SMALLGAD: Capacitively-coupled AC-LGAD pixel detector for particle detection

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Outline

- A walk down memory lane : Capacitively Coupled Pixel Detectors
- ENIG deposition and electrode formation on ASIC
- The SMALLGAD Concept
- Possible application for neutron detection at SNS
- Ongoing activities

Capacitive coupling of pixelated detectors

Capacitively Coupled Pixel Detectors (CCPD)

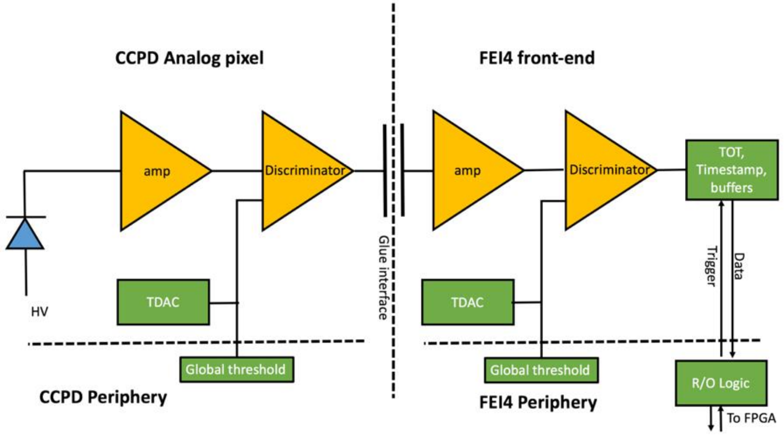
Capacitively-Coupled pixel detectors use thin layers of glue to couple the Active sensor containing amplifier and discriminator to a known readout ASIC:

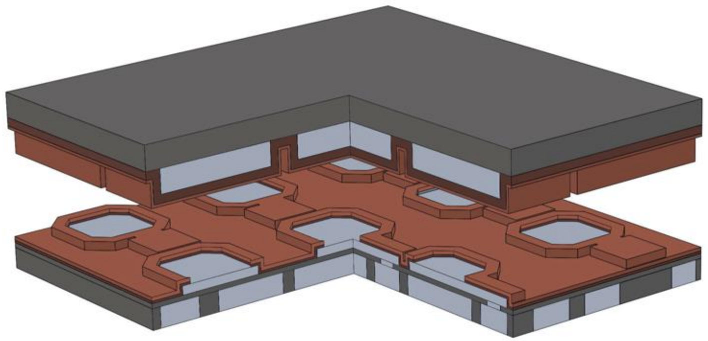
- Possible to study Pixel design while decoupling from readout architecture
- Allows radiation testing of the pixel cell and configuration registers

Multiple prototypes developed in IBM H18 and AMS H35 technologies

HV2FEI4: Proof of concept
CCPDv2: **First radiation hard design**, trial of multiple pixel architecture
CCPDV4: Bug fixes and noise improvement
CCPDv5: Like CCPDv4 but produced **with AMS aH18**
H35DEMO: **Large area sensor with high-resistivity substrate**

$dQ = C\, dV/dt$

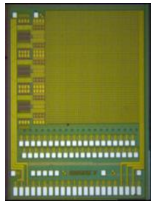




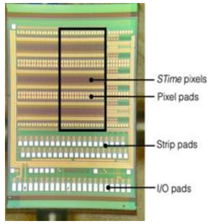
Capacitively-Coupled sensors

CCPDv2

CCPDv3

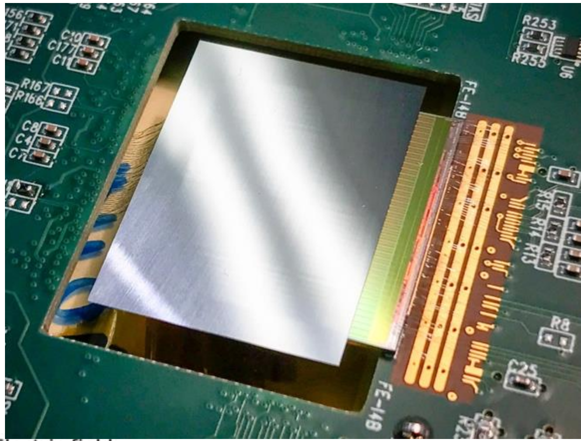


CCPDv4



H35DEMO

CCPD Assembly Process

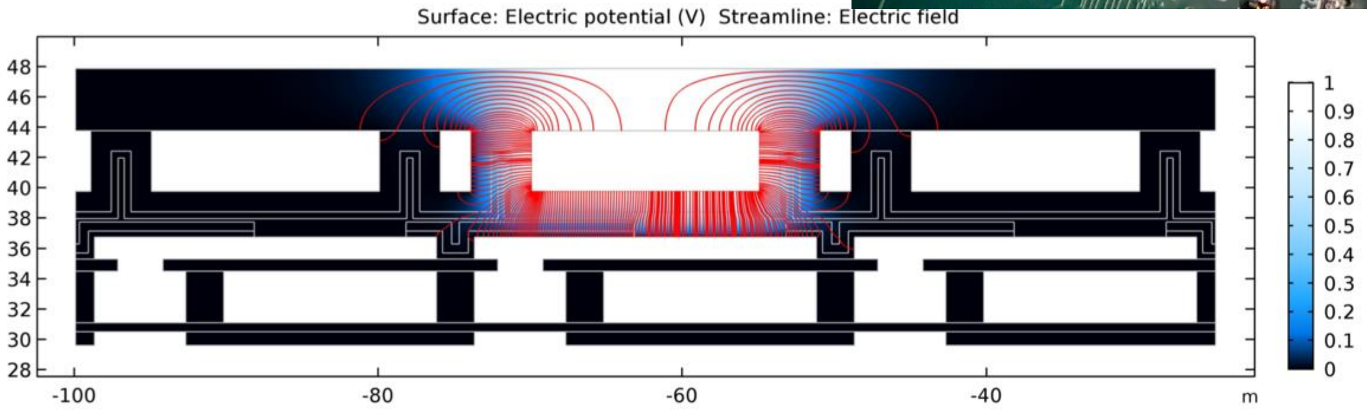


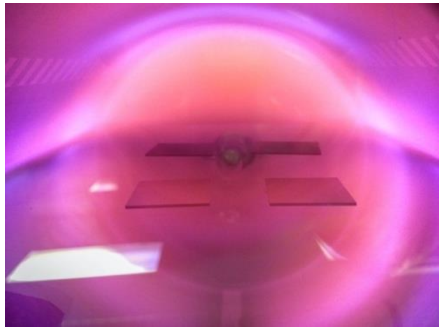
A large effort was undertaken by collaborating groups in ATLAS to develop a reliable process for the gluing of CCPD sensors to their ASIC

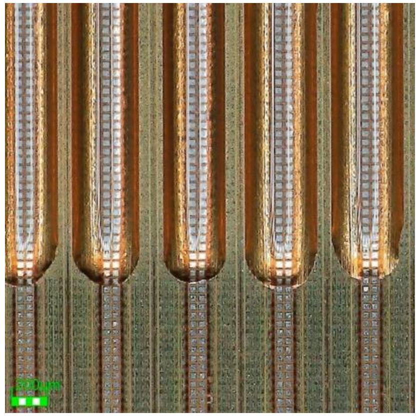
- Optimization of sensor preparation process (probing, gluing)
- Optimization of glue deposition process, flip-chip and curing
- Simulation of Capacitive-Coupling to optimize electrodes for better coupling

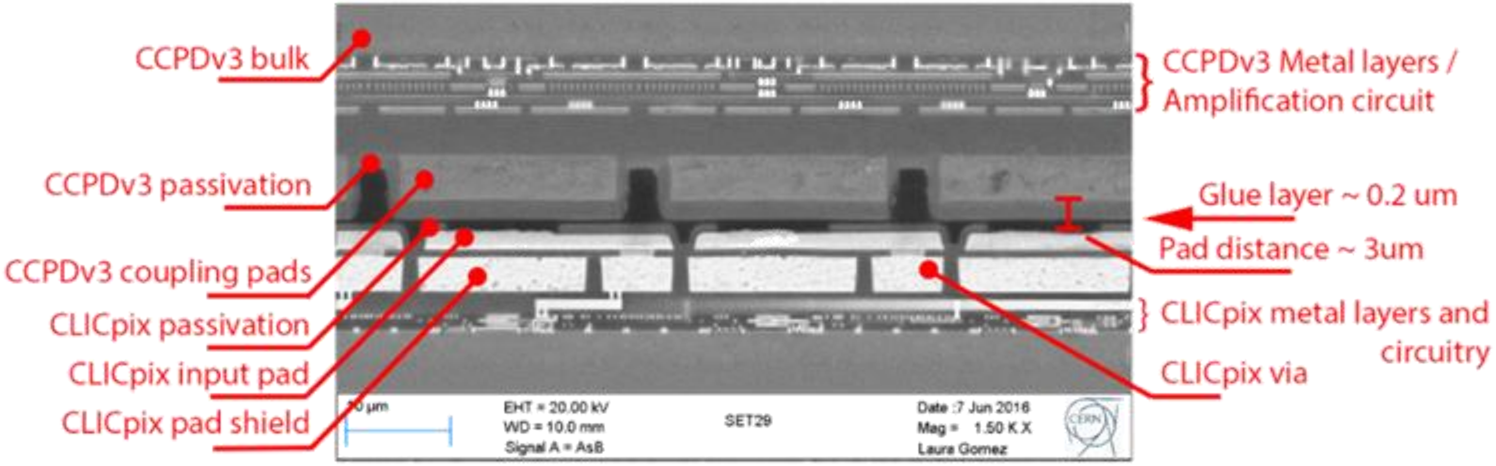
We developed a process that resulted in a good assembly yield (~ 70%) with excellent uniformity of coupling over cm^2, with thickness of glue layer reaching down to 200nm of glue

Finite-element simulations of coupling capacitances in capacitively coupled pixel detectors, M. Vicente et al. , CLCdp-NOTE-2017-003 + PhD thesis









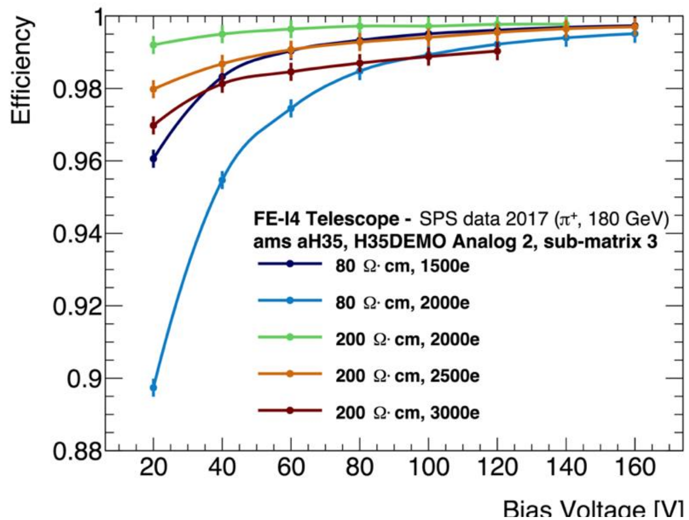
CCPD Characterization

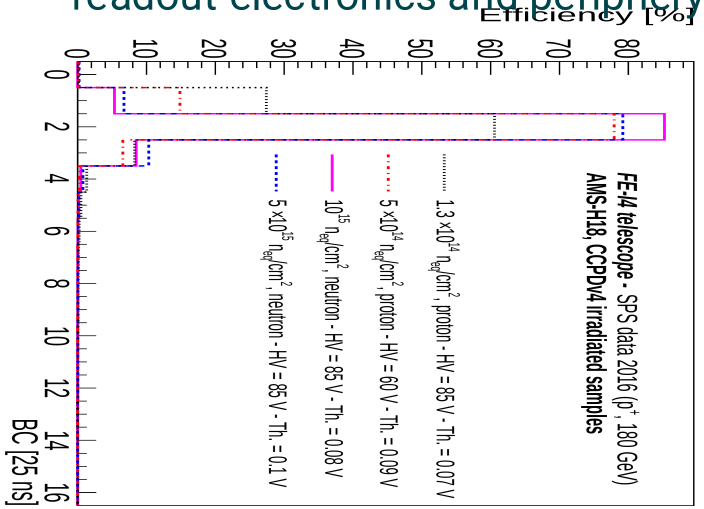
Test beam measurement of ams H35 HV-CMOS capacitively coupled pixel sensor prototypes with high-resistivity substrate, M. Benoit et al., J. Inst. Vol 13 (2018), arXiv:1712.08338

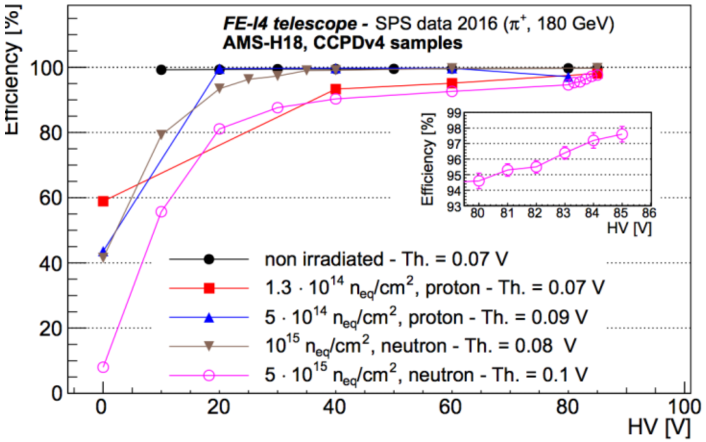
Our characterization work demonstrated for the first time:

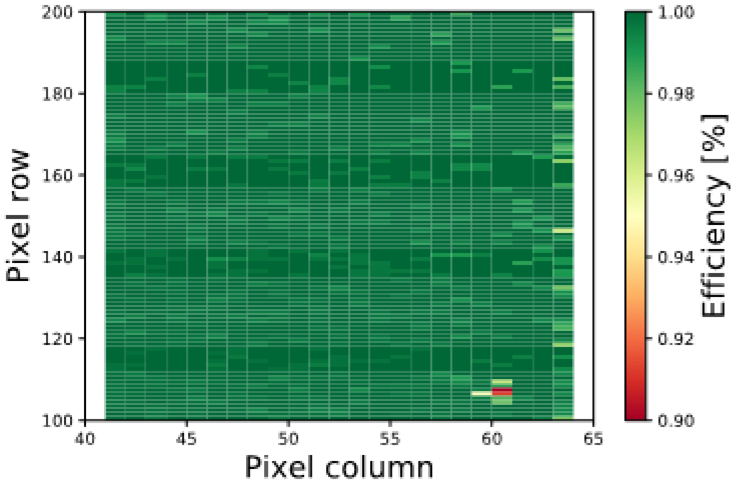
- The **radiation hardness** of the HV-CMOS front-end technology up to $5\text{x}10^{15}$ n_{eq}/cm^2
- The integration of **High-Resistivity substrate** in the HV-CMOS foundry process
- The realization of highly uniform CCPD sensors on **a large area** ($2\text{x}2cm^2$)

The success of the CCPD R&D demonstrated that a large area CMOS matrix can be realized in HV-CMOS technology. The next step towards a fully monolithic detector required us to integrate readout electronics and periphery circuitry.









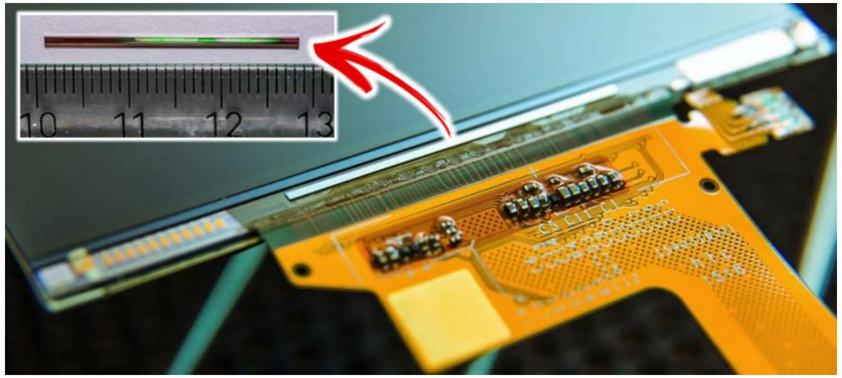
Testbeam results of irradiated ams H18 HV-CMOS pixel sensor prototypes, M. Benoit et al., J. Inst. Vol 13 (2018), arXiv:1611.02669

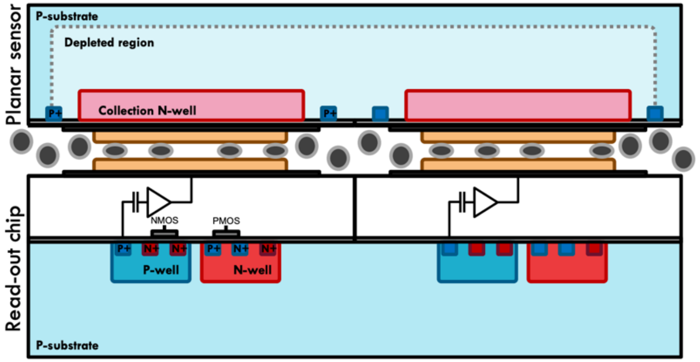
Low-Cost high pitch interconnect technology : ACFs

Anisotropic Conductive Films (ACF)

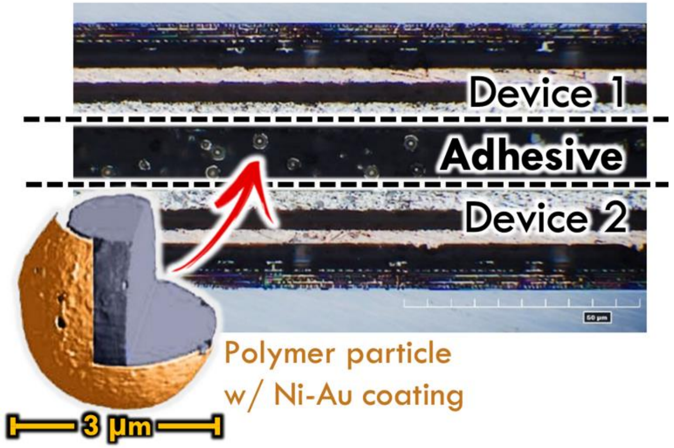
ACF is a technology developed for the LCD Display industry to connect drivers to each pixel row. Next step in the industry is μLED, which are driven individually and can measure as little as 15x15μm^2. Medipix and CLIC have been working with industry partners to adapt this process to pixel sensors

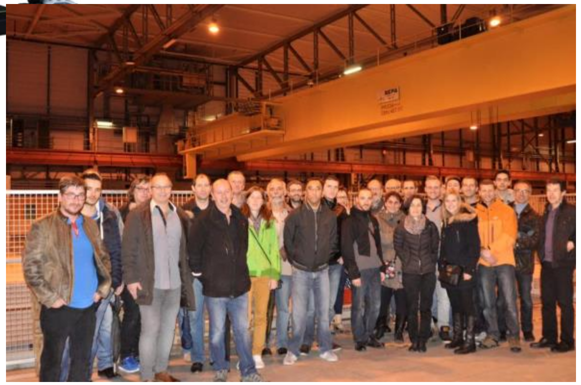
- Low cost, no lithography involved
- Wafer processing for pillar (ENIG) can be done in house with modest equipment

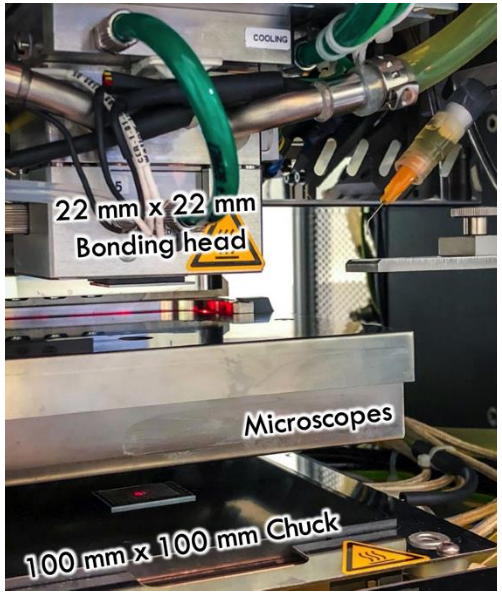




Bonding cross-section







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FC150 Flip-Chip bonder

FC150 Automatic Flip-Chip Bonder

$\pm$ 1 µm post-bond accuracy and 20 µradian leveling

Up to 150 mm substrate and chip bonding for chip-to-chip and chip-to-wafer bonding

Bonding force up to 2000 N and temperature up to 400 $°C$

Active leveling using laser alignment and auto-collimation

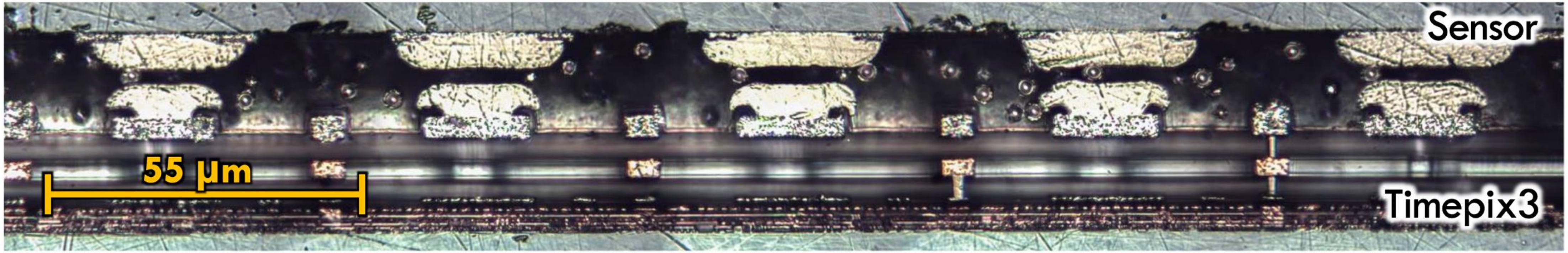
Fully automated bonding process capable

High-precision fluid dispenser integrated for accurate fluid application during bonding

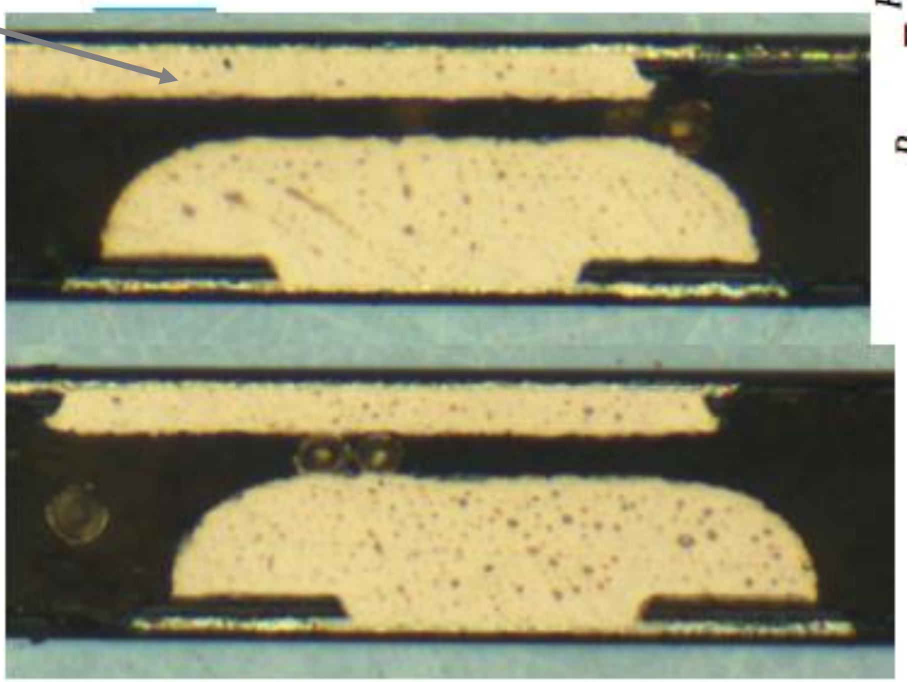
$2M investment from ORNL on prober and flip-chip lab

ACF results

Timepix3-ACF-sensor assembly cross-section



Pads can be planarized via Chemical-Mechanical polishing



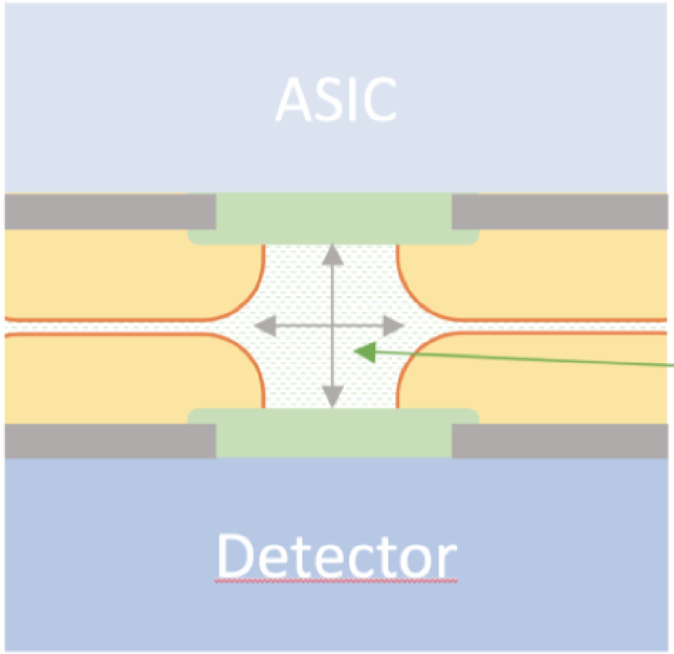


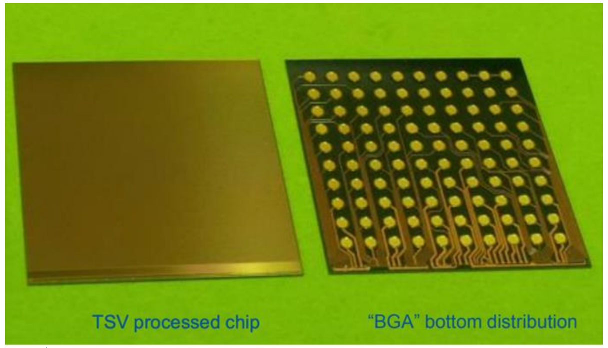
Figure 9: Bump height and available area for squeeze film flow

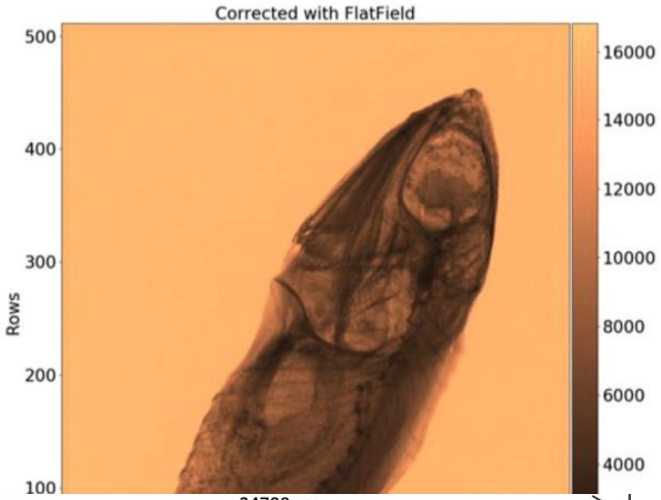
Area available for squeeze flow

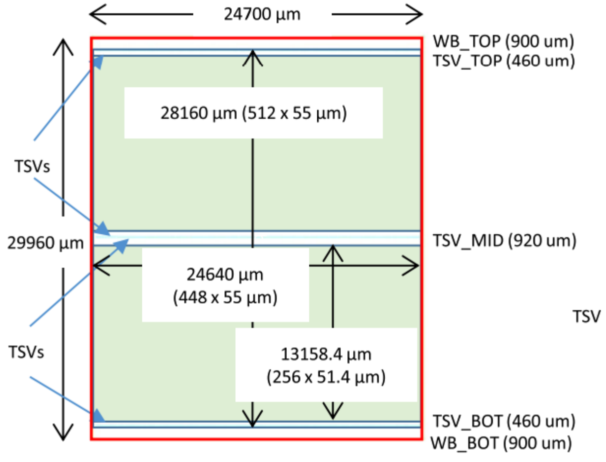
Inter-pad adhesive provide mechanical stability

Timepix4 ASIC

- 55 x 55μm^2 pixels
- 448 x 512 pixel matrix, 24.7x 30 mm
- ToT (16 bit counter,~1.5 keV) and ToA(<200 ps)
- ~3.6Mhz/mm^2/s hit rate capability
- ~800e threshold
- 4 side buttable using TSV connections







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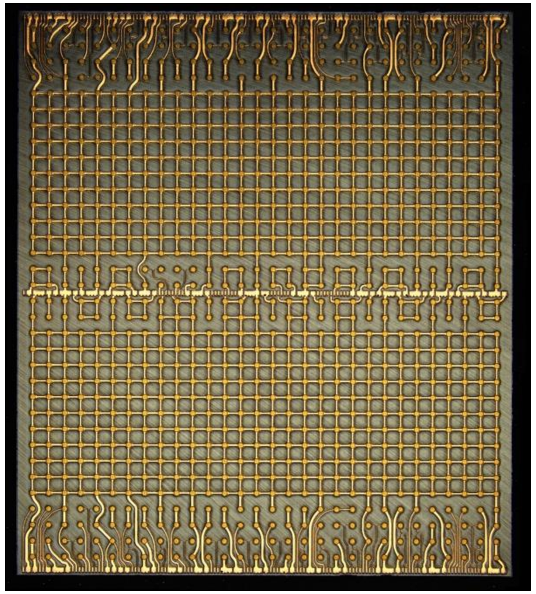

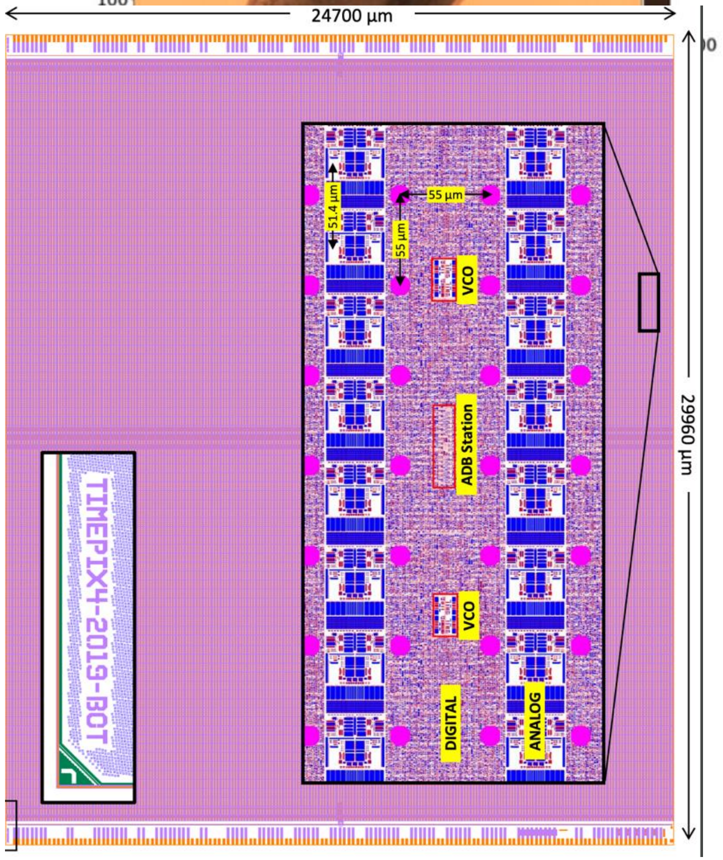

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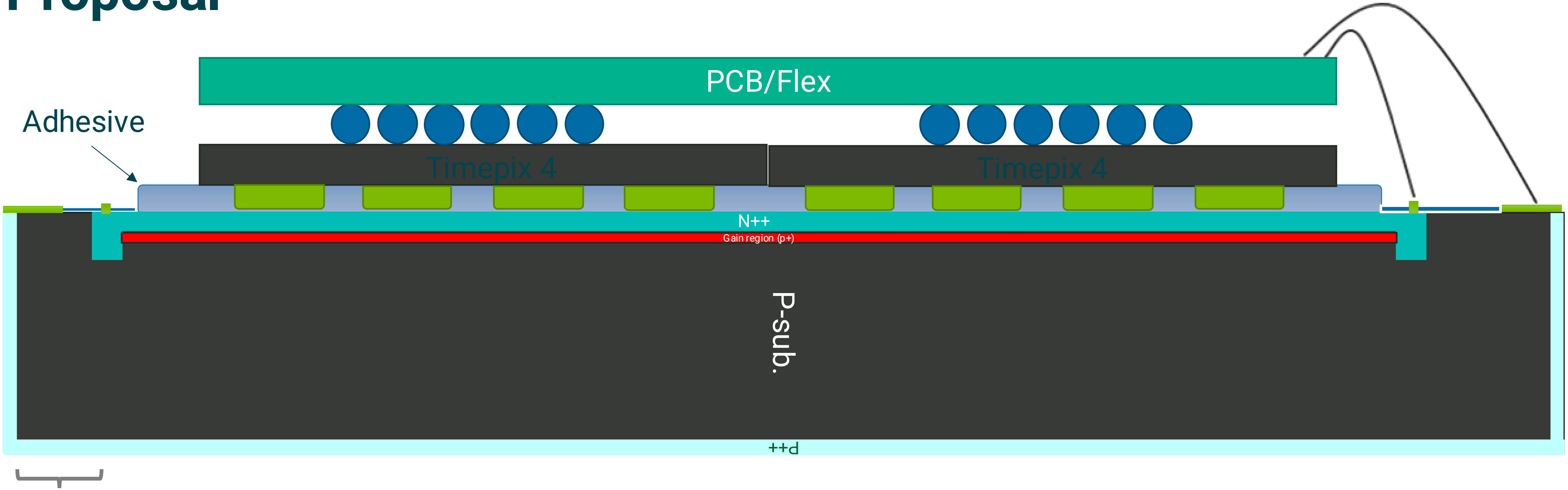
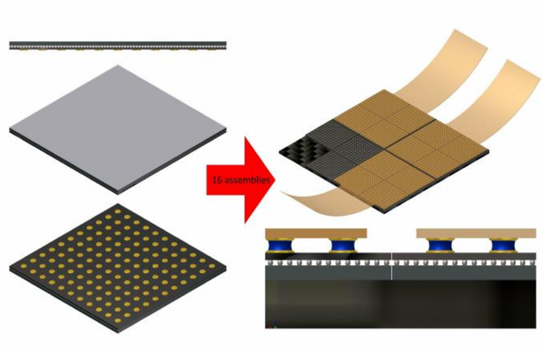
https://iopscience.iop.org/article/10.1088/1748-0221/17/01/C01044/pdf

The Pixelated AC-LGAD concept

Proposal





we can achieve capacitive coupling and transmit signal with good efficiency via a thin adhesive layer

- **No electrode required** on the AC-LGAD side, making it a simpler structure to manufacture.
- AC Coupling can be achieved via a combination of **thin oxide-adhesive layer, ENIG pads from ACF experience**
- **No complex interconnect** method necessary, no lithography
- Multiple ASIC can be tiled on a **large area AC-LGAD**

Capacitive coupling optimization

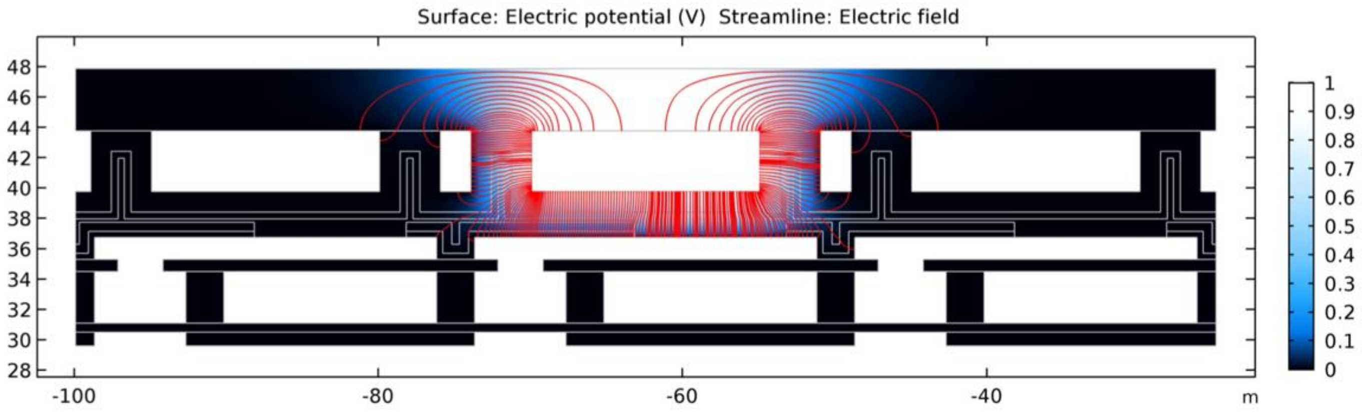
$$\frac{dQ}{dt} = C\frac{dV}{dt}$$

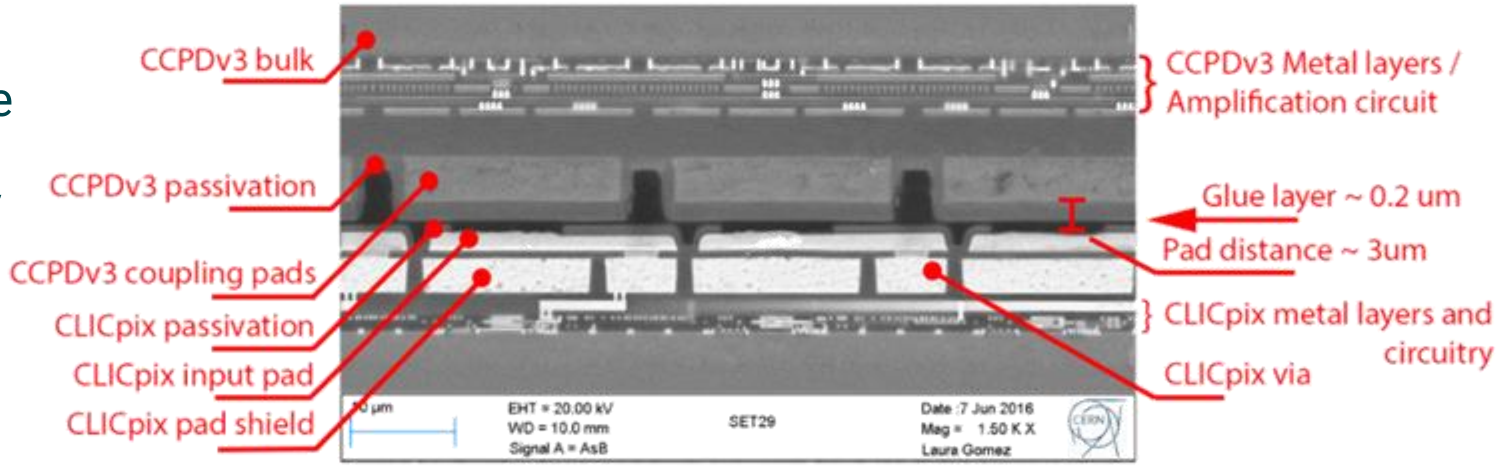
The coupling strength can be optimized for an application via :

- Oxide thickness between ENIG pads and implant
- Adhesive thickness and dielectric properties

Some application with large energy deposition might benefit from signal attenuation while the coupling can be maximized for low energy applications.

The amount of charge sharing can also be optimized via sensor design, by changing the collection electrode implant resistivity





Neutron detection with B10 coated LGADs

Timepix family chip have been routinely used in neutron detection application with Silicon sensors using converter films (B10,LiF,Plastic)

Alpha particles and recoil ions produced by the neutron capture deposit large amount of energy in the sensor, resulting in large clusters in the matrix

- A lot of information is available to determine the precise position of the interaction
  - Charge weighting methods, Machine-learning can be used to reach sub pixel resolution, cope with high occupancy
  - LGAD gain can enhance further the charge spread via diffusion and electrostatic repulsion and increase the spatial resolution

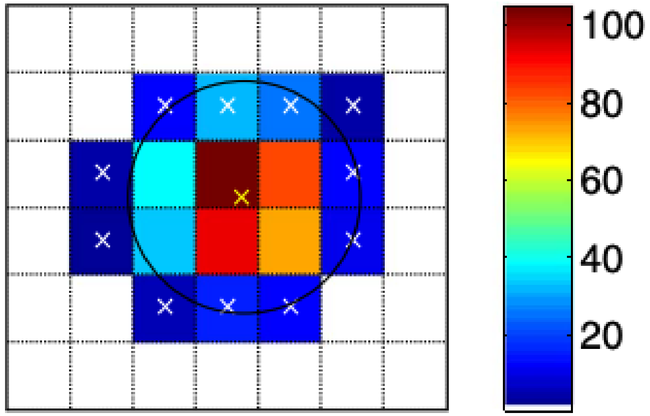
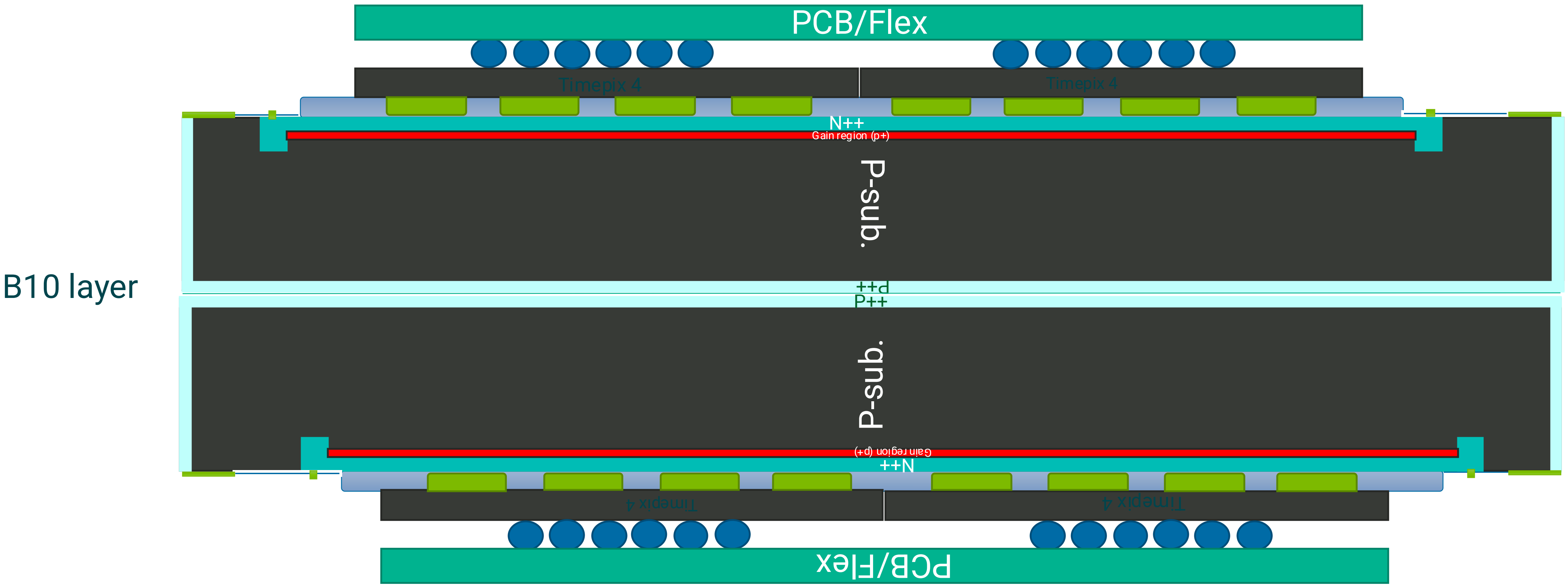


FIG. 3. Discrete Gaussian track imaged by Timepix. The color represents the energy deposited in each pixel. The border pixels are labeled by white crosses. This track has parameters (Tables I and II): *Area* = 17, *Maximum distance from the circle* = 0.51, *Roundness* = 0.78, *Cluster volume* = 0.59 MeV, *Registered amplitude* = 103 keV.

$$^{10}B + n \begin{array}{l} \rightarrow \alpha_1^*(1.47MeV) + {}^7Li^*(0.84meV) + \gamma \\ \rightarrow \alpha_0(1.78MeV) + {}^7Li(1.01MeV) \end{array} .$$

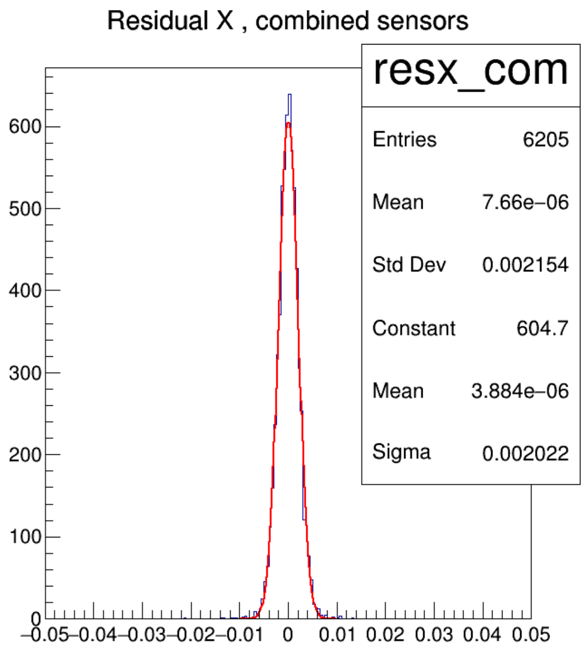
Double sided AC-LGAD hybrid for neutrons

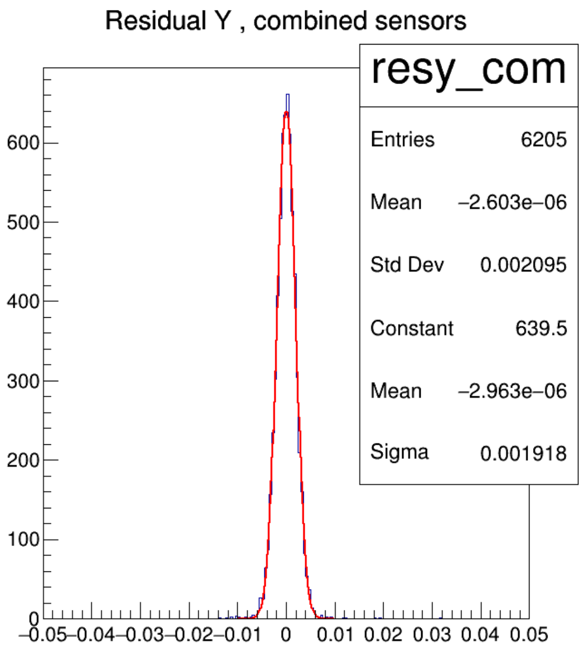


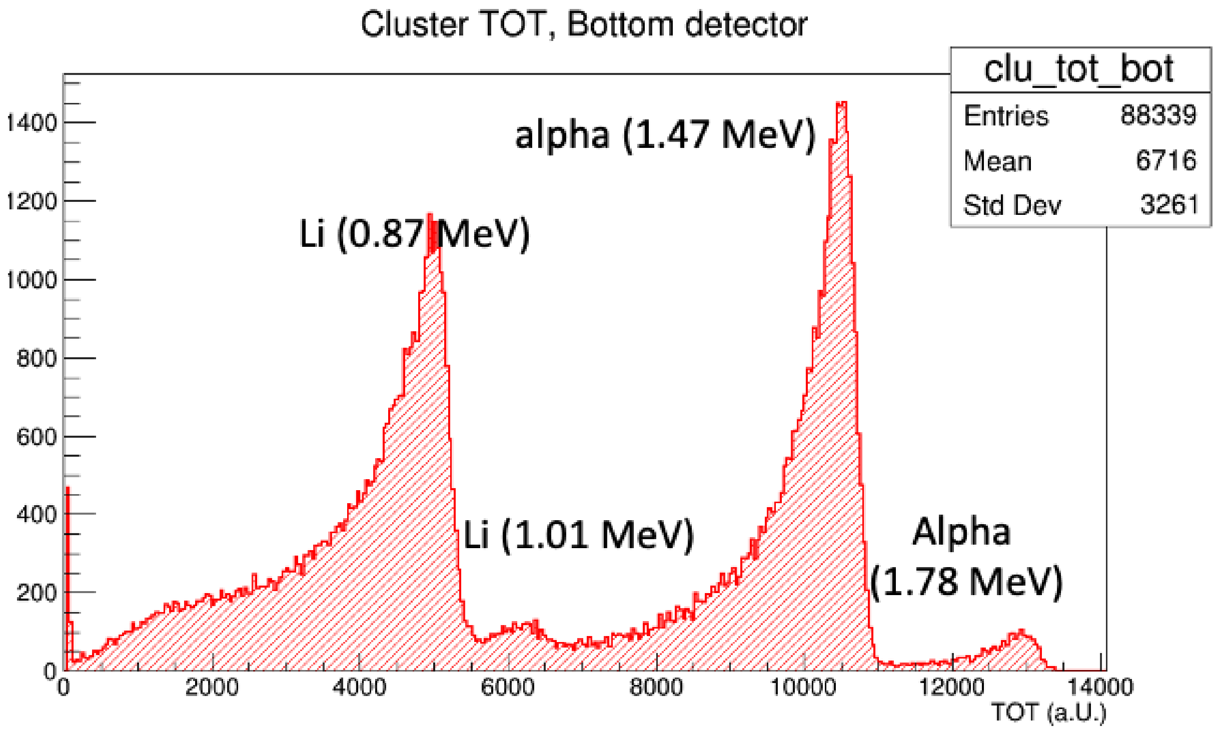
Capturing both side of interaction offer more information on kinematic

$$^{10}B + n \begin{cases} \rightarrow \alpha_1^*(1.47MeV) + {}^7Li^*(0.84meV) + \gamma \\ \rightarrow \alpha_0(1.78MeV) + {}^7Li(1.01MeV) \end{cases}.$$

Neutron detection double sided Timepix simulation







Detailed simulation of the Timepix4 geometry with non-LGAD Silicon sensors show a **resolution of < 2 μm can be achieved by simple charge weighting**

AC-LGAD with enlarged clusters has potential to achieve even better resolution.
Clustering and hit reconstruction using FPGA/ML/AI possible , in case of high data rate

SMALLGAD activities ongoing

- Working on subcontract with BNL for fabrication of a wafer run with Timepix4 size sensors, both with pixelization and without
  - Challenge in realizing LGAD gain layer with good uniformity on large area
  - We hope to get sufficient yield for a proof-of-principle prototype assembled at BNL using capacitive coupling
- We had discussion @ CERN with Timepix4 Collaboration to participate to next round of Through-Silicon-Vias (TSV) processing of the next spin of Timepix4 with IZM in FY25
  - First trial at processing full 300 mm wafers
  - ASIC with TSV have almost no dead area , perfect for tiling large area sensors
  - Wirebond-less interface to Timepix4 already demonstrated with ACF that could be done with the FC150 at ORNL

Outlook

- The SMALLGAD Concept derives from past experience in capacitive coupling of pixel detector with built-in amplification (gain)
- This concept could greatly simplify the bonding process for AC-LGAD and provide a cost-effective method to mate ASIC and sensor in application such as TOF detector at EIC and beyond.
- We are aiming at leveraging our involvement in the timepix4 Collaboration to also study large area LGAD detectors and simplify integration of the sensor and ASIC
- We are looking for collaborator for simulation, testing and to provide other ASIC that we could mate to the detector for testing!

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