# *ePIC-ZDC W-Si EMCAL*

ePIC TIC meeting

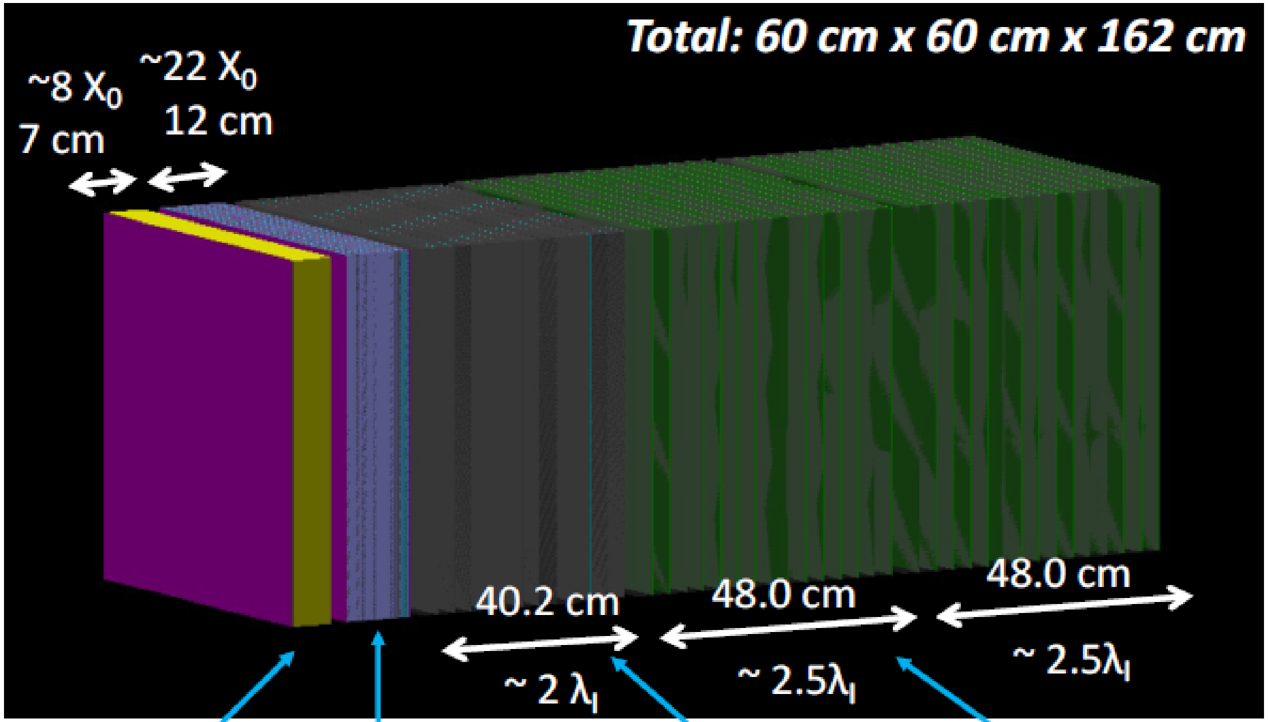
December 18th, 2023

Yuji Goto (RIKEN)

# ePIC-ZDC 1st design

## Previous ~~Current~~ ZDC design

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




Crystal ($PbWO_4$) + Silicon Pixel layer

W/Si calo. 3 Pixel layers are inserted.

Pb/Si calo.

Pb/Sci. calo.

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# ZDC requirement

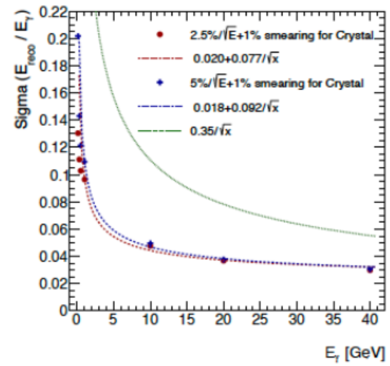
- EM energy resolution
  - Not demanding, but degradation may occur for crystals and/or photon sensors due to radiation
- EM position 0.5mm
  - Fine pitch layer needed
- Hadron energy resolution
  - $50\%/\sqrt{E}$
- Neutron position
  - $3\text{mrad}/\sqrt{E}$ or 6mm @ 275 GeV
  - Better resolution 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

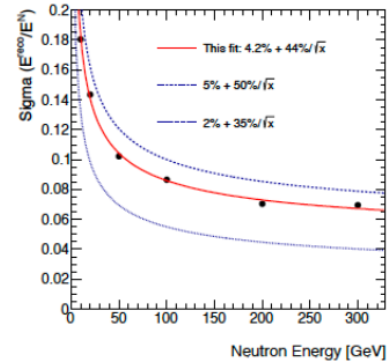
| | Energy range | Energy resolution | Position resolution | Others |
|---|---|---|---|---|
| Neutron | up to the beam energy | $\frac{50\%}{\sqrt{E}} + 5\%$, ideally $\frac{35\%}{\sqrt{E}} + 2\%$ | $\frac{3\text{mrad}}{\sqrt{E}}$ | Acceptance: 60 cm × 60 cm |
| | | Note: The acceptance is required from meson structure measurement. Pion structure measurement may require a position resoultion of 1 mm. | | |
| Photon | 0.1 – 1 GeV | 20 – 30% | | Efficiency: 90 – 99% |
| | | Note: Used as a veto in e+Pb exclusive $J/\psi$ production | | |
| | 20 – 40 GeV | $\frac{35\%}{\sqrt{E}}$ | 0.5–1 mm | |
| | | Note: u-channel exclusive electromagnetic $\pi^0$ 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 $\Lambda$ or $\Sigma$. | | |

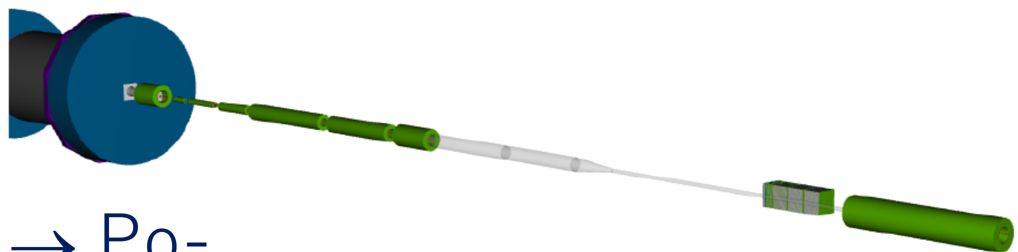
**Table 2:** Physics requirement for ZDC

# *ZDC previous design*

- Simulation by S. Shimizu
  - RIKEN→KEK/ATLAS in 2022
- Single particle simulation
  - Required resolution obtained
- Implemented in ECCE and ePIC simulation software



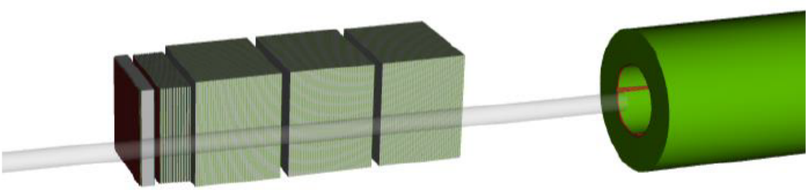



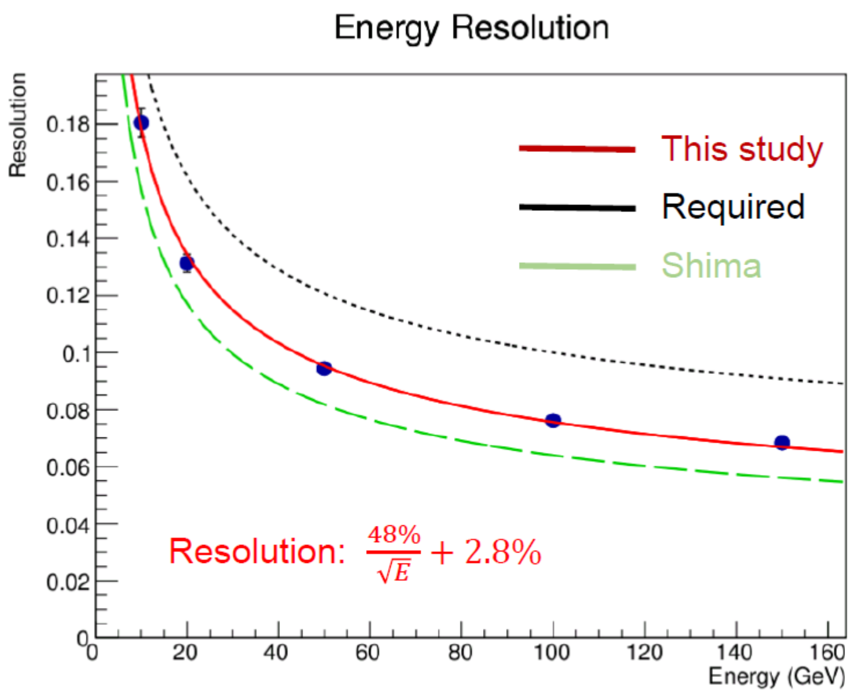
- Simulation: S. Shimizu → Po-Ju Lin (NCU)

| ECCE-style ZDC | git repository | status | command |
| --- | --- | --- | --- |
| Geometry | eic/epic* | checked OK | dd_web_display → geometry viewer |
| Simulation | | checked OK | ddsim → root file |
| Reconstruction | eic/EICrecon | raw hits collection container can be included in the output file | eicrecon → root file |

# ZDC updated design

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



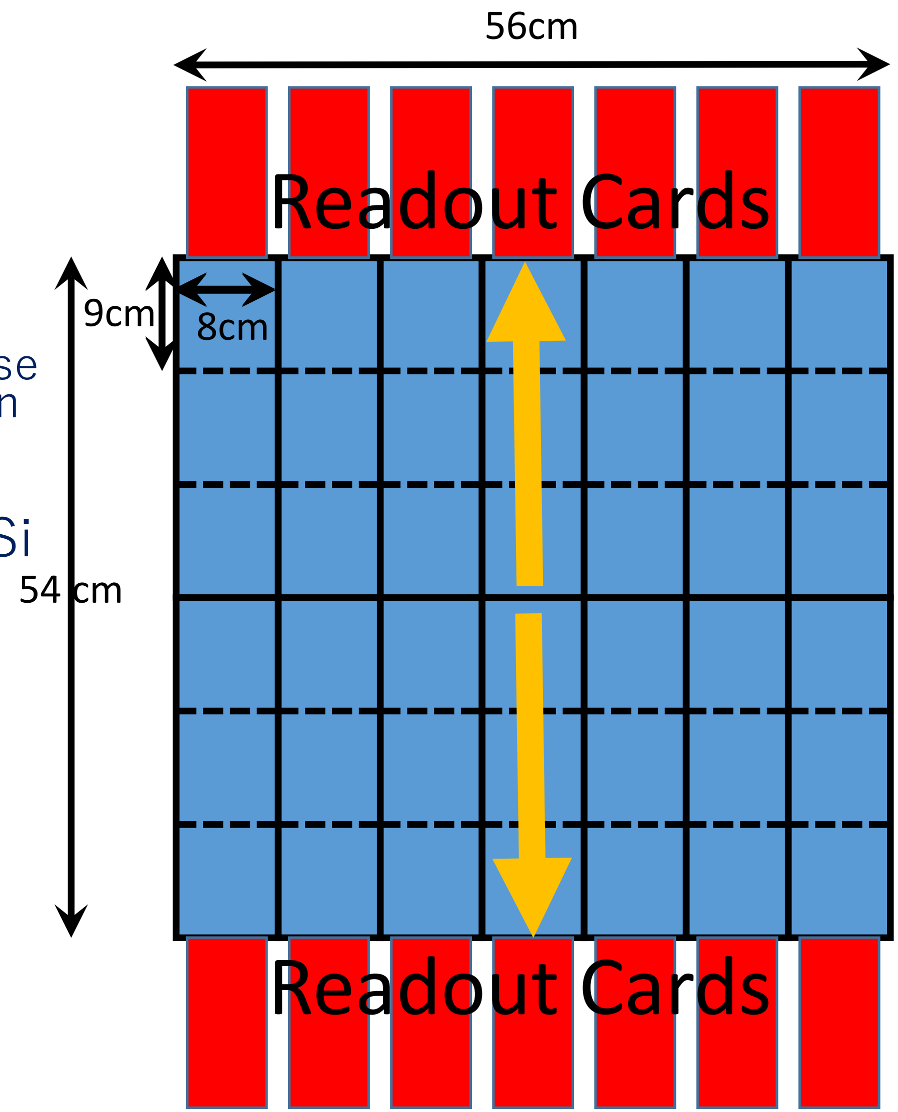


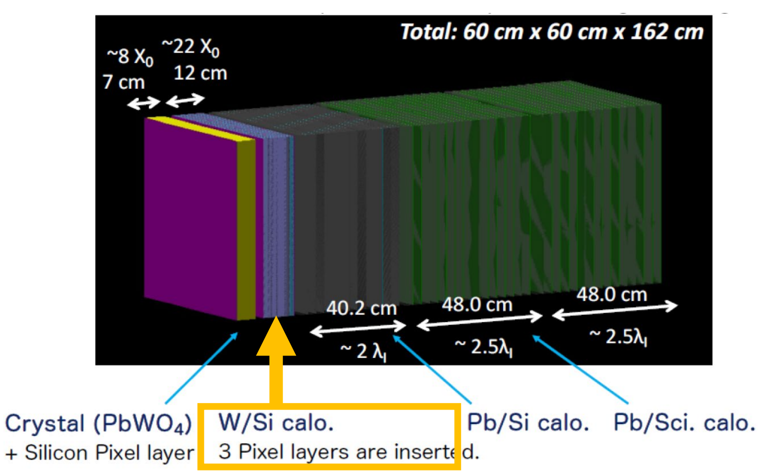

➢ Use only three Pb/Sci blocks to fit the dimension limitation
- Overall length approximately 182.7 cm
- Gaps between crystal-W/Si and W/Si-PbSci: 2 cm
- Gaps between Pb/Sci blocks: 5 cm
- In Pb/Sci: Lead thickness = 10.0 mm, scintillator thickness = 2.5mm

Slide by Po-Ju Lin (NCU)

# EM calorimeter

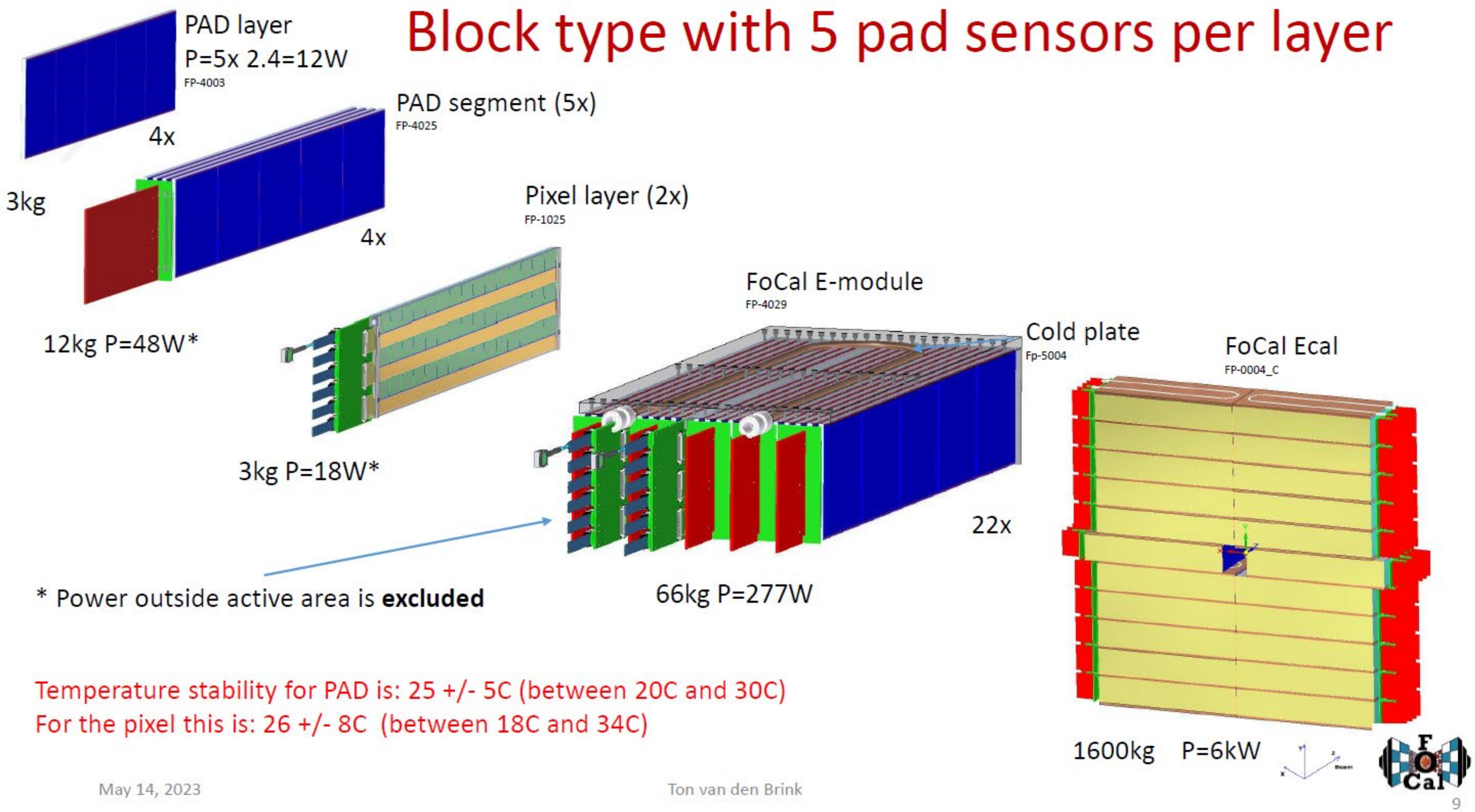
- W-Si imaging calorimeter
  - ALICE FoCal-E Pad technology
- 2nd design
  - Lateral dimension based on FoCal-E Pad sensor size 9cm x 8cm → 6 sensors x 7 sensors = 54cm x 56cm
    - Smaller than the 1st design because EM shower leakage is smaller than hadron shower leakage
  - Number of Si readout layers;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



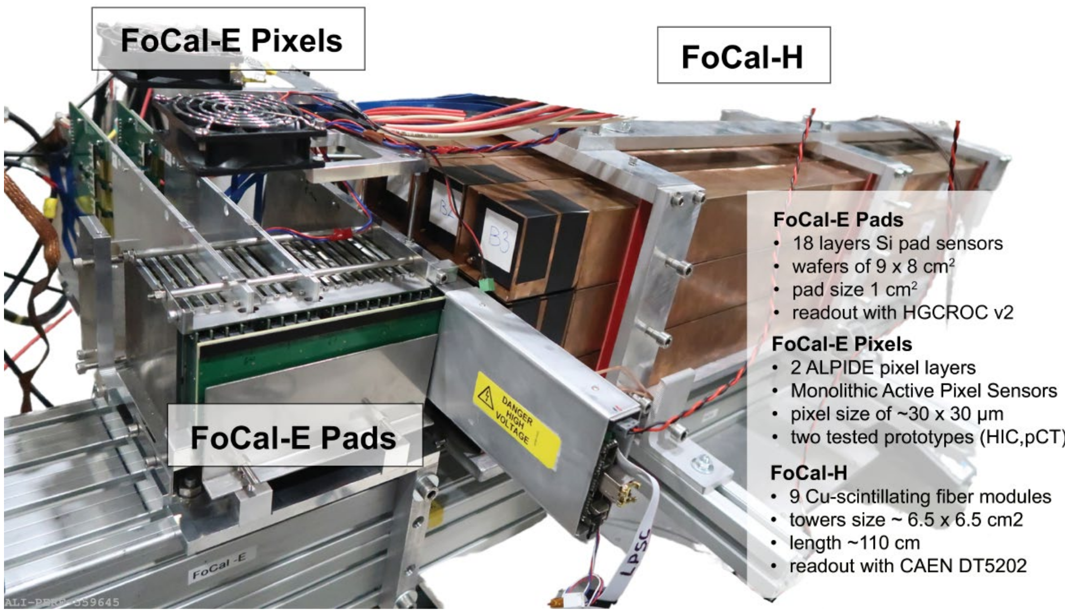
# *FoCal-E design*

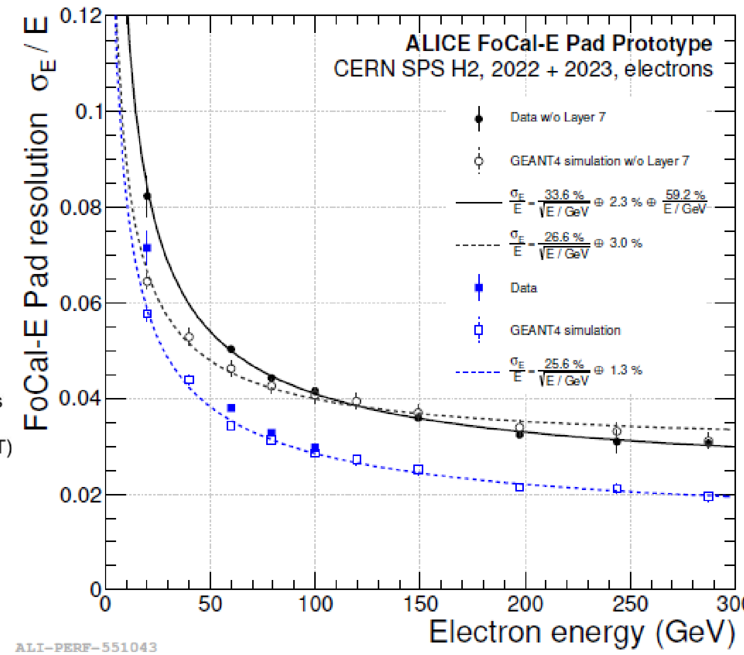
- Including cooling & support



# *FoCal test beam*

- arXiv/2311.0413
  - Various test beams in 2021-23 at CERN PS and SPS




- Test beams in Japan
  - FoCal-E Pad test beams at Tohoku Univ. ELPH
    - Next: February 2024
  - Neutron irradiation test in 2022-23 at RIKEN RANS
    - Sensor, photodetectors, chips, cables

# ePIC ZDC W-Si EMCAL cost

- Based on ALICE-FoCal-E
  - 88cm x 90cm, 110 towers
  - 1cm x 1cm /cell, 8 x 9 cells / tower
  - Si Pad 18 layers
    - Si Pad sensors:2,000kCHF = $2,200K
    - Si Pad readout:550kCHF = $605K
    - Si Pad power:250kCHF = $275K
  - W plates (3.5 mm) 20 layers
    - 500kCHF = $550K
- ePIC-ZDC W+Silicon EMCAL
  - 60cm x 60cm, 50 towers
  - Si Pad sensors: 1cm x 1cm /cell
    - $2,200K x 50 / 110 / 18 layers = $55.6K/layer
  - Si Pad readout + power
    - $880K x 50 / 110 / 18 layers = $22.2K/layer
  - Si small-Pad sensors: 3mm x 3mm /cell
    - Assume same price of sensor: $55.6K/layer
  - Si small-Pad readout + power
    - Number of channels 10x10/3/3 times more
    - $22.2K x 10x10/3/3 = $247K/layer
  - W plates (3.5 mm)
    - $550K x 50 / 110 / 20 layers = $12.5K/layer

# ePIC ZDC W-Si EMCAL cost

- Si Pad sensor 20 layers
  - $55.6K x 20 = $1,110K
- Si Pad readout 20layers
  - $22.2K x 20 = $440K
- Si small-Pad sensor 3 layers
  - $55.6K x 3 = $170K
- Si small-Pad readout 3 layers
  - $247K x 3 = $740K
- W plates (3.5 mm) 22 layers
  - $12.5K x 22 = $270K
- Total: $2,730K

# *Backup Slides*

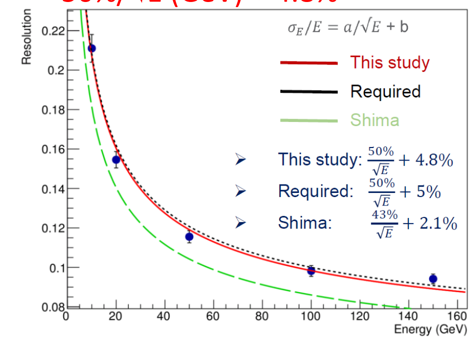
# ZDC updated design outline

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

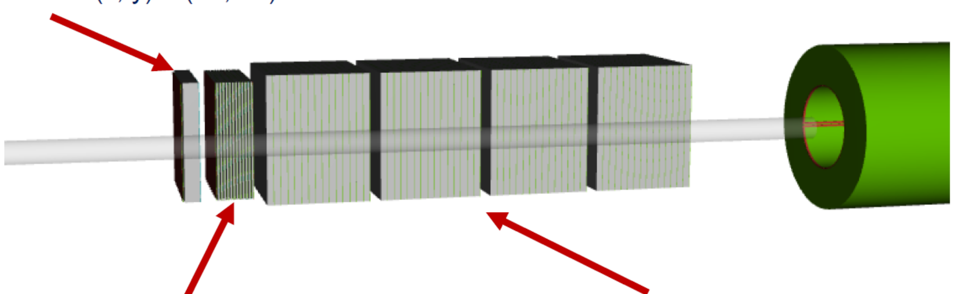
# *ZDC updated design*

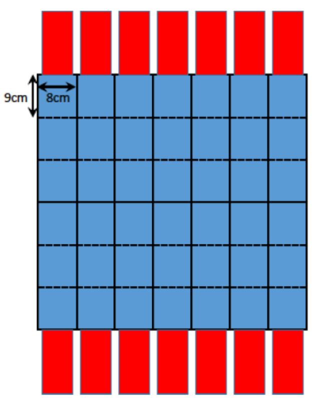
- Cost reduction design
  - Smaller EMCAL
  - Pb-Si imaging HCAL removed
  - By Po-Ju Lin (NCU)

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



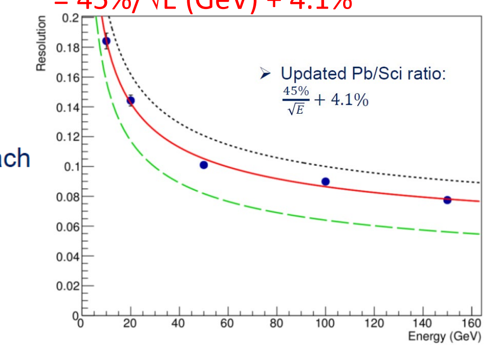

- 1st Silicon & crystal calorimeter:
  - Smaller lateral dimension (x, y) = (56, 54) cm.
- Silicon Pixel lateral size (x, y) = (4, 3) mm





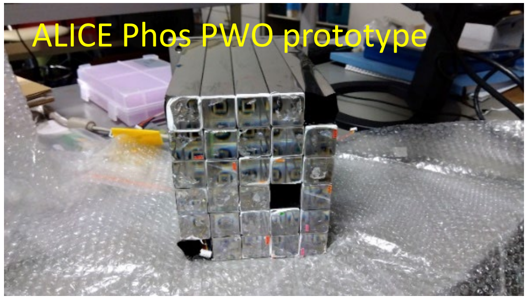

- W-Si imagine calorimeter
  - Smaller lateral dimension (x, y) = (56, 54) cm.
  - Smaller number of layers $1X_0 \times 22 \rightarrow 2X_0 \times 12$ layers
- Pb-Scintillator + fused silica
  - Towers of 10cm x 10cm x 48cm, each module is 60cm x 60cm x 48cm
  - 4 modules
  - Not yet have the implementation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

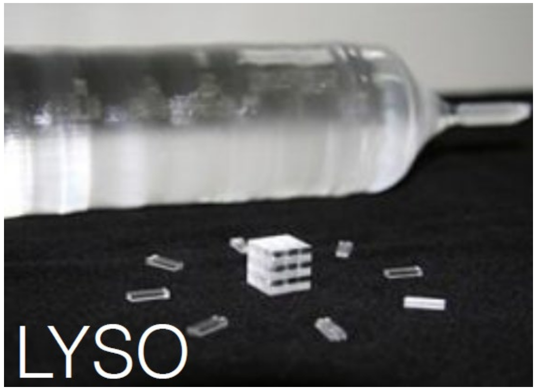
HCAL Pb : Scint = 4 : 1
Neutron energy resolution
= 45%/√E (GeV) + 4.1%

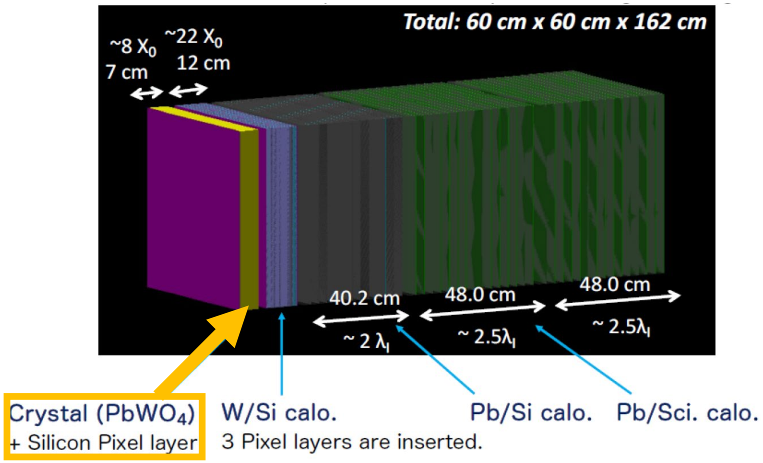


# *EM calorimeter*

- Crystal calorimeter
- 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



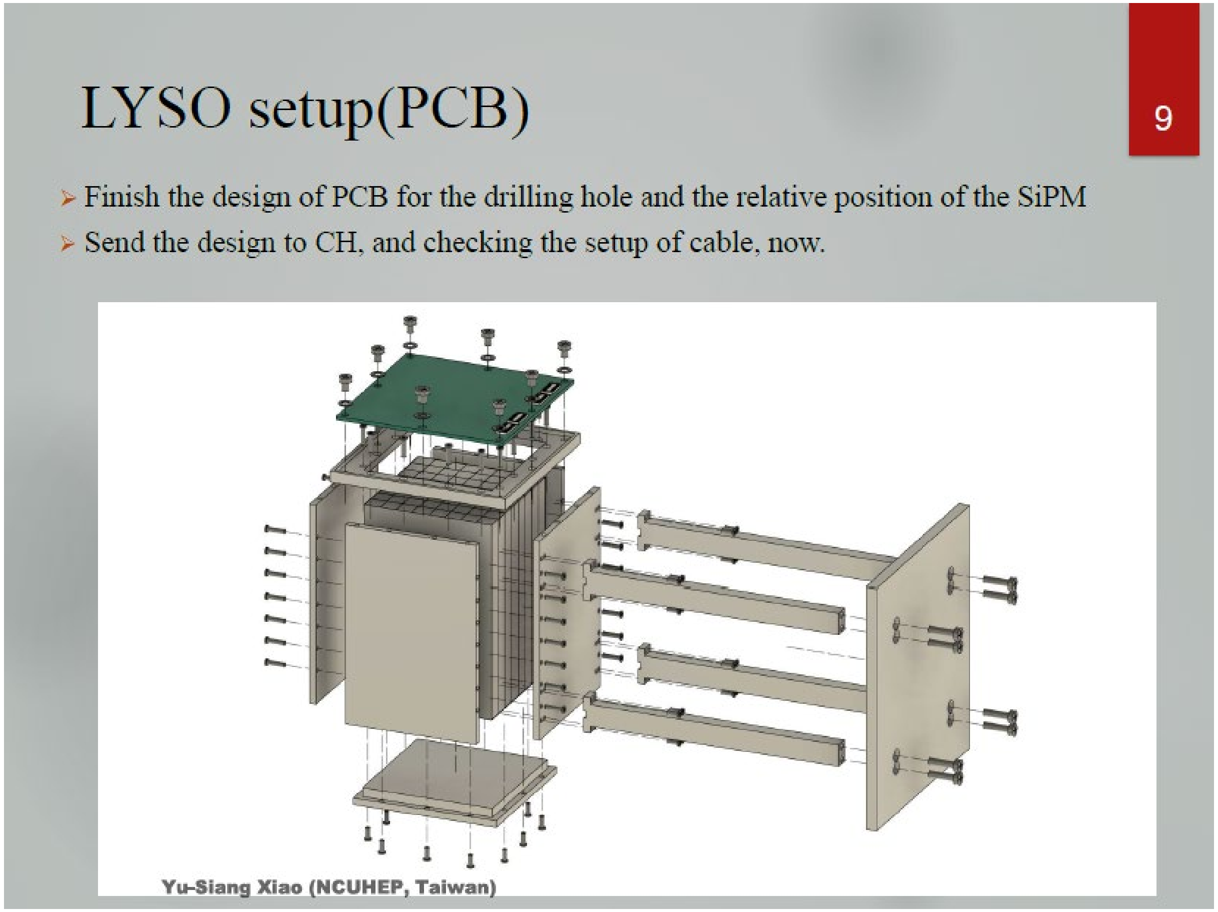




| | $X_0$ | LY (ph/MeV) | T dep. of LY (%/K) | Decay time (ns) | $\lambda_{em}$ nm |
|---|---|---|---|---|---|
| **$PbWO_4$ (CMS)** | 0.89 cm | 200 | -1.98 | 5 (73%)<br>14 (23%)<br>110 (4%) | 420 |
| **LYSO** | 1.14 cm | 30,000 (market standard) | -0.28 | 36 | 420 |
| **SciGlass** | 2.4-2.8 cm | >100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

# *EM calorimeter*

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




Slide by Yu-Siang Xiao (NCU)

# EM calorimeter

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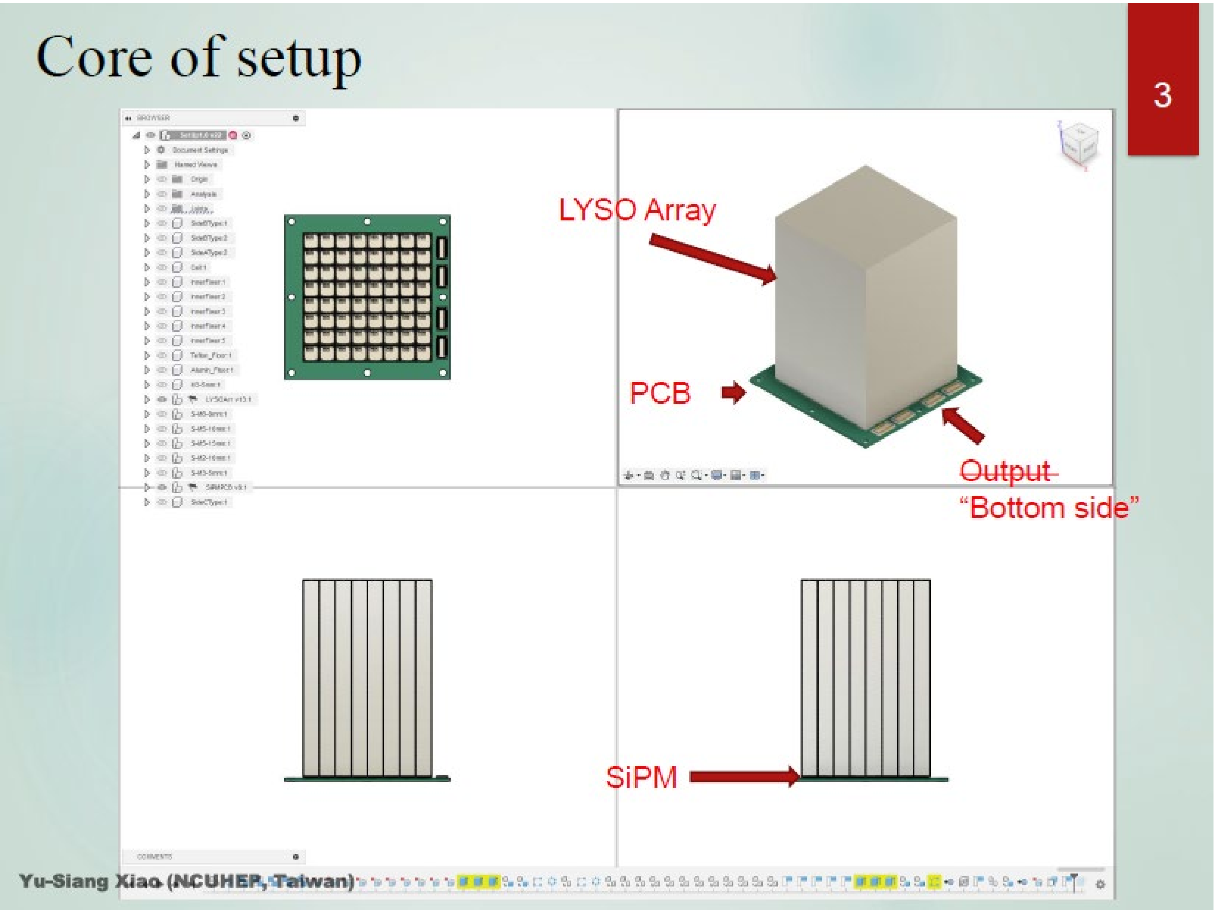
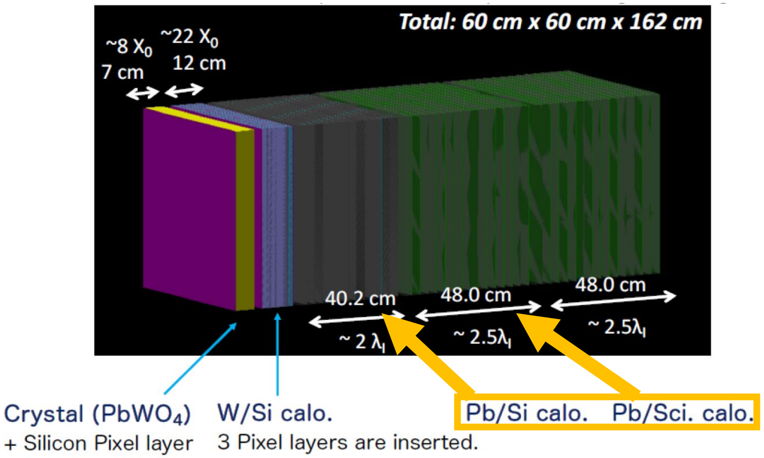


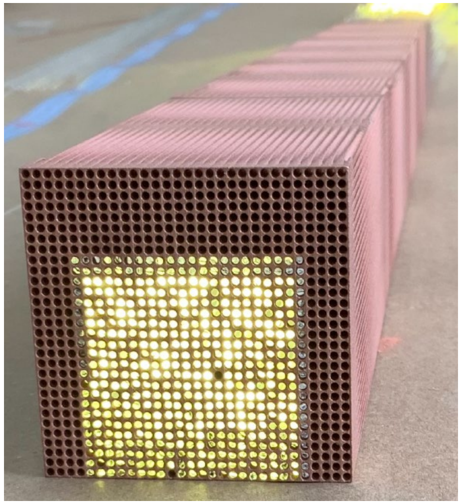
# *Hadron calorimeter*

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

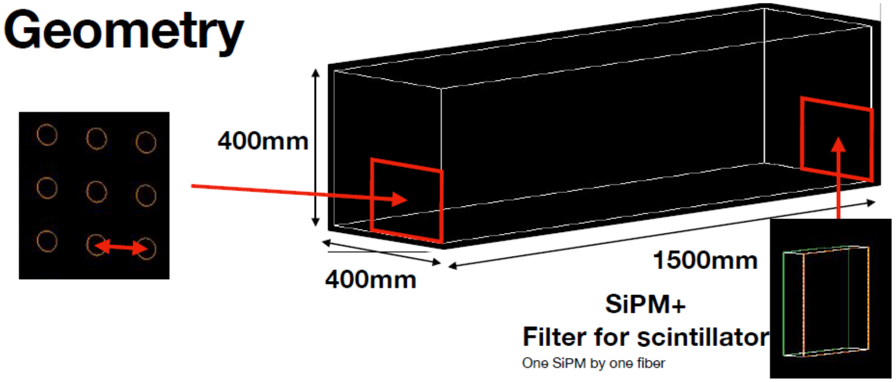


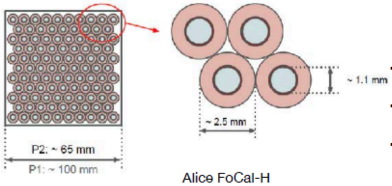
# *Hadron calorimeter*

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



## Geometry



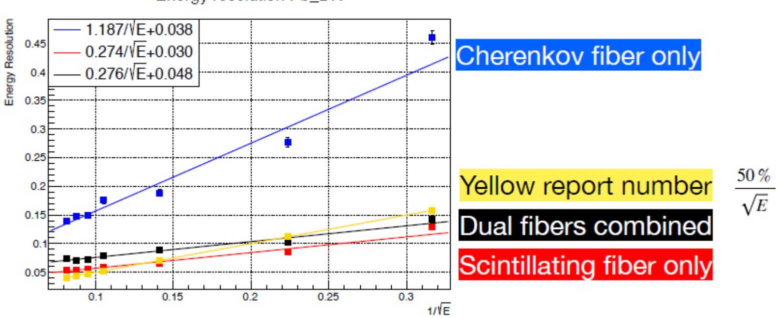




**Alice Focal-h as the reference**

- 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

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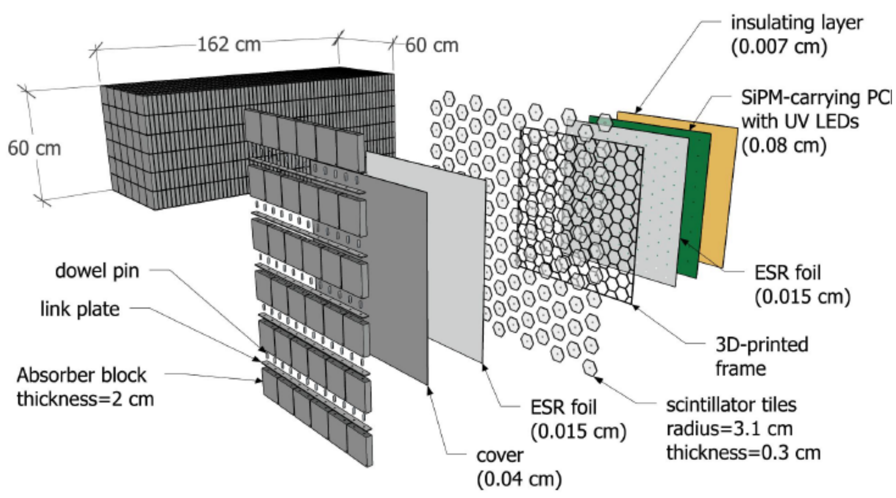
# *Hadron calorimeter*

- 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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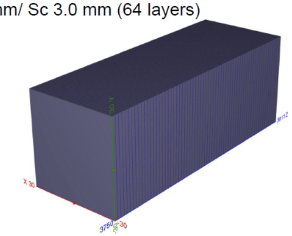
# *Hadron calorimeter*

## • SiPM-on-technology option for ZDC HCAL

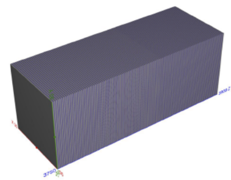
### ZDC geometry in DD4HEP

- 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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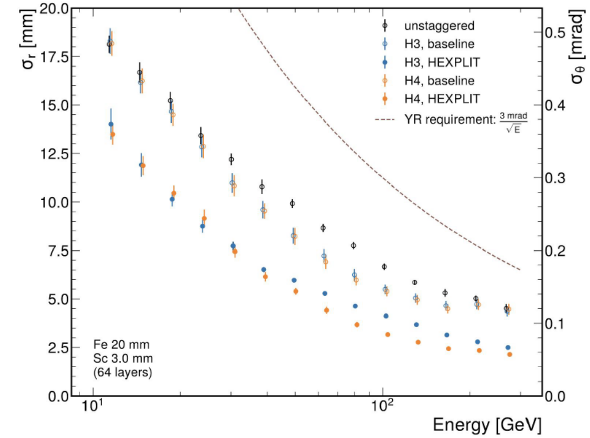
### Position resolutions for neutrons with a realistic ZDC model




- 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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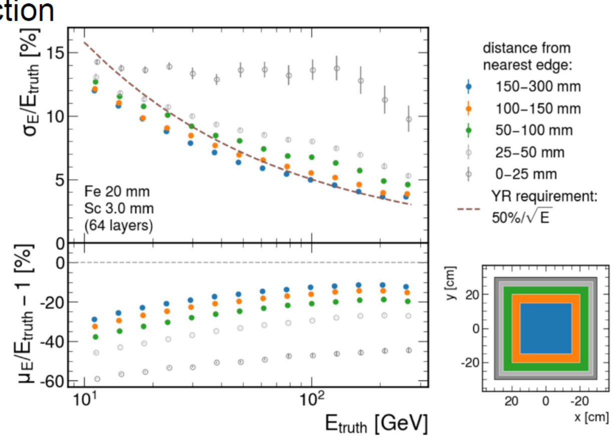
### Energy reconstruction

ZDC neutron simulations, 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)

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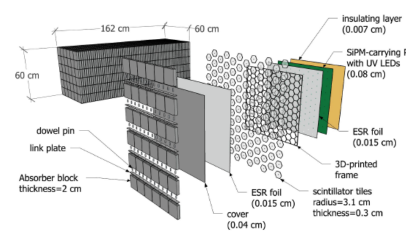
### Summary and Conclusions

- 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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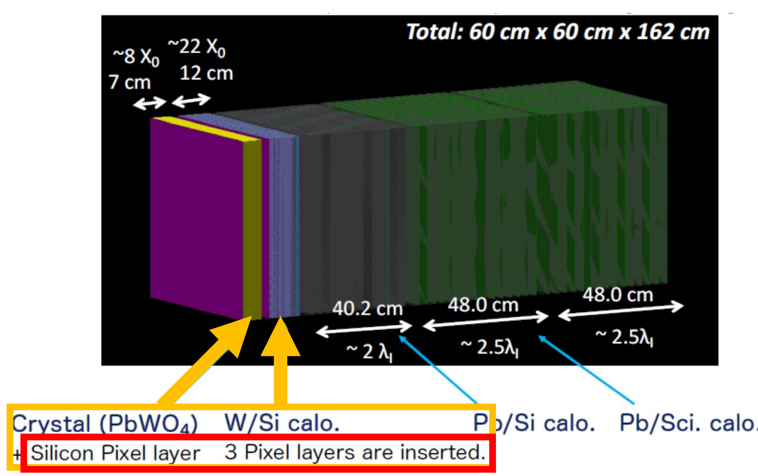
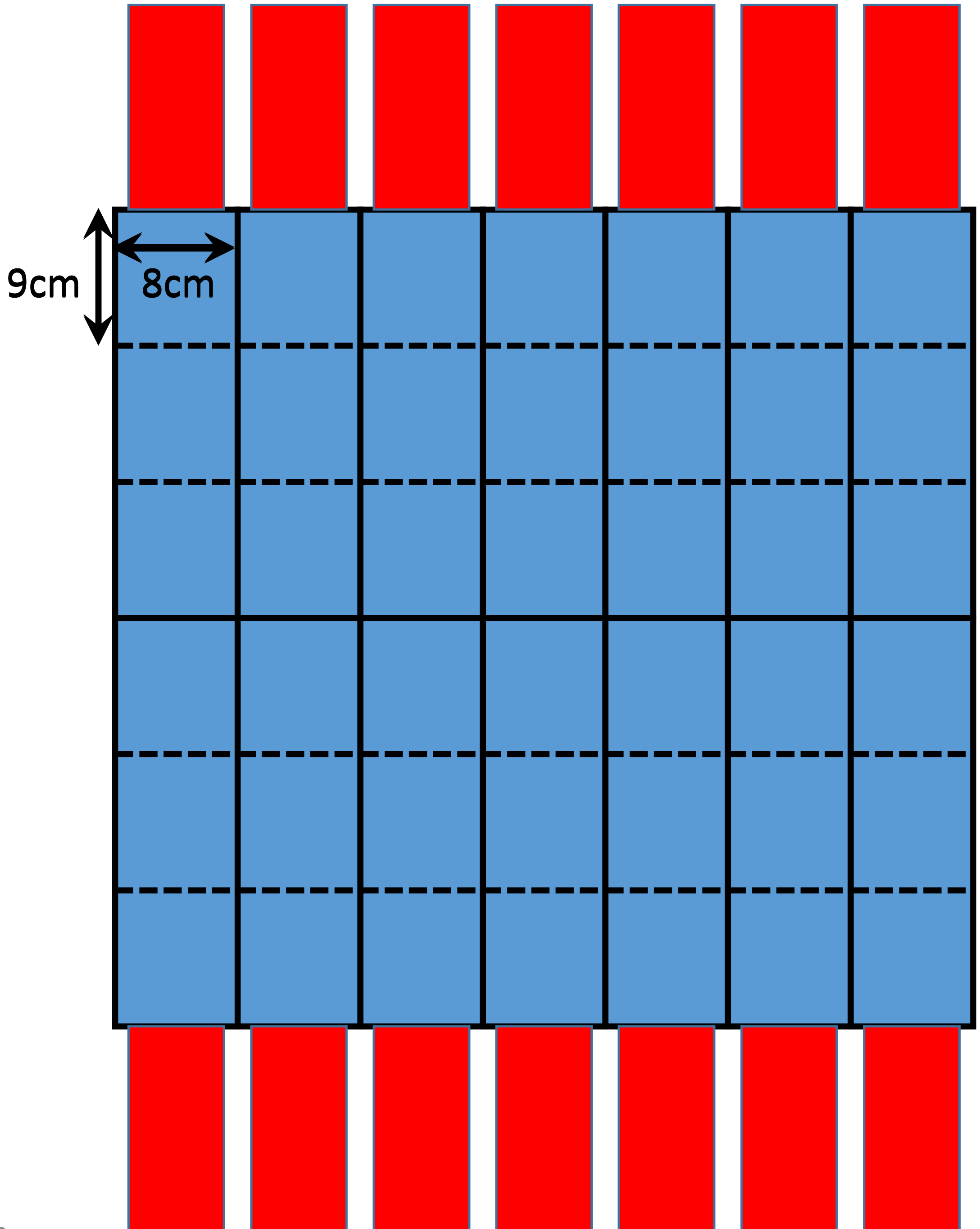
# *Position layer*

- 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?




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

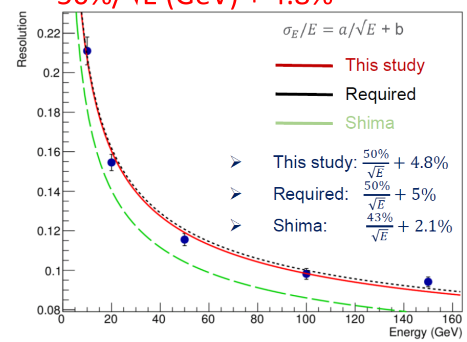
# ZDC design review

- Crystal calorimeter
  - 1st design: 60cm x 60cm PWO crystal 8$X_0$
  - 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 22$X_0$ (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. 1$X_0$ x 22 layers $\rightarrow$ 2$X_0$ 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?

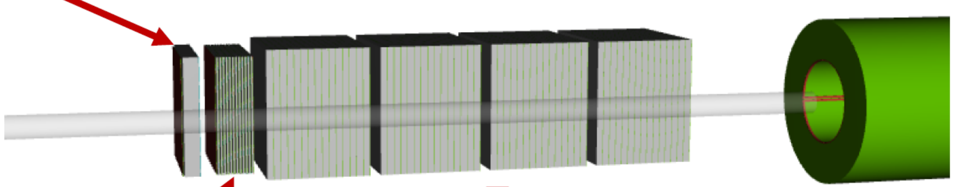
# ZDC design review

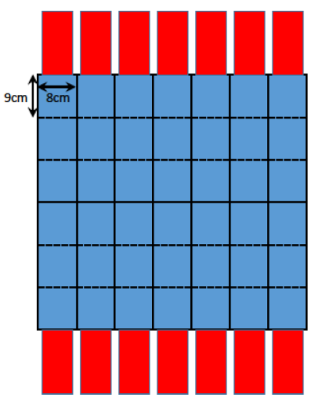
- More cost effective design
  - Smaller EMCAL
  - Pb-Si HCAL removed
  - By Po-Ju Lin

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




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



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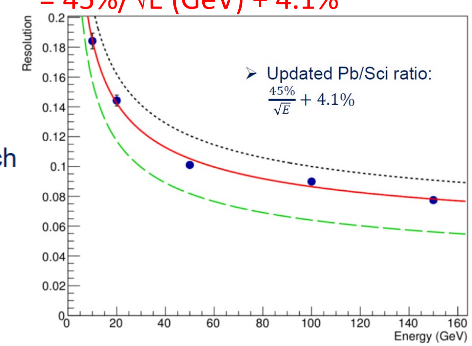


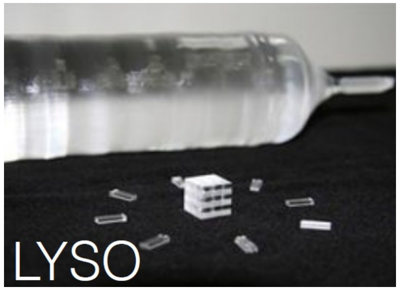
# ZDC design review

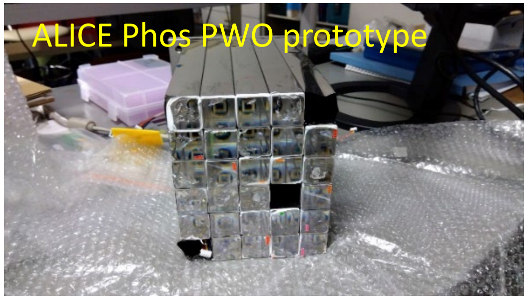
- Position layer
  - 3mm x 3mm required
- Open question yet
  - ALICE FoCal-E pixel layer (MAPS)
    - Too good position resolution
  - Smaller pad layer
  - AC-LGAD (position & timing layer)

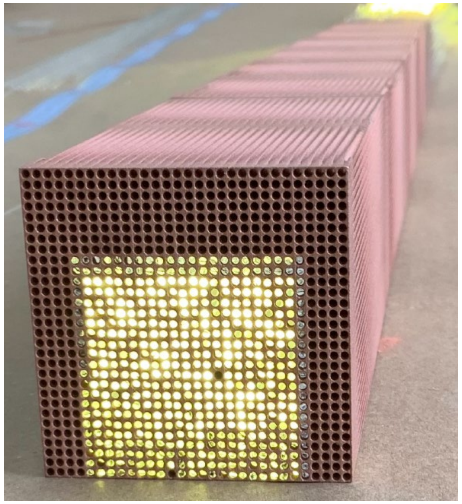
# ZDC design review

- 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

| | $X_0$ | LY (ph/MeV) | T dep. of LY (%/K) | Decay time (ns) | $\lambda_{em}$ nm |
|---|---|---|---|---|---|
| $PbWO_4$ (CMS) | 0.89 cm | 200 | -1.98 | 5 (73%)<br>14 (23%)<br>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 |



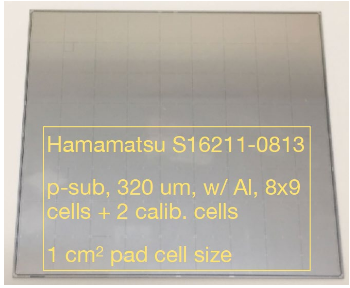
- HCAL
  - Korea group
  - Dual-readout calorimeter

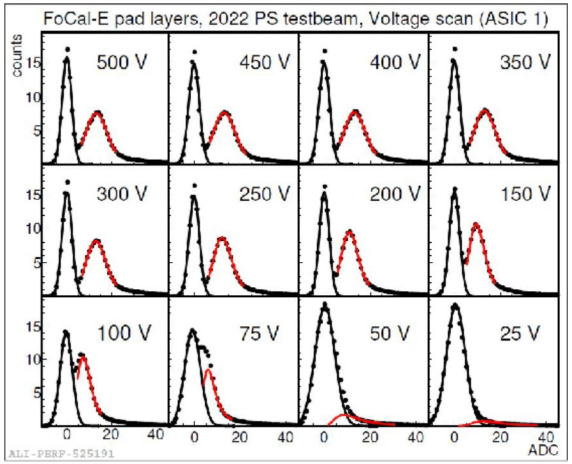
# ZDC Development

- 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

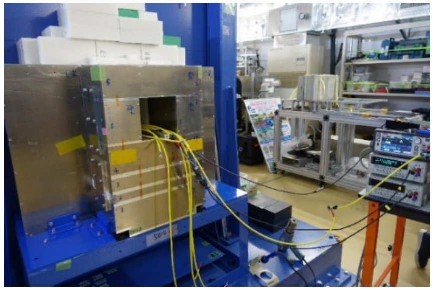
# Test-beam studies

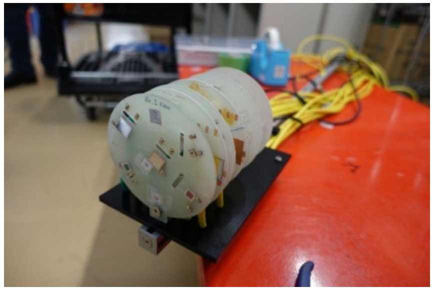
- ALICE FoCal-E test beam @ Tohoku-ELPH & CERN-PS/SPS
  - p-sub sensor, HGCROC v2 for readout
  - Clear MIP peaks observed for almost all channels and layers
  - Reaching full depletion voltage around 300 V

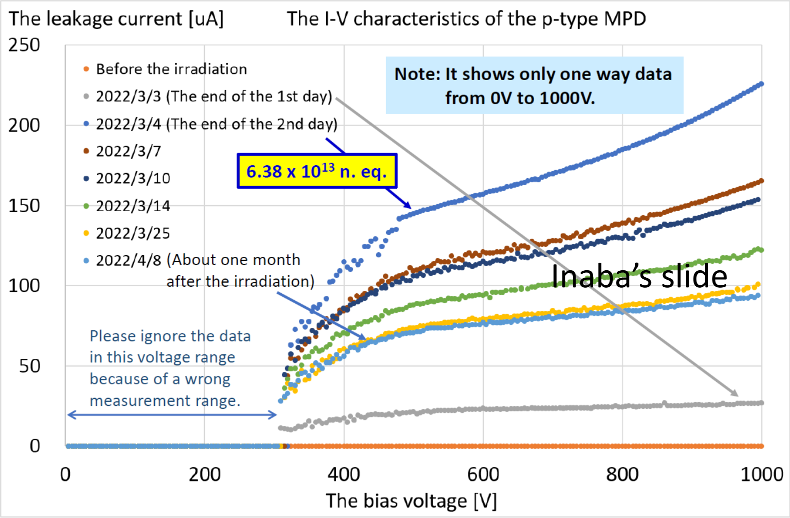



- Neutron irradiation test @ RIKEN-RANS
  - Sensor, photodetectors, chips, cables
  - For FoCal-E, sPHENIX, ePIC-ZDC
  - Up to ~$10^{14}$ neutrons/cm$^2$

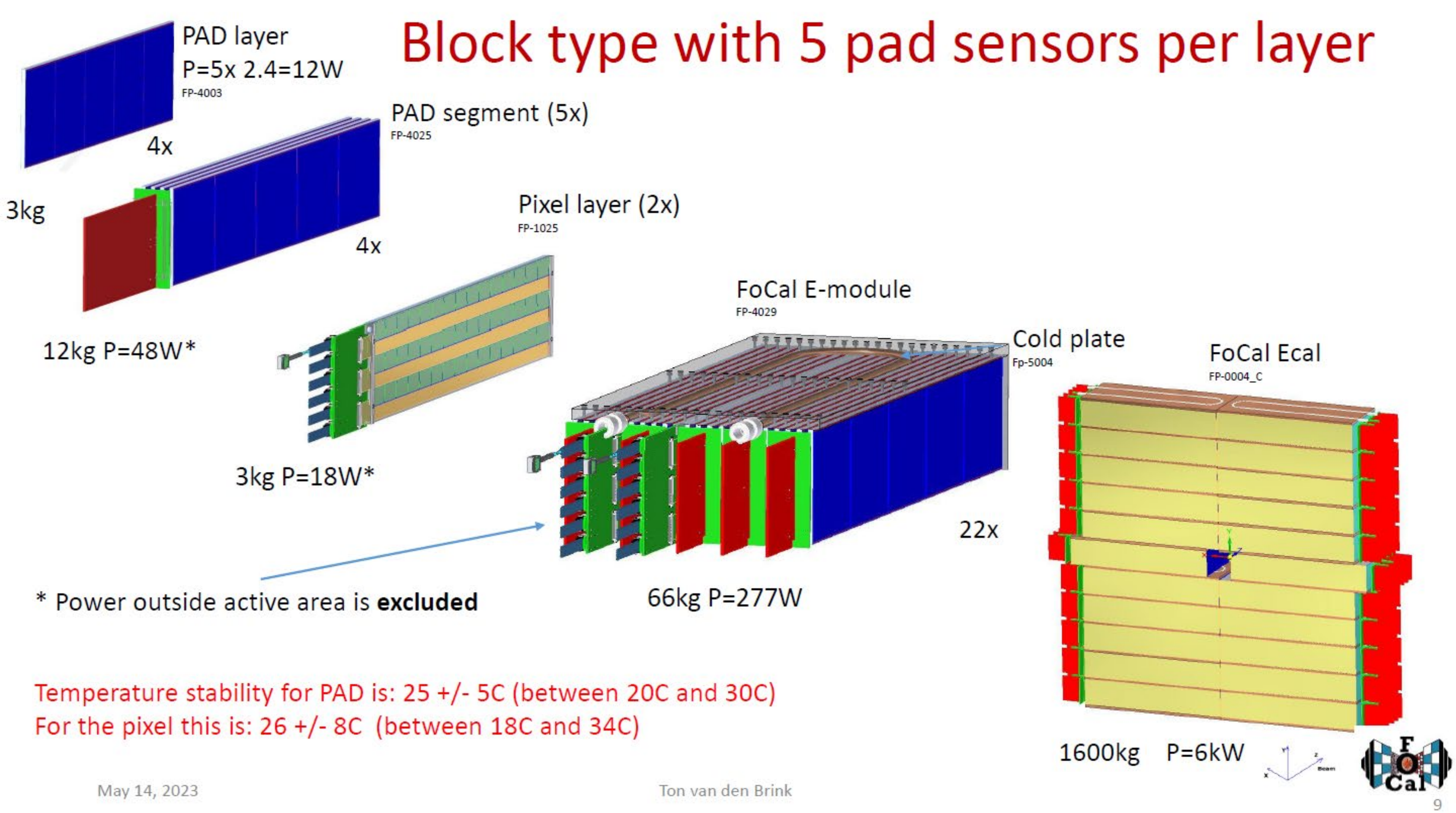






# *ALICE-FoCal structure*

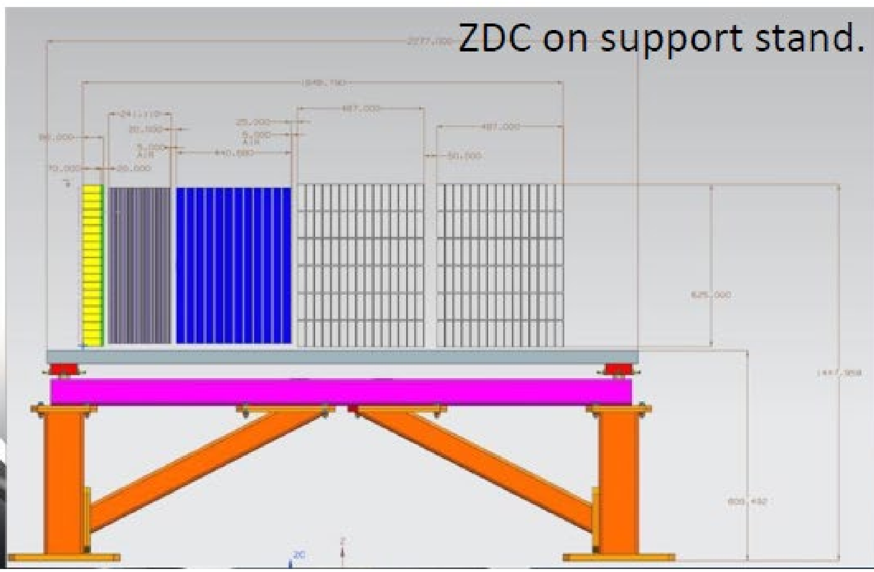
- Including cooling & support

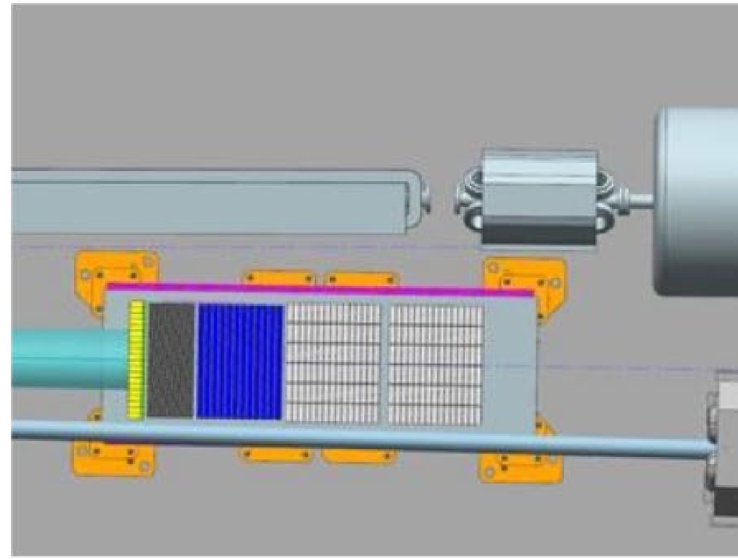


# *ZDC integration issues*

## 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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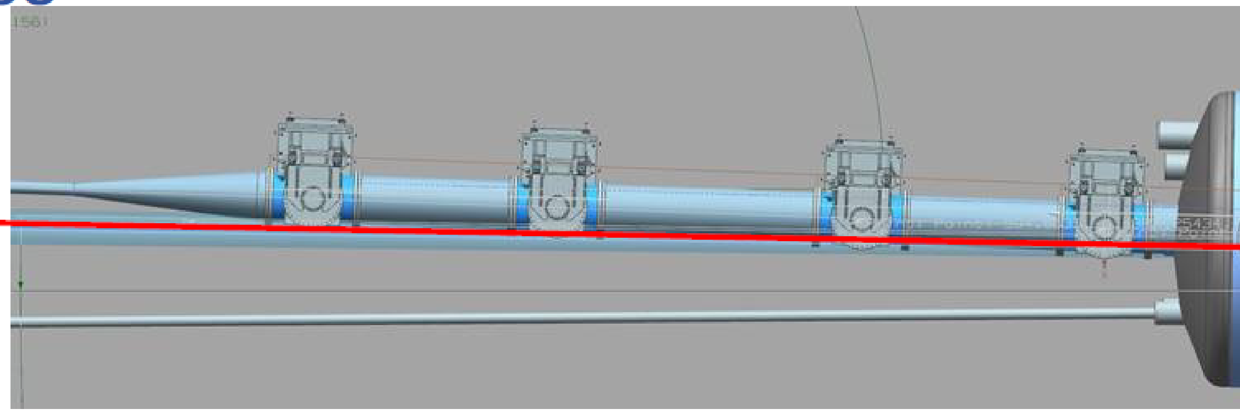
Slide shown by Alex Jentsch in Warsaw meeting in July

# *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