# India-ALICE@CERN-LHC (selected current activities)

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# Indian group and ALICE

1993



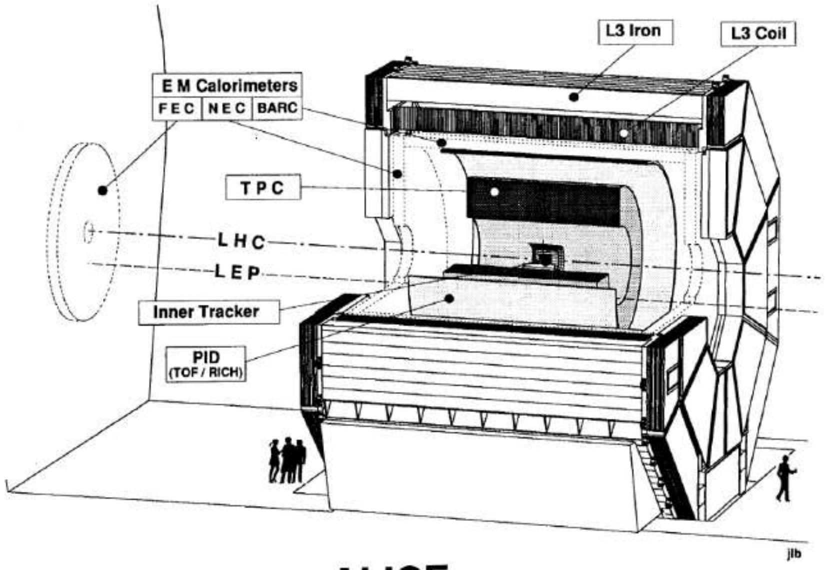
CERN/LHCC/93-16
LHCC/I 4
1 March 1993

**India founding member of ALICE**

Letter of Intent

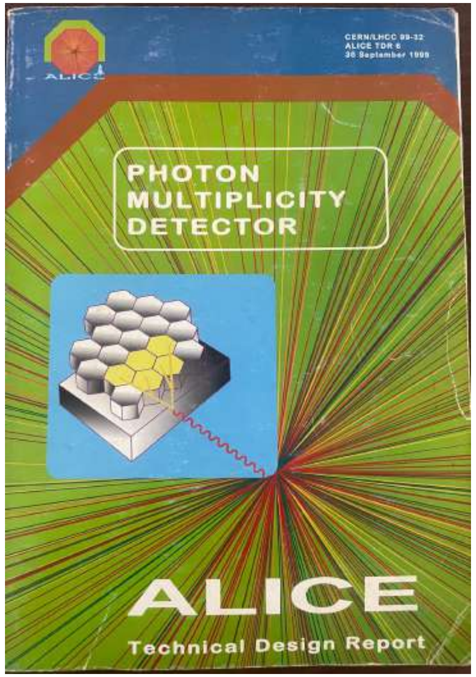
for

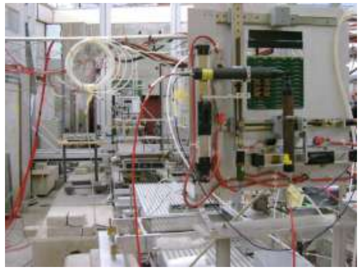
A Large Ion Collider Experiment




ALICE

1999



**Members of the ALICE Collaboration**

**Athens, Greece,** Nuclear and Particle Physics Division, University of Athens:
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**Bari, Italy,** Dipartimento di Elettronica ed Elettrotecnica del Politecnico and Sezione INFN:
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**Frankfurt, Germany,** Institut fur Kernphysik der Universität:
D. Ferenc[1], M. Gaździcki, R. Renfordt, D. Röhrich, R. Stock, H. Ströbele and S. Wenig.

**Geneva, Switzerland,** Universitè de Geneve:
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**Heidelberg, Germany,** Max Plank Institut:
P. Wurm.

# India-ALICE

India-ALICE@CERN-LHC funded by DAE-India and DST-India

सत्यमेव जयते
Department of Science and Technology
Ministry of Science and Technology
Government of India

ALICE Collaboration ALICE RRB-D 00-41

The European Organization for Nuclear Research (CERN)

and

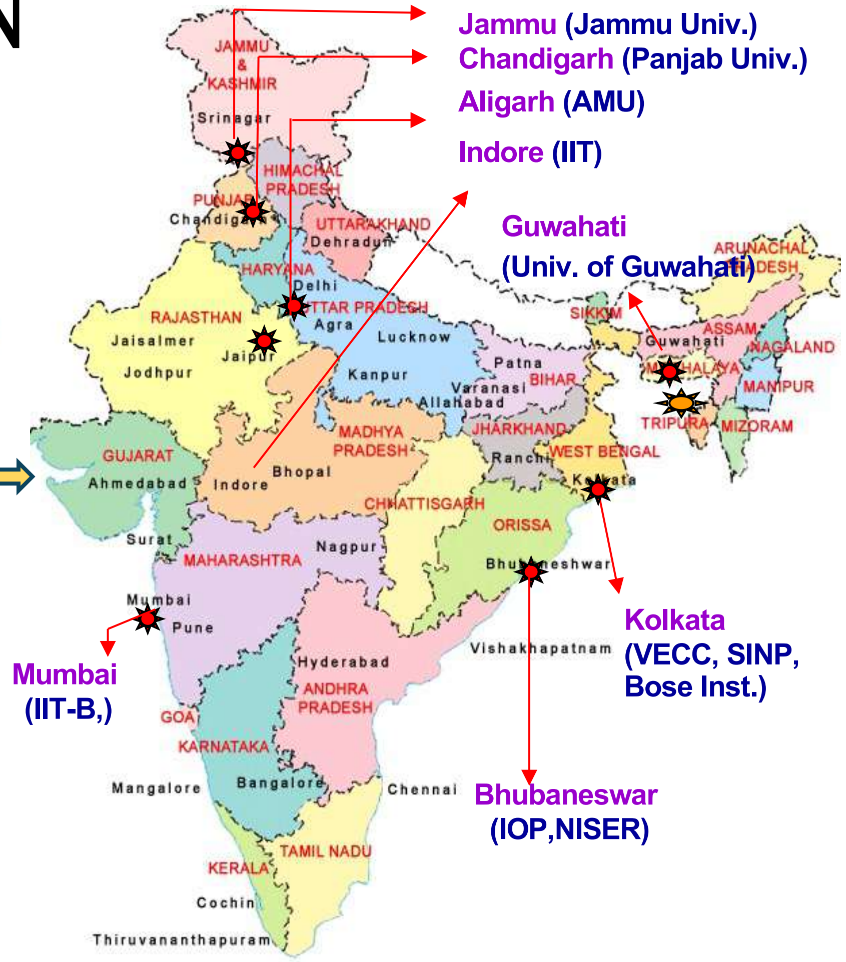
Department of Atomic Energy, Mumbai

declare that they agree on the present Memorandum of Understanding for the ALICE Experiment.

| | |
|---|---|
| Done in Geneva, | Done in ..........Mumbai...... |
| 30th June, 2000 | 16th August 2000 |
| For CERN | For Department of Atomic Energy. |
| R.J. Cashmore | R. Chidambaram |
| R.J. Cashmore | डॉ. आर. चिदंबरम / Dr. R. CHIDAMBARAM |
| Director of Research | सचिव / Secretary, परमाणु ऊर्जा विभाग, Department of Atomic Energy, भारत सरकार / Government of India, सी. एस. एम. मार्ग, बम्बई-400 039. C.S.M. Marg, Bombay-400 039. |

31/05/2000 9/9 Memorandum of Understanding

# India-ALICE-CERN




39 countries, 164 institutes, 1917 members

about 1000 signing authors

India in ALICE

- 125+ members
- 50+ Ph.D. scientists
- 35 authors

India is a major partner in ALICE since its inception.

Largest non-European participation

Indian Institutes in ALICE

1. Kolkata: VECC
2. Kolkata: SINP
3. Kolkata: Bose Institute
4. Kolkata: University of Calcutta*
5. Kolkata; Jadavpur University*
6. Aligarh: Aligarh Muslim University
7. Bhubaneswar: Institute of Physics
8. Bhubaneswar: NISER
8. Chandigarh: Panjab University
9. Guahati: University of Guahati
10. Indore: IIT
11.Jammu: University of Jammu
12. Mumbai: IIT, Bombay
13. IISER Berhampur*
14. University of Kashmir-Srinagar*
15. Central University of Tamil Nadu*
16.Cooch Behar Panchanan Varma University-Coochbehar *
17. Mumbai: BARC*

* Associate members

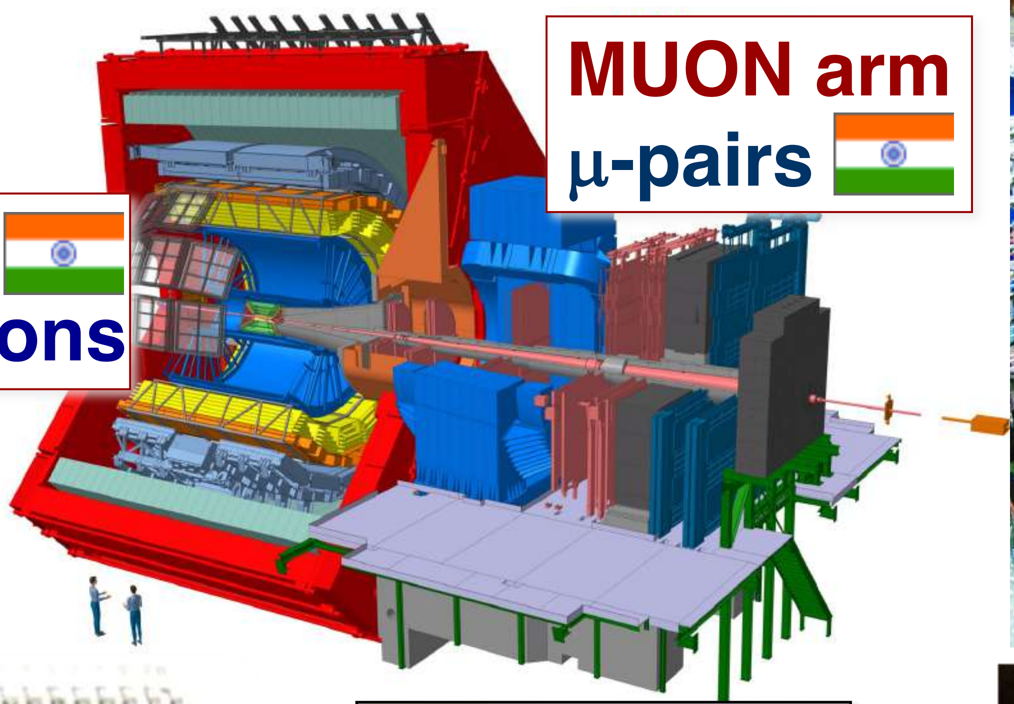
# India participation in ALICE-physics @CERN-LHC

Study of quark gluon plasma and its properties
Involvement in almost all physics working groups

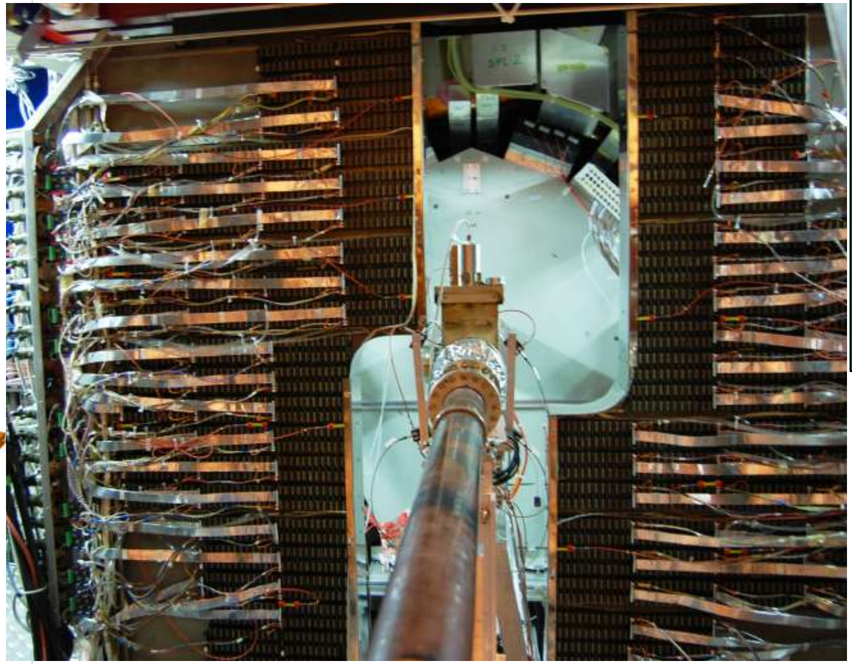
| Physics WG | ~ Indians involved | Analysis work carried out by Indian groups |
|---|---|---|
| PWG-MM | 8 | Analysis of the PMD data |
| PWG-CF | 14 | EbyE fluctuations, higher moments, intermittency, Particle correlations, Flow, and HBT |
| PWG-LF | 18 | Spectra, All hadronic resonances: $K^*$, $\varphi$, $\Lambda*$, … Nuclei and exotica |
| PWG-DQ | 10 | $J/\psi$ production, Inclusive production of Upsilon(1S), Upsilon(2S) and Upsilon(3S) Heavy Flavour muons |
| PWG-JE | 5 | Jet shape, jet properties |
| PWG-GA | 2 | Neutral pions, isolated photons |
| PWG-HF | 18 | Hadronic decays of heavy flavour Heavy flavour leptons Correlations and jets |

# India participation in ALICE-detector@CERN-LHC

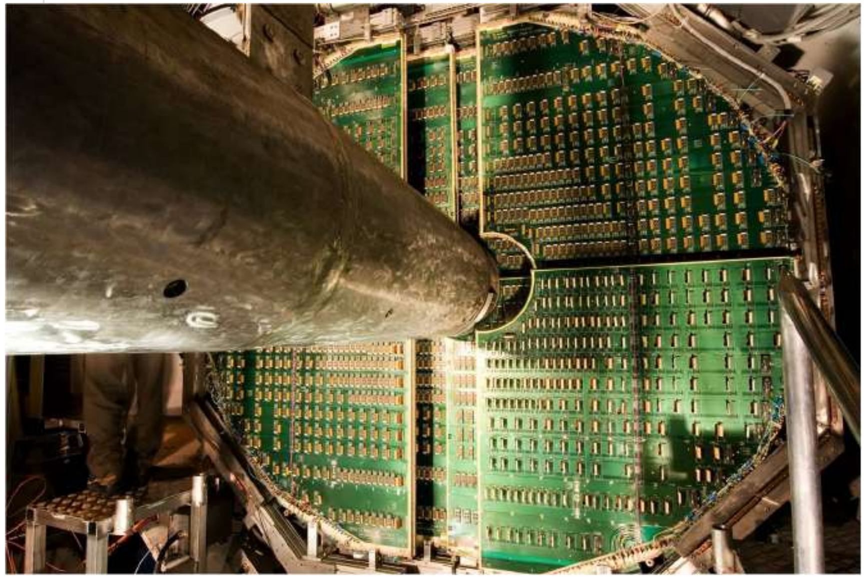
**PMD**
**photons**

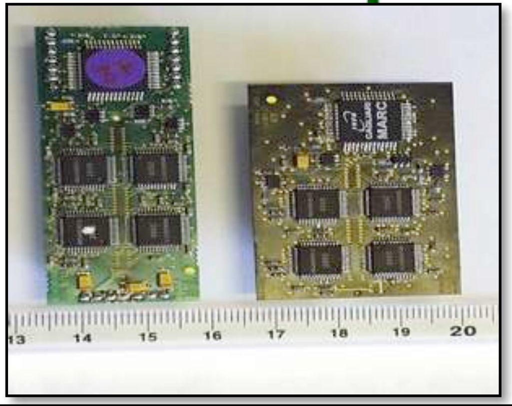


**MUON arm**
**μ-pairs**



PMD: 100 % Indian effort: from conception to commissioning (design, fabrication, installation, controls, DAQ)
48 Modules with 221,184 gas cells



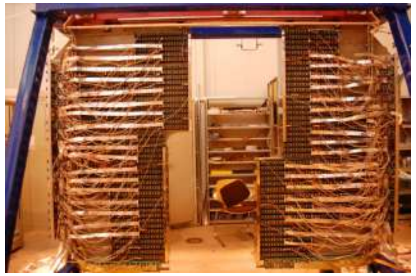
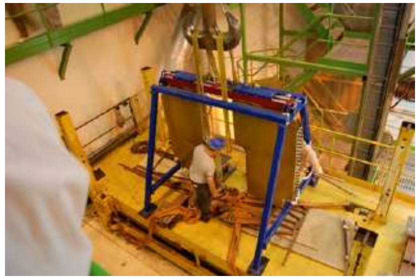
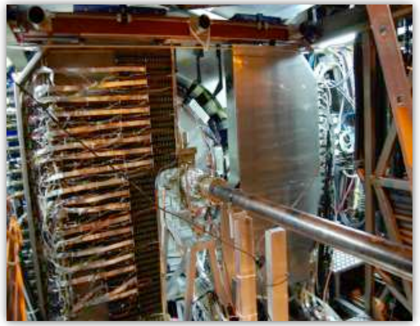
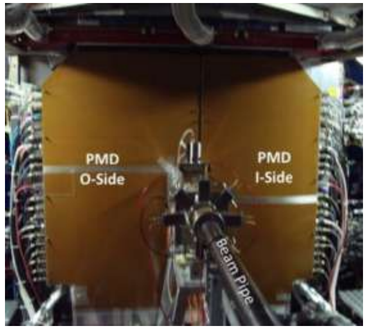



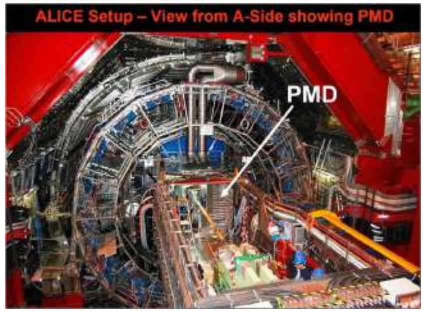
Station-2 of Muon arm Collaboration France, India, Italy and Russia
Cathode Pad Chambers ~100m$^2$
1.1x10$^6$ channels, occupancy < 5% (in Pb+Pb)
Read out rate:1 kHz
Chamber material thickness: ~ 3% X0
Spatial resolution: ~50 μm

MANAS: 16-channel shaping-amplifier and track-and-hold
MANU board: readout of 1.1 million-channel
First large-scale production of ASICs in India

## PMD Commissioning - August 2008



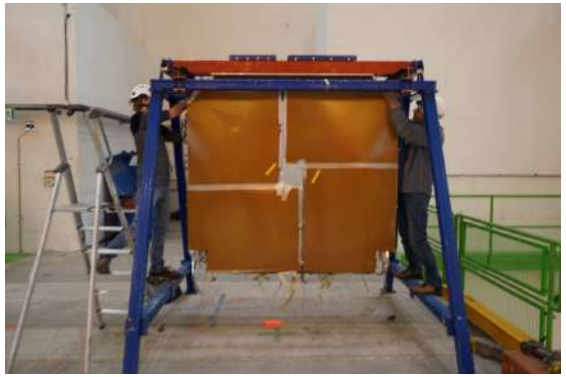





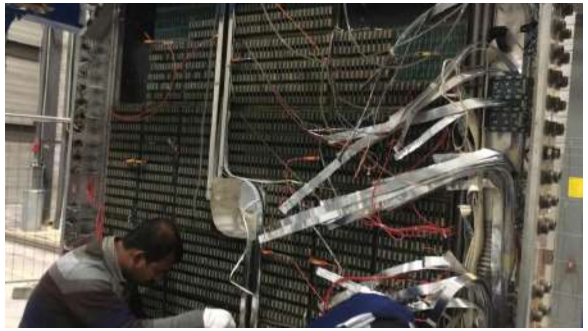
*Placing on record thanks to ALICE:*

- Technical Coordination
- Run Coordination
- Offline Coordination
- Physics Coordination
- ALICE Management

## PMD De-commissioning - December 2018

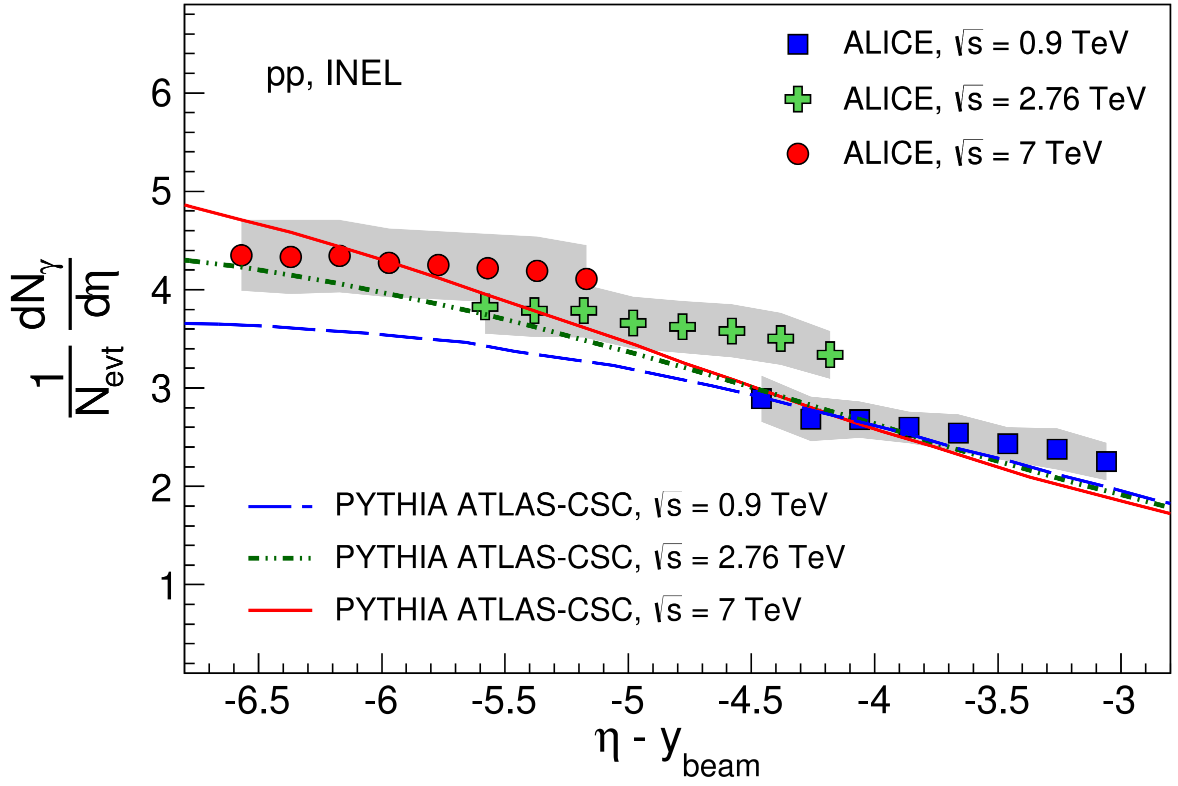


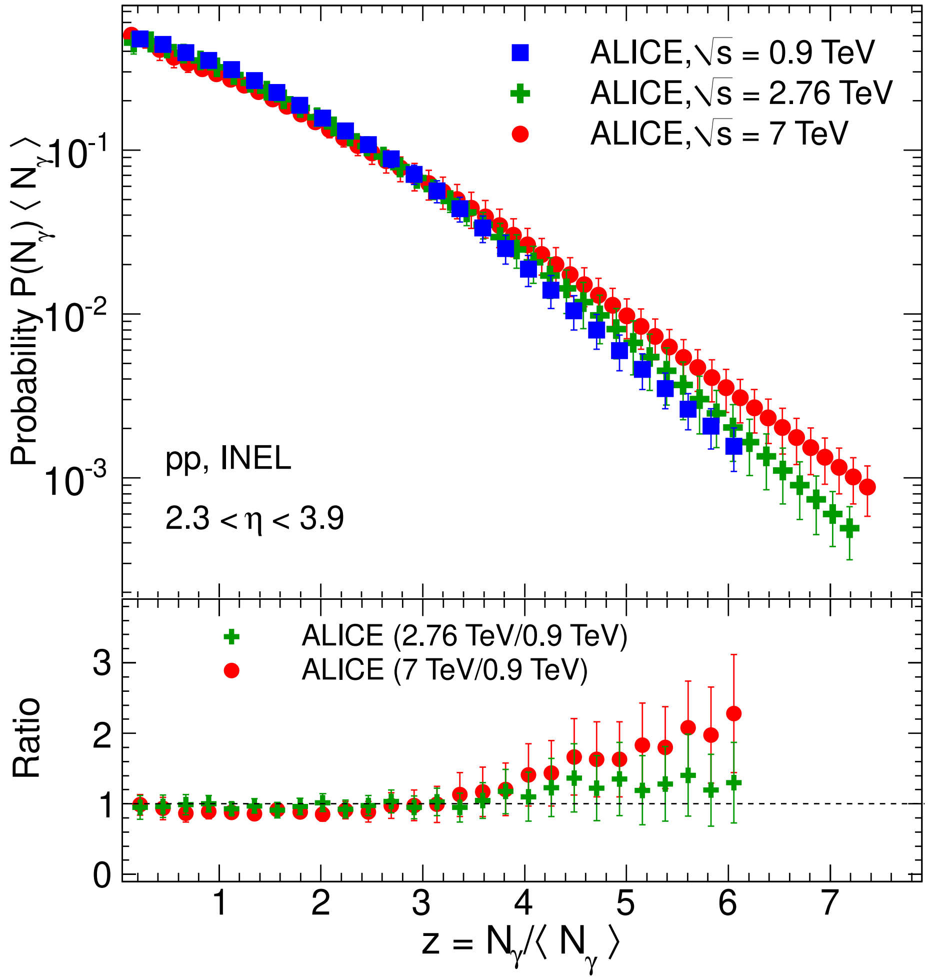





# Physics publications from PMD so far (1)

Inclusive photon production at forward rapidities in proton-proton collisions at $\sqrt{s}$ = 0.9, 2.76 and 7 TeV, ALICE, EPJC 75 (2015) 146

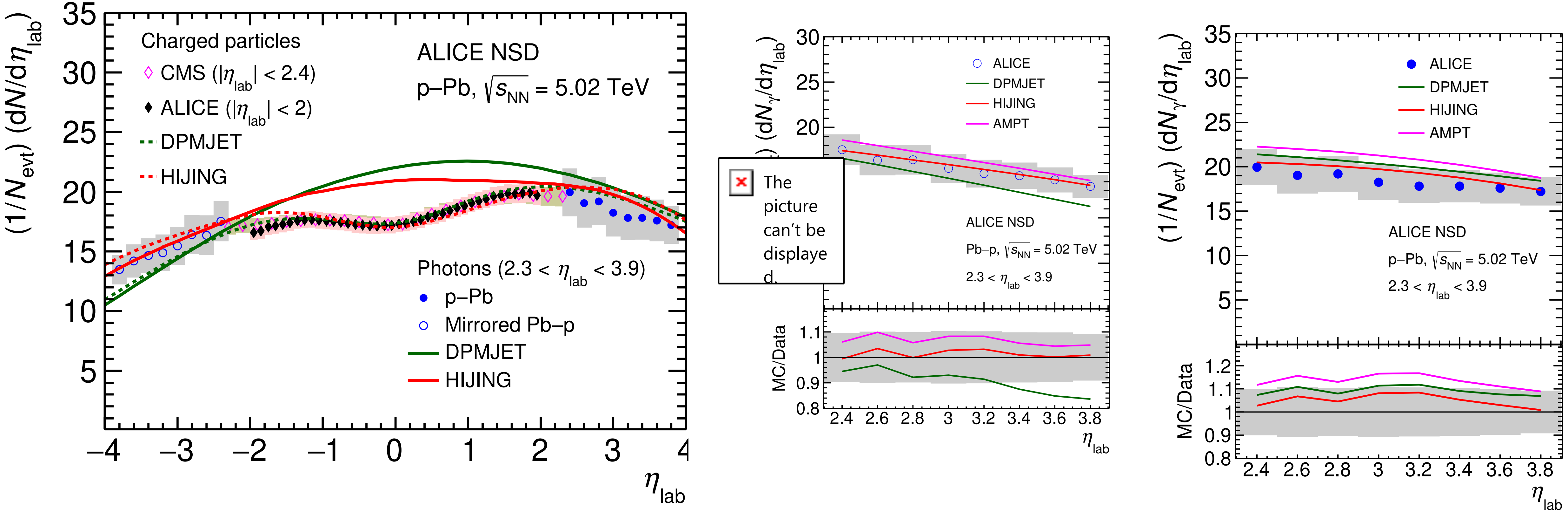



Hints of violation of longitudinal scaling and KNO scaling

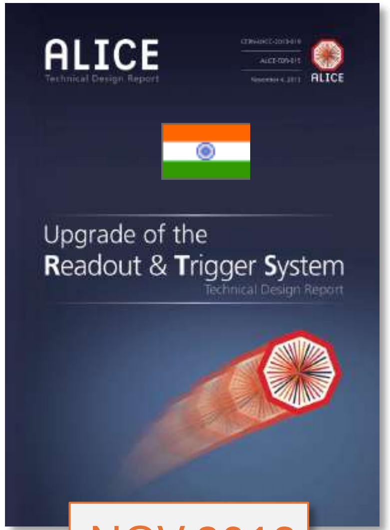
# Physics publications from PMD so far (2)

Inclusive photon production at forward rapidities in pp and p−Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV, ALICE, Eur. Phys. J. C 83 (2023) 661




These results of inclusive photon production in pp and p–Pb collisions provide important input for the tuning of theoretical models and MC event generators and help to establish the baseline measurements to interpret the Pb–Pb data.

# India participation in ALICE-2.0@CERN-LHC




NOV 2013


MAR 2014


MAY 2015

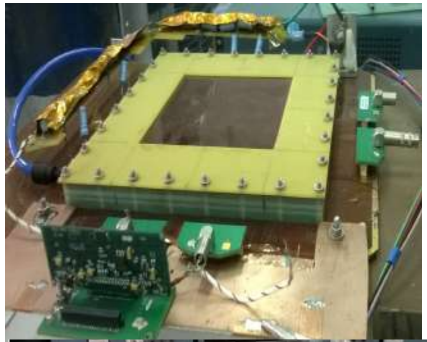
<u>Indian contribution</u>

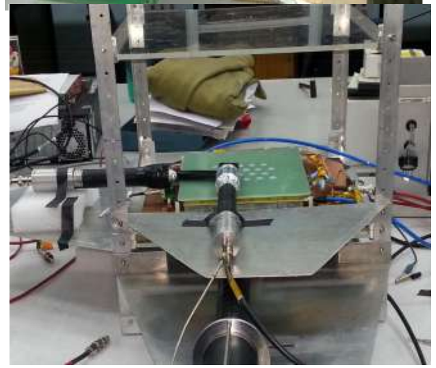
- Common Readout Unit (CRU)
- TPC – GEM detectors
- Muon Forward Tracker (MFT)

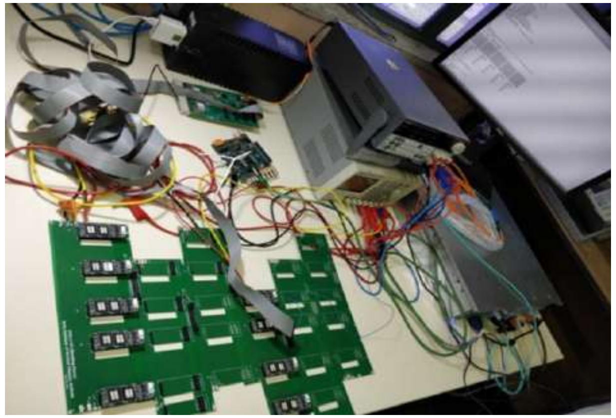
Dec 2016 - PCIe40 BOARD IMAGES, First PCB@VECC

May 12, 2017: First CRU Board@VECC

GEM detector for ALICE TPC



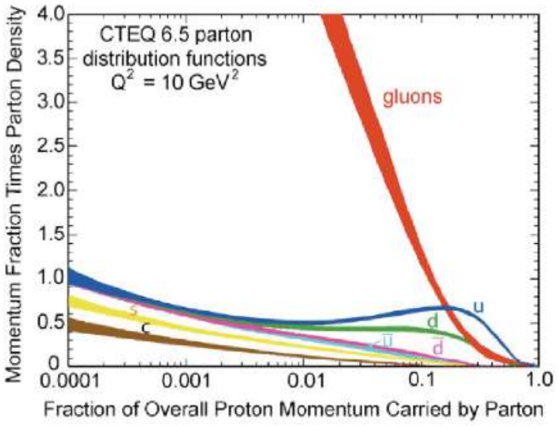




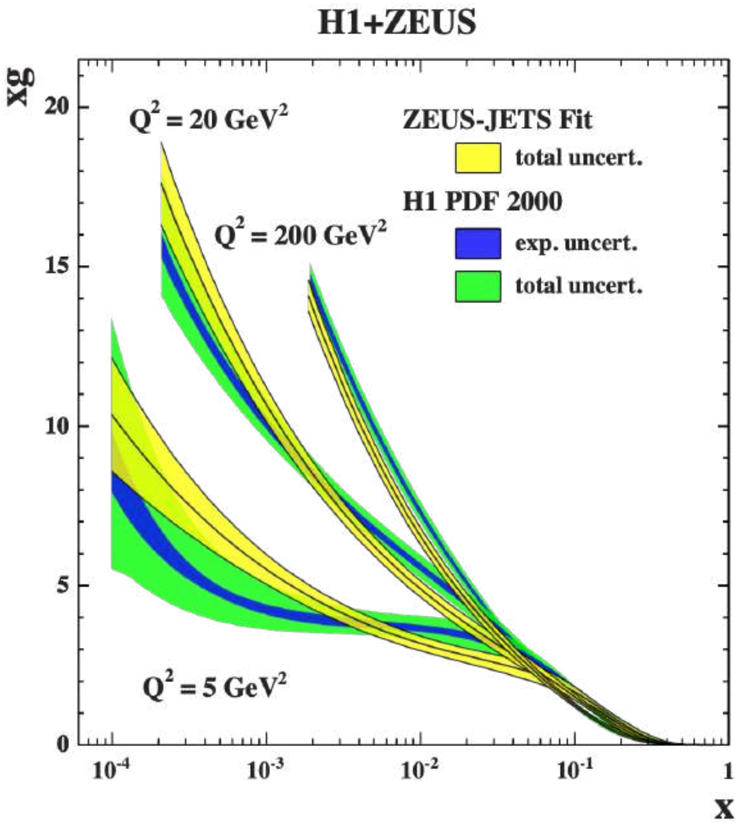
Test set-up at SINP for one PCB segment of the readout mother-board of 2nd Muon Tracking station of ALICE

A full readout motherboard being tested and validated at CERN. Each motherboard has has 7 segments and 18 such motherboards designed indigenously and fabricated in India

# Physics with forward region in ALICE




Low-x parton distribution function and gluon saturation



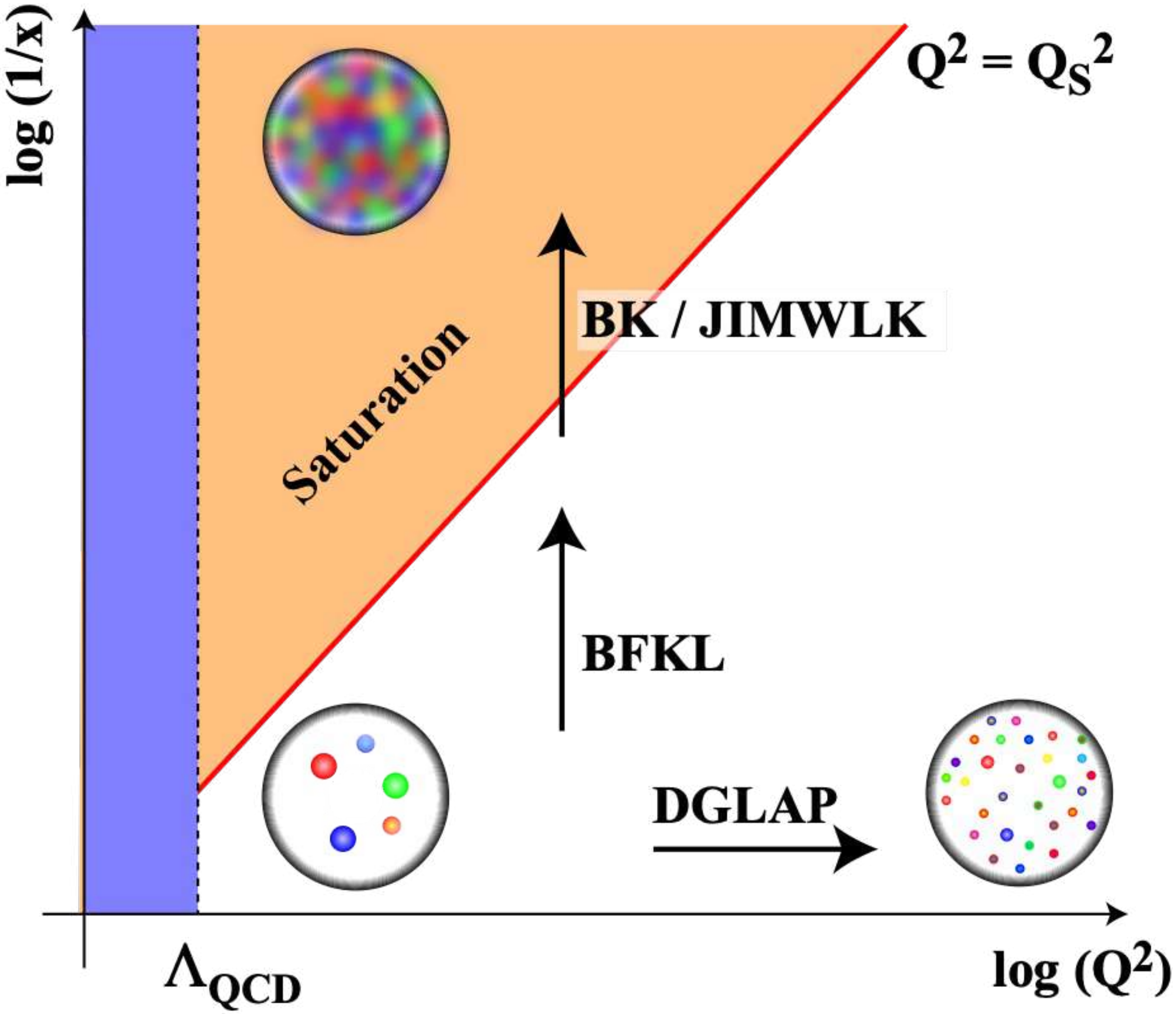

- low-x structure of protons and nuclei essentially unconstrained experimentally
- gluon density increases with $Q^2$ and $1/x$
- leads to very high gluon density
- problems with unitarity(?)

Gluon saturation

# Physics with forward region in ALICE

Low-x parton distribution function and gluon saturation

*Nucl. Phys.* B188 (1981) 555–576
*Nucl. Phys.* B268 (1986) 427–452




from evolution equations (DGLAP, BFKL):

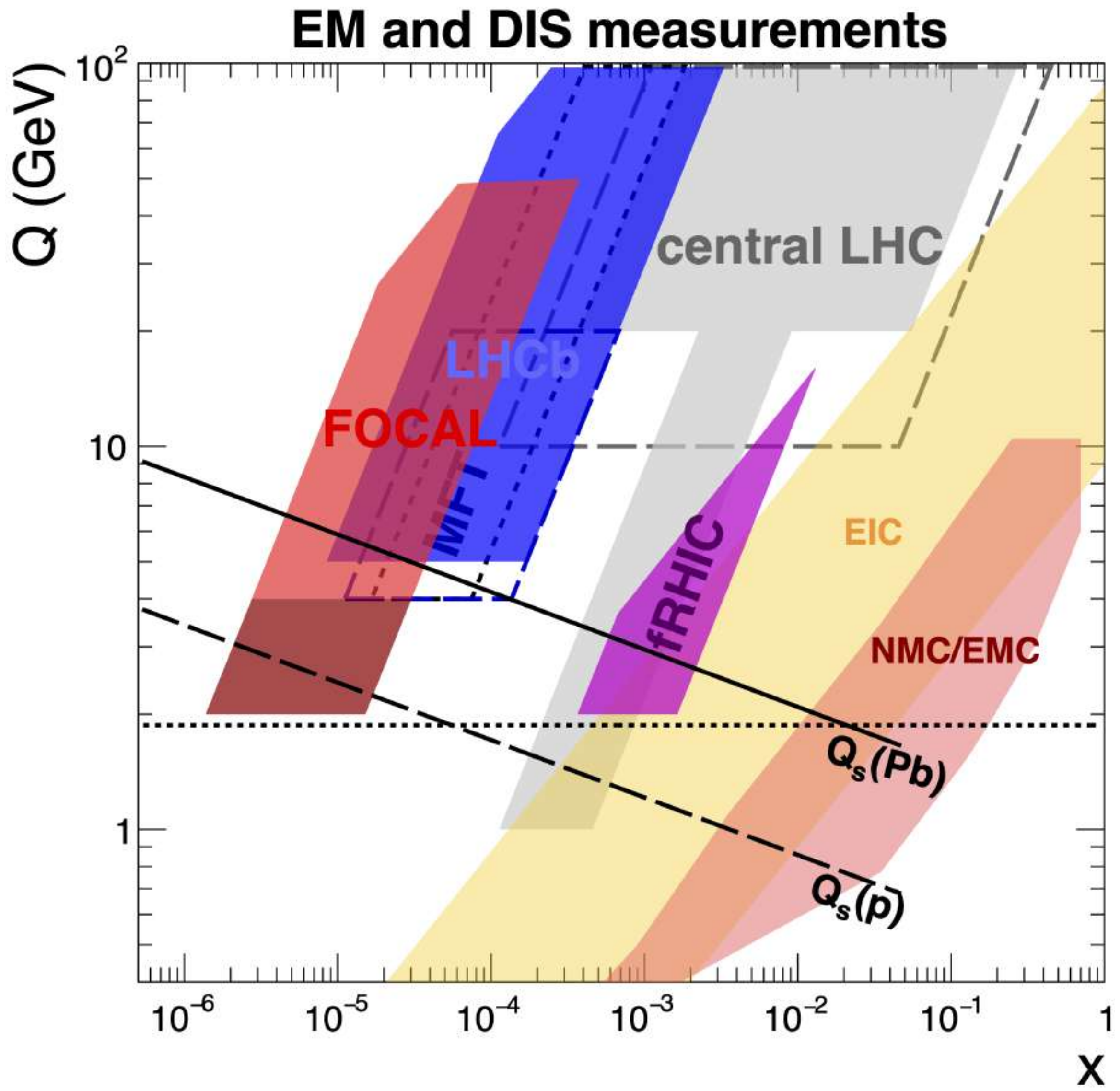
- for high density non-linear processes become important
- gluon saturation below saturation scale
- enhanced in nuclei

$$Q_s^2(x) \approx \frac{\alpha_S}{\pi R^2} xG(x, Q^2) \propto A^{1/3} \cdot x^{-\lambda}$$

No proof of non-linear dynamics yet

# Physics with forward region in ALICE

Low-x parton distribution function and gluon saturation




**Observables:**

– **inclusive isolated photon production**

– **isolated photon+jet** (same as inclusive isolated photons)

– **inclusive jets**

– **dijet photoproduction in UPCs**

– **cross section ratios of J/ψ and ψ(2*S*) production on ion vs. on proton targets in UPCs**

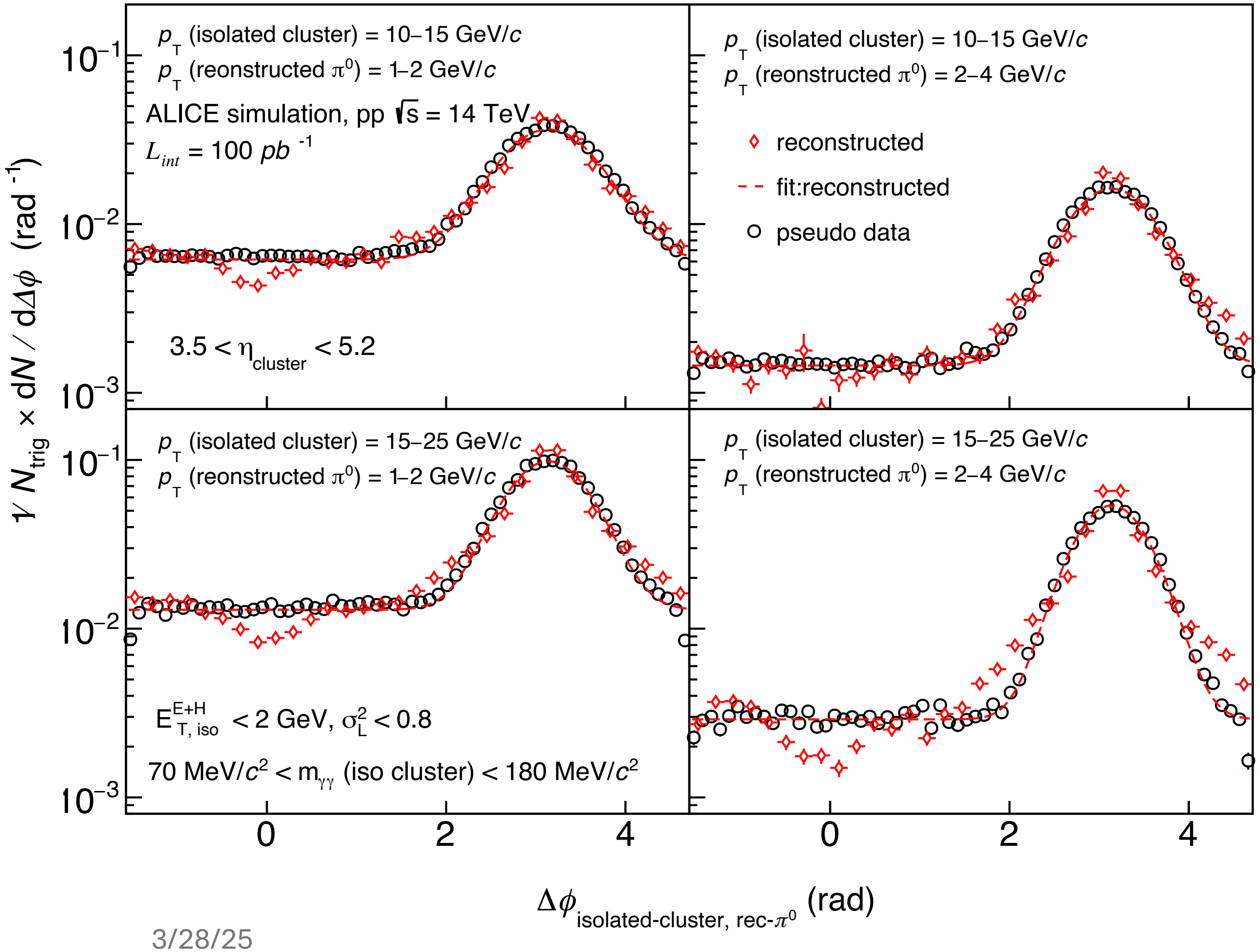
– **γ-$\pi^0$ correlation**: calculation of the partonic-level process only requires the dipole cross section, but the $\pi^0$ Fragmentation Function presents an additional uncertainty which is harder to control theoretically. *This channel could be reclassified as "cleanly interpretable" if there is sufficient theoretical confidence in the $\pi^0$ FF at NLO.*

– **dijets and dihadrons**: quadrupole evolution at NLO needs to be constructed and solved. This is doable in principle but is numerically complex- a dedicated theory effort is needed.

– **the cross section ratio for exclusive production of J/ψ and ψ(2*S*) in UPCs**. The main uncertainty is the scale dependence at NLO.

# Isolated cluster–$\pi^0$ correlation (NISER)

Azimuthal distribution of isolated cluster–$\pi^0$ correlation functions in the FoCal acceptance in pp collisions at $\sqrt{s}$ = 14 TeV.



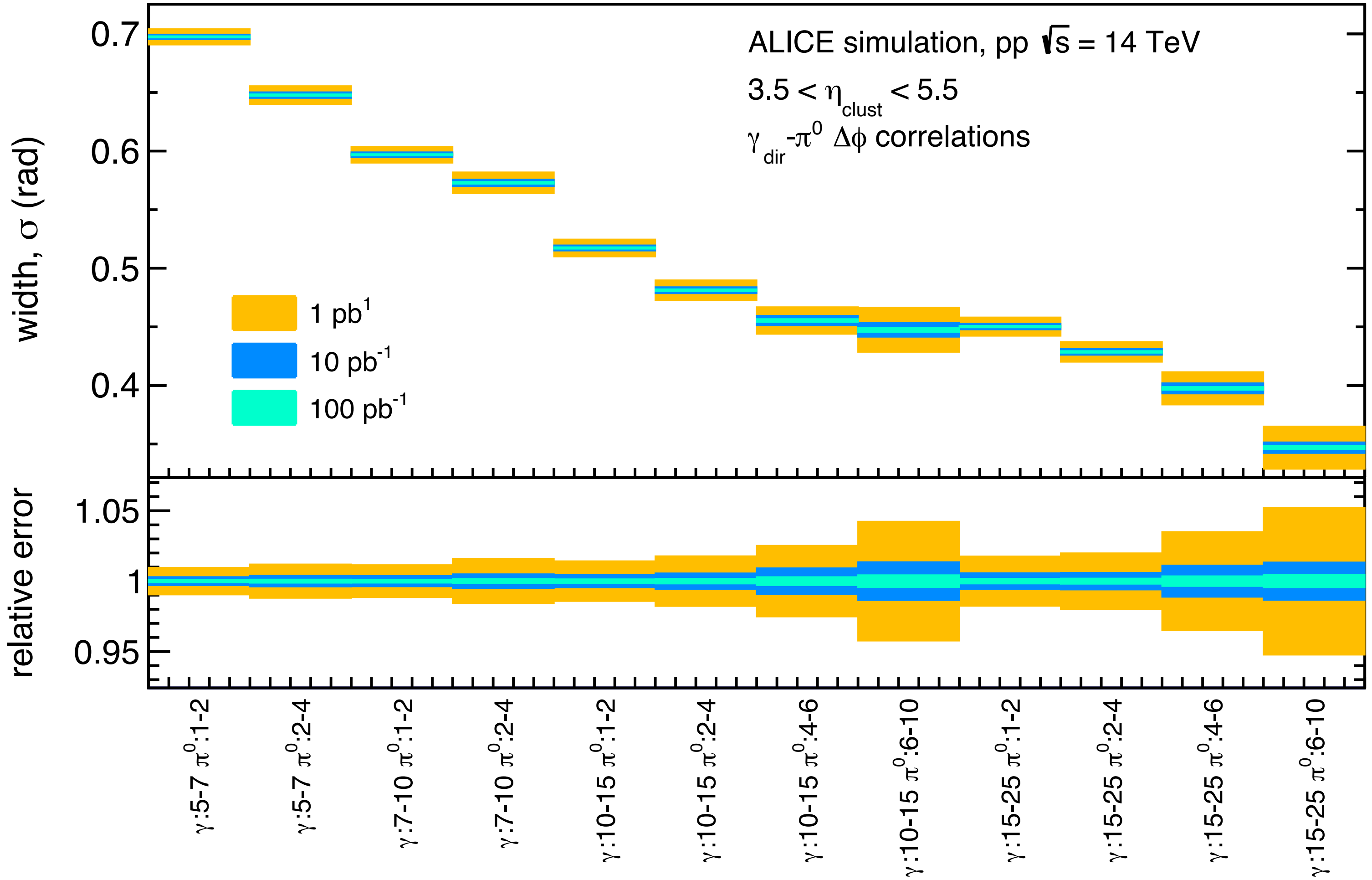

Statistical precision of this measurement for the projected Run 4 integrated luminosity, Lint = 100 pb $^{-1}$.

$$f(\Delta\varphi) = c + \frac{1}{\sigma\sqrt{2\pi}} e^{-(\Delta\varphi-\mu)^2/2\sigma^2}$$

The fit function on measured distributions used to get pseudo-data for Lint = 100 pb $^{-1}$.

The width and error are calculated from the pseudo-data.

# Estimation of the precision of width measurement (NISER)

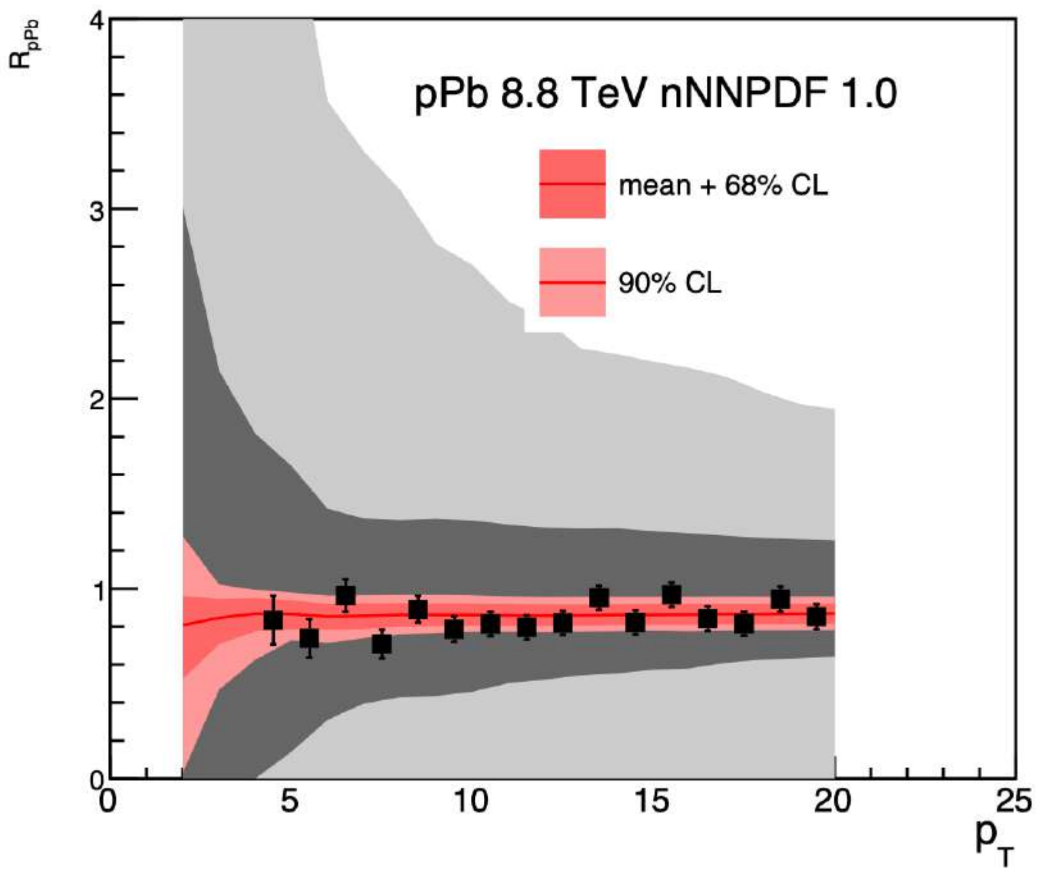



The bands in lower panel, provide estimates of the sensitivity of this measurement to modifications in the $\gamma_{dir}$–$\pi^0$ azimuthal distribution due to saturation effects for 100 $pb^{-1}$ ,10 $pb^{-1}$ , and 1 $pb^{-1}$

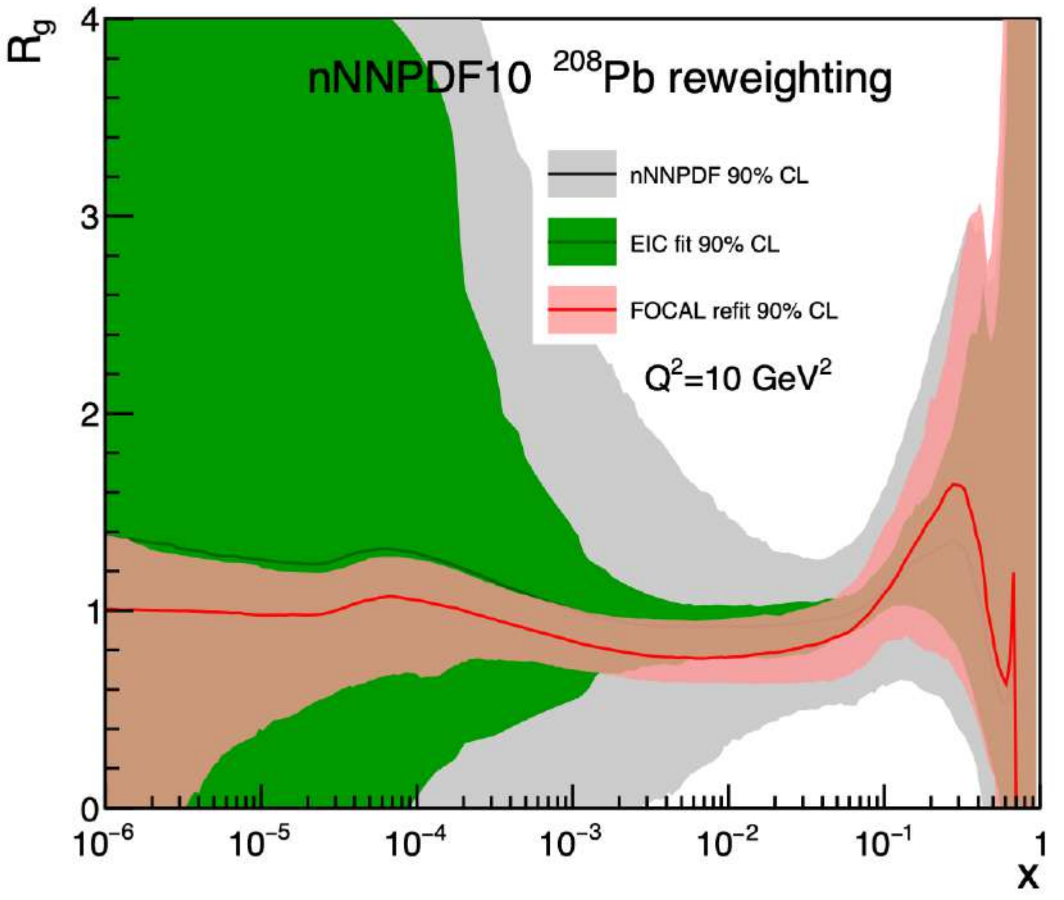
# Impact on Recent nNNPDF

M. van Leeuwen, arXiv:1909.05338, based on R. Khalek et al., arXiv:1904.00018

FoCal pseudodata with nNNPDF




Impact of FoCal refit on nNNPDF

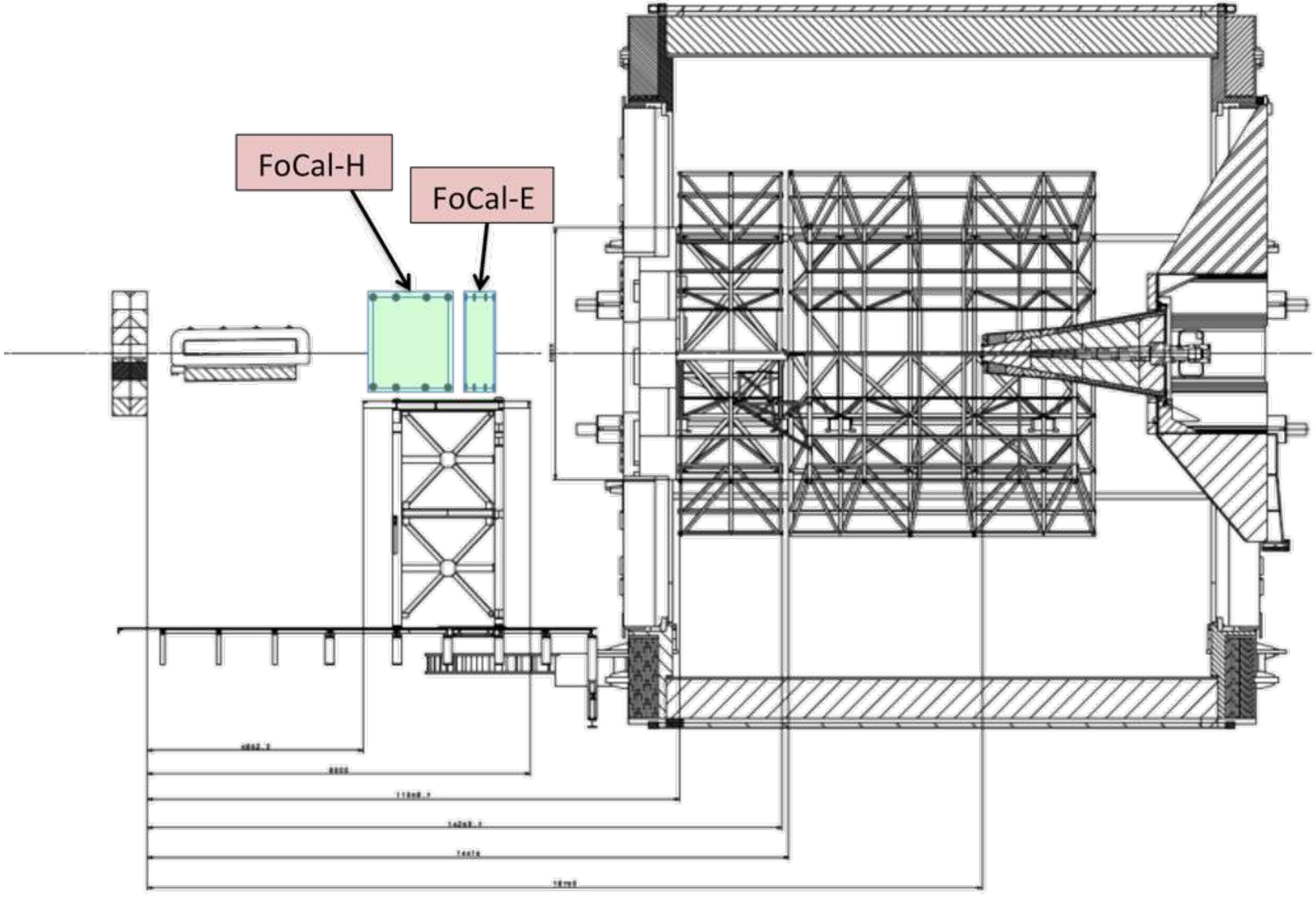



$$x \approx \frac{2p_{\mathrm{T}}}{\sqrt{s}} \exp(-y)$$

Recent nuclear PDFs: nNNPDF minimises theoretical assumptions

- No constraints on $x < 10^{-2}$ from DIS
- FOCAL provides significant constraints over a broad range of $x \sim 10^{-5} - 10^{-2}$
- Outperforming significantly the EIC in this aspect

# Forward calorimeter (FOCAL) in ALICE



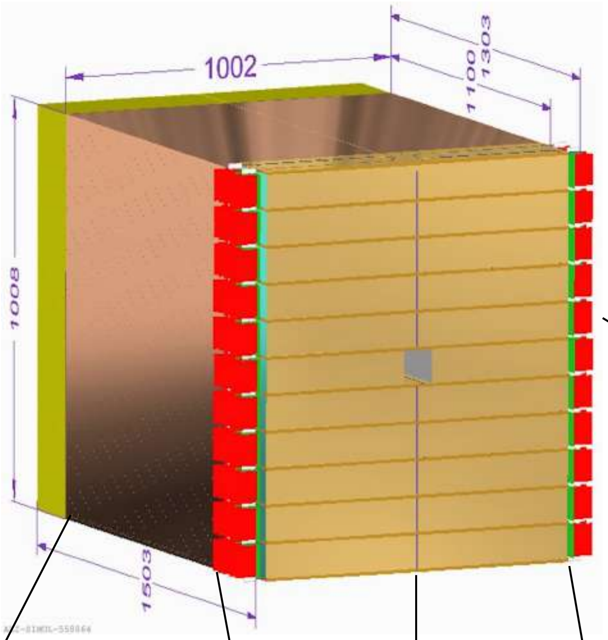

**FoCal-E**: high granularity Si-W electromagnetic calorimeter for $\gamma$ and $\pi^0$ measurement

**FoCal-H**: conventional hadronic calorimeter for isolation and jets

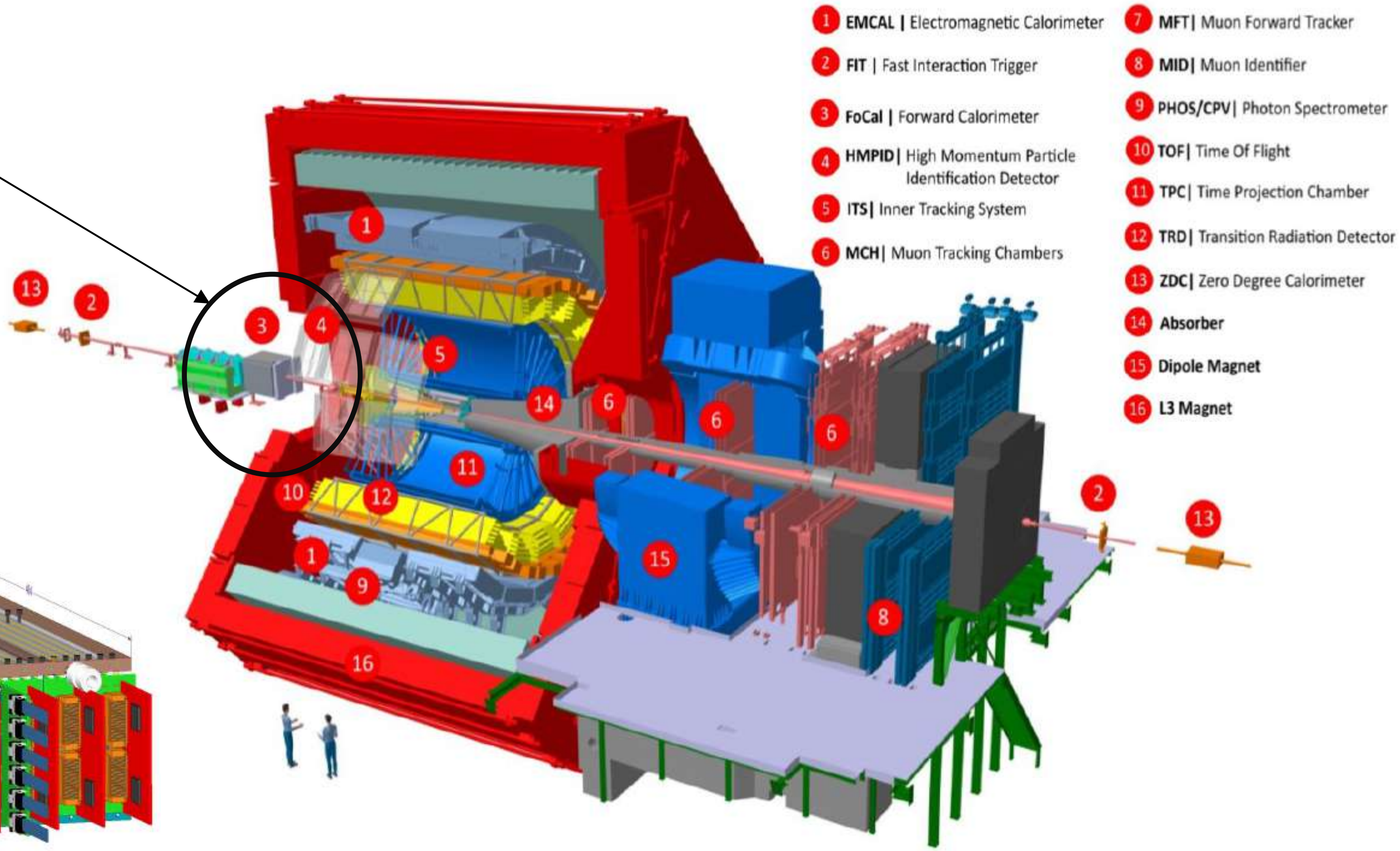
at $z \approx 7$m: $3.2 < \eta < 5.8$

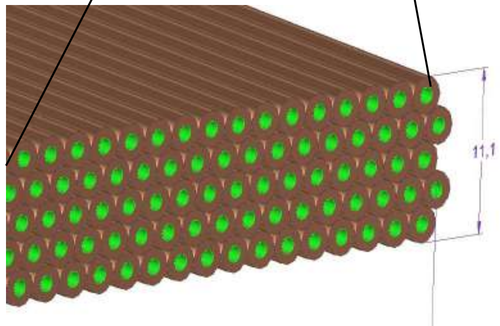
TDR approved by LHCC and RRB

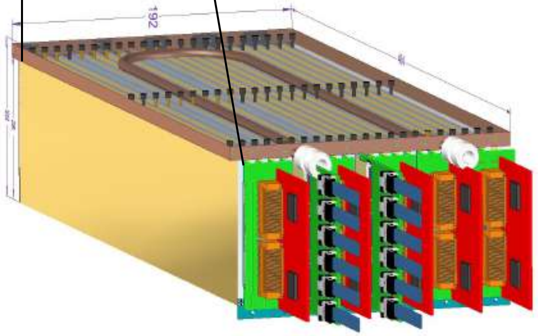
# Forward calorimeter (FOCAL) in ALICE




**3.2<η<5.8 (3.4<η<5.5)**



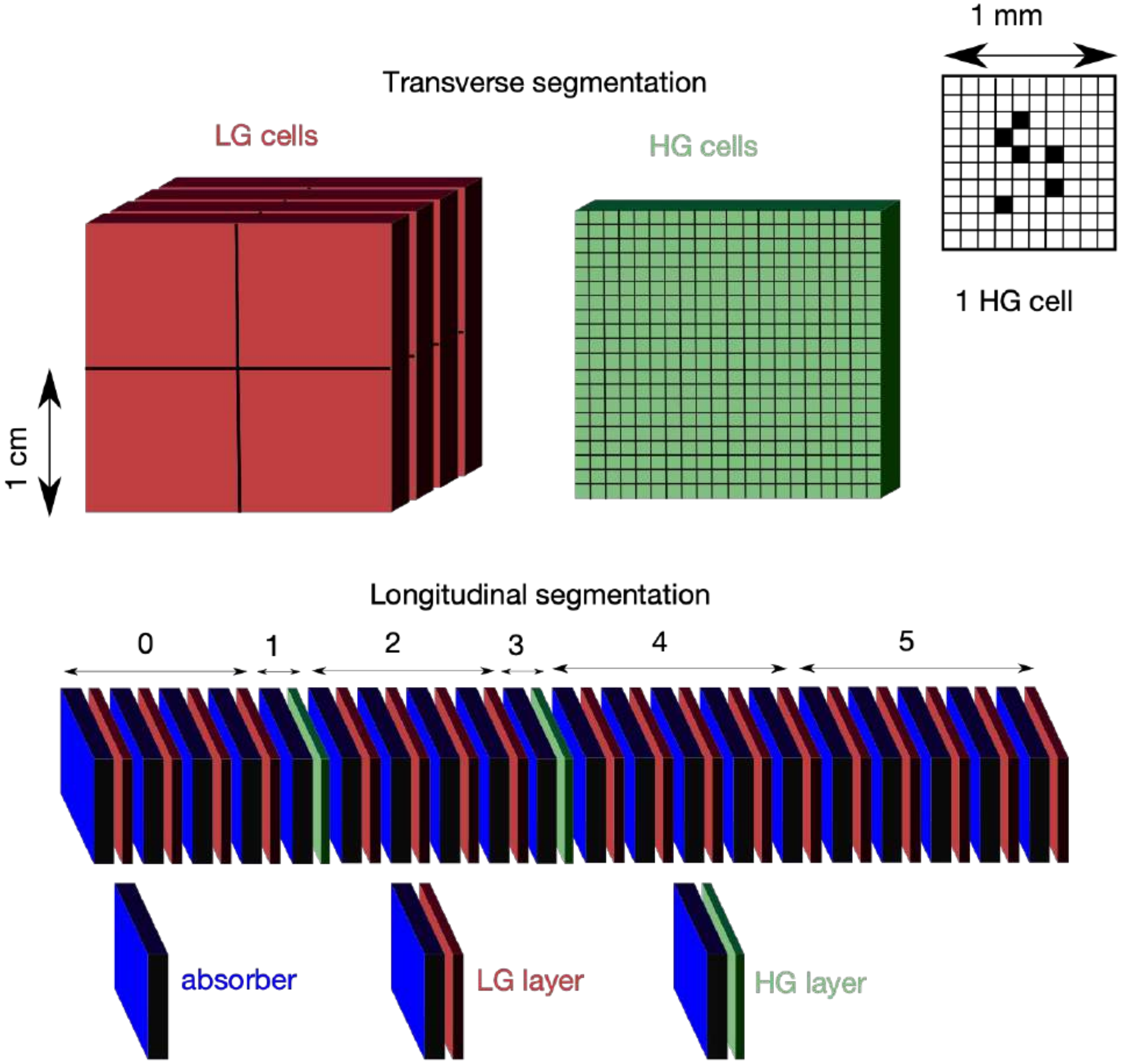




FoCal-H
Transversally segmented spaghetti calorimeter
Tot thickness ~ 6 $\lambda$had

FoCal-E

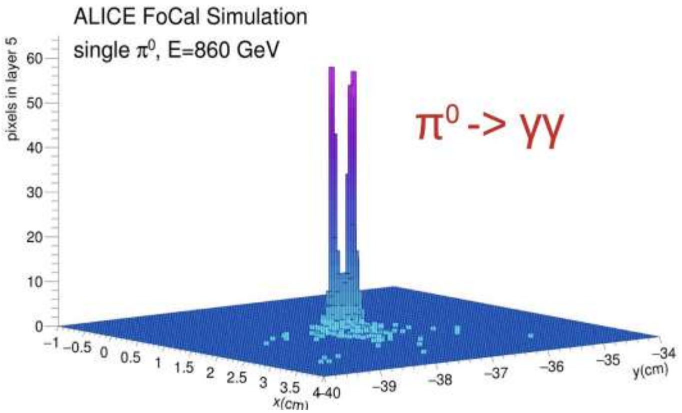
20 Layers (LG + HG Si detectors + W absorbers). Tot ( ~ 20 $X_0$)

# Forward EM-calorimeter (FOCAL) in ALICE



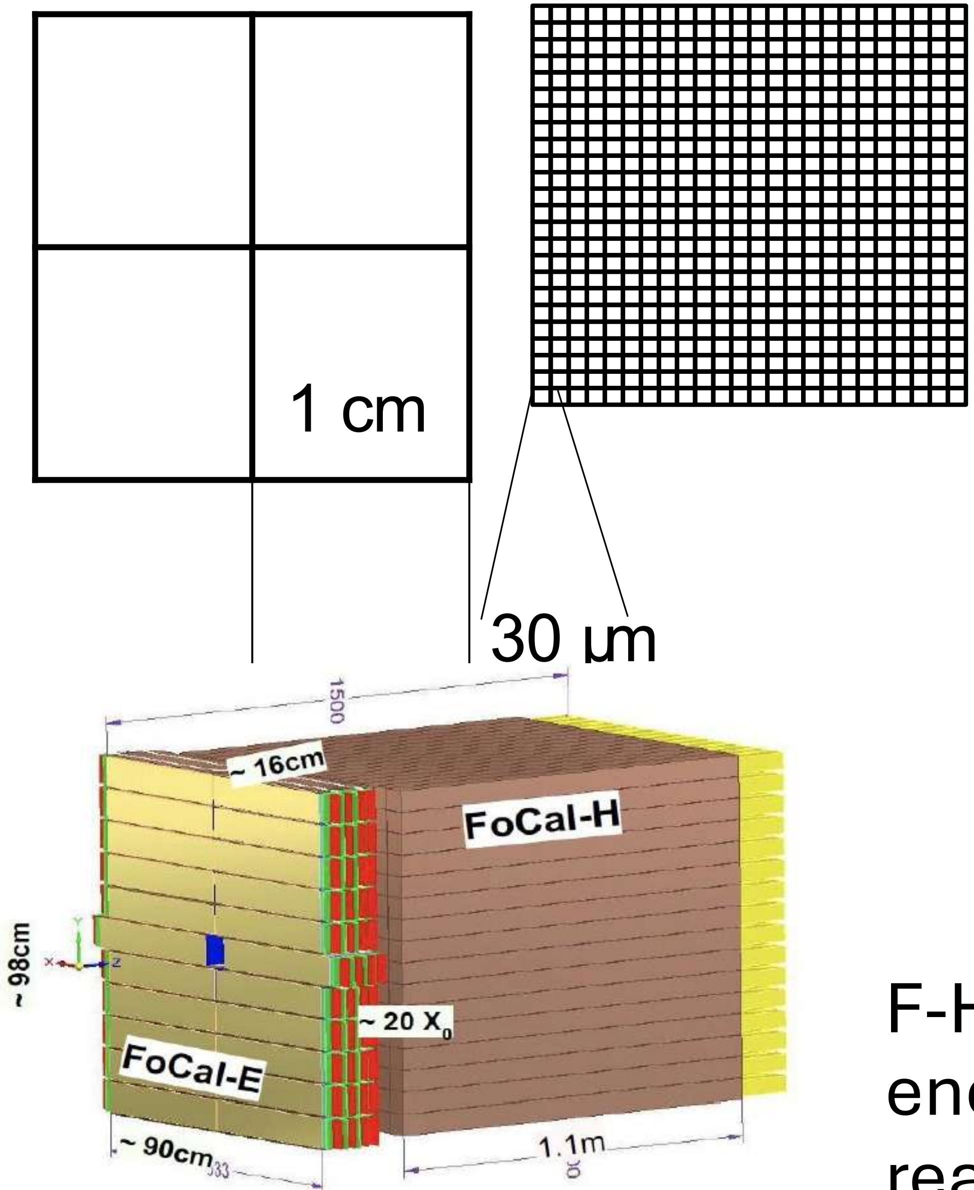

20 layers:
W (3.5mm ≈ 1 $X_0$) + Si-sensors
hybrid design (2 types of sensors)

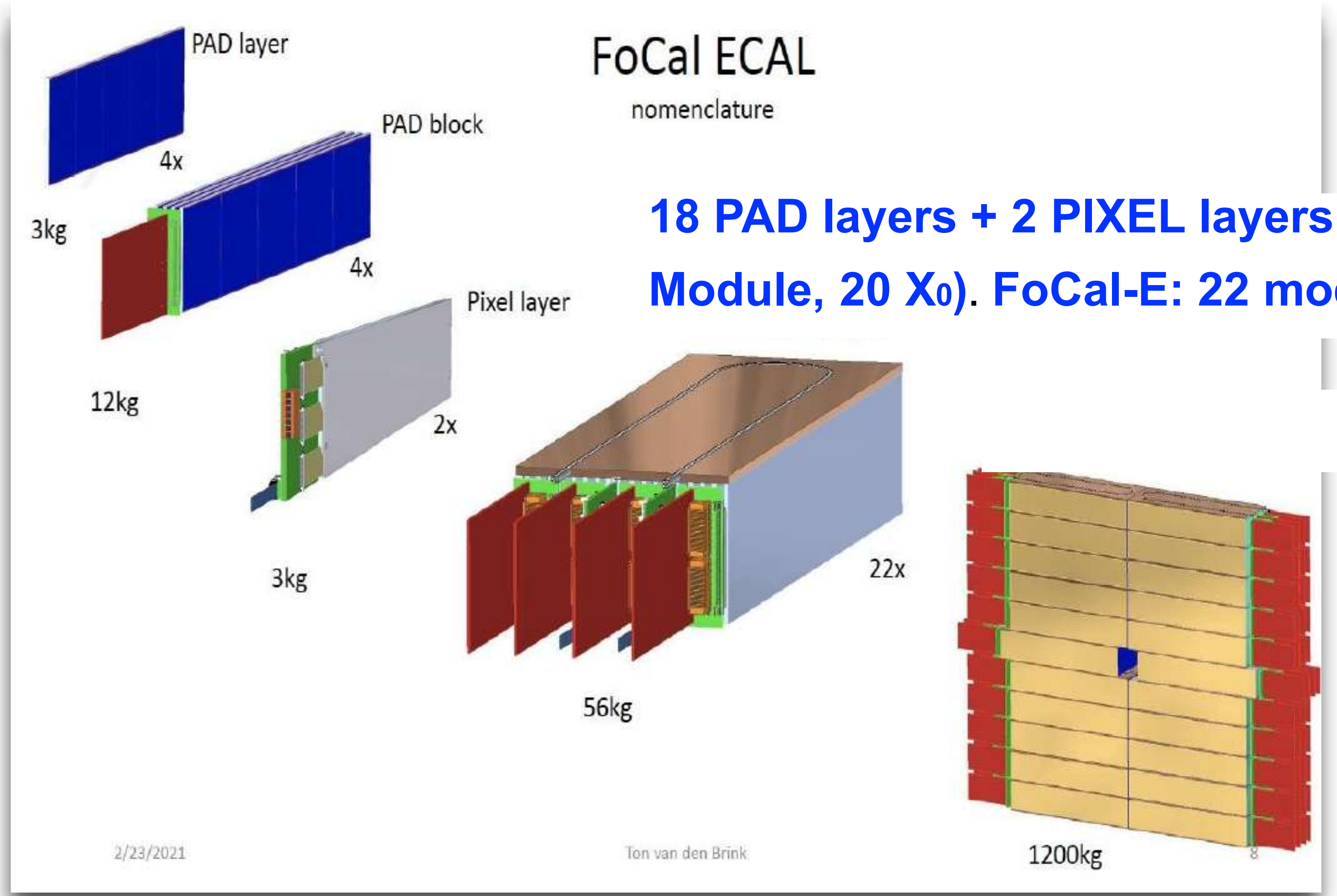
- **Si-pads** (≈ 1 cm$^2$):
  energy measurement, timing(?)
- **CMOS pixels** (≈ 30x30 $\mu$m$^2$):
  two-shower separation, position resolution



# FOCAL Design

**E-Pad** **E-Pixel**

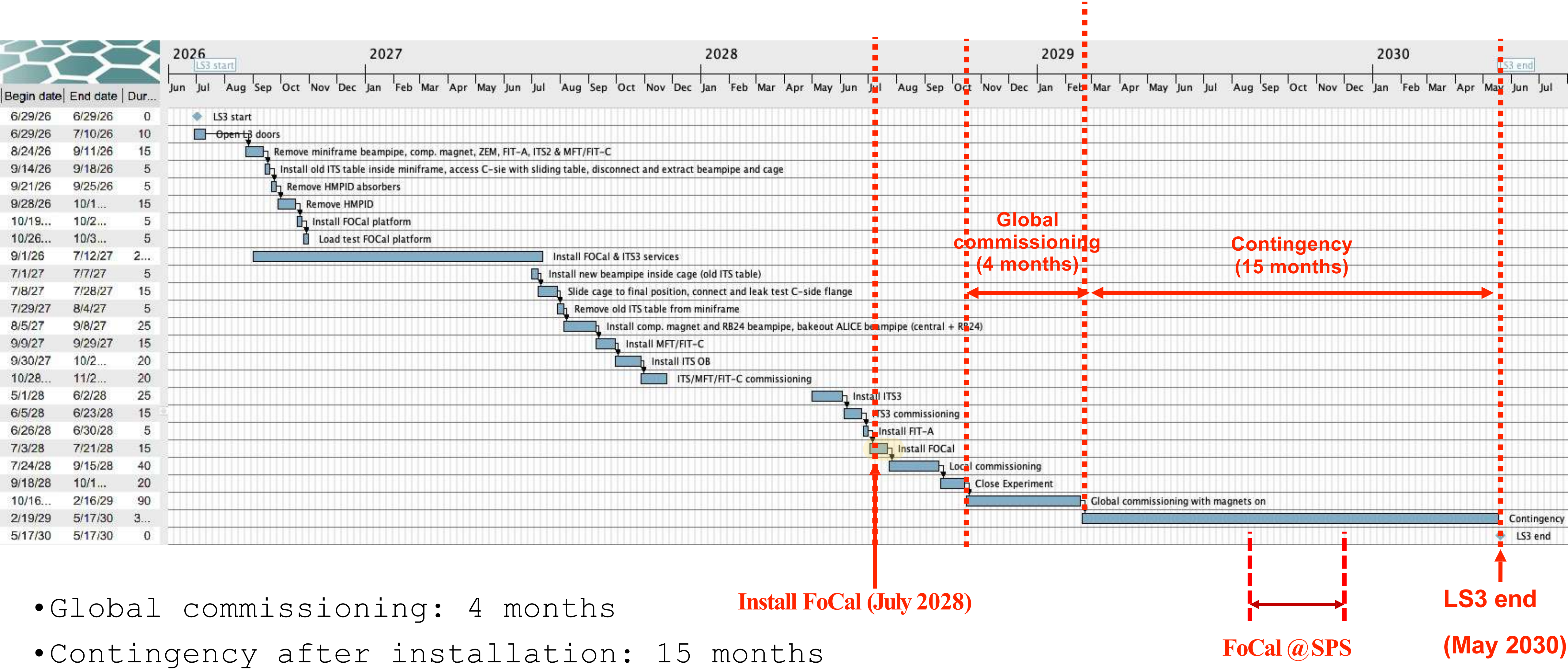



**18 PAD layers + 2 PIXEL layers ( = 1 Module, 20 $X_0$). FoCal-E: 22 modules**

F-H-Cal design: Cu capillary-tubes* enclosing BCF scintillating fibers SiPM readout

# ALICE LS3 schedule

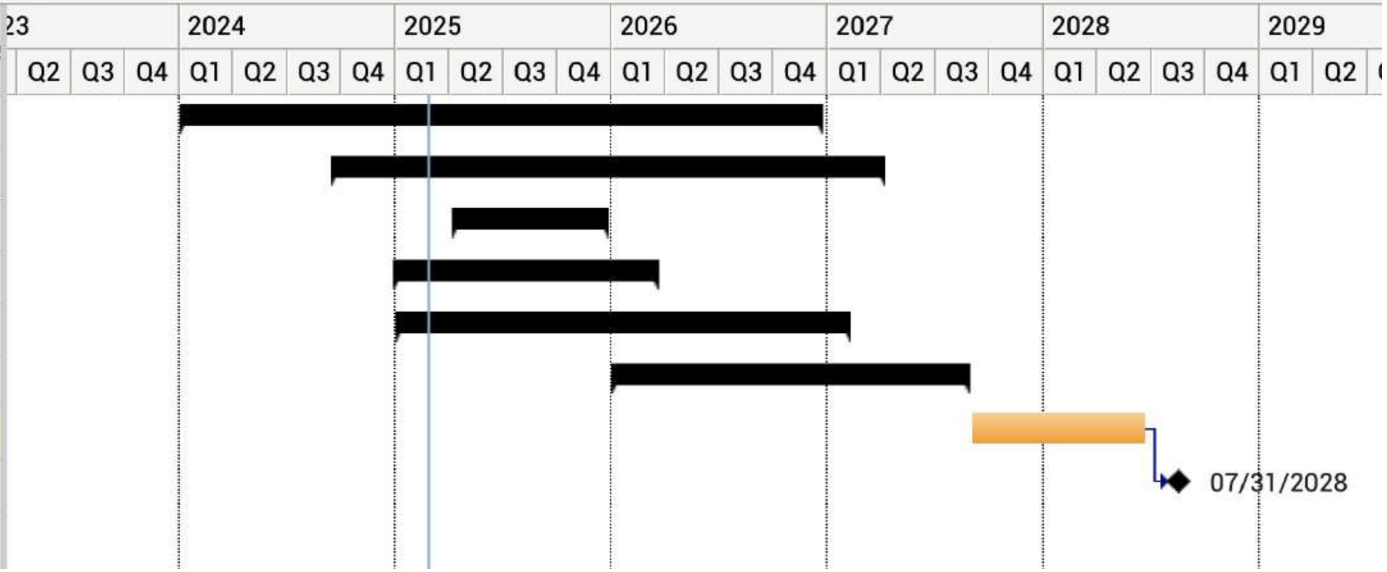



- Global commissioning: 4 months
- Contingency after installation: 15 months

→this period could be used for calibration with beams at SPS

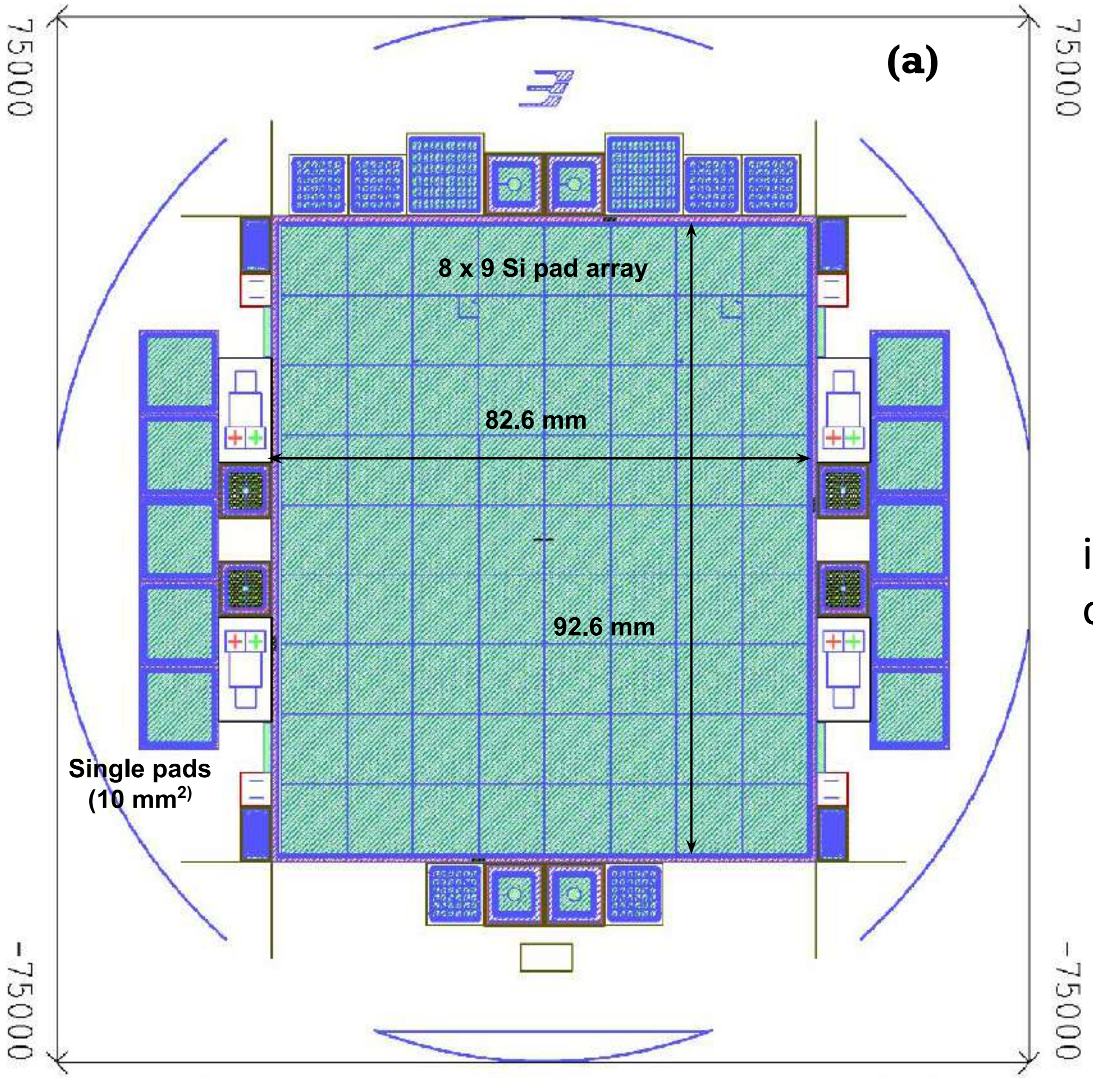
# FoCal-E PAD

| | Name | Duration | Start | Finish | Pre |
|---|---|---|---|---|---|
| 1 | ⊞3.1: Silicon sensors | 778days? | 01/01/2024 | 12/23/2026 | |
| 12 | ⊞3.2: Tungston plates | 671days? | 09/12/2024 | 04/08/2027 | |
| 19 | ⊞3.3: Prototype module | 191days | 04/04/2025 | 12/26/2025 | |
| 24 | ⊞3.4: Module design | 321days | 12/27/2024 | 03/20/2026 | |
| 29 | ⊞3.5: Pad-sensor unit assembly | 550days | 12/31/2024 | 02/08/2027 | |
| 34 | ⊞3.6: Pad segment assembly | 435days? | 12/29/2025 | 08/27/2027 | |
| 40 | Contingency | 209days? | 09/01/2027 | 06/19/2028 | 39 |
| 41 | FoCal installation | 30days | 06/20/2028 | 07/31/2028 | 40 |



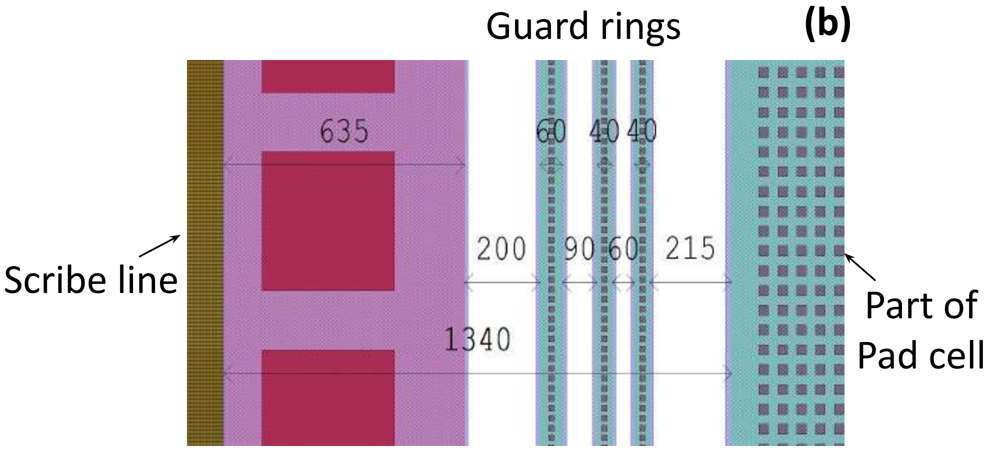

- Test production module in 2025
- Sensor production will be completed by the end of 2026
- Tungsten plate: by Q1 2027 (two batches)
- Pad sensor unit: by Q1 2027
- Pad segment (layer): by Q3 2027
- PIXEL-PAD integration: June 2027 - June 2028

# Prototype: Design of the 8×9 Si pad array

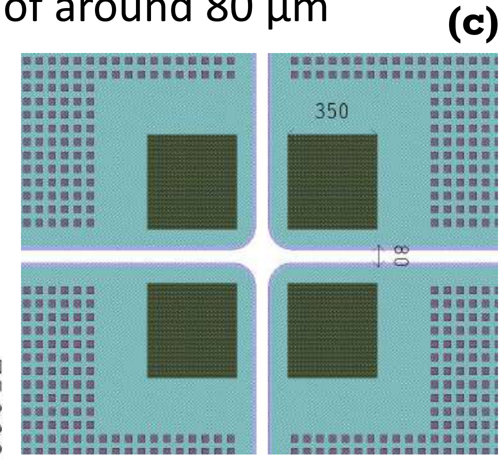



Wafer-level mask design

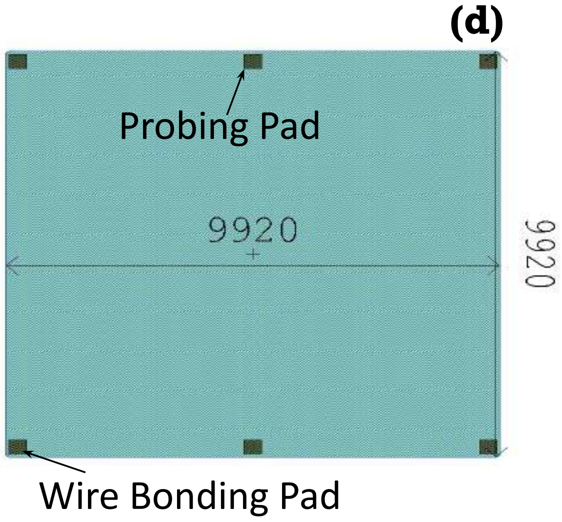
Guard ring design



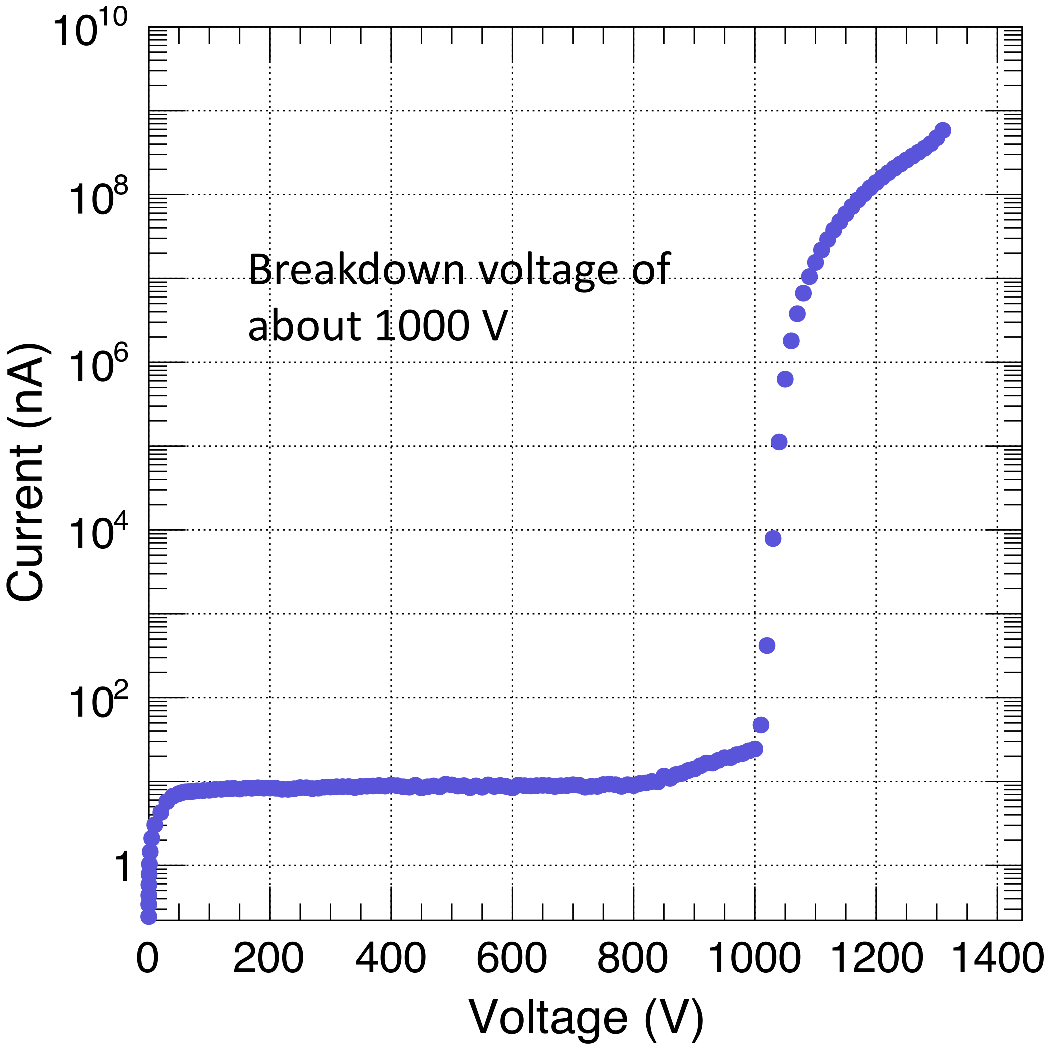

inter pad distance of around 80 µm

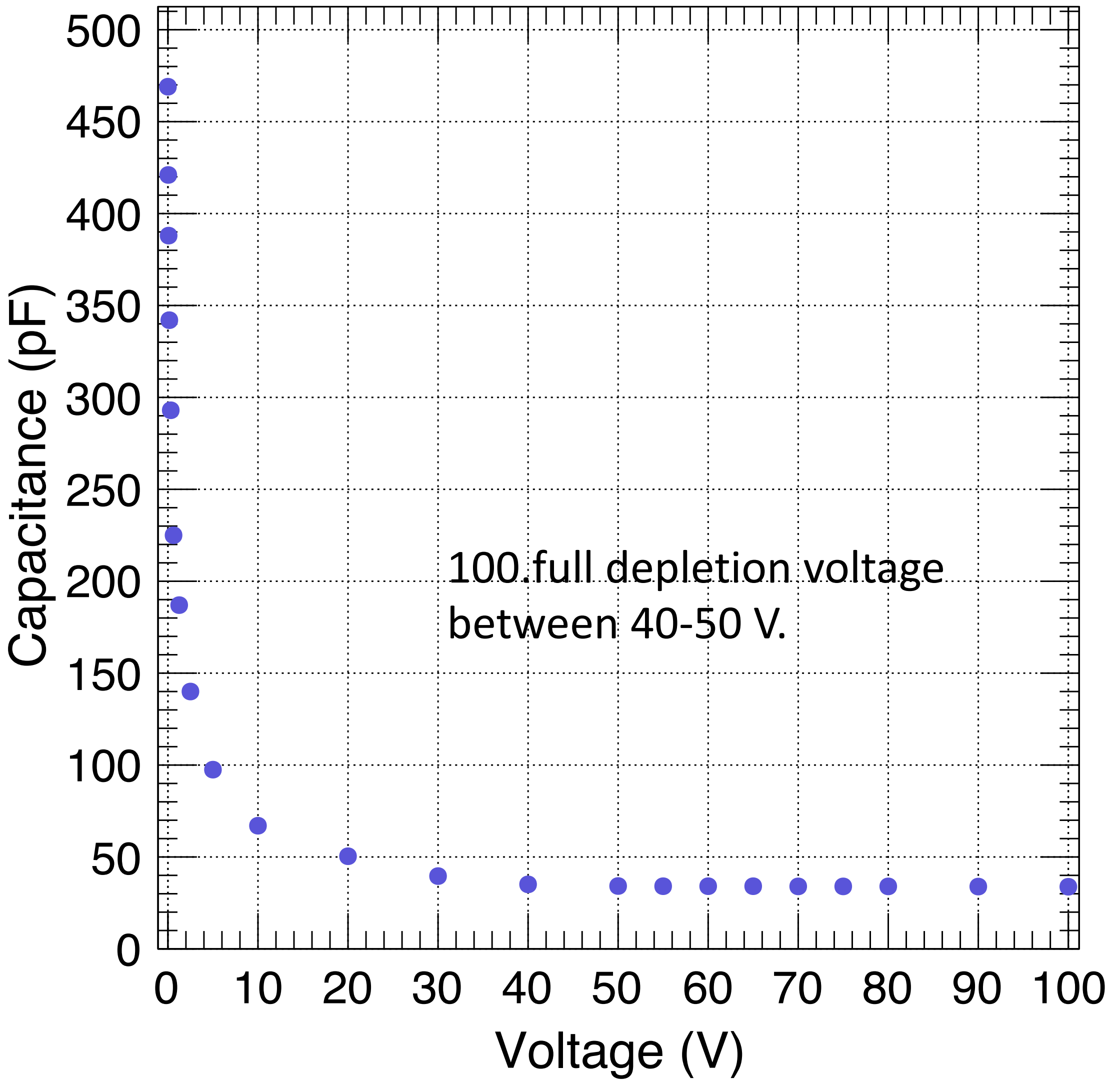



Layout of a single pad cell



# Simulations (TCAD)



# Design parameters

| Design/Process paramter | Values |
|---|---|
| Die dimension | 82.6 mm × 92.6 mm |
| Single Pixel dimension | 9.92 mm × 9.92 mm |
| Pixel pitch | 10 mm |
| Gap between pixels | 80 μm |
| No. of Guard Rings (GR) | 3 (+ 1 N-type GR) |
| Distance from scribe line to first pixel | 1340 μm |
| Breakdown voltage | 1000 V |
| Full depletion voltage | 50 V |
| Pad capacitance | $< 50$ pF/cm$^2$ |
| Metal overhang | 5 μm |
| Radius of curvature of PAD corner | 75 μm |
| Initial Oxide thickness | 0.6 μm |
| Screen Oxide thickness | 0.05 μm |
| P-N junction thickness | $\sim 1$ μm |
| Front Metal thickness | 0.5 μm |
| Back Metal thickness | 6 μm |
| Passivation layer material | PECVD SiN |
| Passivation layer thickness | 0.15 μm |
| Gettering Agent | Air implantation |

Design goal: leakage current ~ 10 nA or smaller
Capacitance ~ 40-50 pF
Full depletion voltage ~ 50-60 V

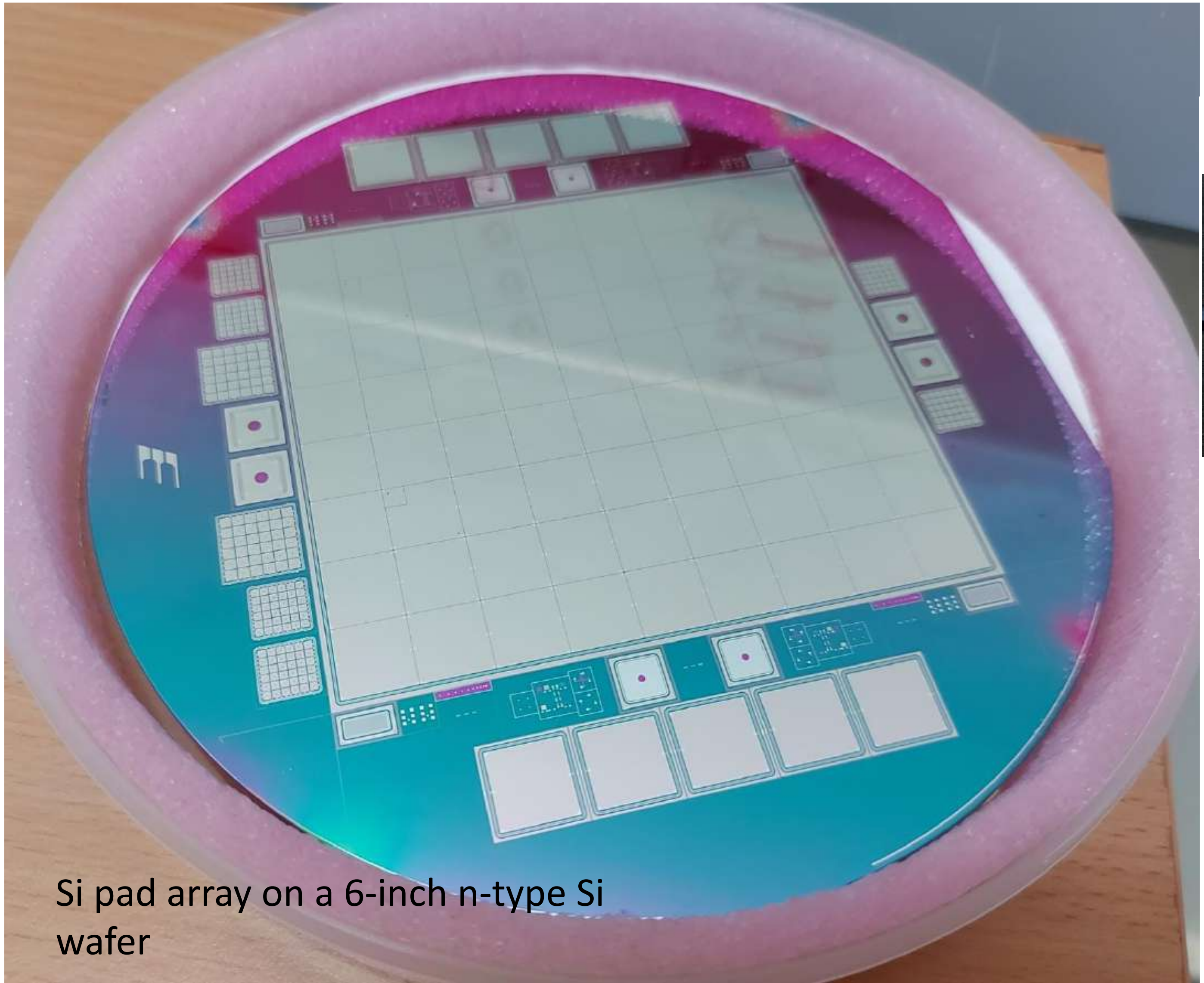
Specification of Si wafers used for device fabrication.

| Parameter | Description |
|---|---|
| Type | n-type prime, Single crystal Si |
| Growth | Float Zone (FZ) |
| Diameter | 150 ± 0.5 mm |
| Orientation | ⟨1 0 0⟩ |
| Thickness | 325 ± 20 μm |
| Substrate resistivity | $\sim 7$ kΩ cm |
| Dopant | Phosphorus, n-type |
| Total Thickness Variation (TTV) | 10 μm |
| Maximum Oxygen and Carbon Conc. | $10^{16}$/cm$^3$ |
| Minority carrier recombination lifetime | 1 ms |

Specification of photo-mask used during device fabrication

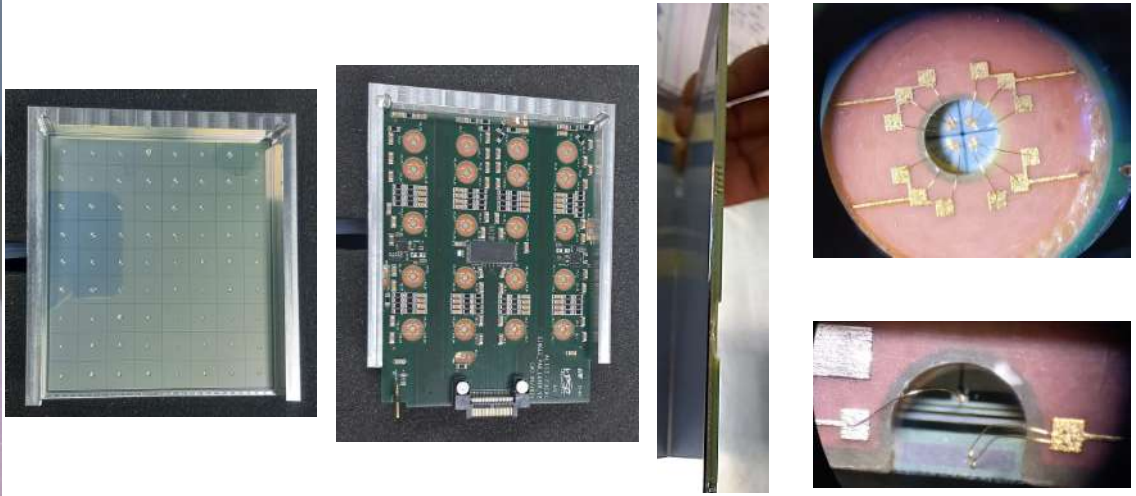
| Parameter | Description |
|---|---|
| Material | Soda lime glass / Anti-reflective chrome |
| Dimensions | $7'' \times 7'' \times 0.12''$ |
| Pattern generation | Direct write |
| Max. defect size | 0.5 μm |
| Max. defect density | 0 |
| Min. size of layout elements in layer | 10 μm ± 1 μm |
| Writing grids | 0.1 μm |
| Mask order | 7″/Bright Field (BF)/Chrome Down (CD)/Right Reading (RR) (for 4 layers) and 7″/Dark Field (DF)/CD/RR (for 1 layer) |
| Max. misalignment between layers | 0.5 μm |

# Detector – prototype + electronics



Si pad array on a 6-inch n-type Si wafer

Bharat Electronics Limited (BEL) wafer fab in Bengaluru, India

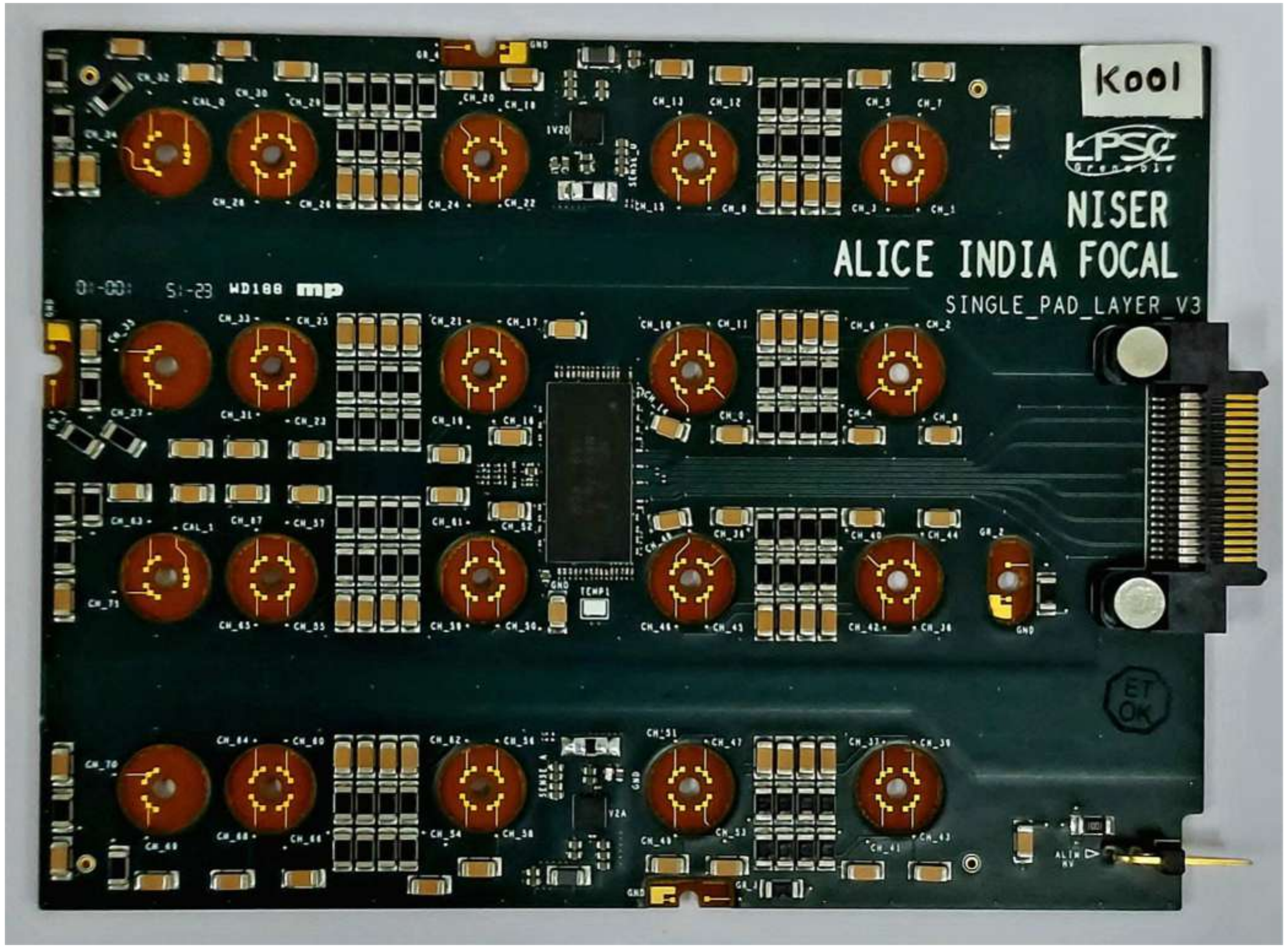


(a) (b) (c) (d)

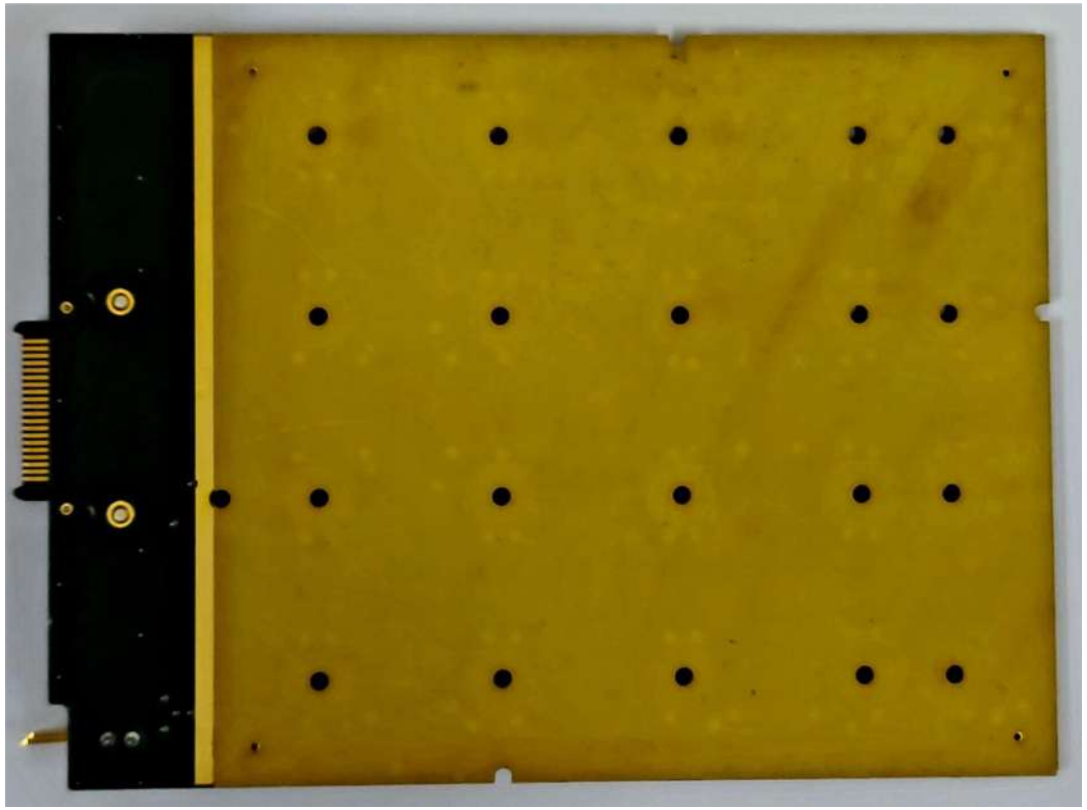
FEE board (82.6 mm× 100.6 mm) is placed on top of the detector

# Update on Single pad array PCB: LPSC, Grenoble design

Front view: 8 cm x 11 cm



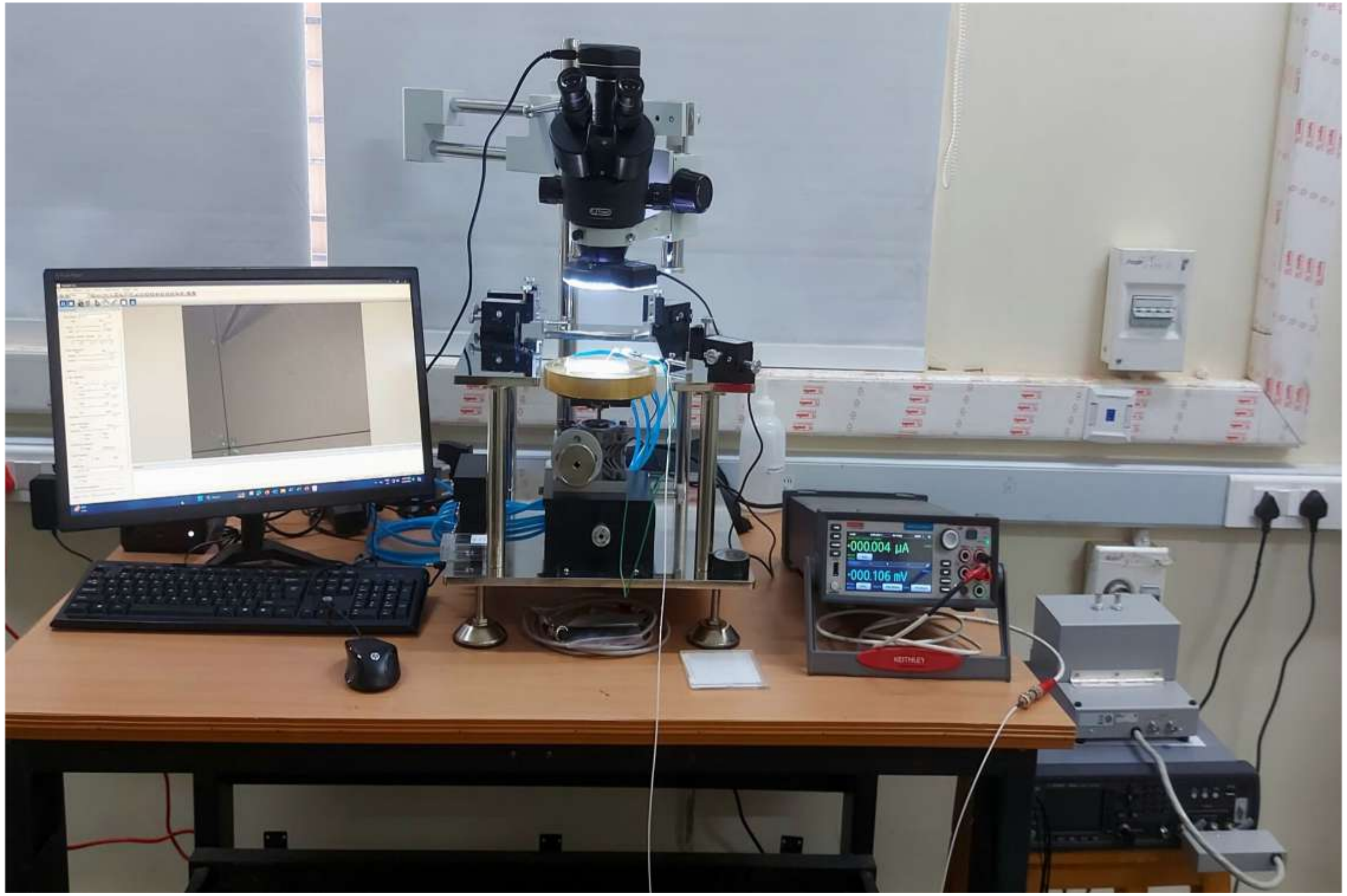

Back view



Si pad array detector readout PCB fabricated, 3 assembled and tested, its working as it should.
(Thanks to Kirti, Micropack Private Limited and KHMDL, Bangalore, India)

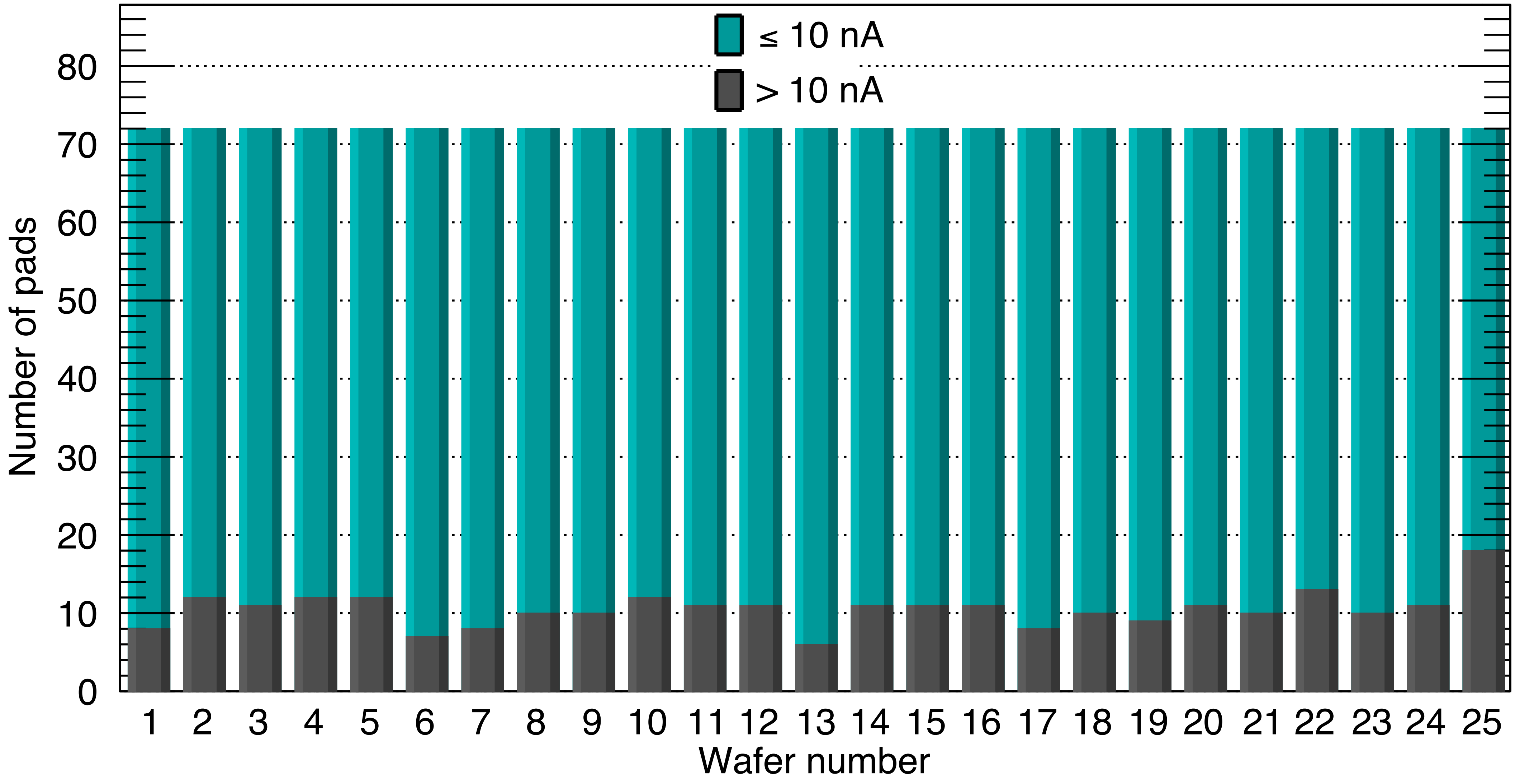
# Basic probe station @ NISER

Probe station with dark box in clean room (class 1000)



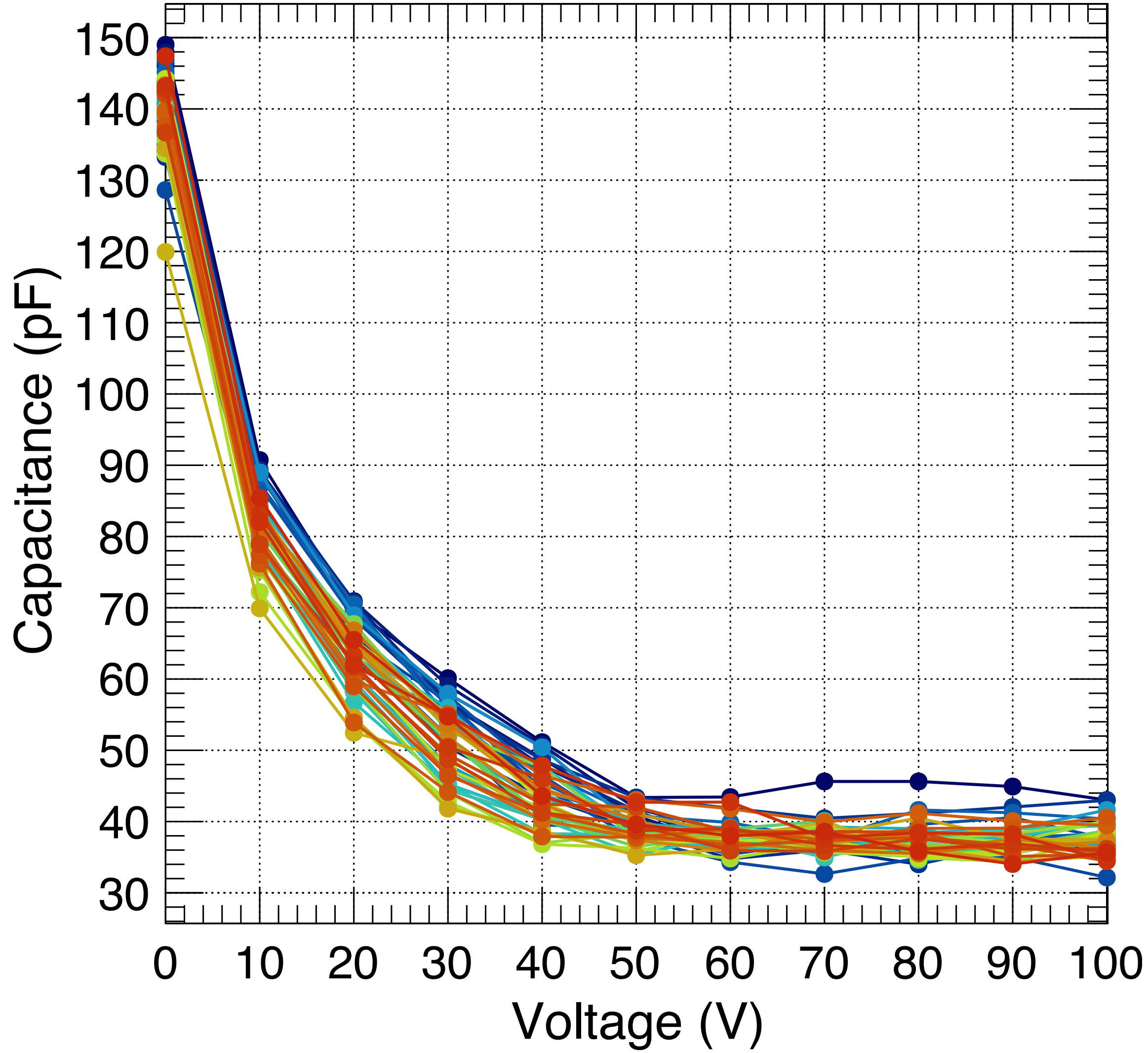

Assembled basic Si-detector wafer/die probe station: Ready to perform IV/CV of single pad cell, work in progress for IV/CV of Si pad array

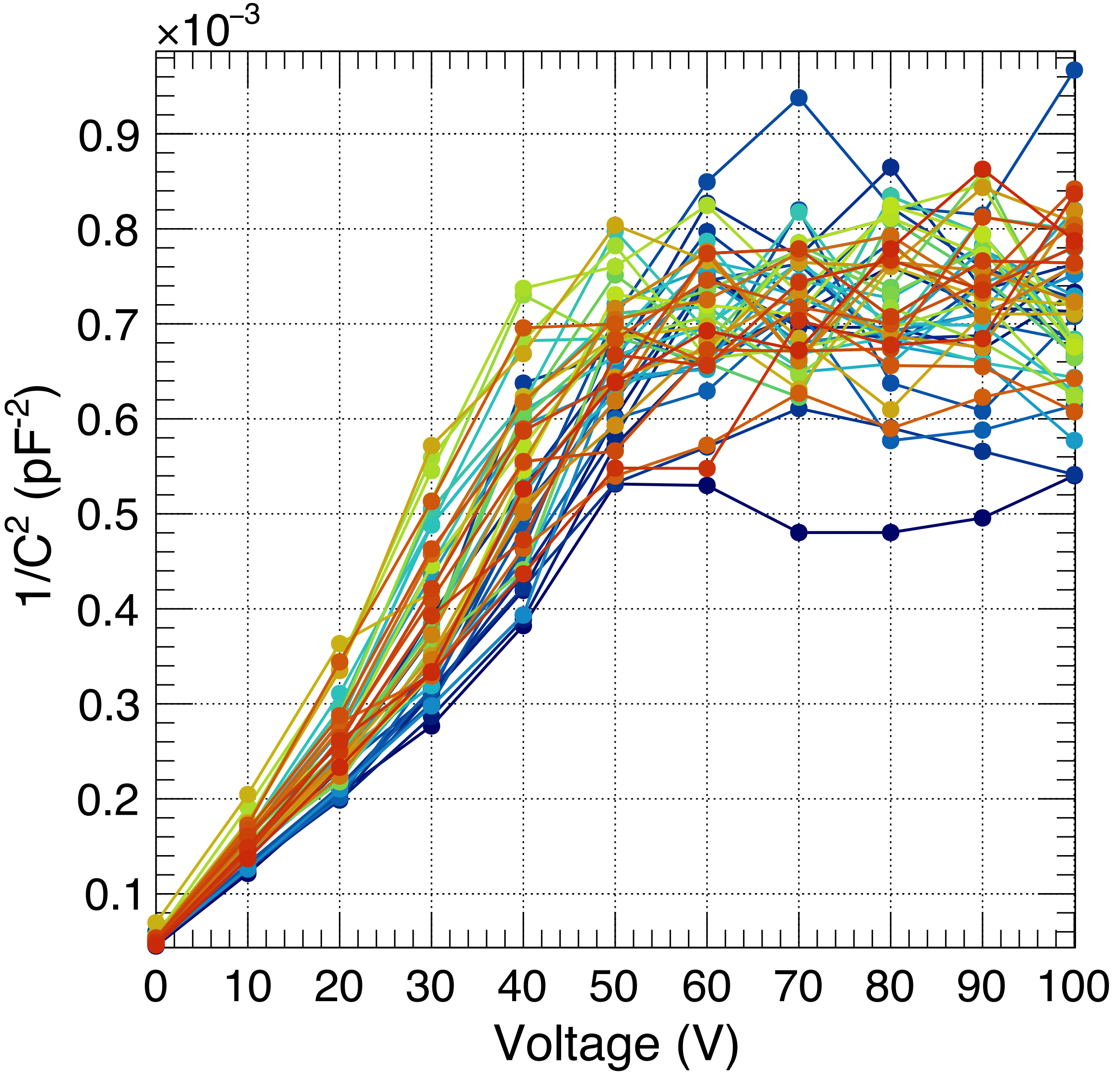
# Laboratory tests (1)




Meets design requirements

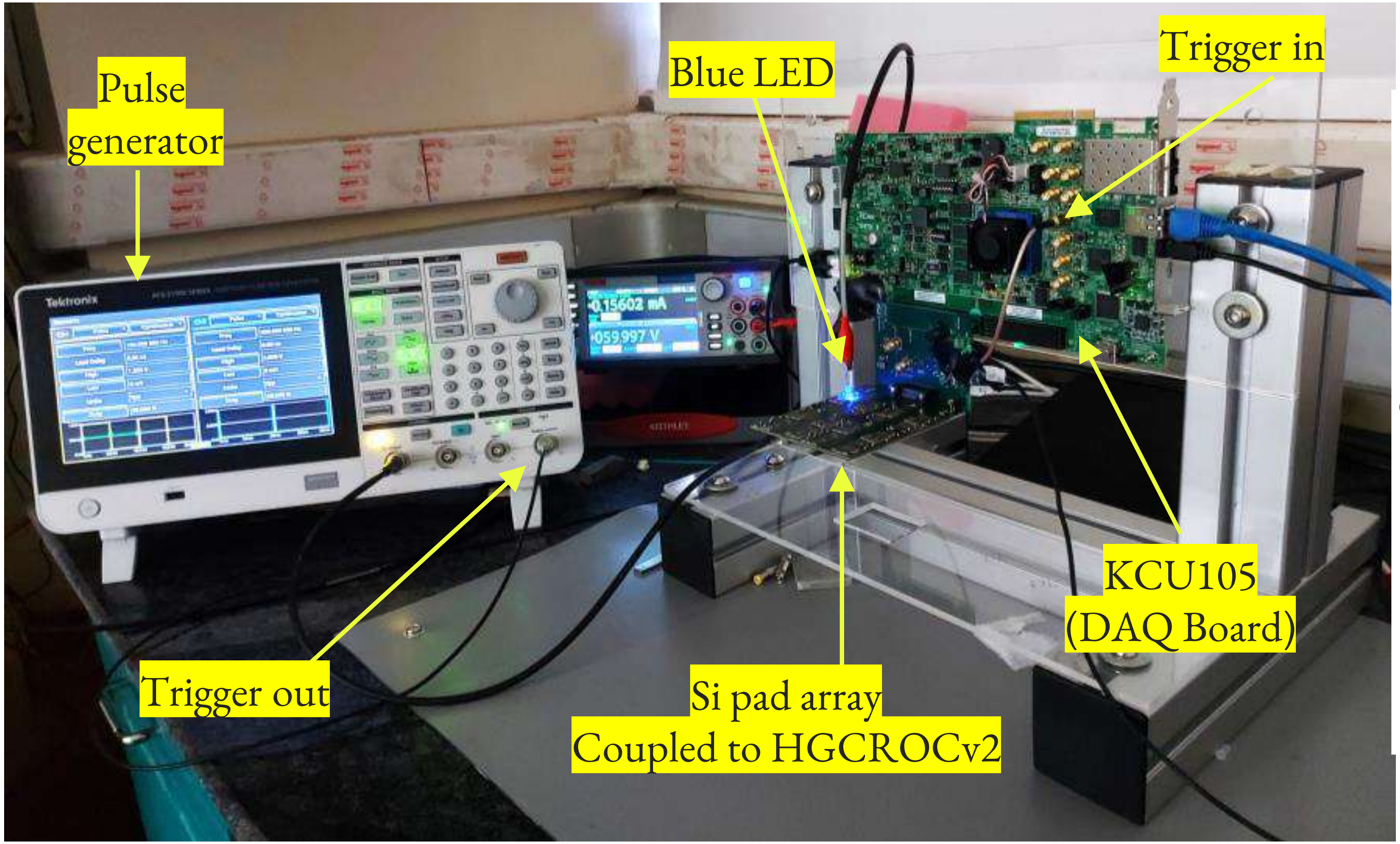
# Laboratory tests (2)

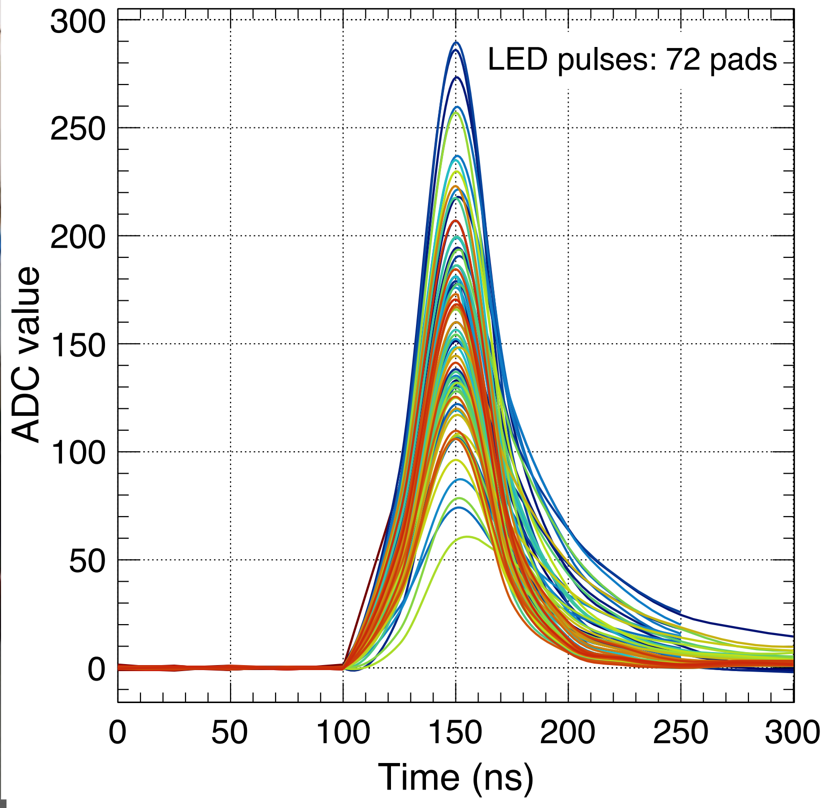



Meets design requirements

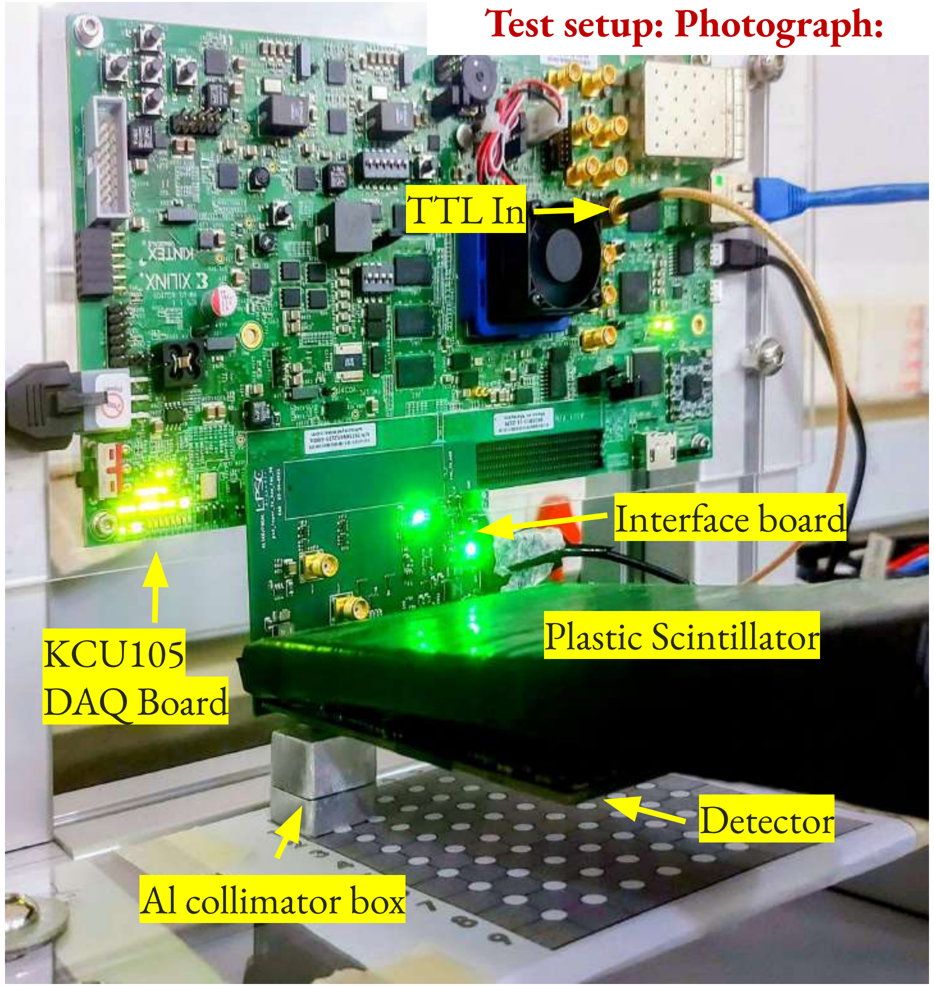
# LED test set-up at NISER



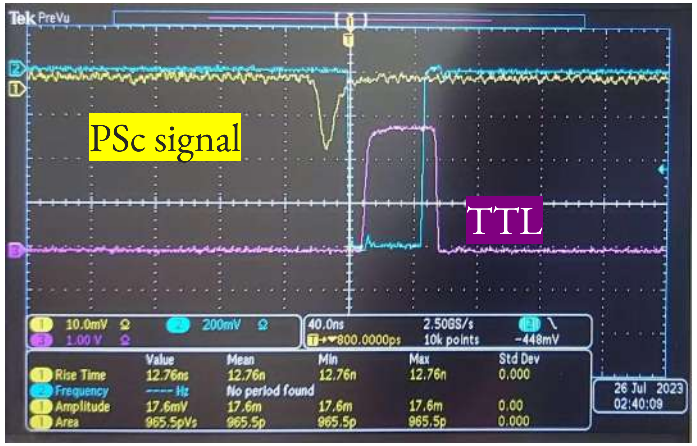



# Sr-90 source test at NISER

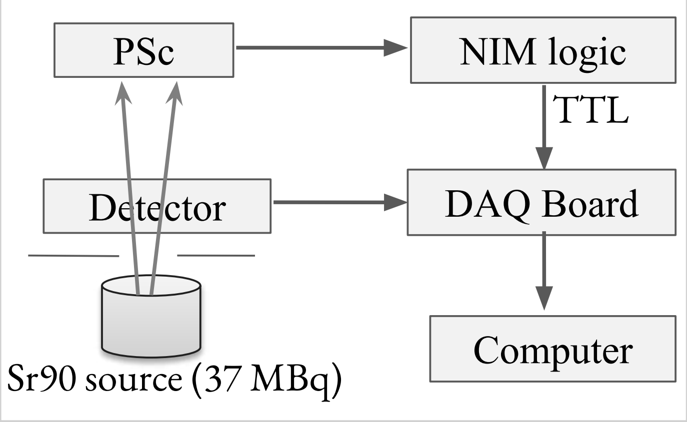
**Test setup: Photograph:**

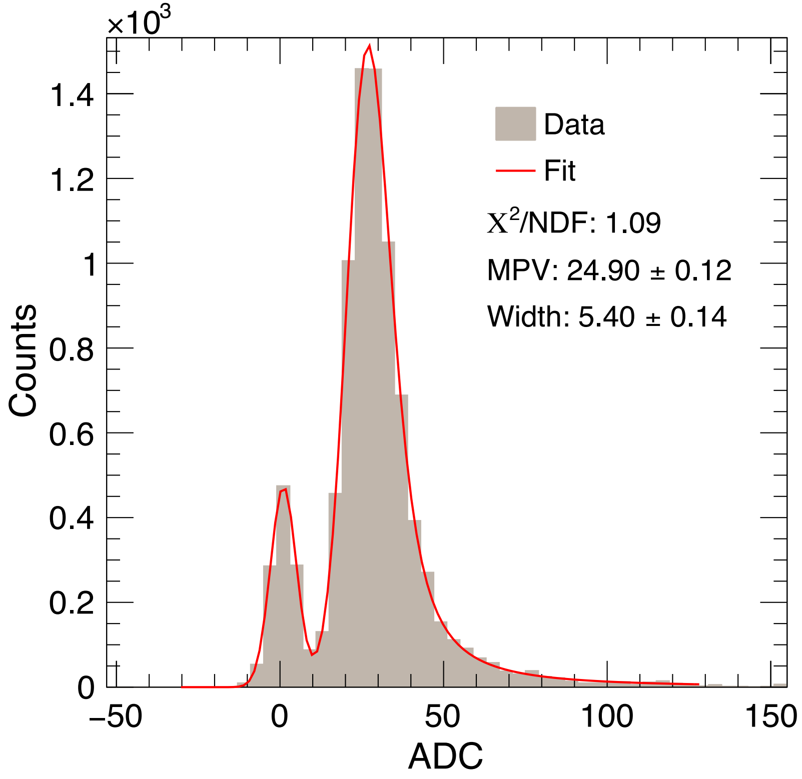



**Sr90 e- signals from PSc & TTL clock:**



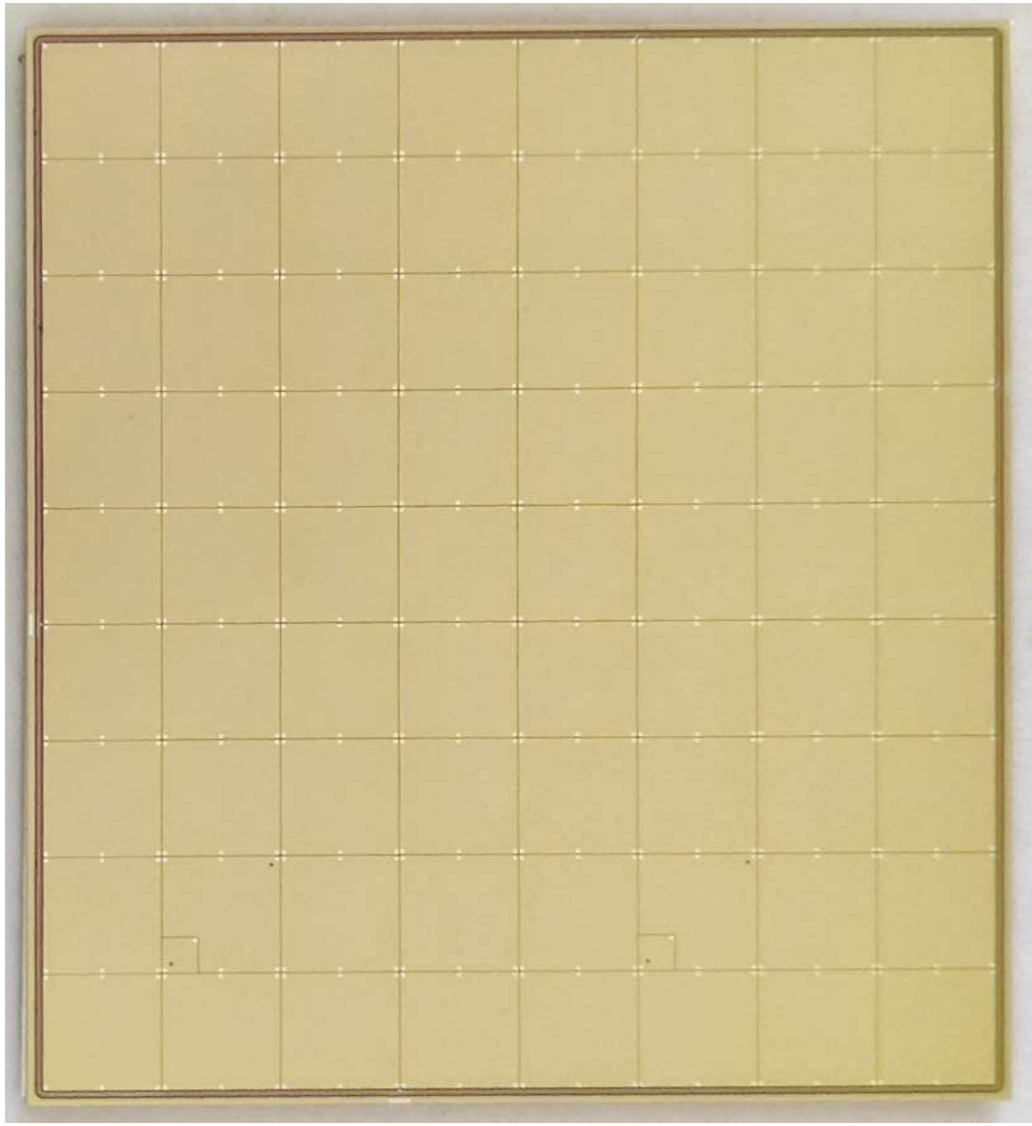

**Test setup: Schematic:**



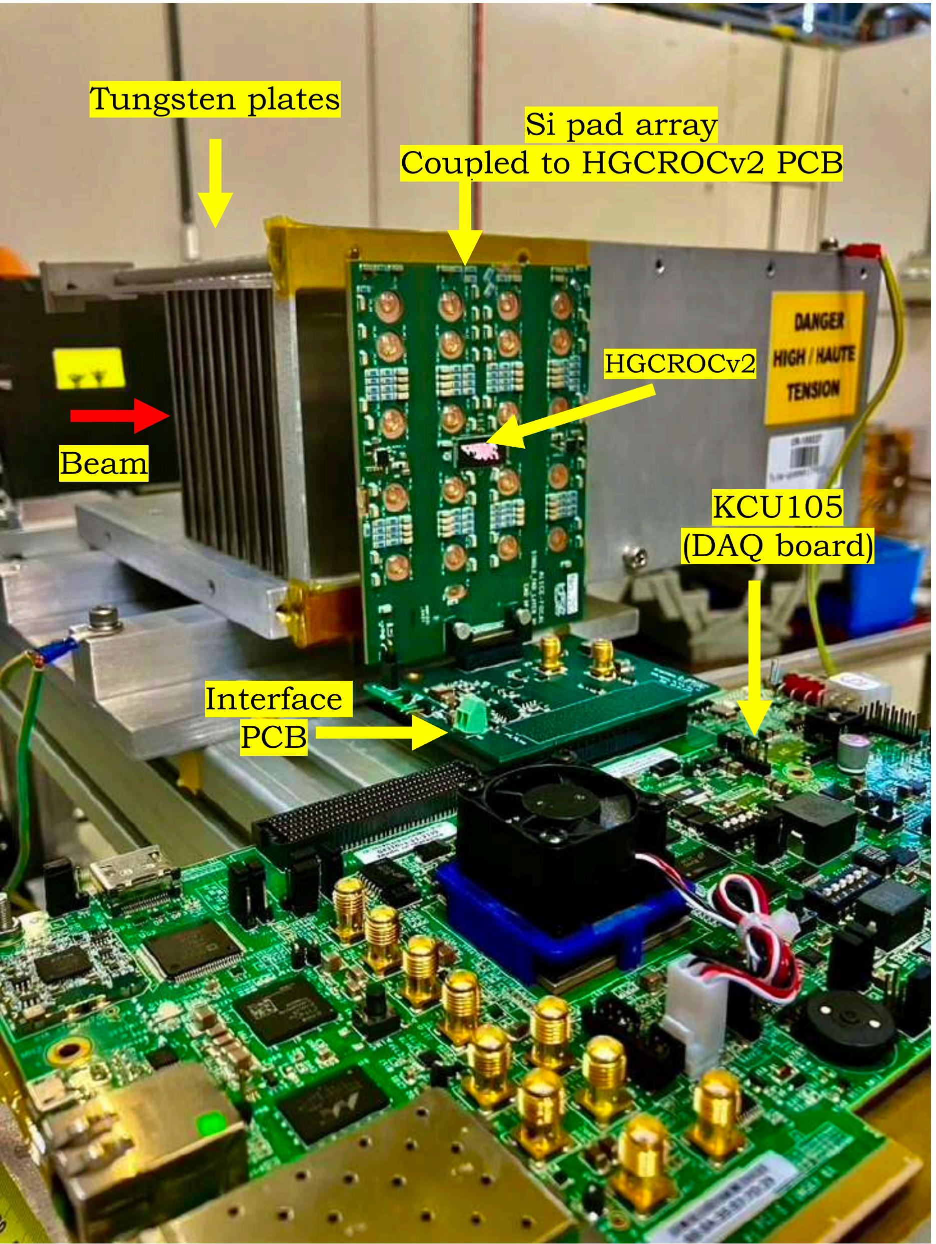



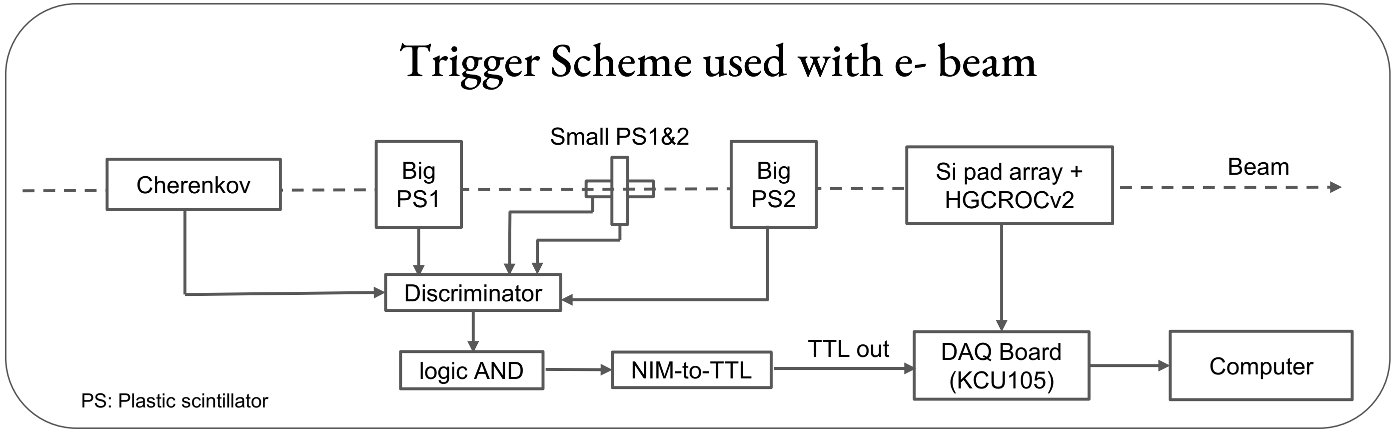

~ 2 MeV electron response.

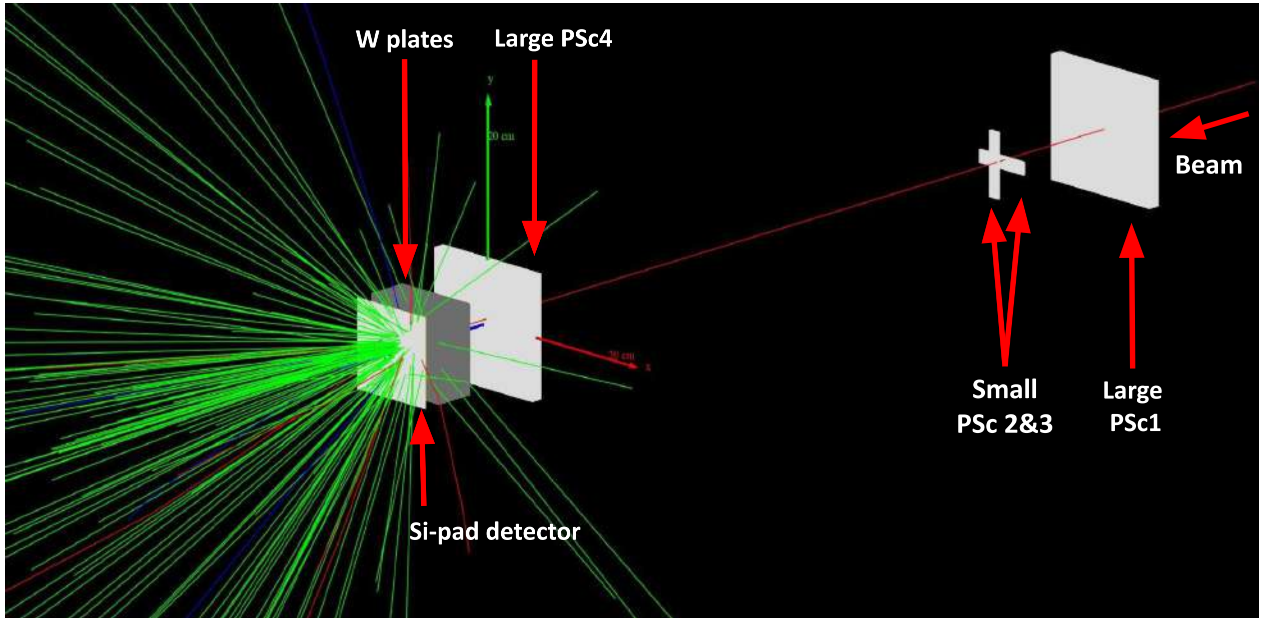
# Test beam at CERN – T9



# Test-set-up at CERN

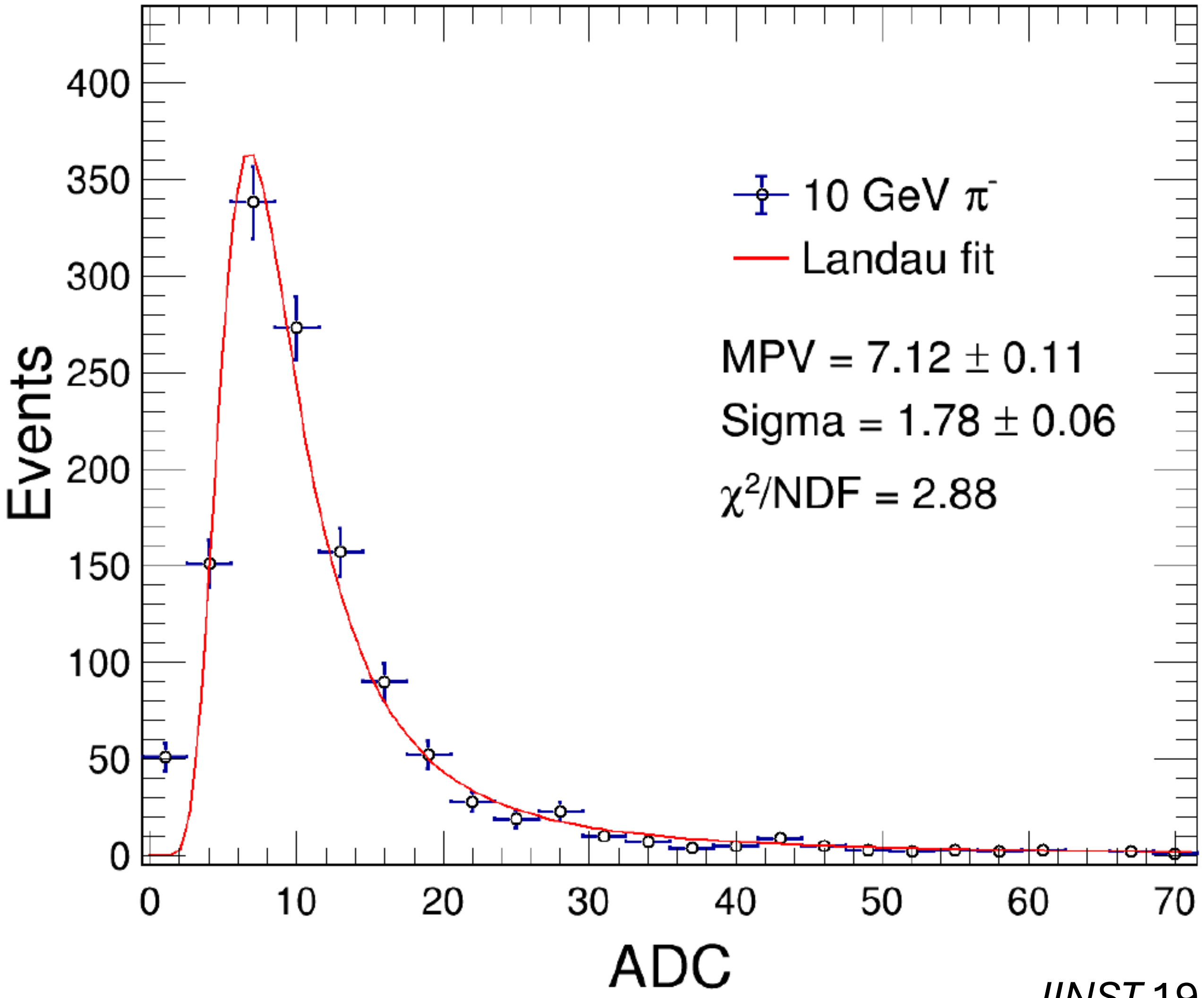


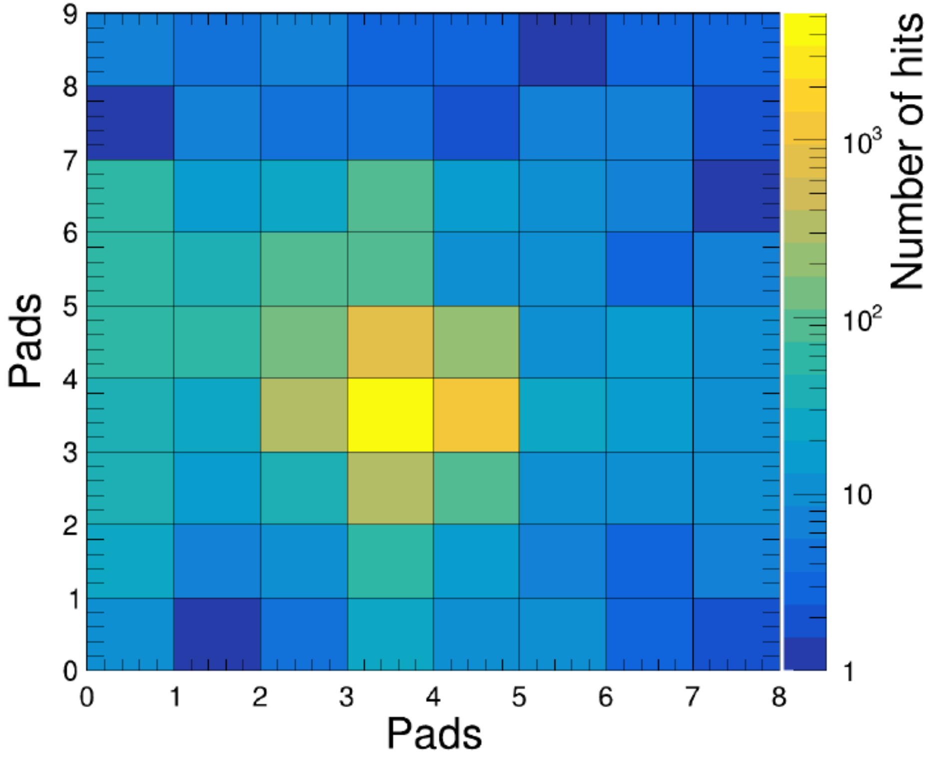




*JINST* 19 (2024) 09, P09016

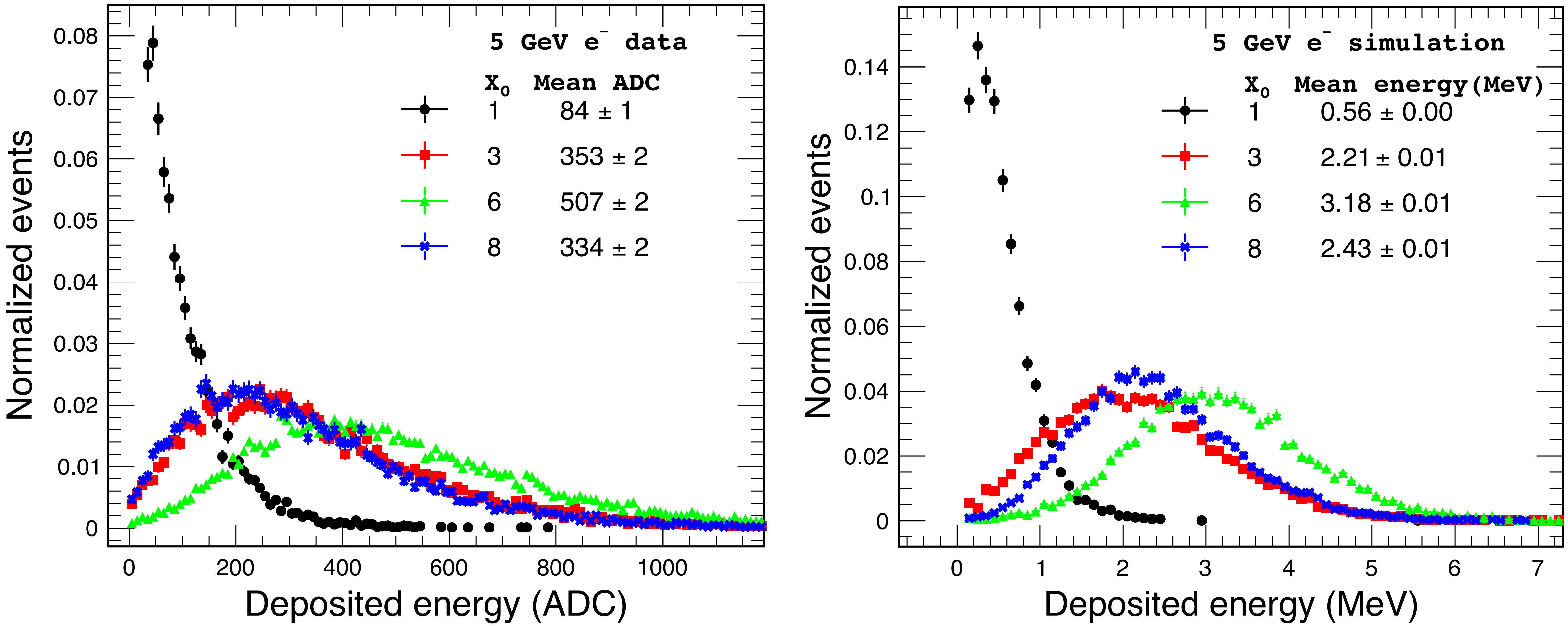
# Response to Pion beam



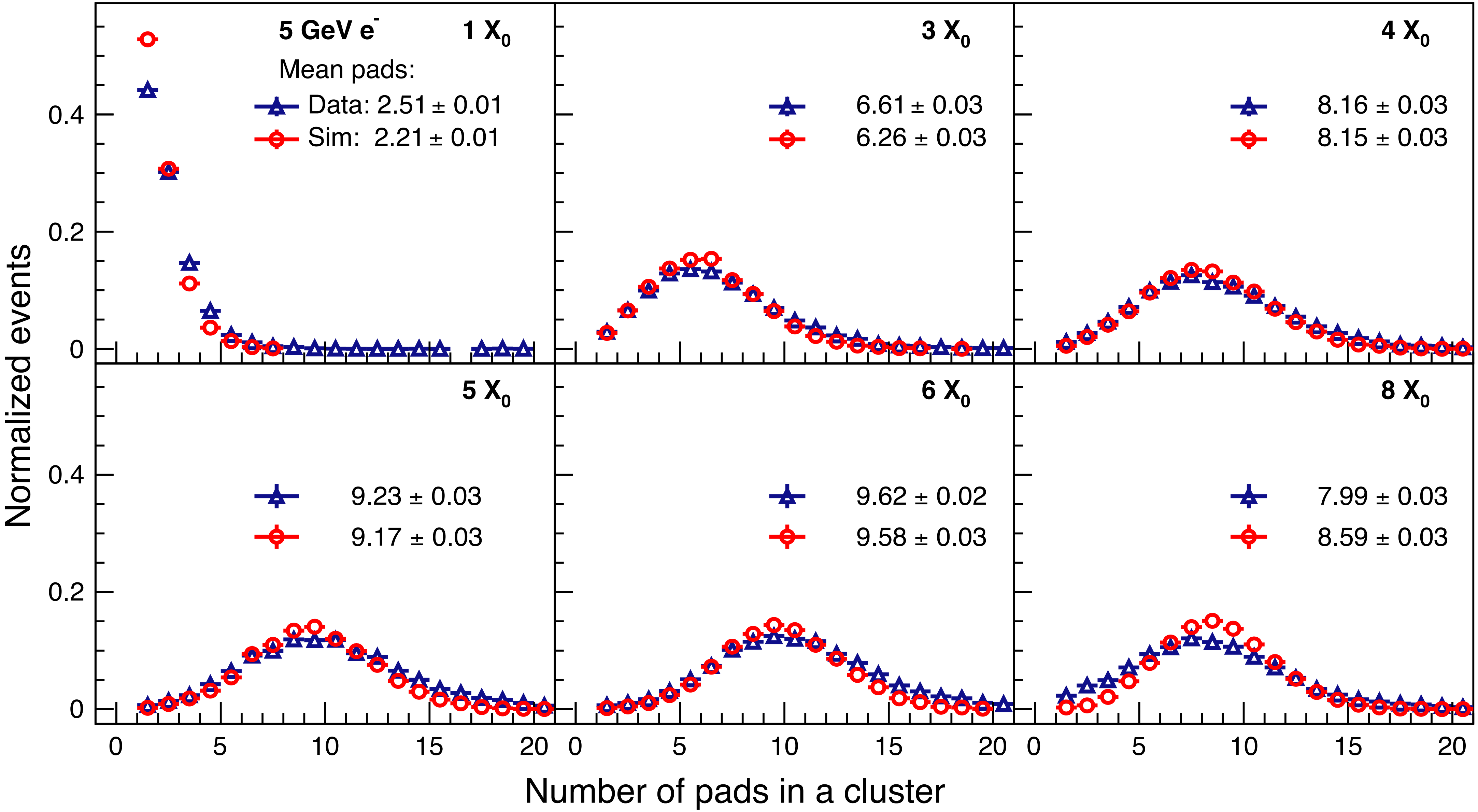

*JINST* 19 (2024) 09, P09016

# Response to electron-beam



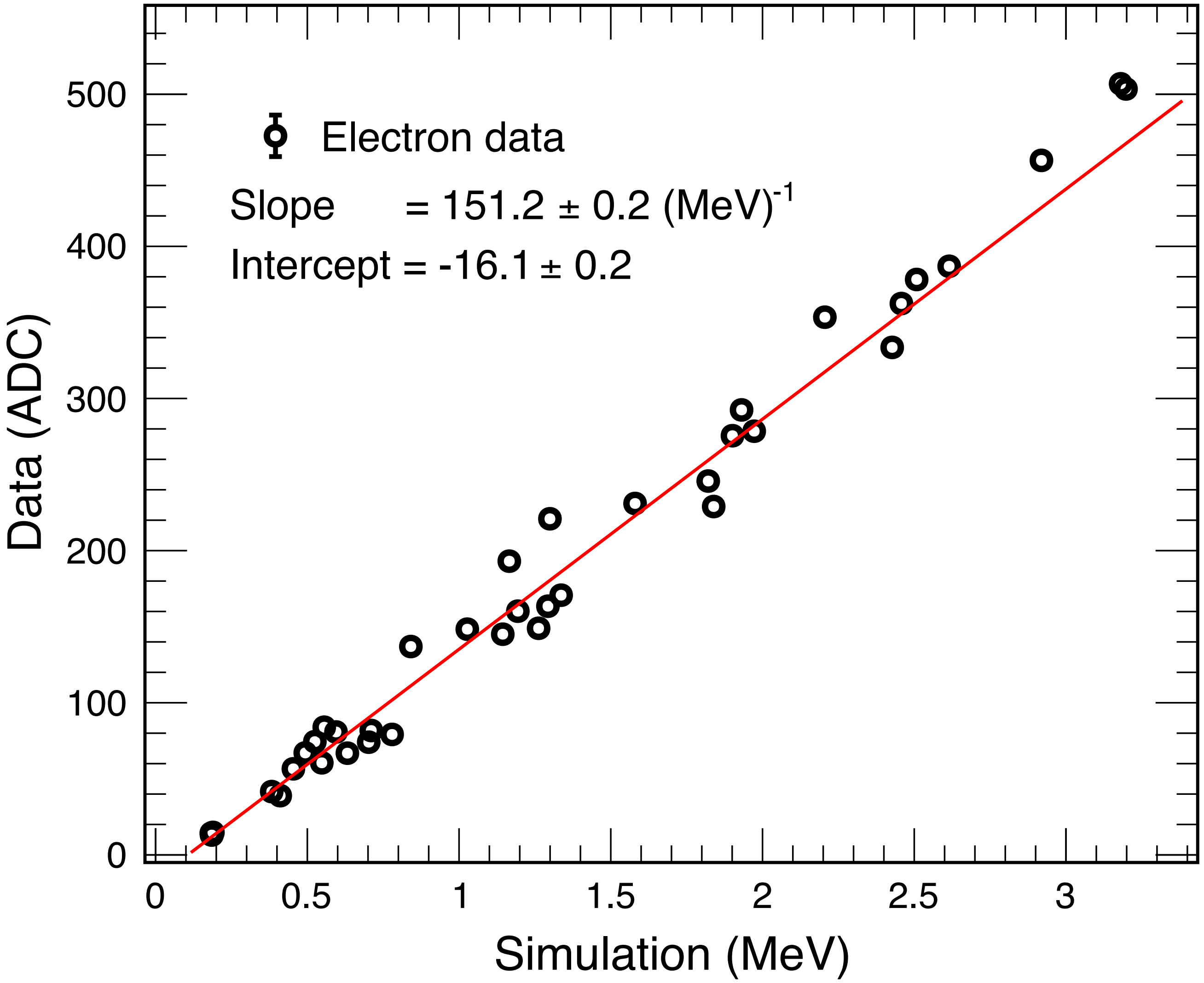

*JINST* 19 (2024) 09, P09016

# Response to electron-beam



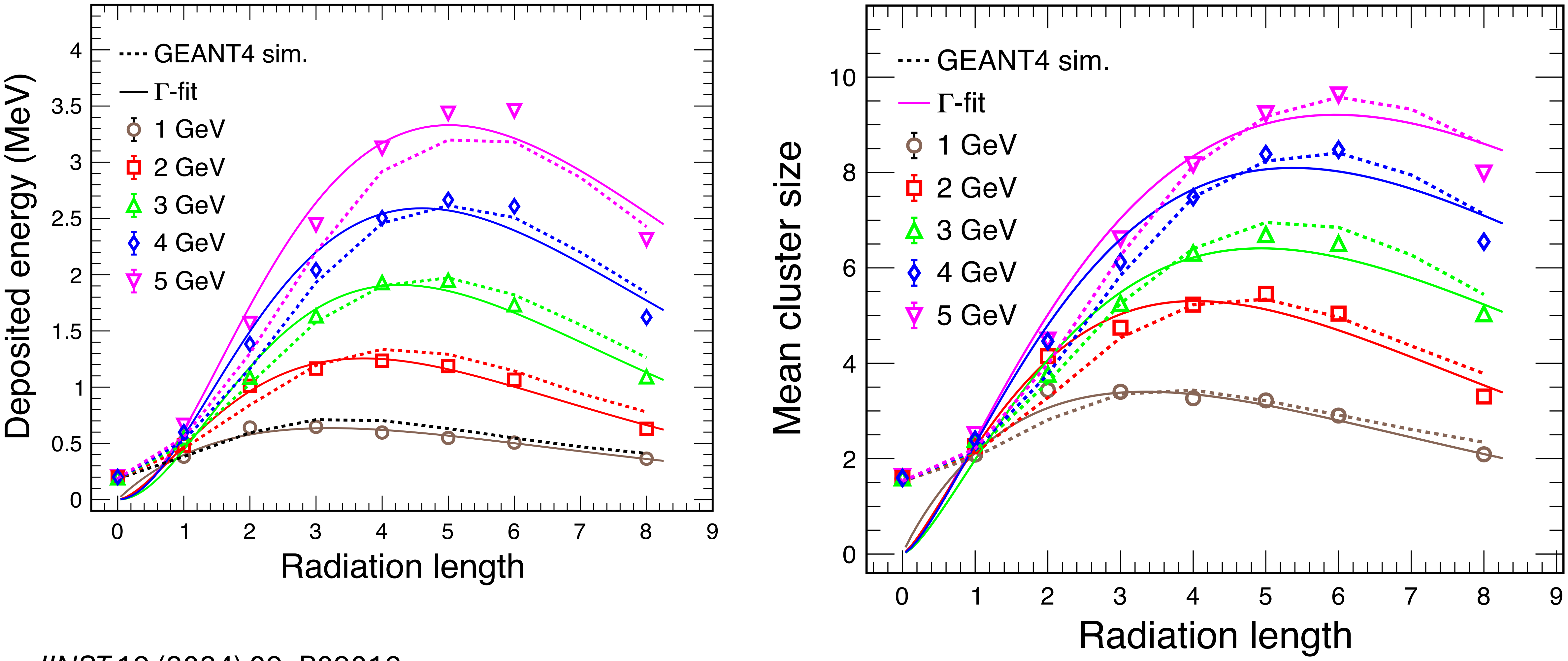

*JINST* 19 (2024) 09, P09016

# Calibration



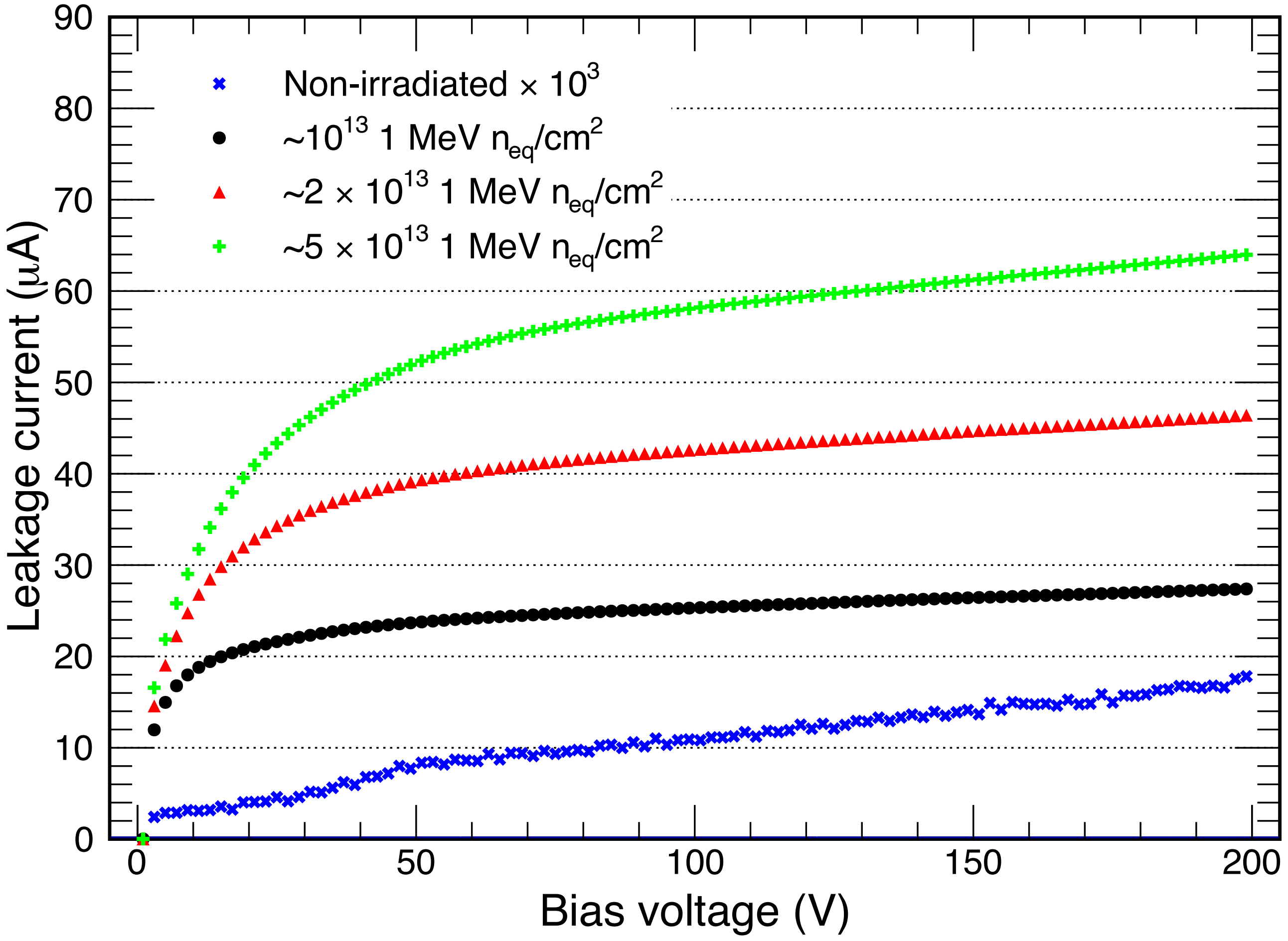

*JINST* 19 (2024) 09, P09016

# Longitudinal profile

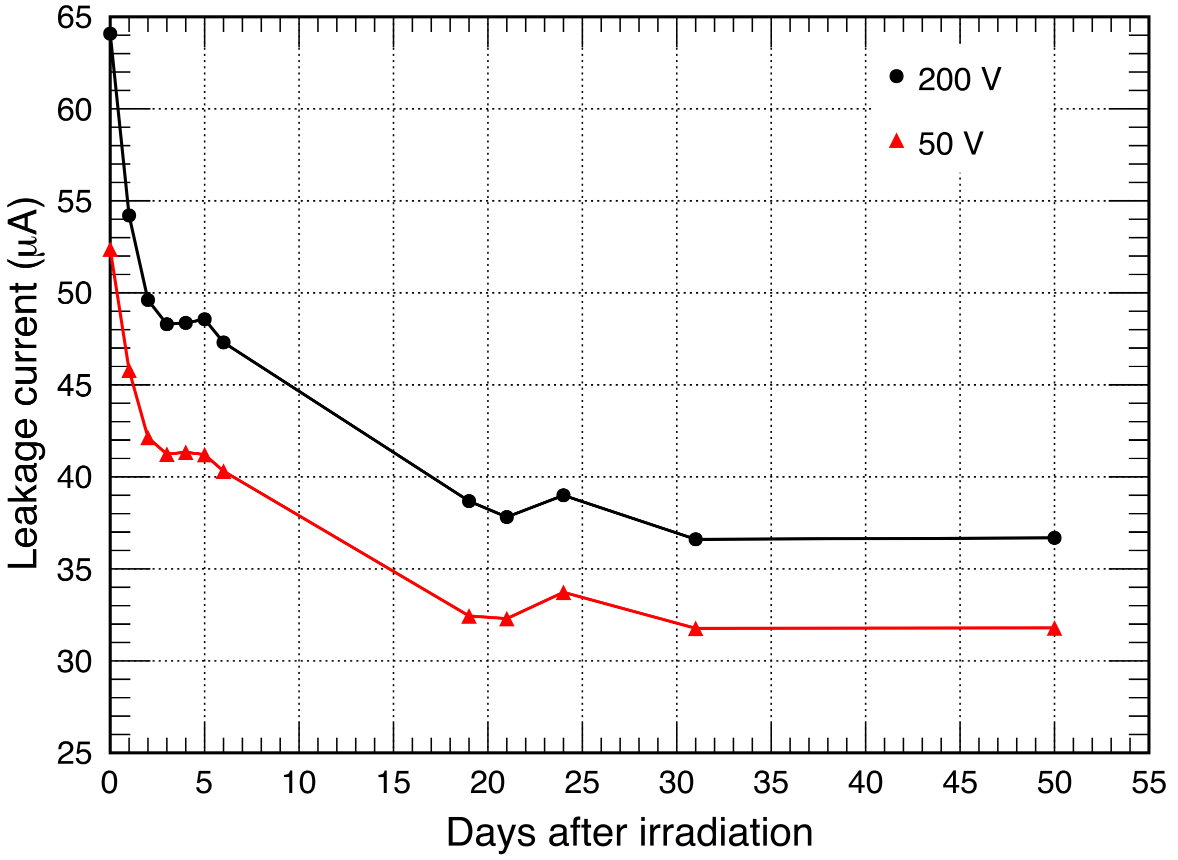



*JINST* 19 (2024) 09, P09016

# Irradiation test results




•e-Print: [2406.08144](https://arxiv.org/abs/2406.08144) [physics.ins-det]




Irradiated with fast neutrons up to the fluence of 5 × 10^13 1 MeV $n_{eq}/cm_2$ at the RIKEN Accelerator-driven compact Neutron Systems (RANS) in Japan,

The irradiated pad showed no response to the $_{90}$Sr source at voltages up to 180 V

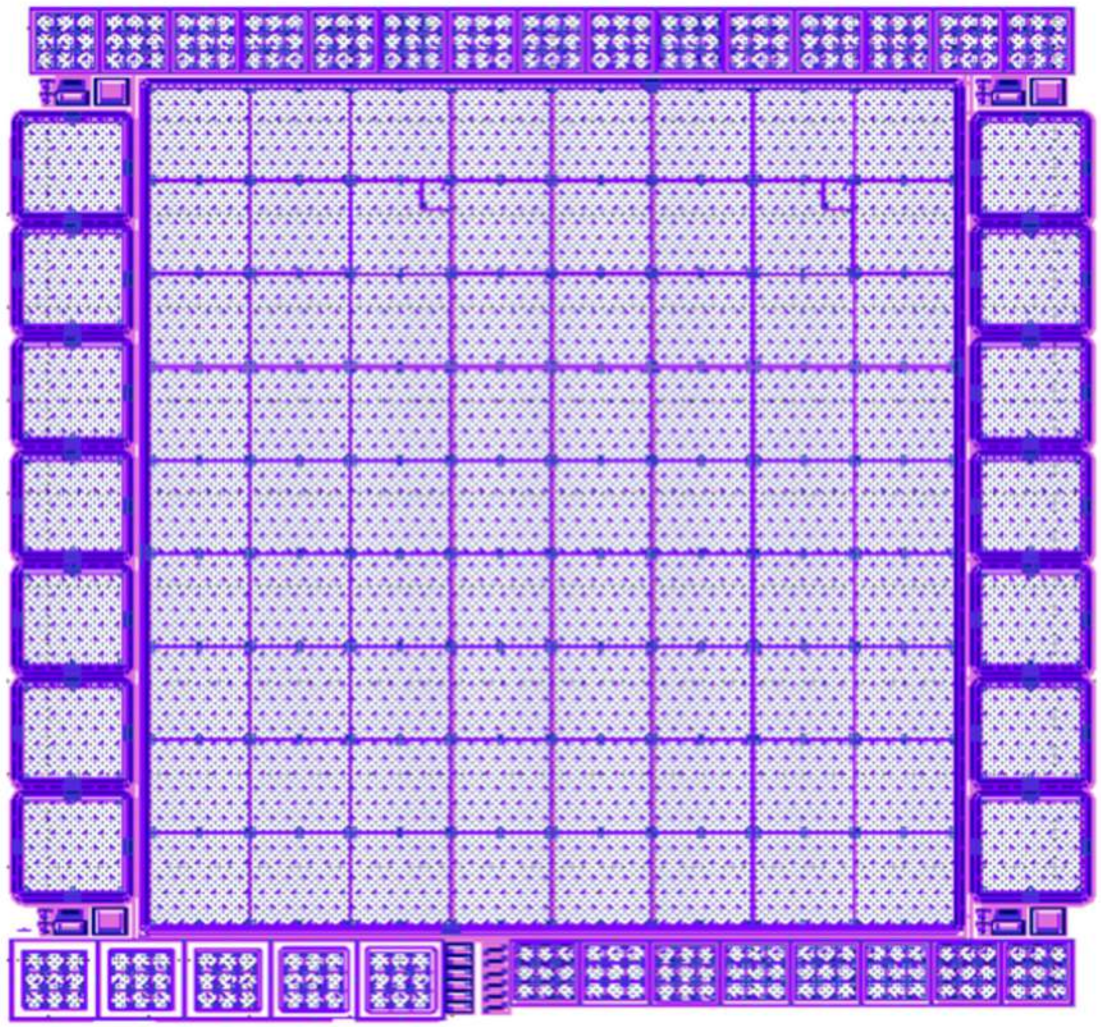
P-type Si pad array (8x9) development

Semiconductor Lab. Mohali and NISER Bhubaneswar, India

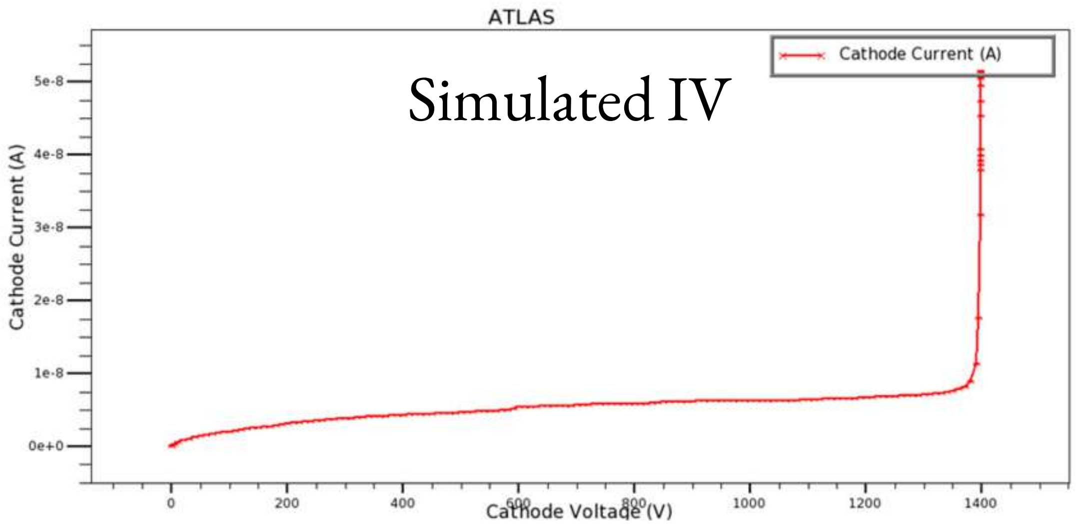
Similar R&D ongoing with BEL+VECC, Kolkata

# P-type Si pad array (8x9): Design details

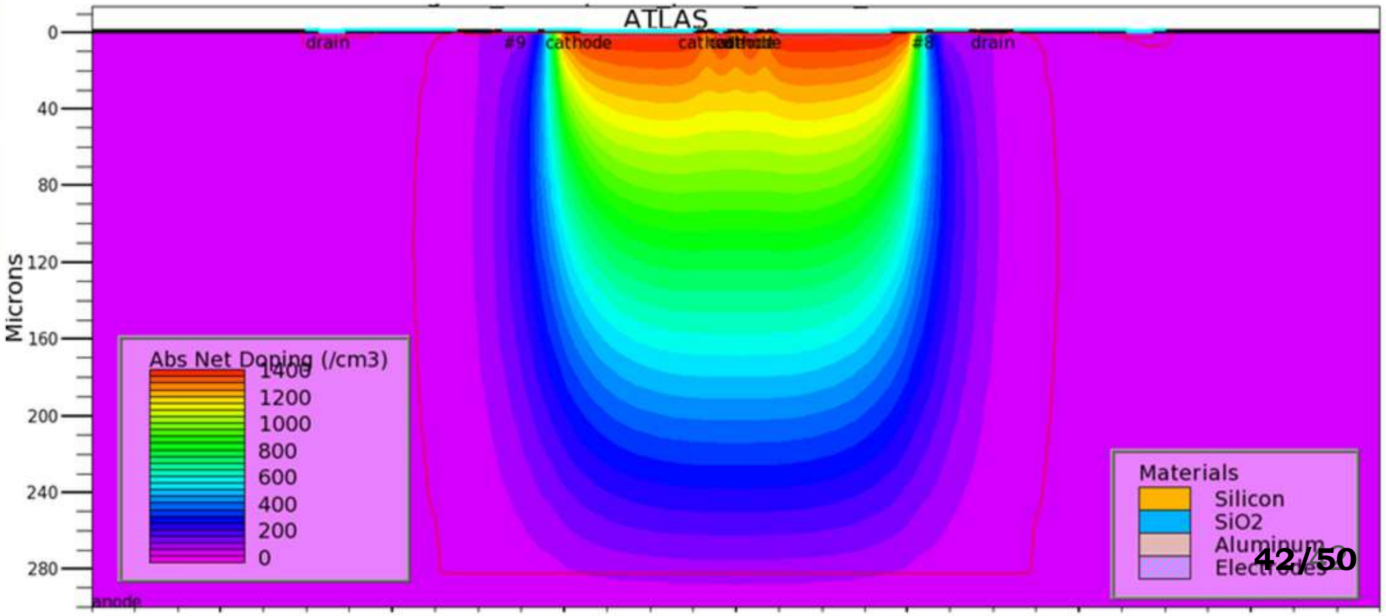
Detector layout



Plots received from SCL, Mohali

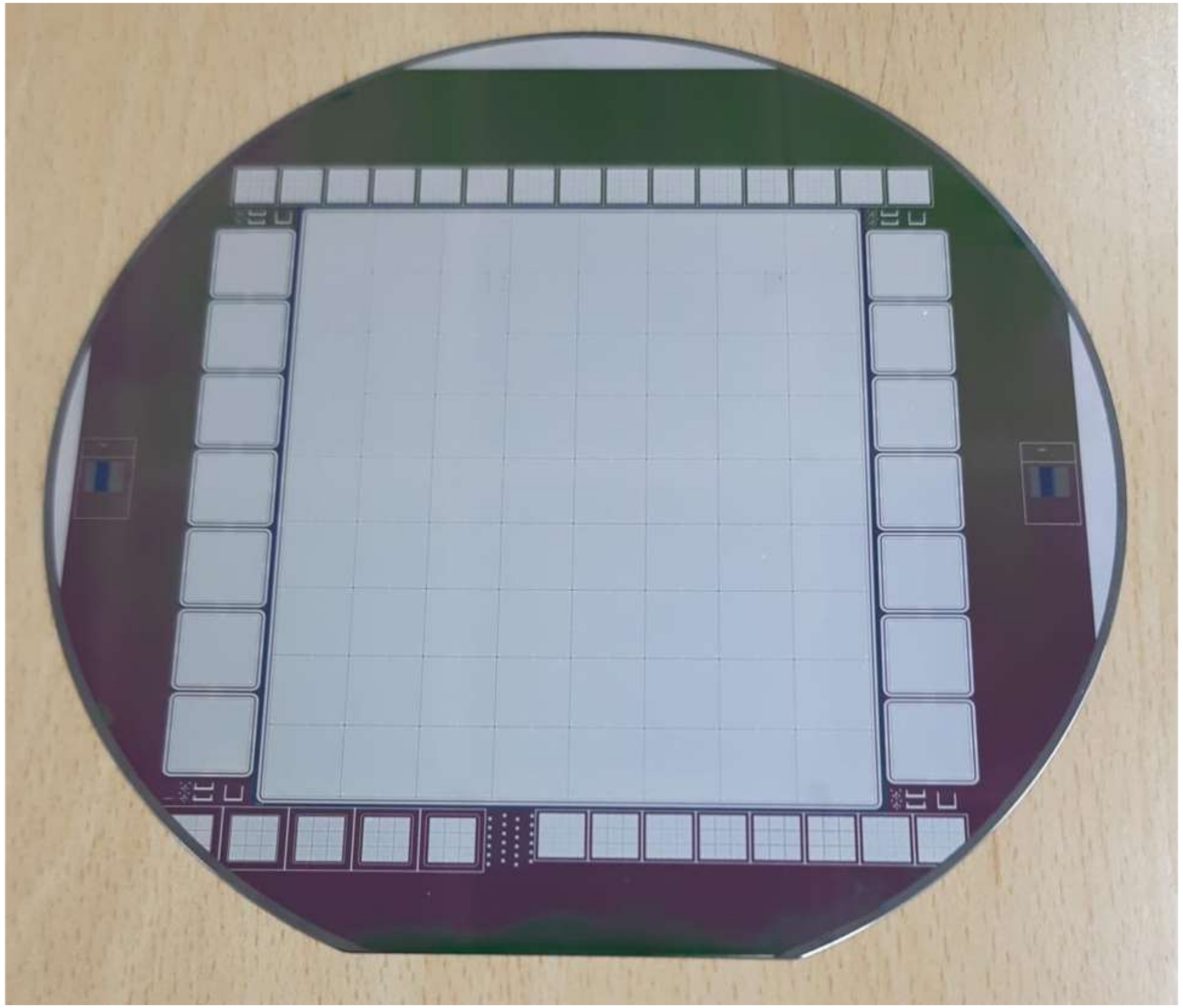



TCAD Simulation results



# P-type si pad array (8x9): Some photographs after fabrication

Detector at 6-inch wafer level

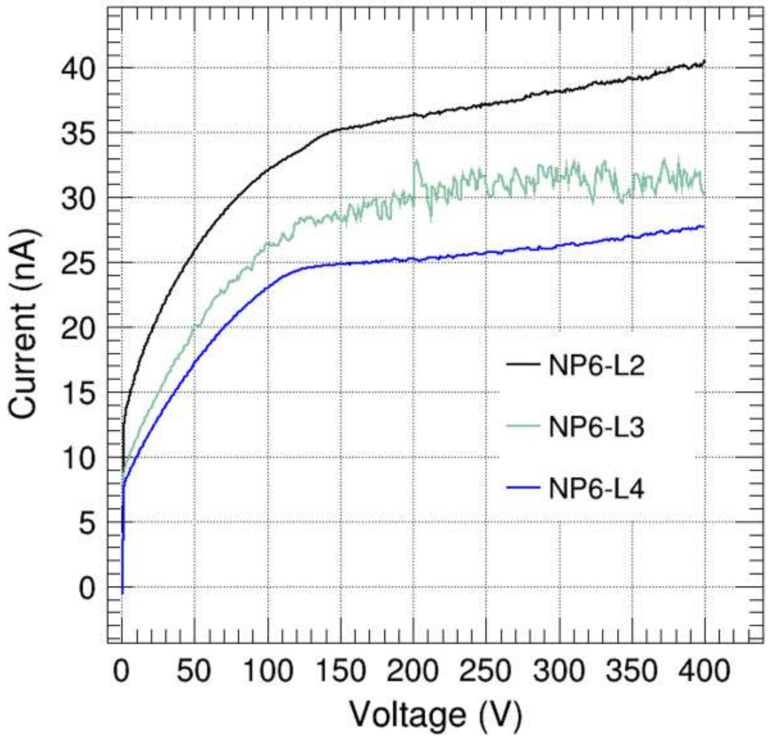


Diced 8x9 Si pad array

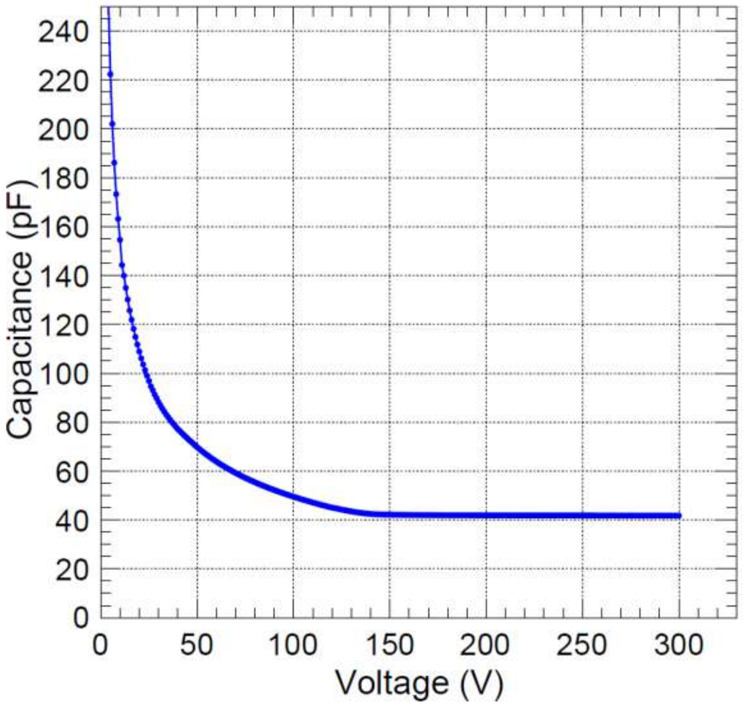
Packaged single pad cell

Photos received from SCL, Mohali

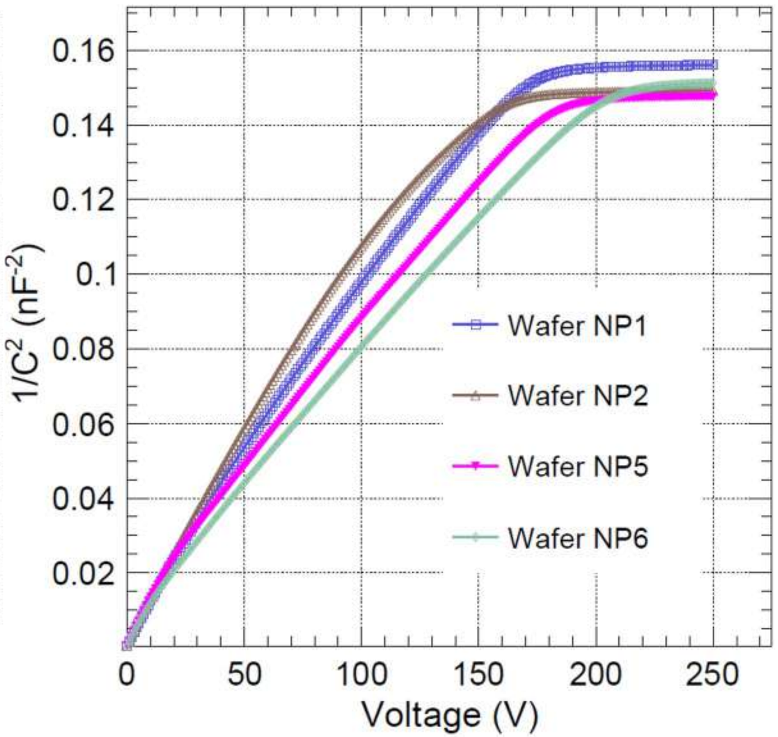
# Electrical characterization results: IV and CV test




Selected few good pads
on a single wafer



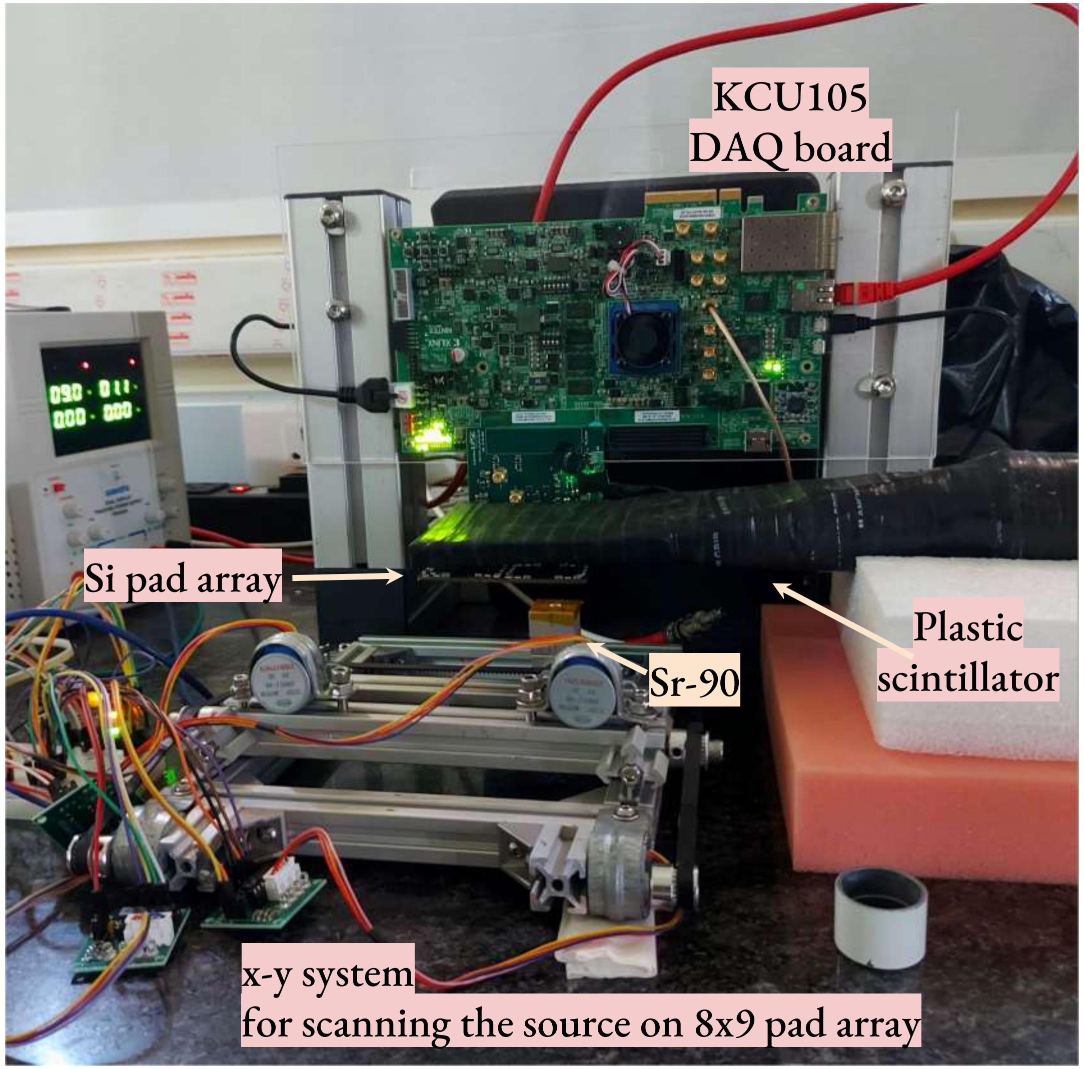

Detector capacitance ~ 40 pF/cm²



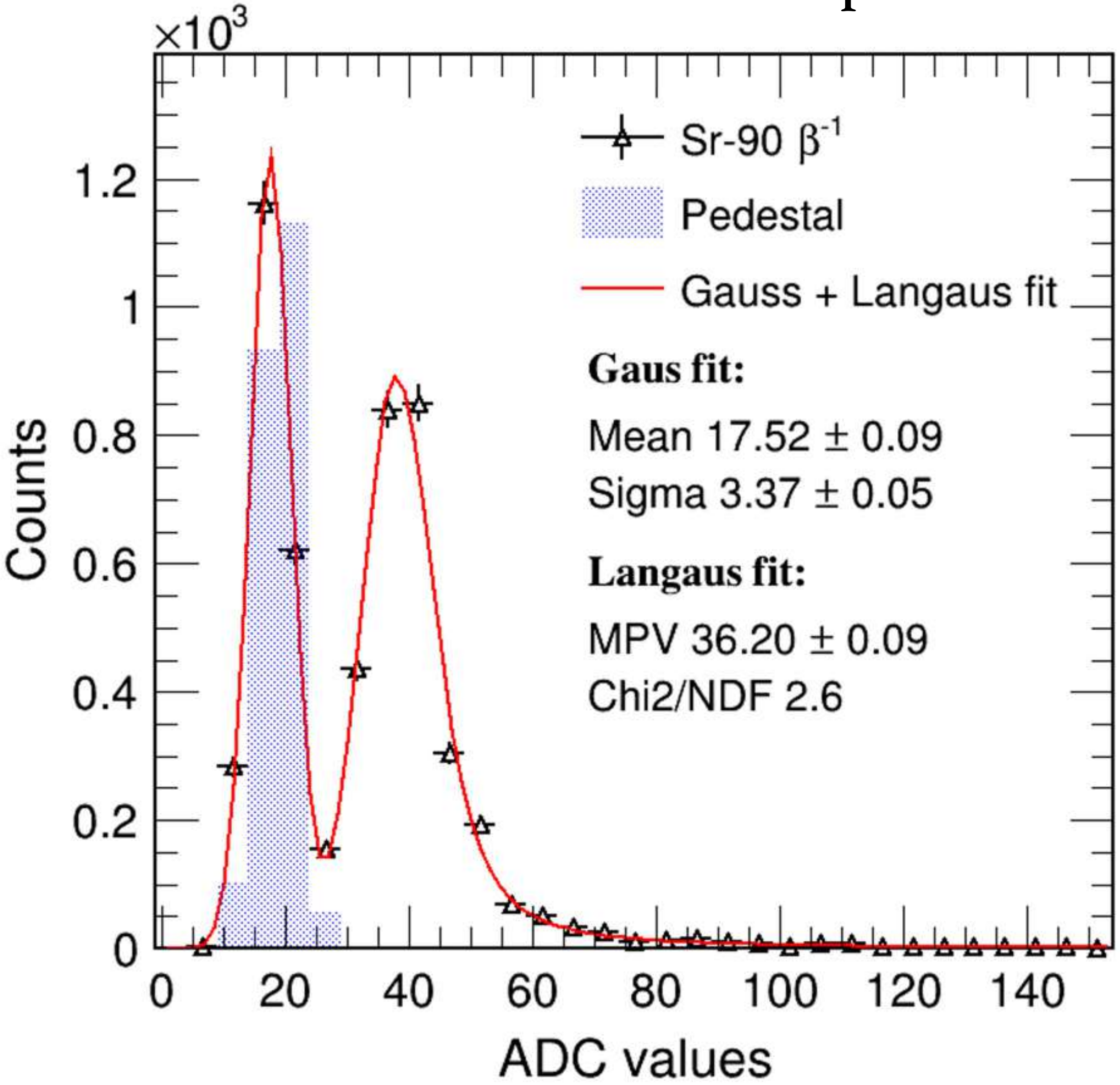

Full depletion ~ 220V

# Test of packaged array with HGCROCv2 chip at NISER

## Test setup at NISER Si

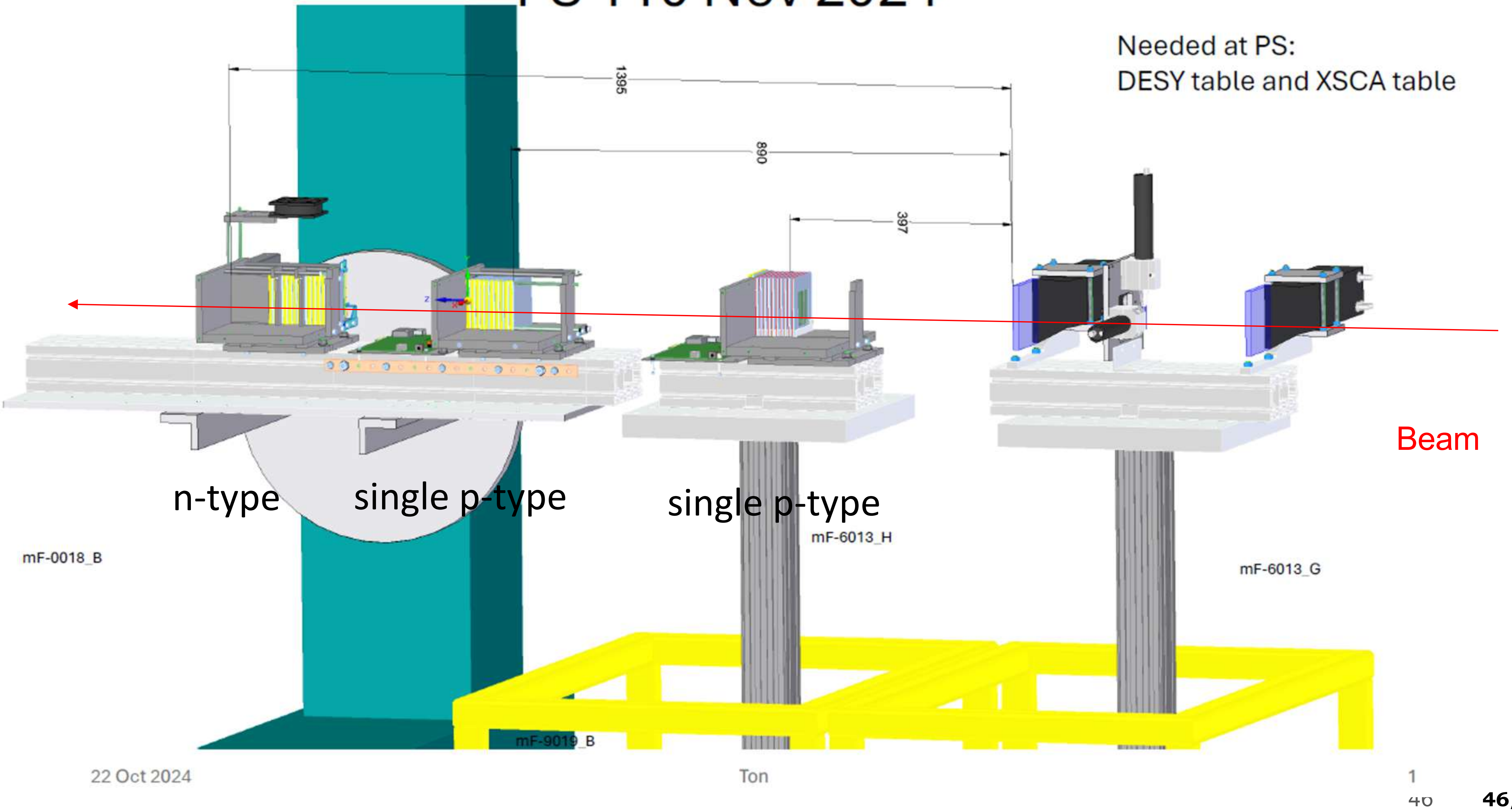



## Sr90 e- source: MIP spectrum

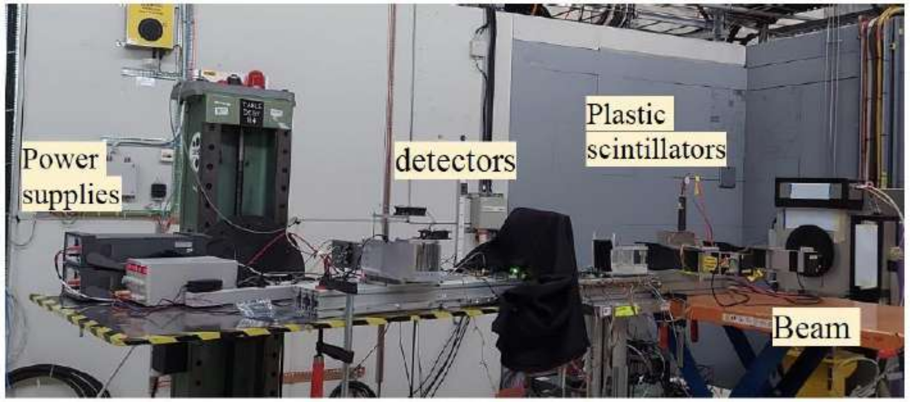


# PS-T10 Nov 2024

Needed at PS:
DESY table and XSCA table



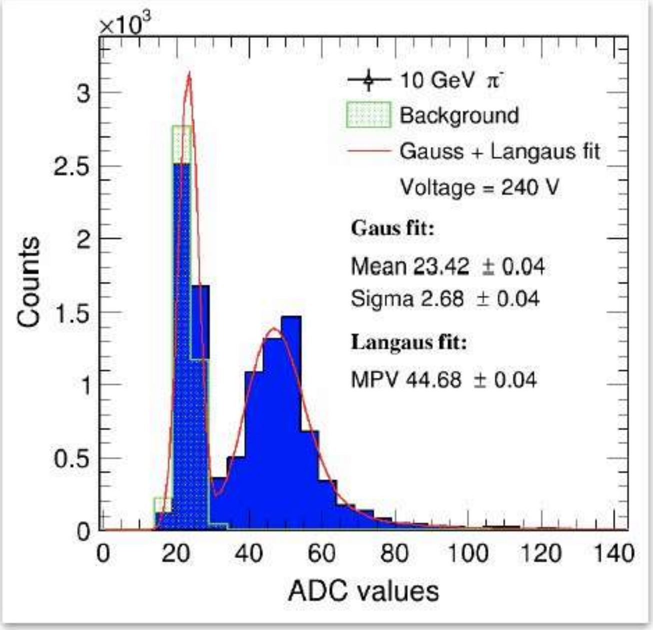
# FoCal-E PAD (India)



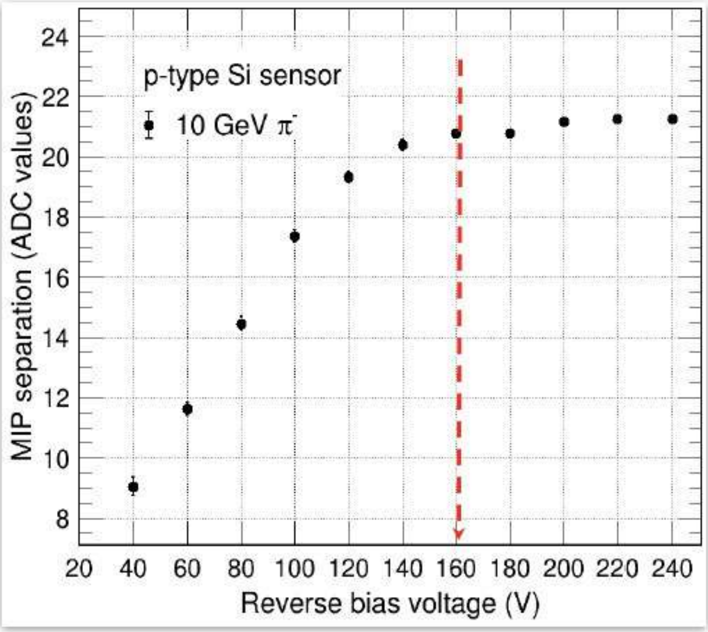


## P-type (SCL) Array: MIP & Voltage Scan for 10 GeV$\pi^-$

Typical MIP distribution




MIP separation vs. Bias voltage

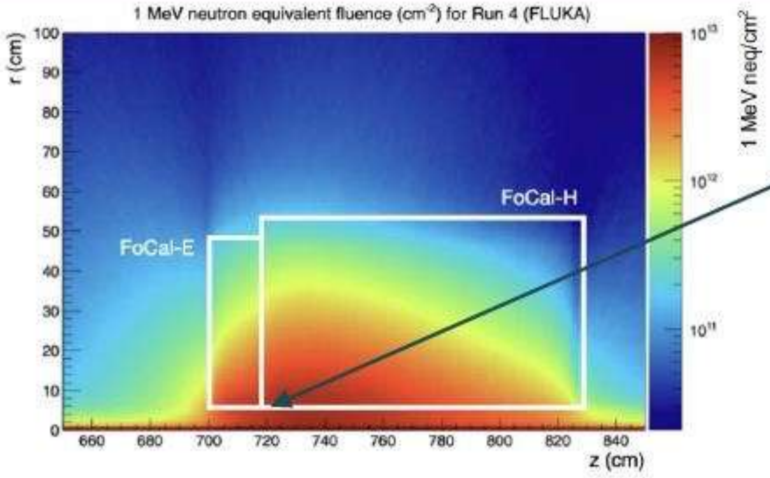



- Observed clear MIP signal using 10 GeV $\pi$-
- Voltage scan confirms the full depletion of the detector ~ 160 V

- Indian produced p-type main sensors
- Tested at CERN PS Oct-Nov, 2024
- presented here from wafer foundry SCL (Chandigarh)

# Pad 2025

## Irradiation campaign 2025 @IRRAD

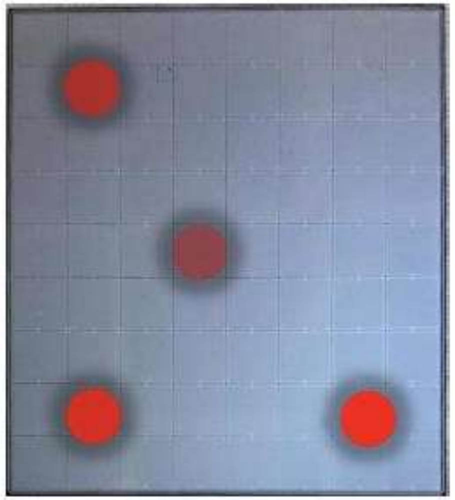



NIEL $\approx$ 7 $10^{13}$ neq / cm$^2$
TID $\approx$ 3.5 Mrad

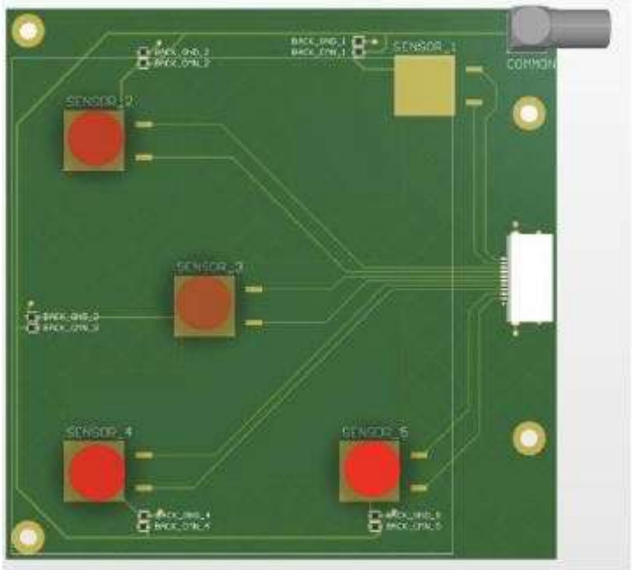
Including a safety factor of 10

New simulations in progress:

- Comparison with Radmon
- Estimation of charge particle flux (for SEE rate)



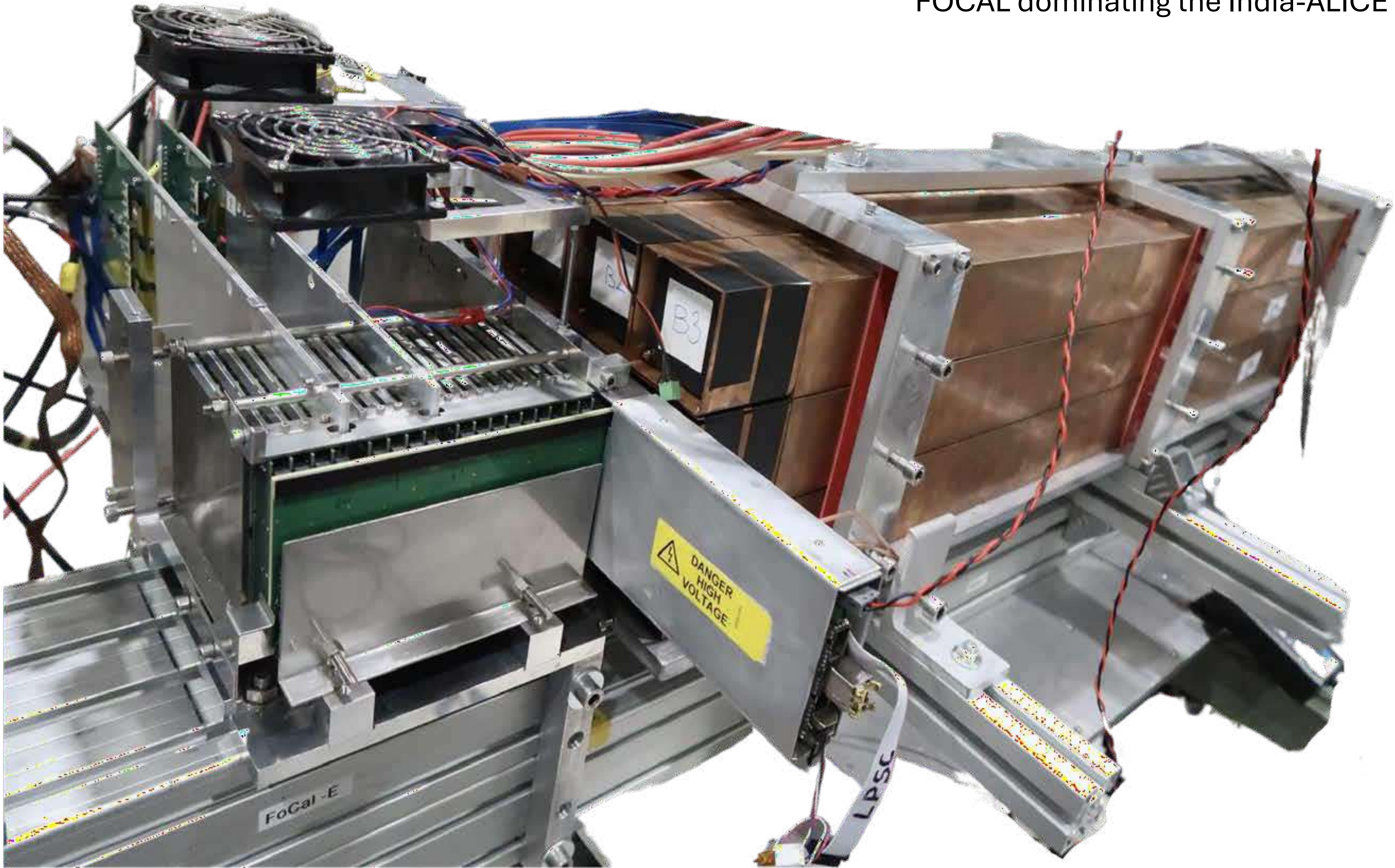
- Full sensors from HPK and SCL characterized before (IV/CV) and after irradiation IV/CV/MIP).
- Some sensors (>2) irradiated at 7 $10^{13}$ neq / cm$^2$
- Full sensors irradiated in spots:
  - Control
  - $\sim 10^{11}$ neq / cm$^2$
  - $\sim 10^{12}$ neq / cm$^2$
  - $\sim$7 $10^{13}$ neq / cm$^2$
  - $\sim$7 $10^{14}$ neq / cm$^2$




1x1 cm$^2$ from HPK and SCL:

- IV/CV before and after irradiation
- IV monitoring during irradiation

FOCAL dominating the India-ALICE activities



# Acknowledgements

Thanks for this opportunity

# Acknowledgements

Department of Science & Technology, Government of India