ALICE FoCal

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The FoCal proposal

Physics Goal: unravel nucleus structure at small-x

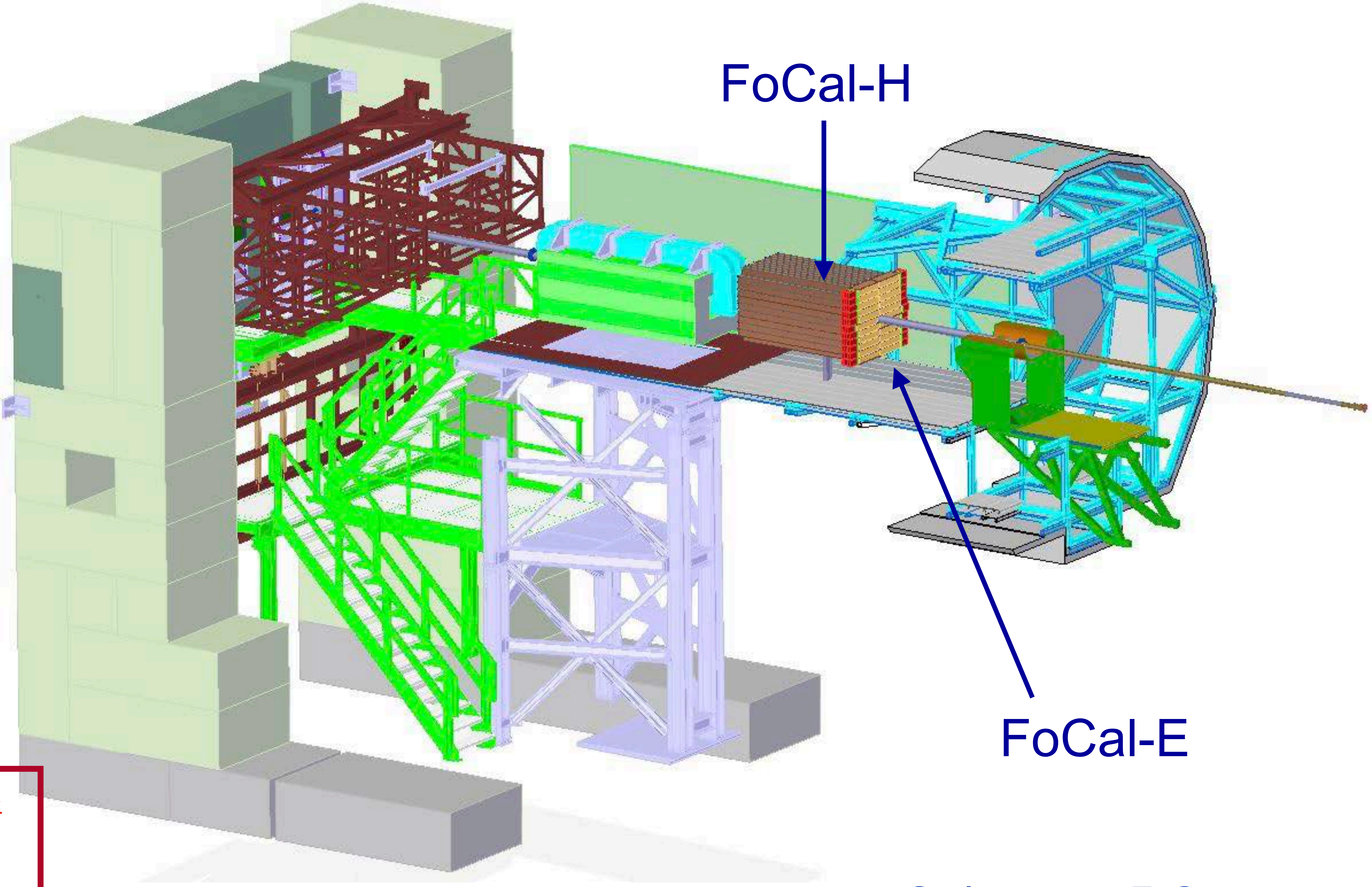
Observables in 3.4 < η < 5.8 @ LHC:

- π^0 (and other neutral mesons)
- Isolated (direct) photons
- Jets (and di-jets)
- etc…

FoCal

FoCal-E: high-granularity Si-W sampling calorimeter for photons and π^0

FoCal-H: conventional metal-scintillator sampling calorimeter for photon isolation and jets



3.4 < η < 5.8

(baseline design @ 7m from IP)

FoCal LoI has been approved by LHCC on June 5, 2020

Public Note (LoI) : CERN-LHCC-2020-009

- Test beam: 2021 - 2022
- TDR submission : 2022

FoCal: Physics goals

1. Quantify nuclear modification of the gluon density at small-x
- Isolated photons in pp and pPb collisions

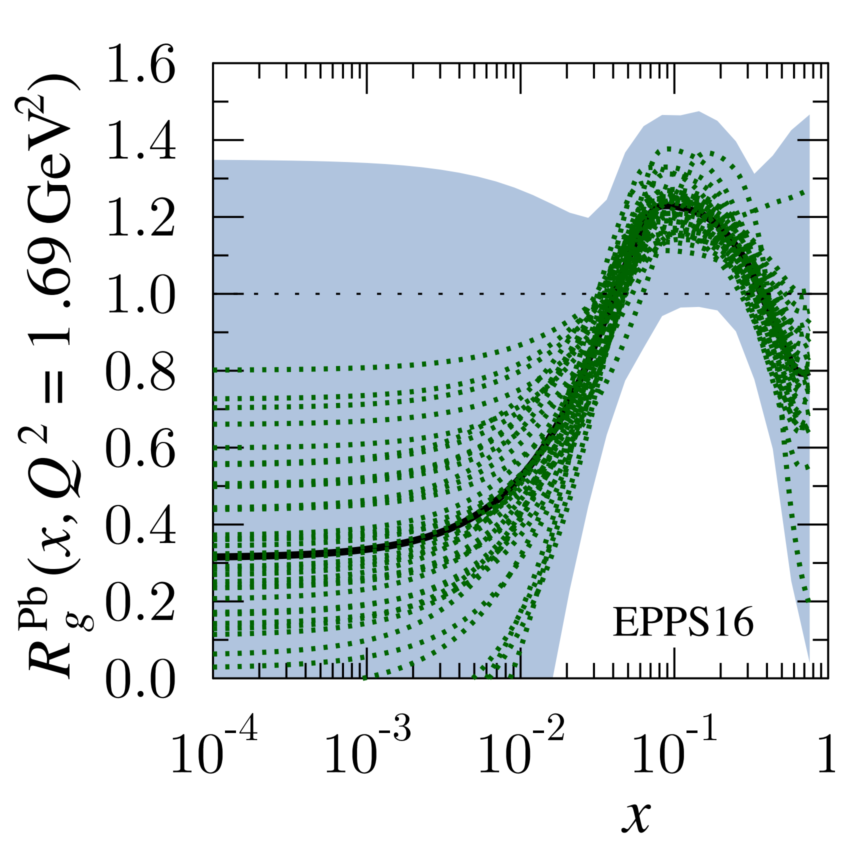
2. Explore non-linear QCD evolution
- Azimuthal π^0-π^0 and isolated photon-π^0 (or jet) correlations in pp and pPb collisions

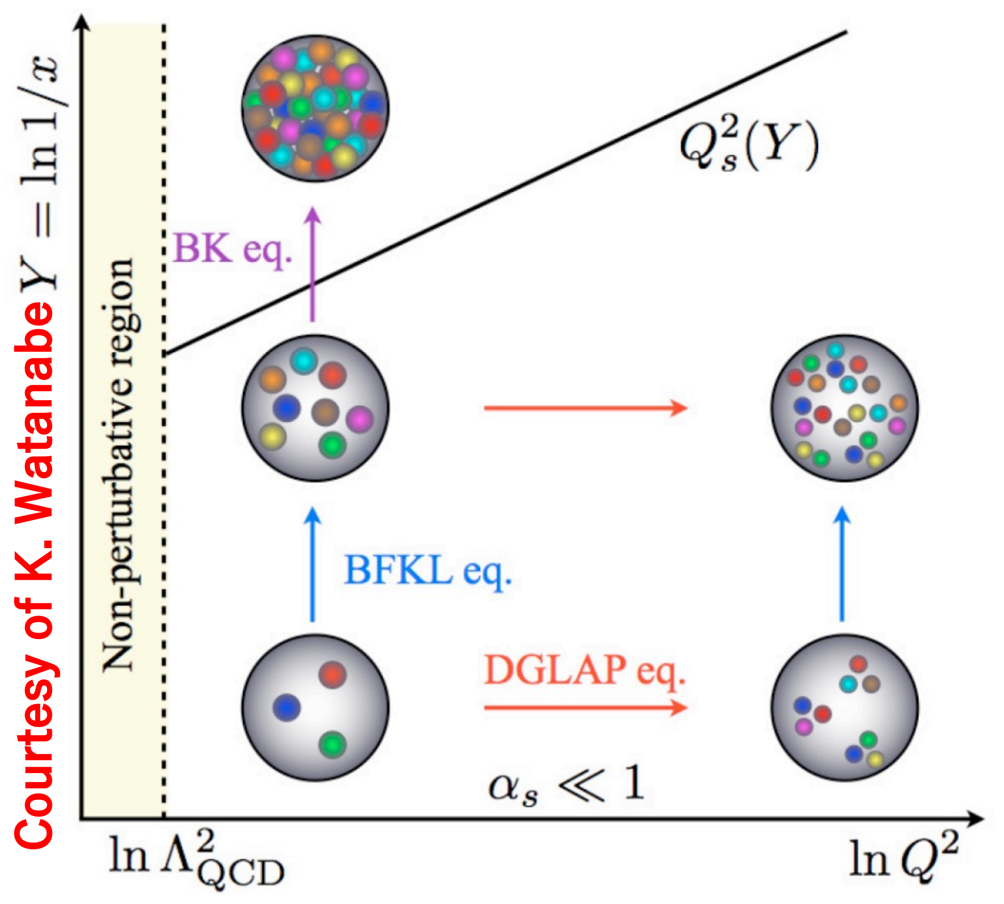
3. Investigate the origin of long range flow-like correlations
- Azimuthal π^0-h correlations using FoCal and central ALICE (and muon arm?) in pp and pPb collisions

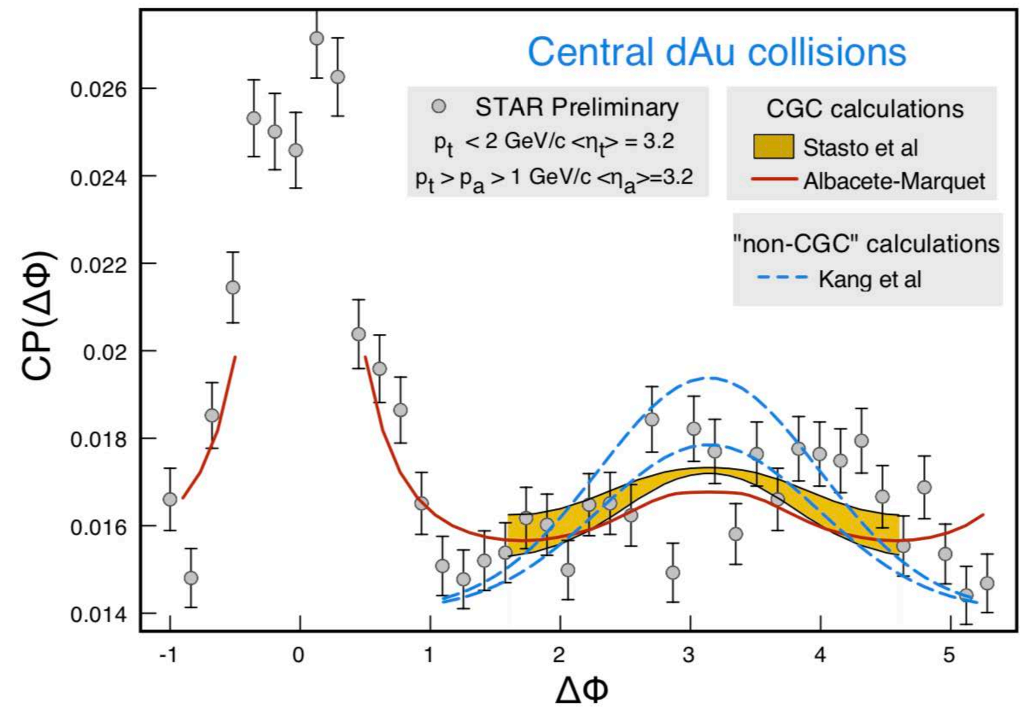
4. Explore jet quenching at forward rapidity
- Measure high p_T neutral pion production in PbPb

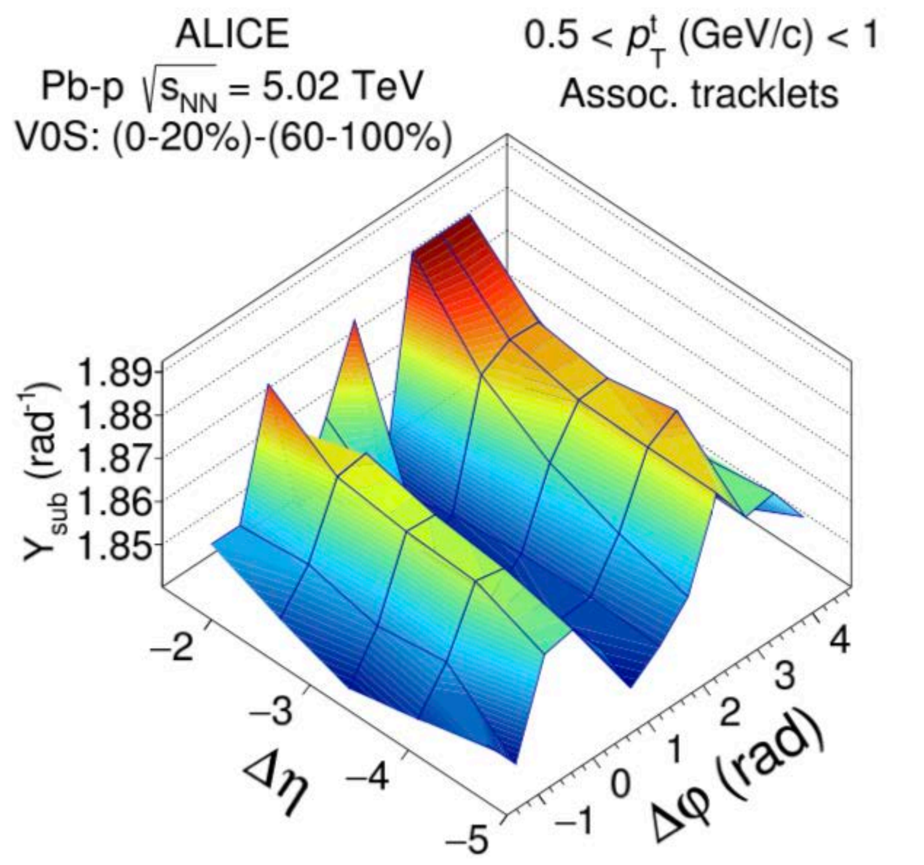
Access to an unexplored small-x and low Q² region:

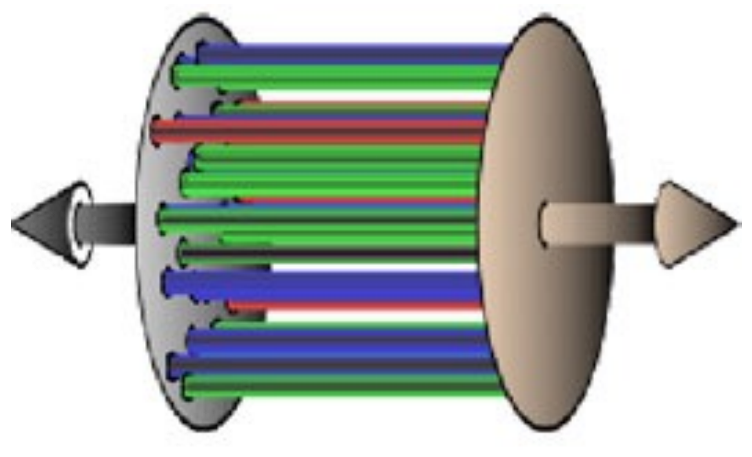
- Direct photon, π^0 and jet (+correlations) measurements at very forward rapidity in pp and p-Pb @ LHC

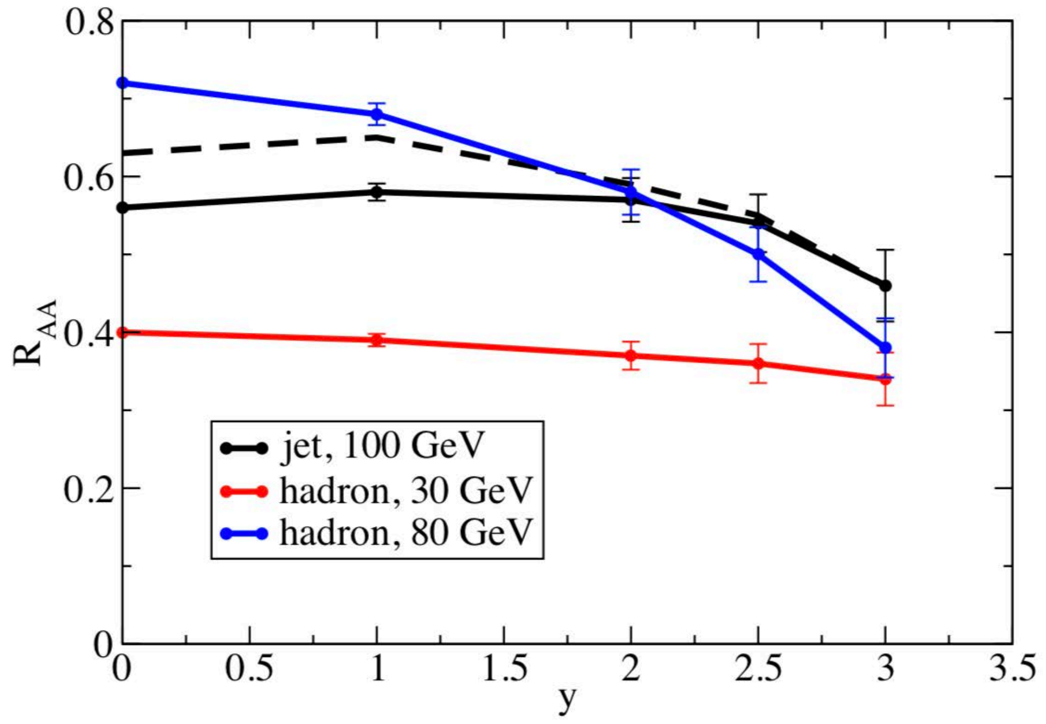




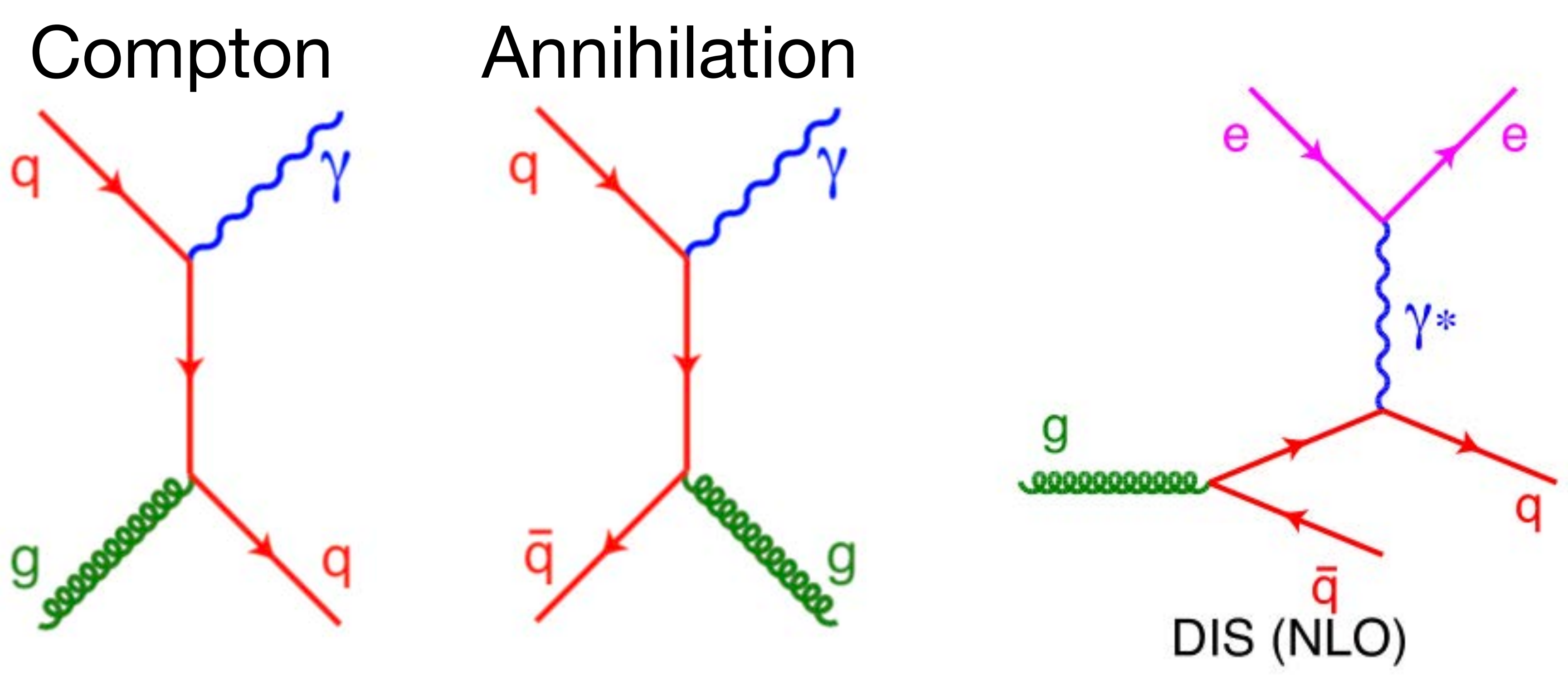


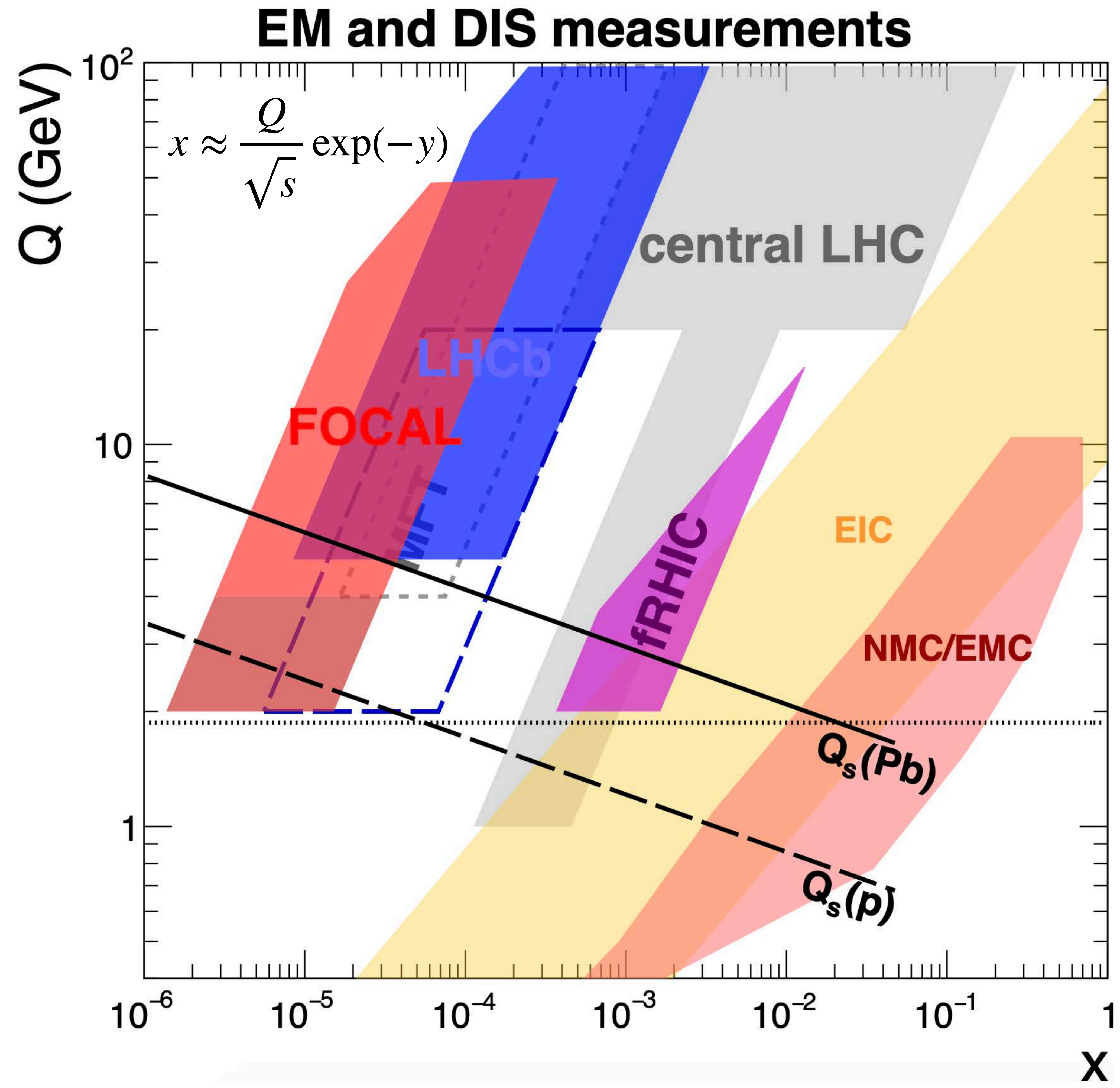






Forward isolated photons and the LHC small-x program





- Measure isolated photons forward
  - At LO more than 70% from Compton with direct sensitivity to gluon density
  - Not affected by final state effects nor hadronization
  - Uniquely low-x coverage at LHC (similar to LHeC)

Strong small-x program at LHC

- Various experiments/measurements: isolated γ, DY, open charm (+UPC)
- Test factorization/universality
- Complementary to RHICf + EIC

Preparation for prototype beam test in 2021/22 and TDR

1)FoCal-E PAD
2)FoCal-E PAD readout
3)FoCal-E PIXEL
4)FoCal-H
5)Ongoing activities

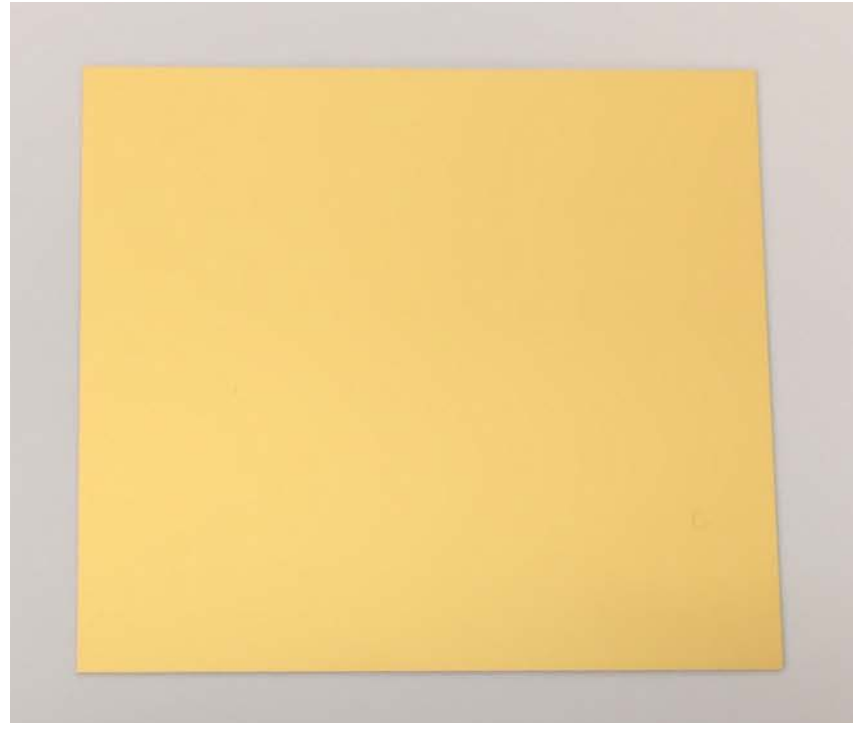
1) FoCal-E PAD: main sensor (8x9, p-type, 320um)

front side (w/ Al)

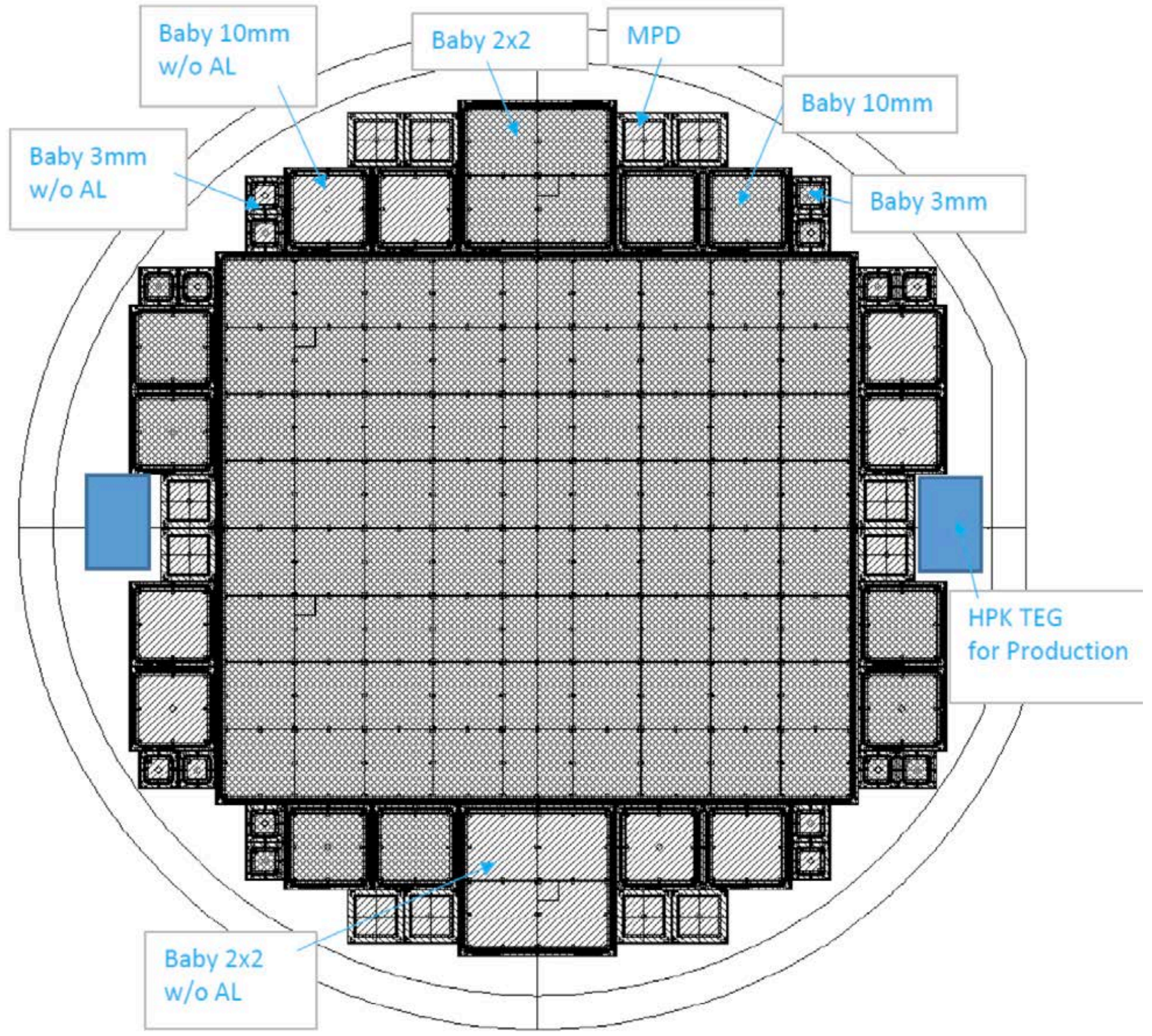
Hamamatsu S16211-0813

p-sub, 320 um, w/ Al,

1 cm² pad cell size



back side (Au)

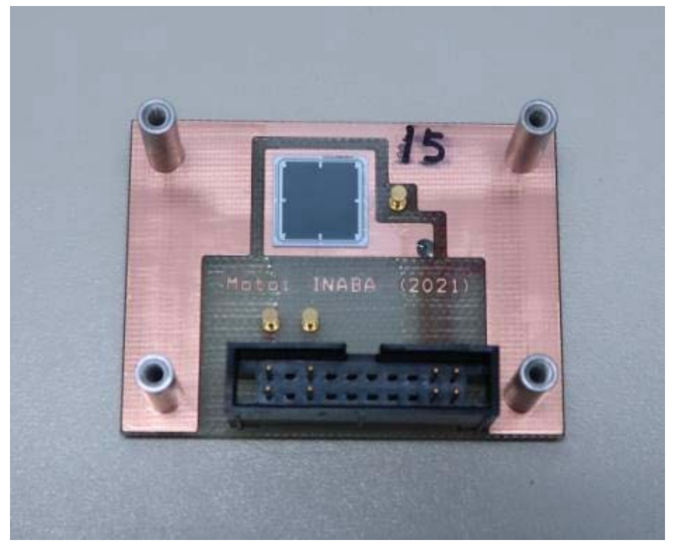


First time use of p-type for FoCal

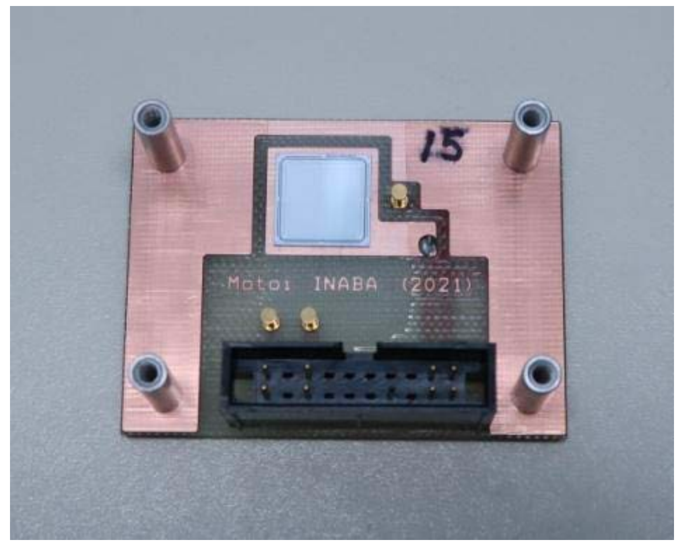
- 8x9 cells + calibration cells (w/Al), produced 30, and delivered.
- Various type of test cells were also produced (next slides).
- More rad. hard than n-type.
- Compatible with HGCROC.

(Tsukuba / RIKEN)

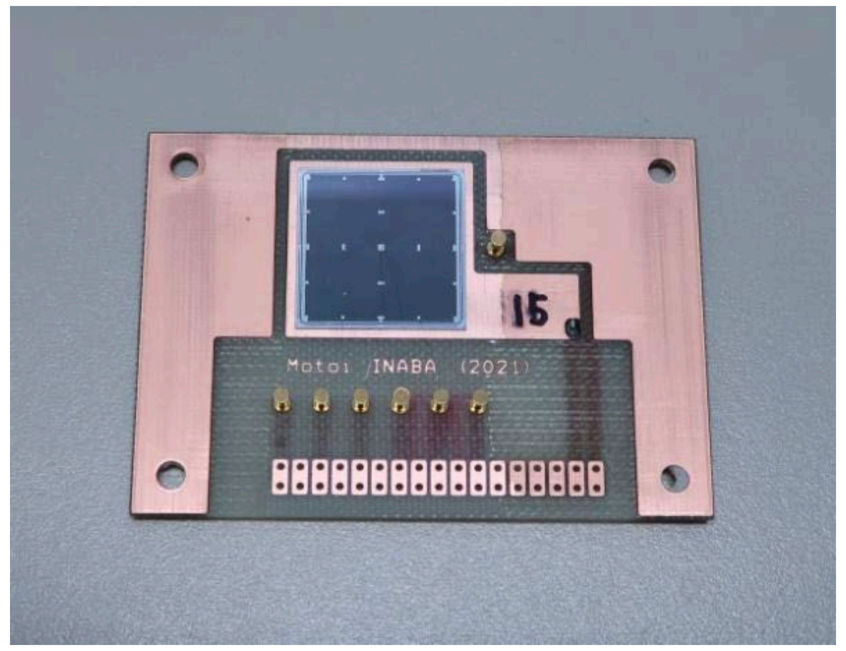
p-type sensor (test cells, “babies”)



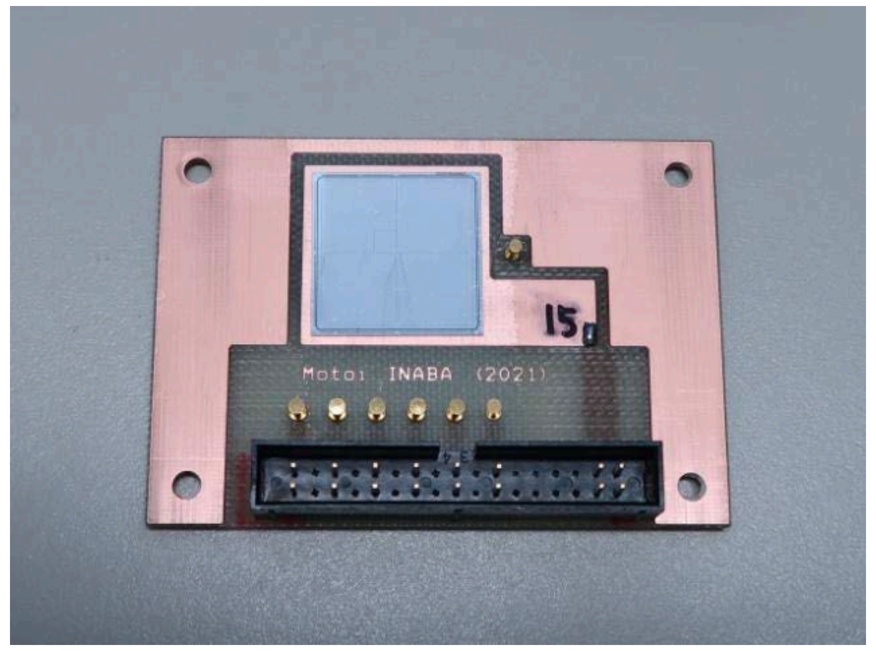
1x1 test cell (DC)



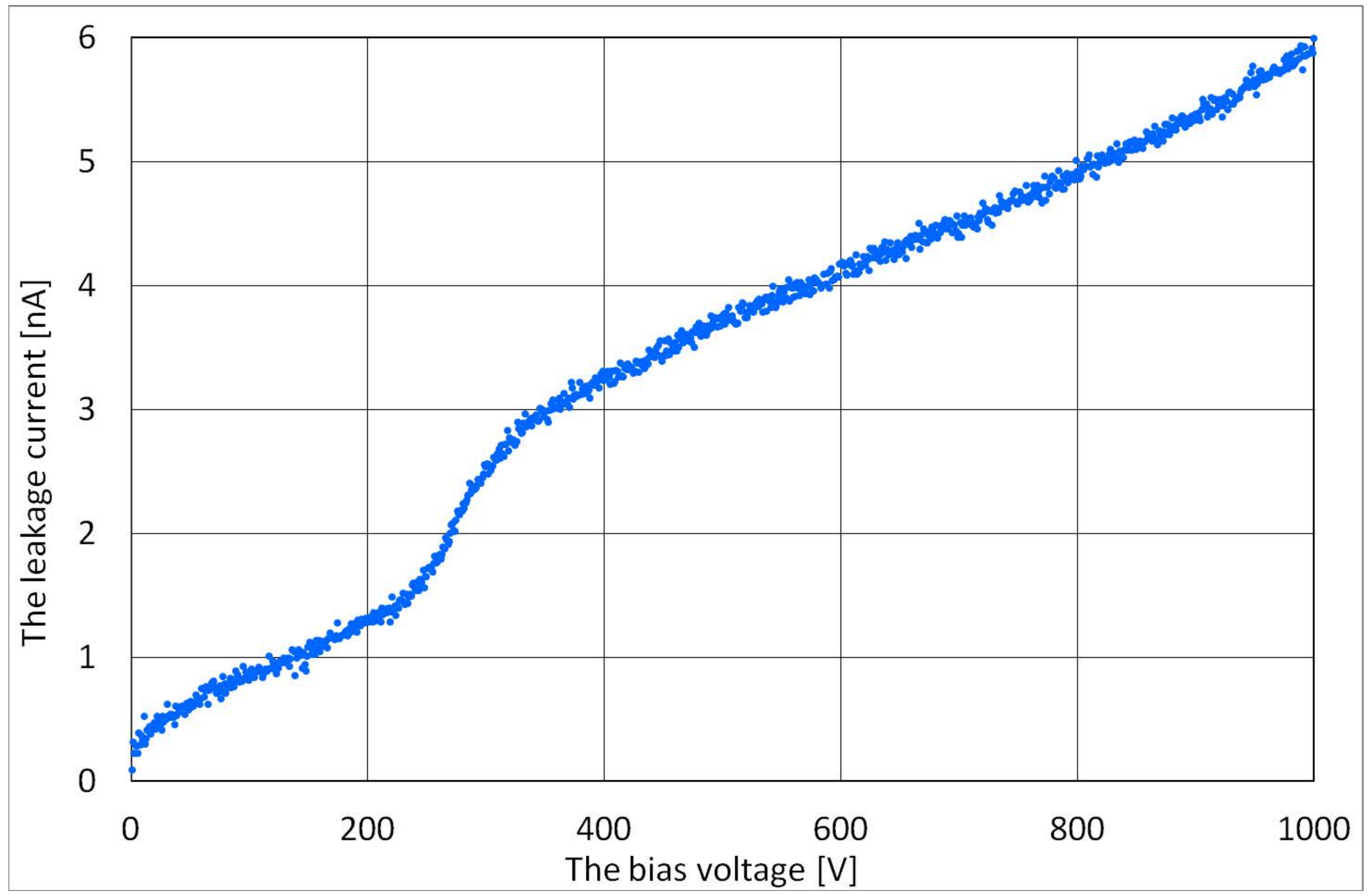
1x1 test cell w/ Al (DC)



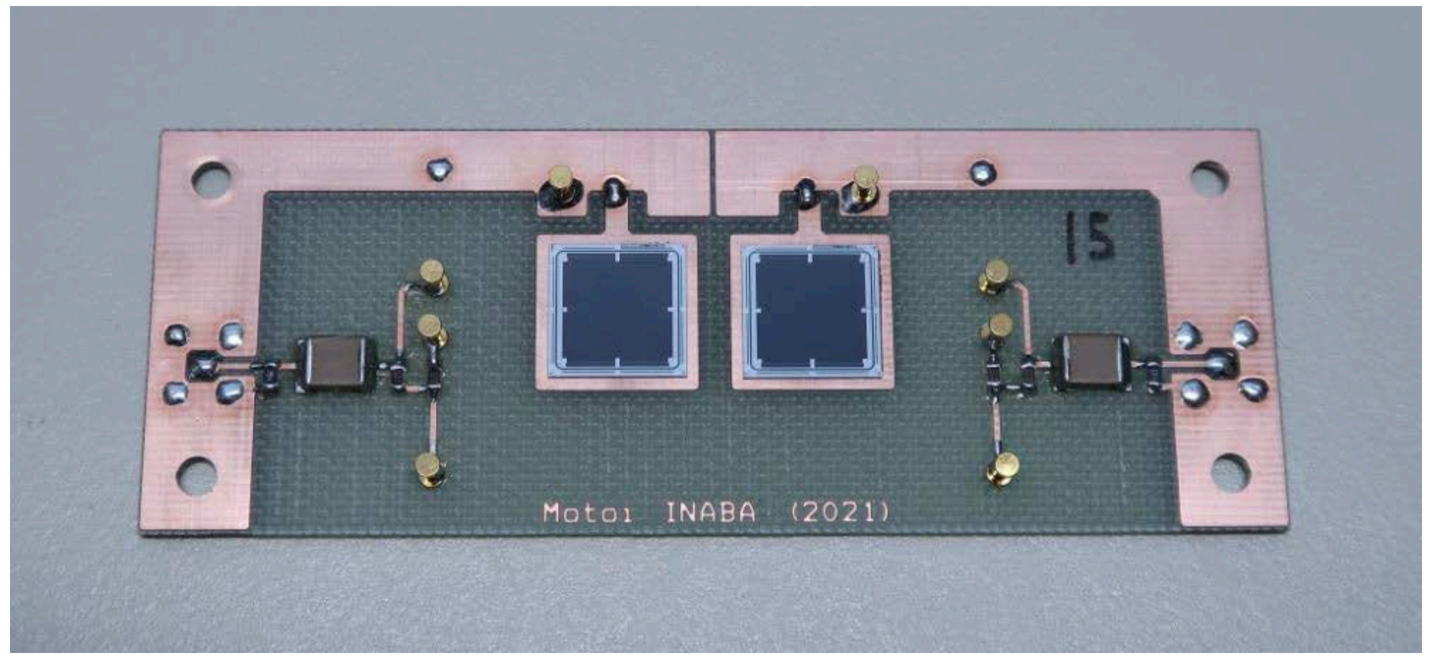
2x2 test cell (DC)



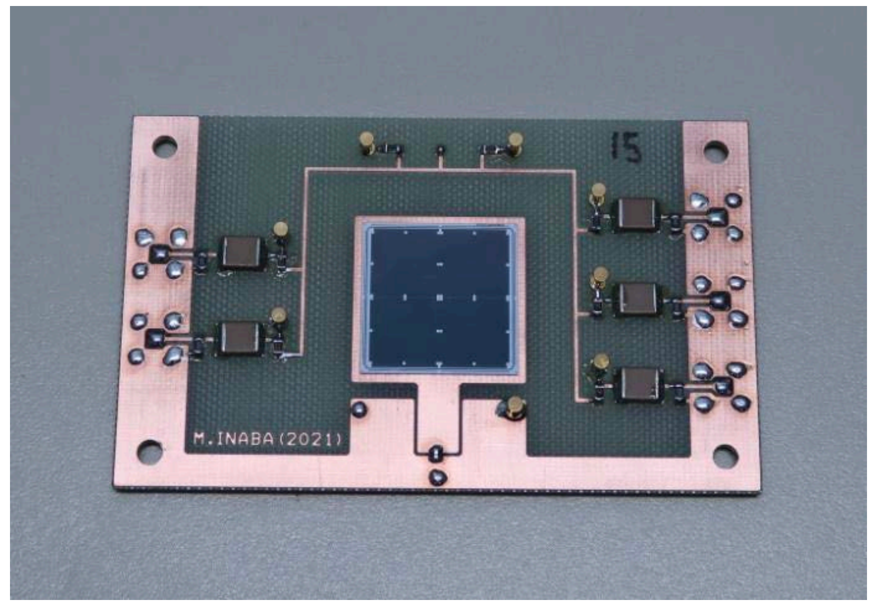
2x2 test cell w/ Al (DC)



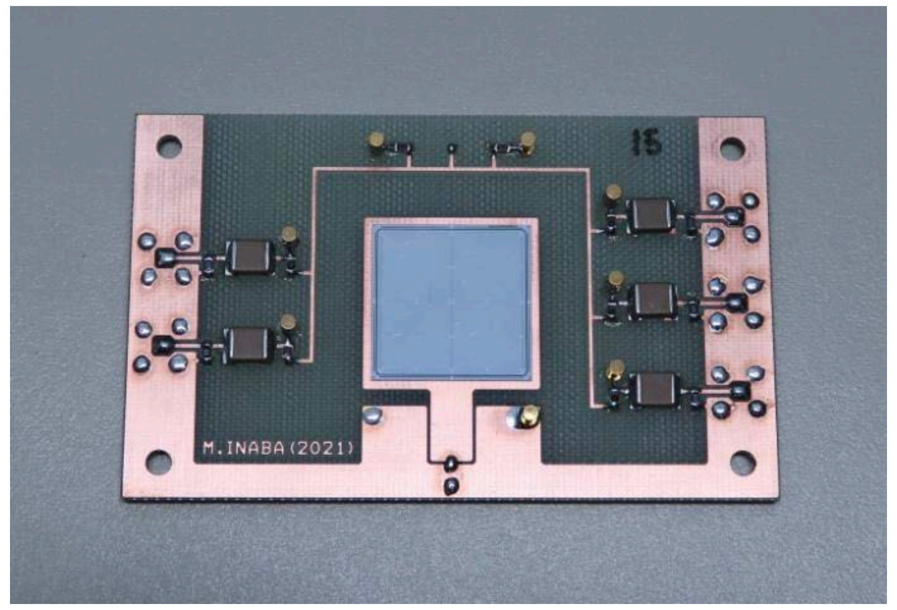
I-V: p-type 1x1 test cell w/ Al



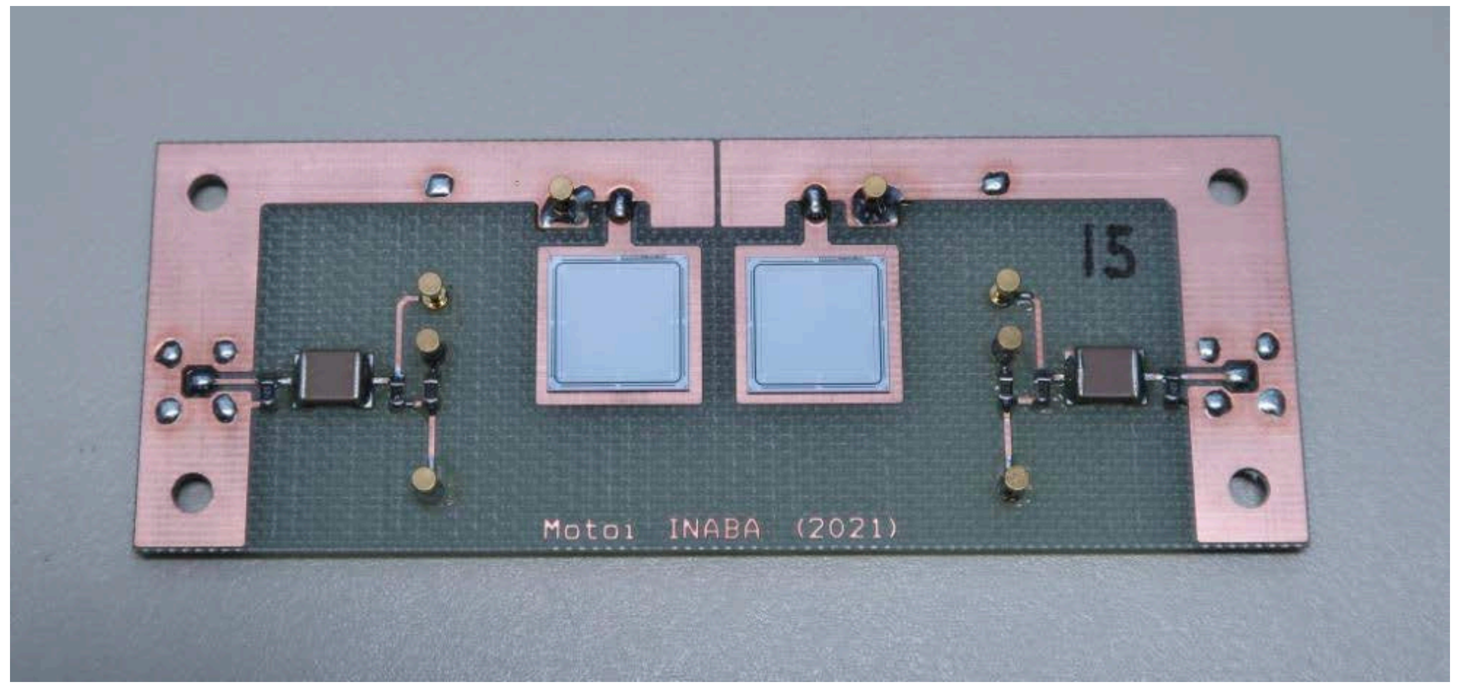
1x1 test cells (AC)



2x2 test cell (AC)



2x2 test cell w/ Al (AC)

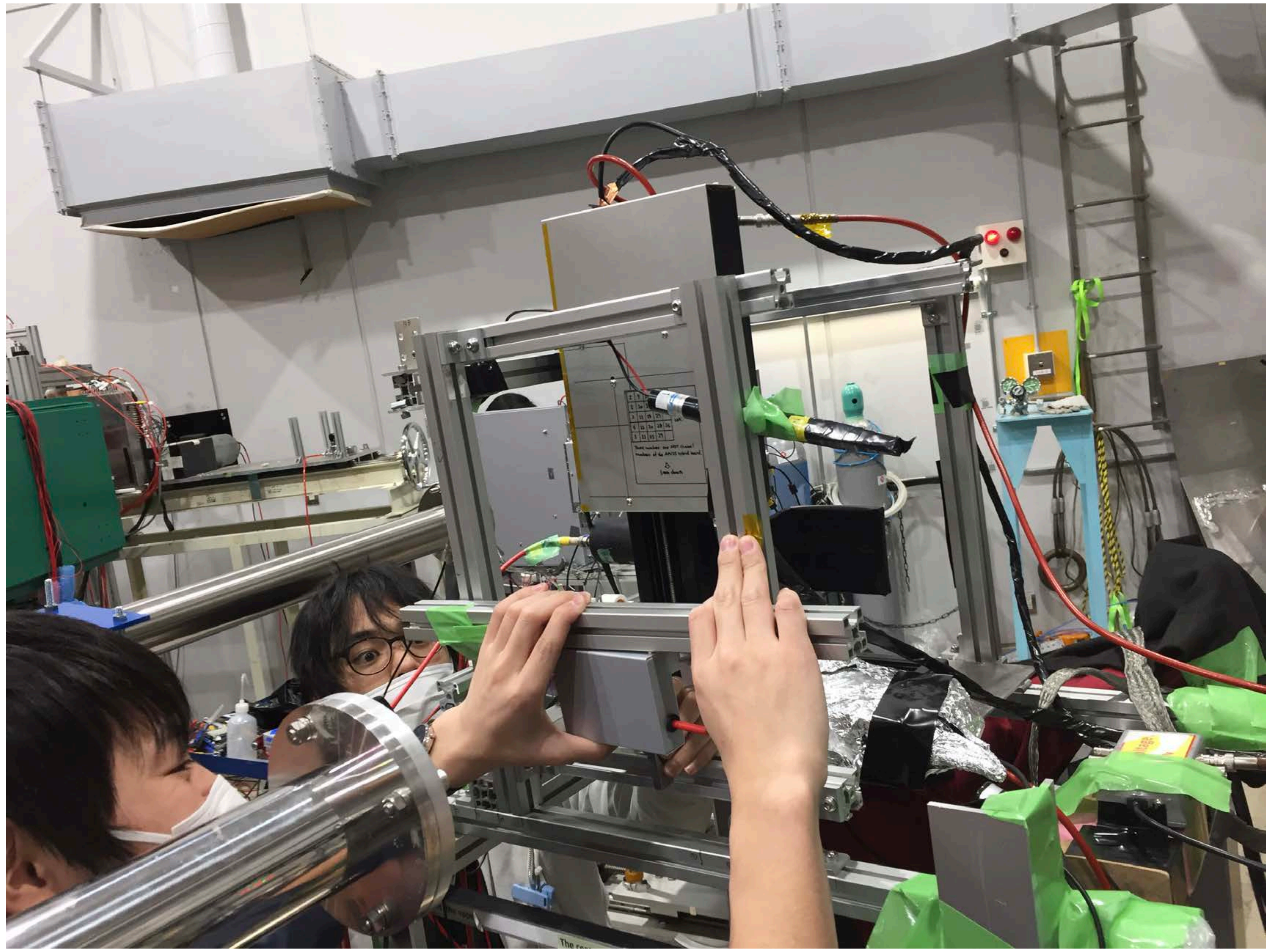


1x1 test cells w/ AL (AC)

New p-type test cells for understanding of basic characteristics of sensor and for lab. test.

- Measured I-V curve, systematic measurements are on-going.
- “AC” type for the APV25 hybrid board at test beam.
- “DC” type for the CAEN digitizer with pre-amplifiers at test beam.

ELPH test beam for p-type sensor test

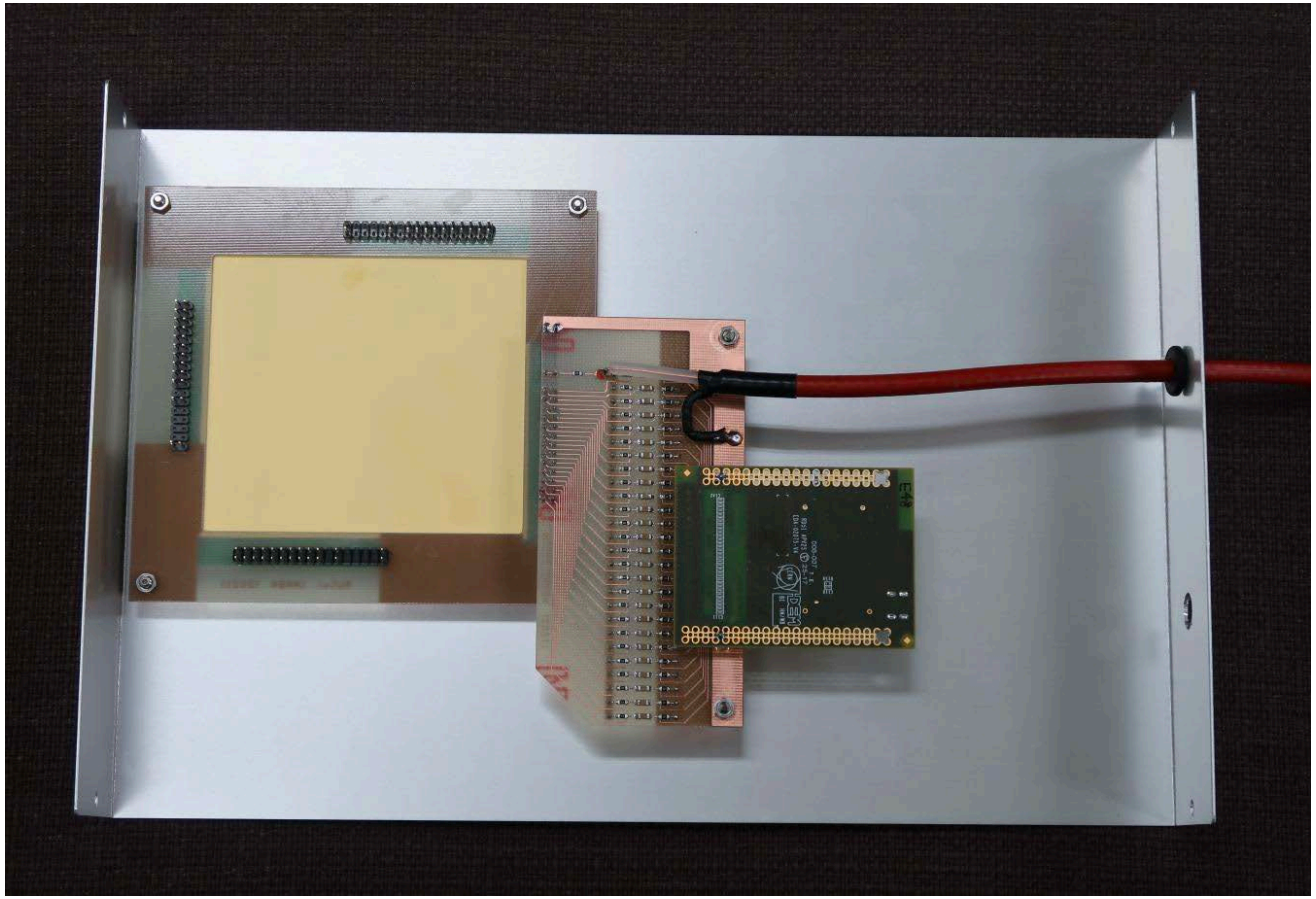


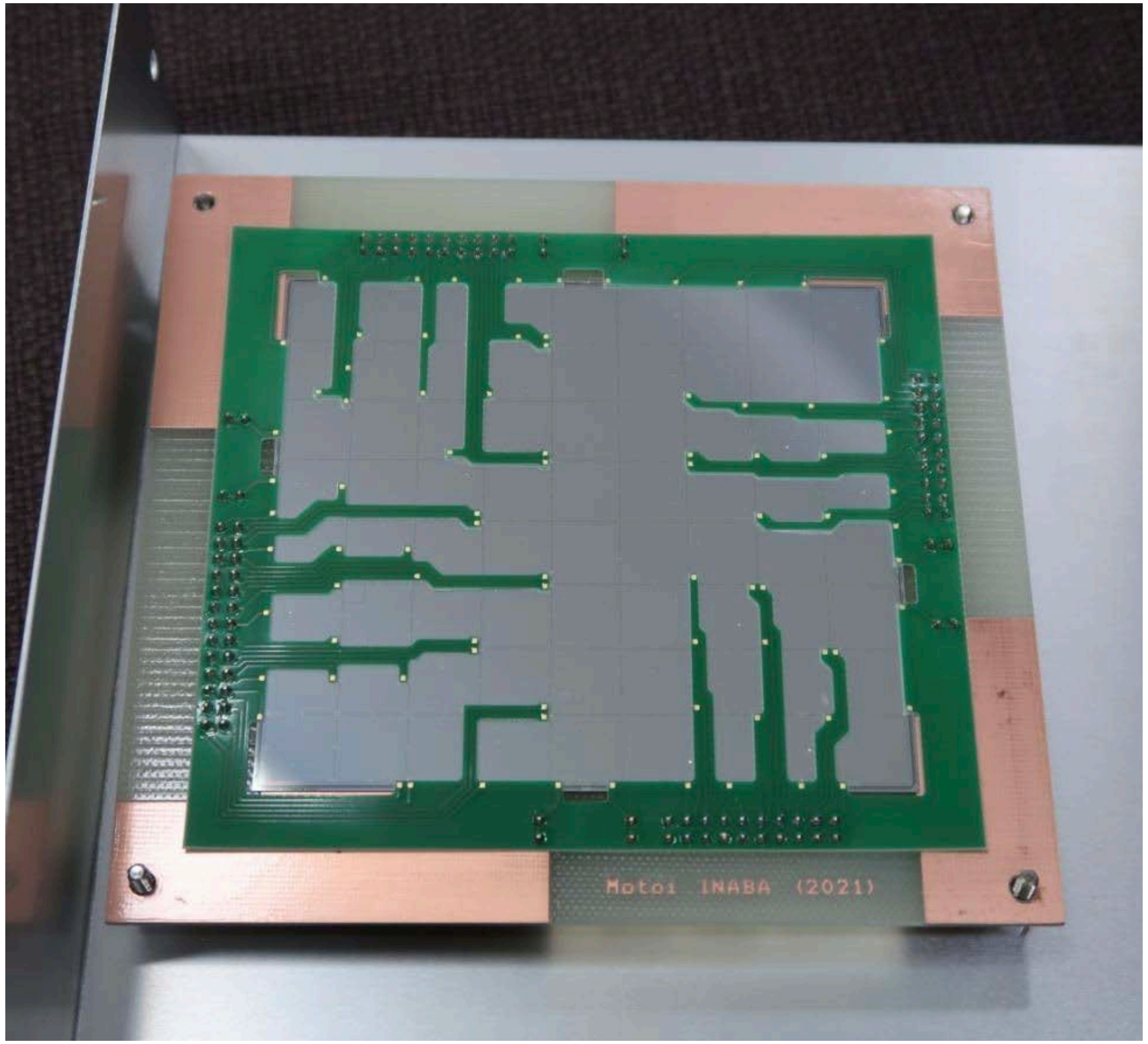
ELPH test beam:

- **Goal: measure MIP signals for p-type main chip and babies.**
- Feb. 16-19, 2021 @ ELPH (Research Center for Electron Photon Science), Tohoku Univ., Japan
- 600 MeV/c, position beams from gamma conversion (Au 20 um)
- Participating institutes: Tsukuba, Tsukuba Tech, RIKEN, Hiroshima, Nara Women
- Readout: APV25 hybrid + SRS and CAEN digitizer, not the final readout.

ELPH test beam results

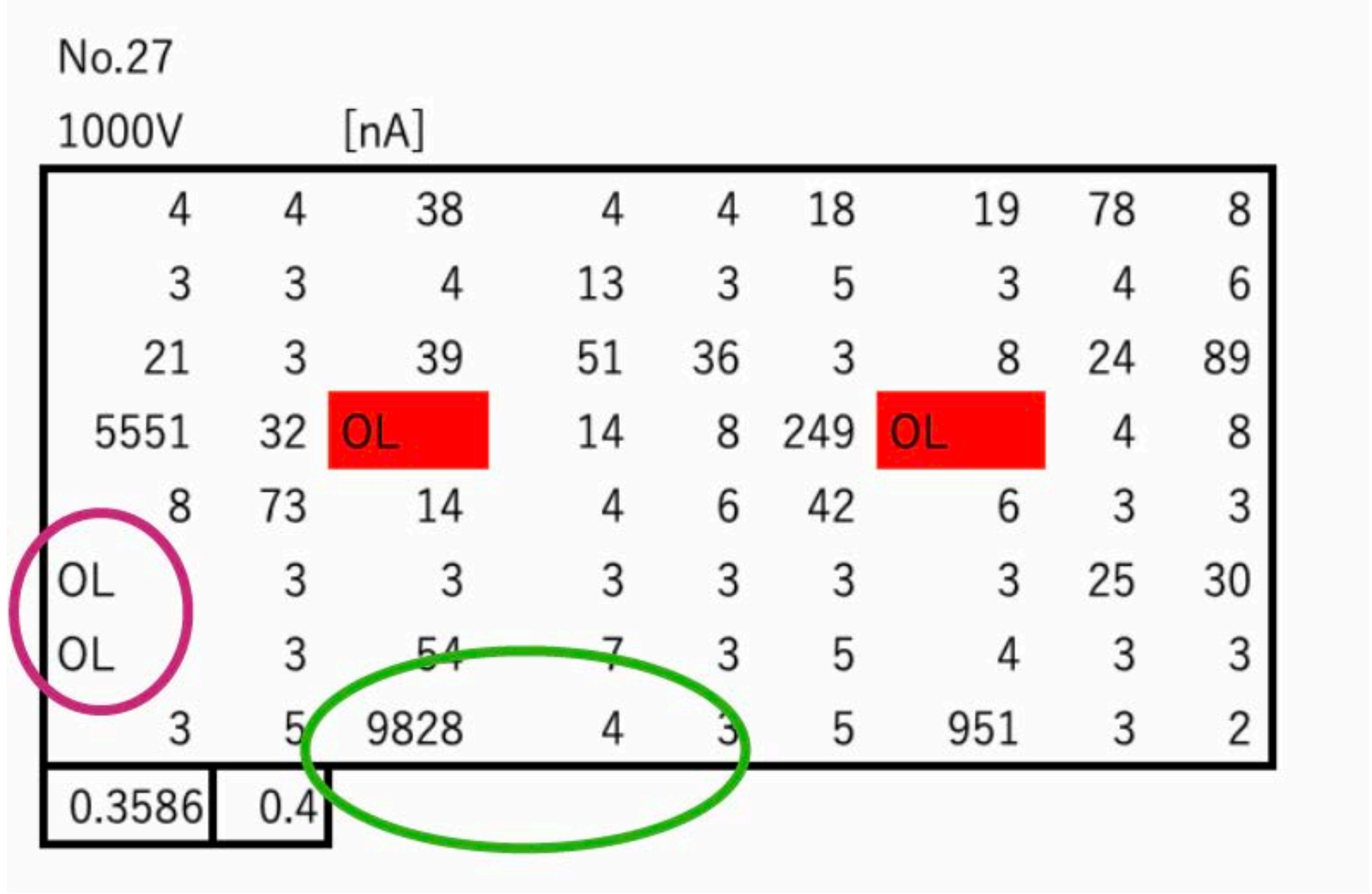
9x8 main chip w/Al





ELPH test beam results

9x8 main chip w/Al

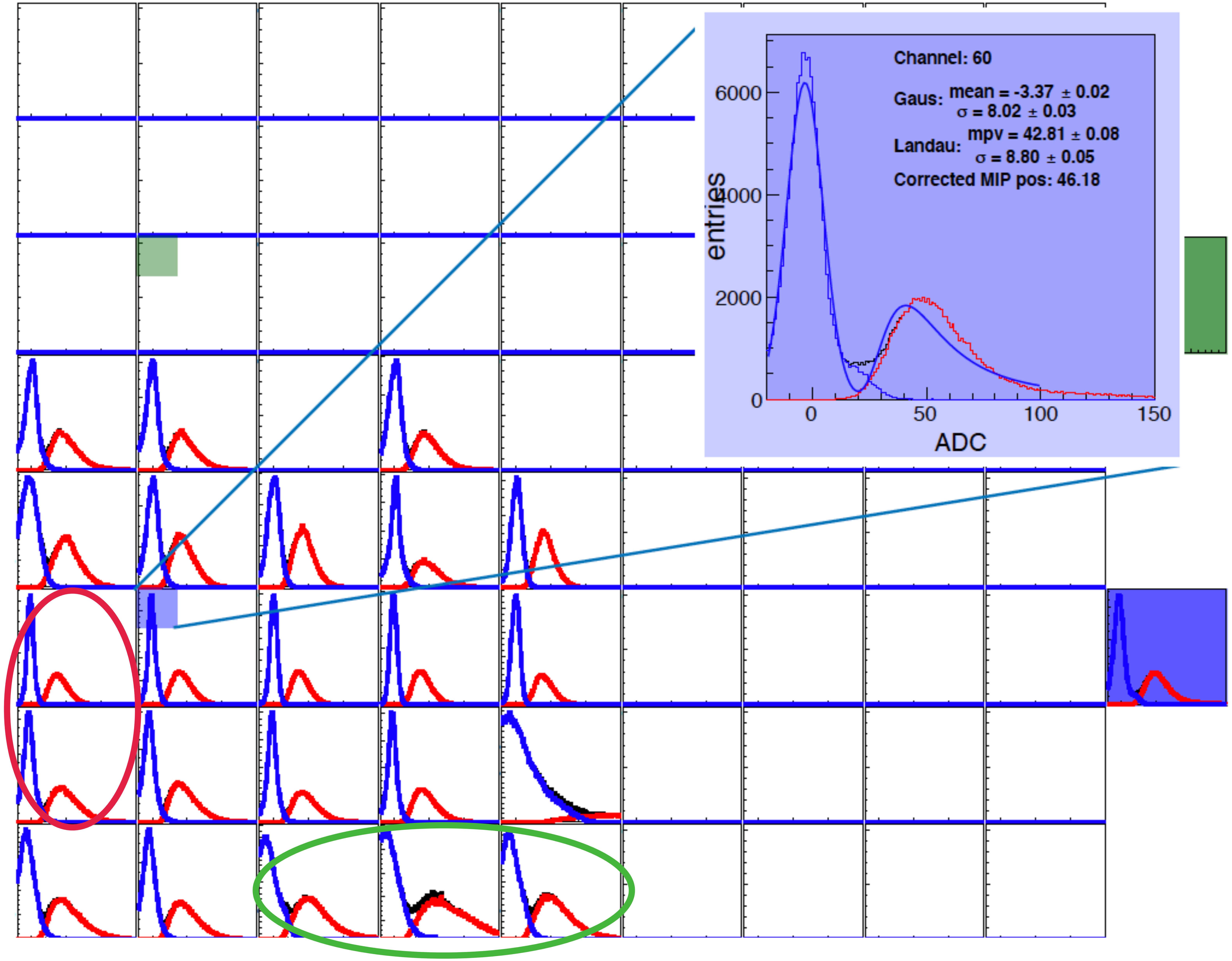


No.27
1000V [nA]

4	4	38	4	4	18	19	78	8
3	3	4	13	3	5	3	4	6
21	3	39	51	36	3	8	24	89
5551	32	OL	14	8	249	OL	4	8
8	73	14	4	6	42	6	3	3
OL	3	3	3	3	3	3	25	30
OL	3	54	7	3	5	4	3	3
3	5	9828	4	3	5	951	3	2

0.3586	0.4

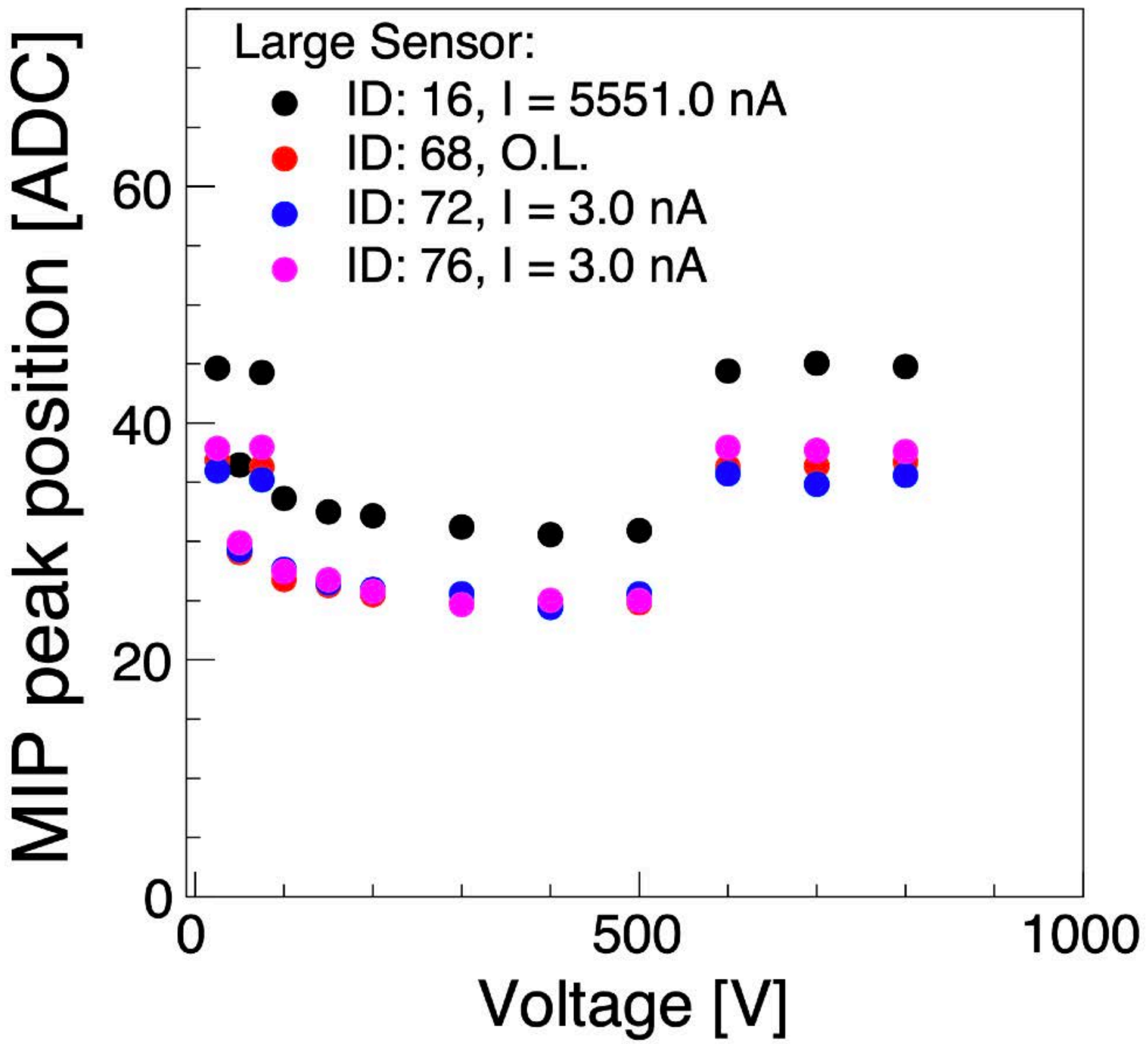
Hamamatsu data sheet on dark current at 1000V

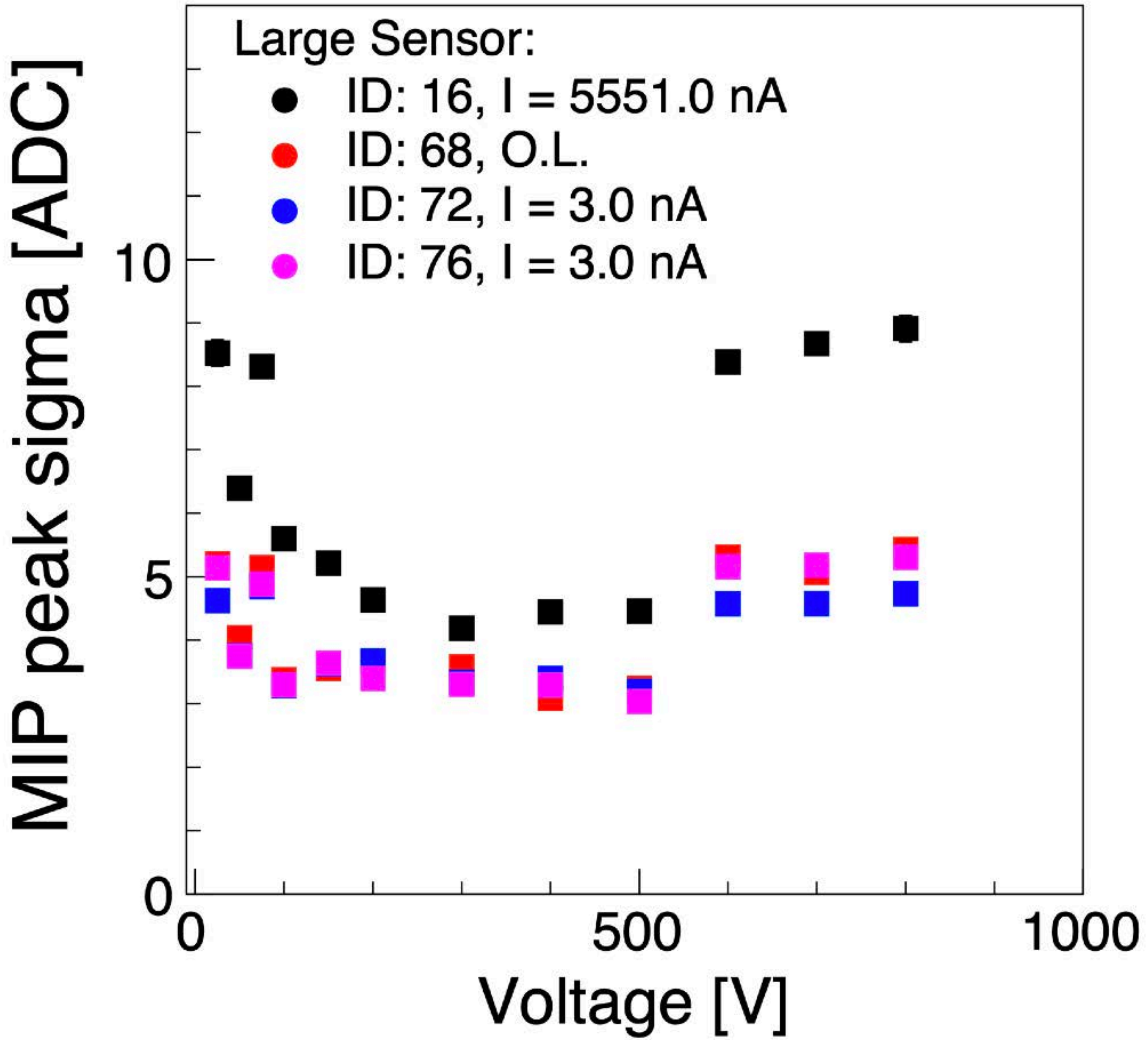


- **Clear MIP response for all measured cells**
- including those with high current in Hamamatsu test
- More detail studies by laser and cosmic are ongoing in the lab.

ELPH test beam results

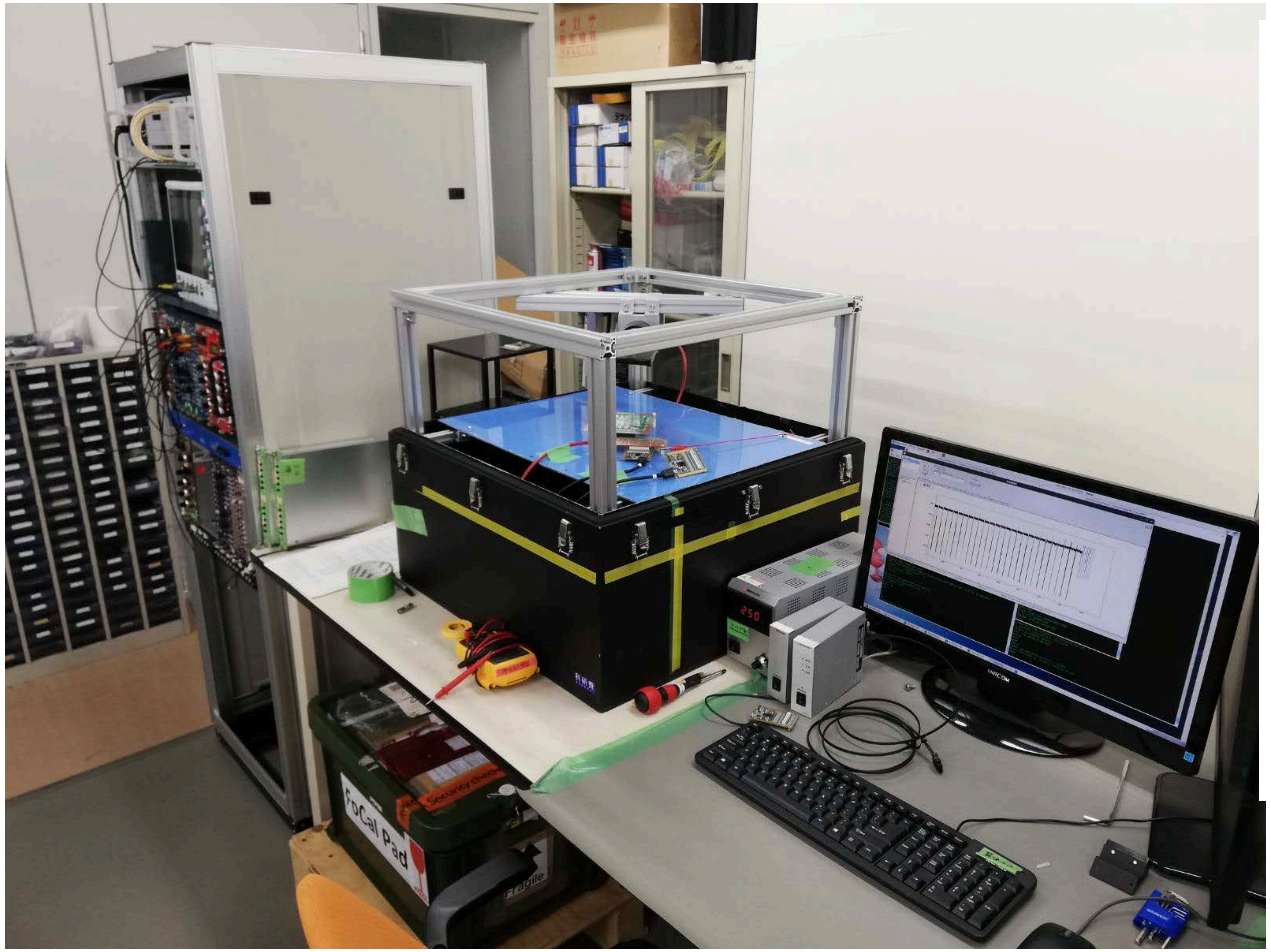
9x8 main chip w/Al

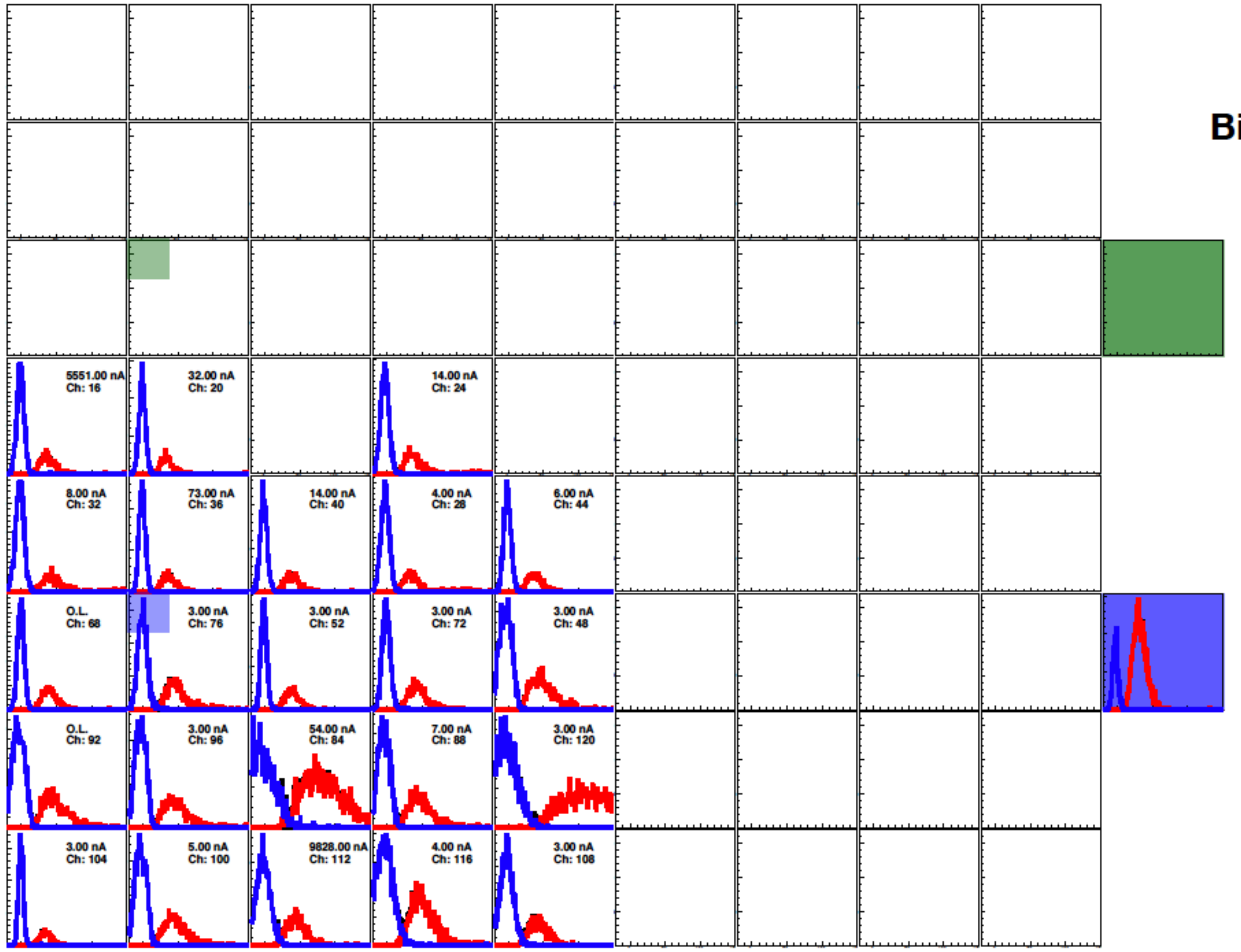




- **Stable response in 200 - 500 V.**
- <u>Next steps</u>:
  - Switch readout from APV to HGCROC for the next ELPH test beam (end of July), and SPS test in 2021/2022.
  - Radiation hardness test on p-type sensor (plan: neutron sources at RIKEN in 2021).

Cosmic test bench with APV25 hybrid readout





Bias 250 V

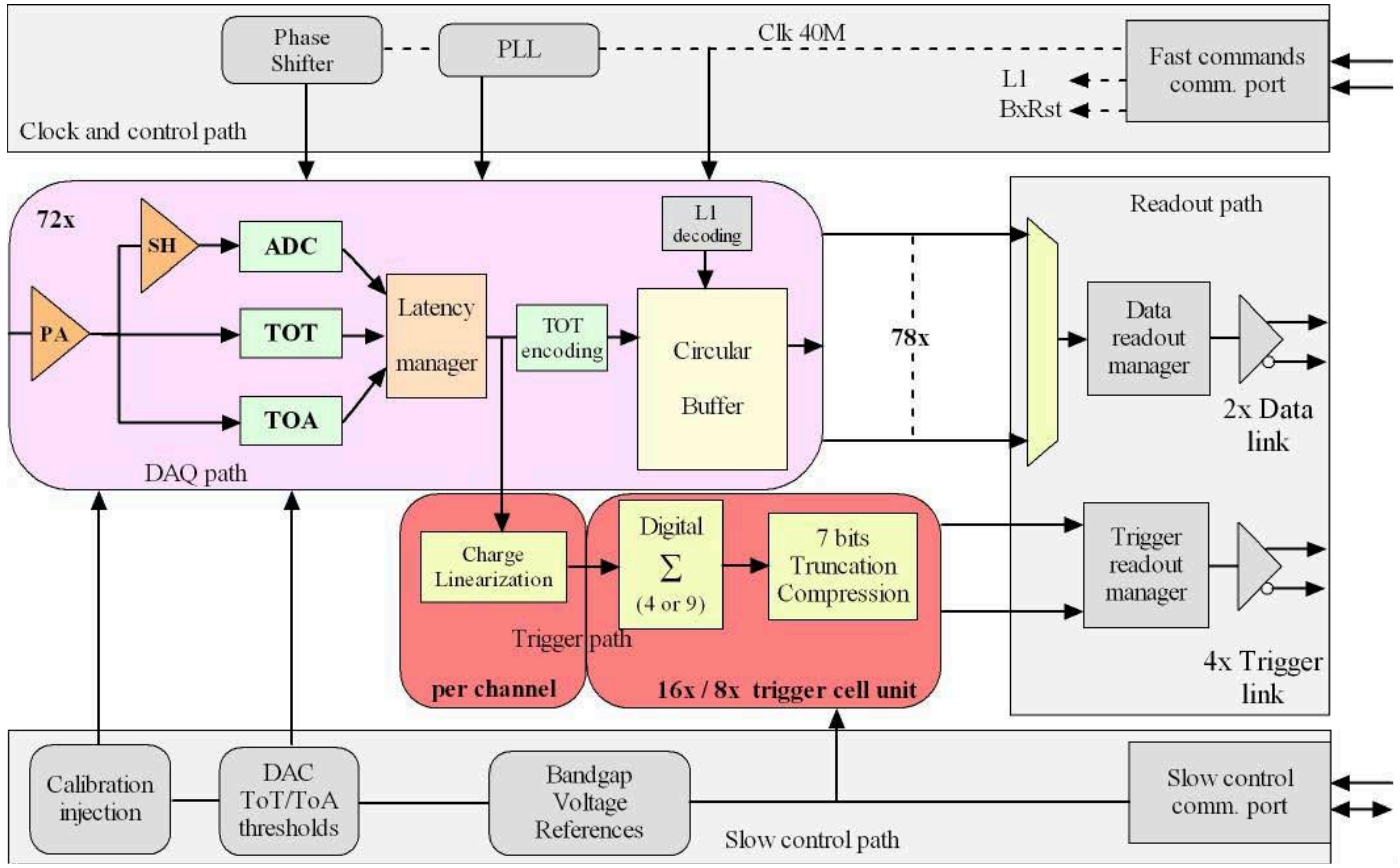
N. Novitzky

- Clear MIP signals seen by the cosmic ray data taking for 8x9 main sensor.
- Plan: will order new design of p-type main sensors (20) and n-type (20) in 2021.

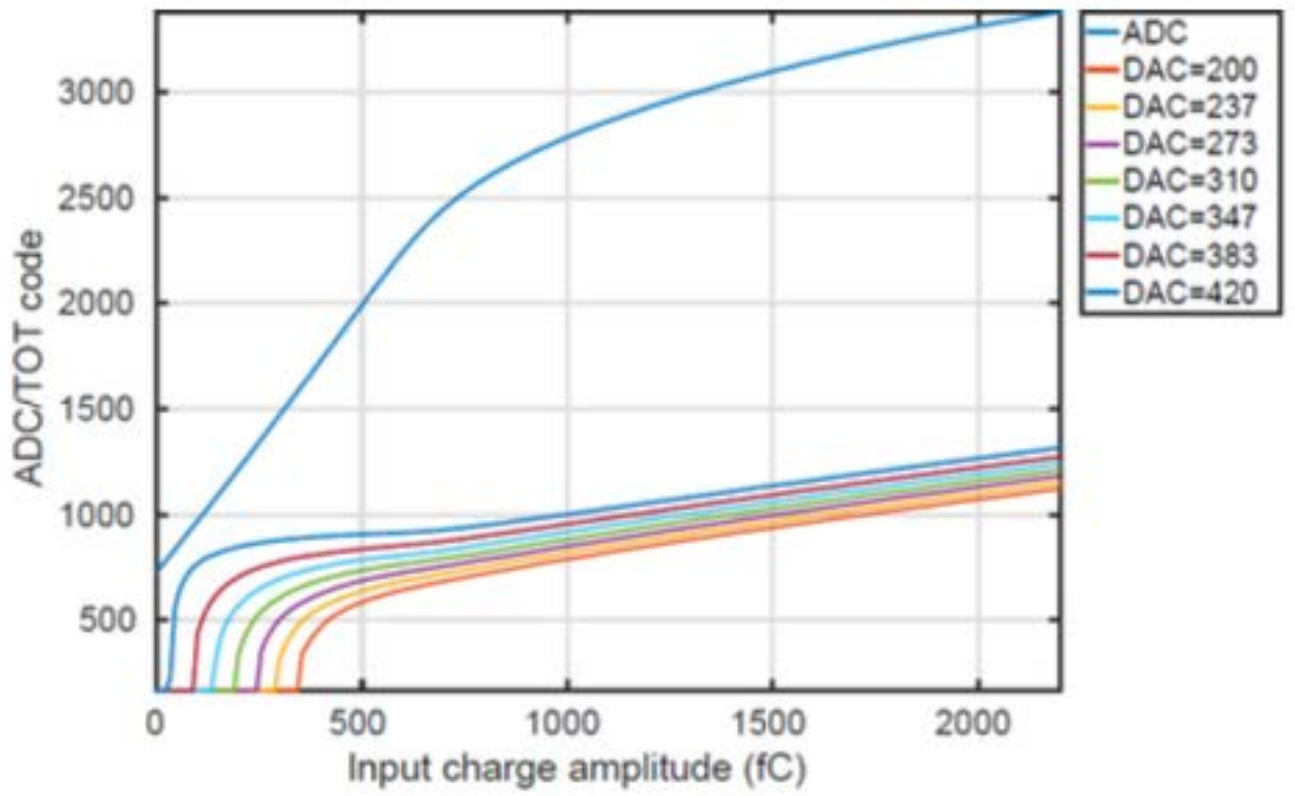
2) HGCROC for FoCal-E PAD readout

Readout ASIC: HGCROC (CMS HGCAL)

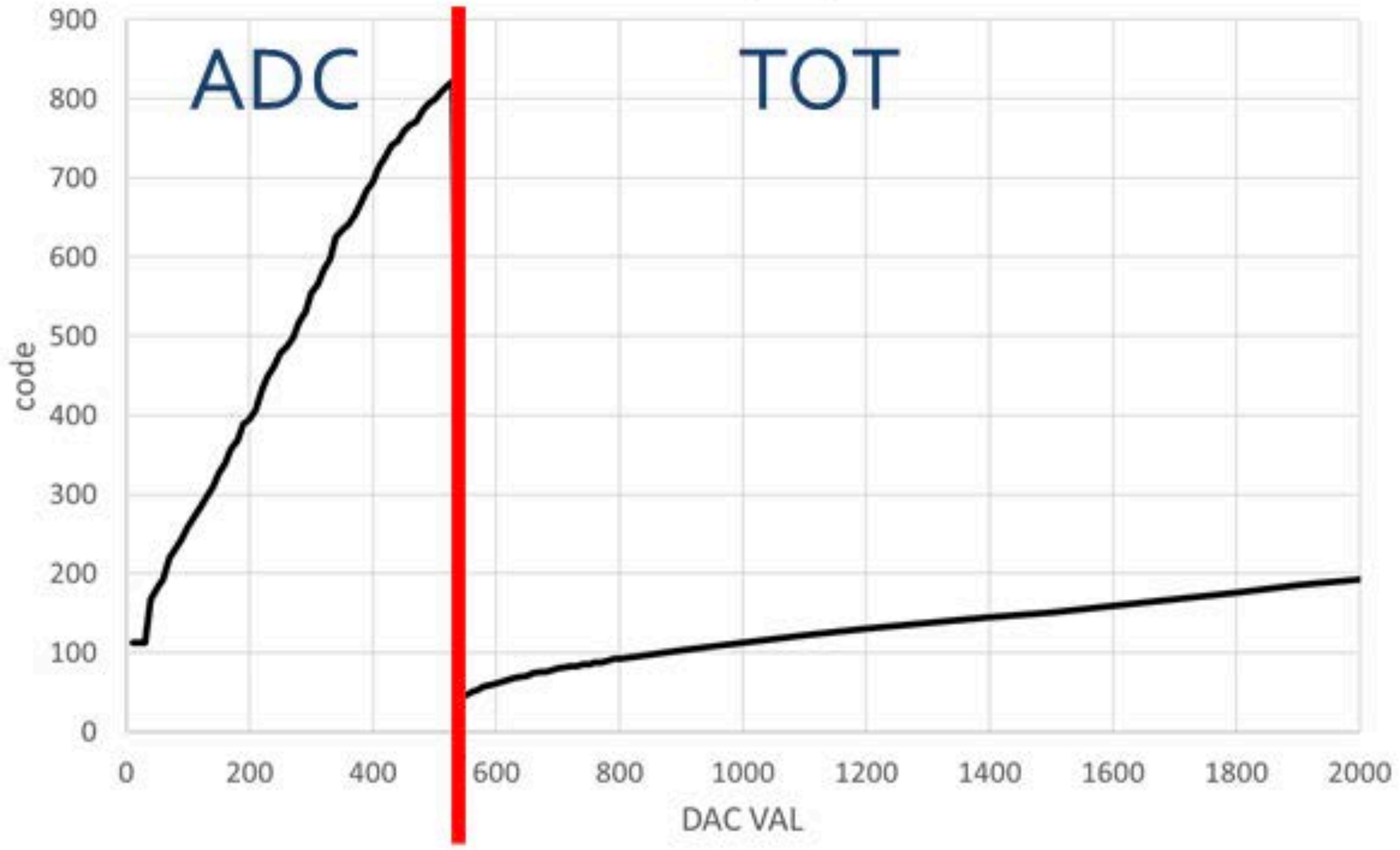
- 72 channels (+4 for CMN +2 for calib. cell) per chip: ADC (10 bits) + ToT (12 bits).
- Dynamic range: 0.2 fC to 10 pC (MIP to 1 TeV shower).
- Readout samples all channels @ 40 MHz.
- **Successful data taking by HGCROC (ADC/ToT) + KCU105 w/ charge injection (Grenoble/ Tsukuba).**

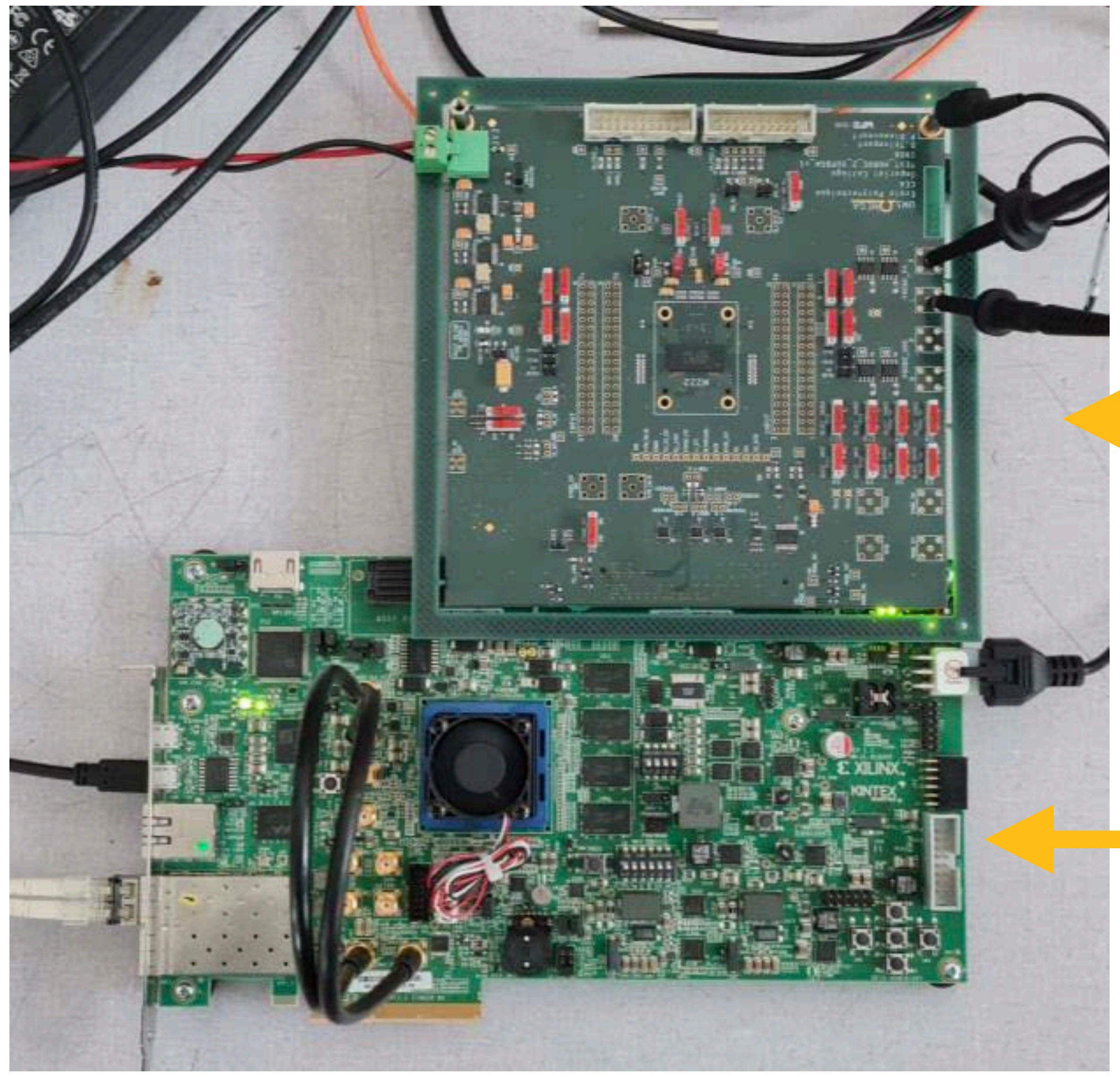


HGCAL TDR



ADC+ToT by charge injection (Grenoble)

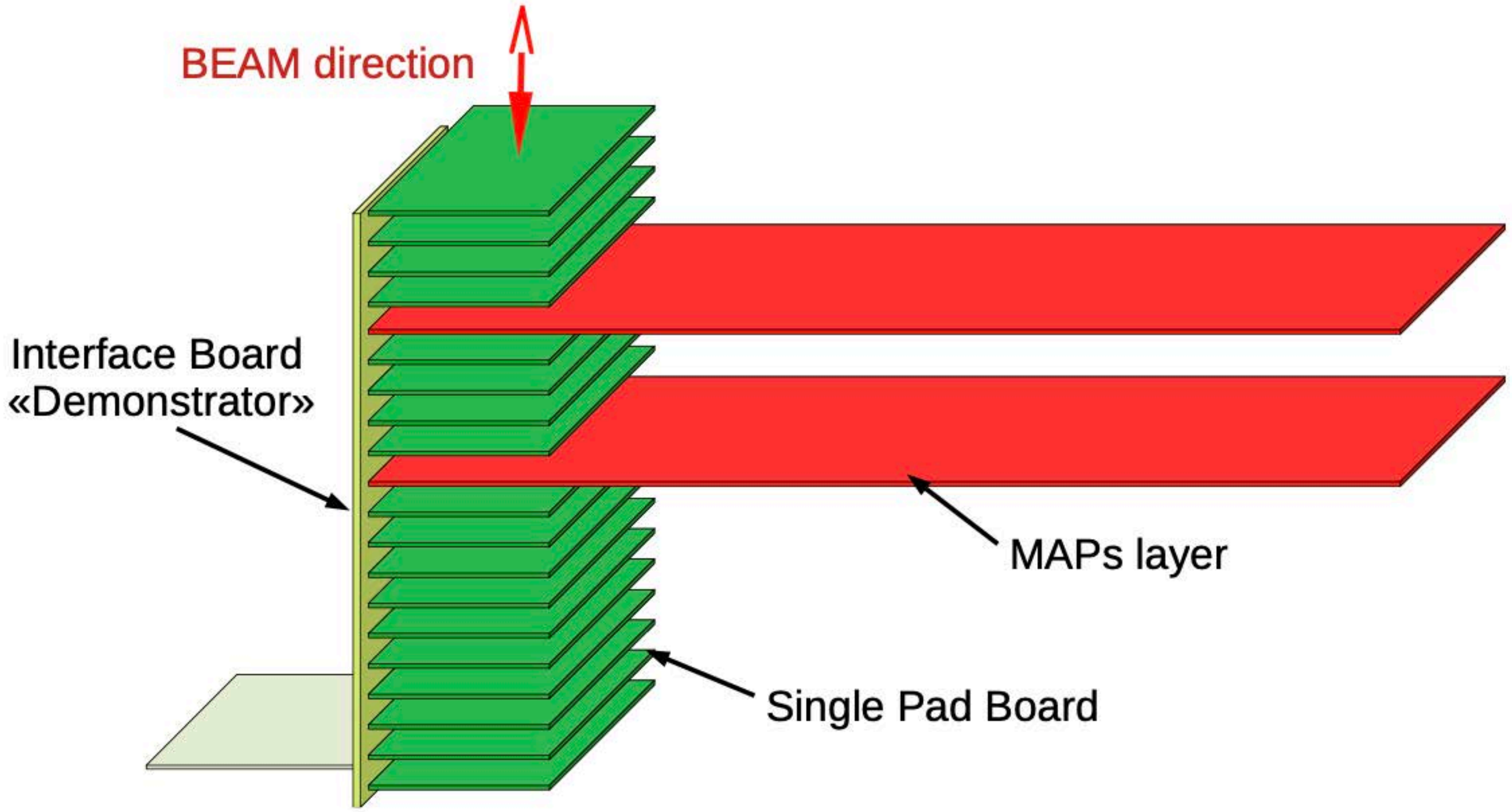




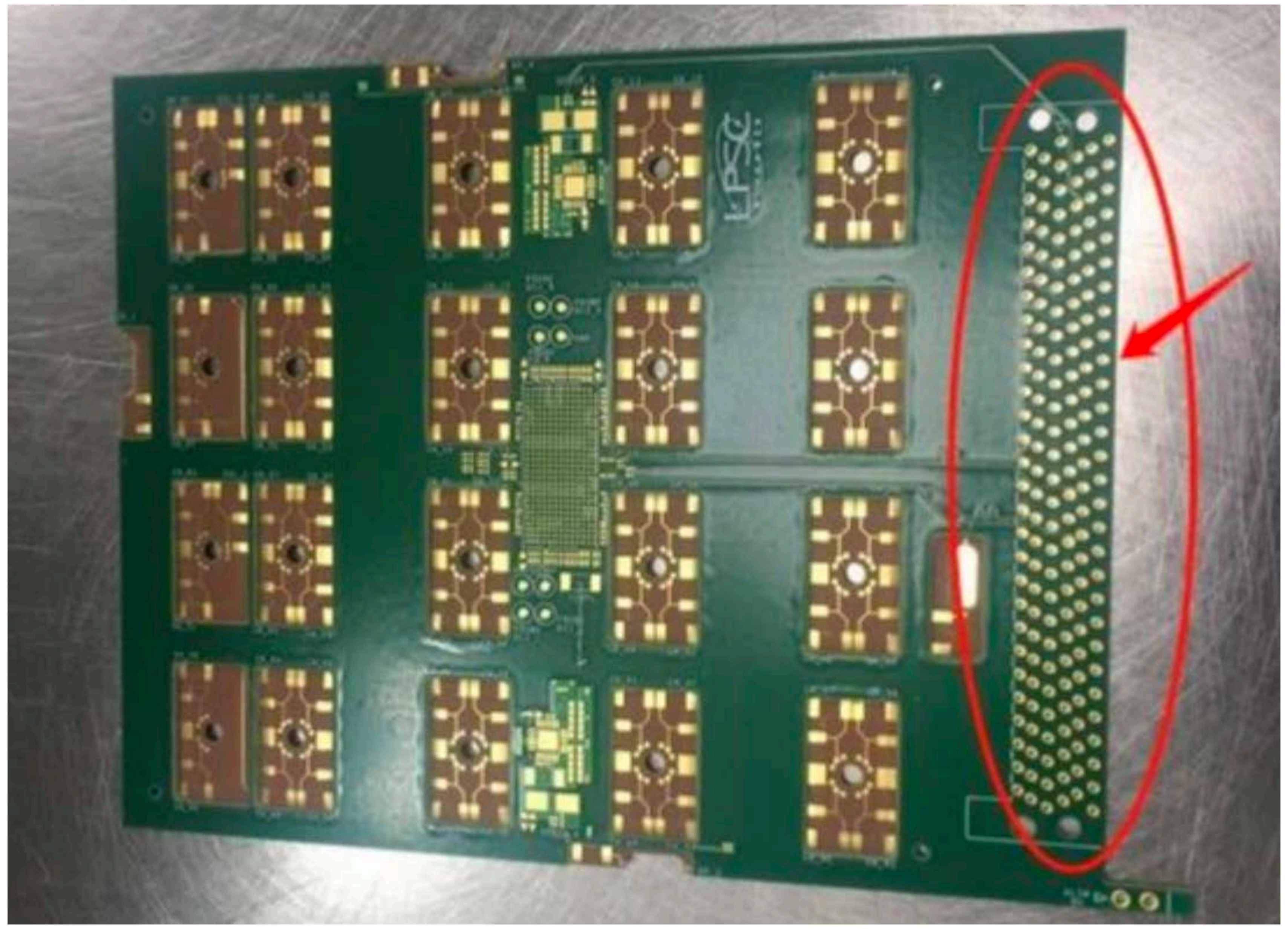
HGCROC test board

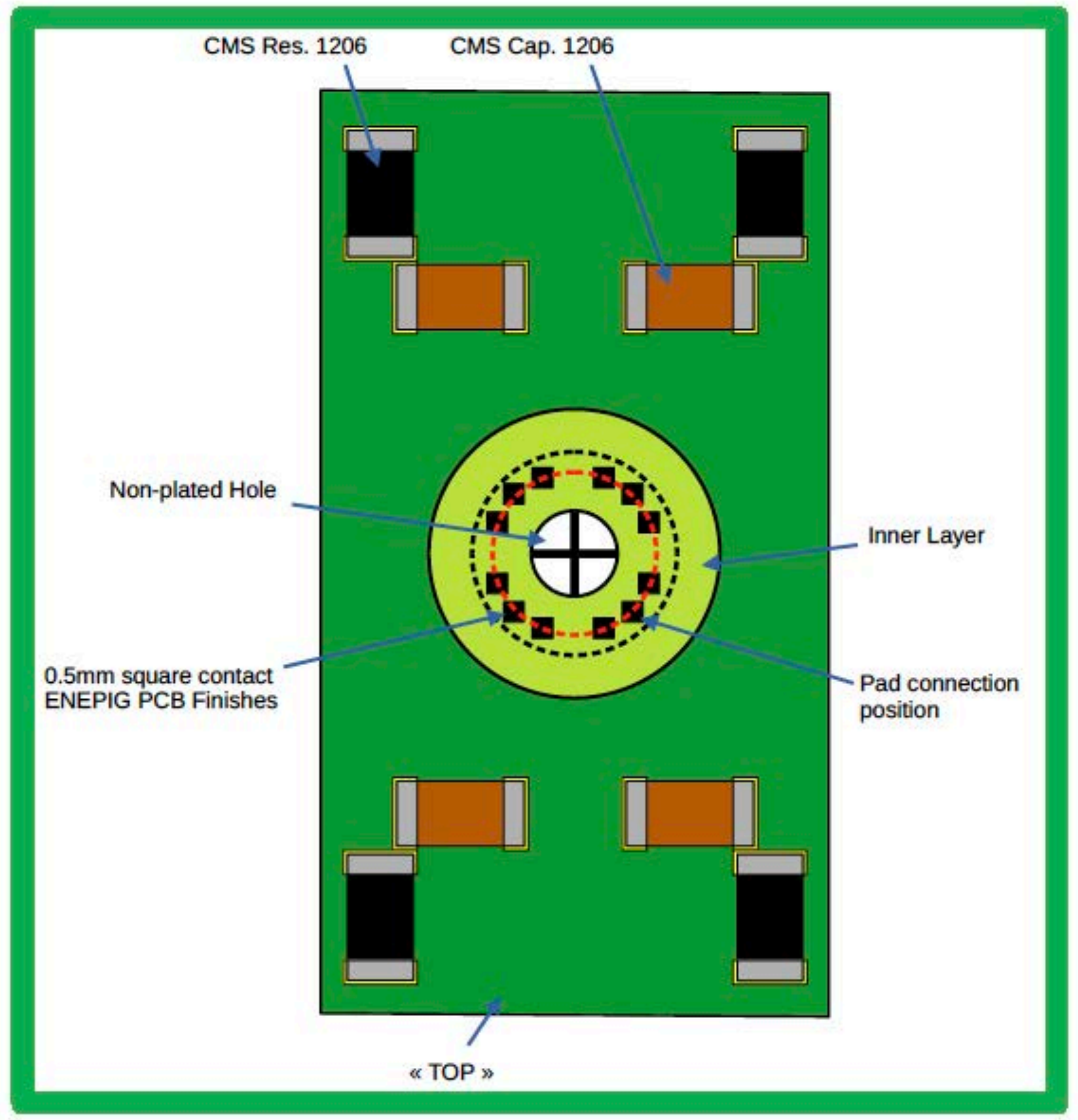
XILINX FPGA KCU105

2021/2022 test beam prototype



PCB received on Jan. 25th, 2021



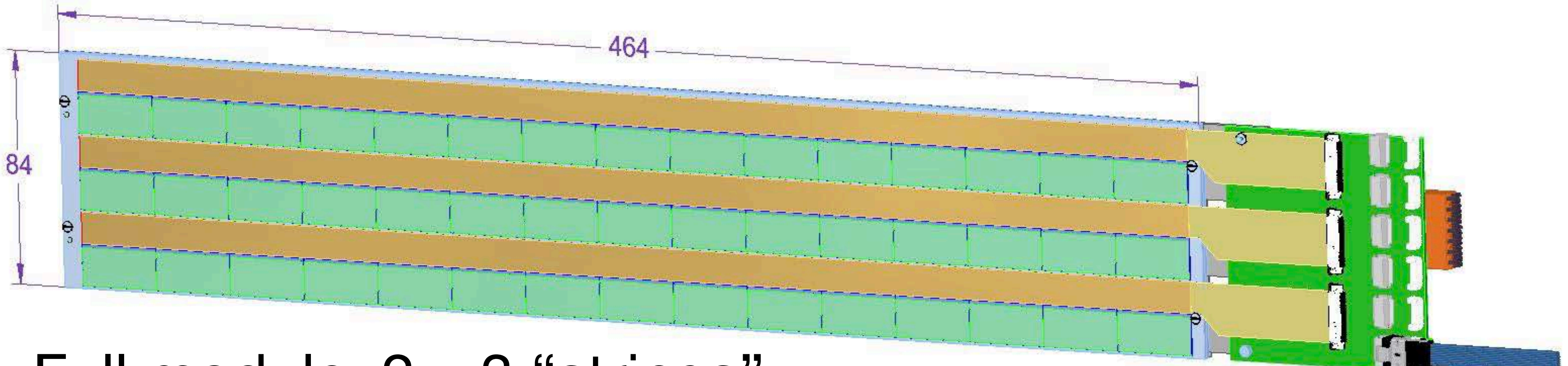


2021 prototype design:

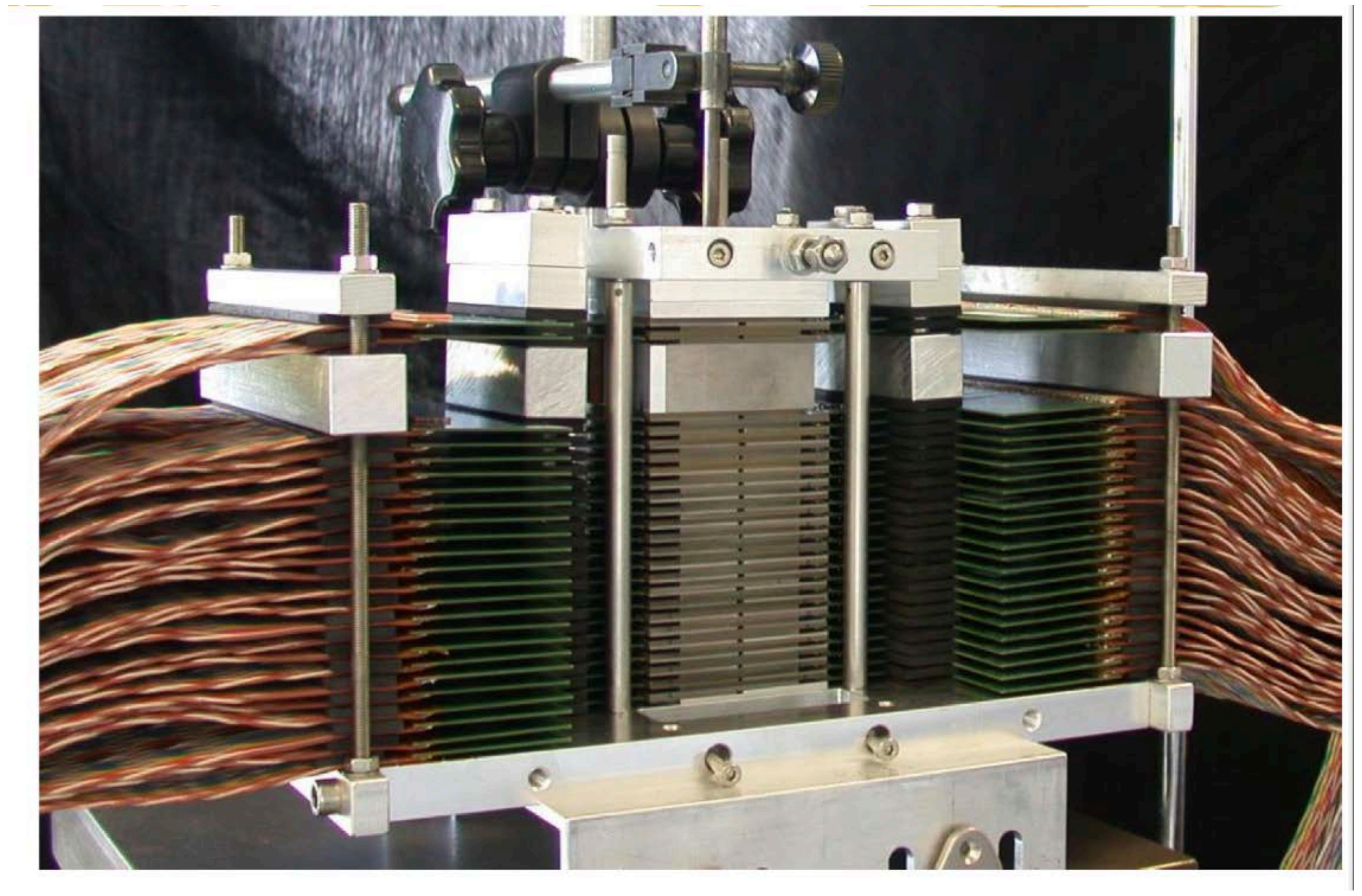
- PCB for one HGCROC (single PAD board).
- Connects to one sensor (72 cells) w/Interface board, and then one aggregator board.
- **Board ready for lab test**; revisions needed for mechanical stability (under way).

3) FoCal-E PIXEL

9 ALPIDE chips on a flex cable:
30 x1.5 cm^2
(developed for pCT application)

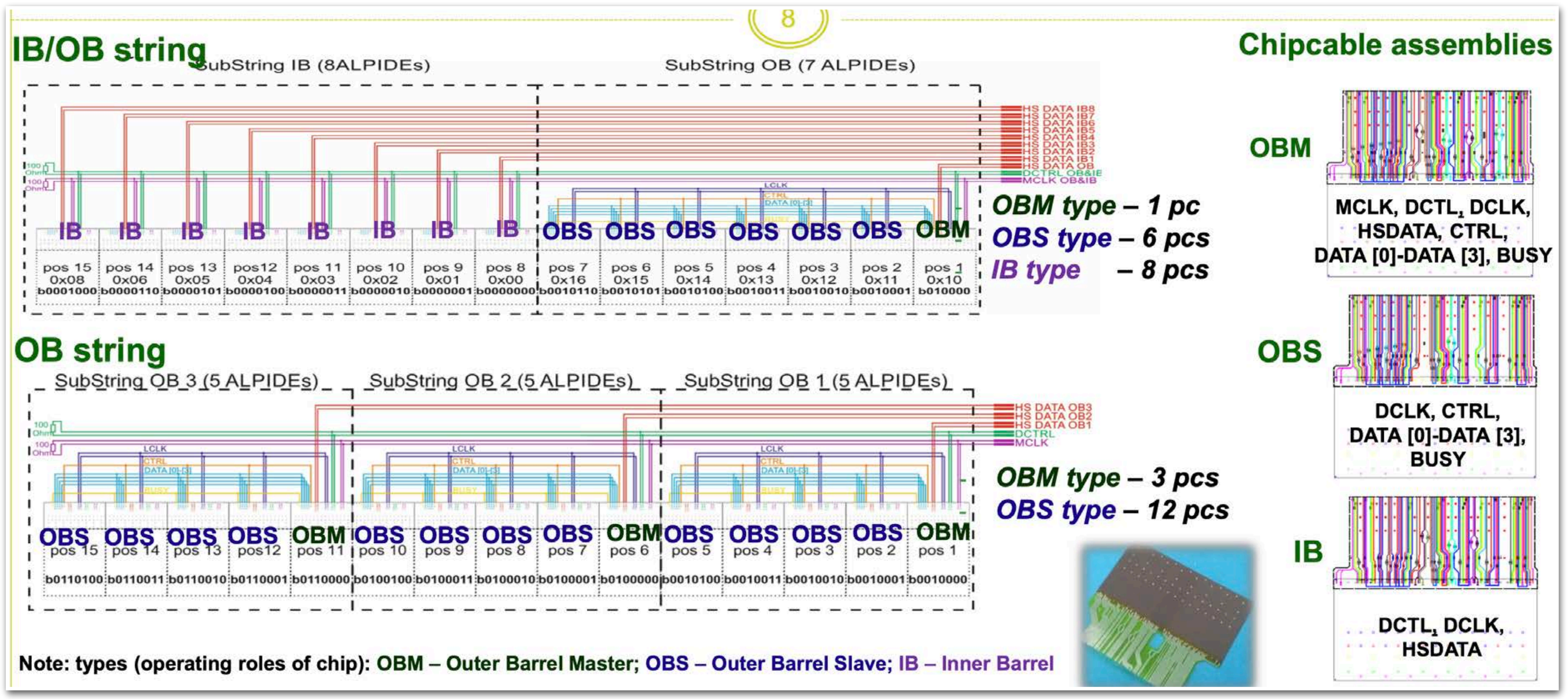


Full module: 2 x 3 “strings”
→FoCal design: 15-chip flex cables

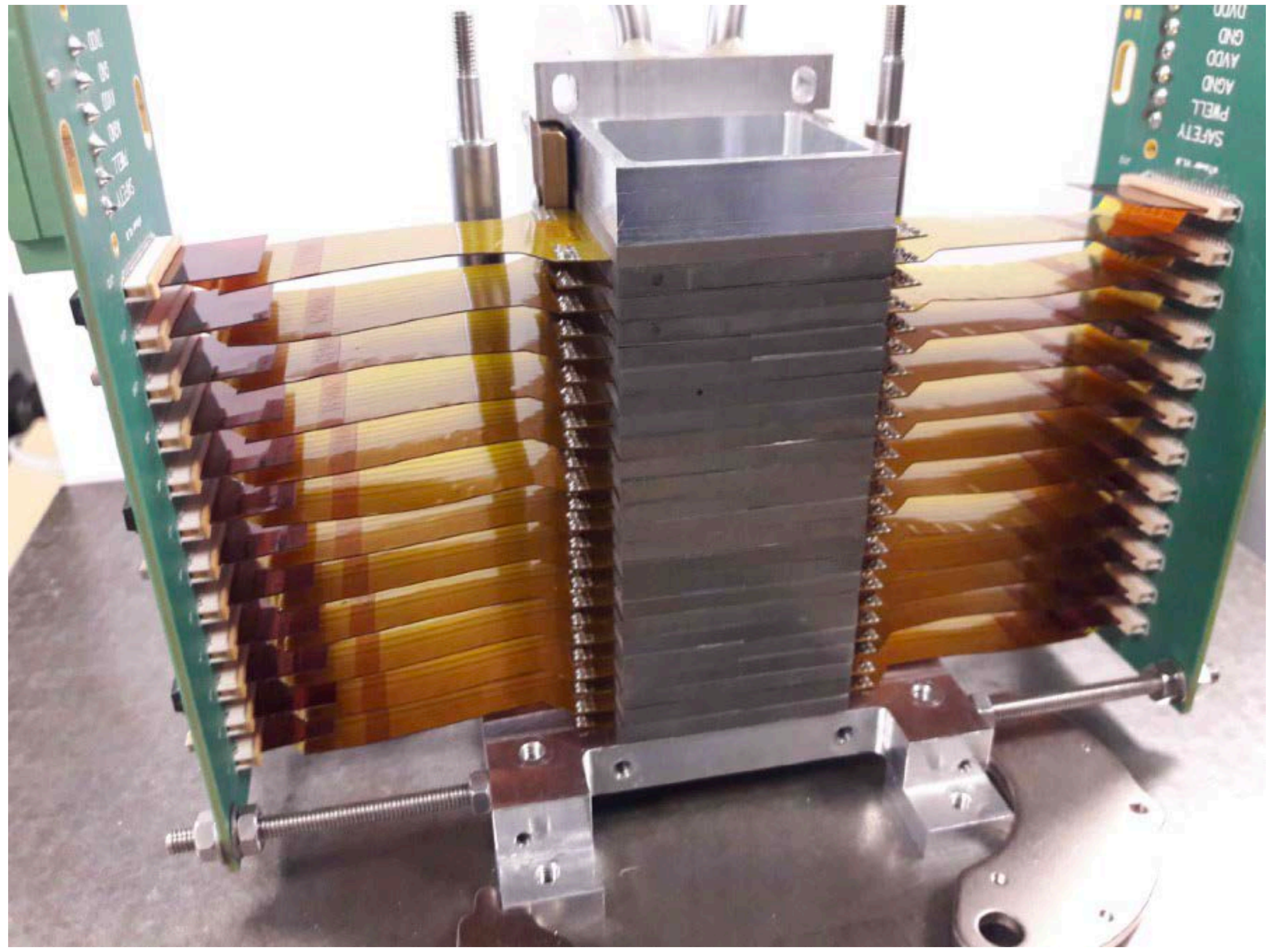


MIMOSA pixel calorimeter

Flex cable design is progressing

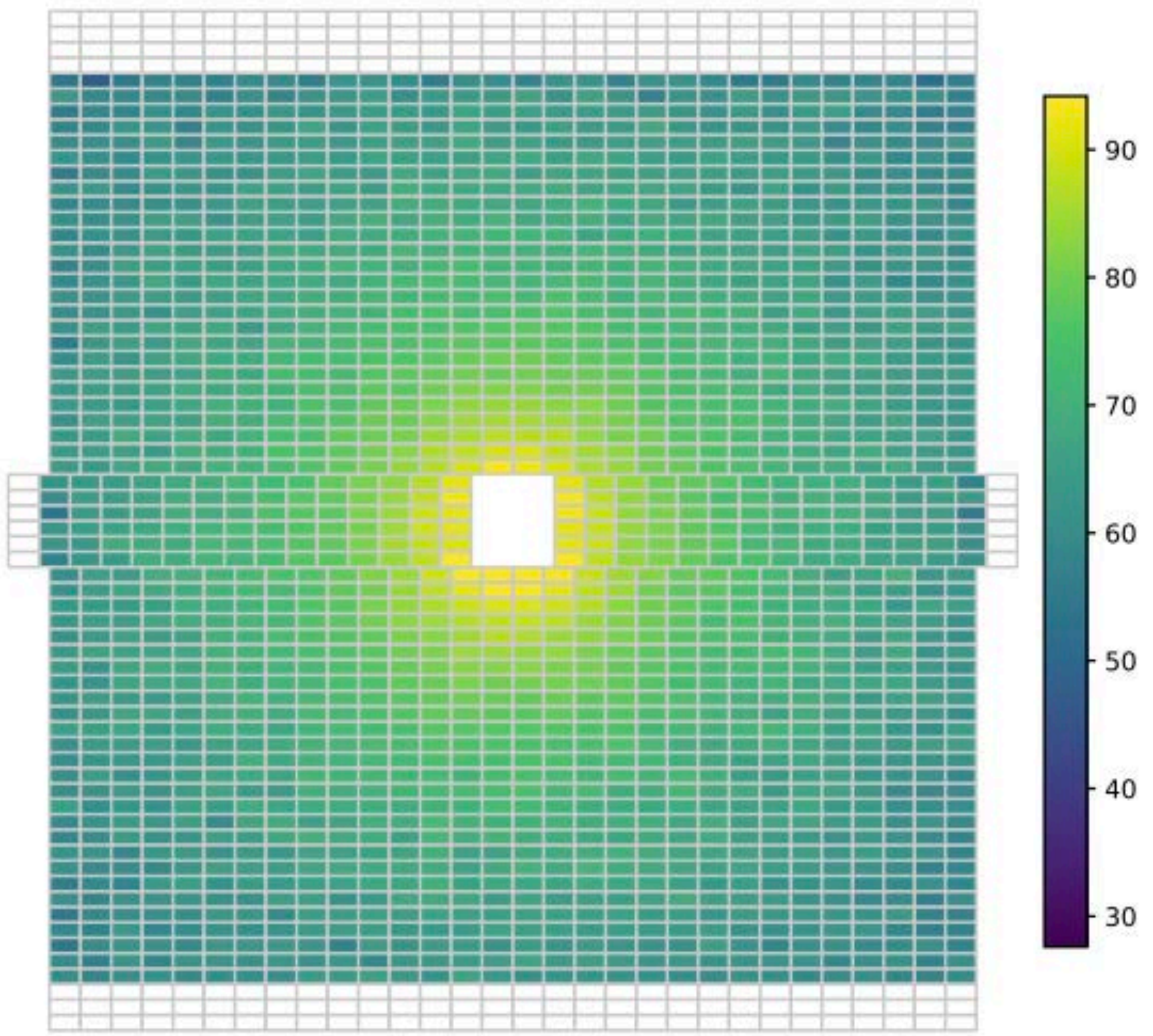


(Bergen, Utrecht / Nikhef, LTU, Kharkov)

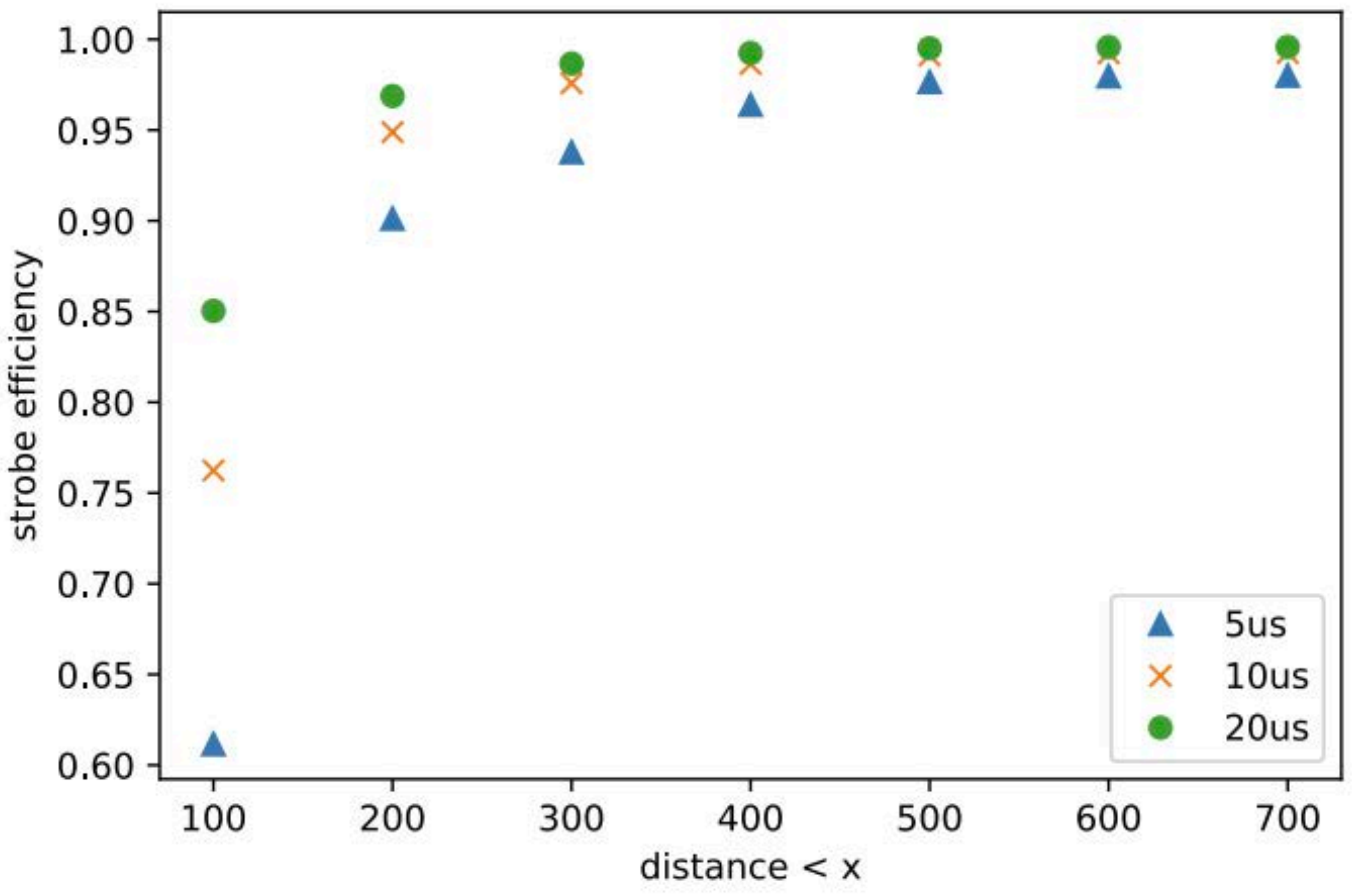


EPICAL: (sm)all-pixel E-cal prototype

PIXEL occupancy study

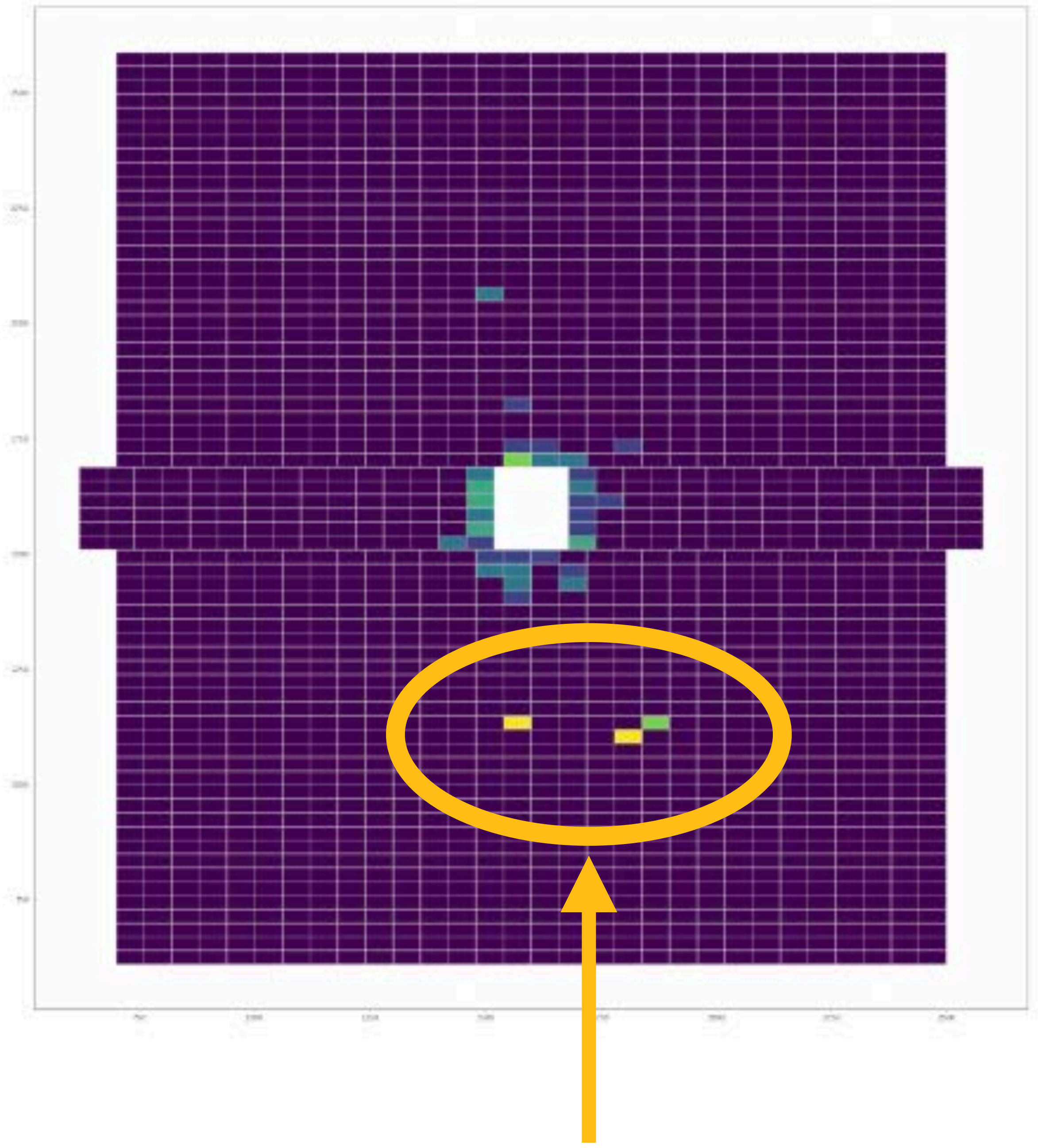


Efficiency vs distance to beam

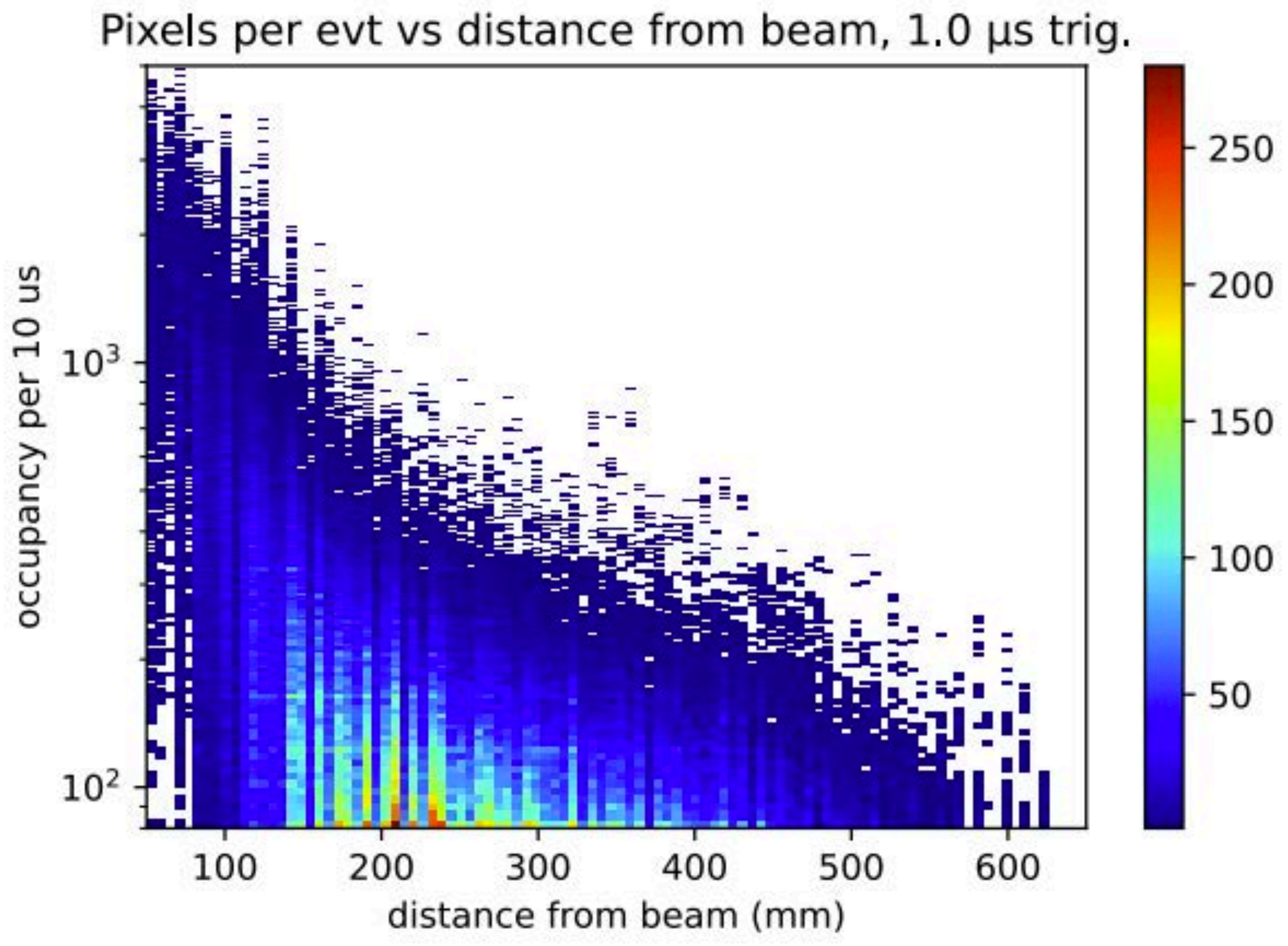


Front-end shaping time ~10 μs

Readout error map

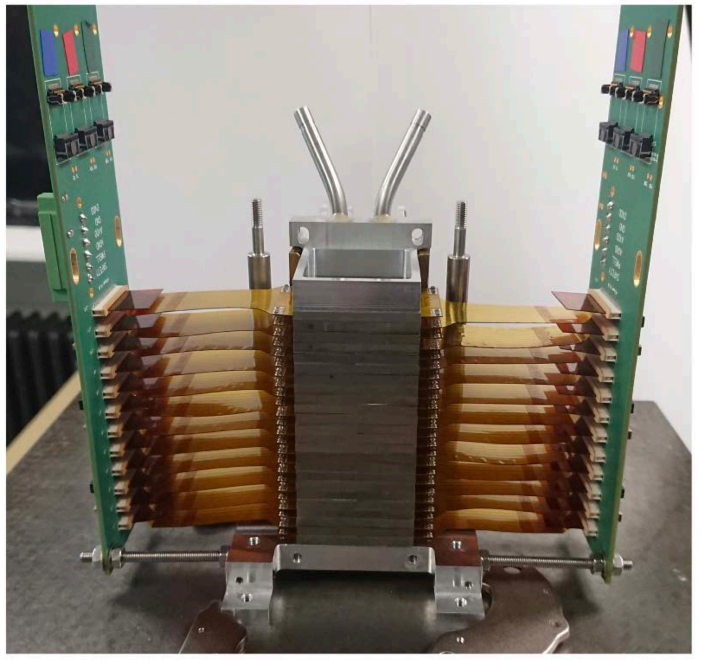


Solution: add one IB/OB module with high-rate connectivity

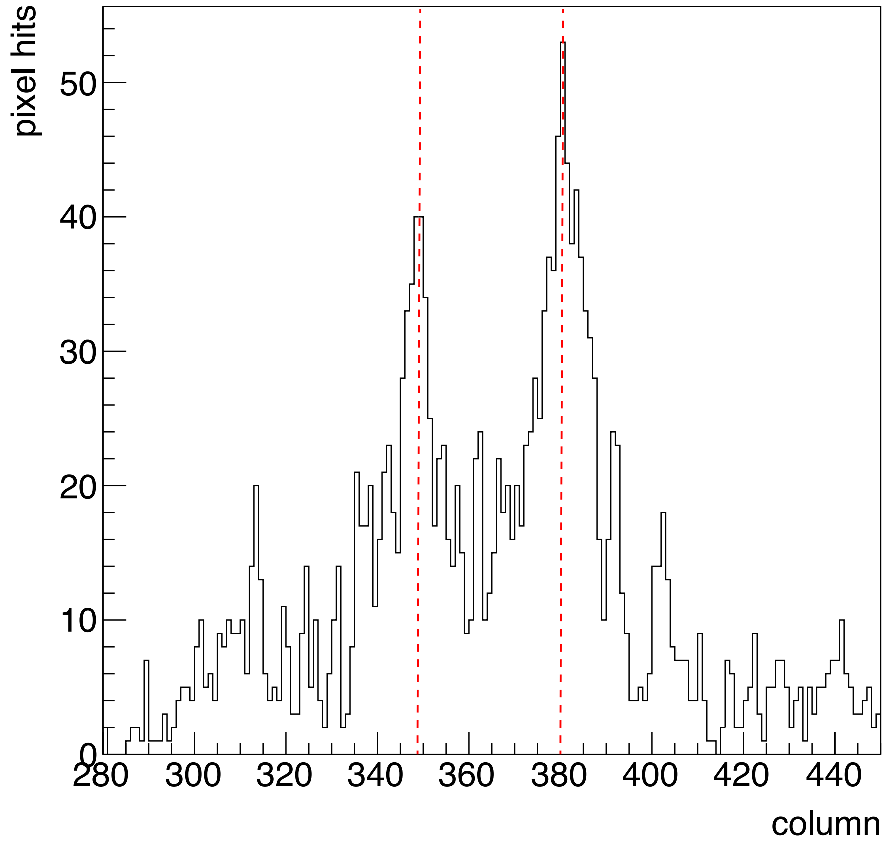


Remaining readout errors only near beam (mask nearest pixels if needed)

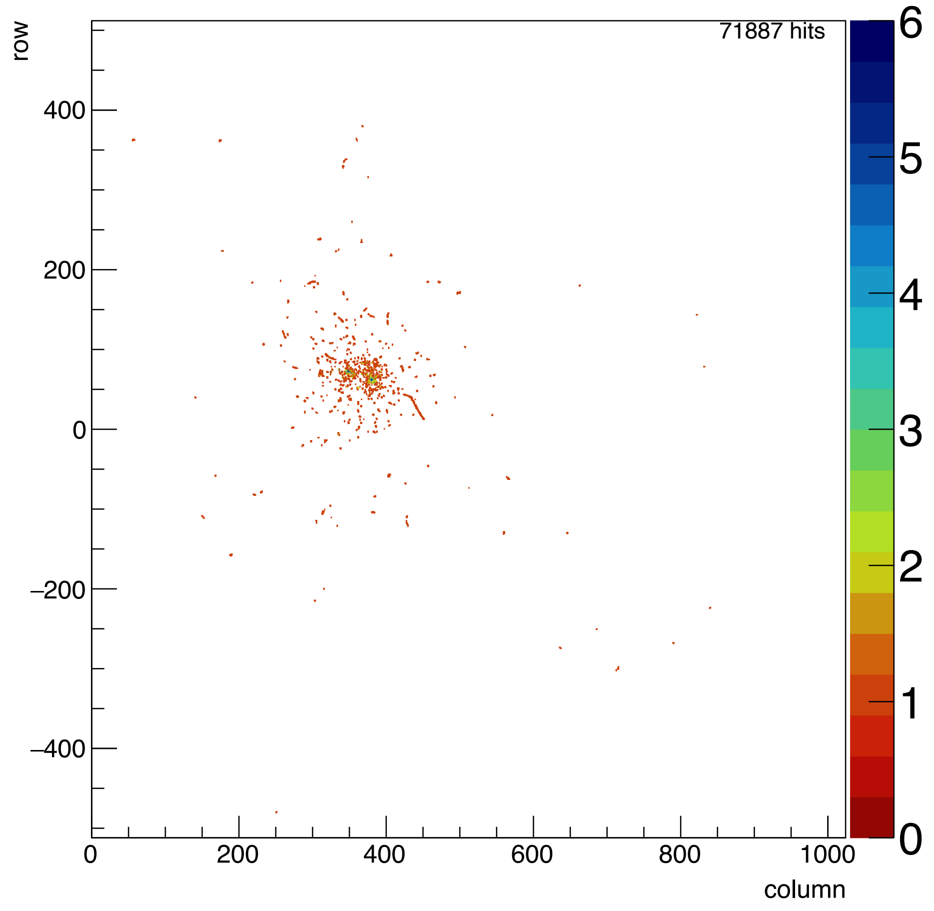
EPICAL-2 test beam at DESY (2019/2020)



Two shower separation

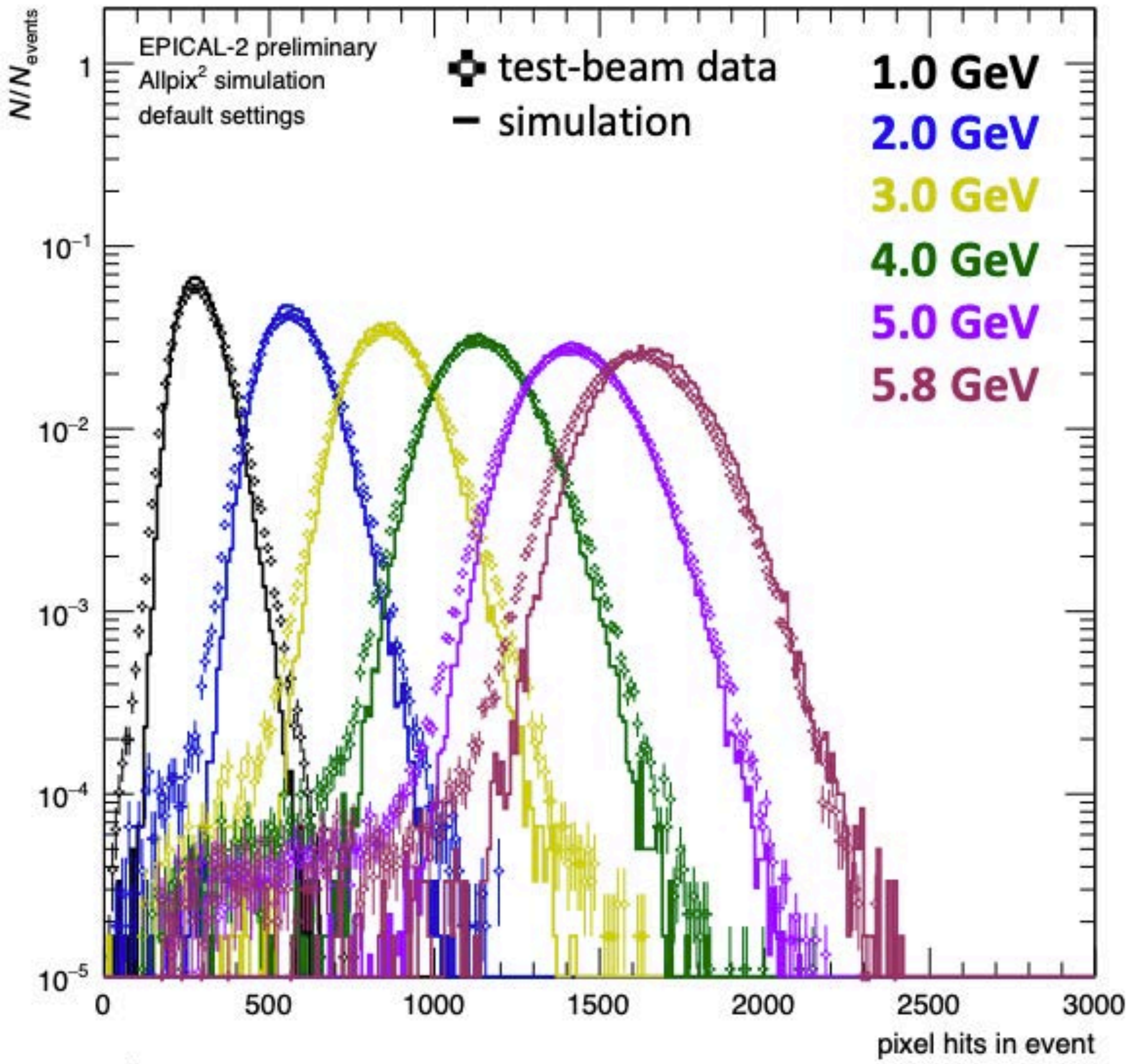


EPICAL-2 preliminary
Allpix² simulation
30 GeV e- + 250 GeV e-
1.2 mm separation
single event
first 6 layers integrated



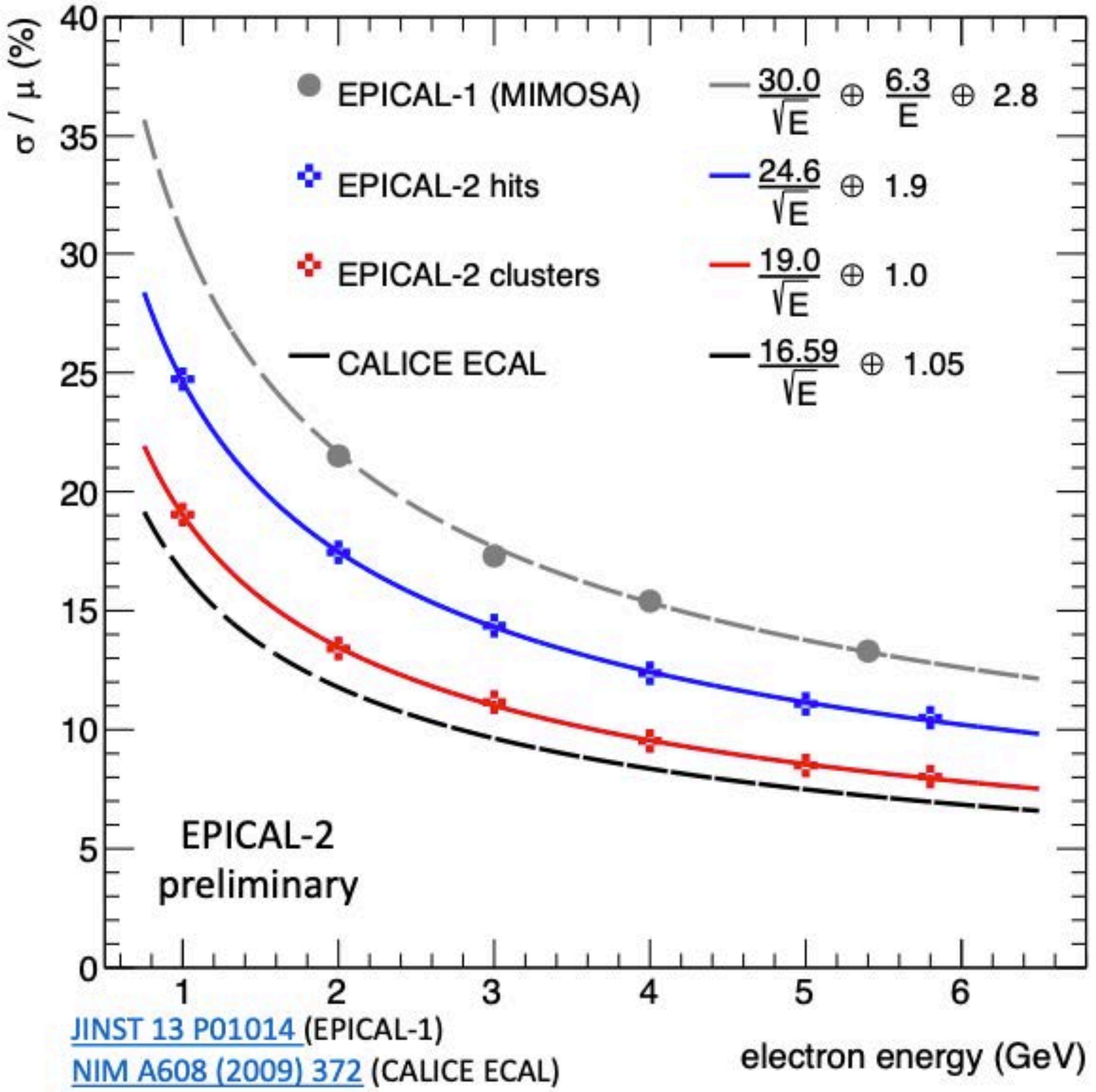
Two-shower separation down to 1 mm should be possible

Number of pixel hits



Detailed response simulations with AllPix²

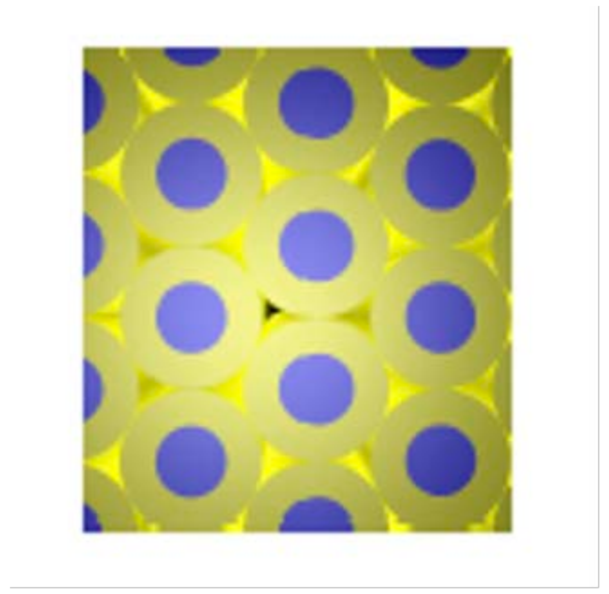
Energy resolution

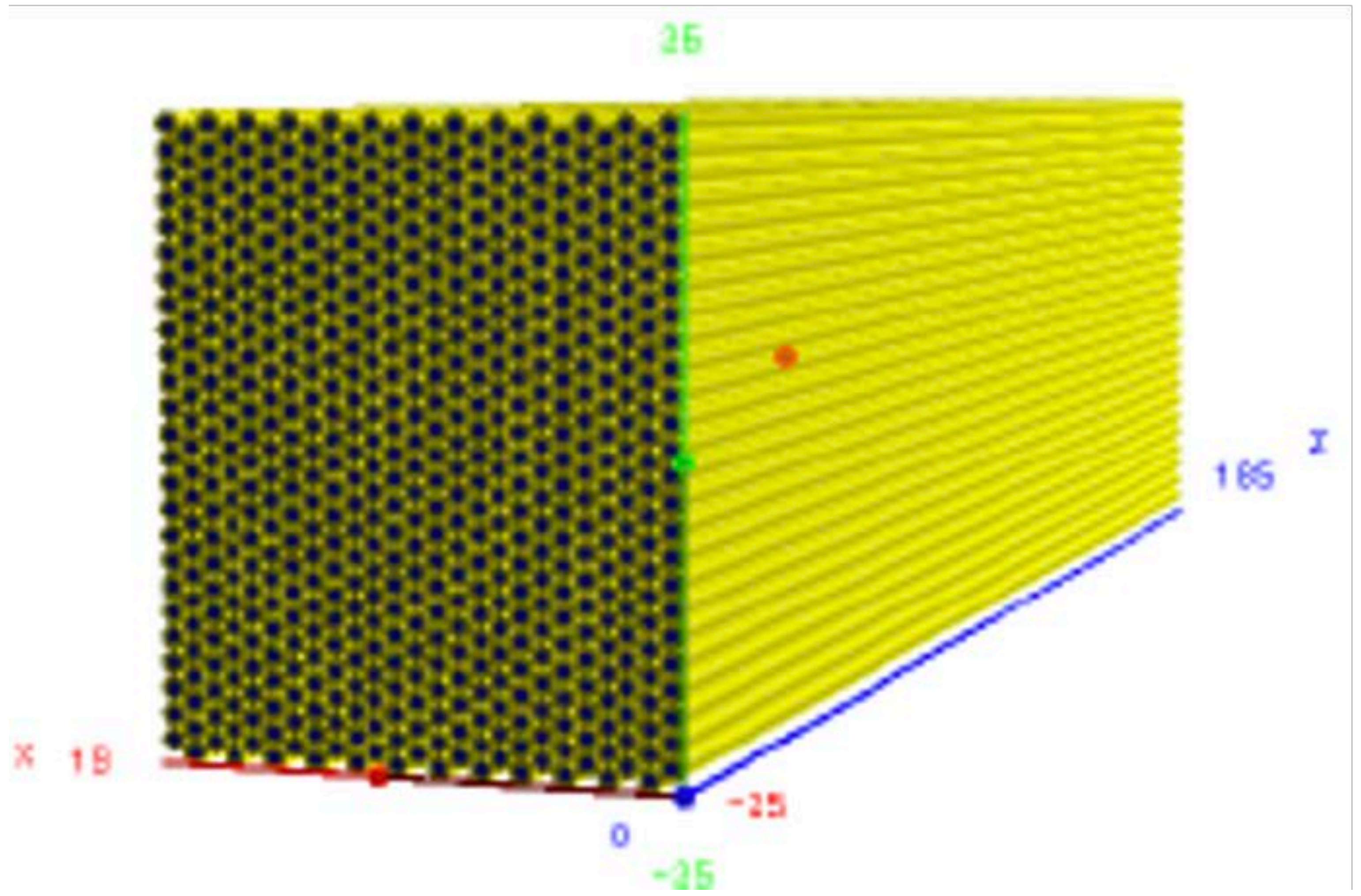


Cluster counting provide better energy resolution than hit counting

Digital pixel calorimetry: good energy resolution and excellent spatial resolution

4) FoCal-H





(Similar approach suggested and being tested by IDEA collaboration in Oct 2020, e.g. see talk)

Plan for test beam (2021)

- HCal prototype based on Cu capillary tubes
- Fibers and tube samples acquired

Performance/resolution simulations (on-going)

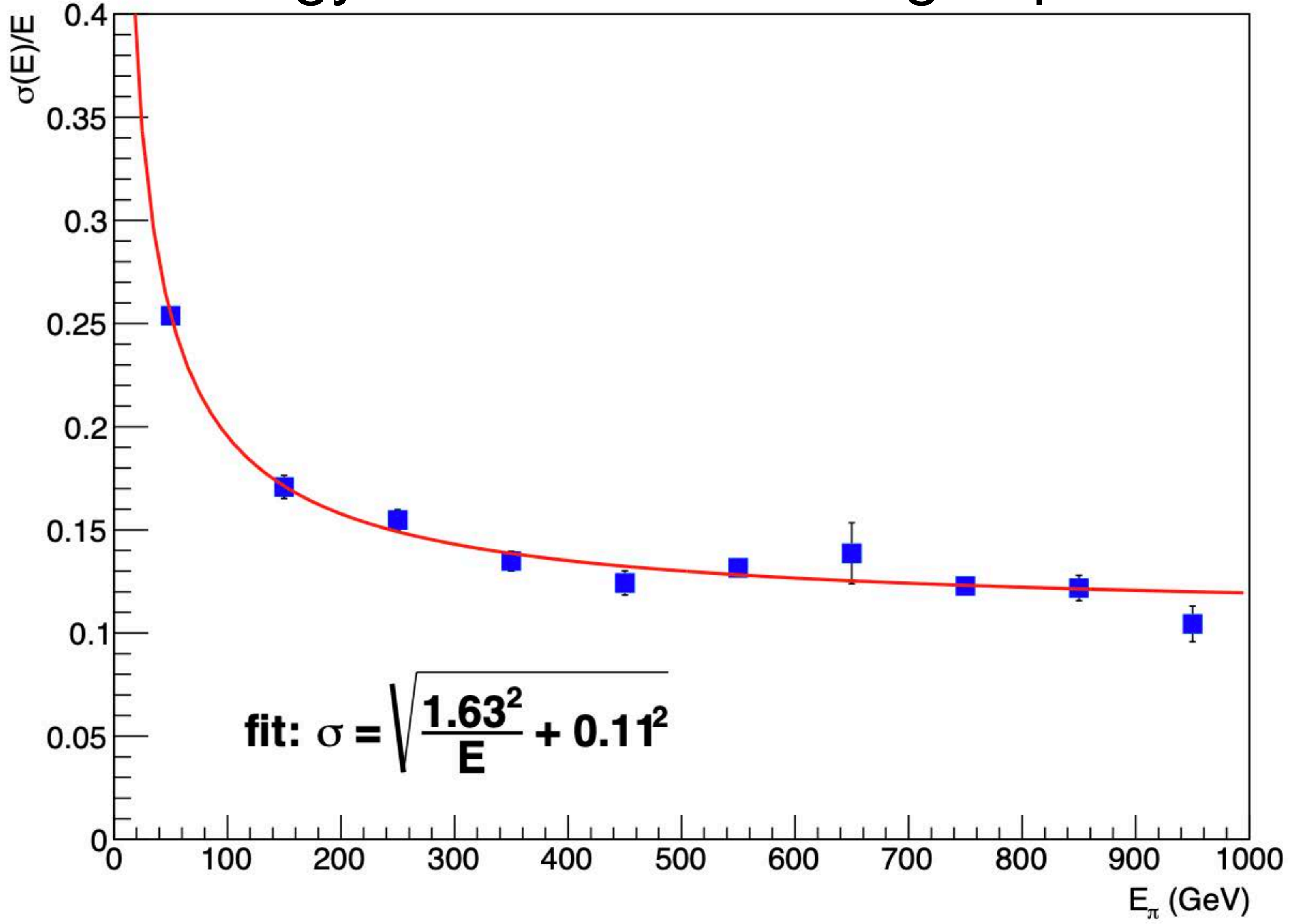
- Optimize performance, e.g. optimal ratio of active-passive material, granularity.
- large run time in had. shower simulation, but solutions being worked out

Choice of readout (SiPM/APD)

- SiPM being explored: more cost-effective and HGCROC compatible version exists

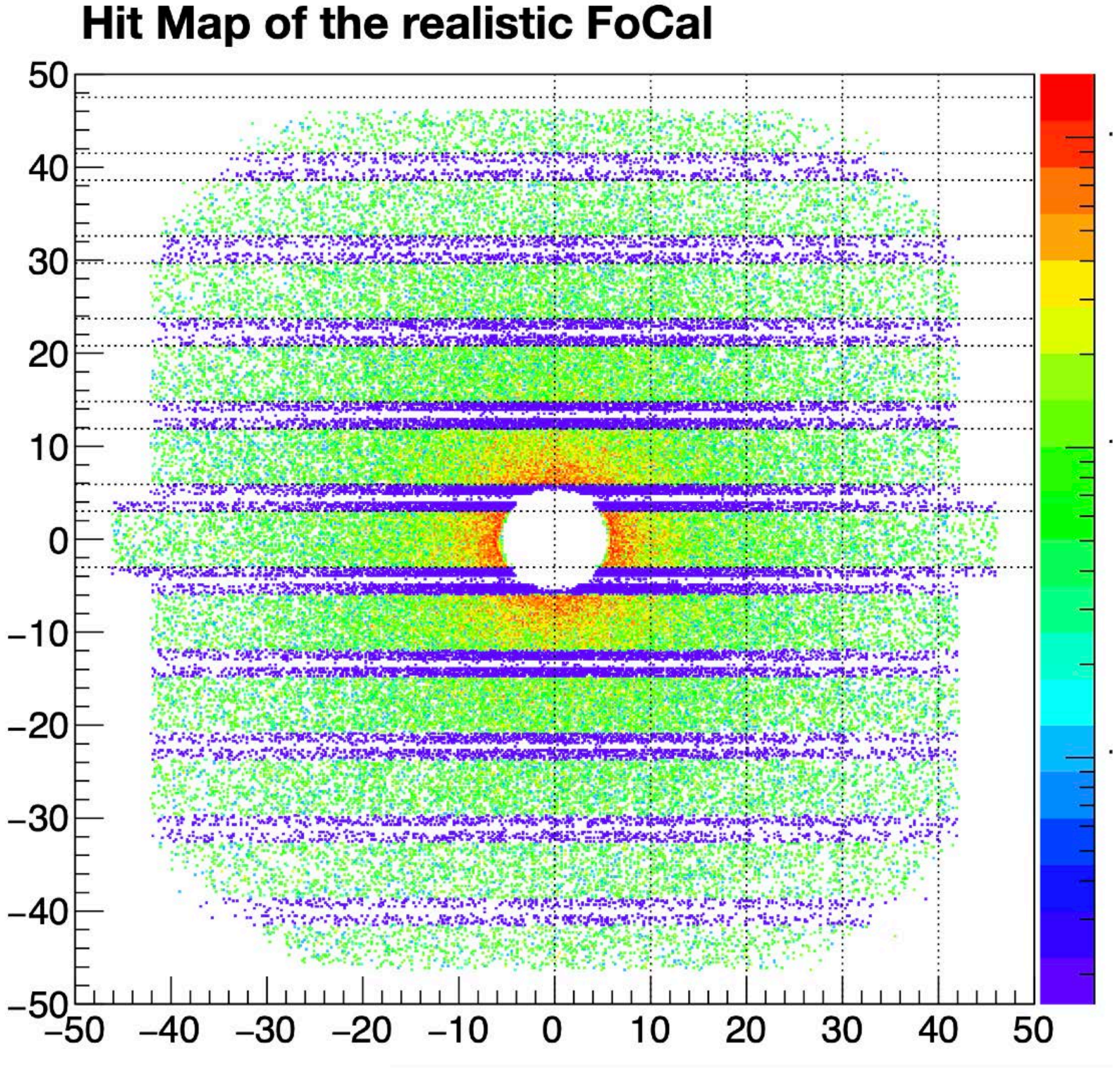
(Copenhagen)

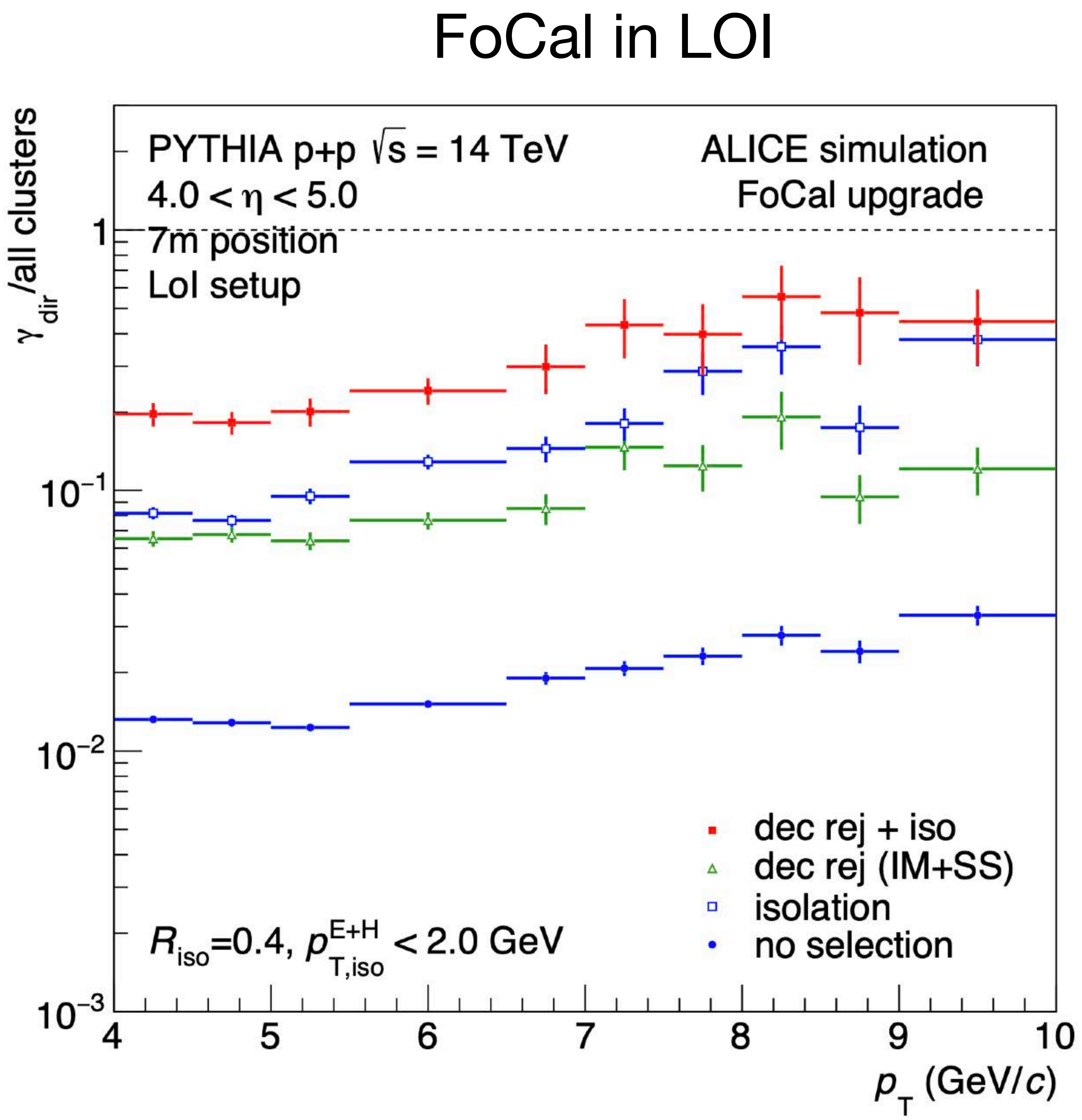
Energy resolution for charged pions

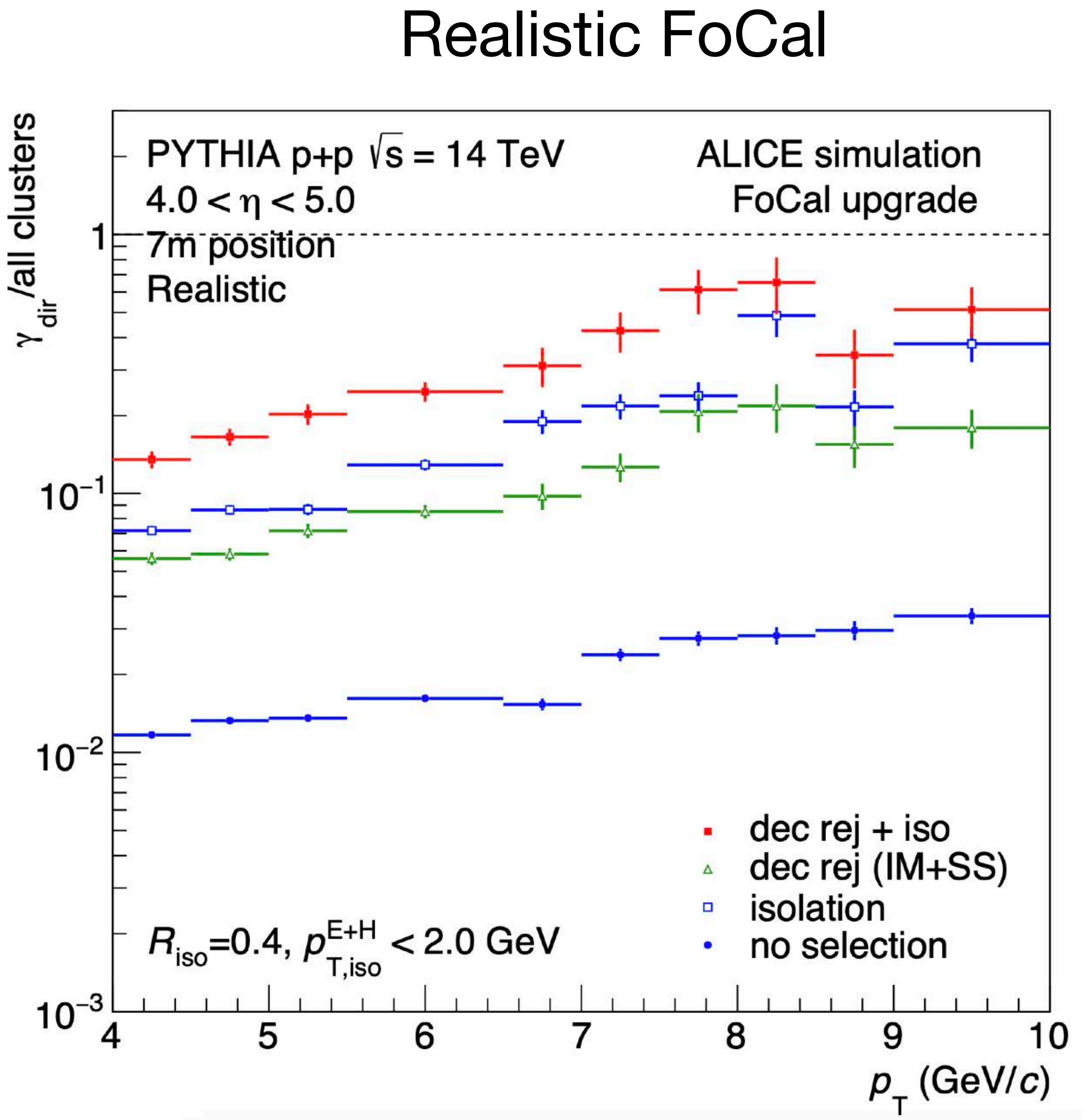


5) Ongoing activities

Simulations with realistic dead area







- Overall π^0 efficiency drops by ~20% due to cluster loss at edges.
- Performance for direct photons not significantly affected.
  - Will be followed up with higher statistics.

FoCal SPS test beam in 2021/2022

- **SPS-H6 beam line, up to ~120 GeV**
- **Sep-Oct. in 2021, and another one in 2022.**

FoCal-E

- 2 single pad (2021), and 2 pixel layers
- 18 single pad (2022), and 2 pixel layers
- Use final readout: HGCROC for PAD

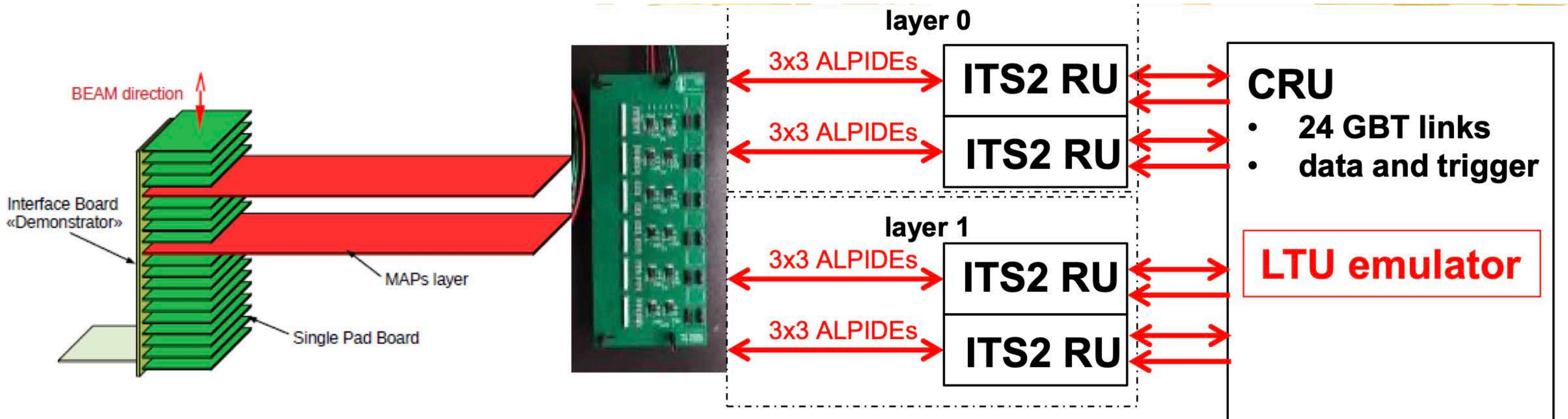
FoCal-H

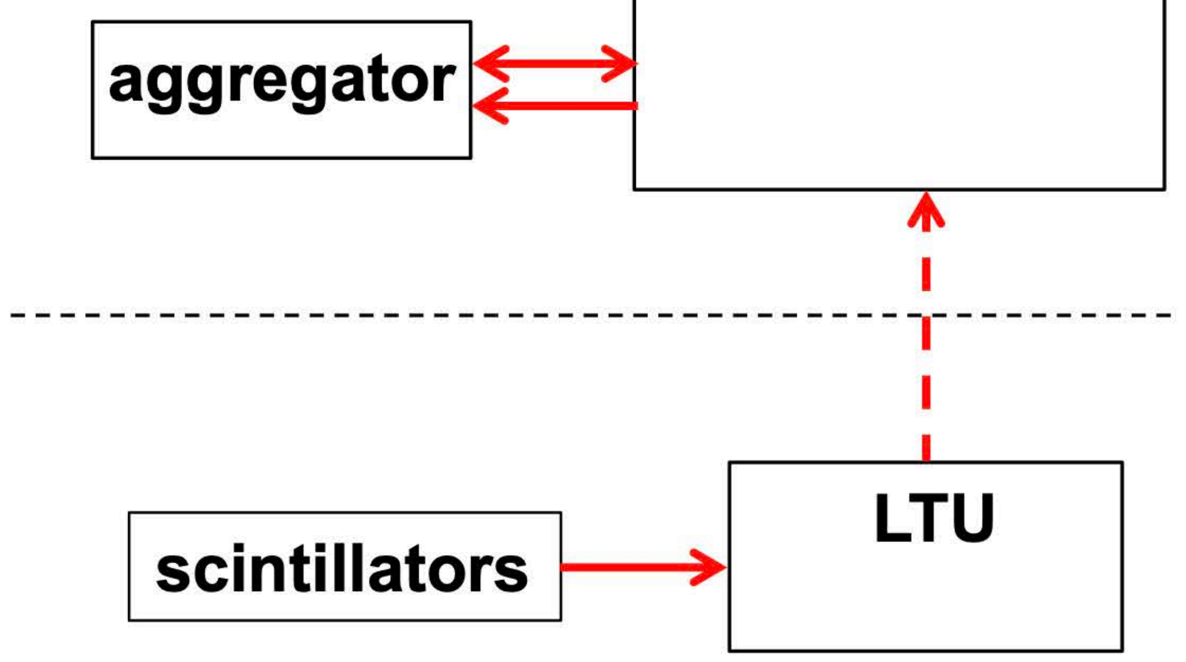
- 10 x10cm^2 area
- 60-80cm depth (TBD)
- Not yet final readout

Common DAQ

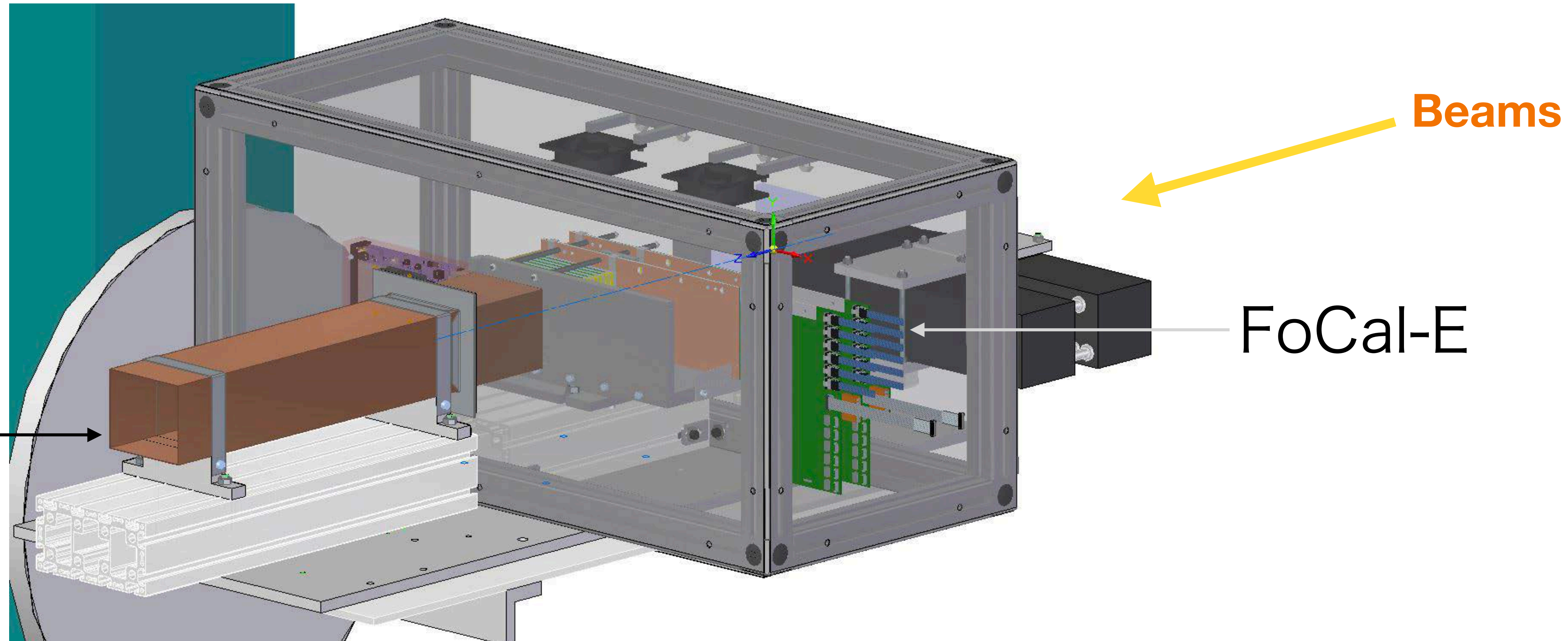
(e.g. hadron rejection using HCal info in ECal)

✦ At the same beam time, EPICAL will take data for high energy points





- **periodic trigger**
  - **LTU emulator inside CRU sends BCID**
  - **RU generates ALPIDE strobes**
- **physics trigger**

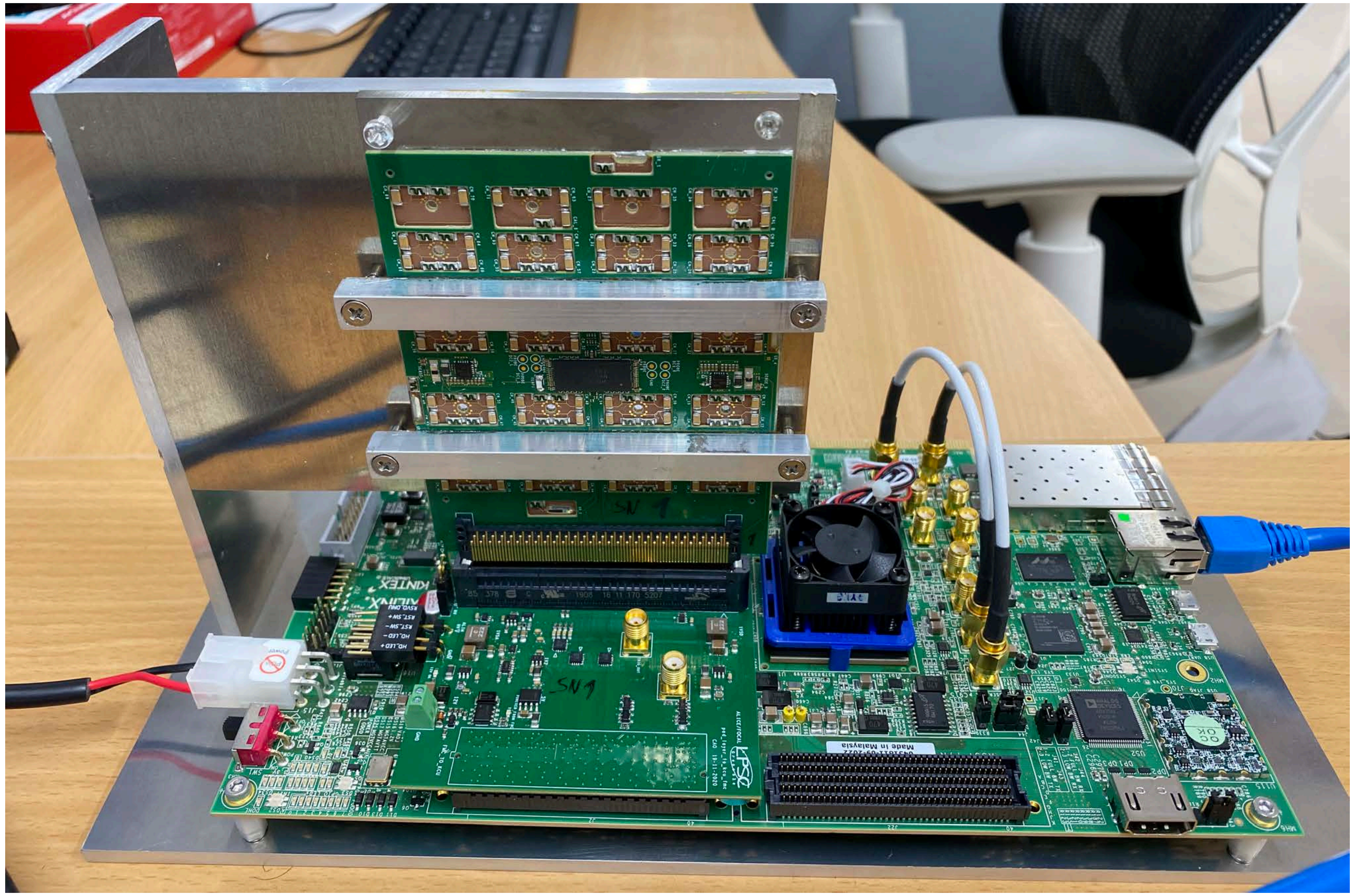


ELPH test beam in July 2021

- First beam test using HGCROC for PAD readout.
- Goal: MIP measurements by p-type 8x9 sensor w/ HGCROC.
- Used also for SPS test beam in Sep-Oct. 2021.
- Wire bonding has been done, readout test is ongoing.

KEK manual bonder

(deep access type)



ELPH test beam setup

Irradiation test at RIKEN

- RIKEN (Wako) RANS, (**R**IKEN **A**ccelerator driven compact **N**eutron **S**ource)
- **RANS**: Proton 7MeV, 100μA, 6 x 10^{13}proton/s, Be target, Neutron 5MeV max., 10^{12}neutron/s from the target.
- **RANS-II**: Proton 2.49MeV, 100μA, Li target, Neutron 0.7MeV max.
- RIKEN/ Tsukuba/ Tsukuba Tech.
- Plan: IV, CV measurements for n-type, p-type sensor with neutron monitor (Kyushu Univ.)

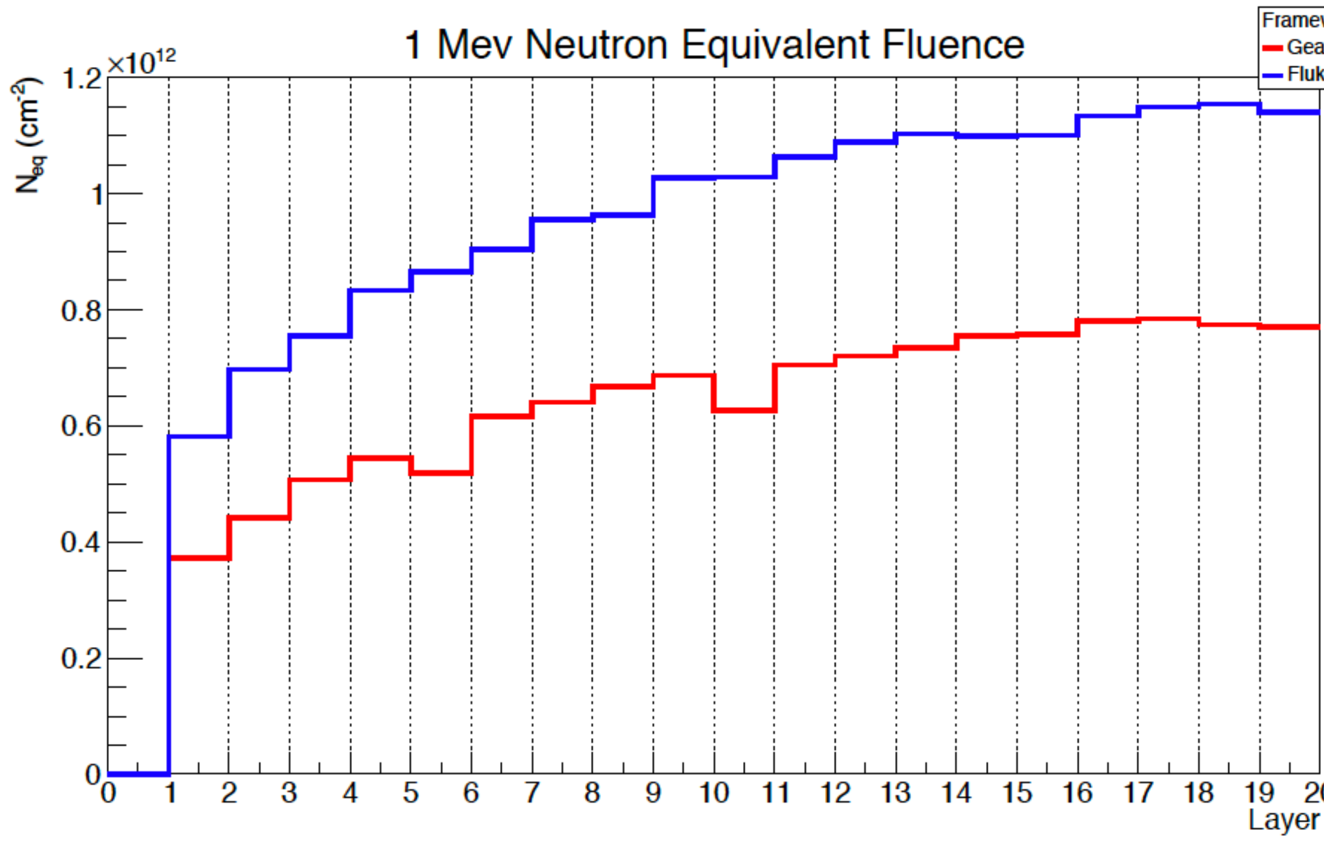


Figure 12: NIEL weighted 1 MeV Neutron equivalent fluence for an integrated luminosity of 10 nb^{-1} Pb-Pb + 50 nb^{-1} p-Pb + 6 pb^{-1} pp for each layer in FoCAL.

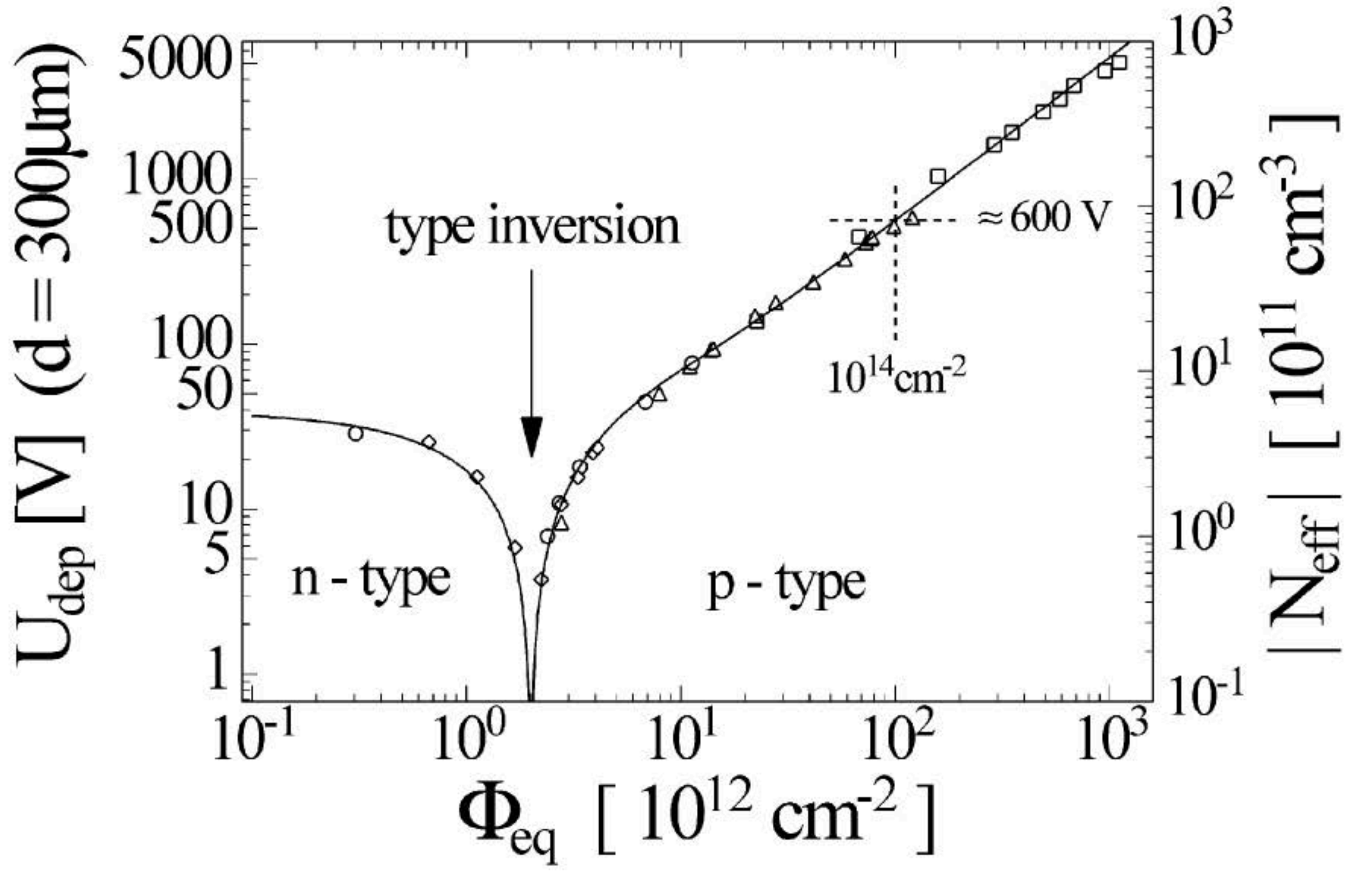
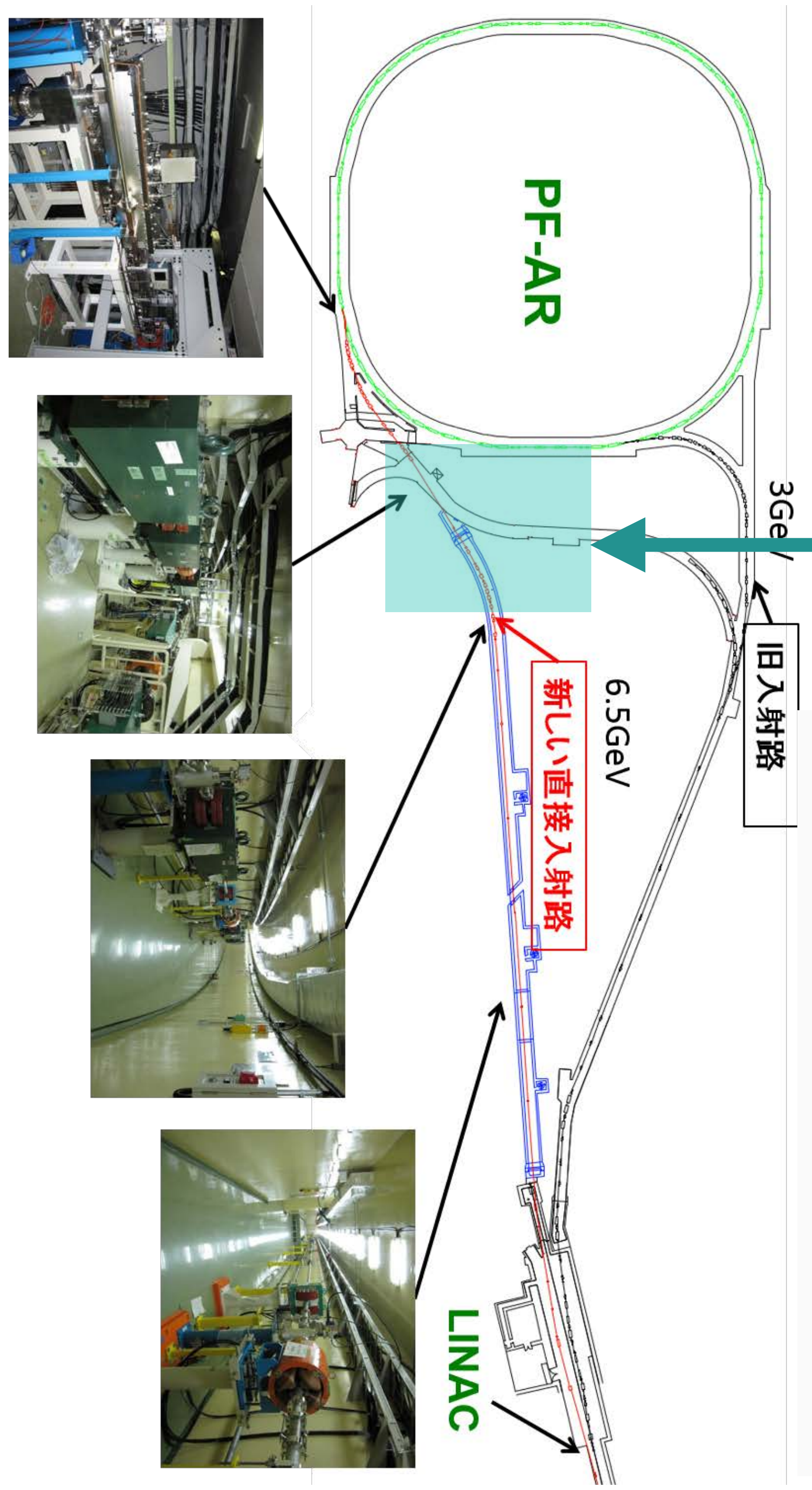
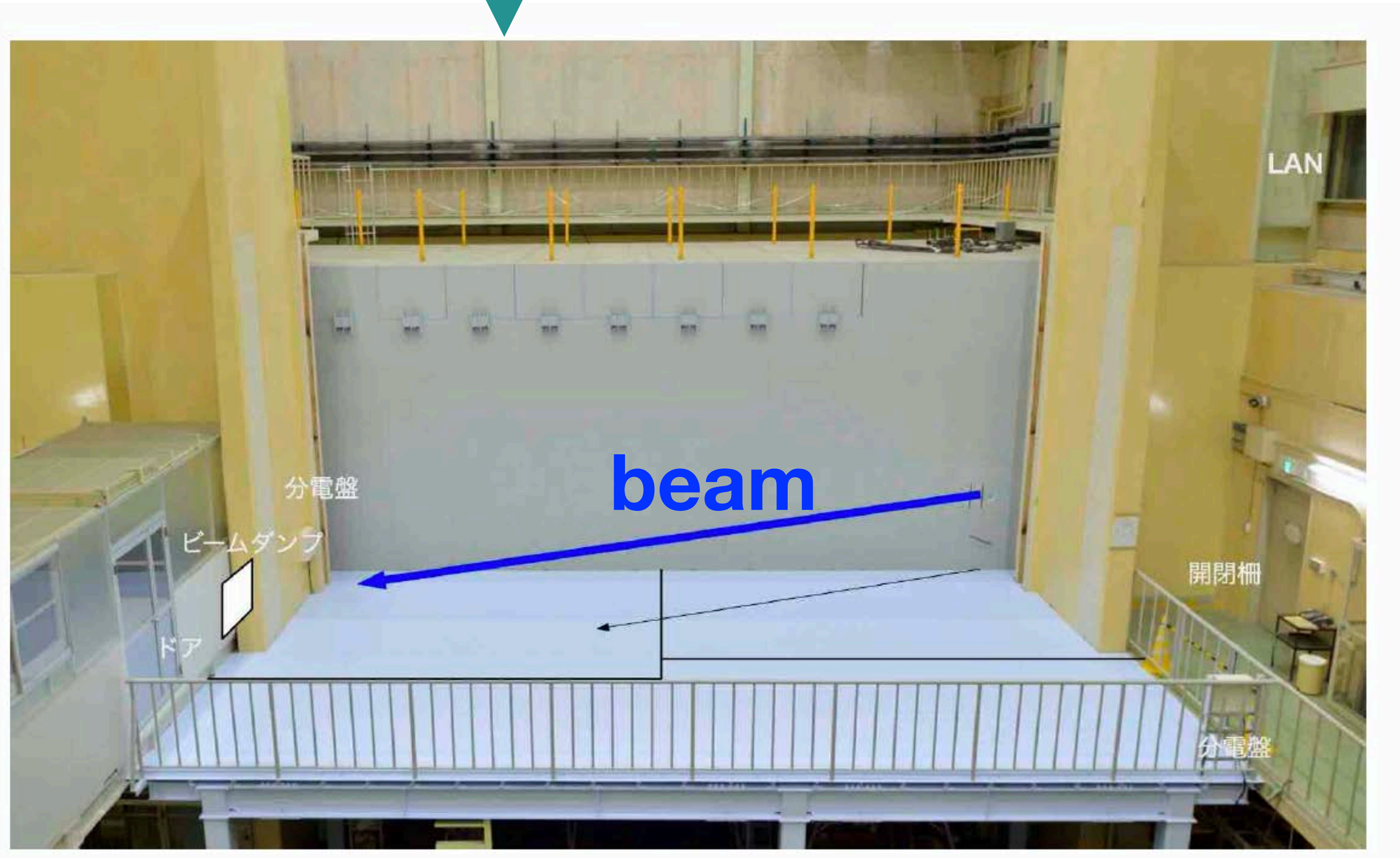


Fig. 4. Change in the bulk material as measured immediately after irradiation [20].

KEK PF-AR

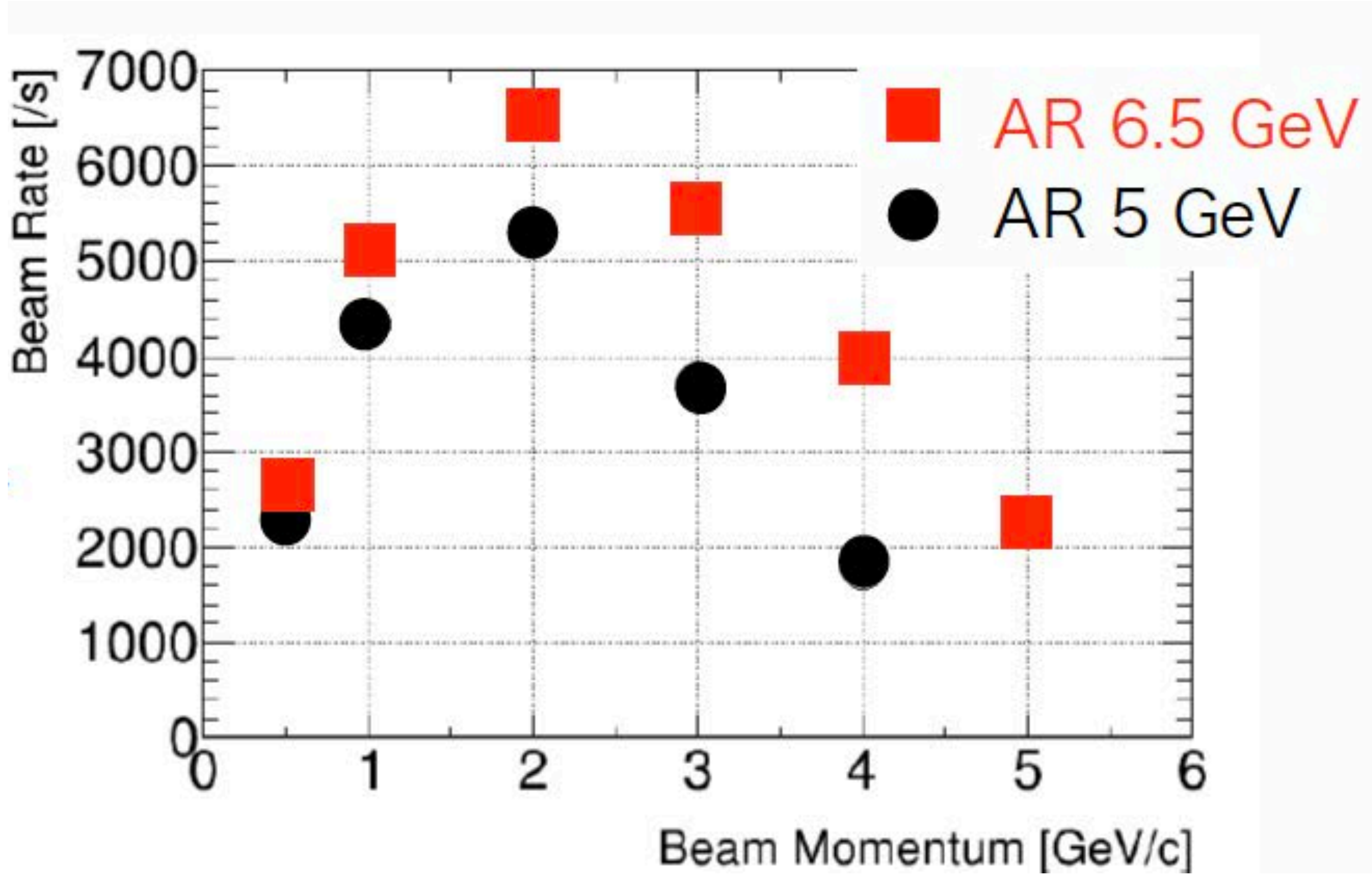


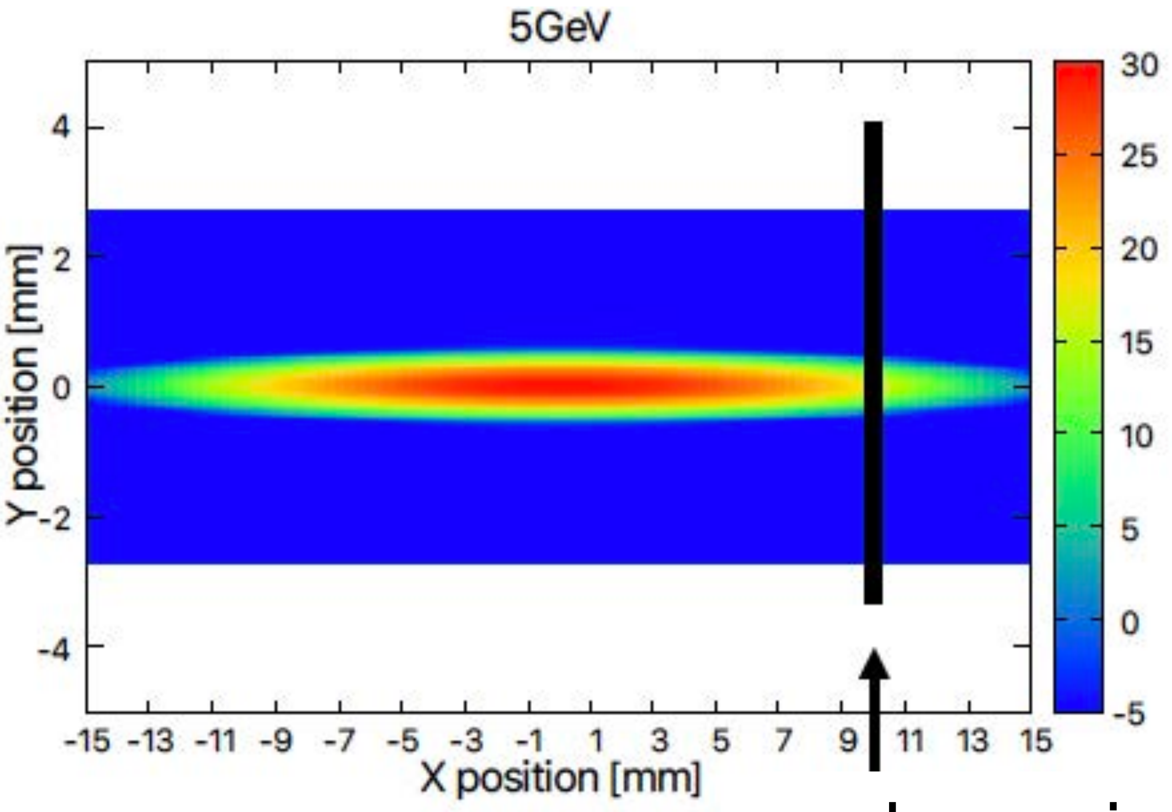
New experimental area



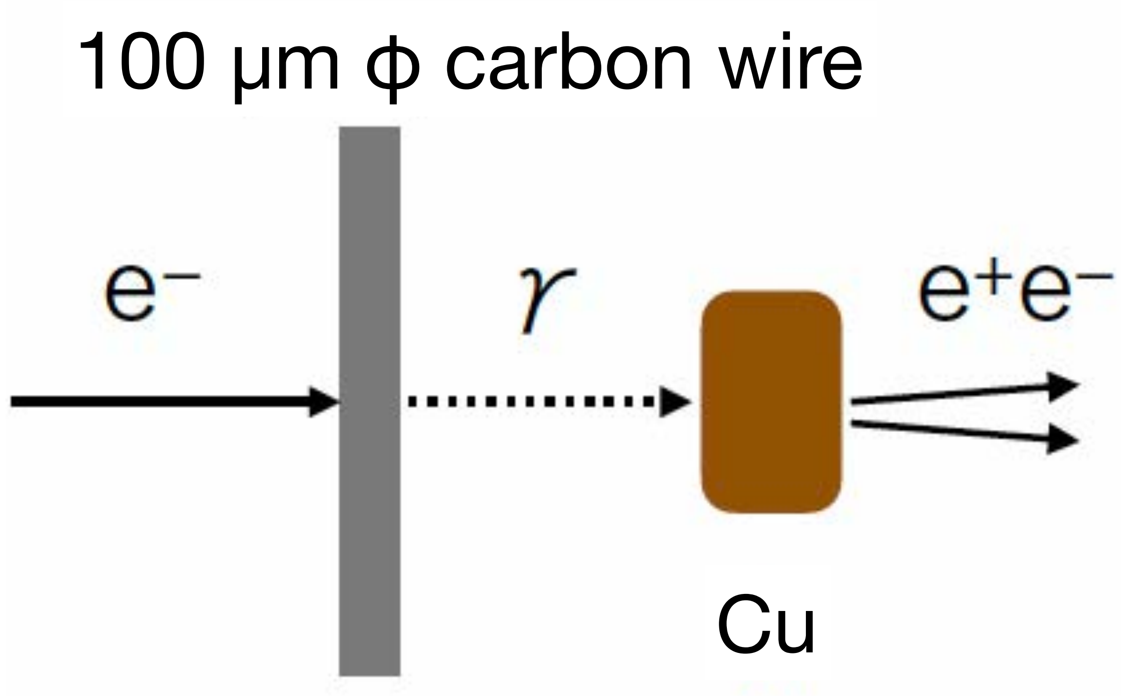
Photon Factory Advance Ring (PF-AR)

- 6.5 GeV and 5 GeV operation
- 1.3 μs cycle (single bunch)





carbon wire to beam halo



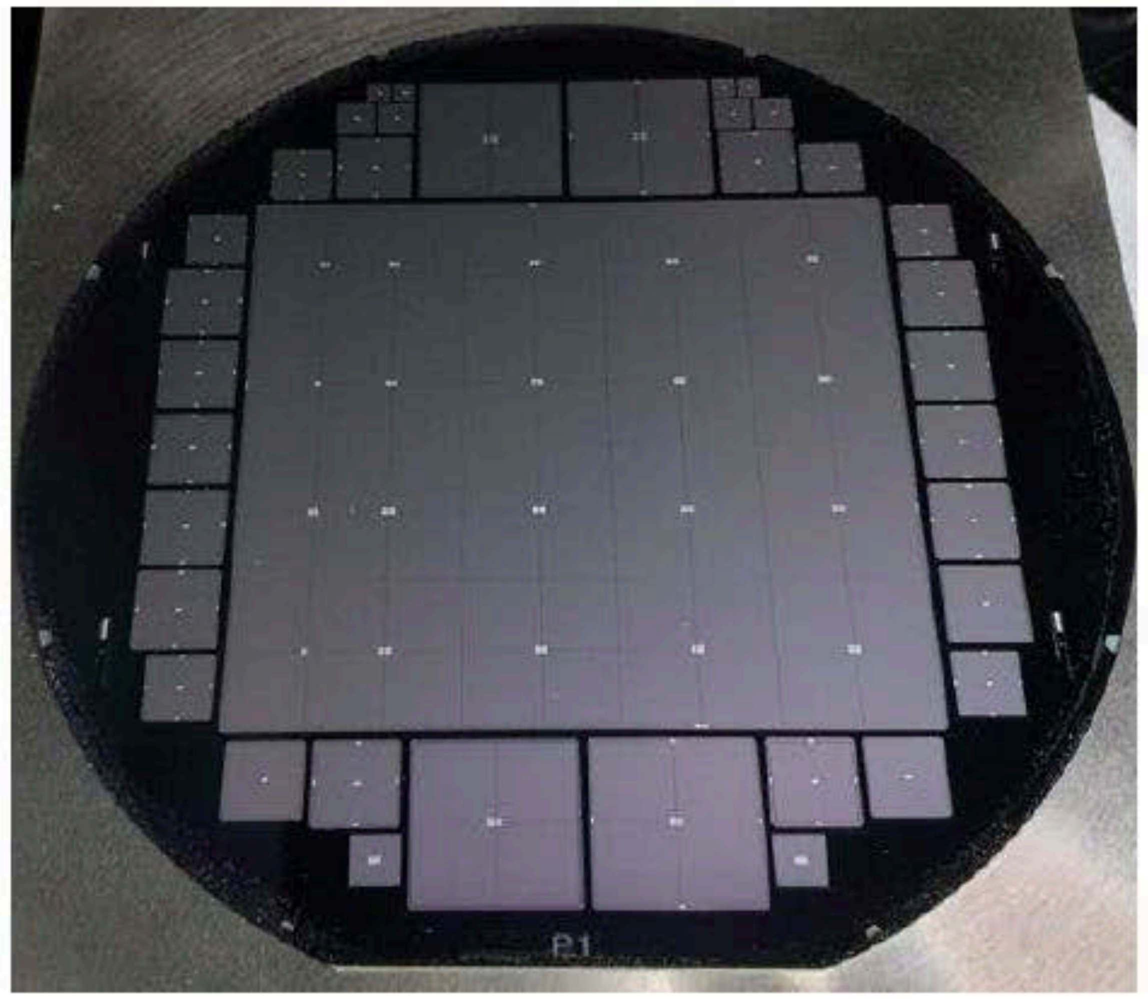
- Beam optics committing during the summer shutdown, July-Sep. 2021
- In mid-October, the first beam expected.
- Together with Kyushu Univ, we are going to make beam monitor
- We are potentially a main user of this beam line after commissioning.
- Good for FoCal final R&D and calibration etc.

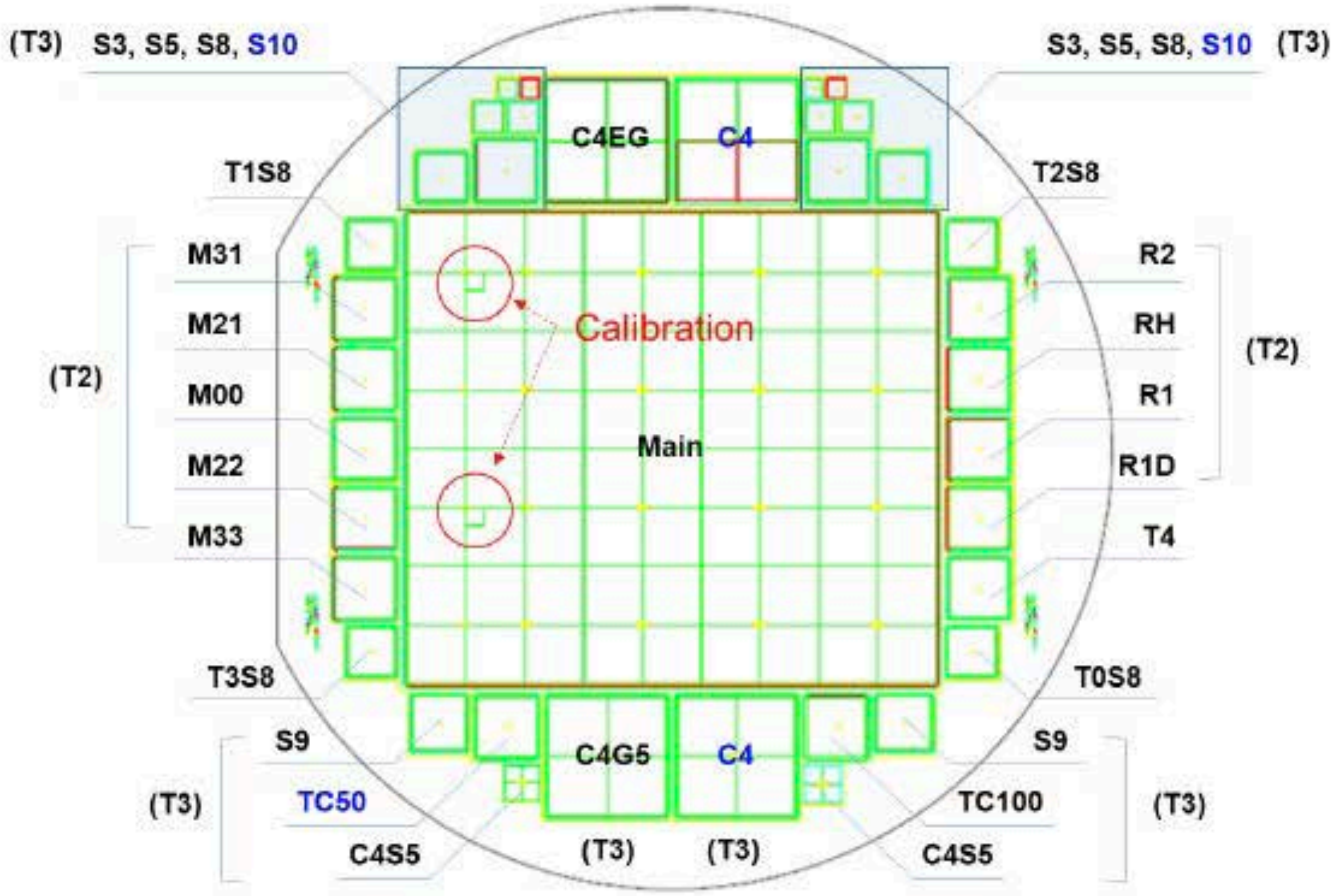
Yonsei/Hanyang activity

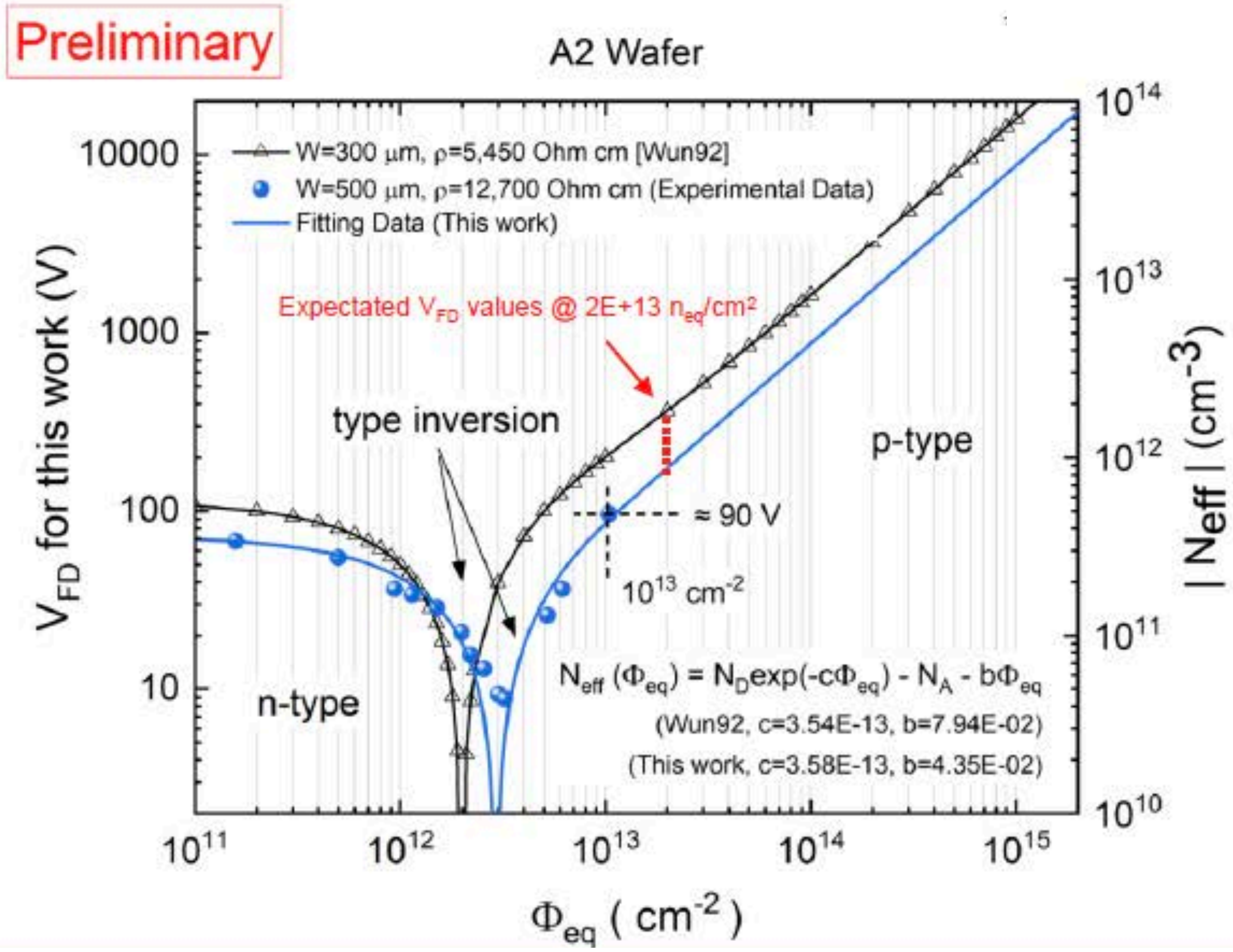
Si PIN Sensor

ALICE FoCal Collaboration Meeting (Indico), Si PIN Sensor Proton Irradiation Test, June. 23th, 2021, D. G. Kim

- ✓ 6 fab-out sensors (see next slide for the properties)
- ✓ We will focus on the properties of test patterns for today.







Youngil Kwon, Dong Geon Kim

- Irradiation test using protons and neutrons (reactor)
- IV, CV measurements using probe cards.

Timeline

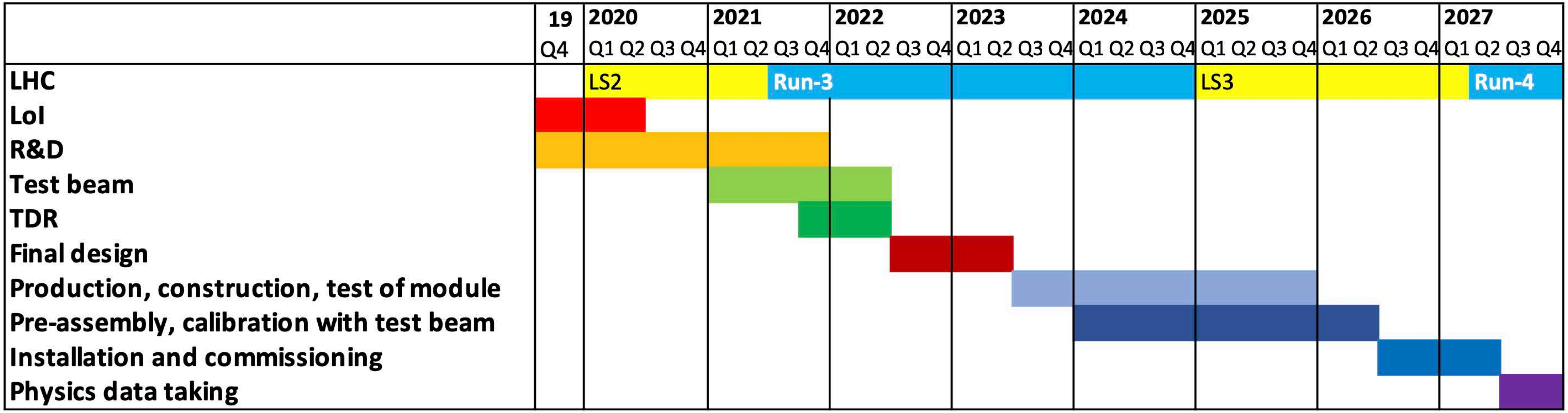


Table 6: Project timeline

Year	Activity
2016–2021	**R&D**
2020	Letter of Intent
2020–2022	**final design** Technical Design Report design/technical qualifications
2023–2027	**Construction and Installation**
2023–2025	production, construction and test of detector modules
2024–2025	pre-assembly calibration with test beam
2026	installation and commissioning
06/2027	Start of Run 4

- Next important step:
  Entering the engineering phase towards testbeam(s) 2021/22 and TDR
- Production estimated to fit well into 24 months
  - Plus half a year of "learning curve"

(not adjusted for Covid-19 changes)

Summary & next steps

Prototype construction for SPS test beam in 2021/2022:

- FoCal-E: Construct one full module with close-to-final readout well on track.
- FoCal-H: First prototype from Cu capillary tubes being constructed.

TDR preparation:

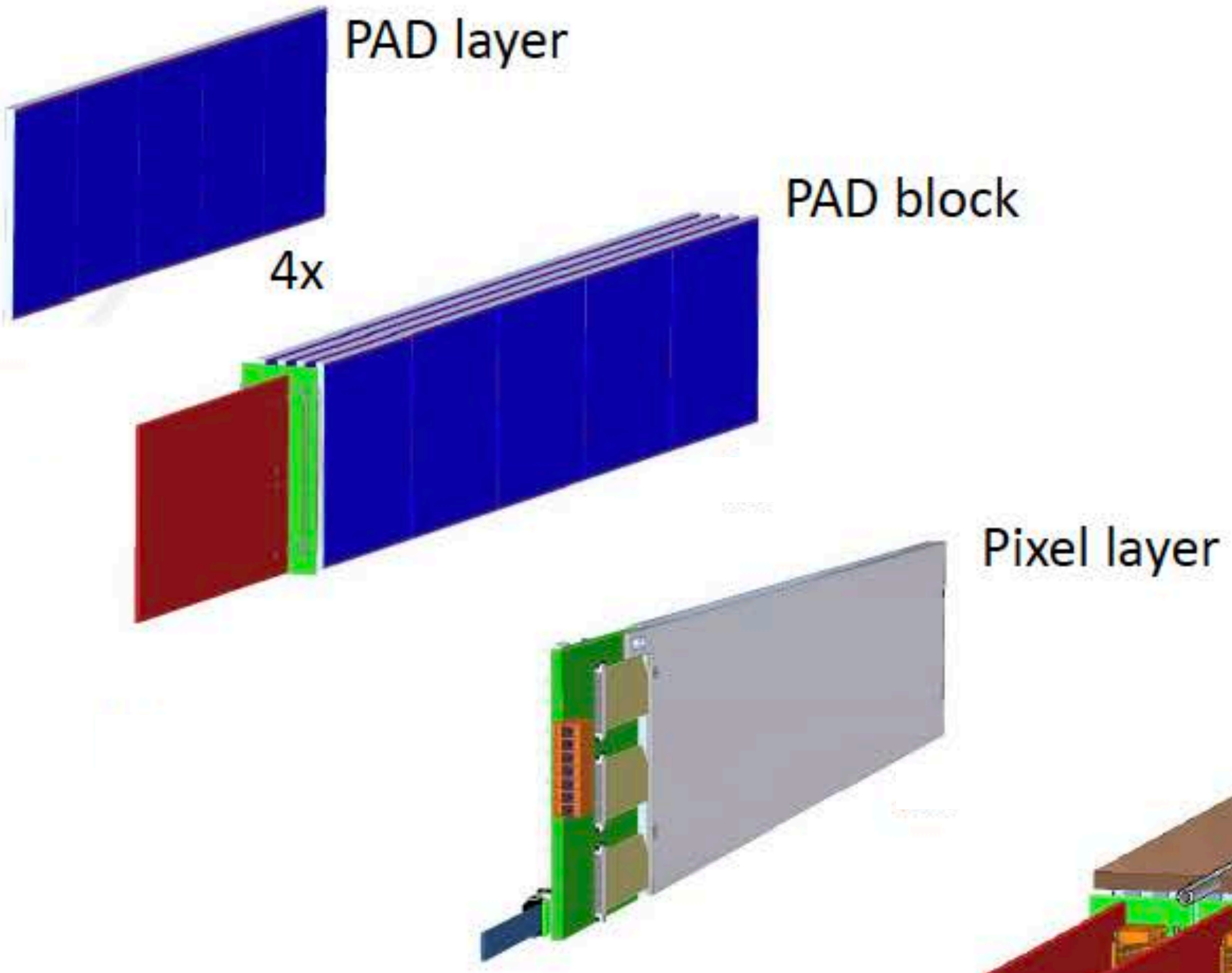
- Module design, integration and cooling.
- Detailed assembly process.
- Refine radiation estimates, preliminary testing.
- Physics performance simulations with more realistic setup (dead areas, pile up).

List of institutes participating in FoCal (from LoI)

BARC	Bhaba Atomic Research Centre, Mumbai, India	V.B. Chandratre
Berkeley	Lawrence Berkeley National Laboratory, Berkeley, USA	M. Ploskon
Bhubaneswar	Institute of Physics, Bhubaneswar, India	P. K. Sahu
Bergen	University of Bergen, Bergen, Norway	D. Roehrich
Bose	Bose Institute, Kolkata, India	S. Das
CCNU	Central China Normal University	D. Zhou
Detroit	Wayne State University, Detroit, USA	J. Putschke
Gauhati	Gauhati University, India	B. Bhattacharjee
Grenoble	LPCS Grenoble, France	R. Guernane
Hiroshima	Hiroshima University, Hiroshima, Japan	T. Sugitate
Houston	University of Houston, Houston, USA	R. Bellwied
HVL	Western Norway University of Applied Sciences, Bergen Norway	H. Helstrup
IITB	Indian Institute of Technology Bombay, Mumbai, India	R. Varma
Indore	Indian Institute of Technology Indore, Indore, India	R. Sahoo
INR RAS	Inst. f. Nuclear Research Russian Acad. of Science, Moscow, Russia	T. Karavicheva
Jammu	Jammu University, Jammu, India	A. Bhasin
Jyväskylä	University of Jyväskylä, Jyväskylä , Finland	S. Räsänen
Knoxville	University of Tennessee, Knoxville, USA	K. Read
Nara	Nara Women's University, Nara, Japan	M. Shimomura
NBI	Niels Bohr Institure, Copenhagen, Denmark	I. Bearden
MEPhI	National Research Nuclear University, Moscow, Russia	A. Bolozdyny
NISER	National Institute of Science Education and Research (NISER)	B. Mohanty
Oak Ridge	Oak Ridge National Laboratory (ORNL),Oak Ridge, USA	C. Loizides
Oslo	University of Oslo, Oslo, Norway	T. Tveter
Panjab	Panjab University, Chandigarh, India	L. Kumar
RIKEN	Institute of Physical and Chemical Research, Toky, Japan	Y. Goto
Sao Paulo	Universidade de Sao Paulo (USP), Sao Paulo, Brazil	M. Munhoz
Tsukuba	University of Tsukuba	T. Chujo
Tsukuba Tech	Tsukuba University of Technology	M. Inaba
UFRGS	Universidade Federál Do Rio Grande Do Sul	M.B. Gay Ducati
UU/Nikhef	Utrecht University, Utrecht, and Nikhef, Amsterdam, Netherlands	T. Peitzmann
VECC	Variable Energy Cyclotron Centre, Kolkata, India	S. Chattopadhyay
USN	University of South-Eastern Norway, Konsberg, Norway	J. Lien
Yonsei	Yonsei University, Seoul, Korea	Y. Kwon

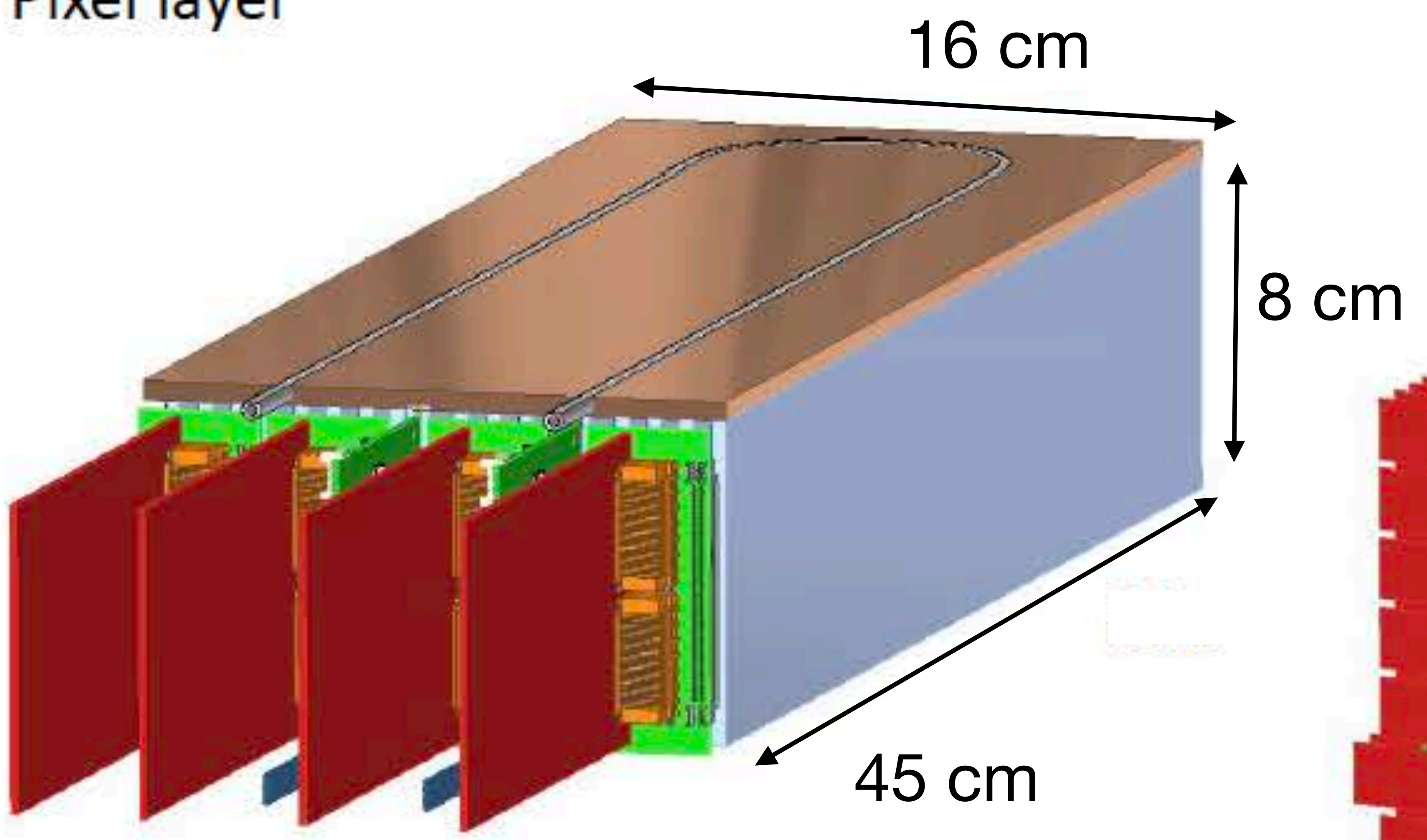
Thank you for your attentions!

FoCal-E integration

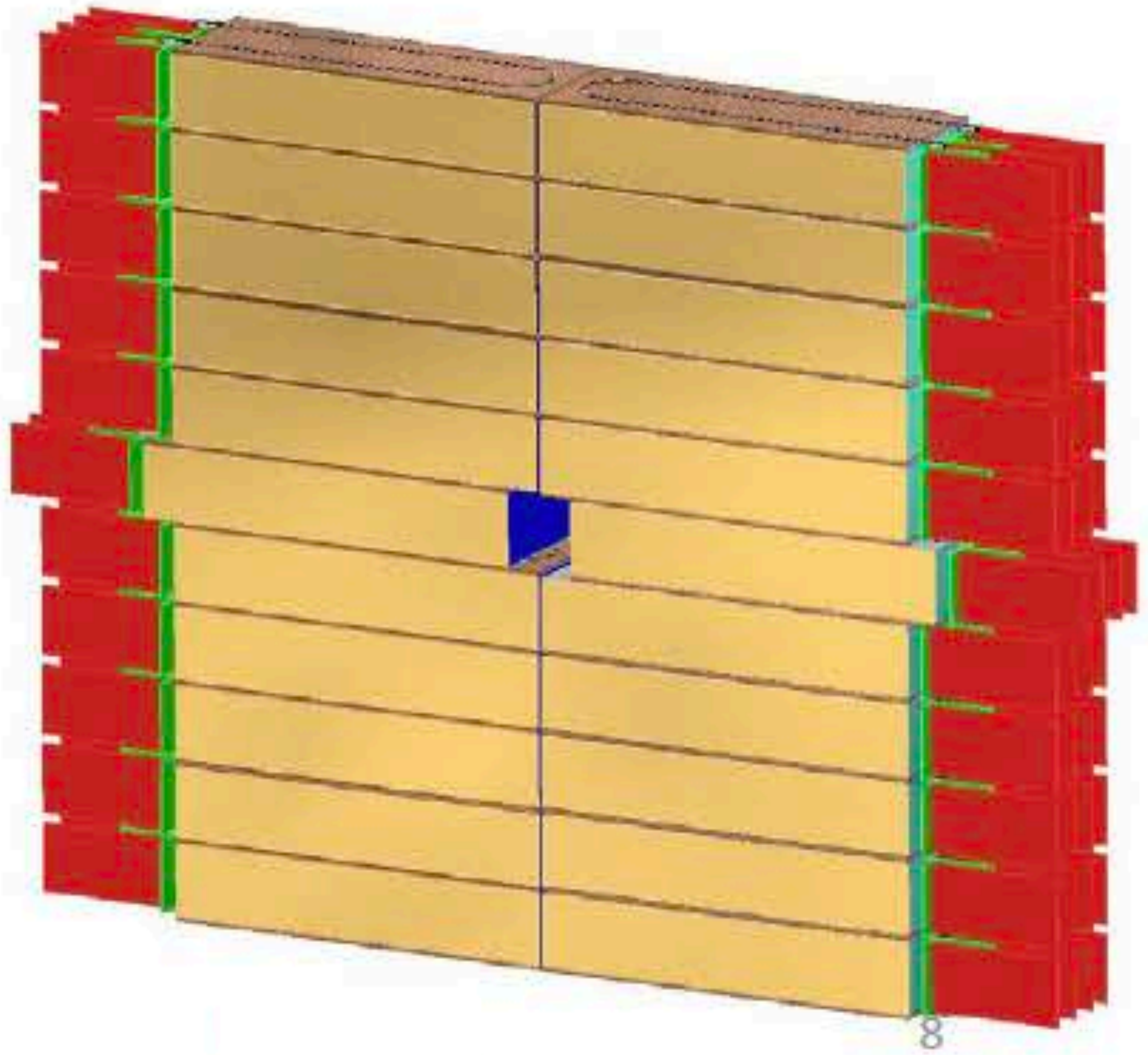


Module:

18 PAD layers + 2 PIXEL layers

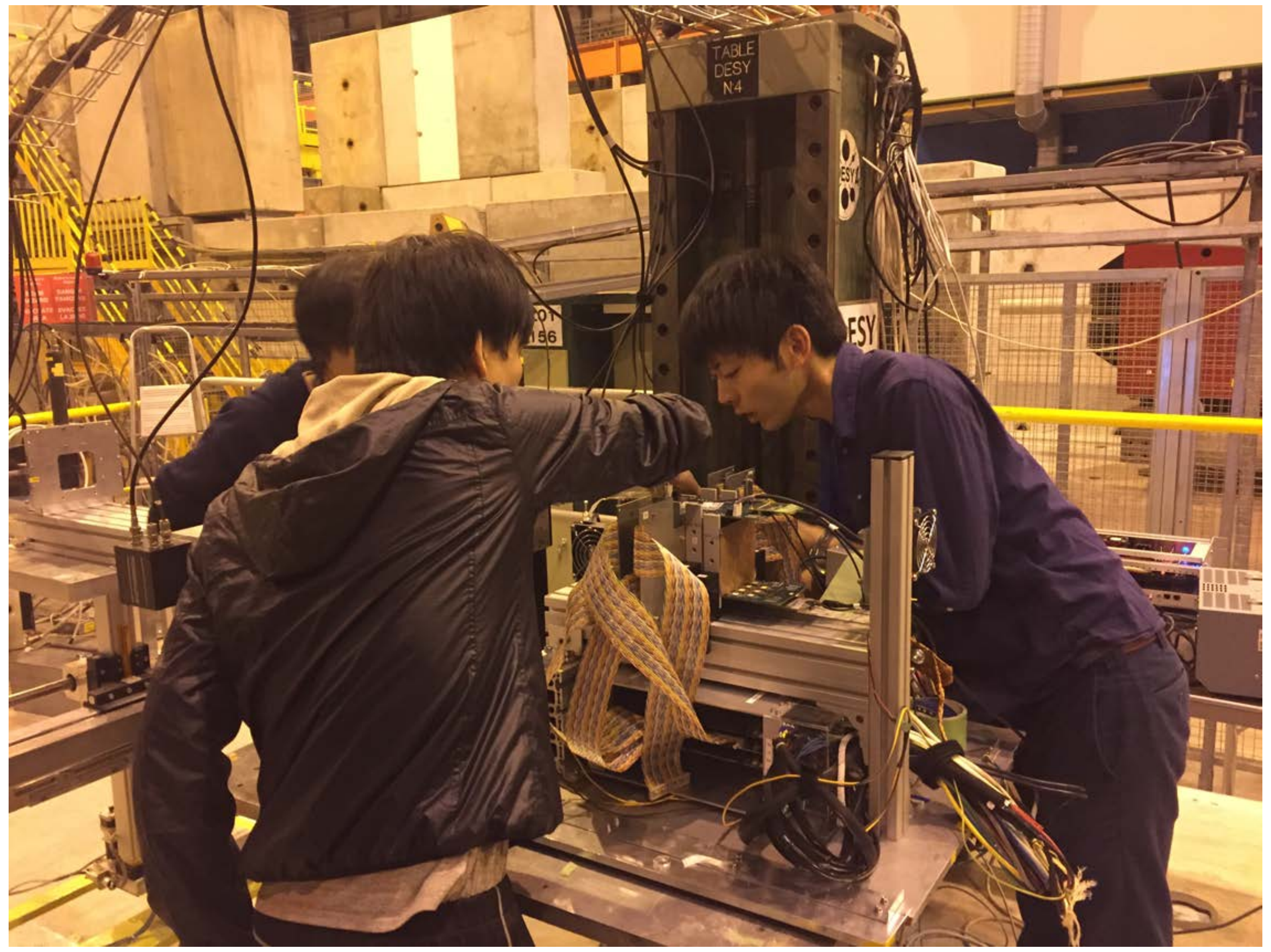


FoCal-E: 22 modules

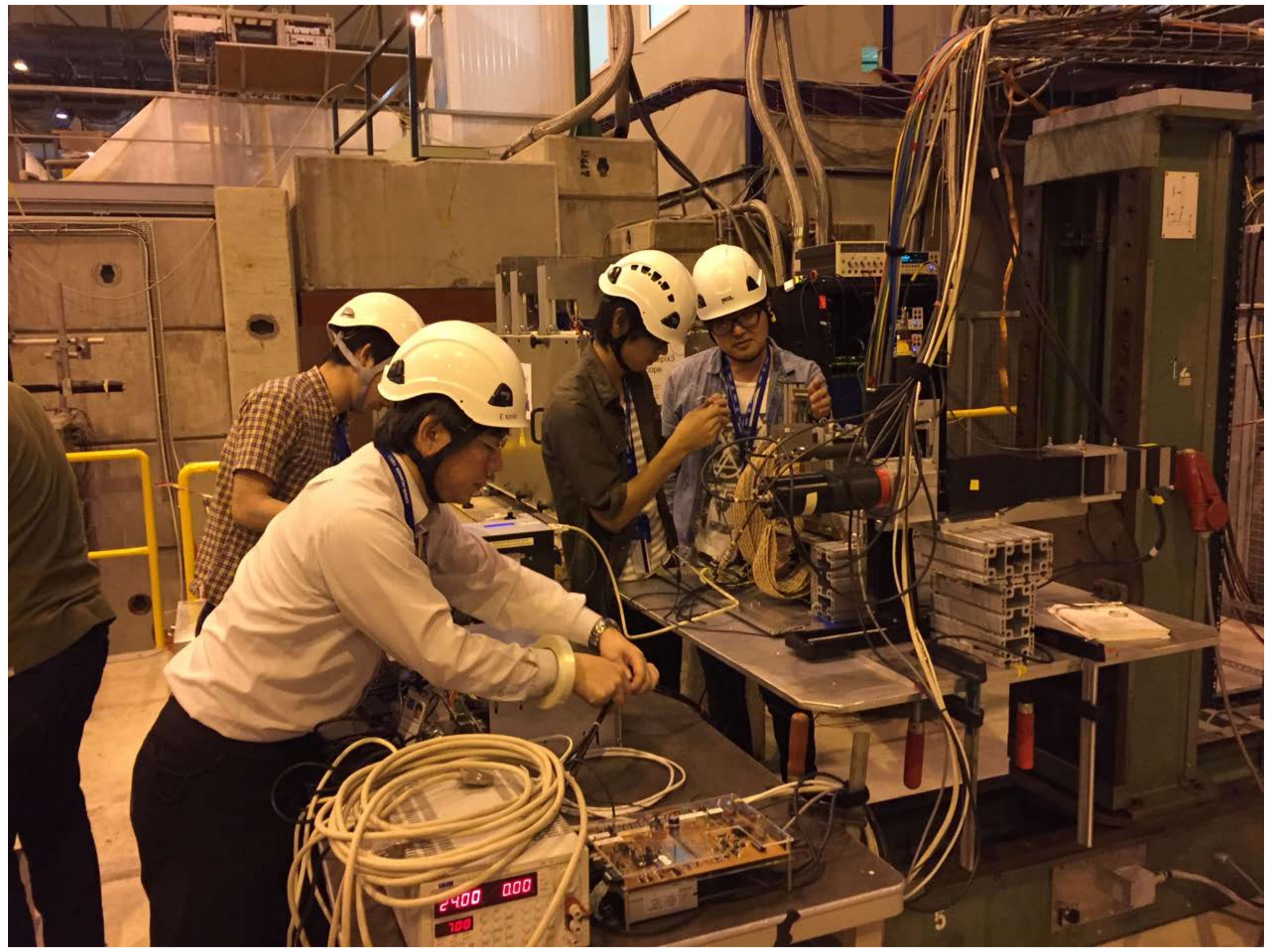


Readout, power, cooling are connected on one side

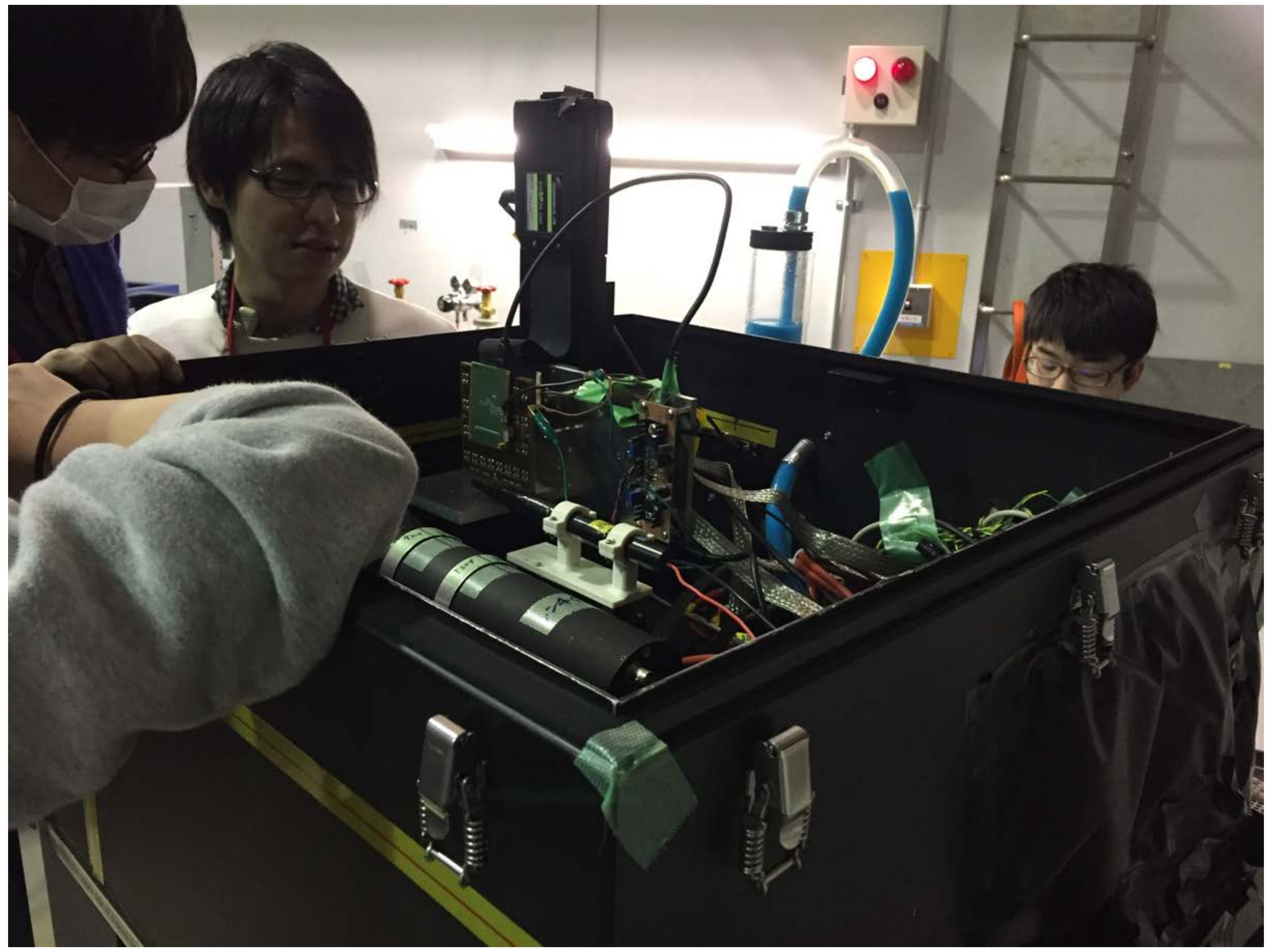
CERN PS/SPS (2014)



CERN SPS (2015)

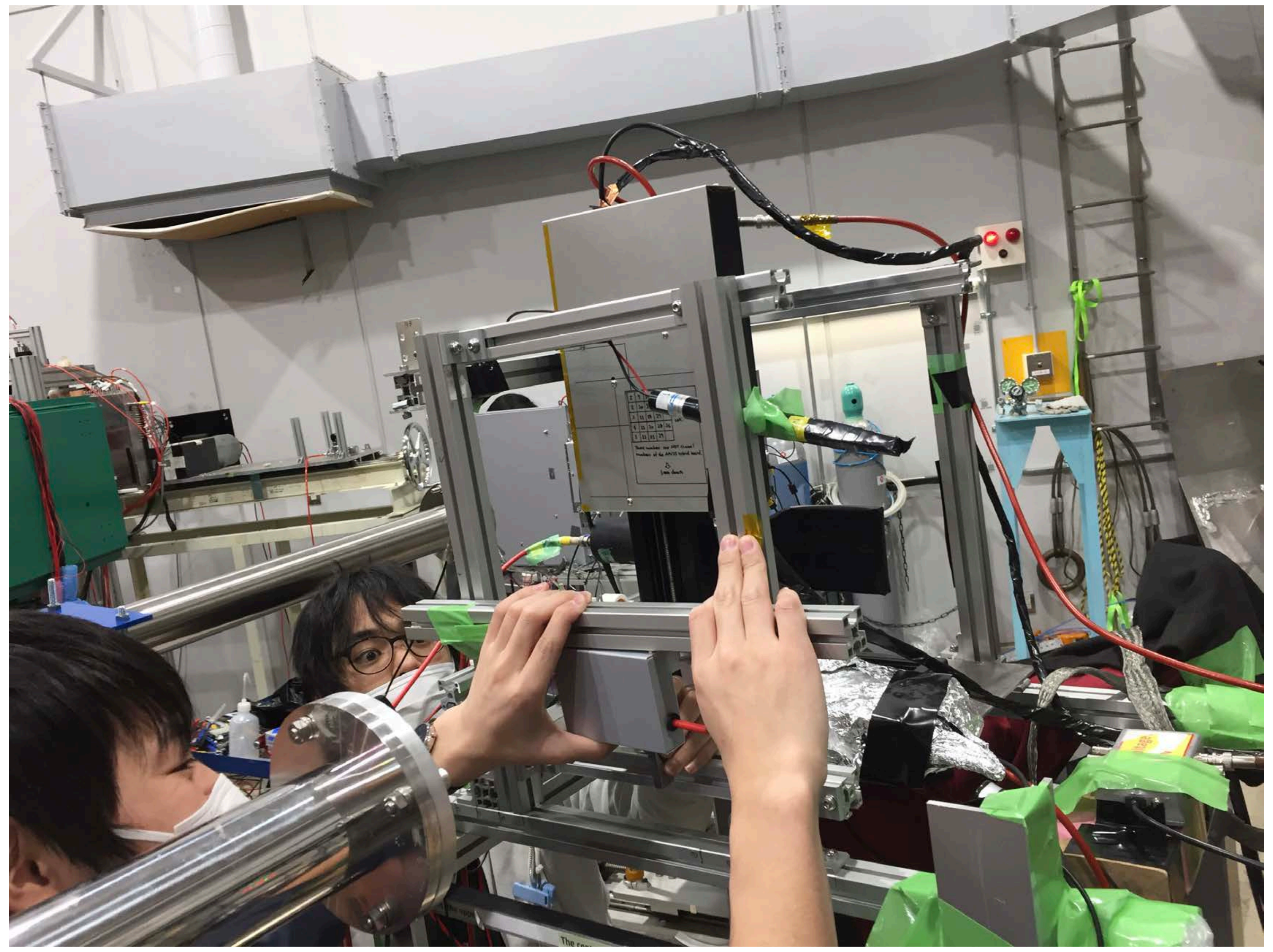


CERN SPS (2016)



ELPH (2017)

CERN PS/SPS (2018)



ELPH (2021.02)

Pad prototypes and results

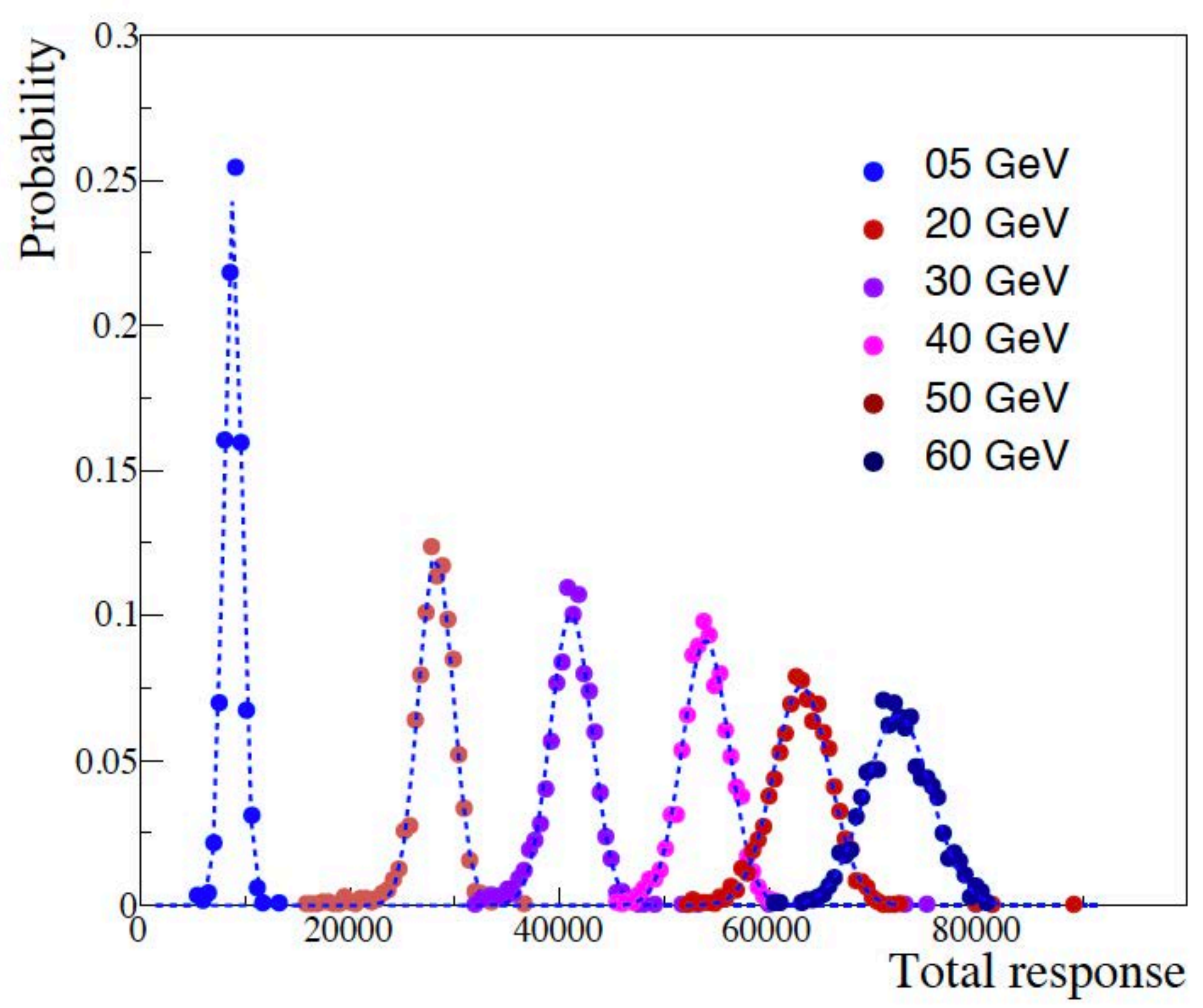
Experience gained over past years

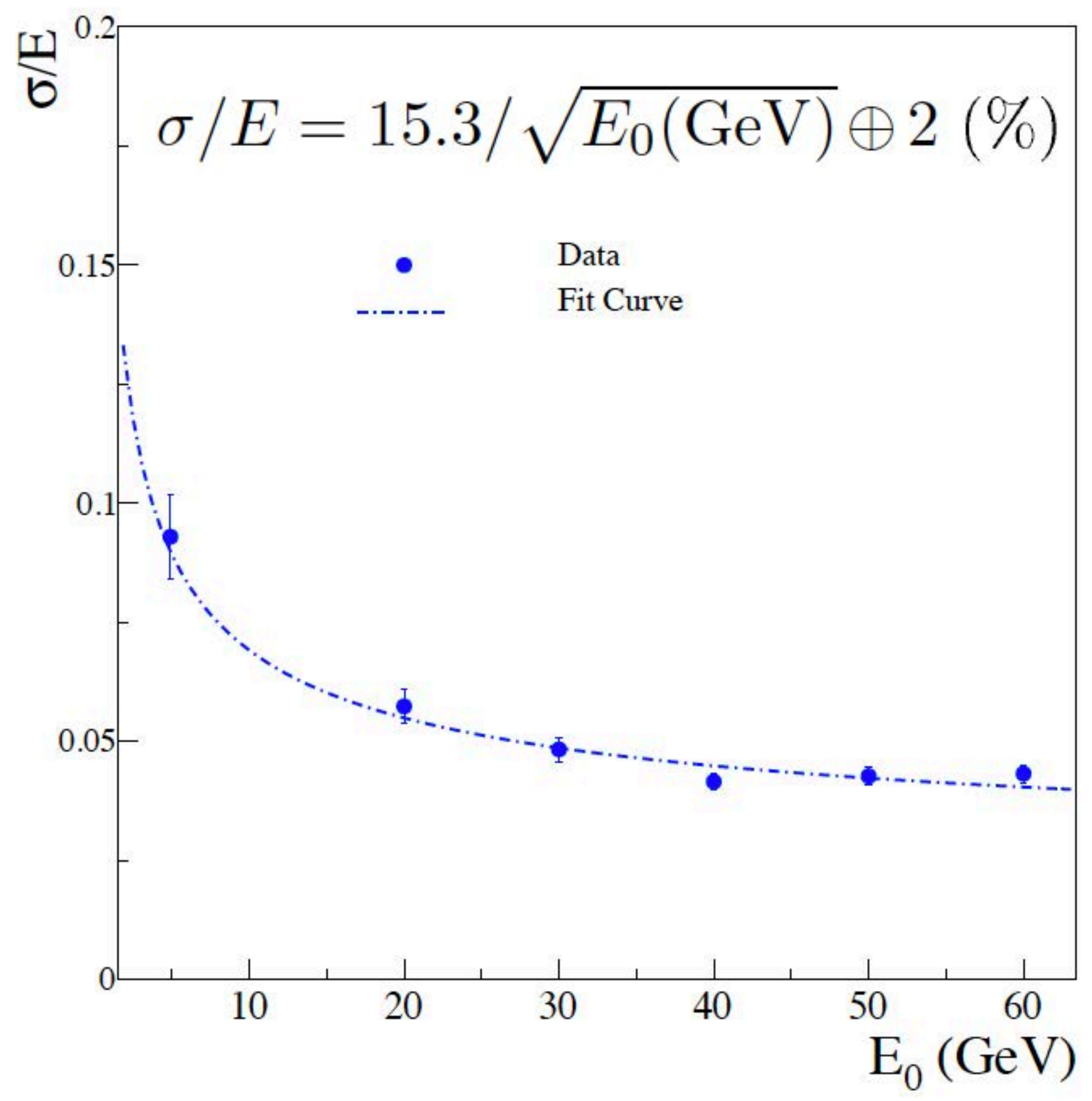
- Series of beam tests (PS, SPS): 2012-2018
- Beam times shared pad + pixel technology

Large activity in Japan (Tsukuba, Tsukuba Tech, Nara W, Hiroshima), India (VECC, BARC), US (ORNL)

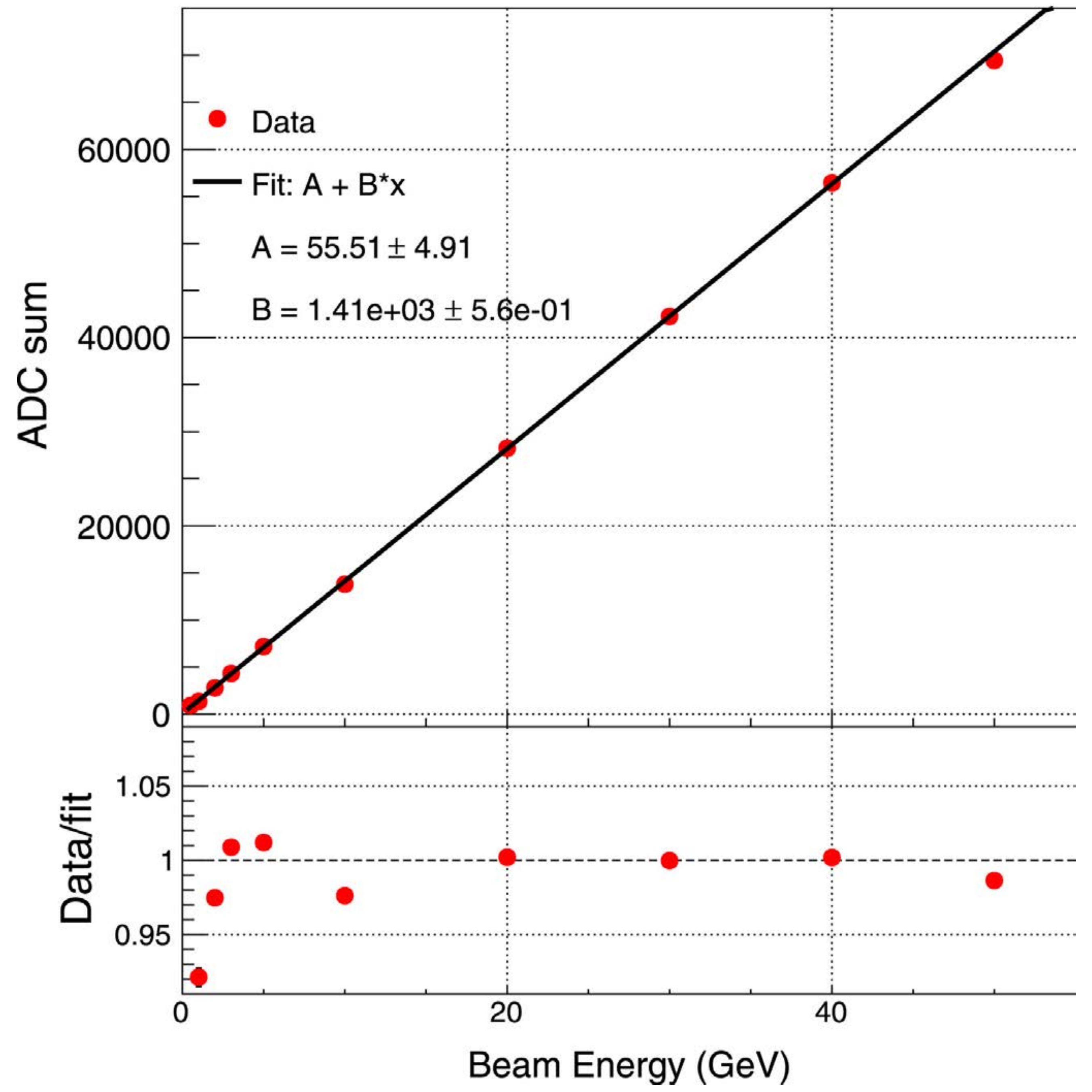
- **Indian prototypes:**
  - NIM A 764 (2014) 24
  - JINST 15 (2020) 03, P03015
- **ORNL / Japan prototype:**
  - NIM A 988 (2021) 164796, T. Awes, C.L Britton, T. Chujo, et al.,
  - https://arxiv.org/abs/1912.11115

New!

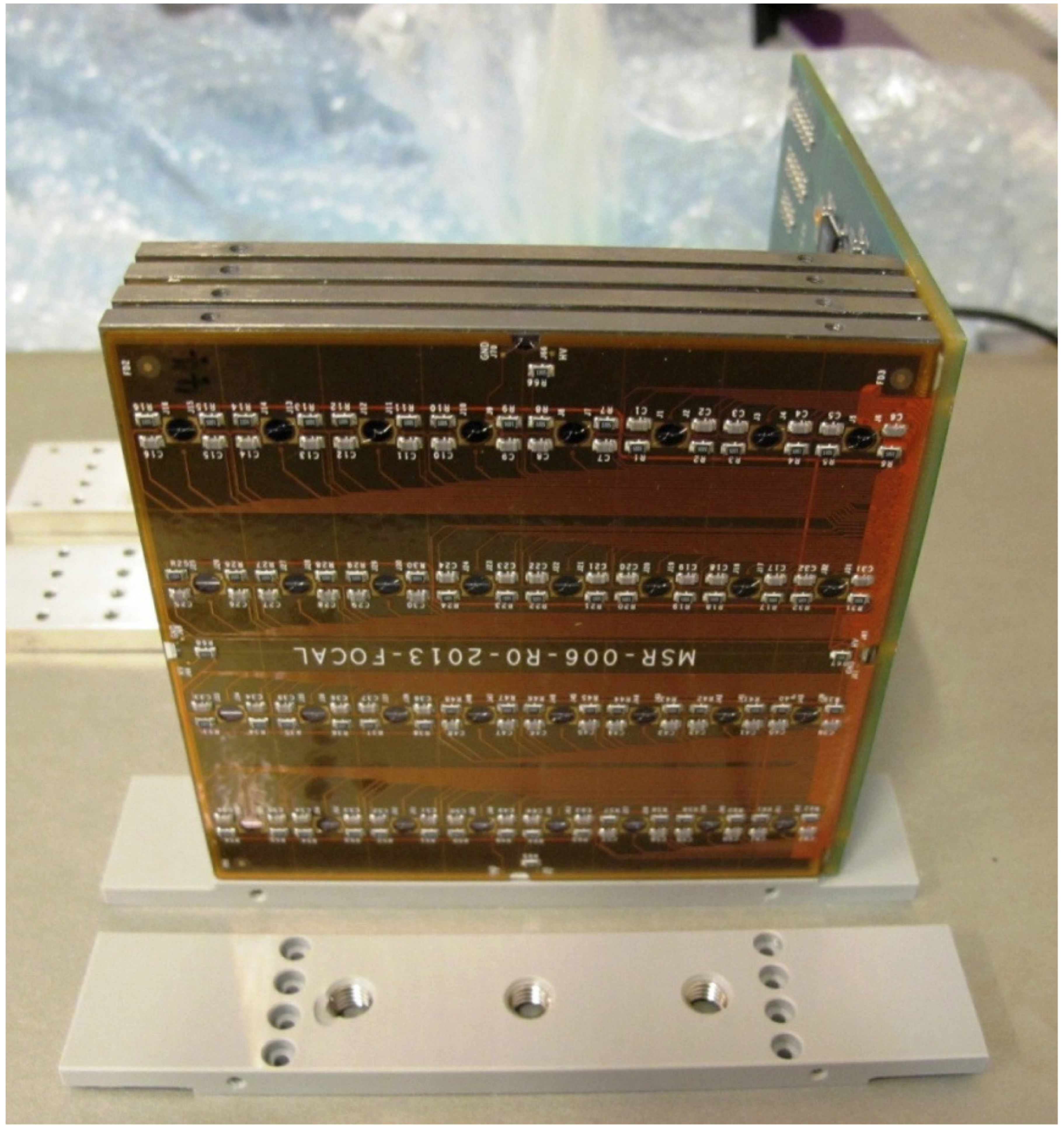


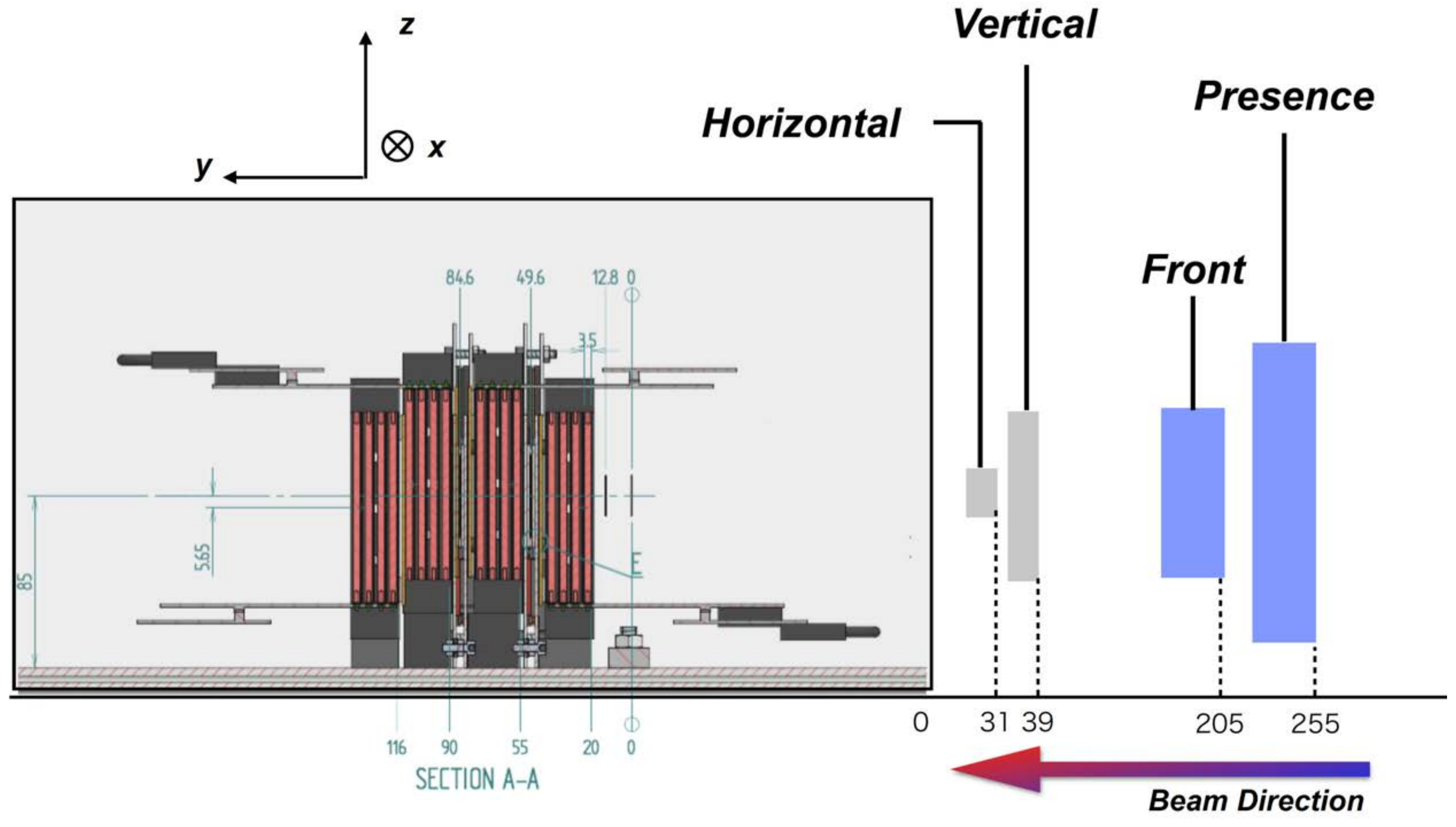


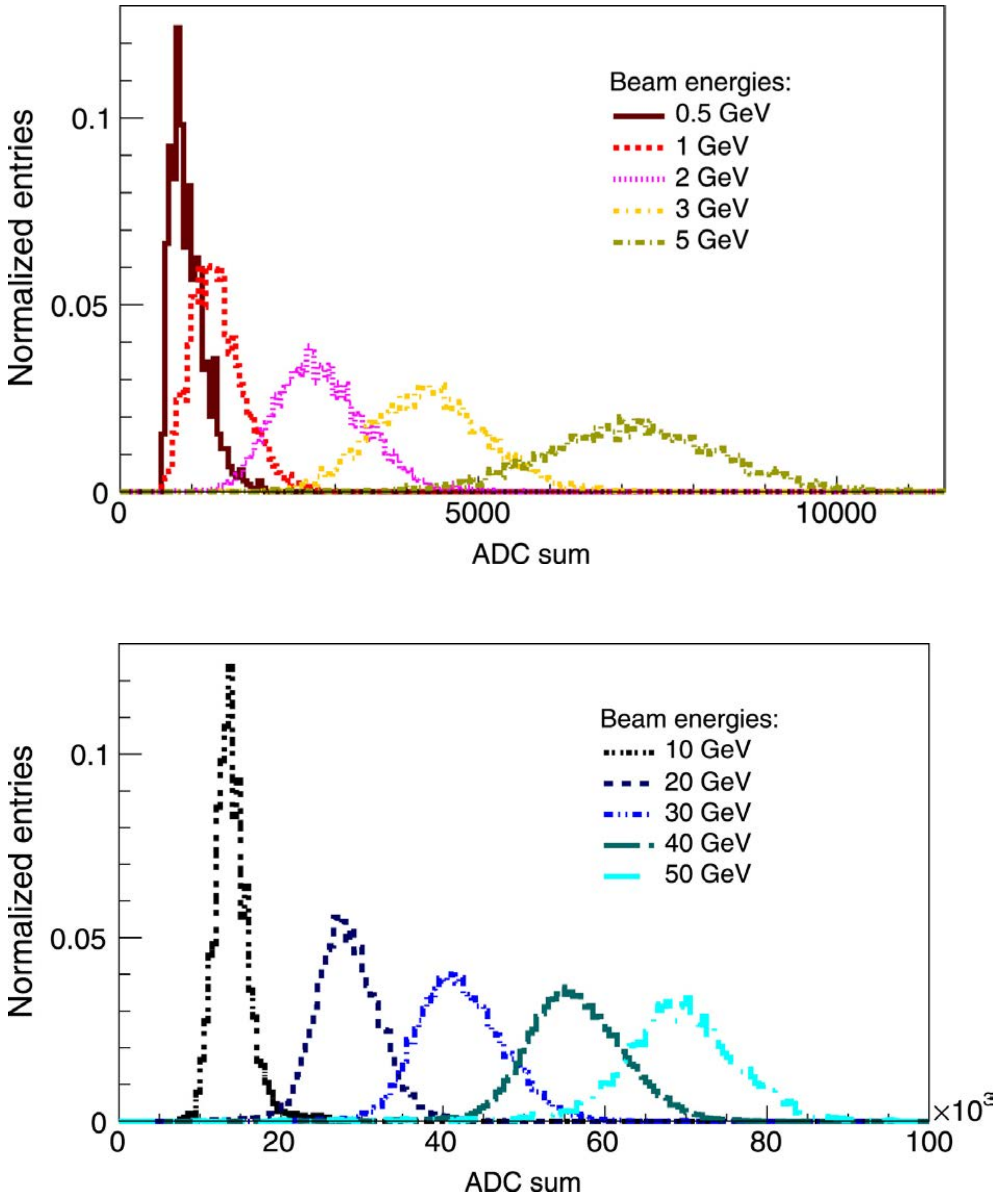
Indian prototypes : MANAS readout

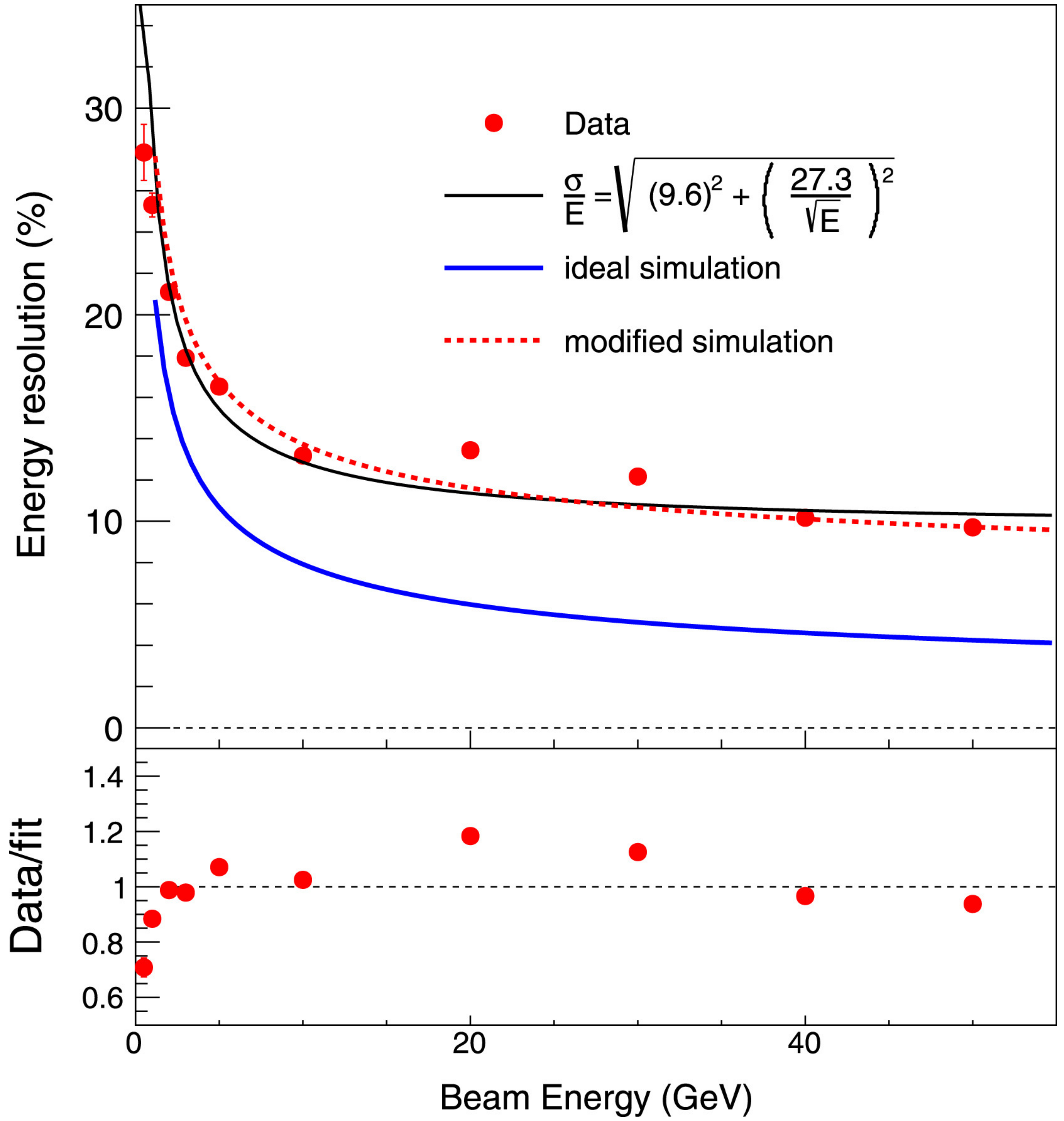


ORNL / Japan prototypes : APV25 hybrid readout



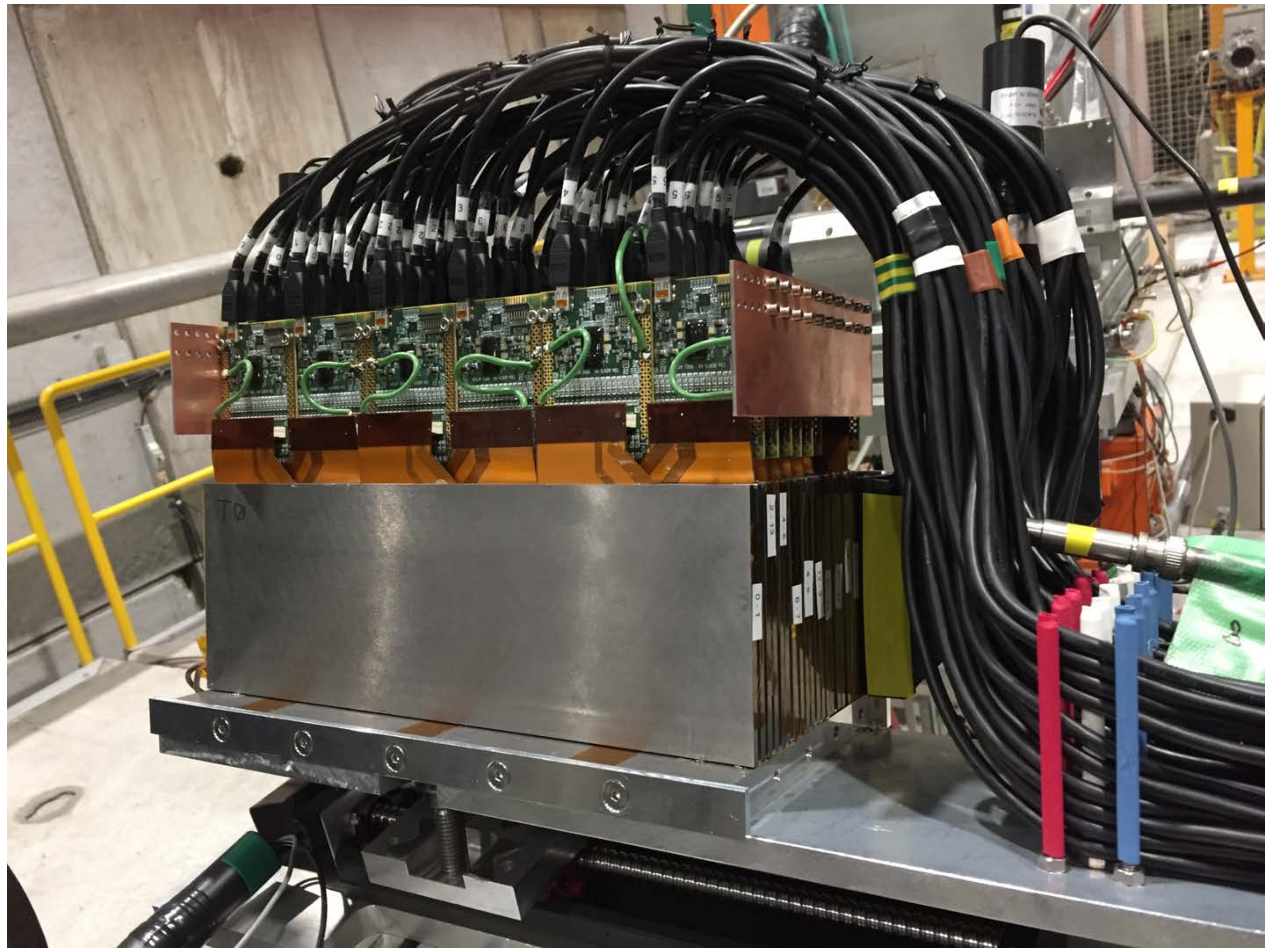




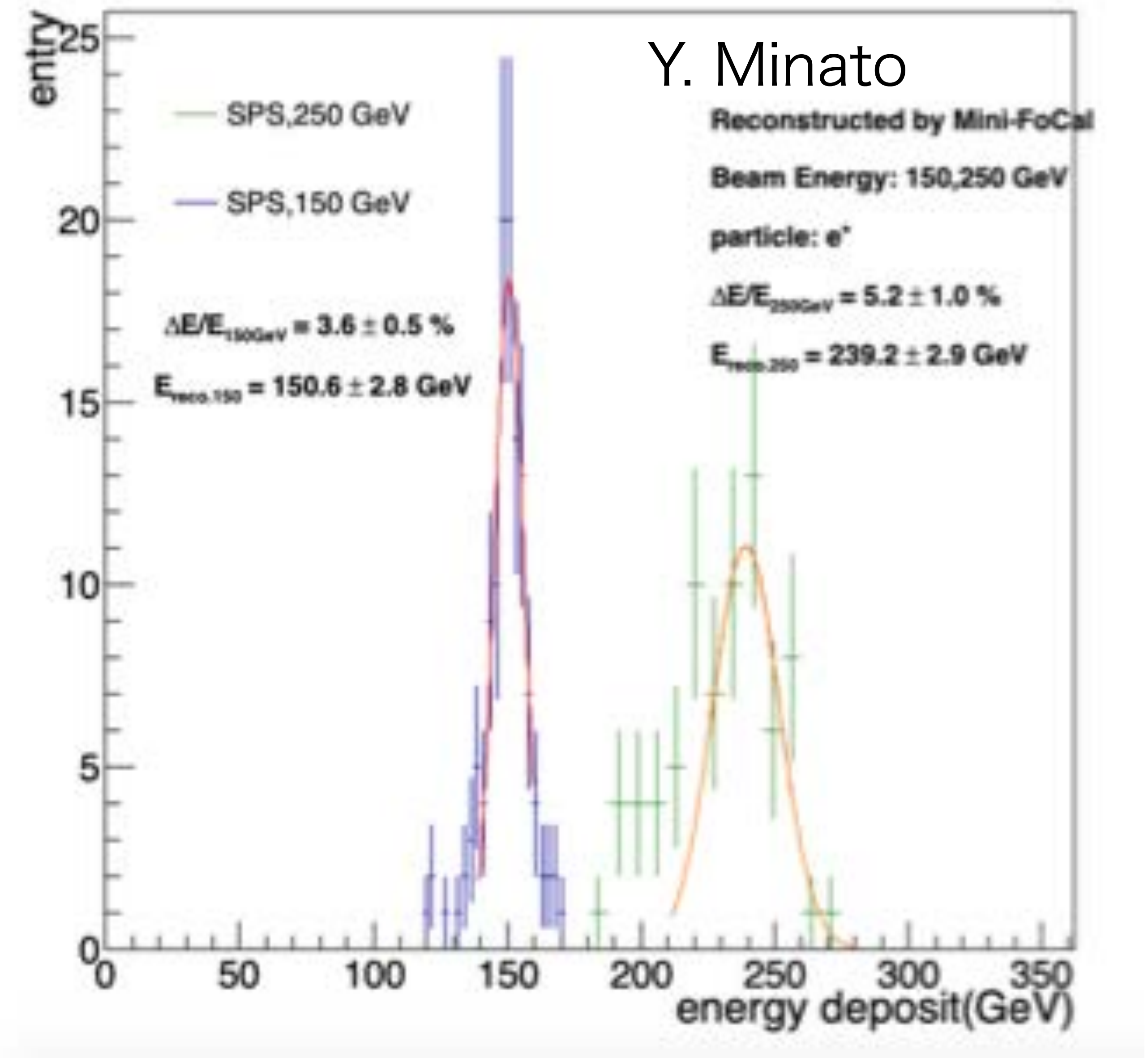


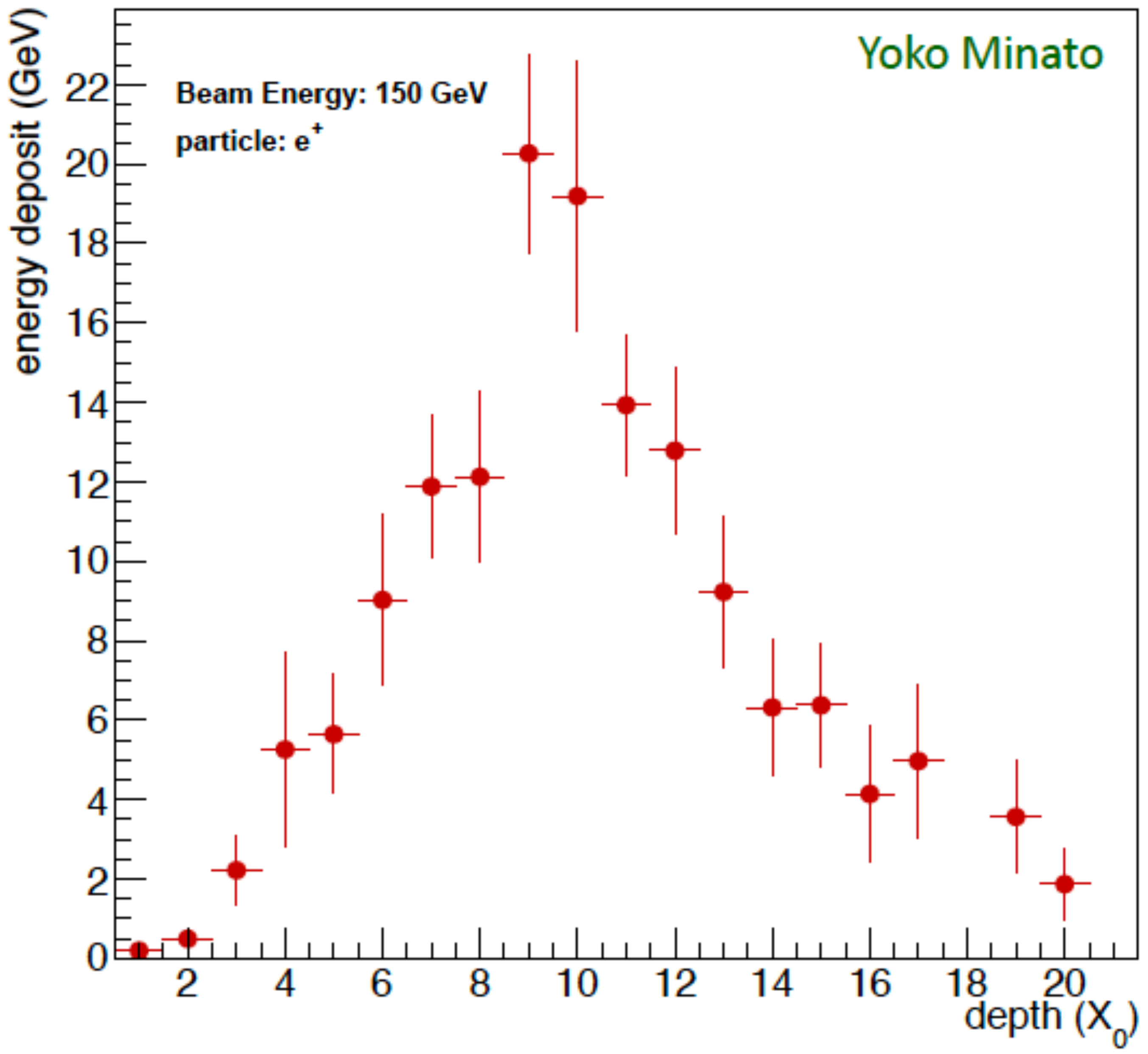
- ORNL / Japan prototype:
  - NIM A 988 (2021) 164796, T. Awes, C.L Britton, T. Chujo, et al.,
  - https://arxiv.org/abs/1912.11115

Full module mini-FoCal at PS and SPS (2018)



Test beam analysis results

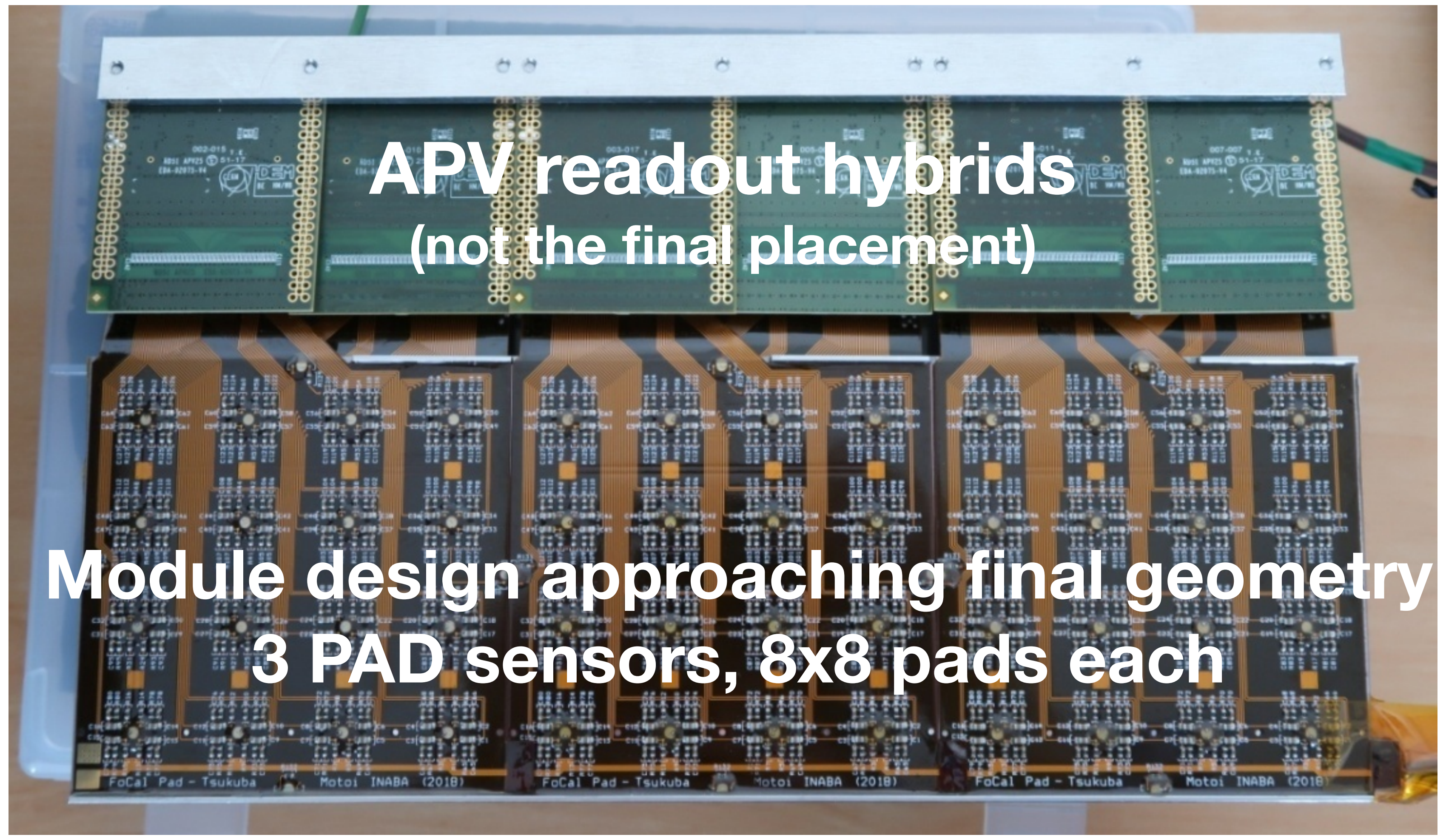




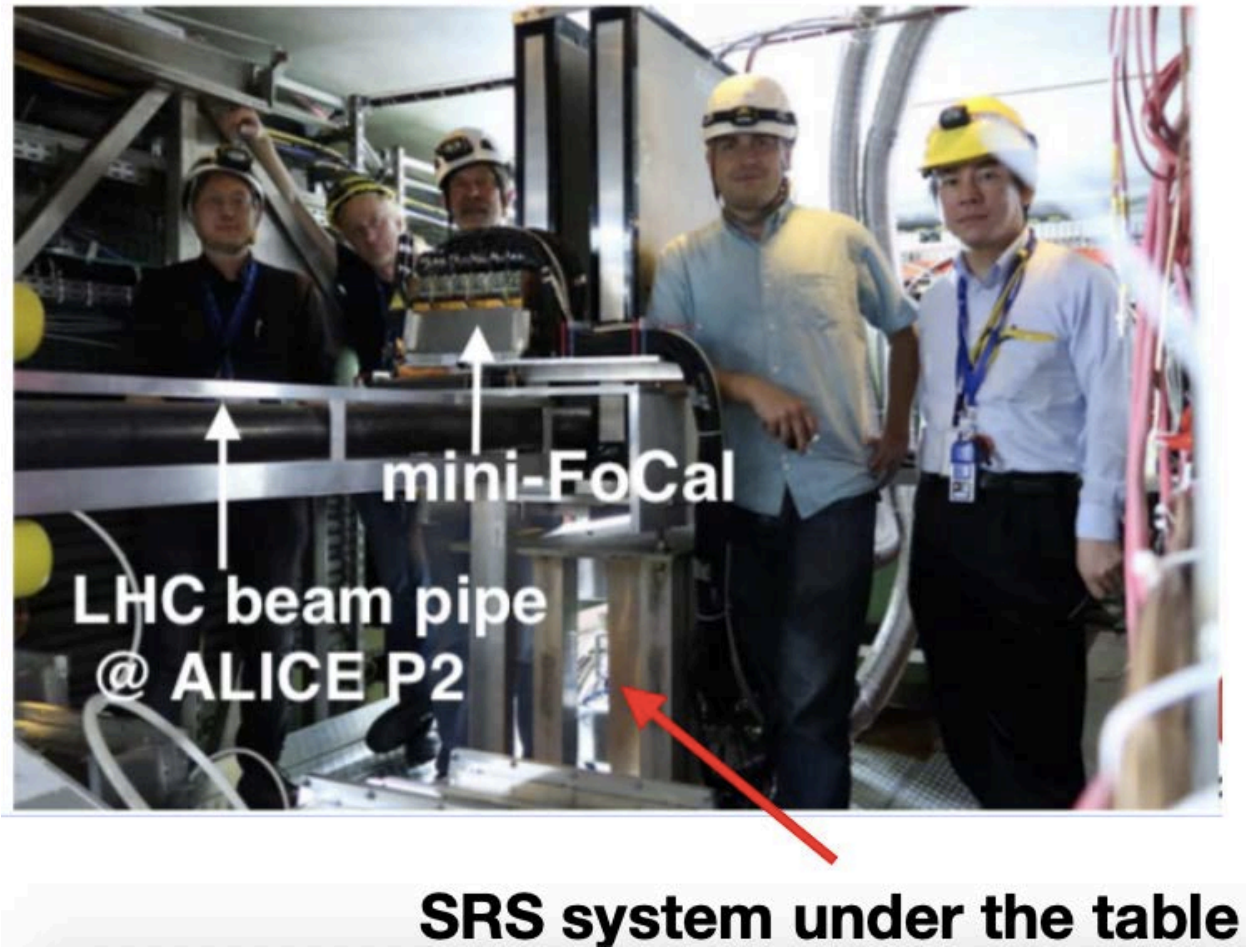
$\Delta E/E = 3.6$ %

@ 150 GeV/c , e^- (SPS)

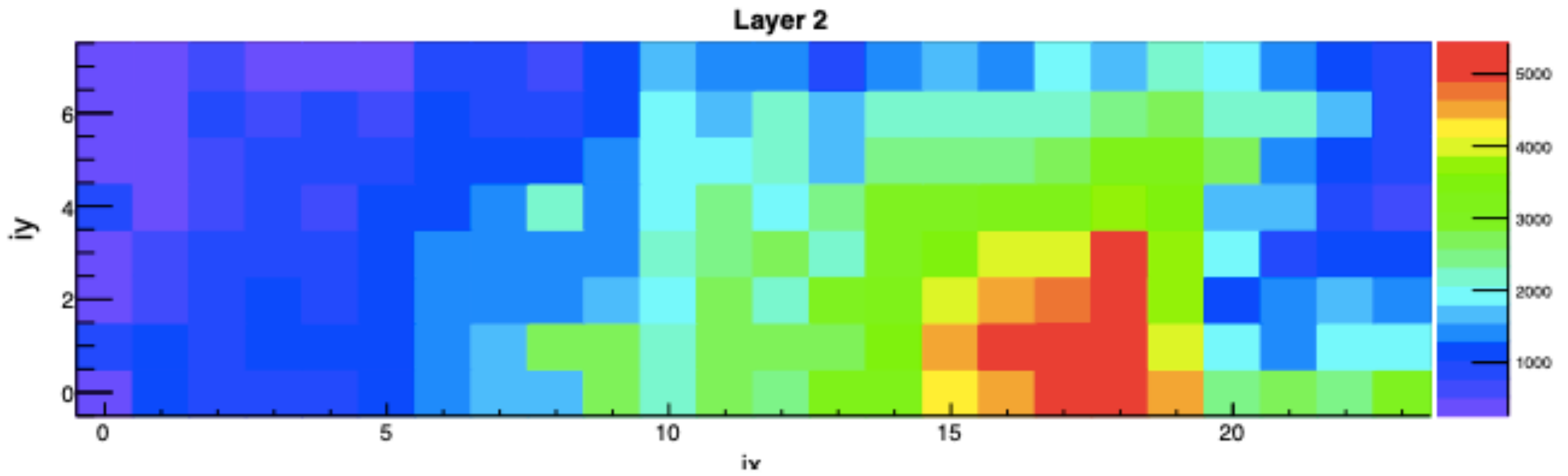
- 60 instrumented pad sensor wafers
- ~3600 channels
- APV25 hybrid + SRS readout
- built in Tsukuba
- beam tests at CERN (PS, SPS, ALICE)



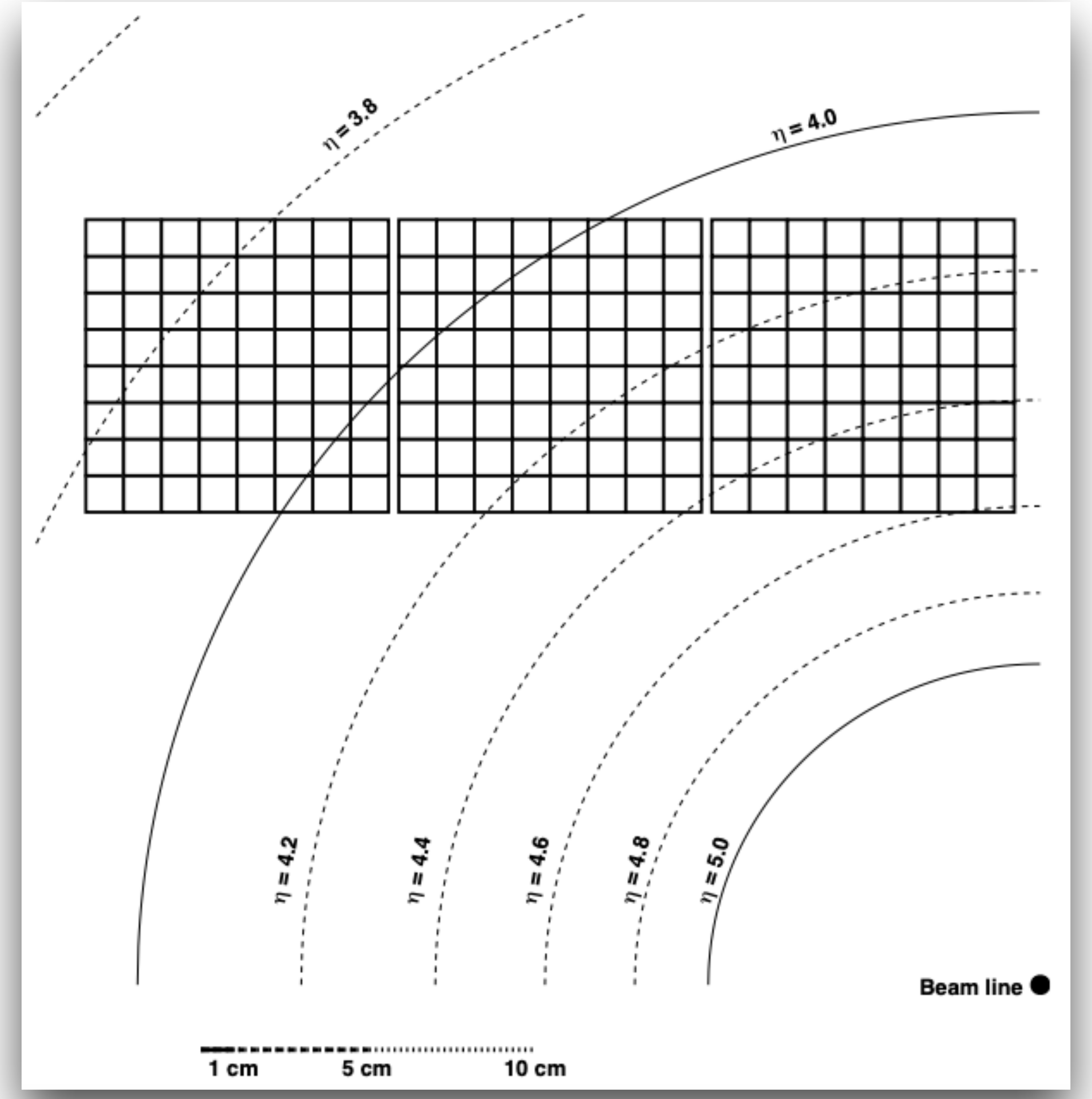
mini-FoCal in ALICE (2018)



Hit Map of mini-FoCal in ALICE



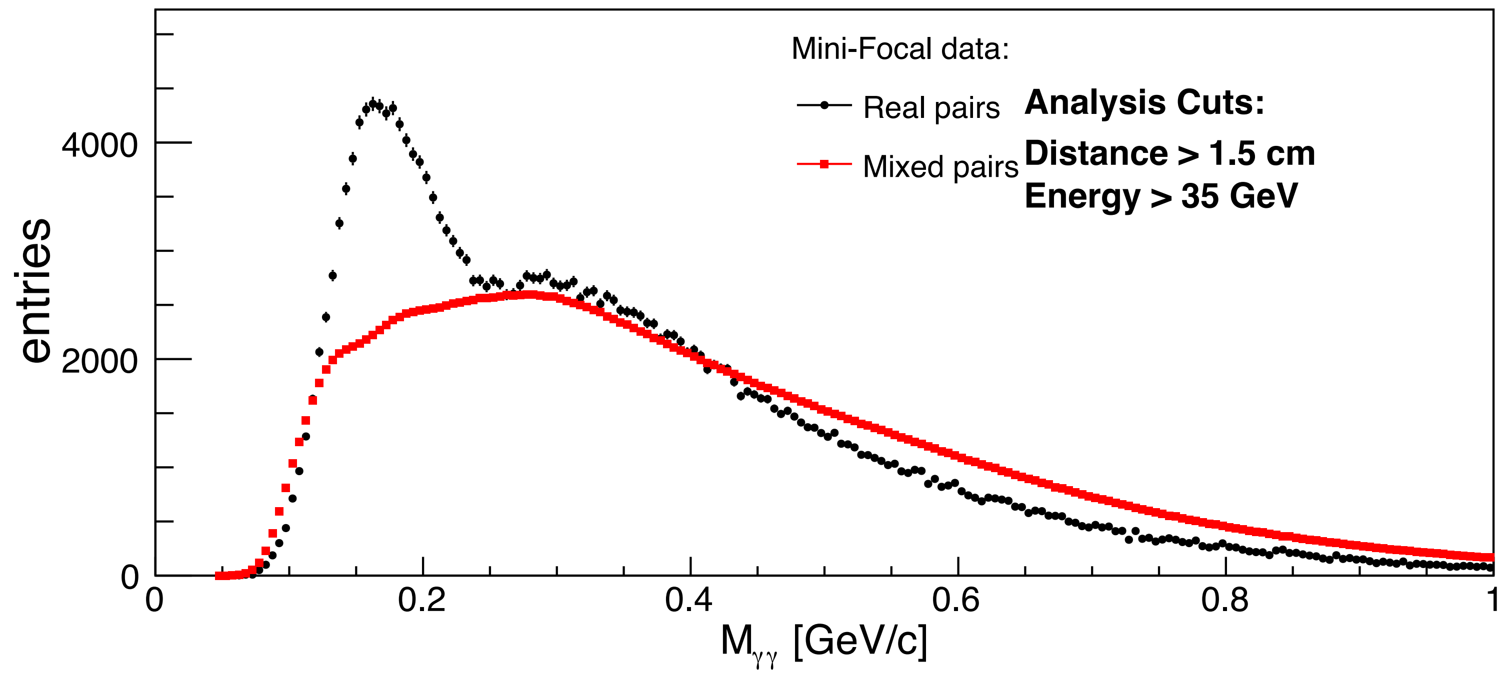
Acceptance



Goal: measure/verify backgrounds in situ with p+p @ √s = 13 TeV collisions in ALICE

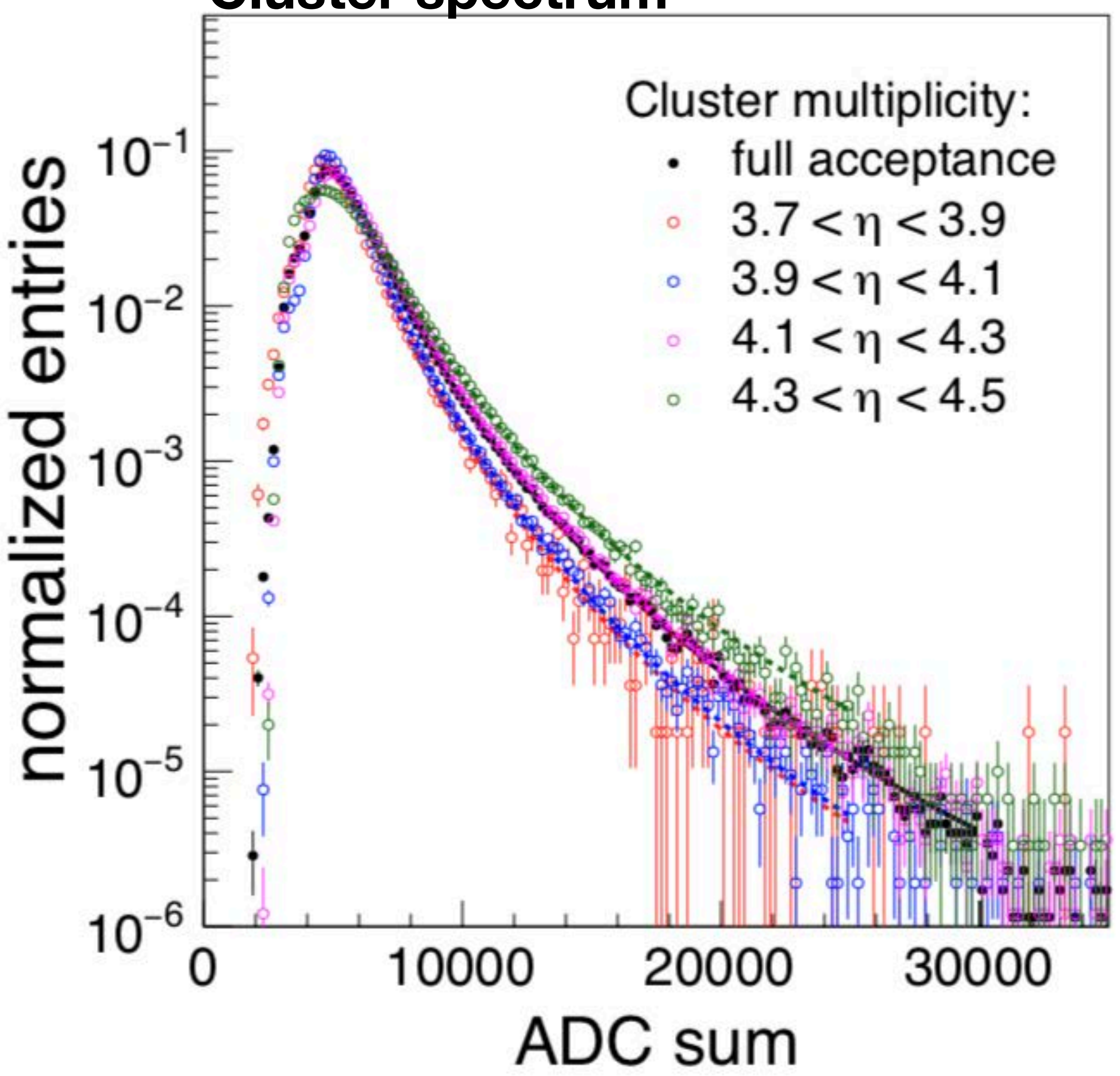
- Calibration based on test beam
- Comparison to MC (cluster spectrum, slid lines)

π^0 peak



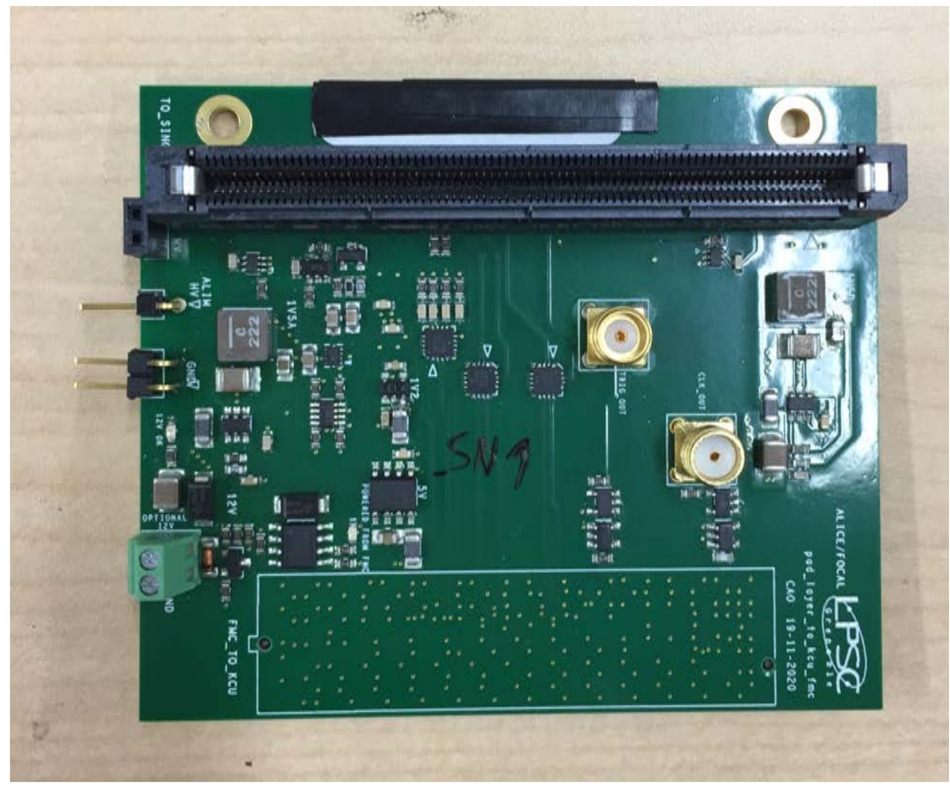
N. Novitzky

Cluster spectrum



HGCROC test bench, KUC105

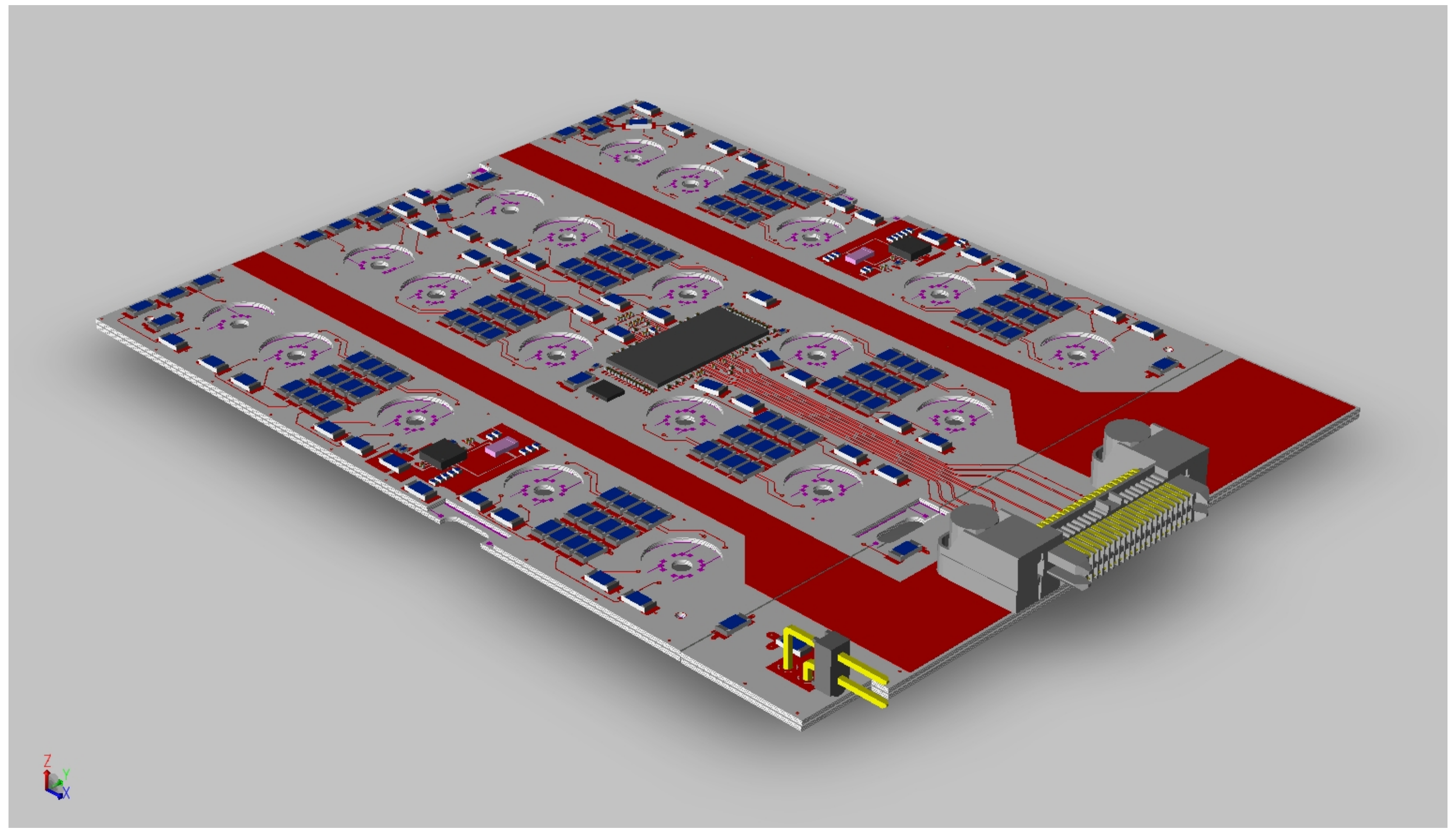
**Grenoble LPSC:
Single pad board connected to the KCU105 via the test interface board**

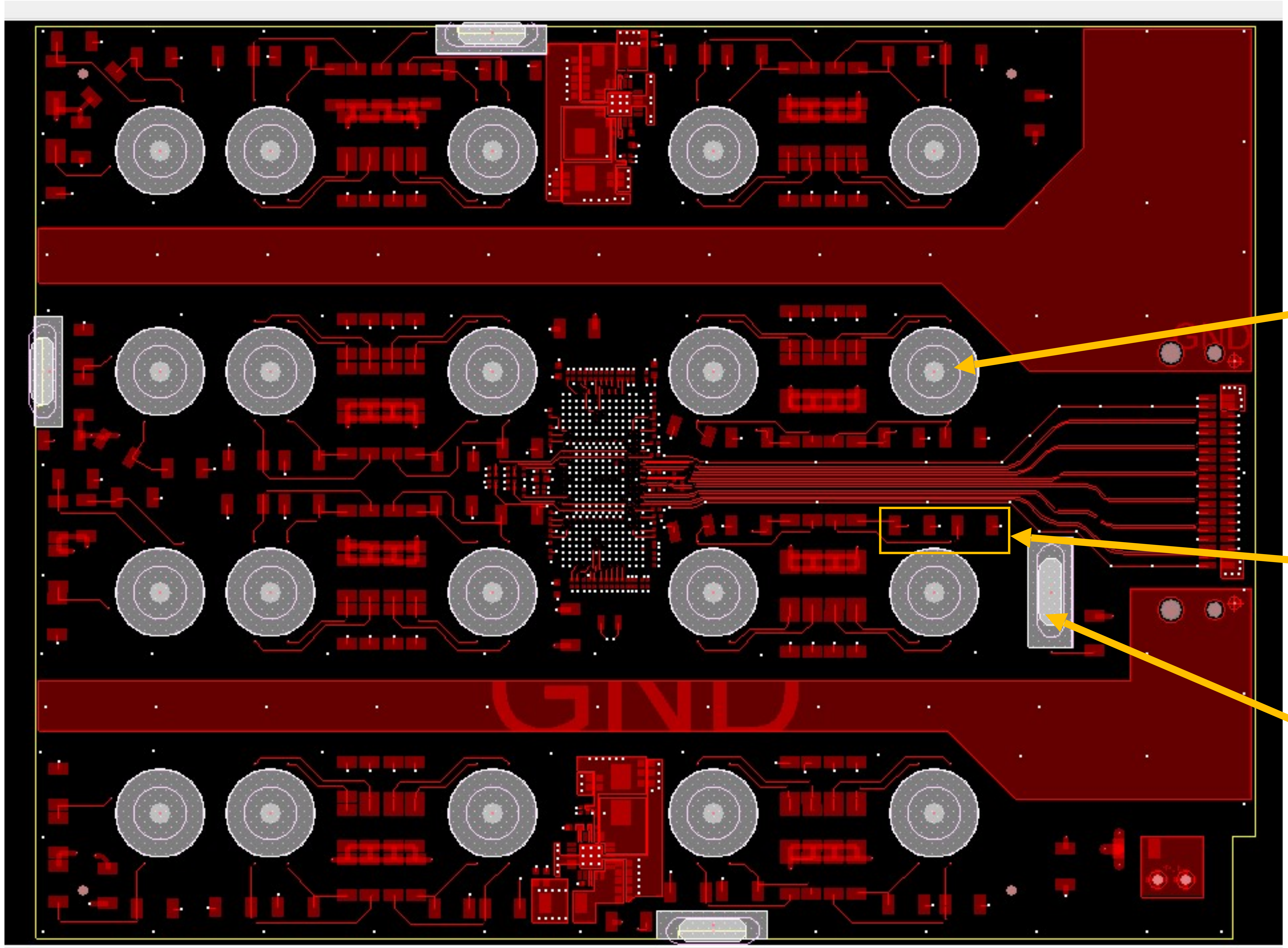


interface card

- Purchased KUC105 in 2020, will be set it up at lab (Norbert).
- First PCB + HGCROC (2 boards) will be delivered Tsukuba in April. (we also need an interface board)
- After receiving PCB from Grenoble, we will start the readout test immediately, then do assembly and wire bonding, laser test, and ELPH test beam in July.

Single pad board V2





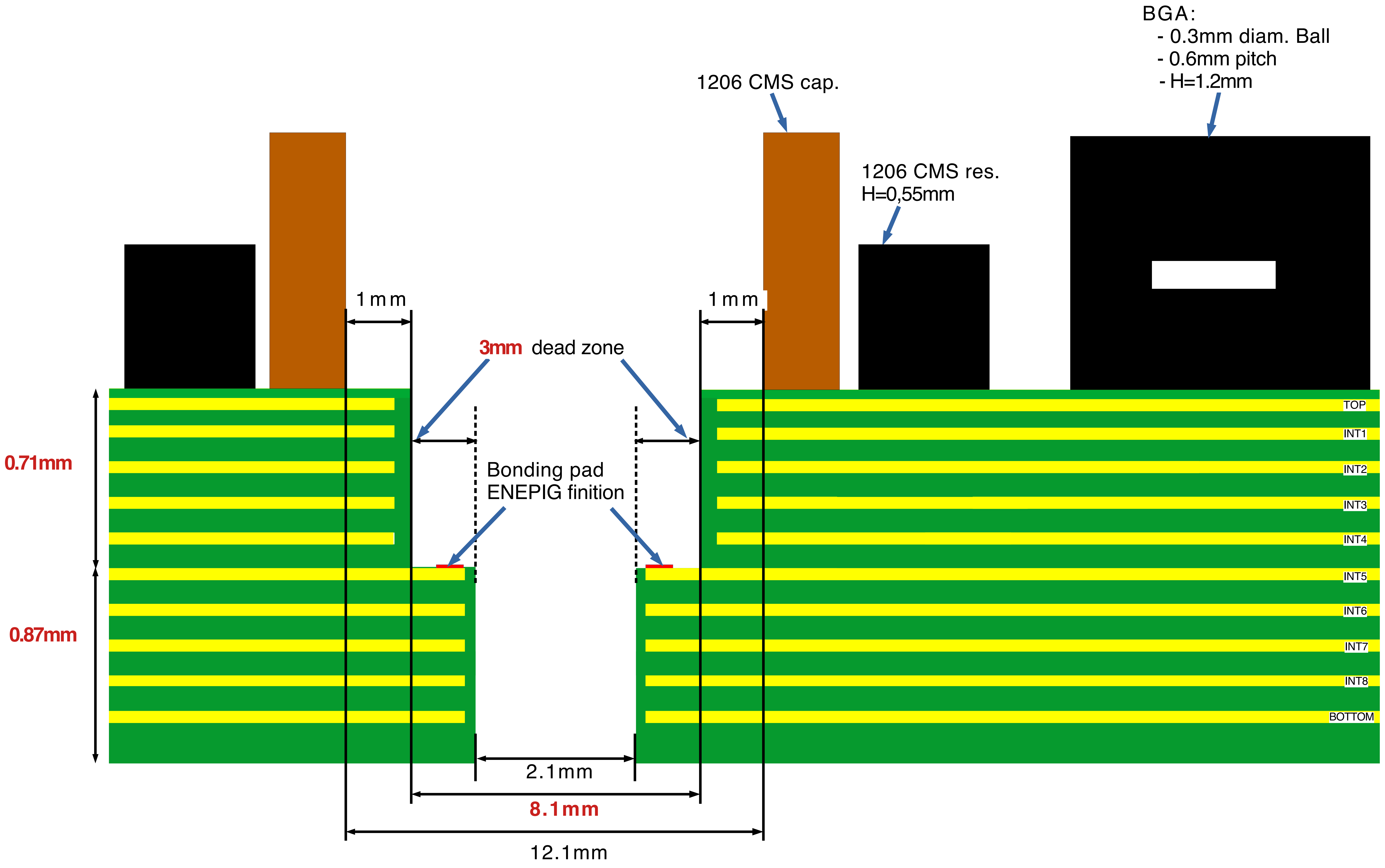
Cavity of 8.1mm
+ hole of 2.1mm

cms 1206 cap whith h=1.6mm
Cavity distance of 1mm

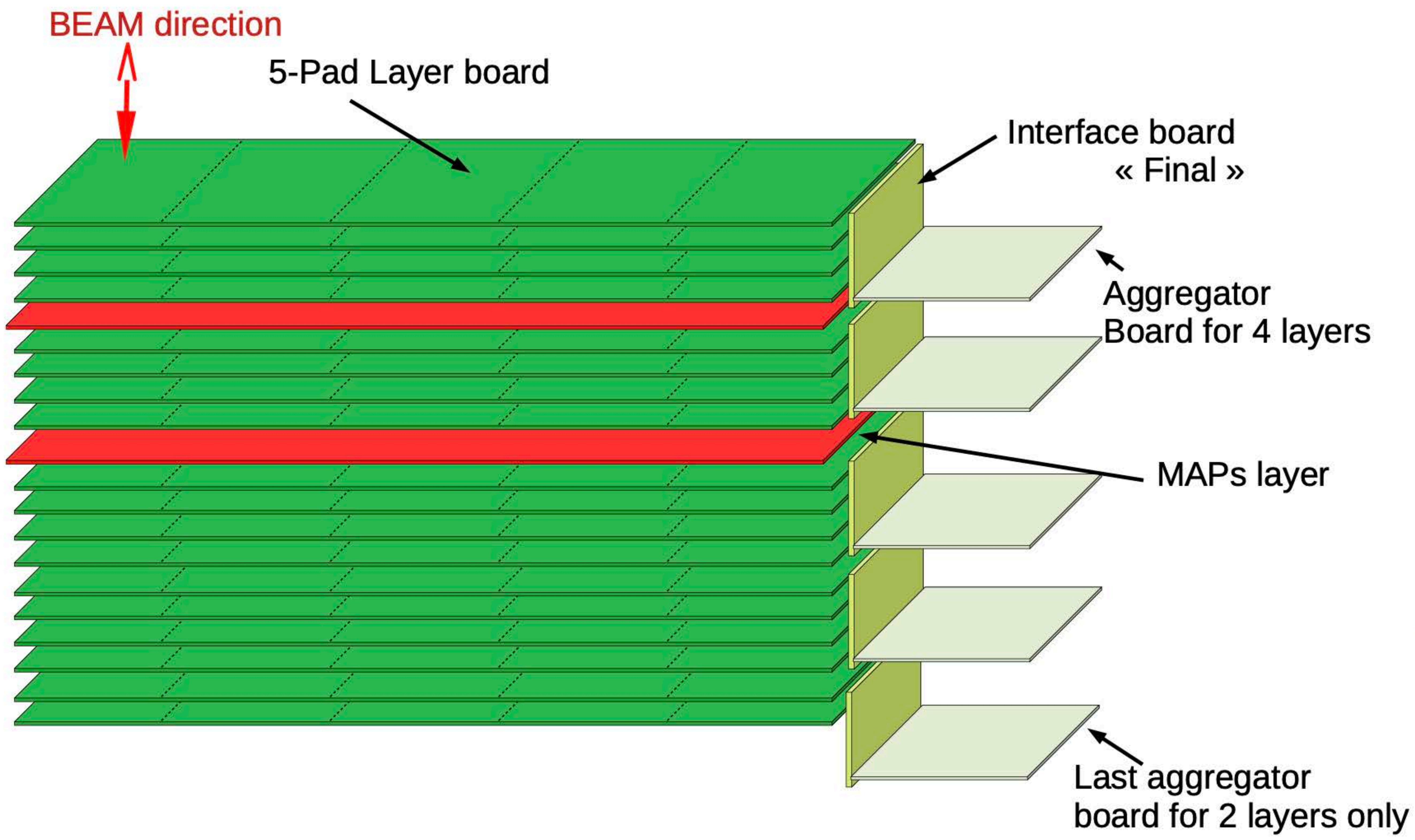
Oblong holes for biasing (GND and HVT)

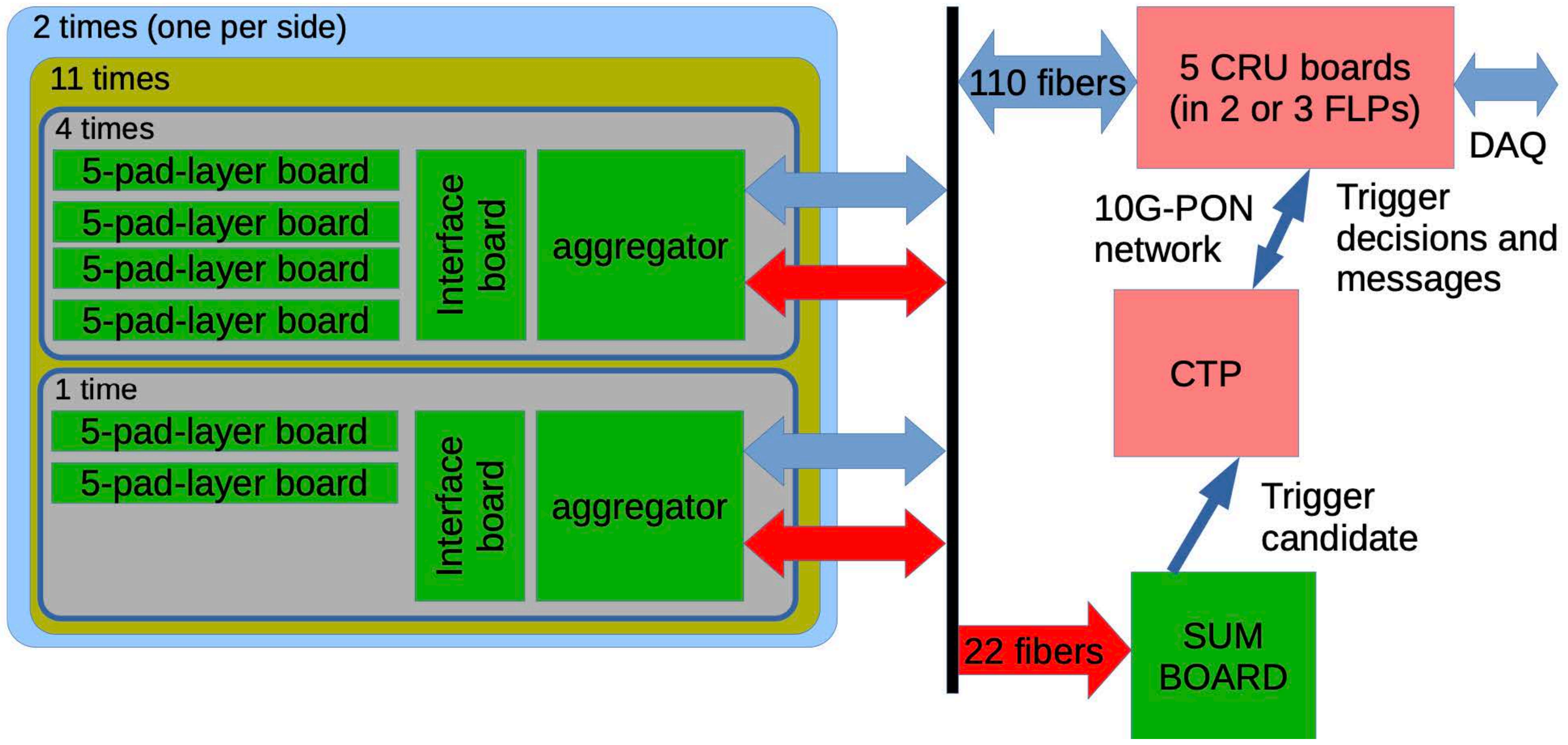
PCB final version to be submitted

Cross section view



FoCal-E PAD readout



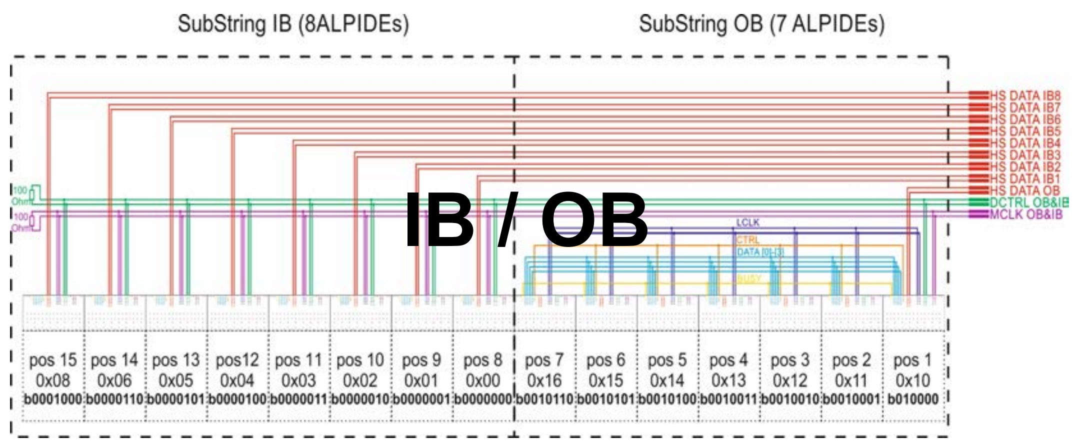


- 5-pad-layer PCB for 5 HGCROCs, each HGCROC connects to one PAD sensor (72 cells, 4 CMN, 2 calib.)
- Aggregator board to efficiently readout out data from 4 boards
- Sum board to provide trigger decision based on parts of the shower (under consideration)

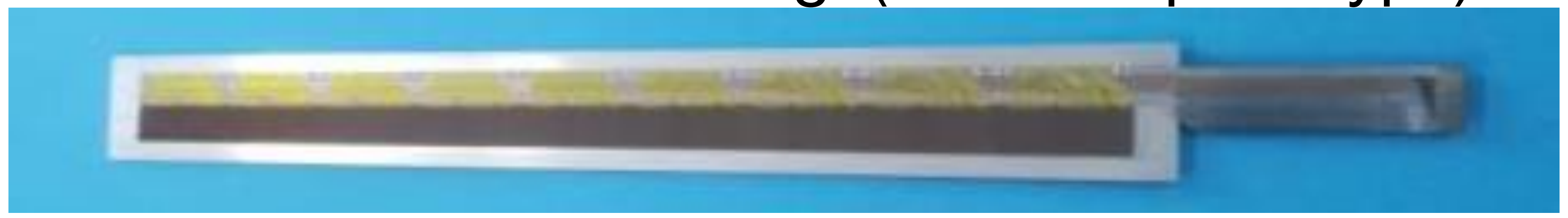
(Grenoble)

Pixel layer readout: Based on ITS components

15 ALPIDE per string



Flex PCB ‘string’ (9 sensor prototype)

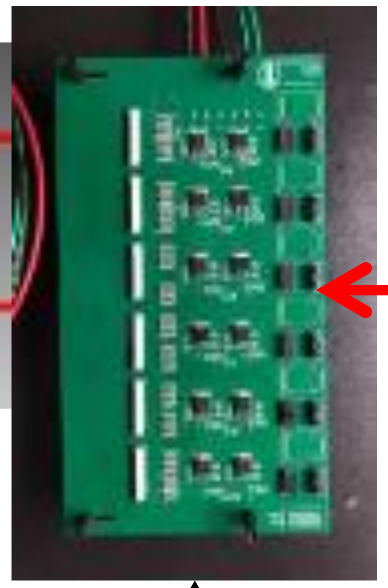


Pixel layers (2 layers / module)

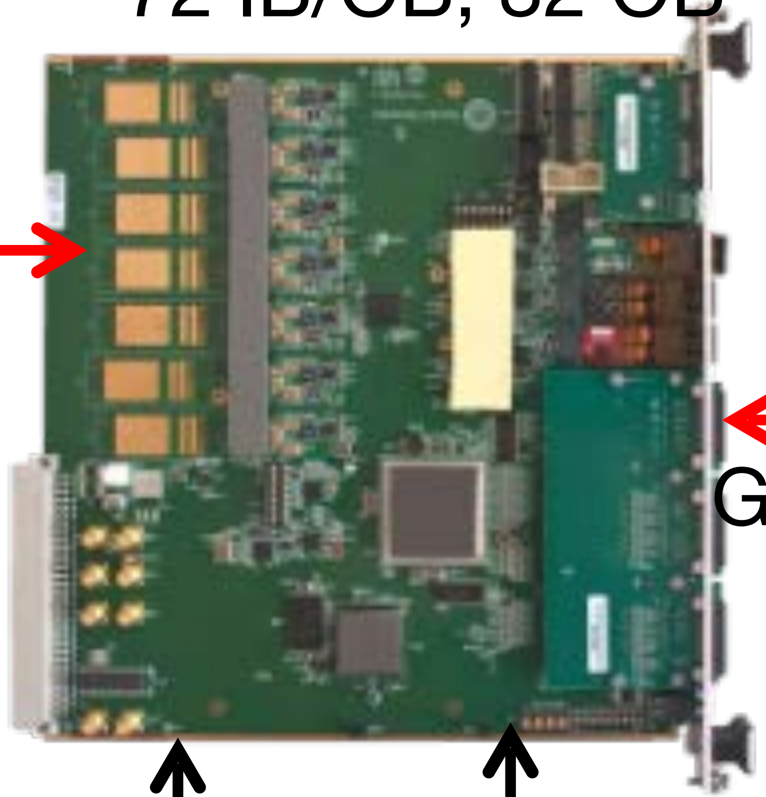
- ITS2 ALPIDE sensors
- ITS2 readout chain (RU & CRU)
- Transition board
  - Exists but needs to be made smaller

2 x 3 strings on thin Al carrier (module)

Transition Board



ITS2 Readout Unit (RU)
72 IB/OB, 32 OB



280
GBT links

6 FLP, 12 CRU

EPN

Cooling

ITS2
Power units

Trigger
LTU← CTP

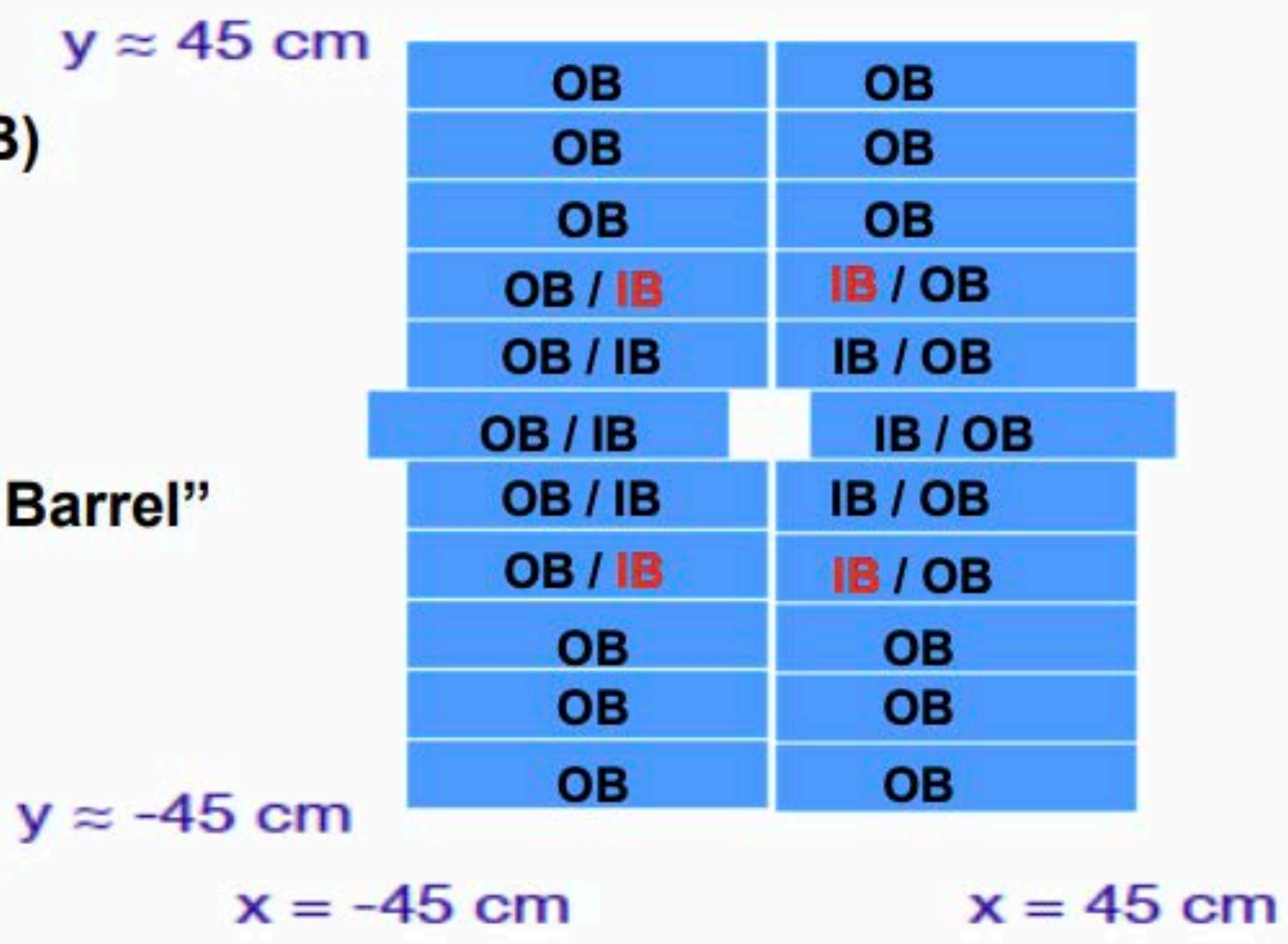
DCS

Pixel readout: Outer / Inner Barrel

Two types of modules:
1) IB/OB: high+low occupancy (inner/outer barrel)
2) OB: low occupancy (outer barrel)

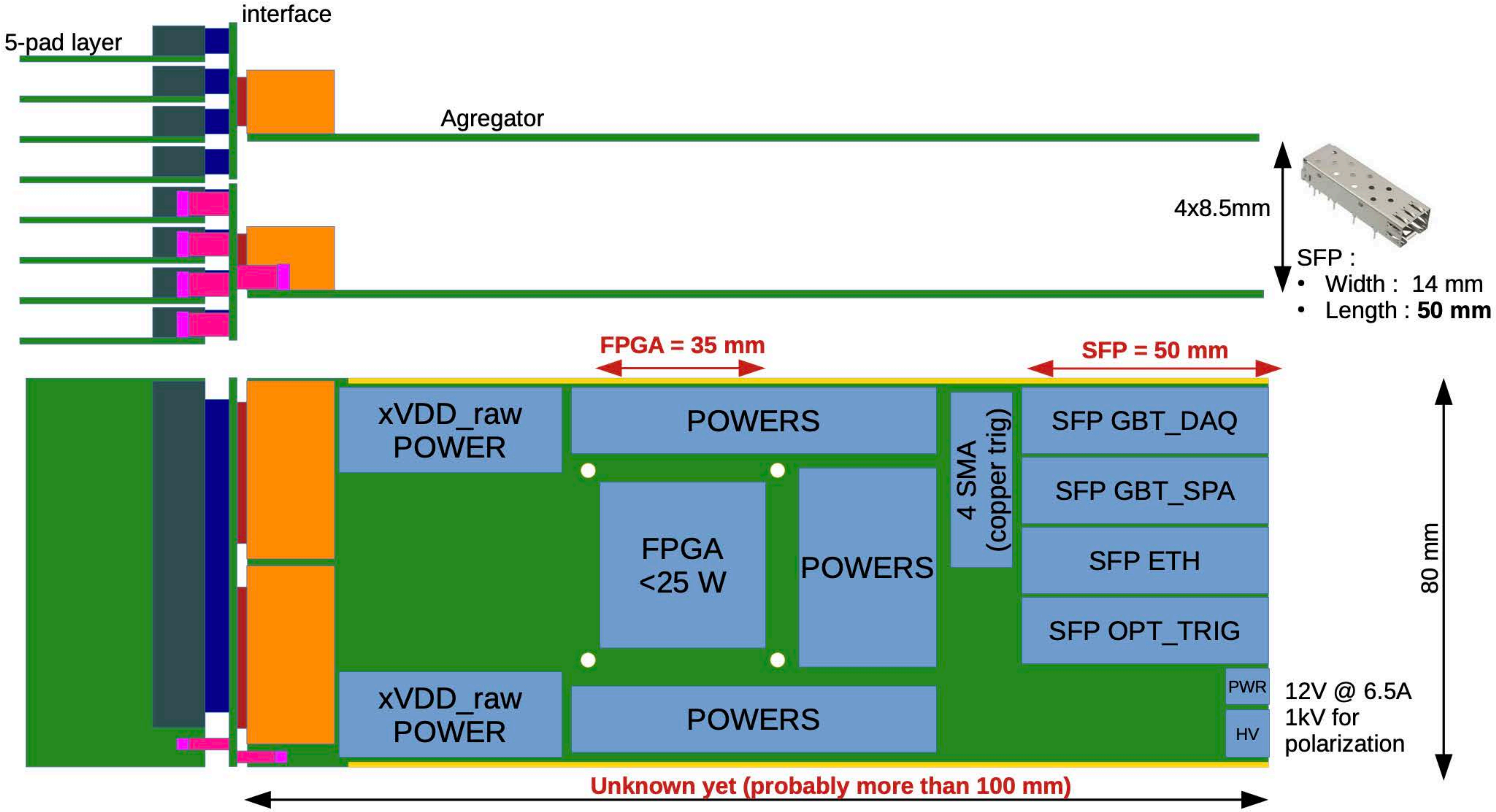
update

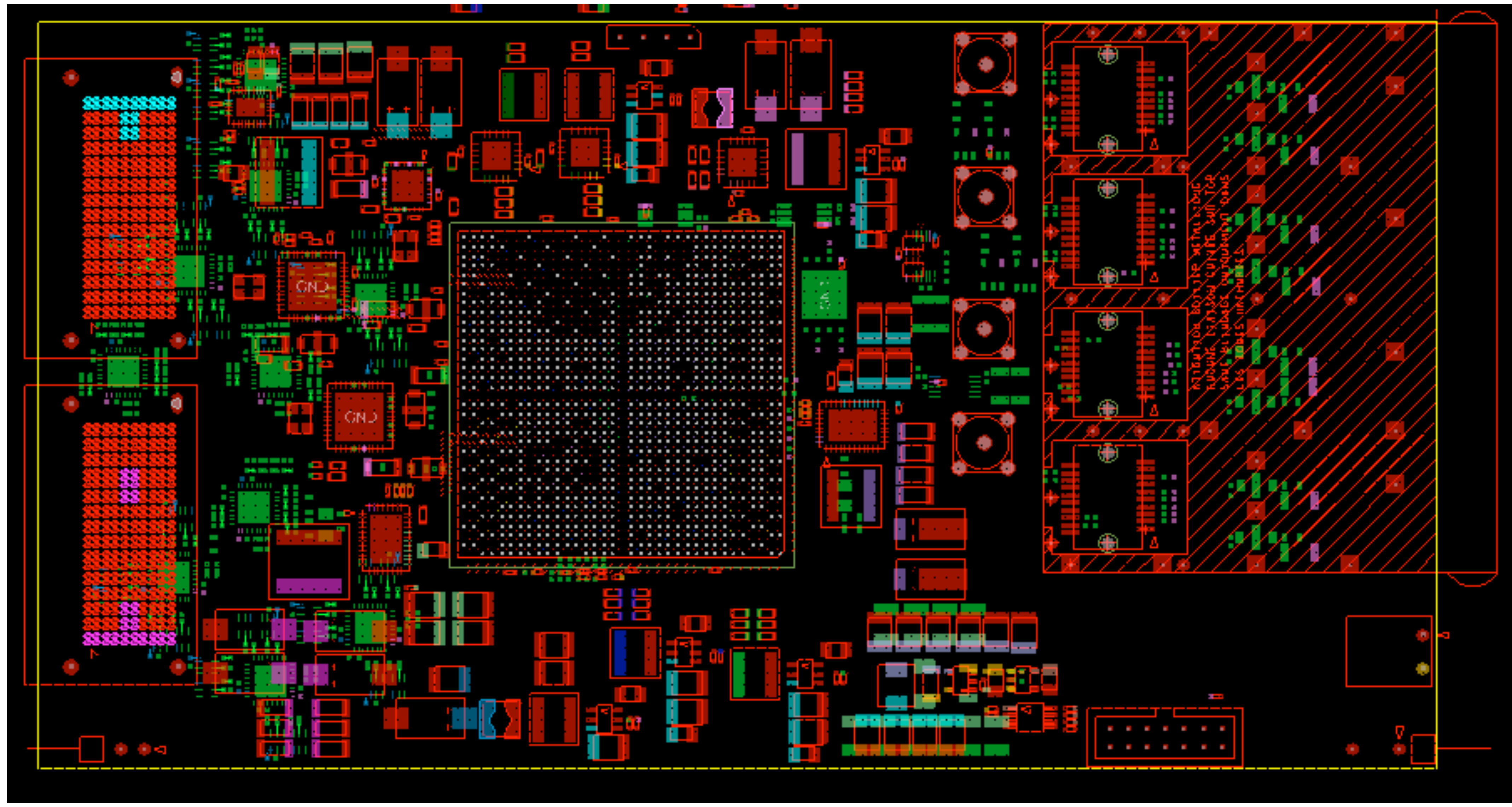
- **12 "Outer Barrel" modules (OB)**
  - **ALPIDEs are read out in Master/Slave mode**
- **10 mixed "Inner Barrel / Outer Barrel" modules (IB/OB)**
  - **All IB-ALPIDEs are read out directly by 1.2 Gb/s link**



Update: add one more high-rate module in each quadrant

Aggregator board



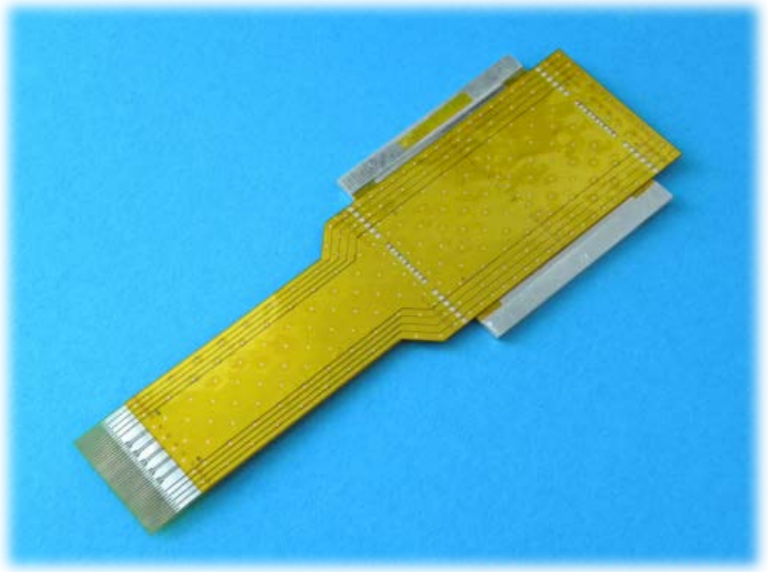


Current size 80x150mm
Red is top, green is bottom side

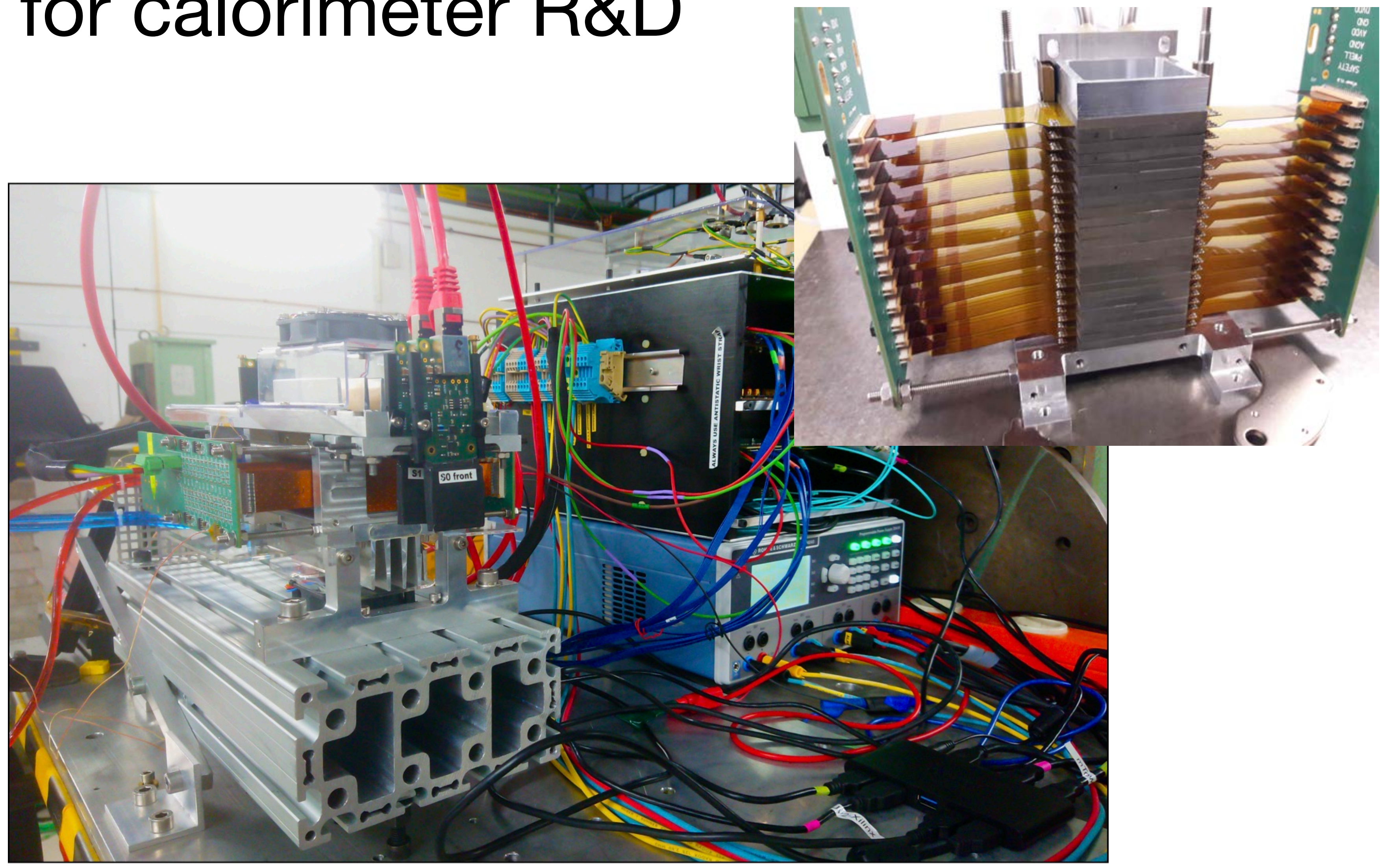
- Technical aspects to be considered early on, e.g. how to hold the boards, rails?
- Cooling will be needed: to be studied
- Available space for the board: 10 cm — challenging

ALPIDE pixel test beams

2-chip modules for calorimeter R&D



mTower layer prototype
(LTU, Kharkov)



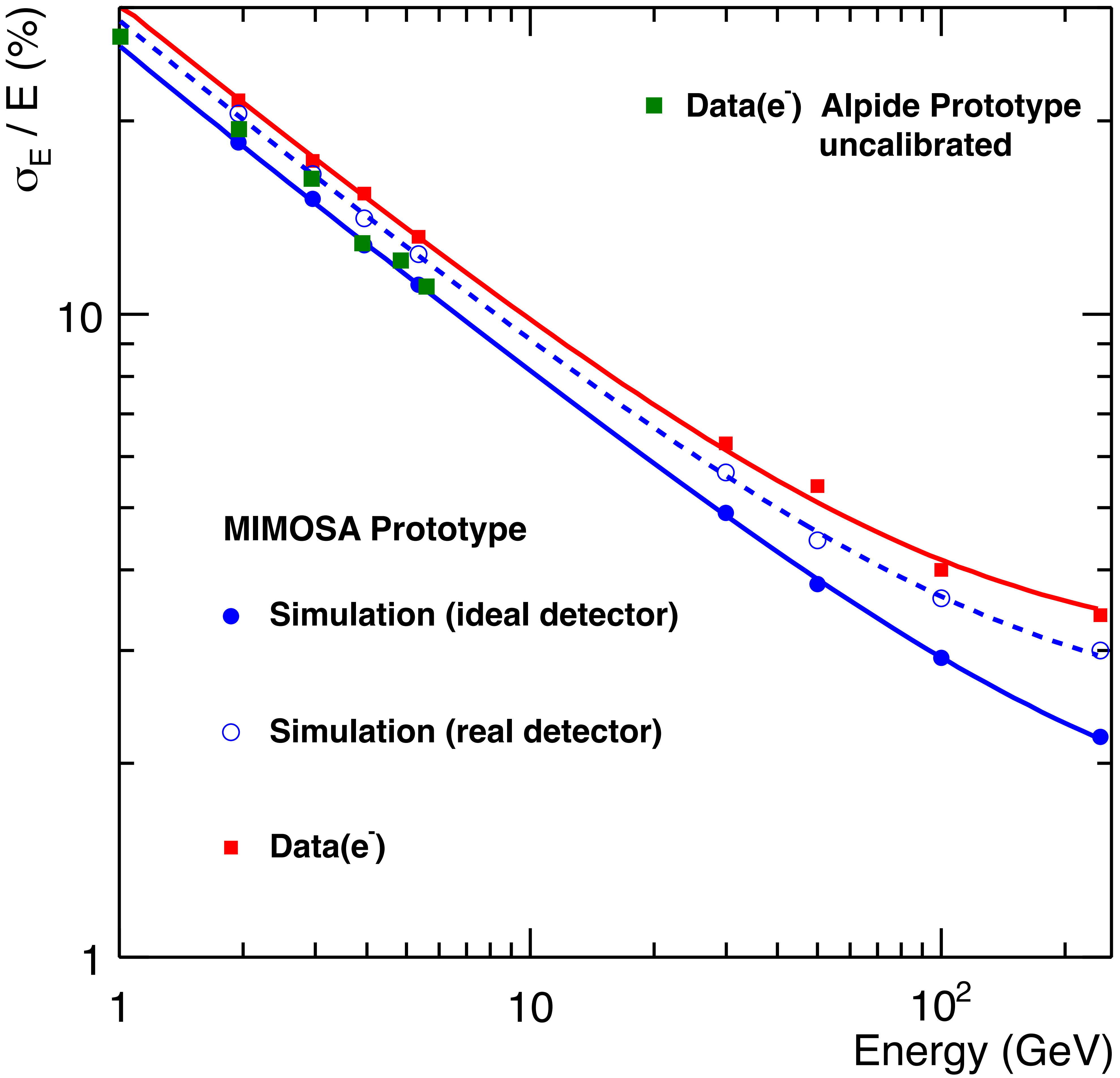
Test beams at DESY: Nov 2019, Feb 2020

9 chip module

Developments with flex cables for medical application: proton-CT

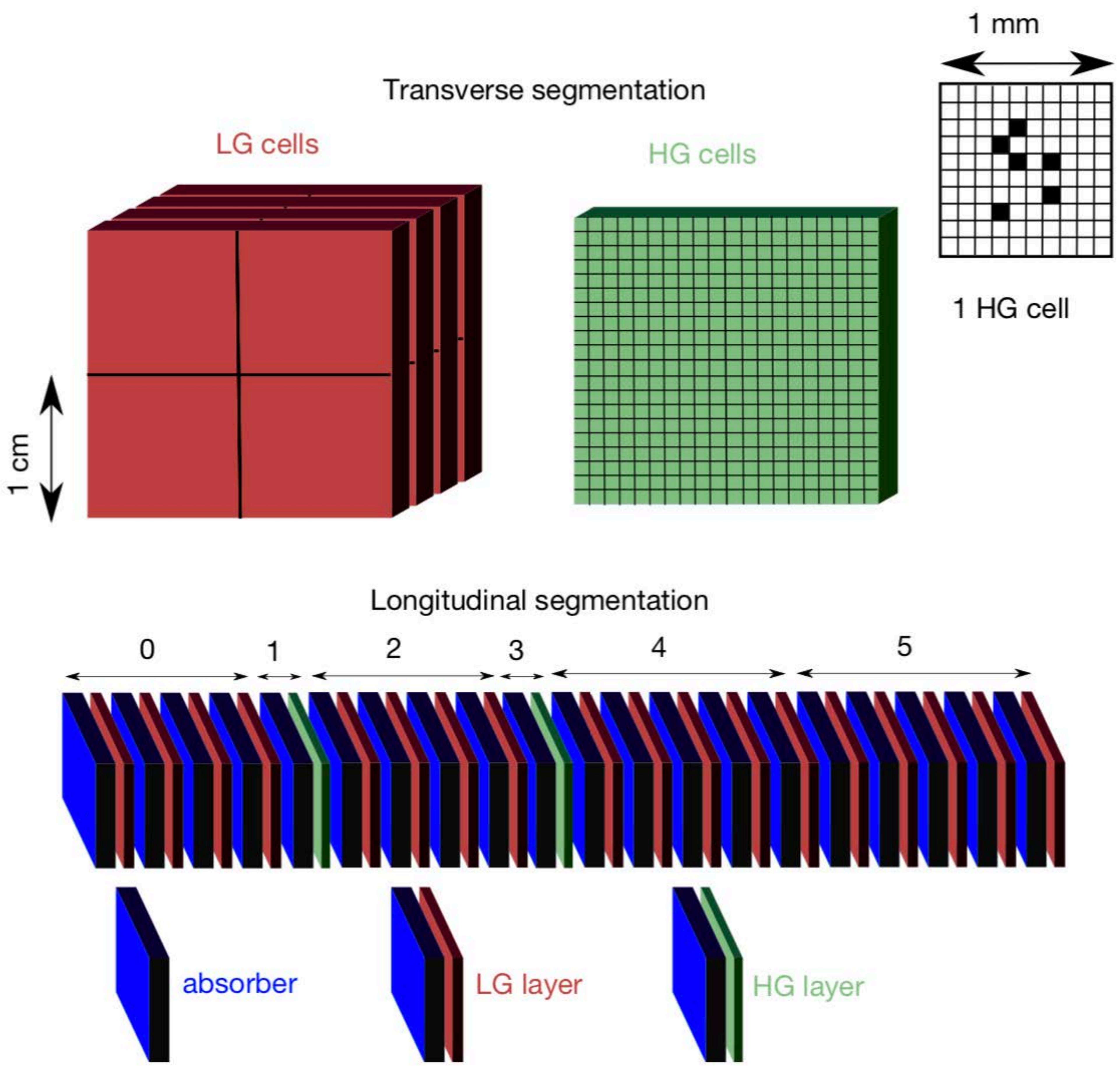
Bergen, Norway

ALPIDE energy resolution



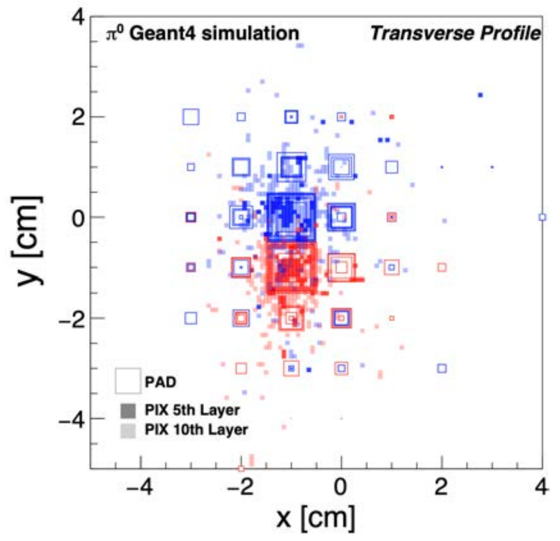
First results with ALPIDE promising:
Better energy resolution than MIMOSA

FoCal-E conceptual design

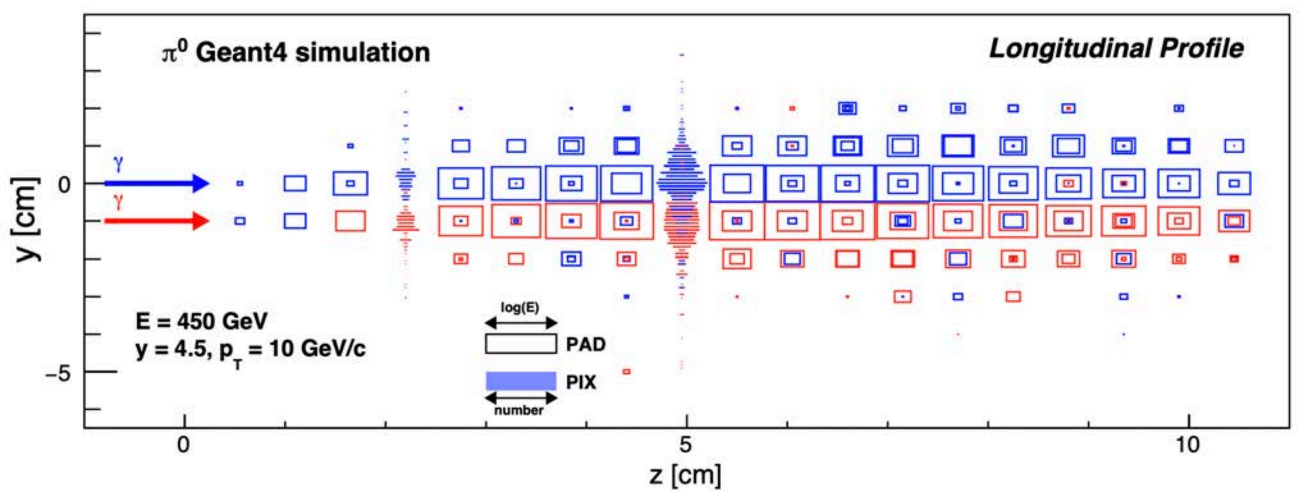


FoCal-E:

- Separate γ/π^0 at high energy
  - W(3.5 mm ≈ $1X_0$) + silicon sensors, 20 layers in total
- Two types: PAD (LG, 18 layers) and PIXEL (HG, 2 layers)
- Pad layers provide shower profile and total energy
- Pixel layers (ALPIDE, 30 um pixel) provide position resolution to resolve overlapping showers
- Two photon separation from π^0 decay (p_T=10 GeV, η=4.5) ~5mm



Trans. profile

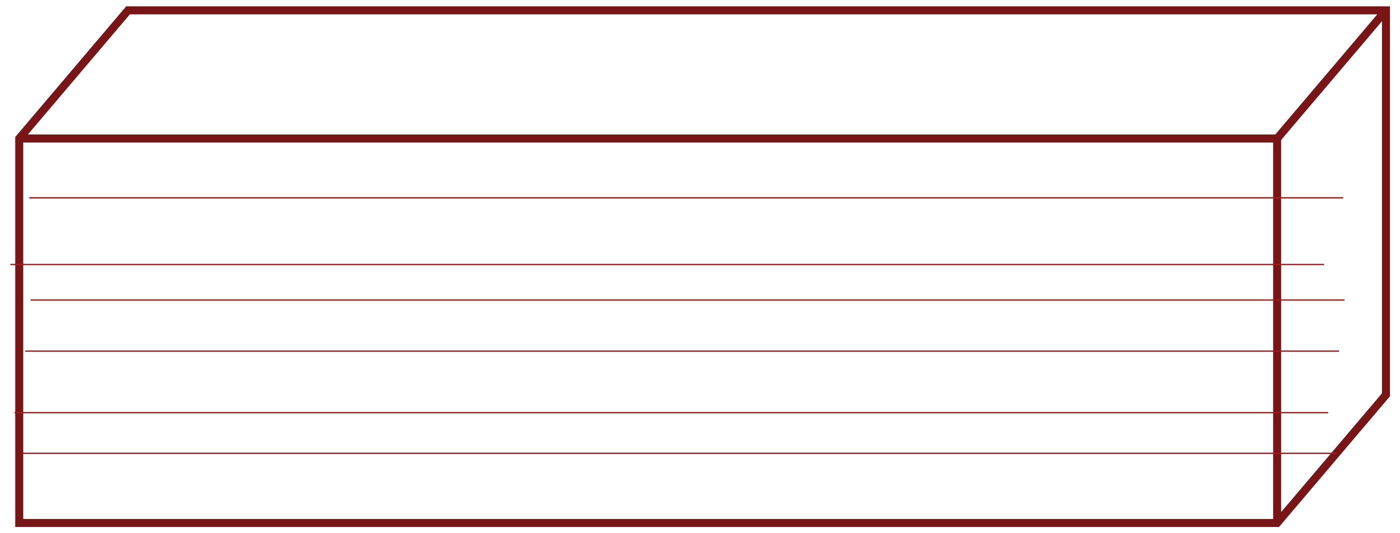


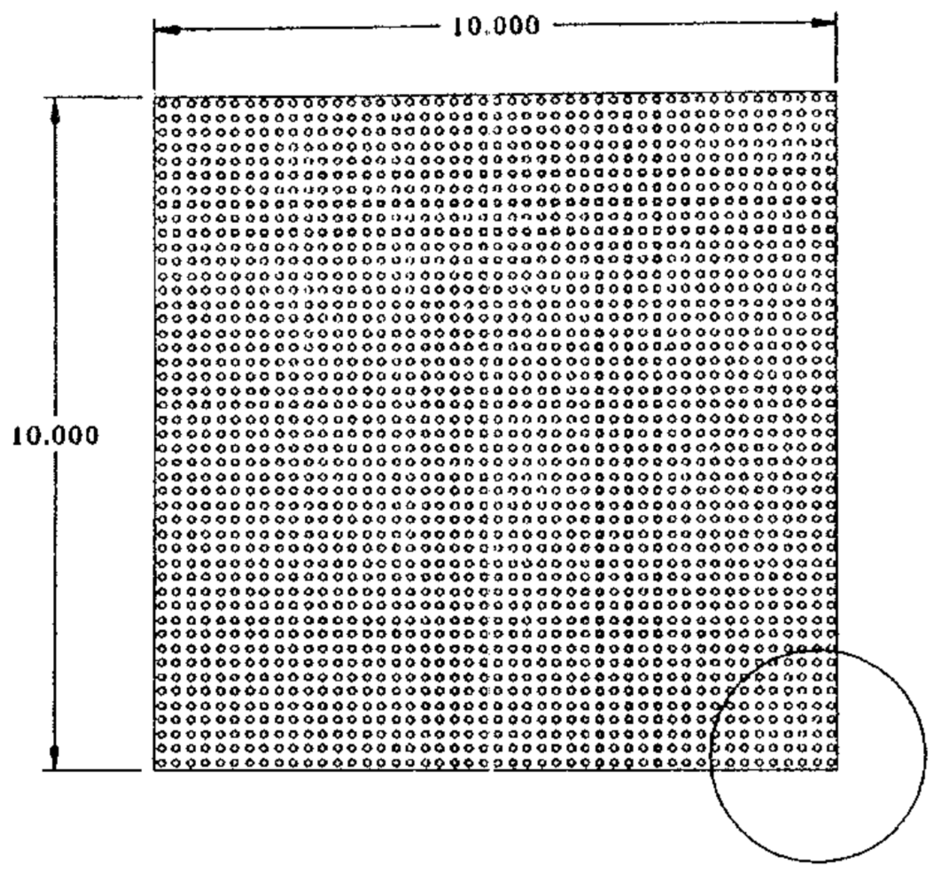
Longitudinal profile (2γ showers)

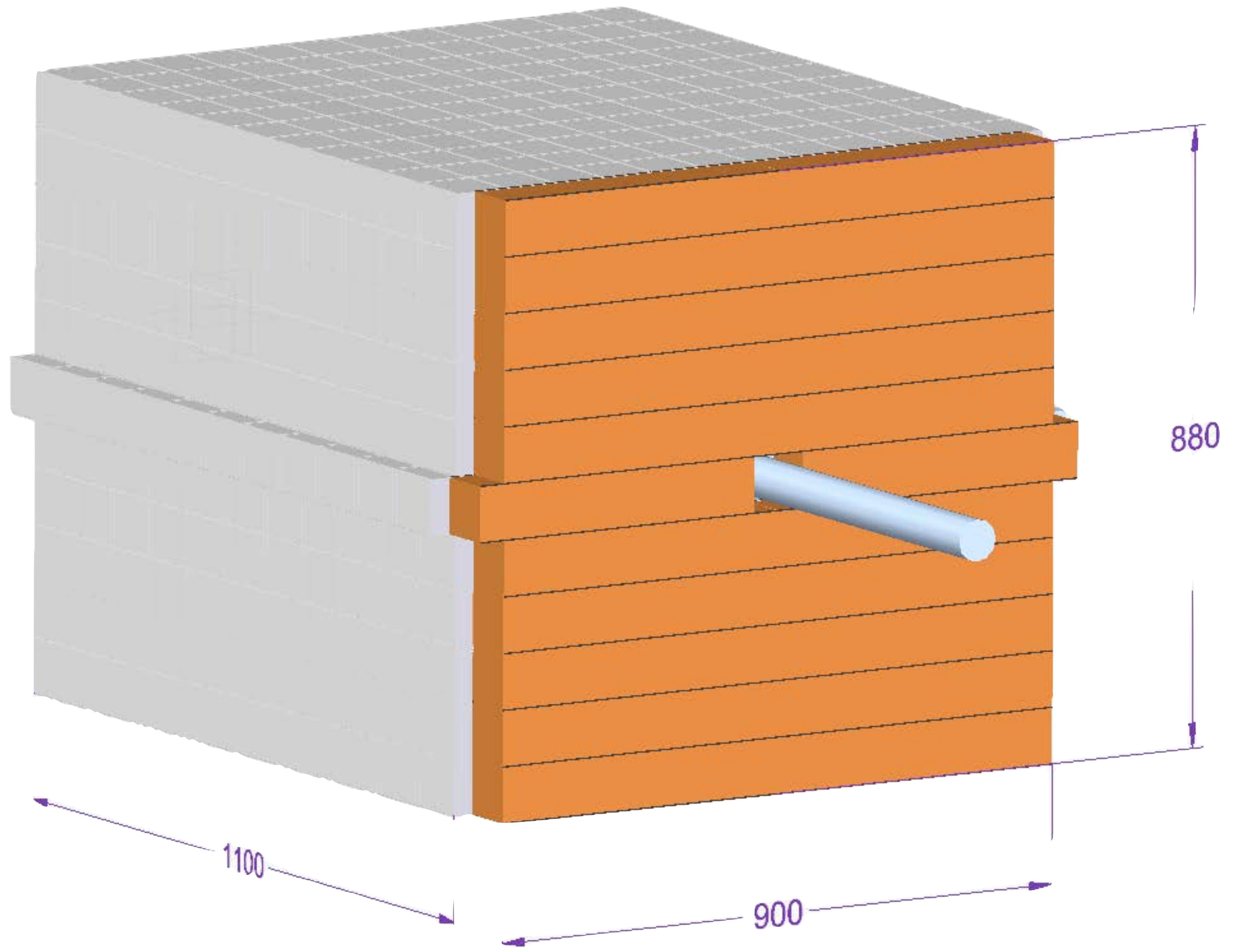
FoCal-H conceptual design

Geometry can be based on
SPACAL design: spaghetti calorimeter

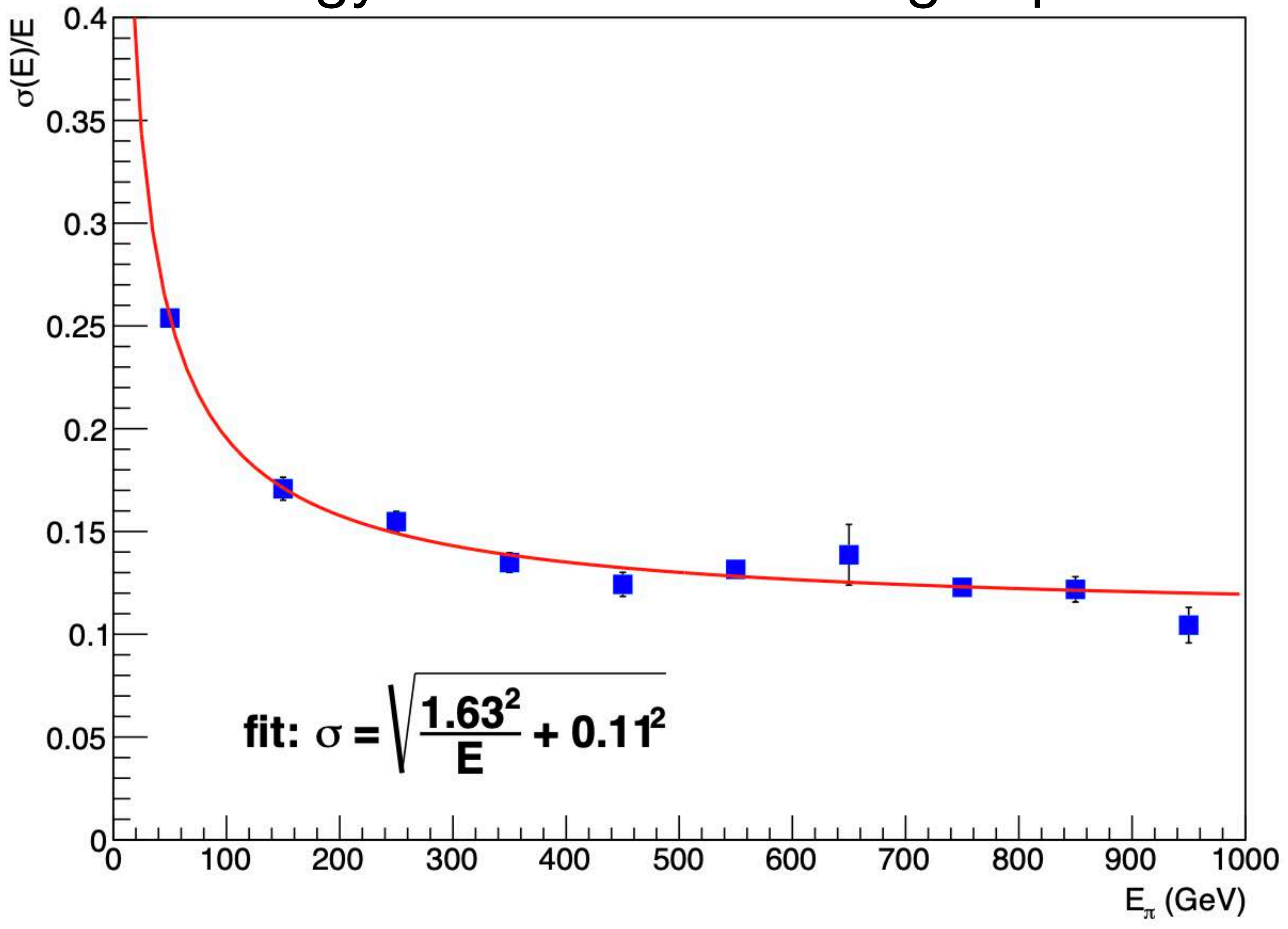
Nuclear Instruments and Methods in Physics Research A 406 (1998) 227–258







Energy resolution for charged pions



- Simulation uses sandwich-structure:
  - **34 layers of 3cm absorber and 0.2cm scintillator**
- Good performance for isolation and jets
  - Single hadron energy resolution of 10-25%
  - E_T = 2 GeV for isolation about E = 100 GeV at η = 4.5
  - Constant term (e/h compensation) more, sampling-fraction less important
- Conventional metal-scintillator design
  - Sampling / tower structure not yet defined
  - No longitudinal readout required

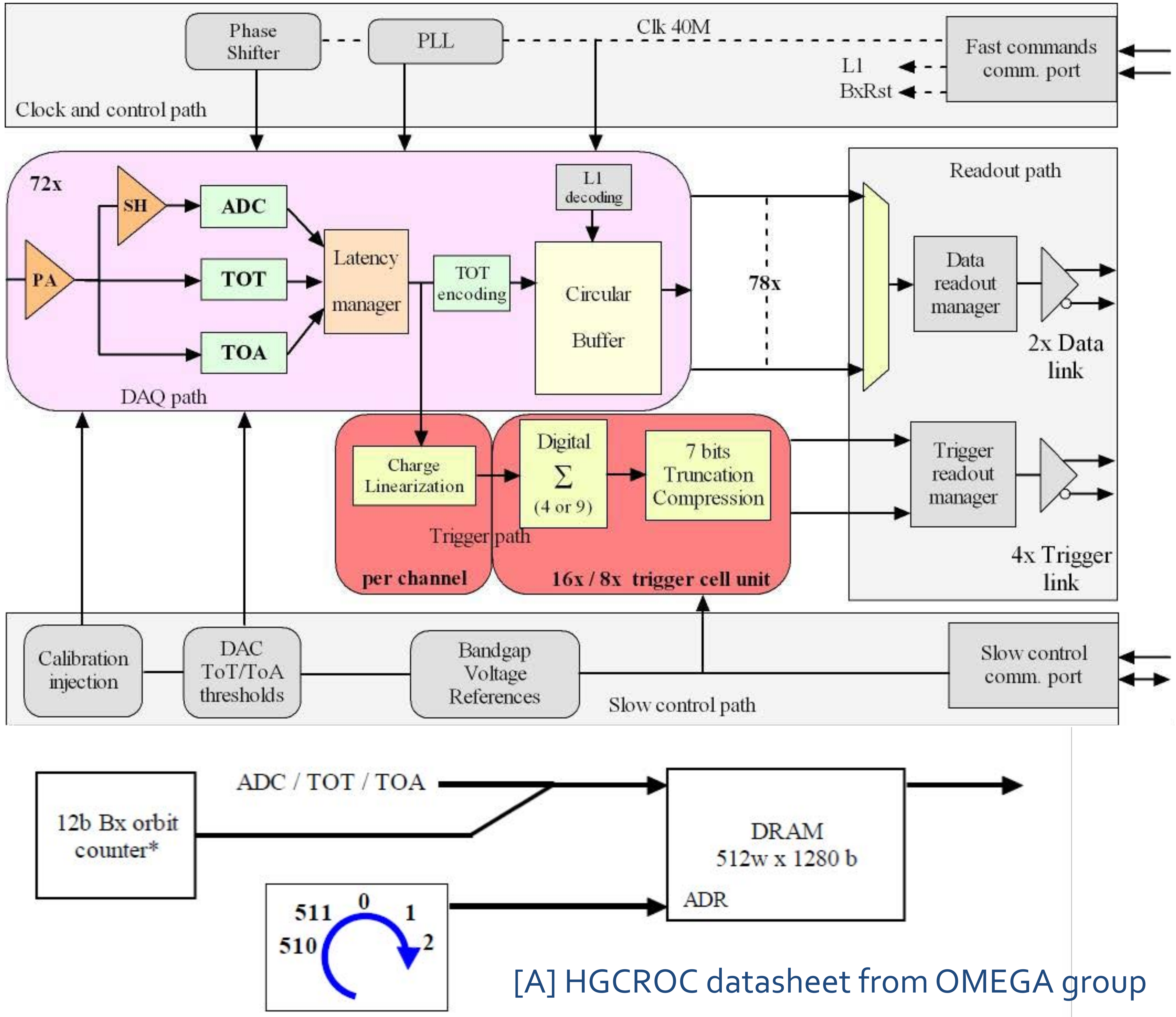
1.1 m long: ~6 λ_I

Tower size: 2-5 cm

~1k towers

HGCROC description

- 72 channels + 4 channels for common mode subtraction + 2 special calibration channels
- 32b Digital Data continuously stored in 512 length DRAM @40MHz
  - 72 ch. x 32b x 40MHz: **huge data volume**
  - ➔ Only **Local-L1-triggered** data are read out
- Idle packet is continuously sent out when no L1-trigger is activated
- The data processing for the trigger "information" path
  - 32b: 4b header + 7b x 4
  - Sum of 4 or **9 channels** depending on the sensor



[A] HGCROC datasheet from OMEGA group