ZDC updated design

ePIC TIC meeting

October 9th, 2023

Yuji Goto (RIKEN)

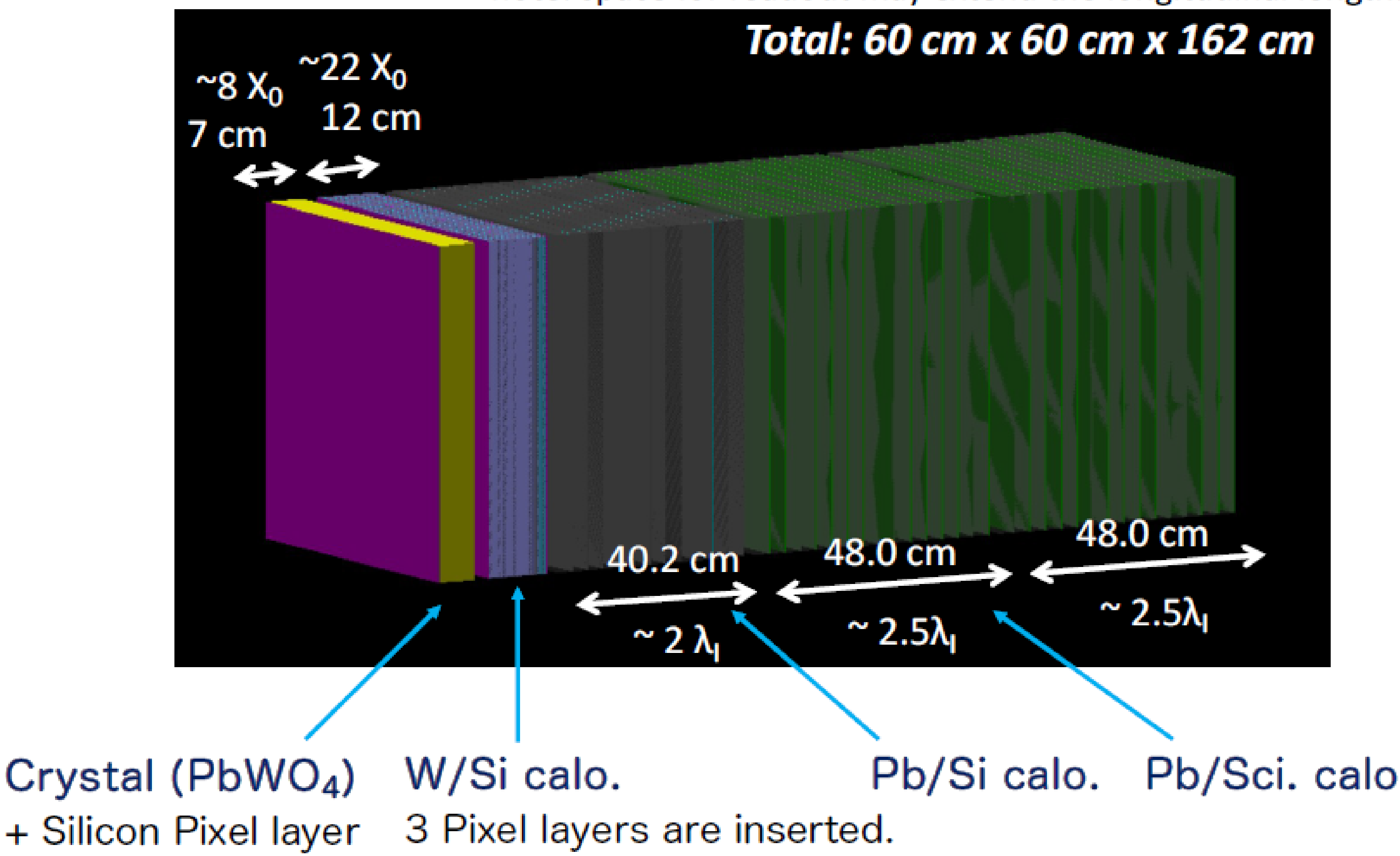
ZDC updated design outline

- EM calorimeter
  - Dimension
  - Crystal scintillator evaluation
- Hadron calorimeter
  - No imaging layer
  - Design
- Position (& timing) layer
  - Pad/pixel size
  - Technology

ePIC-ZDC 1st design

Previous ~~Current~~ ZDC design

*note: space for readout may extend the longitudinal length.



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ZDC requirement

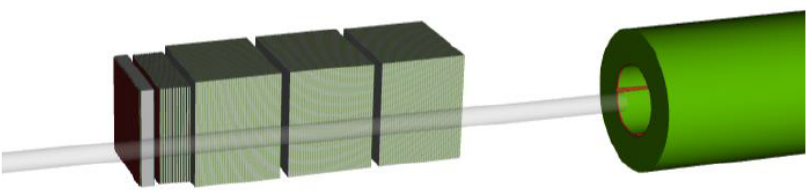
- EM energy resolution
  - Not demanding, but degradation may occur for crystals and/or photon sensors due to radiation
- EM position 0.5mm
  - Fine pitch layer needed
- Hadron energy resolution
  - $50\%/\sqrt{E}$
- Neutron position
  - 3mrad/√E or 6mm @ 275 GeV
  - Better resolution is not necessary since energy resolution also contributes to p_T
  - Crucial to determine the zero degree: still good position resolution is useful
- Calibration: kinematic end point (275 GeV)
- Need dynamic range up to multi TeV for HI

	Energy range	Energy resolution	Position resolution	Others
Neutron	up to the beam energy	$\frac{50\%}{\sqrt{E}} + 5\%$, ideally $\frac{35\%}{\sqrt{E}} + 2\%$	$\frac{3\text{mrad}}{\sqrt{E}}$	Acceptance: 60 cm × 60 cm
Neutron	up to the beam energy	Note: The acceptance is required from meson structure measurement. Pion structure measurement may require a position resoultion of 1 mm.		
Photon	0.1 – 1 GeV	20 – 30%		Efficiency: 90 – 99%
Photon	0.1 – 1 GeV	Note: Used as a veto in e+Pb exclusive J/ψ production		
Photon	20 – 40 GeV	$\frac{35\%}{\sqrt{E}}$	0.5–1 mm	
Photon	20 – 40 GeV	Note: u-channel exclusive electromagnetic π^0 production has a milder requirement of $\frac{45\%}{\sqrt{E}} + 7\%$ and 2 cm, respectively. Events will have two photons, but a single-photon tagging is also useful. Kaon structure measurement requires to tag a neutron and 2 or 3 photons, as decay products of Λ or Σ.		

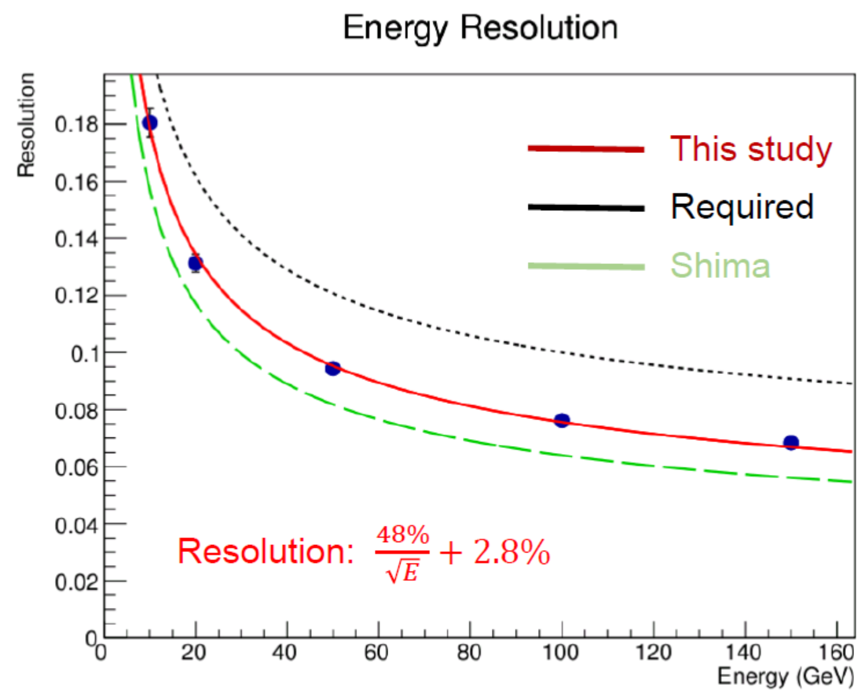
Table 2: Physics requirement for ZDC

ZDC updated design

- Cost reduction design
  - Smaller EMCAL
  - Pb-Si imaging HCAL removed
  - By Po-Ju Lin (NCU) and Michael Pitt (Kansas)



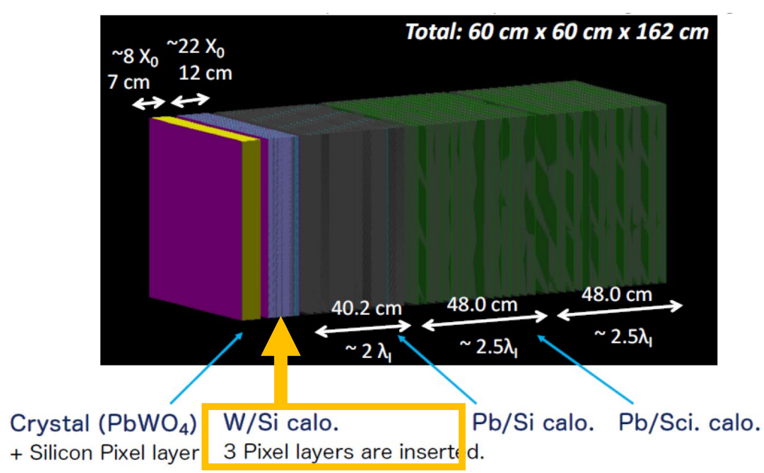
➢ Use only three Pb/Sci blocks to fit the dimension limitation
- Overall length approximately 182.7 cm
- Gaps between crystal-W/Si and W/Si-PbSci: 2 cm
- Gaps between Pb/Sci blocks: 5 cm
- In Pb/Sci: Lead thickness = 10.0 mm, scintillator thickness = 2.5mm

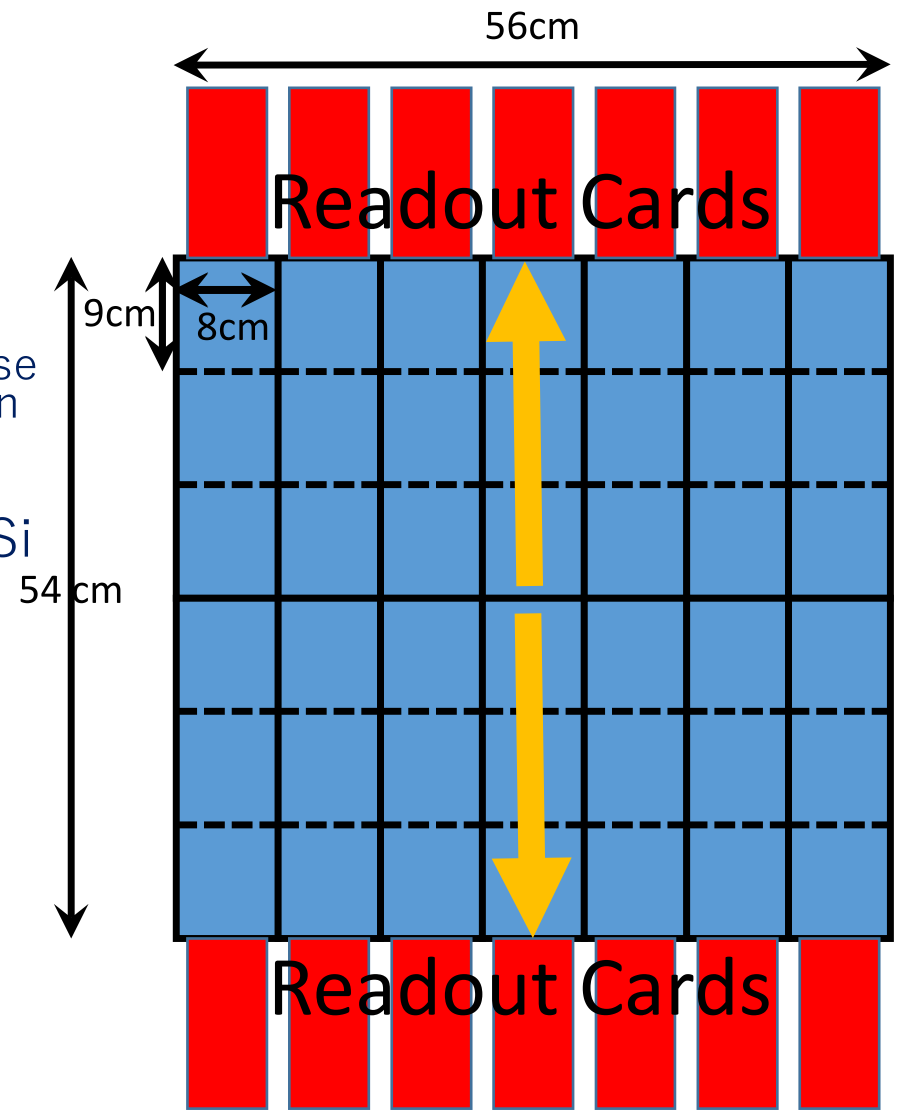


Slide by Po-Ju Lin (NCU)

EM calorimeter

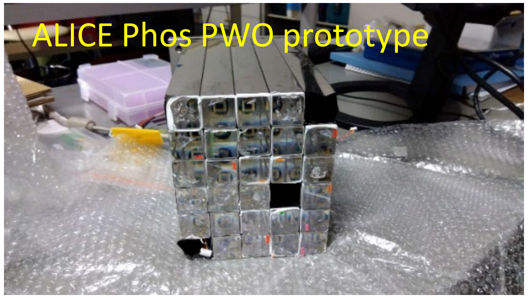
- W-Si imaging calorimeter
  - ALICE FoCal-E Pad technology
- 2nd design
  - Lateral dimension based on FoCal-E Pad sensor size 9cm x 8cm → 6 sensors x 7 sensors = 54cm x 56cm
    - Smaller than the 1st design because EM shower leakage is smaller than hadron shower leakage
  - Number of Si readout layers; e.g. $2X_0$ (7.0mm) x 11 W layers + 11 Si readout layers
    - Cost reduction option

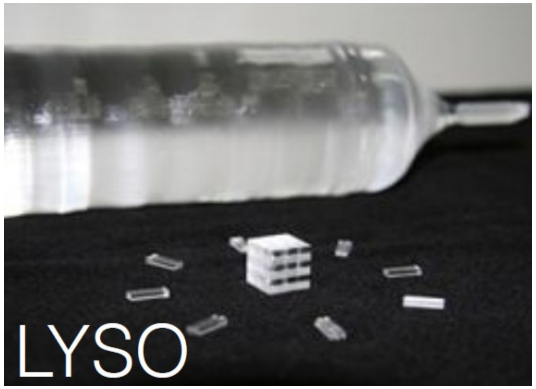


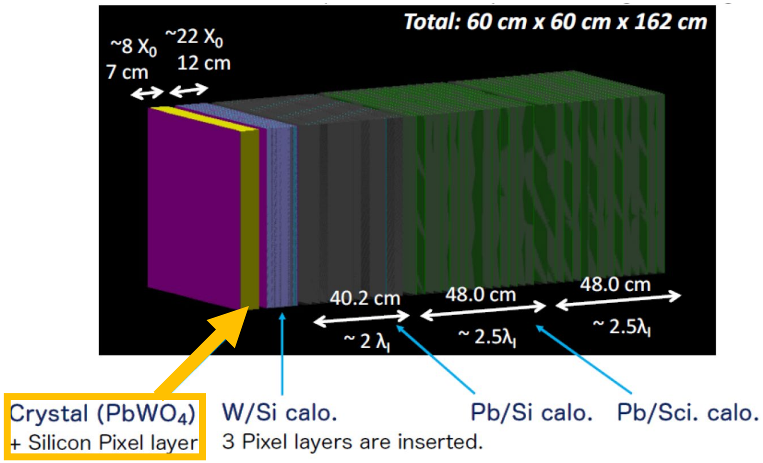


EM calorimeter

- Crystal calorimeter
- 2nd design
  - Lateral dimension 54cm x 56cm matching to W-Si imaging calorimeter
  - Crystal scintillator choice
    - $PbWO_4$ vs LYSO
    - LYSO crystal by Taiwan group (from CMS)
    - Cooperation with B0 EMCAL
- Crystal calorimeter should be removable if possible
  - Necessary only in eA collisions
  - To reduce radiation



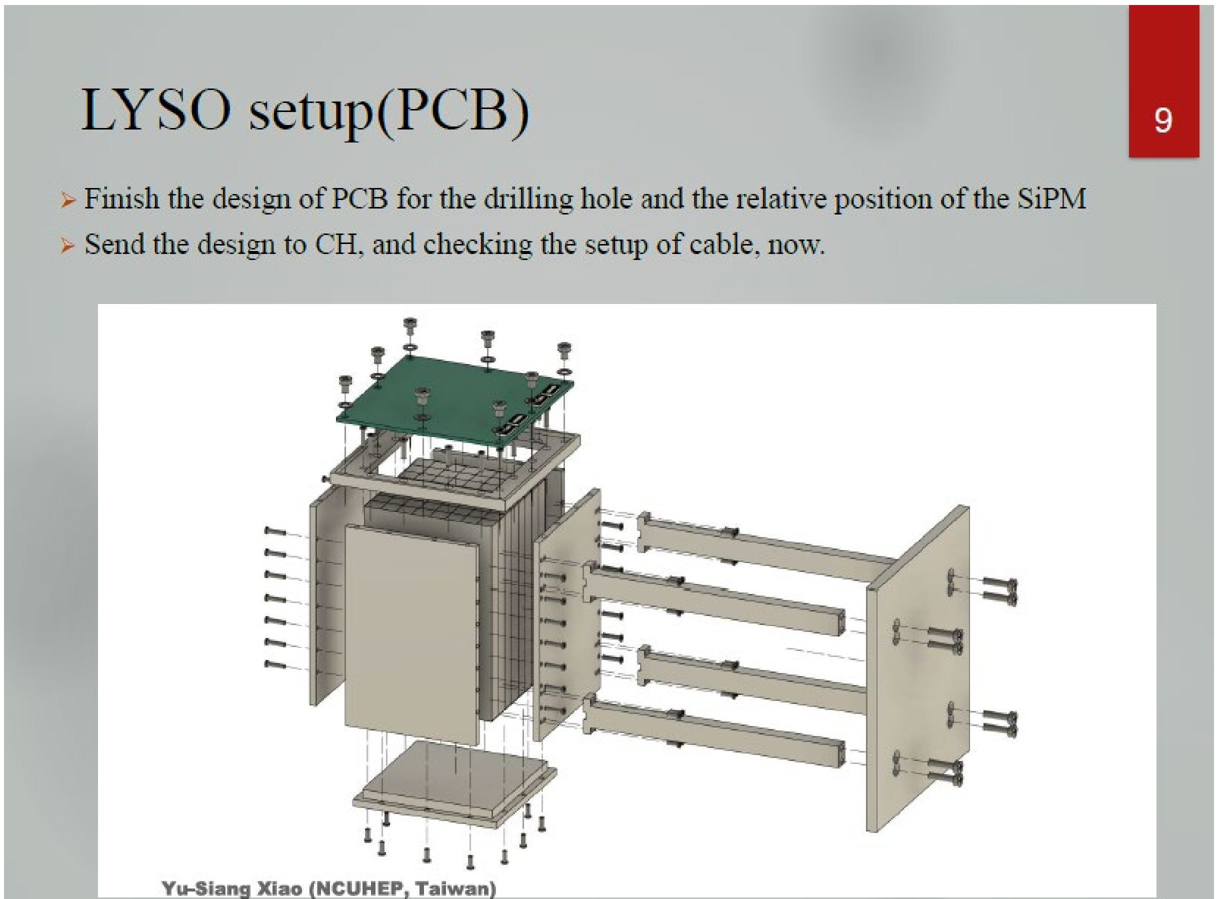




	X_0	LY (ph/MeV)	T dep. of LY (%/K)	Decay time (ns)	λ_{em} nm
$PbWO_4$ (CMS)	0.89 cm	200	-1.98	5 (73%) 14 (23%) 110 (4%)	420
LYSO	1.14 cm	30,000 (market standard)	-0.28	36	420
SciGlass	2.4-2.8 cm	>100		22-400	440-460

EM calorimeter

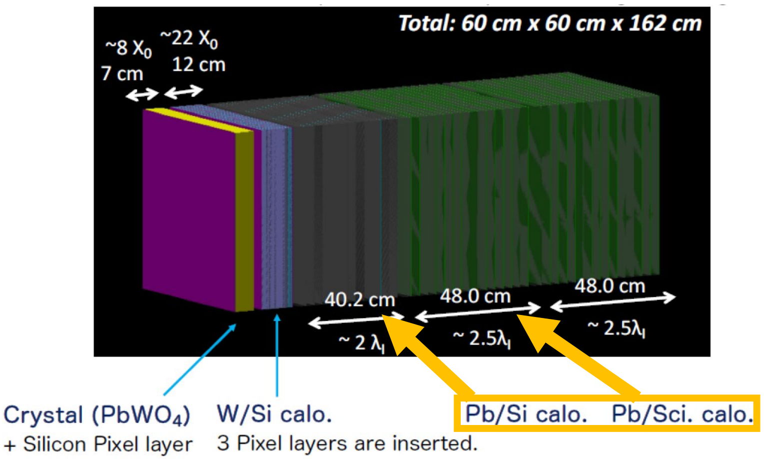
- Crystal calorimeter
  - LYSO test module design for test beam by Taiwan group



Slide by Yu-Siang Xiao (NCU)

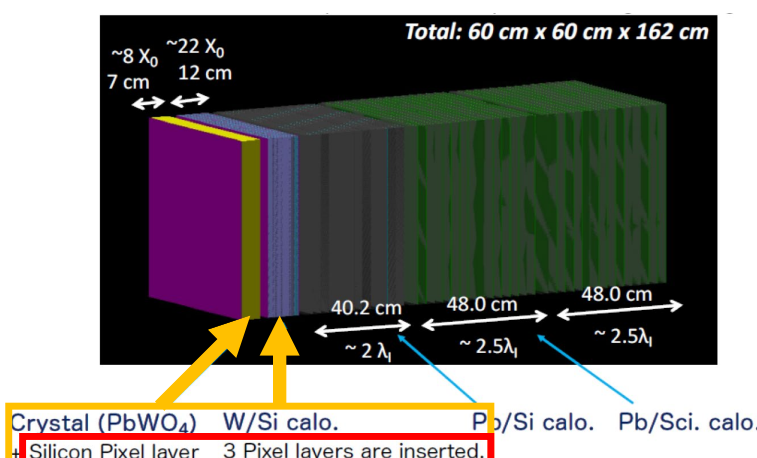
Hadron calorimeter

- 2nd design
  - No Pb-Si imaging calorimeter
  - Pb-(Scintillator + Fused silica) by Korea group
    - Capillary design
  - Presentation by Yongsun Kim (Sejong Univ., Korea)



Position layer

- Front of the crystal calorimeter (1 layer)
- Front + 2 layers inserted in the EM imaging calorimeter (3 layers)
- 2nd design
    - 3mm x 3mm silicon pad with FoCal-E pad technology + simple analogue readout
    - 1mm x 1mm silicon pad with FoCal-E pad technology + simple digital readout
        - Proposed by Tsukuba Univ, Tsukuba Tech Univ, and Nagasaki Institute of Applied Science (ALICE FoCal-E group)
    - FoCal-E pixel technology
        - 30um x 30um MAPS/ALPIDE
    - AC-LGAD layer?

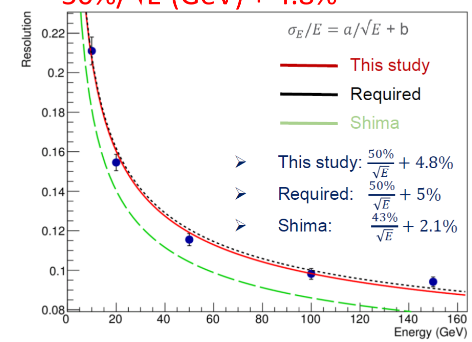


Backup Slides

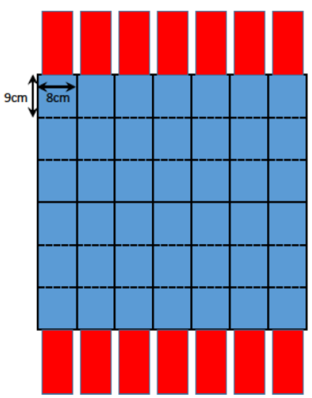
ZDC updated design

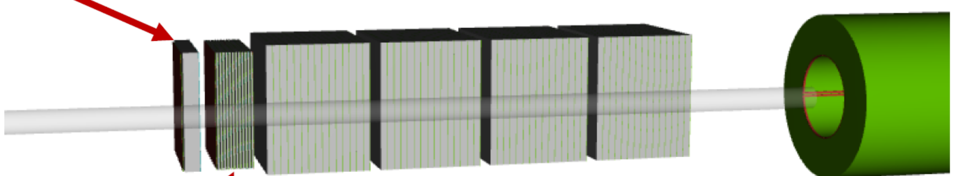
- Cost reduction design
  - Smaller EMCAL
  - Pb-Si imaging HCAL removed
  - By Po-Ju Lin (NCU)

HCAL Pb : Scint = 15 : 1
Neutron energy resolution
= 50%/√E (GeV) + 4.8%



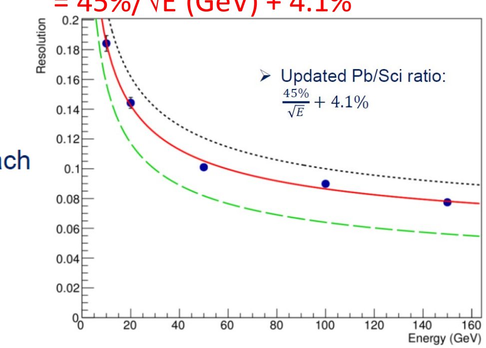
- 1st Silicon & crystal calorimeter:
  - Smaller lateral dimension (x, y) = (56, 54) cm.
- Silicon Pixel lateral size (x, y) = (4, 3) mm





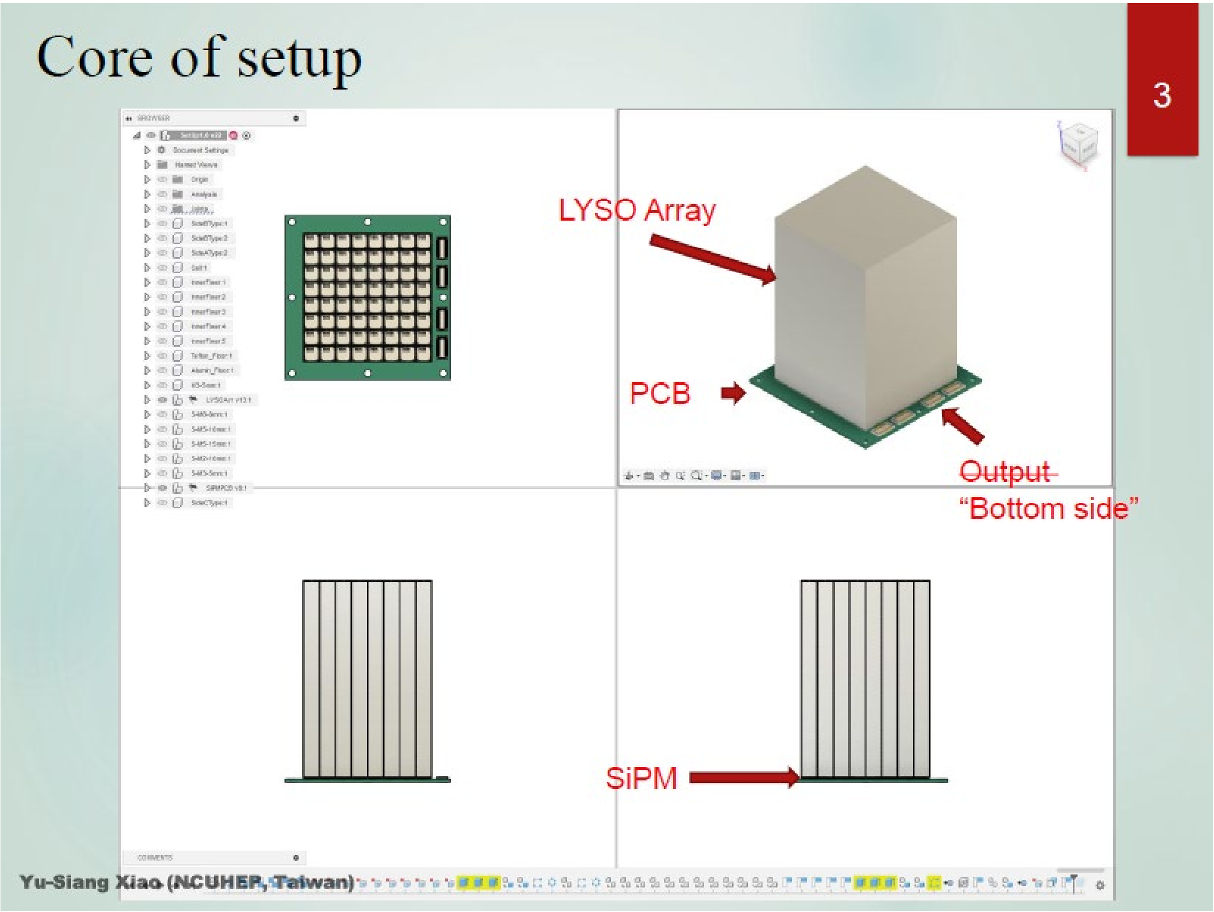
- W-Si imagine calorimeter
  - Smaller lateral dimension (x, y) = (56, 54) cm.
  - Smaller number of layers $1X_0 \times 22 \rightarrow 2X_0 \times 12$ layers
- Pb-Scintillator + fused silica
  - Towers of 10cm x 10cm x 48cm, each module is 60cm x 60cm x 48cm
  - 4 modules
  - Not yet have the implementation of fused silica – only scintillator now
- Pb-Si modules removed

HCAL Pb : Scint = 4 : 1
Neutron energy resolution
= 45%/√E (GeV) + 4.1%



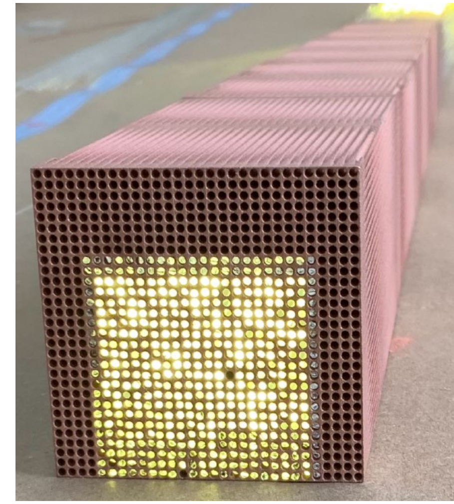
EM calorimeter

- Crystal calorimeter
  - LYSO test module design for test beam by Taiwan group

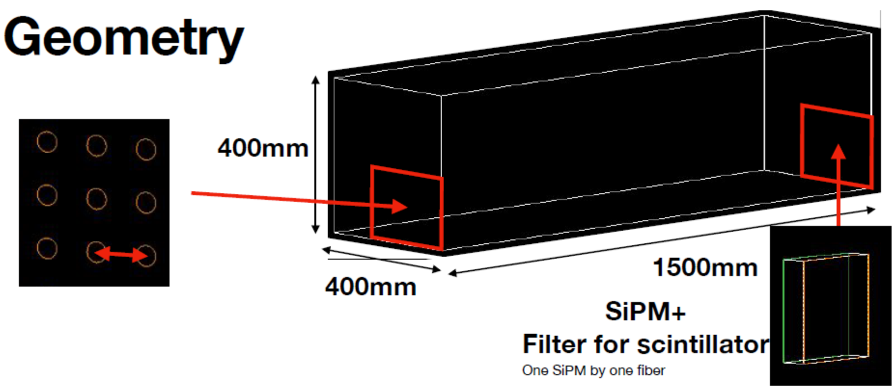


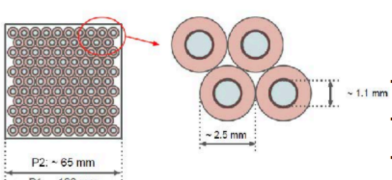
Hadron calorimeter

- Pb-(Scintillator + Fused silica) by Korea group
  - Capillary design



Geometry





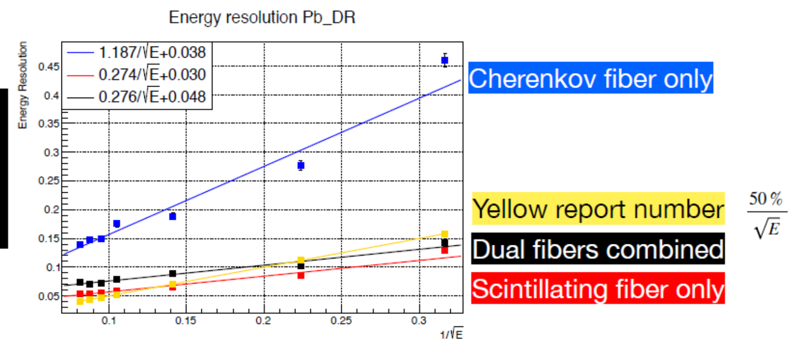
Alice FoCal-H

Alice Focal-h as the reference

- Fiber spacing = 2.5mm
- Number of fiber $160^2 = 25600$
- All fibers are scintillating fibers

Dual readout case

Simulated 7 different neutron energy
10, 20, 50, 90, 110, 130, 150 GeV



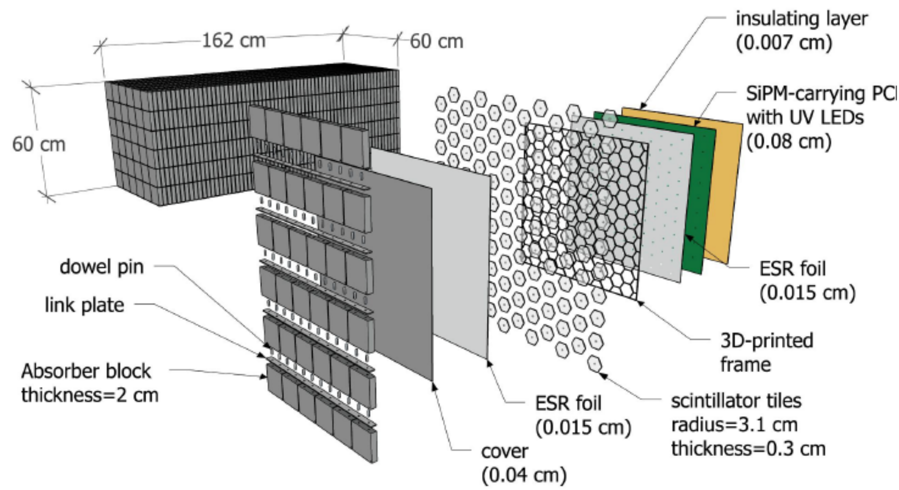
- Quartz fiber: radiation hard, but resolution is too bad by itself
- The use of scintillating fiber is necessary to obtain expected resolution
- The resolution would be even worse if we account readout effect

Hadron calorimeter

- SiPM-on-technology option for ZDC HCAL
  - by Sebouh J. Paul (UCR)
  - ePIC Far-Forward weekly meeting, Sep. 19, 2023
    - https://indico.bnl.gov/event/20611/
  - ePIC Radiation Doses and Particle Fluences
    - https://wiki.bnl.gov/EPIC/index.php?title=Radiation_Doses
    - ZDC neutron fluence < 10^{12} neutron/cm^2 for 6 month operation

A possible SiPM-on-tile ZDC design

- SiPMs and bias & readout (HGROC) and scintillator cells (injection molding) relatively inexpensive.
- Could work with either Fe or Pb, but if we use Fe it could be very inexpensive:
  - Could reuse 2×10×10 cm^3 absorber blocks from STAR



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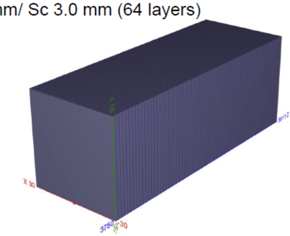
Hadron calorimeter

- SiPM-on-technology option for ZDC HCAL

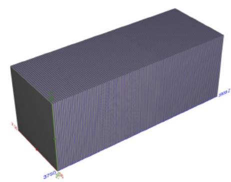
ZDC geometry in DD4HEP

- Two geometries are simulated: Fe/Sc and another Pb/Sc.
- Same digitization and hit-level cuts as applied to HCAL Insert studies (which are based on CALICE studies).
- Larger event sample generated with transverse dimensions of 60x60cm2.
- Neutrons generated over range theta<5.5 mrad and full azimuth

Fe 20 mm/ Sc 3.0 mm (64 layers)



Pb 10 mm/ Sc 2.5 mm (110 layers)



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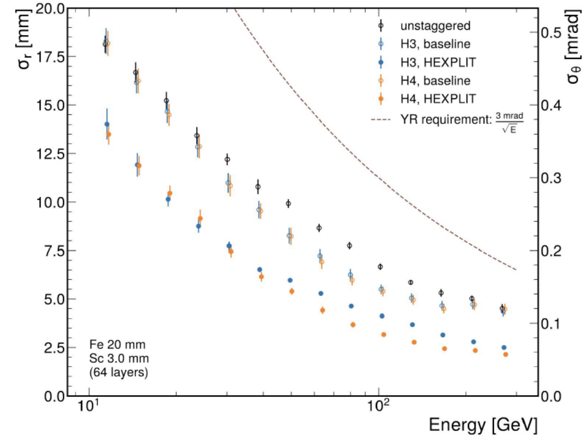
Position resolutions for neutrons with a realistic ZDC model



- Design meets YR requirements with ~25 cm2 cell size, (can be tuned to optimize granularity)
- Meets even ambitious goals relevant for pion structure studies

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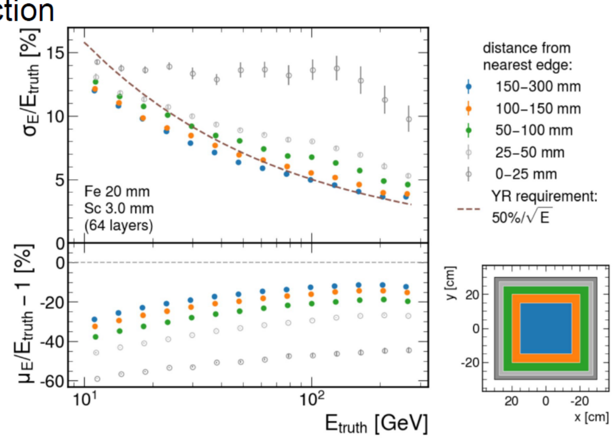
Energy reconstruction

- Baseline or "straw-man" reconstruction adds up energy of all hits with at least 0.5 MIP and divides by the sampling fraction for electrons.
- Bias can be compensated for in "software compensation" techniques, a la CALICE or with AI/ML, which we expect will improve resolution to ~45%/sqrt(E)

ZDC neutron simulations, energy reconstruction



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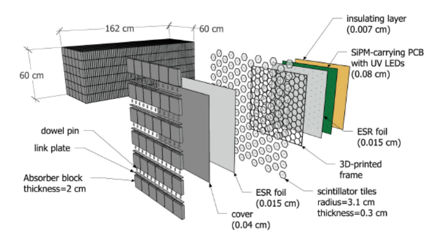
Summary and Conclusions

- We think SiPM-on-tile technology, and HEXPLIT design offer cost-effective solution that could benefit/complement ZDC HCAL design.
- We have shown that a Fe-absorber SiPM-on-tile design can meet YR requirements and more (for position resolution). Very low cost.
- We are also exploring a Pb-absorber SiPM-on-tile design.
- We look forward to further discussion/collaboration with all interested parties



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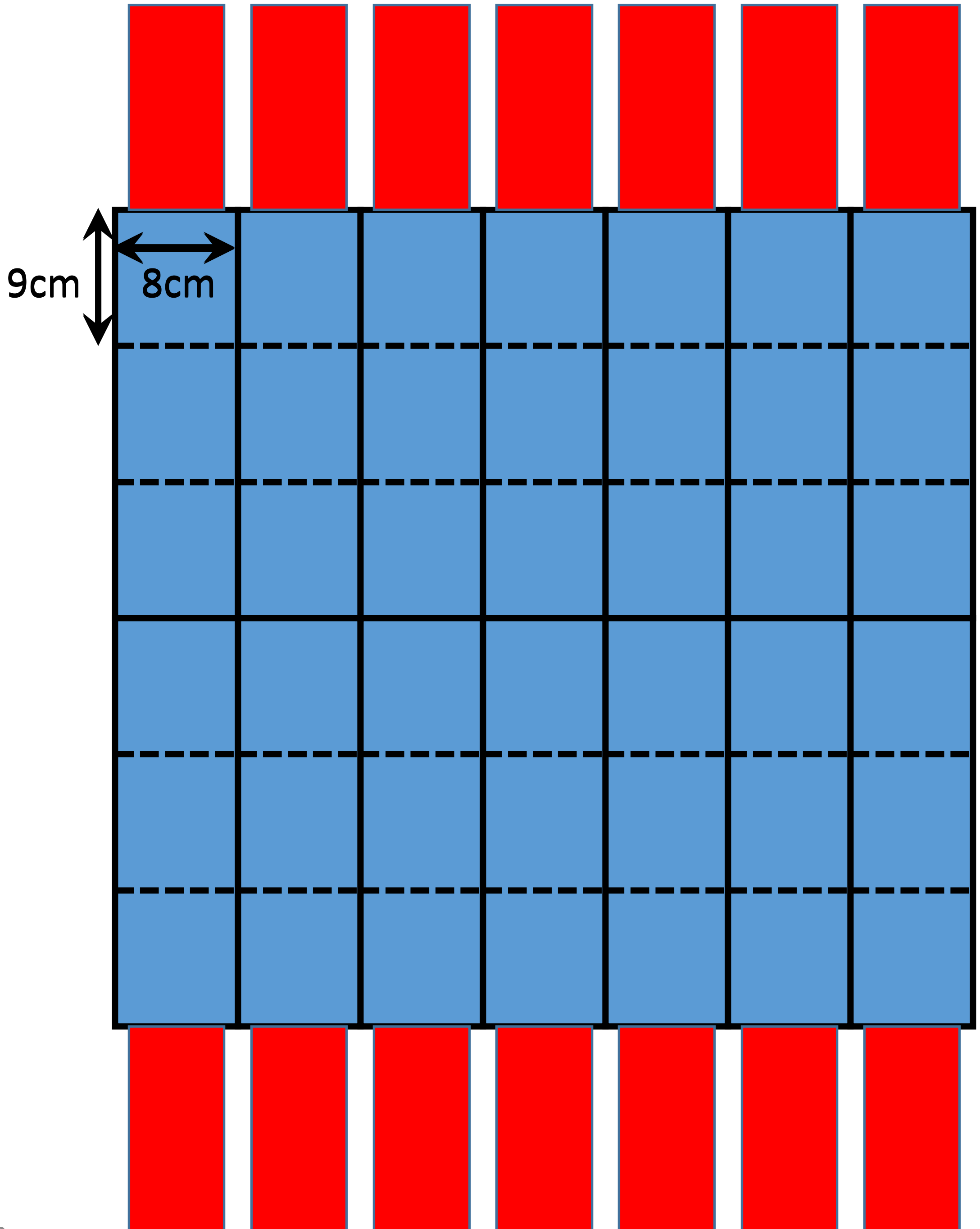

9cm
8cm

ZDC status outline

- ZDC design review
  - Crystal calorimeter
  - Imaging EM calorimeter
  - Hadron calorimeter
  - Position (& timing) layer
- ZDC development
  - Radiation requirement
  - Test beam
  - Cooling & support
- ZDC integration
  - Interference

ePIC ZDC group

- Japan
  - RIKEN
  - Kobe Univ.
  - Shinshu Univ.
  - Univ. of Tsukuba
  - Tsukuba Tech. Univ.
- Taiwan
  - NCU
  - Academia Sinica
- Korea
  - Sejong Univ.
- USA
  - Kansas Univ.
  - PNNL

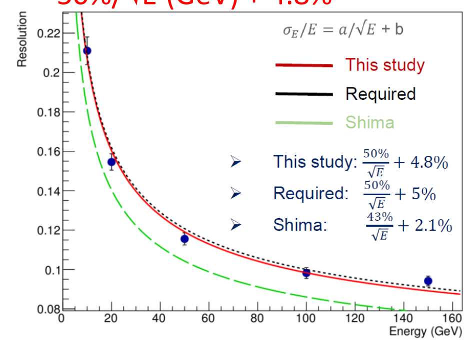
ZDC design review

- Crystal calorimeter
  - 1st design: 60cm x 60cm PWO crystal $8X_0$
  - Design update option:
    - Smaller lateral dimension, 60cm x 60cm necessary to cover lateral hadron shower leakage (EM shower leakage smaller)
- W-Si imaging calorimeter
  - 1st design: 60cm x 60cm W-Si $22X_0$ (22 layers)
  - Design update option:
    - Smaller lateral dimension, e.g. ALICE-FoCal-E Pad size 9cm x 8cm $\rightarrow$ 6 x 7 = 54cm x 56cm
    - Smaller number of layers, e.g. $1X_0$ x 22 layers $\rightarrow$ $2X_0$ x 11 layers?
- Hadron calorimeter
  - 1st design:
    - Pb-Si $0.16\lambda_I$ x 12 layers (40cm)
    - Pb-Scintillator 10cm x 10cm x 48cm ($2.5\lambda_I$) tower, 10 x 10 x 2
  - Design update option:
    - No imaging (Pb-Si) layers
    - Pb-(Scintillator + Fused silica) 10cm x 10cm x 48cm tower 4 x 4?

ZDC design review

- More cost effective design
  - Smaller EMCAL
  - Pb-Si HCAL removed
  - By Po-Ju Lin

HCAL Pb : Scint = 15 : 1
Neutron energy resolution
= 50%/√E (GeV) + 4.8%



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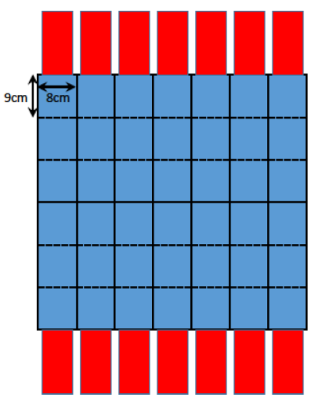

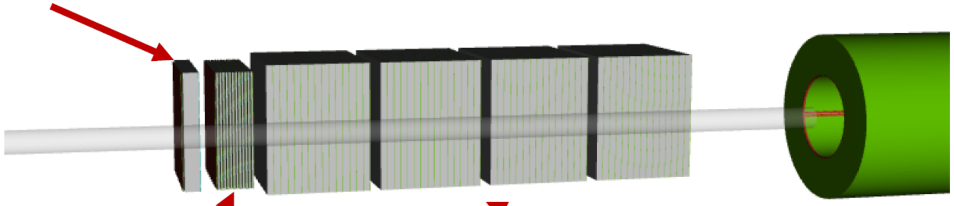

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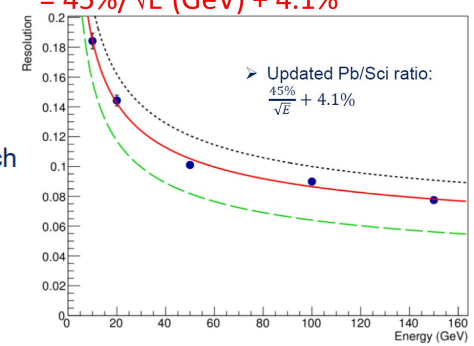

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  - Smaller number of layers $1X_0 \times 22 \rightarrow 2X_0 \times 12$ layers
- Pb-Scintillator + fused silica
  - Towers of 10cm x 10cm x 48cm, each module is 60cm x 60cm x 48cm
  - 4 modules
  - Not yet have the implementation of fused silica – only scintillator now
- Pb-Si modules removed

ZDC design review

- Position layer
    - 3mm x 3mm required
- Open question yet
    - ALICE FoCal-E pixel layer (MAPS)
        - Too good position resolution
    - Smaller pad layer
    - AC-LGAD (position & timing layer)

ZDC design review

- Crystal calorimeter
  - PbWO4 vs LYSO
    - Small prototype to be tested & evaluated @ Tohoku-ELPH in this winter
  - LYSO crystal by Taiwan group (from CMS)
    - More light yield
    - More stable for radiation
    - But higher cost
  - Cooperation with B0 EMCAL started

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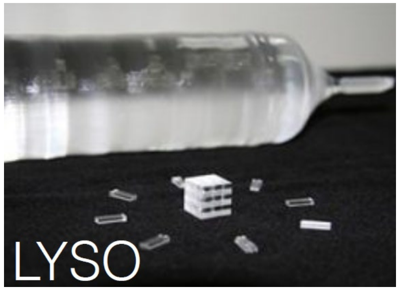
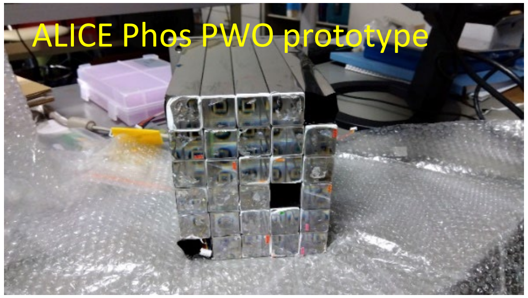
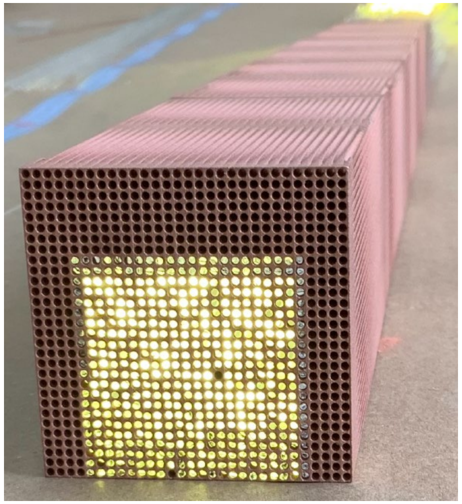






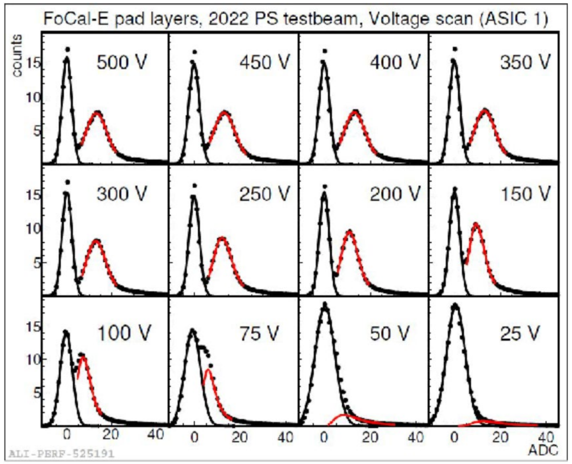
- HCAL
  - Korea group
  - Dual-readout calorimeter

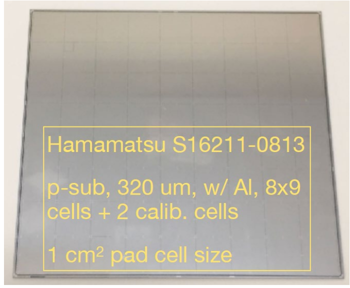
ZDC Development

- Radiation requirement
  - Based on FLUKA simulation by V. Baturin, et al., we assumed 10^{14} neutron/cm^2 lifetime fluence, but this seems be too high.
  - 10^{13} neutron/cm^2 or lower would be appropriate estimation, but it still require radiation hard technology for the ZDC, especially upstream EM calorimeter and even Hadron calorimeter close to the zero degree region.
- Test beam
  - ALICE FoCal-E test beam @ Tohoku-ELPH & CERN-PS/SPS done
  - Crystal calorimeter prototype test beam @ Tohoku-ELPH will be performed in Feb. 2024
- Cooling & support
  - For imaging calorimeter, Taiwan group is going to produce a draft CAD figure based on ALICE FoCal-E design

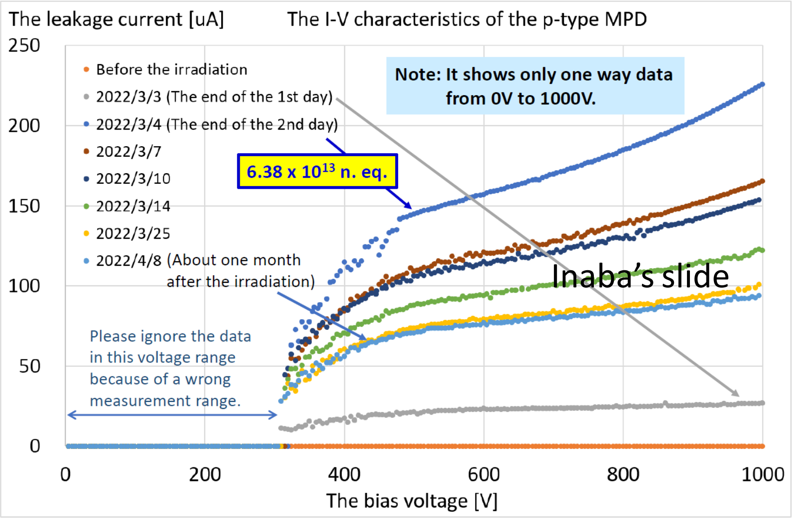
Test-beam studies

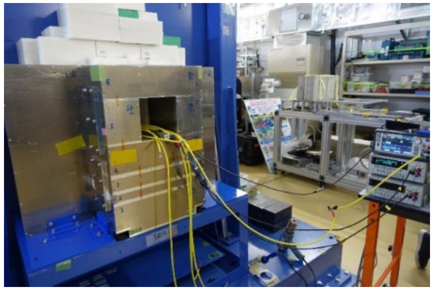
- ALICE FoCal-E test beam @ Tohoku-ELPH & CERN-PS/SPS
  - p-sub sensor, HGCROC v2 for readout
  - Clear MIP peaks observed for almost all channels and layers
  - Reaching full depletion voltage around 300 V





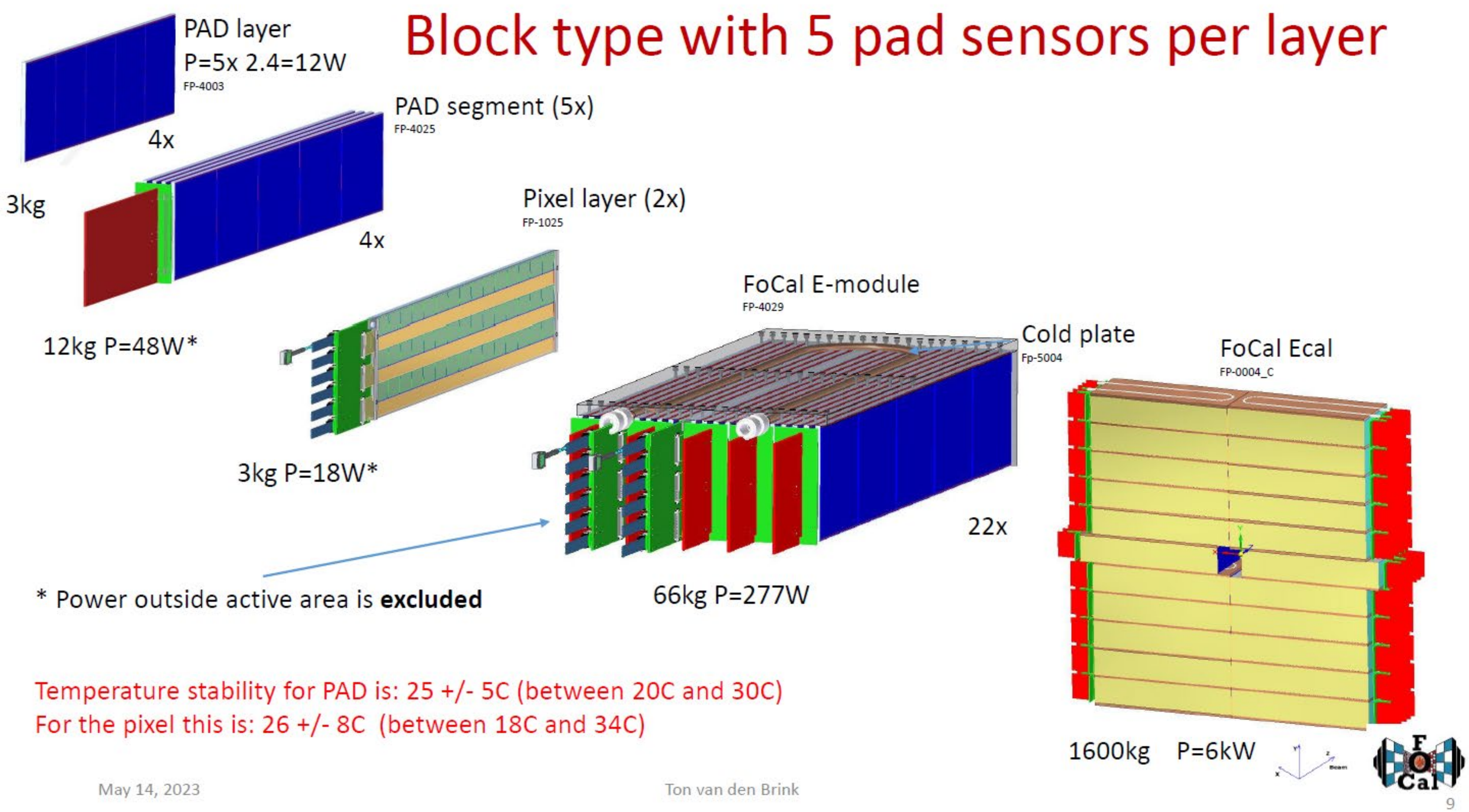
- Neutron irradiation test @ RIKEN-RANS
  - Sensor, photodetectors, chips, cables
  - For FoCal-E, sPHENIX, ePIC-ZDC
  - Up to ~10^{14} neutrons/cm^2





ALICE-FoCal structure

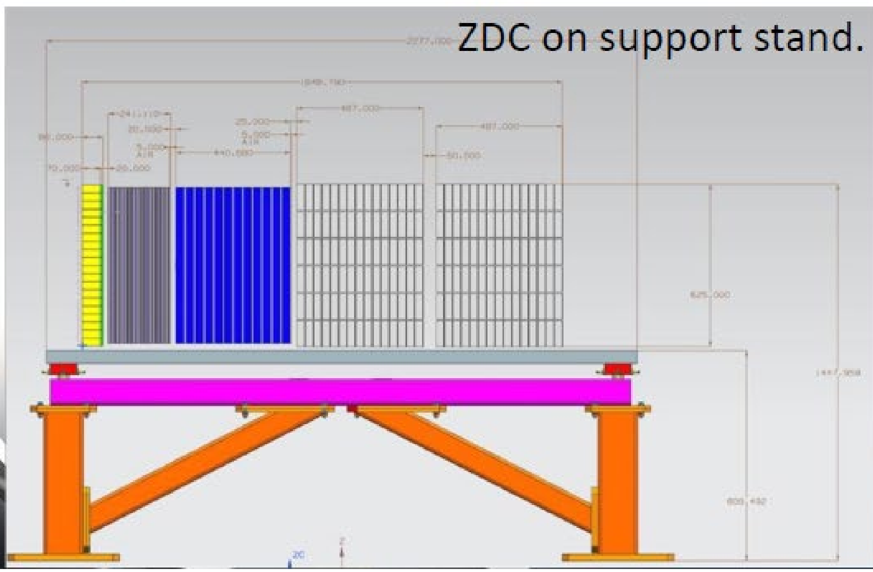
- Including cooling & support

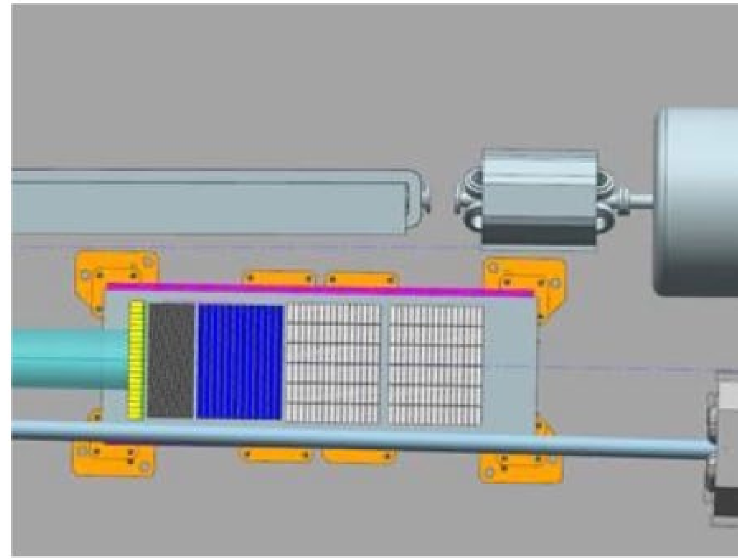


ZDC integration issues

Integration Issues

- ZDC sits outside of the beampipe - main integration issue is keeping it clear of magnet cryostats, crab cavity on electron side, and hadron beam pipe.





- Potential interference with hadron beamline → needs some follow-up with hadron beamline experts.
  - Need 2-3cm clearance between ZDC components and beam pipe, but this needs follow-up.

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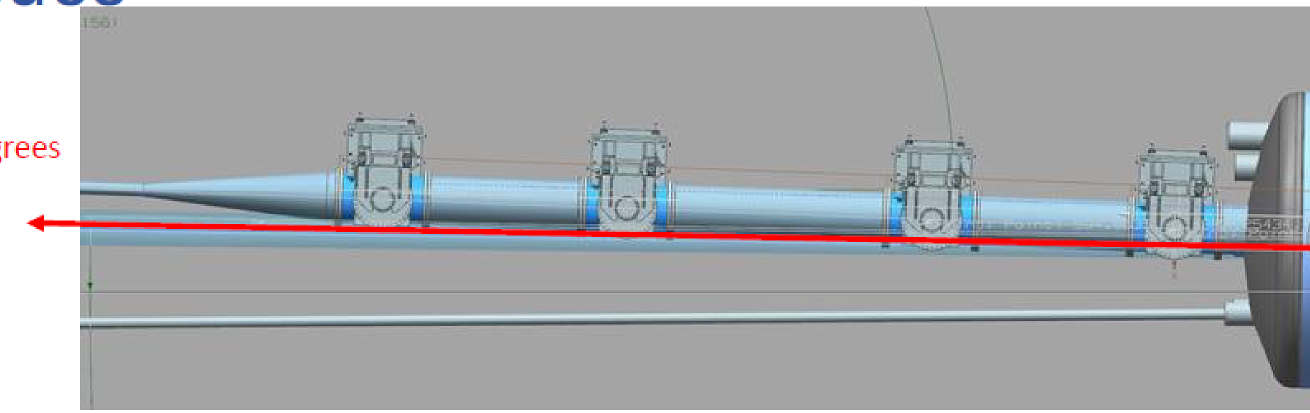
Slide shown by Alex Jentsch in Warsaw meeting in July

ZDC integration issues

Integration Issues



- <u>Neutral particle cone faces two issues:</u>
  - Exit from beampipe at very shallow angle (~ 22mrad) → effective material length O(10cm) for 2mm thick beam pipe wall!
  - With inclusion of OMD/RP support - interference of zero angle neutrals with flanges/support components!
- **This needs some major optimization (underway).**
  - **The present beampipe design was done by Alex Jentsch as a placeholder back in 2021 - we are in need of an engineer to advance the design and aid in optimization (project is aware – in progress).**

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Slide shown by Alex Jentsch in Warsaw meeting in July