 41, 393 (2010)

^{181}Ta + ^{197}Au at 40 AMeV TAPS (GANIL) $\frac{d\sigma}{d\Omega} \propto 1 + A_2 P_2(\cos\theta)$





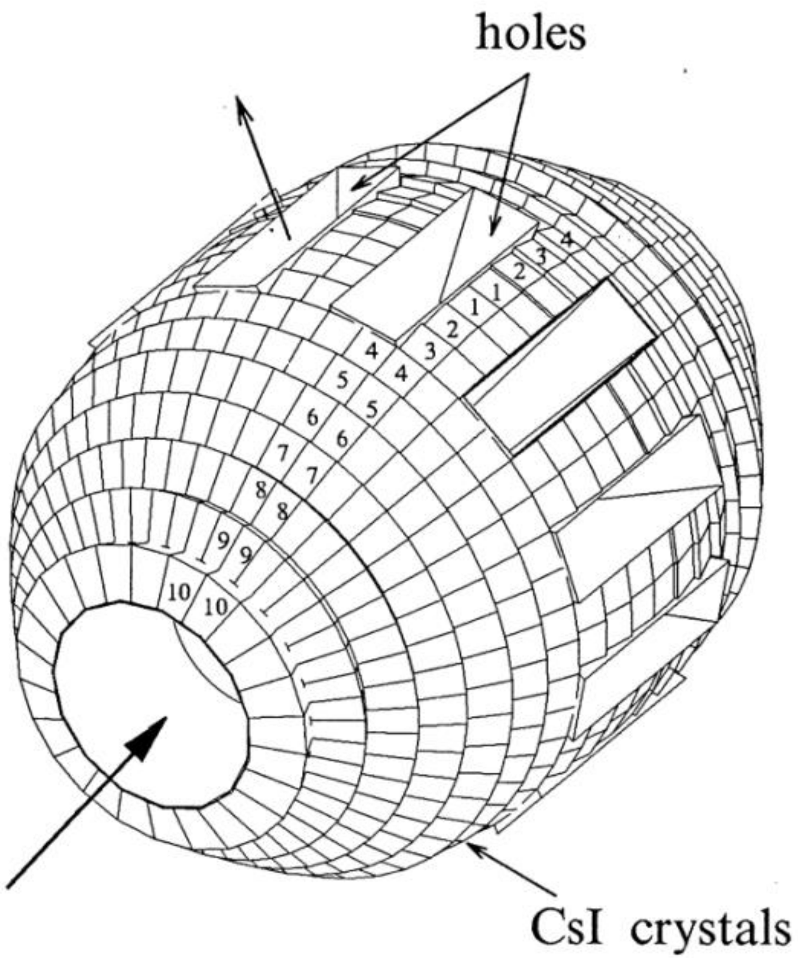
- Measured π^0 angular distributions in Ta+Au at 40 AMeV exhibit a **forward–backward anisotropy** (A_2= 0.31), indicating more pions absorbed along the beam axis.
- After correcting for P_T-dependent reabsorption by the **simple reabsorption model**, the angular distribution of primordial π^0 emission becomes **nearly isotropic** (A_2^{prim}= 0.09).

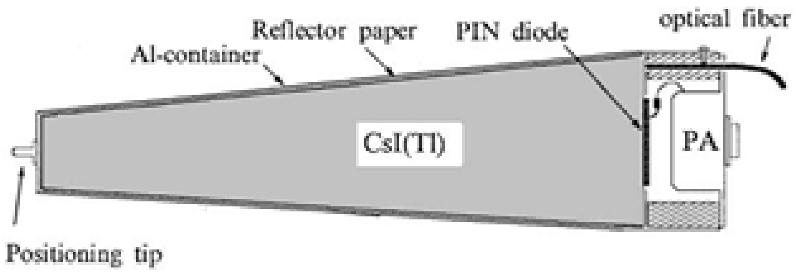


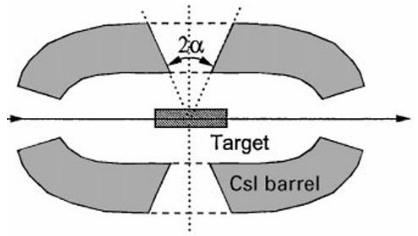
K. Tyminska, T. Matulewicz, K. Piasecki, Acta Phys. Pol. B 33, 981 (2002)

CsI(Tl) Calorimeter

D.V. Dementyev et al., Nucl. Instc. and Methods A 440 (2000) 151.







KEK E246, J-PARC E36

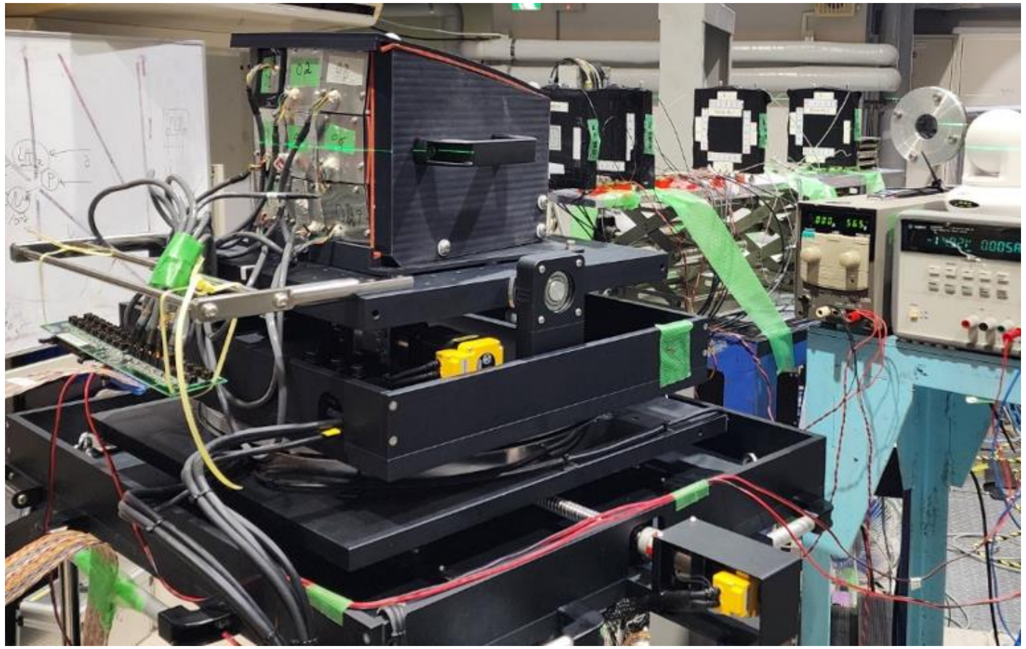
Currently stored at KEK under a dry air supply

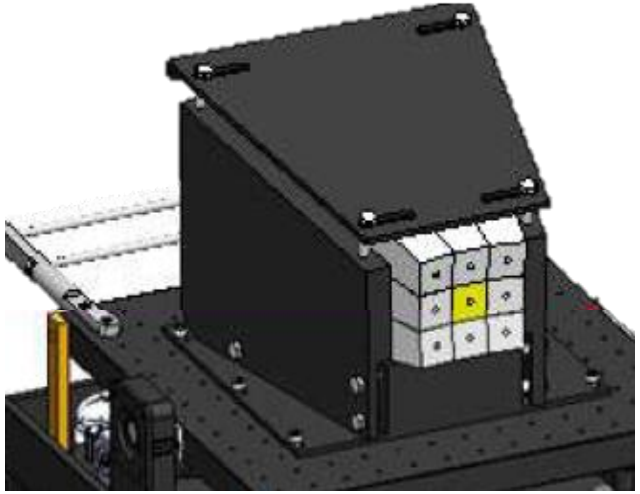
- The CsI(Tl) Calorimeter consists of 768 CsI(Tl) crystals covering **75% of 4π solid angle**.
- An individual crystal covers 7.5˚ in θ and ϕ, except for 48 crystals near the beam axis.
- Average transverse dimensions are **3 x 3 cm²** for front end and **6 x 6 cm²** for rear end.
- The length of crystal is **25 cm (13.5 X_0).**

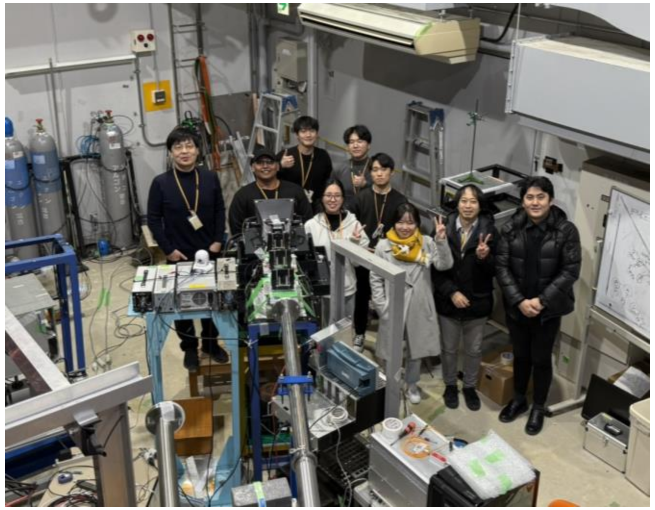
Beam Test at RARiS (Jan 2025)

- Test for **CsI(TI) crystal** and **triggerless DAQ** performance for photon from low energy $\pi^0 \rightarrow \gamma\gamma$ decays
  - E_γ spans 50 – 300 MeV
  - 3 x 3 CsI(TI) array with moving stage

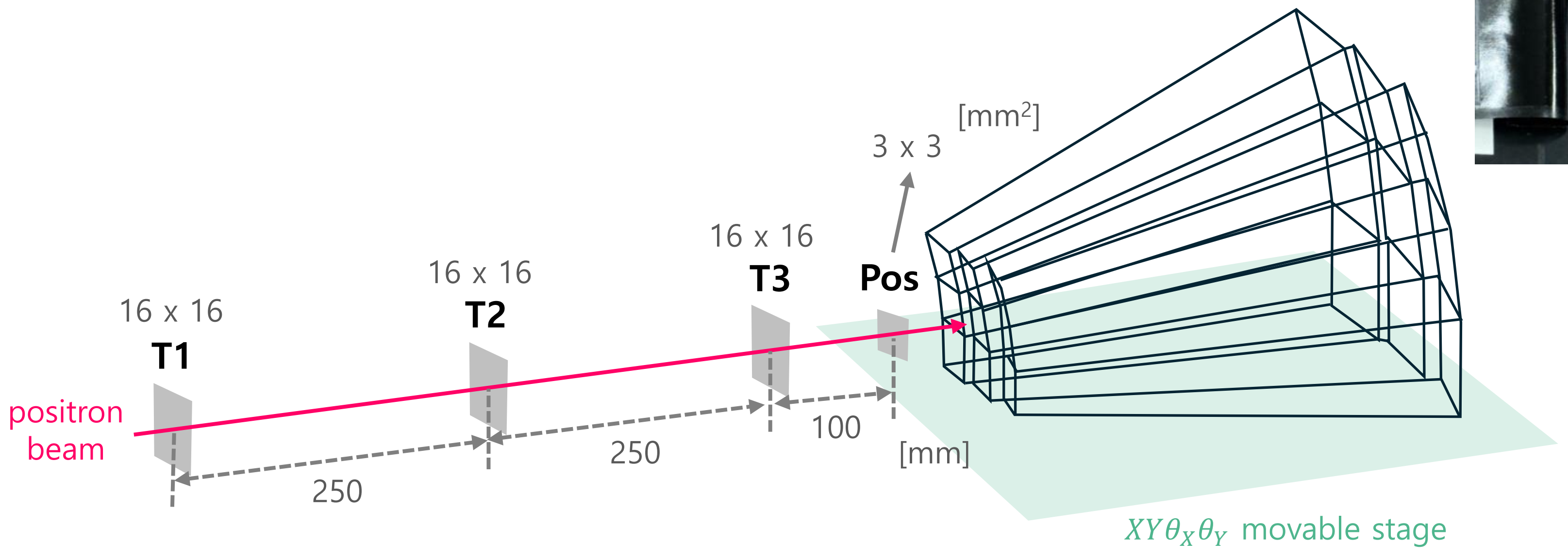
- **Positron beam** at RARiS to generate representative EM showers.

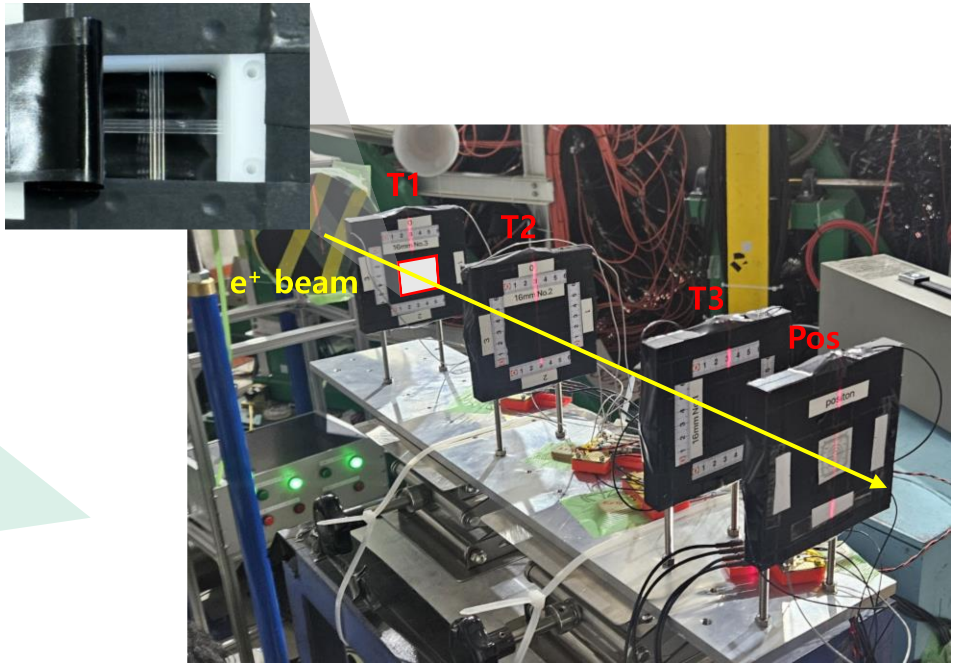




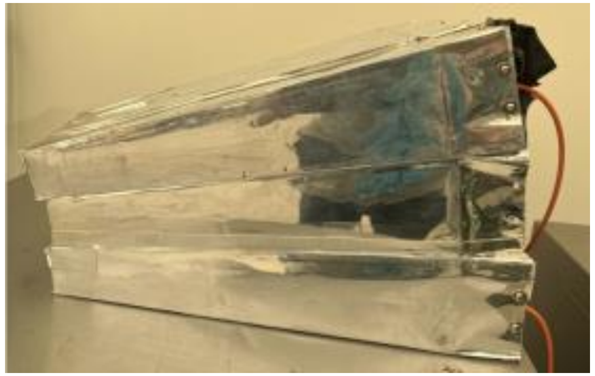


Setup for Beam Test – CsI(TI) Array

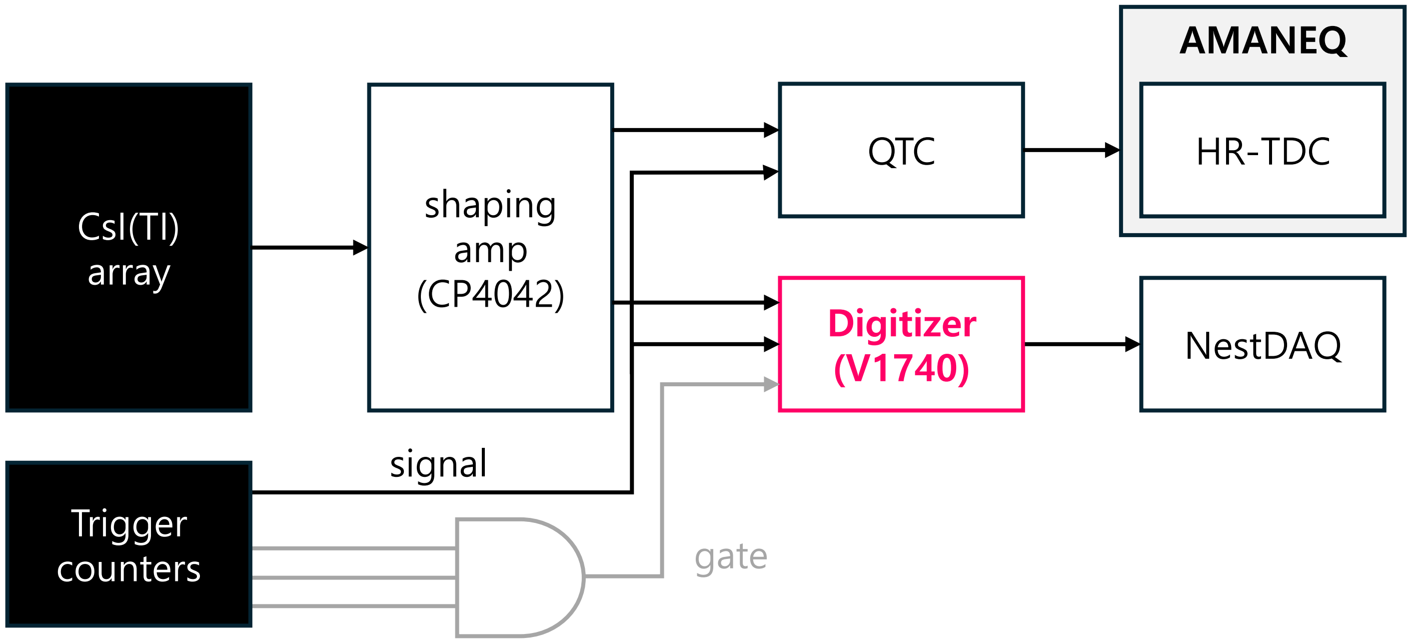




- Coincidence trigger **T1 & T2 & T3**.
- The positron beam momentum was varied from 50 to 300 MeV/c.
- Active area of trigger counter **16 x 16 mm²**, position definition counter **3 x 3 mm²**.

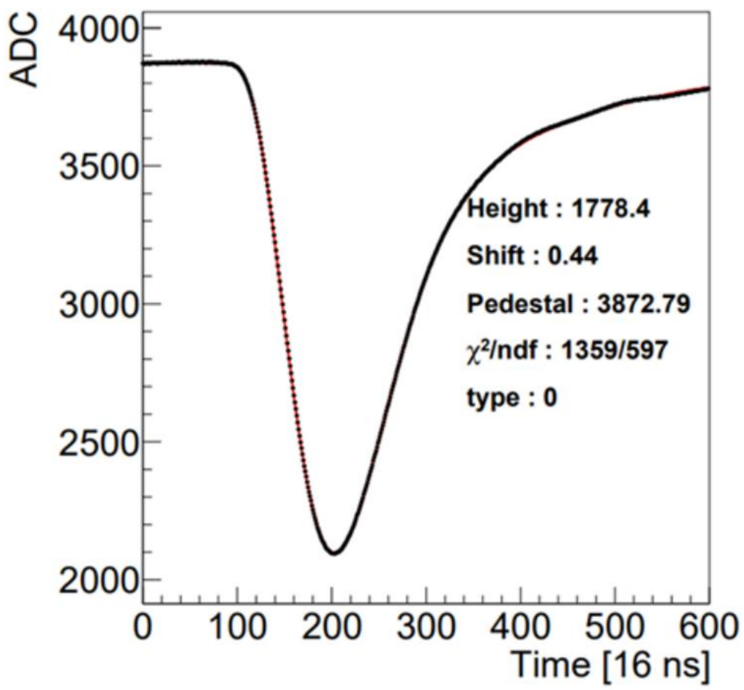


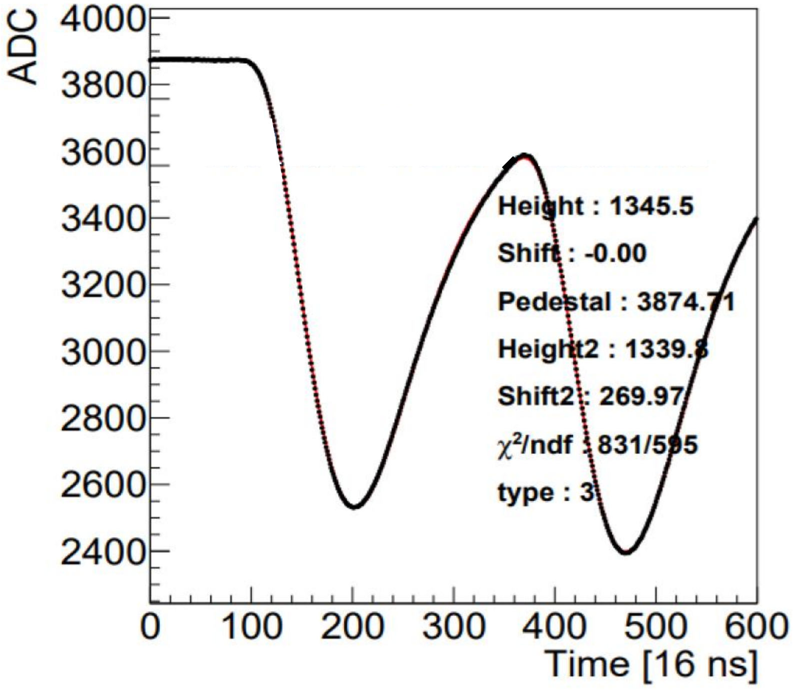
Setup for Beam Test – Data Acquisition System

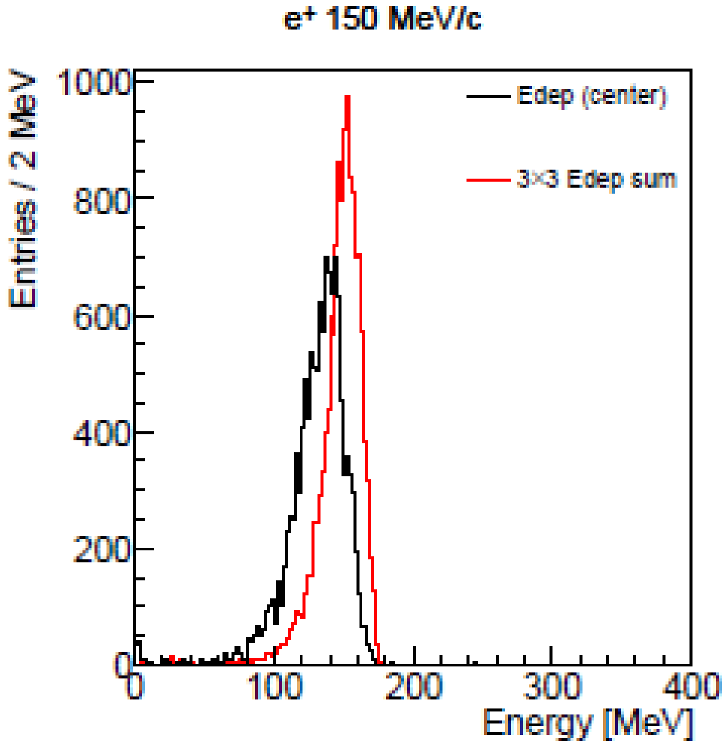


- Data taking with **V1740D** (64 ch, 62.5 MHz, 12-bit digitizer) --> enable discrimination of **pile-up events**
- **FADC** --> Full waveform
- Test triggerless DAQ test with RCNP team

Result





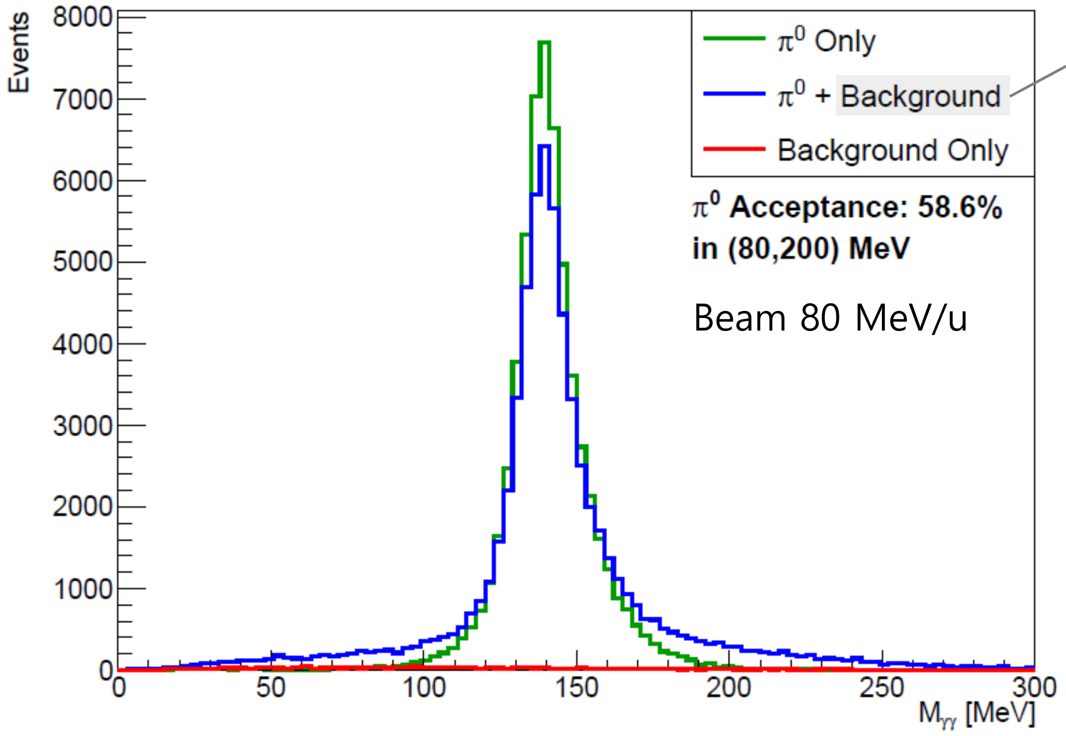


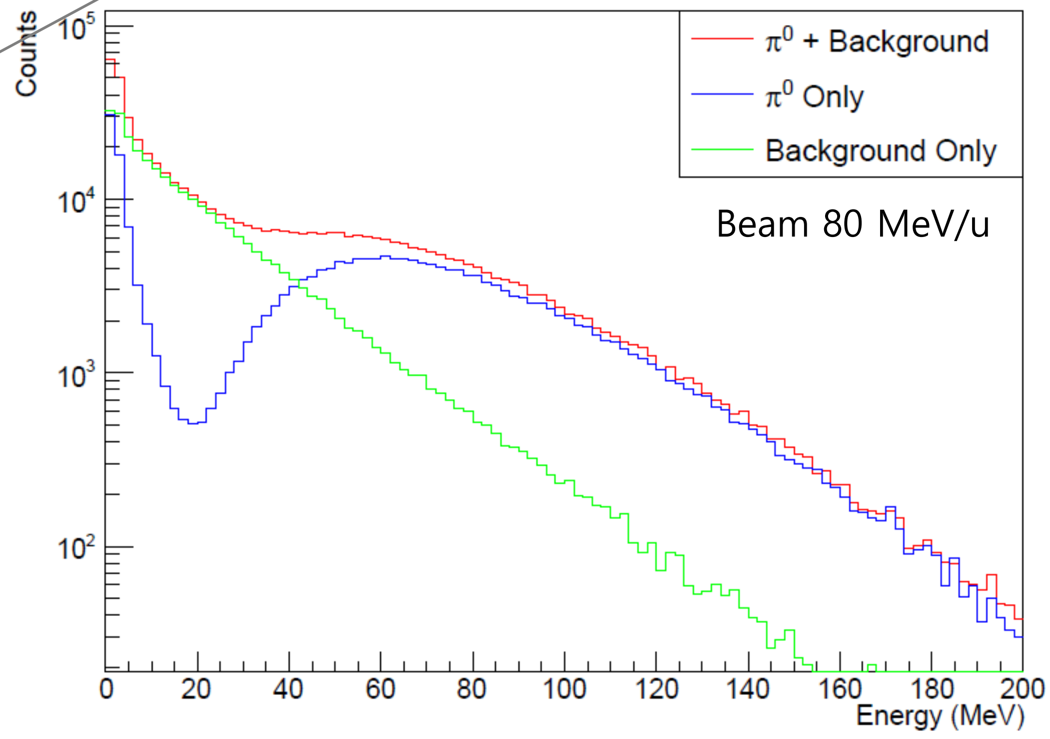
- Can discriminate pile up events
  - pile up ratio is around 1-2% in 800 MeV/c beam
- Now working on cleaning up the event and get the property of edge segment signal

Pion Reconstruction Simulation

$$M(\gamma\gamma) = 2\sqrt{E_1 E_2}\sin\left(\frac{\theta_{12}}{2}\right)$$

angular distribution depending on energy is considered





- Bremsstrahlung photon rate ~ 300 kHz, pion rate ~ 3-300 Hz --> SNR 10^{-3} – 10^{-5}
- Generate **100k** single photon event (energy 0 – 300 MeV) and cluster with **$E_{cluster}$ > 20 MeV, $t_{cluster}$ < 1 us** cut (for both training and test set)

--> using ML(XGBoost), select two cluster with highest energy and calculate invariant mass (~ 134.97 MeV)

Expected Timeline

2025 Jun - Sep

@ RCNP

SUPER DAQ test

2025 Nov

@ KEK RCNP

CsI(Tl) detector

transportation

KEK -> RCNP

2025 Dec

@ RCNP

detector assembly

Spring of 2026

@ RCNP

(beamtime)

$^{12}C + ^{12}C$

at 25 - 80 AMeV

Summary

- To check the performance of the CsI(Tl) detector, we conducted the beam test at RARiS using **positron beam**.
  - Beam momentum 50 – 300 MeV/c to represent gamma from $\pi^0 \rightarrow \gamma\gamma$ decay
  - $XY\theta_X\theta_Y$ remote movable stage
- Pile up events can be discriminated thanks to the **V1740D FADC digitizer.**

Thank you for your attention!

Backup

Prospects

Yield estimation: Total cross section for inclusive π^0 creation of 80 AMeV ^{12}C beam on ^{12}C target

Beam Energy 25 – 80 MeV/u and therefore total cross section $\sigma = 20\ \mathrm{nb}\ - 10\ \mathrm{ub}$

Assume beam intensity $\mathrm{I} = 10^{11}\ \mathrm{pps}$, and target ^{12}C's $\rho = 0.1\ \mathrm{g/cm^2}$

assume that total cross section $\sigma = 1\ \mathrm{ub}$

$$Y_{\pi^0} = (10^{11}\ \mathrm{pps})(0.1\ \mathrm{g\ cm^{-2}})\left(\frac{6.02\ \times\ 10^{23}\ \mathrm{mol^{-1}}}{12\ \mathrm{g\ mol^{-1}}}\right)(10^{-30}\ \mathrm{cm^2}) \simeq 500\ /\mathrm{s}$$

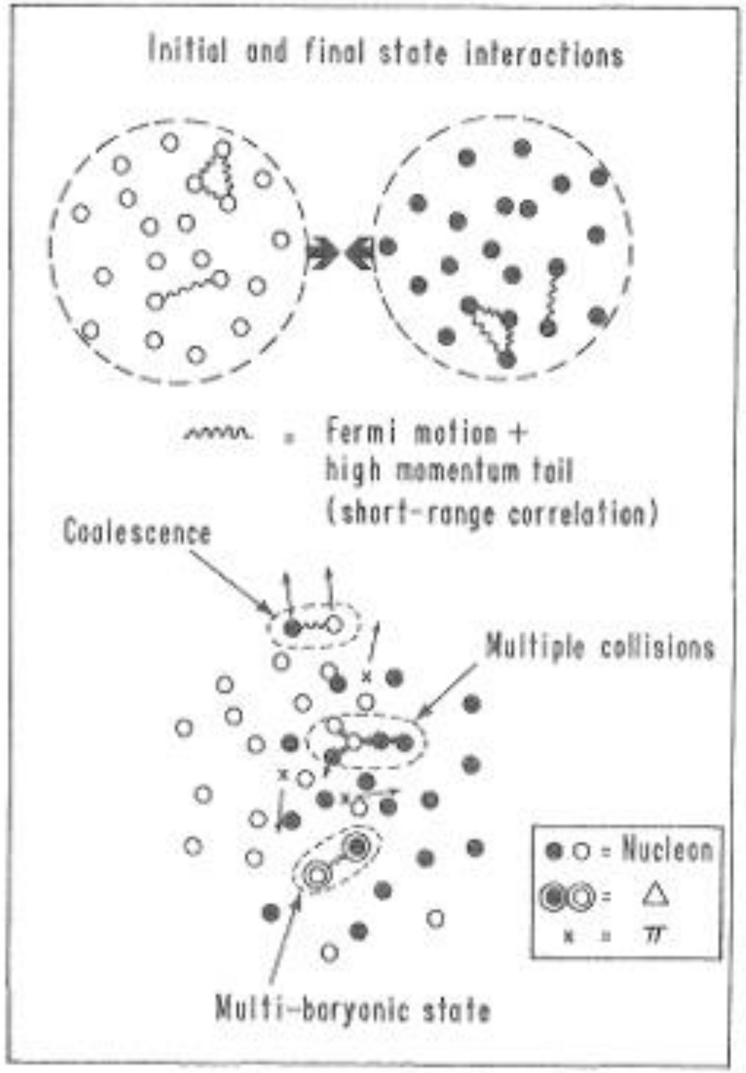
CsI(Tl) 768 Array covers 75% of total solid angle 4pi.

The expected number of π^0 detected in **an hour** is calculated as

$$N_{\pi^0} = (500\ \mathrm{s^{-1}})\left(\frac{3\pi}{4\pi}\right) \simeq 1.3\ \times\ 10^6/\mathrm{s}$$

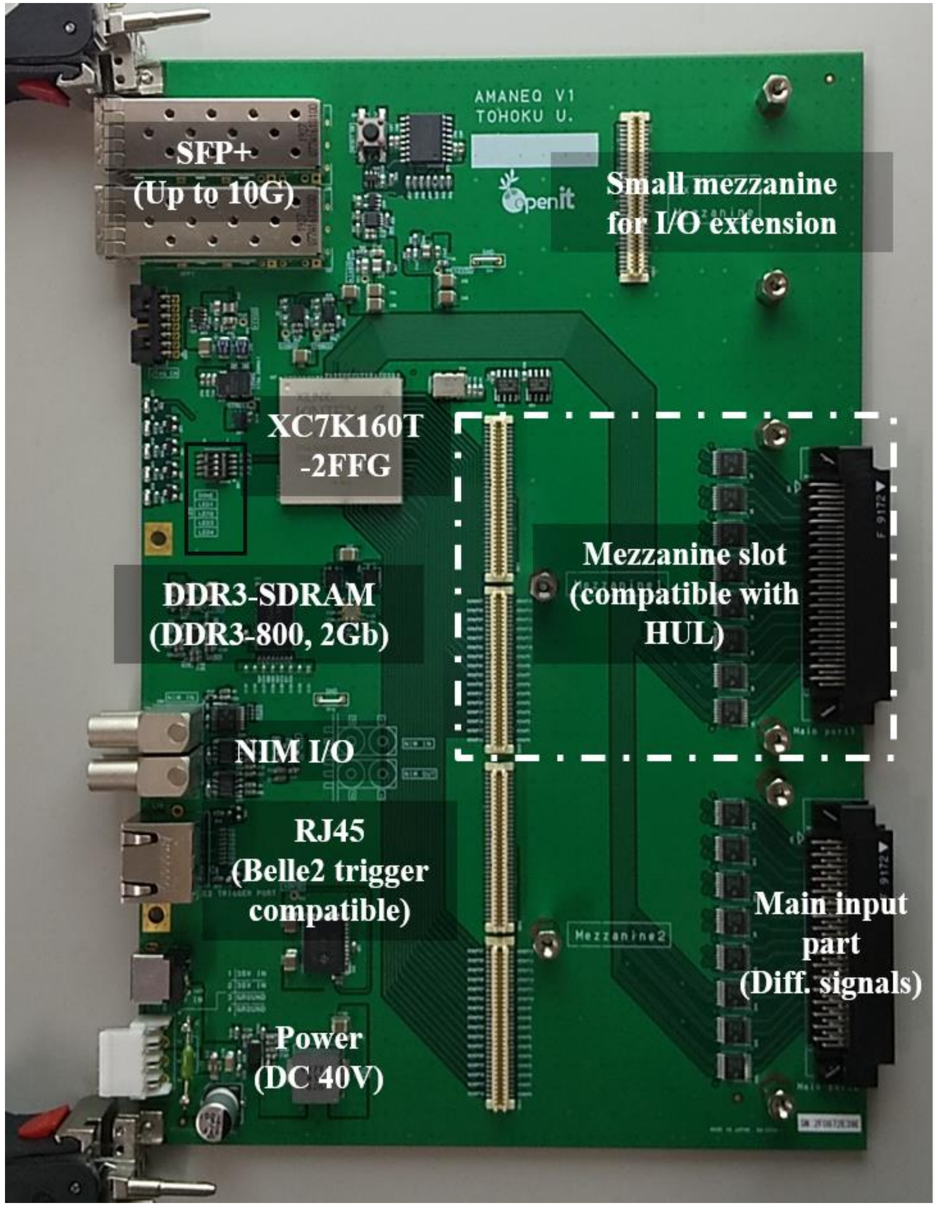
Fermi motion inside the nucleus

Central Nuclear Collisions I The Past and the Future.~ Shoji Nagamiya



AMANEQ

https://openit.kek.jp/project/StrHRTDC



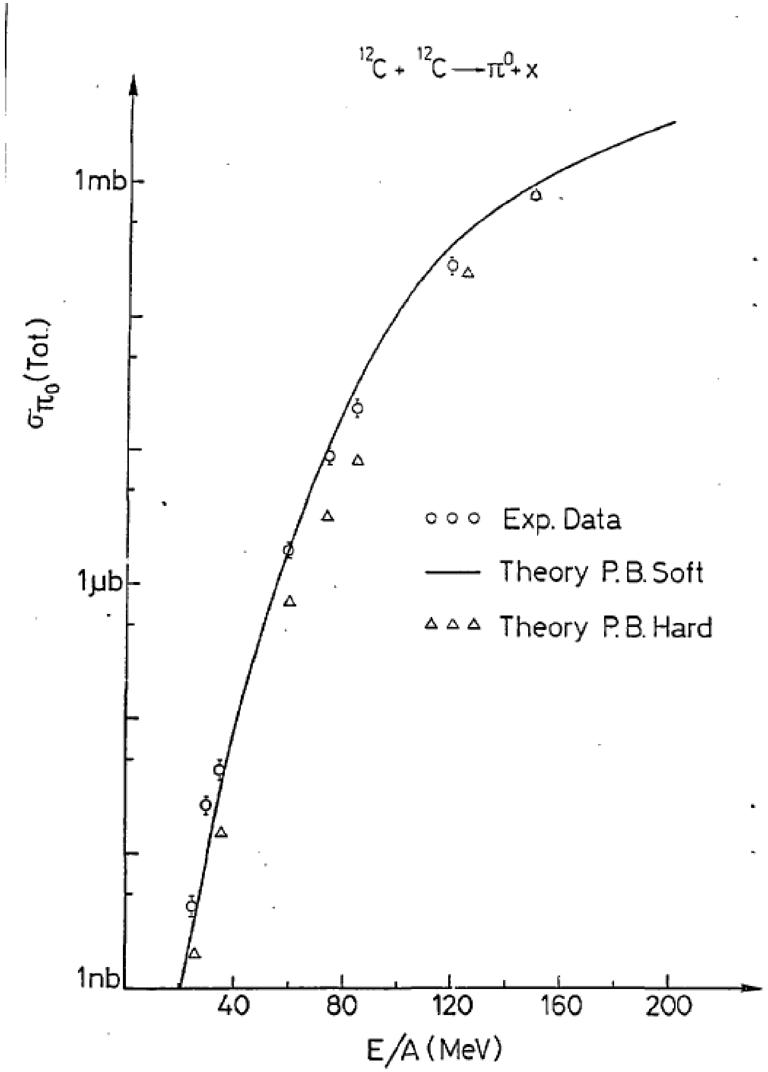
Attach

HUL/AMANEQ mezzanine HR-TDC

32 ch tapped-delay-line (TDL) based HR-TDC

- Input IO std.: LVDS
- TDL consists of a CARRY4 primitive chain.
  - Target resolution: 20-30 ps in σ
- Both leading/trailing edges

$^{12}C + ^{12}C \rightarrow \pi^0 + x$



- absolute threshold in symmetric heavy ion collision (AA -> AA π^0) decreases as mass number increases
- absolute threshold of pp -> pp π^0 in lab frame is 280 MeV
- in 12C + 12C -> π^0 + x collision, absolute threshold is at 22.5 MeV --> based on this, we set the 12C beam energy to be 25 MeV/u to 80 MeV/u .

SINGLE NUCLEON-NUCLEON COLLISION MODEL FOR SUBTHRESHOLD PION PROCUCTION IN HEAVY ION COLLISIONS (GANIL)
V. Belliini, M. Di Toro (1985)

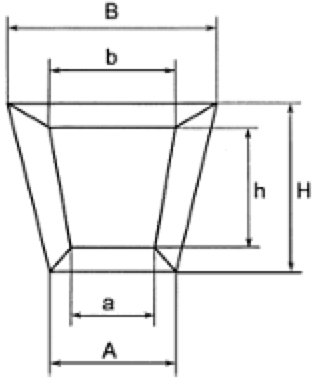
More Informations about CsI(Tl) Crystals

D.V. Dementyev et al., Nucl. Instc. and Methods A 440 (2000) 151.

Table 1
Dimensions of CsI(Tl) crystals in mm

Type number[a]	*A*	*B*	*H*	*a*	*b*	*h*
1	61.14	61.98	57.76	5.63	6.00	24.99
2	59.76	62.31	58.46	5.64	6.77	25.68
3	57.42	61.71	59.69	5.66	7.60	26.92
4	53.30	56.87	61.58	24.86	26.53	28.81
5	50.92	55.61	64.35	24.87	27.17	31.58
6	48.10	54.01	68.37	24.88	27.95	35.60
7	42.26	49.16	70.05	22.27	25.94	37.28
8	35.77	43.69	72.64	19.35	23.70	39.87
9	28.52	37.51	76.42	15.96	21.09	43.65
10	42.15	62.21	82.42	25.08	37.12	49.46

[a]See Fig. 2 for numbering.



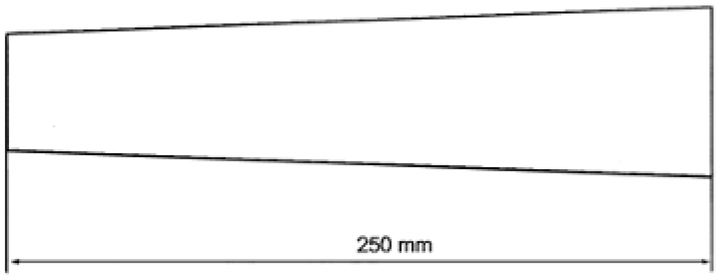


Table 2
Specification of the CsI calorimeter

Crystal	CsI(Tl)
Segmentation	$\Delta\theta = \Delta\phi = 7.5^\circ$
Number of crystals	768
Length of a crystal	25 cm (13.5X_0)
Readout	one PIN diode per crystal
Total crystal weight	1700 kg
Inner diameter	40 cm
Outer diameter	100 cm
Detector length	141 cm
Solid angle coverage	75% of 4π

More Informations about CsI(Tl) Crystals

- Photon energies up to 300 MeV.
- High density, short radiation length (X_0) and Moliere radius (R_M).
- Fast decay time, high light yield, and wavelength matching between scintillator and photon sensor.
- Maximum size in crystal growth and cost performance.

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	CeF_3	BGO	$PbWO_4$	LYSO	GAGG
Density (g/cm^3)	3.67	4.51	4.51	4.89	6.16	7.13	8.28	7.10	6.63
X_0 (cm)	2.59	1.85	1.85	2.03	1.68	1.12	0.89	1.14	1.56
R_M (cm)	4.8	3.5	3.5	3.4	2.6	2.3	2.0	2.07	2.1
Wavelength	410	560	420	310	330	480	420	420	520
(nm)			310	195,210					
Decay time	230	1300	35	620	30	300	5–15	36	90
(ns)			6	0.6					
Light output	1	0.45	0.06	0.21	0.10	0.09	0.01	0.66	1.0
			0.02	0.03					
Cost			$2200			$1600		$8600	$9000

Single NN Collision Model

Useful Formulas (EM showers) [1]

Radiation Length: $X_0 \approx \frac{180A}{Z^2}$ (g.cm-2)

Radiation Length for composite material: $\frac{1}{X_0} = \sum \frac{w_j}{X_j}$

w_j: fraction of material j
X_j: radiation length of material j (in g.cm-2)

Moliere Radius: $R_M = \frac{21MeV}{E_C} X_0$

Moliere Radius for composite material: $\frac{1}{R_M} = \sum \frac{w_j}{R_{Mj}}$

w_j: fraction of material j
R_{Mj}: Moliere Radius of material j (in g.cm-2)

Energy Resolution: $\frac{\sigma}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C$

$\oplus$: quadratic sum
S: Stochastic
N: noise
C: constant

Useful Formulas (EM showers) [2]

$E_c(solid) = \frac{610\text{ MeV}}{Z+1.24}$

$E_c(liquid) = \frac{710\text{ MeV}}{Z+0.92}$

E_C: critical energy

Shower maximum $t_{max} = \frac{\ln E_0 / E_C}{\ln 2}$ $N(t_{max}) \approx \frac{E_0}{E_C}$

Longitudinal containment:

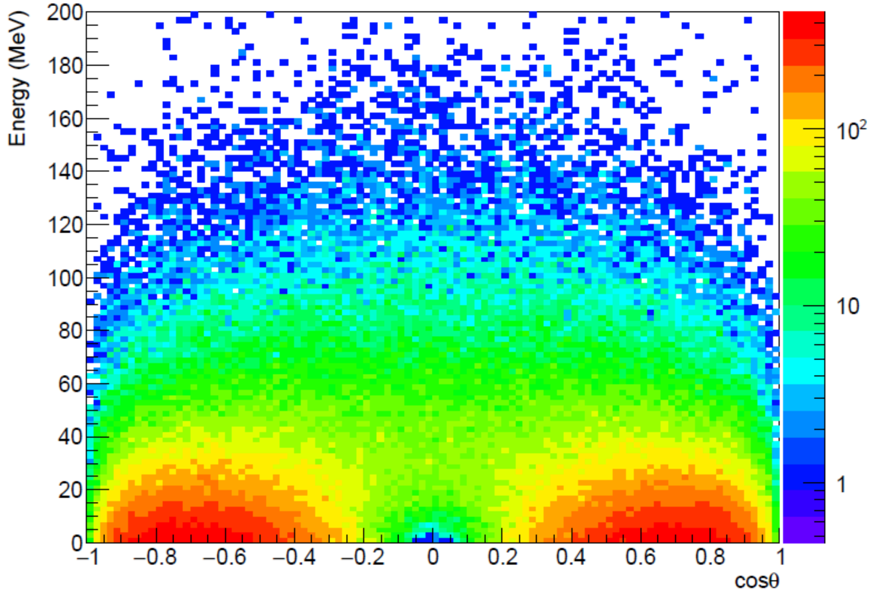
$t_{95\%} = t_{max} + 0.08Z + 9.6$

$$\frac{\sigma_E}{E} = 3.2\% \sqrt{\frac{E_c\ [\text{MeV}] \cdot t_{abs}}{F \cdot E\ [\text{GeV}]}}$$

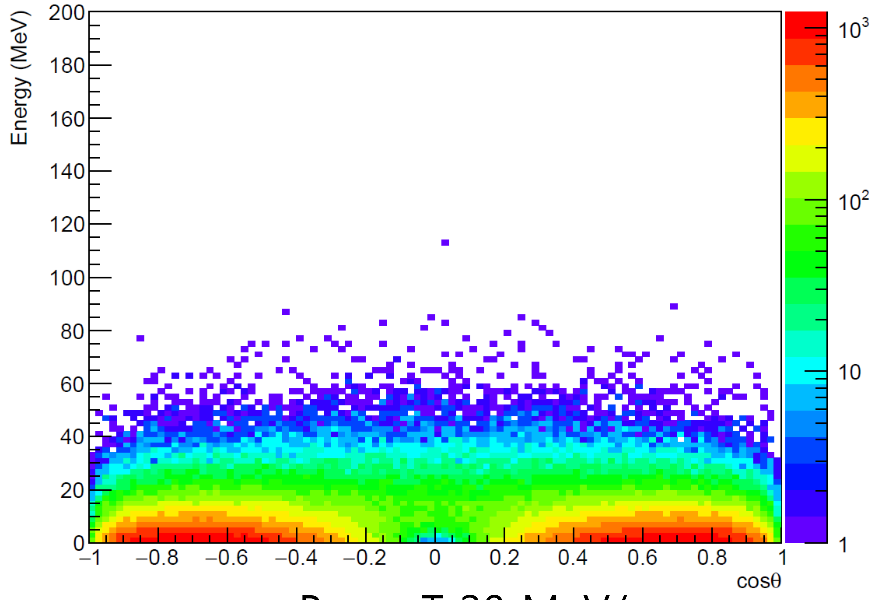
(stochastic contribution)

t_{abs}: thickness of absorber (in units of X_0)
F: factor (~0.2 for liquid noble gaz, 0.06 for Si, ~1 for scintillators)

Simulation) Angular Distribution Depending on the Beam Energy



Beam T 80 MeV/u



Beam T 20 MeV/u

strong anisotropy in

forward backward

$$\frac{d^2\sigma_\gamma}{dE\, d\Omega} \approx \frac{\alpha Z^2 v_L^2 \sin^2\theta}{16\pi^2 E}\pi R^2\left(v_L^2 \cos^2\theta + \tfrac{1}{4}R^2E^2 \sin^2\theta\right).$$

David VASAK, Phys. Lett. B 176 (1986) 3