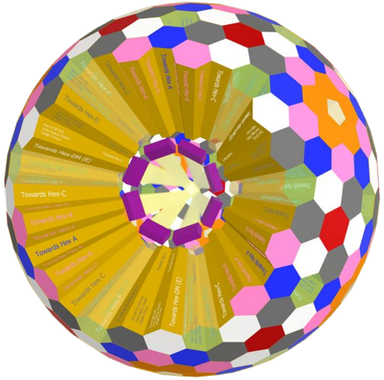
The Case for LYSO

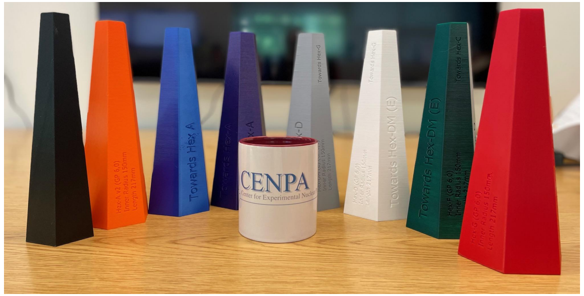
Omar Beesley and Dave Hertzog

Lutetium–yttrium oxyorthosilicate (LYSO):

- By weight: 73% Lutetium, 18% Oxygen, 6% Silicon, **~0% Cerium (dopant)**, 3% Yttrium
- **X_0 = 1.14 cm , R_M = 2.07 cm**
- Decay time = **40 ns**
- Light yield **30,000 γ/MeV**
- λ_{peak} **420 nm** -> conventional PMTs
- Radioactive (< 1 MeV constant rumble) [Omar will address]
- Non hygroscopic
- No Temp dependence
- n = 1.82
- Not so cheap … ☹, but nothing is …

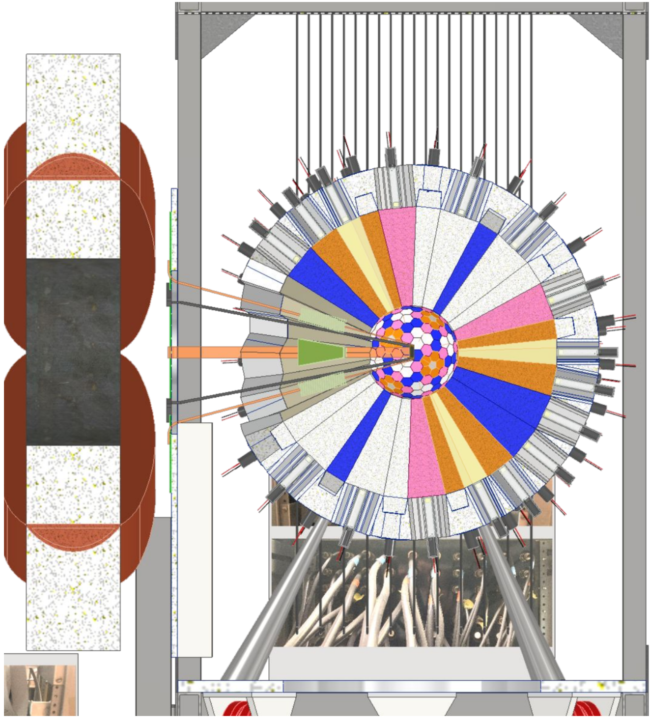
The 311 Crystal Array and its 8 individual elements (to scale)





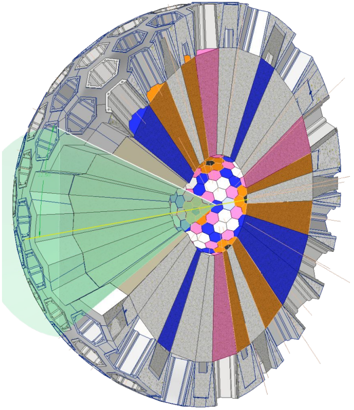
Pent - HexA - HexB - HexC- HexF - HexD, DM - HexG

HexG is largest and will be ordered soon to allow SICCAS time to practice their fabrication process

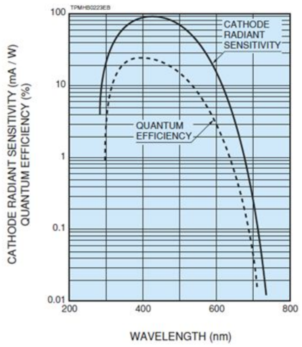


On rails, moveable, onboard electronics

Frame locks in positions. Each Xtal can be removed, or groups can be removed

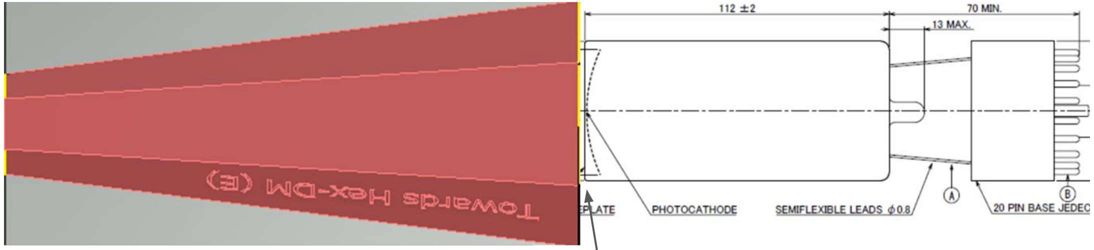


PMT for high rate, linear, “blue”, and tapered base

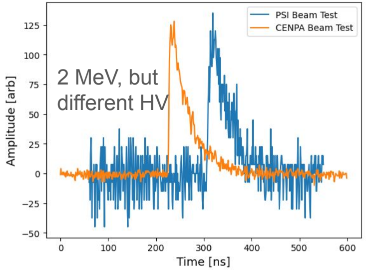


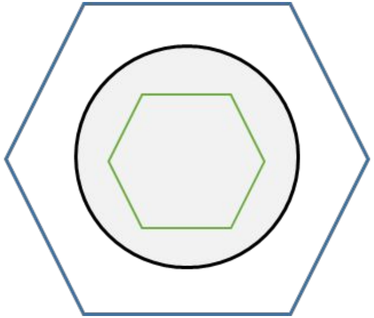
R13089, R13089-100

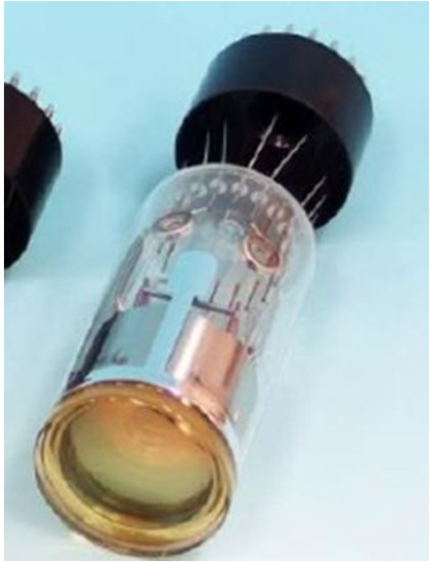
For Scintillation Counting, Fast Time Response
51 mm (2 inch) Diameter, Bialkali (R13089) and Super Bialkali (R13089-100)
Photocathode, 8-stage, Head-on Type



Optical epoxy with n~1.62 optimizes transmission
(e.g., Zeiss OK2030 used in g-2)



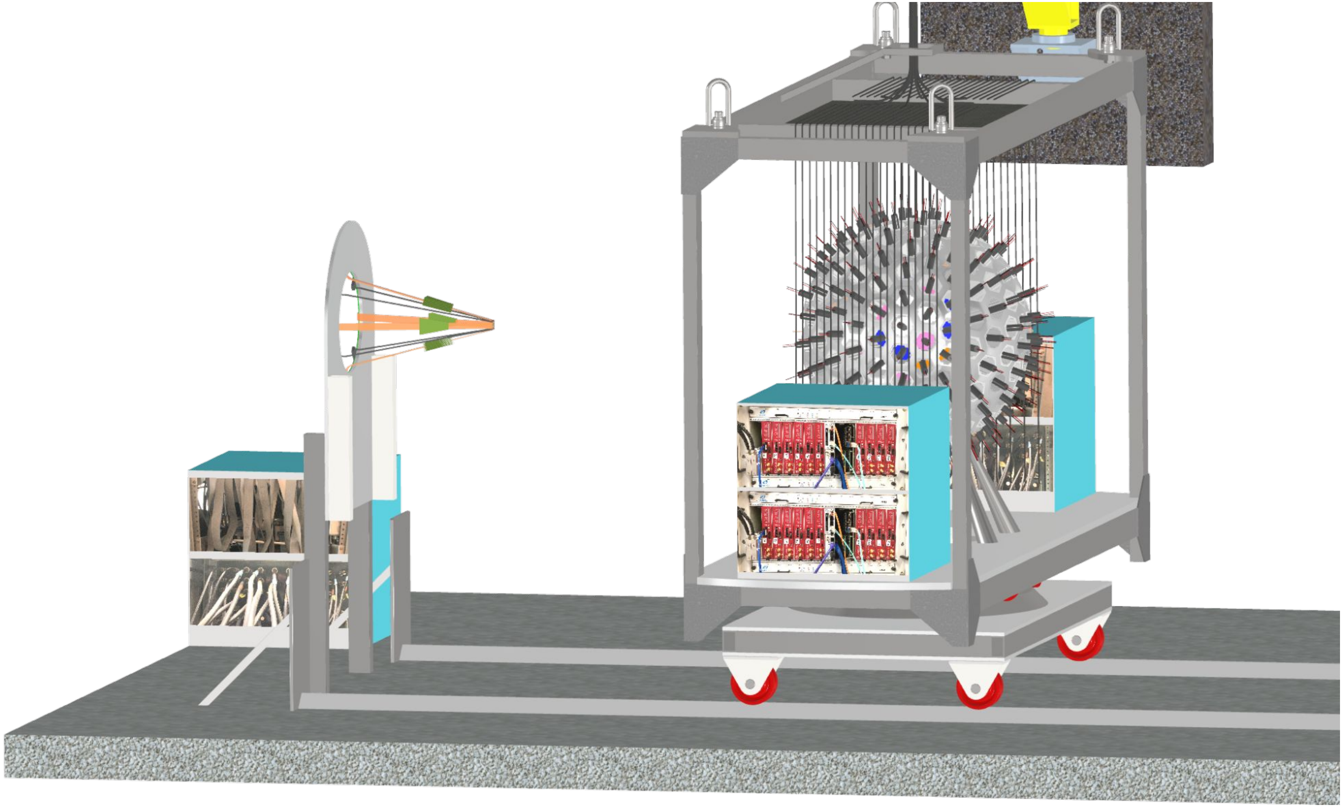




Omar will explain later the
impact of getting the PMT right

Anna working with Hamamatsu

Mechanical (rail/pivot/frame), another view



LYSO in the DAQ under development

- Fast, pedestal-subtracted running total energy sum
    - not LYSO-specific
- Segmentation additionally allows:
    - Compact event size
        - Intelligent sparsification a possibility
            - eg., threshold + nearest neighbors
    - Running mass / angle calculations for π^0 triggering
        - Can be included in phase 1 for study / tuning
    - Potentially interesting triggering flexibility
        - Eg., interesting decay topologies for new BSM models?

From Lawrence; see his Collaboration Meeting talks about this system

Crystals, PMTs, Digitizers, Mechanics, Calib cost

中国科学院上海硅酸盐研究所
SICCAS Since 1928
Shanghai Institute of Ceramics Chinese Academy of Sciences

QUOTE OF LYSO BARS

TO UNIVERSITY OF BRITISH COLUMBIA

Douglas Bryman, Professor/Warren Chair
Department of Physics & Astronomy
Vancouver Campus
325 - 6224 Agricultural Road
Vancouver, BC V6T 1Z1, Canada
doug@triumf.ca
Tel: 604 822 3853
Fax: 604 822 5324

Sept. 13th, 2024

Dear Prof. Doug Bryman,

Thanks for your inquiry about the LYSO bars for your PIONEER calorimeter!
Given your requirements on the dimensions of "Φ(26-38) mm × Φ(63-94) mm×217 mm" crystals, and according to your drawings and specifications in the attachment (PDF), we provide you with the quote of the development for the total 311 pcs LYSO bars (55 pcs Hex-A, 55 pcs Hex-B, 50 pcs Hex-C, 50 pcs Hex-D, 50 pcs Hex-DM, 25 pcs Hex-F, 15 pcs Hex-G, 11 pcs Pent).

311 crystals as specified in attached design document (list price):	$10.76 M USD
Less In-Kind contribution:	$1.56 M USD
Net quote:	$9.20 M USD

The quote is valid for two months from the official issue date.

Best regards, Ding, Dongzhou

Crystals: $9200 k
Includes custom roughening
Assumes 80% yield and passing QC

Max, largest PMTs, all assumblies $343k

Device / Ball Park Piece Price (in JPY net) Components	CHF/350 pc
PMT R580 **(1.5 inch)**	62246
PMT R13089 **(2 inch)**	126063
Divider socket E2183-500 for R580(STD)	58683
Divider socket E2183-501 for R580 (Tapered)	62371
Divider socket for R13089 (STD)	136479
Divider socket for R13089 (Tapered)	136814
Shielding E989-04 (for R580)	40910
Shielding E989-05 (for R13089)	60024
Assembly (including PMT, divider socket and shielding)	
Assembly H3178-51 (STD)	267216
Assembly H3178-51 (Tapered)	237665
Assembly H13719 (STD)	280105
Assembly H13719 (Tapered)	292994

Anna - Hamamatsu quote

DIGITIZER SYSTEM

Channels	Apollo CMs	Boards / CM	#digitizer crates
330	2	14	2

Digitizers	$363K
Digitizer crates	$5K
Apollo CMs	$40K
Server+firefly PCIe	$426K
Total	**$434K**

These are the base inputs used to calculate the above

Apollo CM count:
104 firefly channels / CM
4 channels → PCIe
4 channels → command CM
8 (4) channels → nearest neighbors for LXe (LYSO)
4 firefly channels / board
22 (23) boards or max 264 (275) channels per CM
Assume channels get split uniformly among the CMs

Rough crate cost
vector card sub rack: $300
vector fan tray: $400
card guides: 14 * $50 = $700
power backplane $500
power supply $400
Total $2300

Other costs
PCIe firefly PC card: $3000 / module
Digitizer cost / channel: $1100 (builds in 10% infant mortality+spares on nominal $1K / ADC from the BOE exercise. Engineering costs not included in this number, only production.)
Server for readout (1 / CM): $10K
Apollo CM cost $20K

Lawrence Gibbons

Mechanical:
-Engineering (UW/Ryan)
-Frame&Rails (~$100 k)
-Incidentals (UW)

UV Laser calibration optics				
Component	**quantity**	**price ($)**	**Total ($)**	**Product source**
Filter Wheel (6)	2	13330	26660	Thorlabs
(5) ND filters	2	146.13	292.26	Thorlabs
Picoquant LDH-FA-355	2	44463	88926	Picoquant
Laser driver PDL 800-D	2	6219	12438	Picoquant
50/50 Beam Splitter	3	1490	4470	Newport
Fiber coupler CFC-8X-A	4	1500	6000	Thorlabs
100 channel UV optical splitter	4	14488	57952	SQS Vlaknova Optika
Optical Breadboard	1	2000	2000	
Miscellenous mirrors and			0	
Miscellenous mirrors and breadb	1	12000	12000	Thorlabs, Newportt
		Cost	**210738**	

LYSO Cost Roll Up	**k$**
Crystals	9200
PMTs	343
Digitizers	434
Mechanics	100
Calibration	211
Total	**10288**

Brief review of LYSO Performance in Recent Test Beams

(see submitted paper)

arXiv: 2409.14691

Measurements of a LYSO crystal array from threshold to 100 MeV

O. Beesley[a], J. Carlton[b], B. Davis-Purcell[c], D. Ding[d], S. Foster[b], K. Frahm[e], L. Gibbons[f], T. Gorringe[b], D.W. Hertzog[a], S. Hochrein[e], J. Hui[g], P. Kammel[a], J. LaBounty[a], J. Liu[g,h], R. Roehnelt[a], P. Schwendimann[a], A. Soter[e], E. Swanson[a], B. Taylor[a]

[a] *Center for Nuclear Physics and Astrophysics (CENPA) University of Washington Seattle WA 98195 USA*
[b] *University of Kentucky USA*
[c] *TRIUMF Canada*
[d] *Shanghai Institute of Ceramics Chinese Academy of Sciences (SICCAS) Shanghai 201899 China*
[e] *ETH Zurich Switzerland*
[f] *Cornell University USA*
[g] *Shanghai Jiao Tong University Shanghai 200240 China*
[h] *New Cornerstone Science Laboratory Tsung-Dao Lee Institute Shanghai Jiao Tong University Shanghai 201210 China*

Abstract

We report measurements of ten custom-made high-homogeneity LYSO crystals. The investigation is motivated by the need for a compact, high-resolution, and fast electromagnetic calorimeter for a new rare pion decay experiment. Each $2.5 \times 2.5 \times 18\,\mathrm{cm}^3$ crystal was first characterized for general light yield properties and then its longitudinal response uniformity and energy resolution were measured using low-energy gamma sources. The ten crystals were assembled as an array and subjected to a 30 - 100 MeV positron beam with excellent momentum definition. The energy and timing resolutions were measured as a function of energy, and the spatial resolution was determined at 70 MeV. An additional measurement using monoenergetic 17.6 MeV gammas produced through a p-Li resonance was later made after the photosensors were improved. As an example of the results, the energy resolution at 70 MeV of $1.80 \pm 0.05\%$ is more than two times better than reported results using previous generation LYSO crystals.

Keywords: electromagnetic calorimeter, LYSO, test beam

Preprint submitted to Nuclear Inst. and Methods in Physics Research, A September 14, 2024

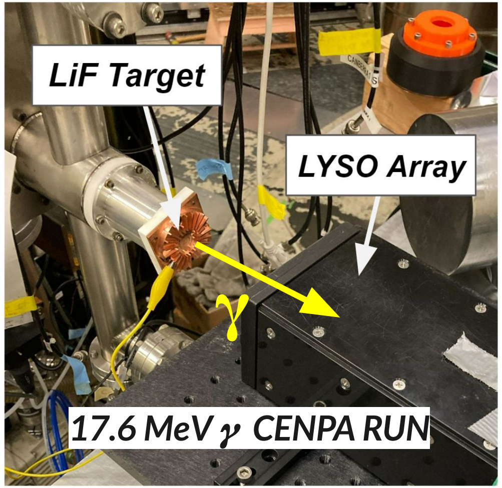
10 Crystal LYSO Array

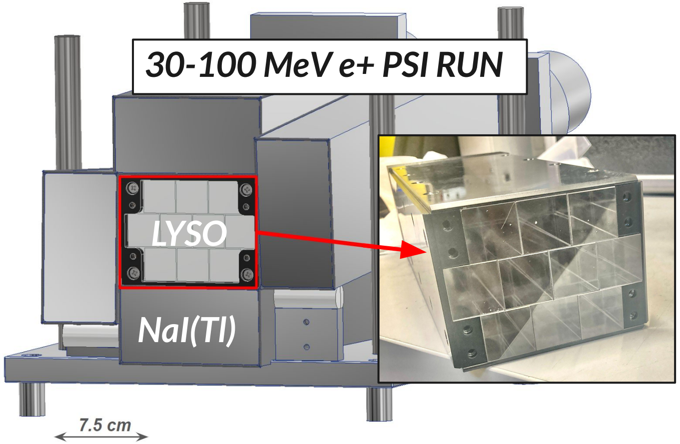
Ten 2.5 x 2.5 x 18 cm^3 LYSO crystals wrapped in ESR tested with:

- 30-100 MeV positrons (and 210 MeV muons) at PiM1 beamline at PSI
- 17.6 MeV gammas at CENPA

Measurements of:

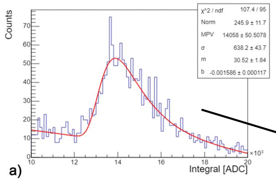
- Longitudinal response uniformity (LRU)
- Time resolution
- Energy resolution
- Spatial resolution



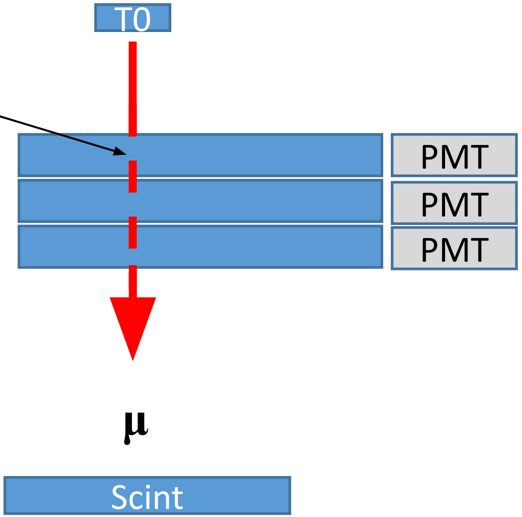


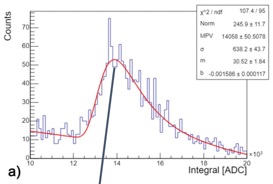
LRU using high energy muons

- PiM1 is ideal up to a few hundred MeV/c
  - **ΔP/P** measured to be **<0.65%**
- Muons @ 210 MeV/c used for transverse tomography



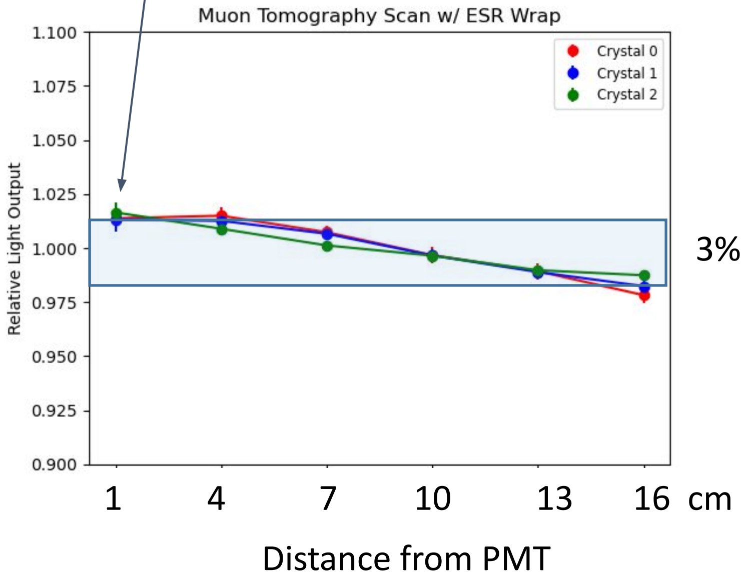
23 MeV MIP deposit in each crystal





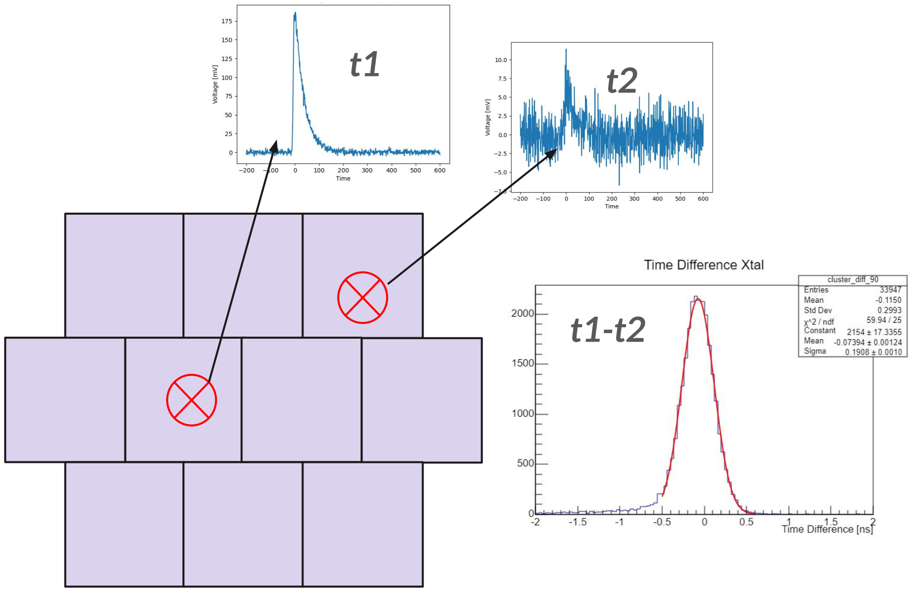
Peak tracked along longitude of crystal

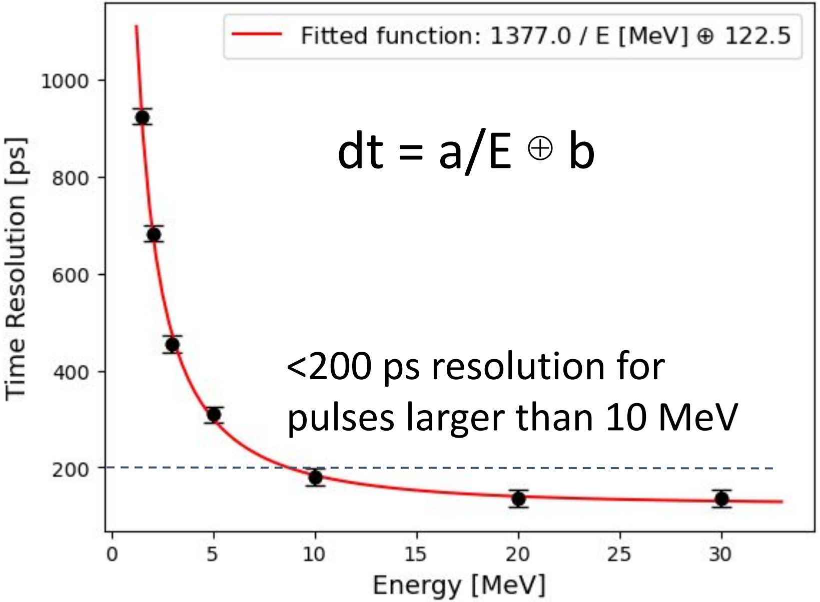
~3% LRU – strong agreement with single crystal LRU measured in the lab



Time resolution of LYSO array

The time difference between the most energetic hit in the array and less energetic secondary hit times was used to determine time resolution



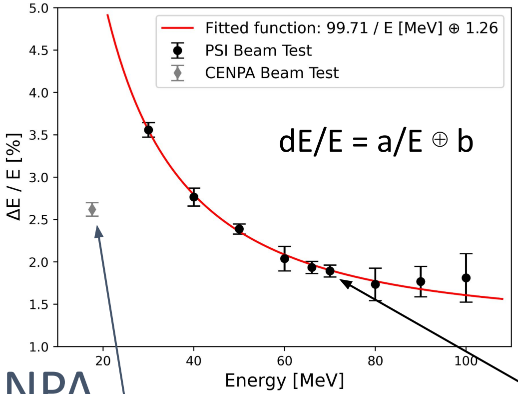


Energy/spatial resolution of LYSO array

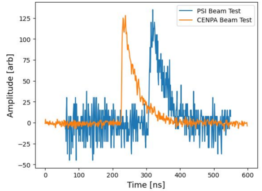
- 1.8% energy resolution for 70 MeV e+
  - Surrounding NaI detectors used to veto events with leakage from the LYSO
  - Significant noise contribution due to PMTs

$$\text{Li-7} + p \rightarrow \text{Be-8} + \gamma, E_\gamma = 17.6\text{MeV}$$

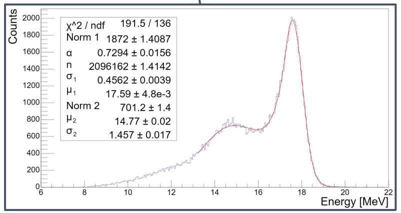
- 2.6% energy resolution for 17.6 MeV gammas from p-Li reaction
  - No NaI detectors
  - PMT voltage dividers upgraded which reduced noise
- 0.6 cm spatial resolution using energy sharing between crystals in the array



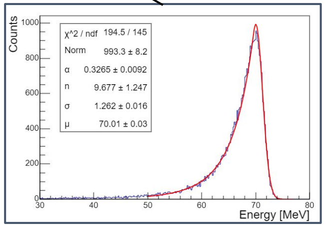
2 MeV pulses



CENPA



PSI

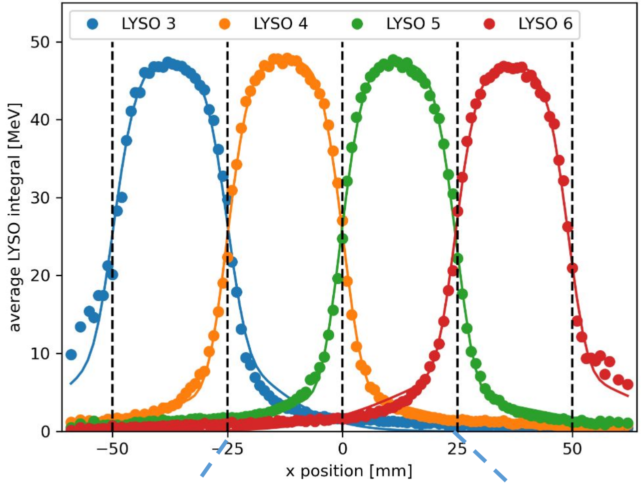


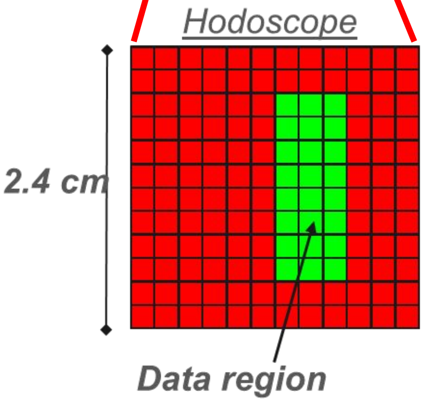
2.6% @ 17.6 MeV
Improved PMT bases allowed for higher operational voltage that lowered noise

1.8% @ 70 MeV
High noise due to low PMT operational voltage degraded energy resolution

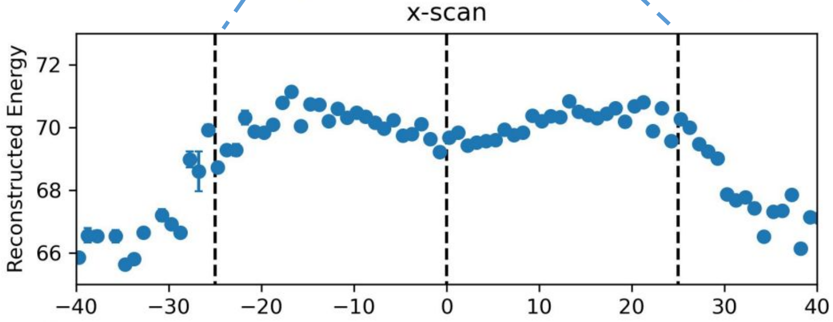
Uniformity across Crystal Boundary at 70 MeV

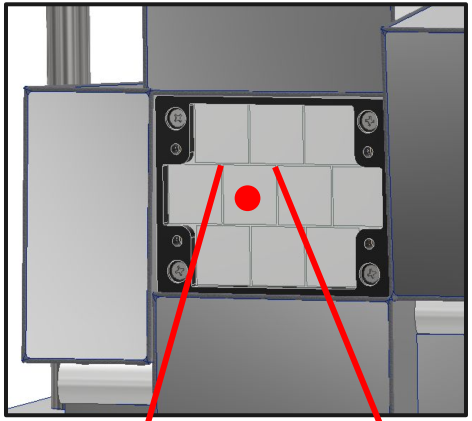
- Used X-Y hodoscope and moving table to scan front of array



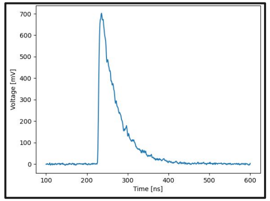


Result: Uniformity: 99.5 % middle / 97.7% array





Current Status of LYSO reconstruction in Simulation



Detector Response

Truth Energies and Times

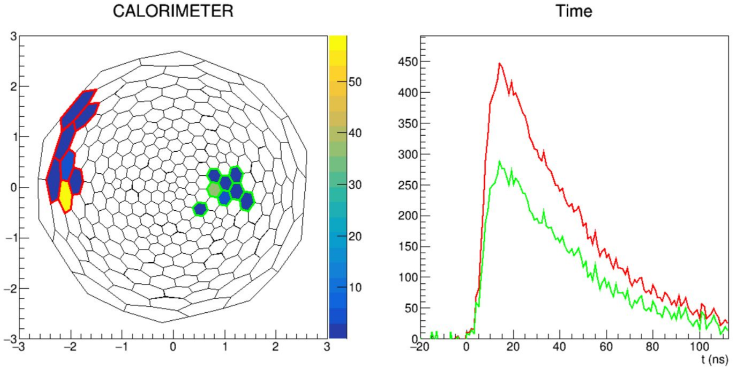
Waveforms

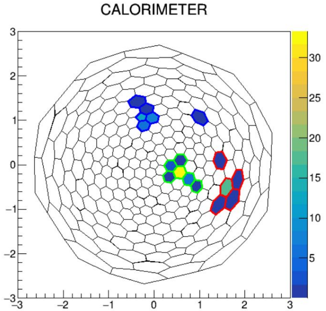
Waveform Fits

Detector response can be skipped

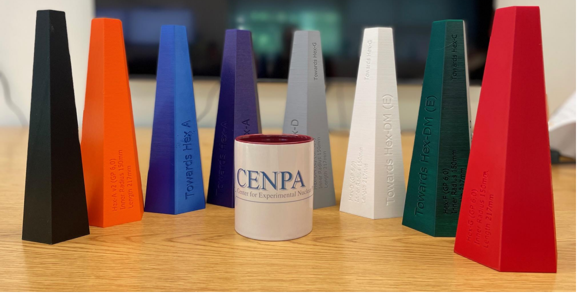
Reconstructed Energies and Times → Clustering Algorithm → Event Recon (Clusters + ATAR Info)

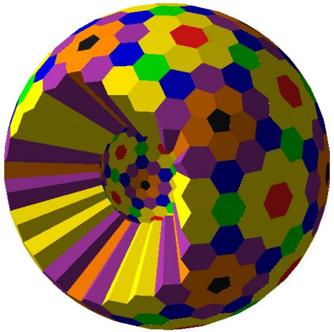
Complete Reconstruction of PiBeta Event





Approximately 6 crystals are lit up per event and most of the energy is deposited in a single crystal. Showers can be very asymmetric at the PIONEER energy scale.





Conclusion of factual presentation

Part II will address:

- Prototyping and development timelines
- Calibrations
- PiBeta
- Effects of gaps between crystals
- LYSO radioactivity
- Tapered crystal effects on uniformity

Backups follow

Optical cements

Optical cements, OK UV-curing

Product description	OK 2008	OK 2009	OK 2030	OK 2035	OK 2055 A
Material number	103.284	104.141	103.392	504.329	423.449
Chemical basis	Epoxy resin, ketone resin, amine hardener	Epoxy resin, ketone resin, amine hardener	Epoxy resin, ketone resin, amine hardener	Epoxy resin, amine hardener	Epoxy resin, amine hardener
Refractive index n_D (20 °C) / n_e (20 °C)	1.559 / 1.563	1.567 / 1.571	1.621	1.692 / 1.700	1.522
Modulus of elasticity (20 °C) [N/mm²]	2,900	2,700	2,000	3,500	2,000
Glass transition temperature [°C]	65	103	57	74	55
Volume shrinkage [%]	5.2	4.4	4.2	5.4	/
Initial viscosity (25 °C), [mPas]	800	1,400	1,150	130	600
Degassing behavior TOC [mg/kg]	/	/	/	≤ 0.5	/
Expansion coefficient [10^{-6}/K]	55 (-30 °C / 50 °C)	31 (at 21 °C)	48 (at 19 °C)	/	/
Useful temperature range [°C]	-55 / 120	-40 / 80	-40 / 80	-40 / 80	-40 / 70
Pot life [min]	90	60	60	90	90
Curing conditions	a) 24 h / RT b) 24 h / RT + 15 h / 50 °C	a) 24 h / RT b) 24 h / RT + 20 h / 50 °C	24 h / RT	24 h / RT + 15 h / 50 °C	24 h / RT
Application characteristics	Standard fine cement, glass-glass corresponds to MIL-A-3920 C, good climate resistance. Optical transmission (20 µm cement layer): min. 90 %T in the range of 310 - 2700 nm, for round and flat optics elements.	Optical cement with adapted n_D (N-BAK4). Transmission from 300 nm, climate-resistant, mainly for flat optic elements. Optical transmission (20 µm cement layer): min. 90% T in the range from 300 - 800 nm.	Optical cement with adapted n_D (F2) for cementing more highly refractive optical elements. Optical transmission (20 µm cement layer): min. 90% T in the range from 340 - 800 nm.	Highly refractive optical cement, two-component. Optical transmission (20 µm cement layer) from 375 nm.	Optical cement for cementing optical function films, especially polar films. Used for larger diameter filters. Optical transmission (20 µm cement layer): min. 90 %T in the range of 340 - 800 nm.
Ordering information	Resin OK 2008 Mat. no. 105.300 Hardener H 980 Mat. no. 103.729	Resin OK 2009 Mat. no. 105.301 Hardener H 980 Mat. no. 103.729	Resin OK 2030 Mat. no. 105.314 Hardener H 950 Mat. no. 103.734	Resin OK 2035 Mat. no. 504.325 Hardener H 970 Mat. no. 105.272	Resin OK 2055 A Mat. no. 423.041 Hardener H 980 Mat. no. 103.729