

Silicon Sensors Development: Tracking, Timing, and X-ray Applications

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Silicon Detector Colloquium
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Hamburg



[Wikimedia]

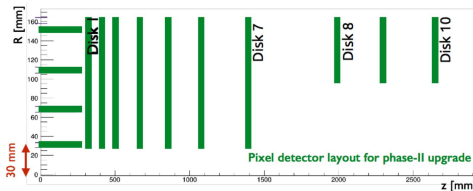
Tracking

CMS Phase II Pixel Upgrade

2025 – 2035: HL-LHC $L = 5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, $\mu = 140$, $\int L = 3000 \text{ fb}^{-1}$

→ **New pixel** and tracker detectors

Possible layout



Detector

- 4 barrel layers
- 10 end-cap disks
- Coverage $|\eta| < 4$
- Area $\approx 4 \text{ m}^2$
- Minimum radius 30 mm

Readout chip

- Ionizing dose $\approx 10 \text{ MGy}$
- Threshold $\approx 1000 \text{ e}^-$
- 65 nm process
- RD 53 collaboration

Sensor

- Pixel 50×50 or $25 \times 100 \mu\text{m}^2$
- $\Phi_{eq} = 2 \cdot 10^{16} \text{ cm}^{-2}$
- Ionizing dose $\approx 10 \text{ MGy}$
- Sensors under study:
 - 3D
 - Thin planar ($75 < d < 200 \mu\text{m}$)

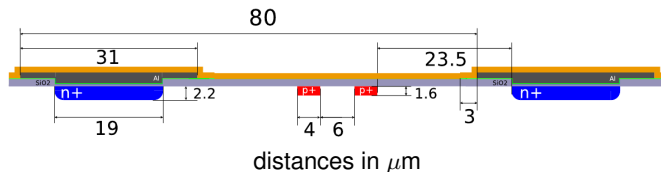
Sensors

No rad-hard (enough) pixel chip
⇒ study strips

Strip

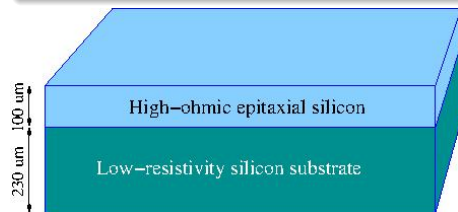
- Epitaxial silicon, p- and n-bulk
- **100 μm active thickness** (1 – 1.5 k Ωcm)
- **Irradiation** with 800 MeV/c and 24 GeV/c **protons**
- Fluences up to **$1.3 \cdot 10^{16} \text{ cm}^{-2}$**
- Also sensors with 200 μm thickness irradiated to $1.3 \cdot 10^{16} \text{ cm}^{-2}$

Strip cross section



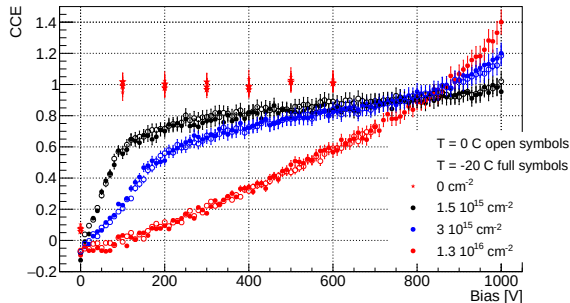
Pad diodes

- 100 μm active thickness
- Same bulk as strips

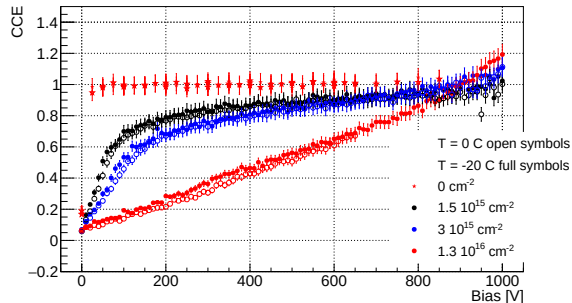


Diode Measurements: CCE

P-bulk



N-bulk



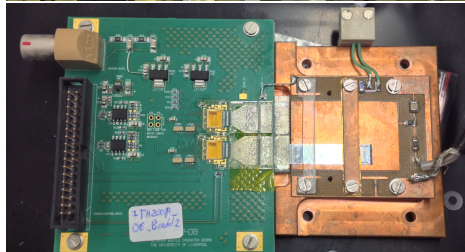
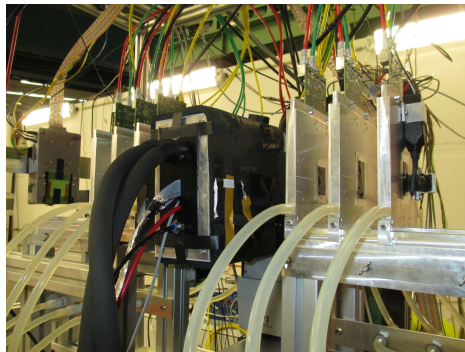
- IR laser
- eh pairs in the whole sensor depth
- $\Phi_{eq} \geq 3 \cdot 10^{15} \text{ cm}^{-2}$
 - CCE > 1 at high voltage
 - Effect more pronounced in p-bulk
 - **Charge multiplication**

$$CCE = \frac{Q(\Phi_{eq}, V)}{Q(0, V > V_{dep})}$$

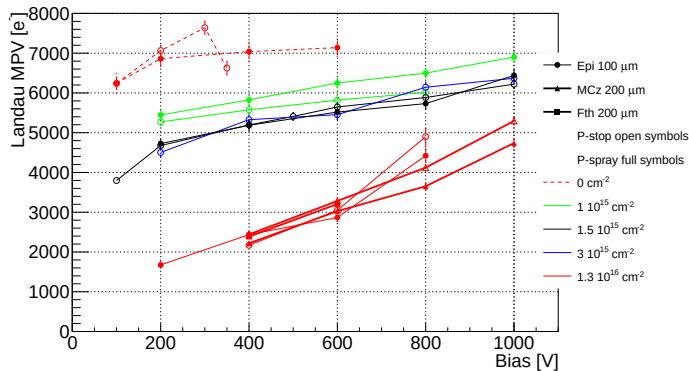
- $\Phi_{eq} = 1.3 \cdot 10^{16} \text{ cm}^{-2}$
 - No clear depletion voltage

Beam Test of Strip Sensors: Setup

- DESY II facility
- 5 GeV/c electrons / positrons
- EUDET/AIDA beam telescope
- Cooling down to -28°C
- ALiBaVa readout system
- **Avoid thresholds**
 - ⇒ use telescope tracks to define clusters
- Noise hits in n-bulk sensors
 - **results from p-bulk sensors**



Signal



100 μm sensors:

- Similar behavior for $\Phi_{eq} \approx 10^{15} \text{ cm}^{-2}$
- Steep rise of signal with bias for $\Phi_{eq} = 1.3 \cdot 10^{16} \text{ cm}^{-2}$

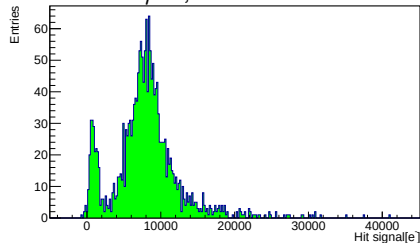
200 μm sensors:

- Higher bias required to achieve same signal as 100 μm sensors

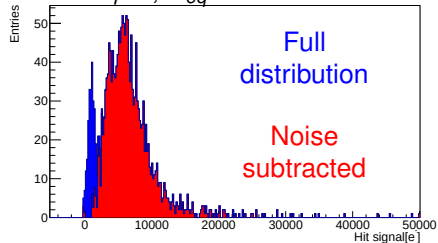
Detection Efficiency

Seed strip charge distribution

100 μm , Non-irradiated



100 μm , $\Phi_{eq} = 3 \cdot 10^{15} \text{ cm}^{-2}$



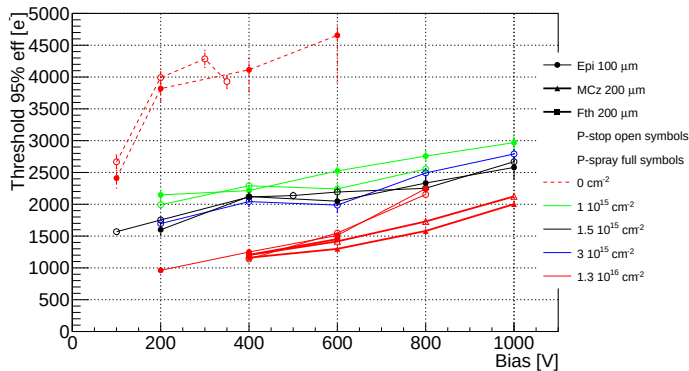
Seed strip: strip with highest signal in a cluster

Zero suppression using threshold

How high can it be?

- Seed strip distribution
- Noise subtraction
- Cut to maintain 95% entries
- Limited to 95% due to noise subtraction and statistics

Threshold to Maintain 95% Efficiency



100 μm sensors:

- Threshold of $\approx 2500 \text{ e}^-$ at $\Phi_{eq} \approx 10^{15} \text{ cm}^{-2}$
- Threshold of $\approx 2000 \text{ e}^-$ at $\Phi_{eq} = 1.3 \cdot 10^{16} \text{ cm}^{-2}$

200 μm sensors:

- Threshold of $\approx 2000 \text{ e}^-$

RD 53 chip threshold $\approx 1000 \text{ e}^-$

Looking Back



[freepik]

- This study (with many others) reinforced the case for thin silicon sensors for HL-LHC
- The results of the collected charge for 100 μm sensors are quoted in the TDR: The Phase-2 Upgrade of the CMS Tracker
- ATLAS and CMS are going to use thin ($\sim 100\text{-}150\ \mu\text{m}$) and 3D sensors for their pixel detectors

Geneva



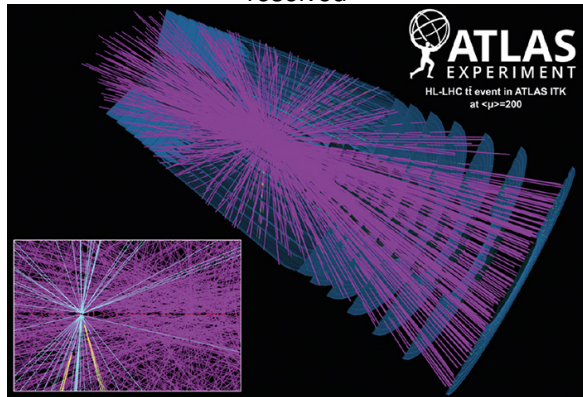
[Wikimedia]

Timing

Minimum Ionizing Particle Timing

- Tracking
- Calorimetry
- PID
- **Counteract HL-LHC pile-up**
200 p-p collisions per bunch crossing
collisions time spread ≈ 180 ps
time resolution on track ≈ 30 ps
 $\Rightarrow$ disentangle primary collisions
- Different devices: silicon detectors, gas detectors, etc.
- Many active groups

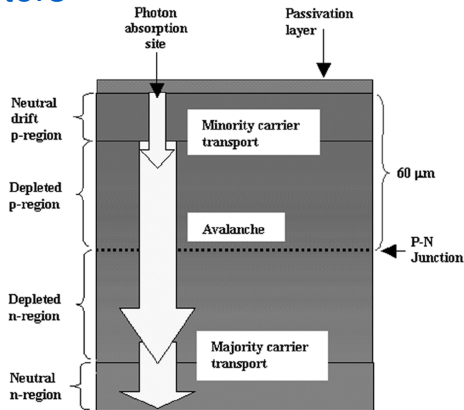
HL-LHC: With the current vertex resolution a significant fraction of the vertices will not be resolved



Technical proposals for MIP timing detectors: ATLAS collaboration[\[1\]](#), CMS collaboration[\[2\]](#)

Deep Diffused Avalanche Photo Detectors

- Charge multiplication
- Gain: ≈ 500
- Bias: ≈ 1800 V
- Never fully depleted
- Die dimensions: $10 \times 10 \text{ mm}^2$
- Nominal active area: $8 \times 8 \text{ mm}^2$
- Thickness: $230 - 280 \mu\text{m}$
- Custom fabrication process
- Produced by Radiation Monitoring Devices (RMD)

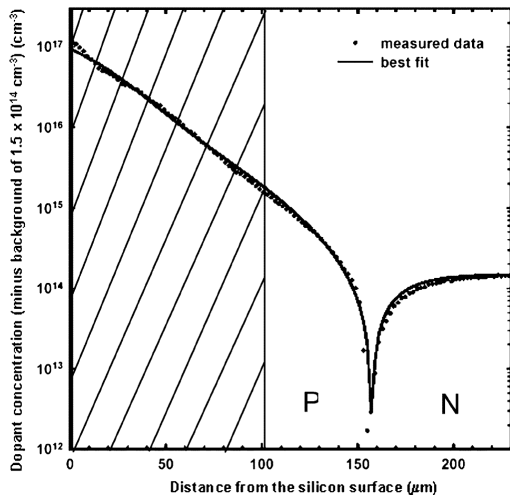


- Diffusion (non-depleted Si)
- Drift (depleted Si)
- Multiplication

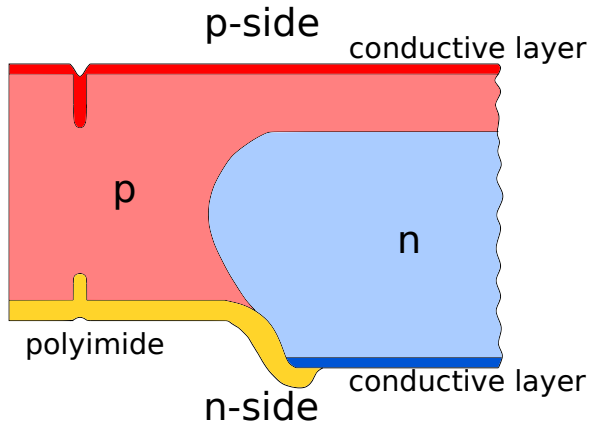
M. McClish et. al. IEEE Trans. Nucl. Sci. Vol. 53, No. 5, 2006 [\[1\]](#)

Deep Diffused Avalanche Photo Detectors

Doping profile

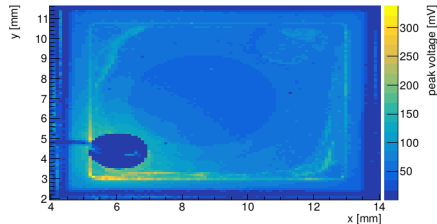


Section (not to scale)

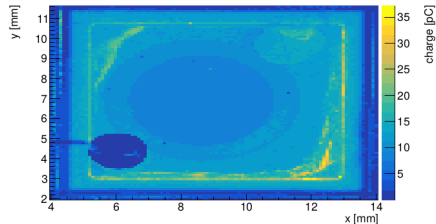


M. McClish et. al. IEEE Trans. Nucl. Sci. Vol. 53, No. 5, 2006 [\[1\]](#)

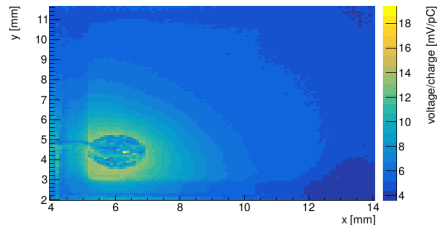
$8 \times 8 \text{ mm}^2$ APDs Uniformity with Laser



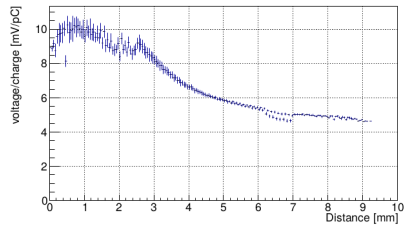
(a) Amplitude



(b) Integrated signal



(c) Ratio

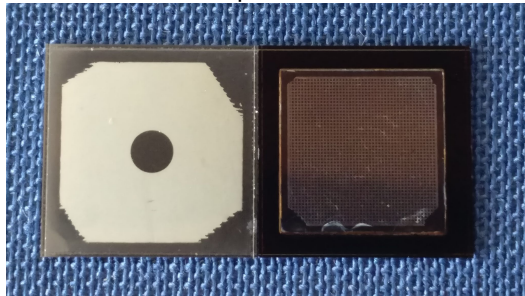


(d) Ratio vs distance

$8 \times 8 \text{ mm}^2$ APDs

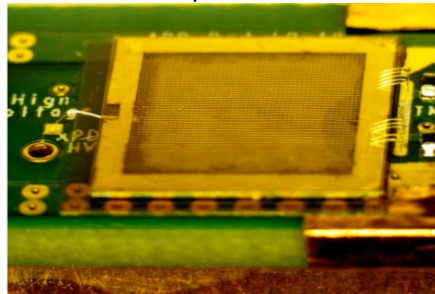
Uniformity of response improved through metallization or mesh readout

DC coupled readout



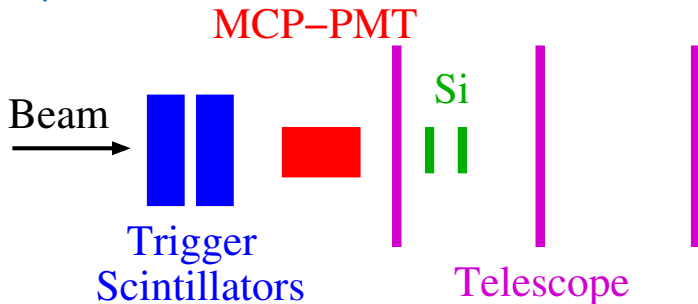
- Aluminum deposited on both sides
- Metallization on single dies at CMi-EPFL

AC coupled readout



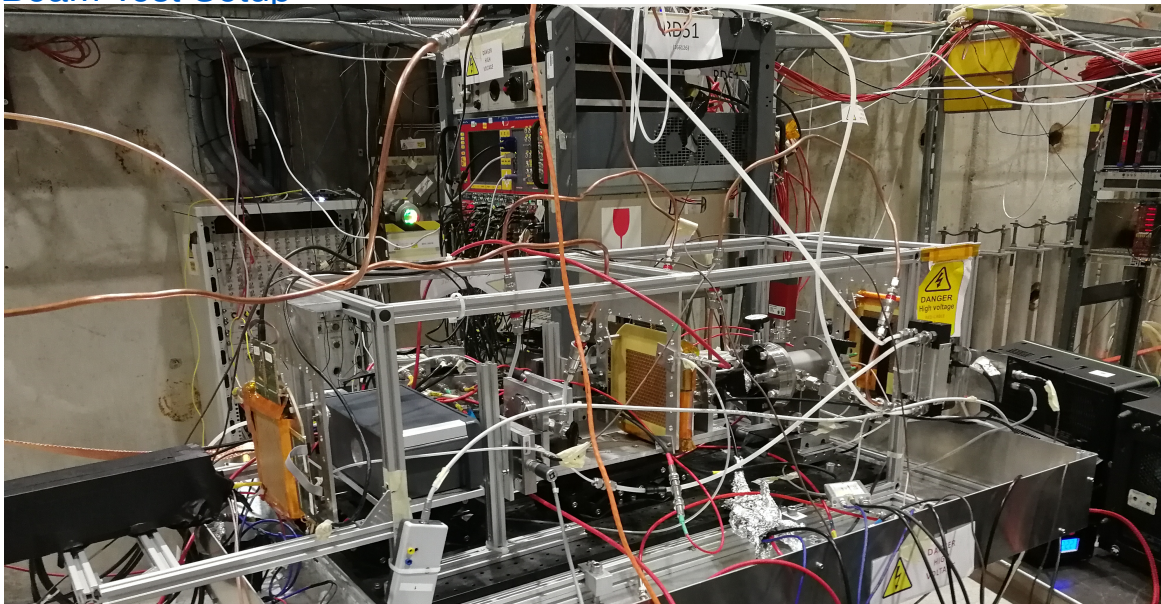
- Mesh on Kapton layer
- Sintered gold on back side
- Studied in previous beam tests ($\sigma_{\Delta t} = 19 \text{ ps}$)
S. White, CHEF 2013 [🔗](#)
J. Va'vra, NIMA 876 (2017) 185-193 [🔗](#)

Beam Test Setup



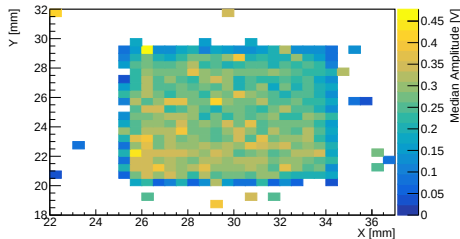
- 100 GeV μ , CERN North Area, H4 beamline
- Amplifier: CIVIDEC 2 GHz 40 dB
- Oscilloscope: Agilent 2.5 GHz 10 Gs/s
- Readout configuration not optimal for timing (due to mechanical constraints)
- Tracking and timing provided by RD51
- MCP-PMT signal shaped to have a few points on leading edge

Beam Test Setup

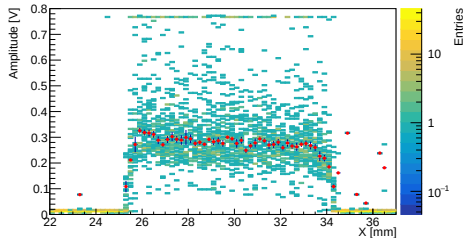


Metallized $8 \times 8 \text{ mm}^2$ APD, 1775 V, 100 GeV μ

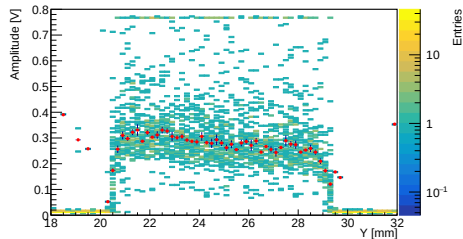
Median Amplitude



Section X (between horizontal lines)



Section Y (between vertical lines)

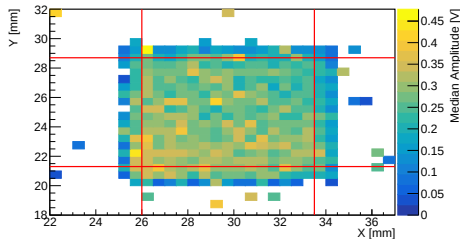


Red points: Median amplitude, excluding events below threshold or saturating the scope scale

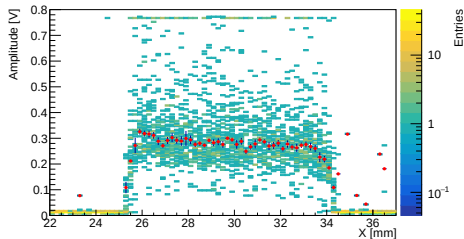
Improved uniformity over the detector

Metallized $8 \times 8 \text{ mm}^2$ APD, 1775 V, 100 GeV μ

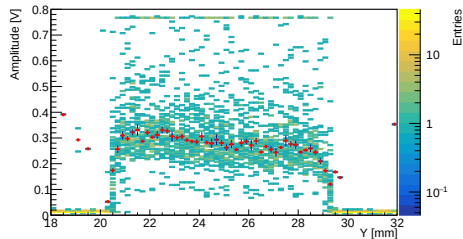
Median Amplitude



Section X (between horizontal lines)



Section Y (between vertical lines)

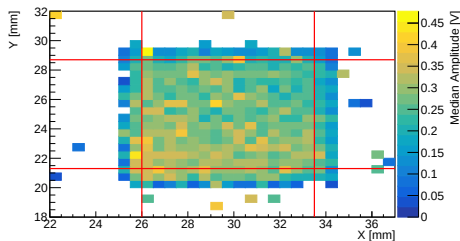


Red points: Median amplitude, excluding events below threshold or saturating the scope scale

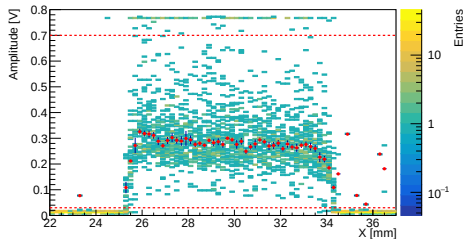
Improved uniformity over the detector

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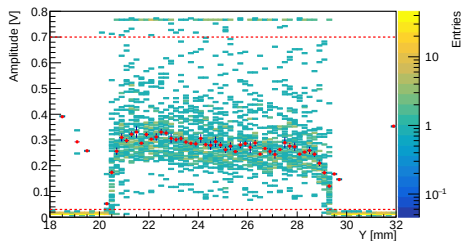
Median Amplitude



Section X (between horizontal lines)



Section Y (between vertical lines)

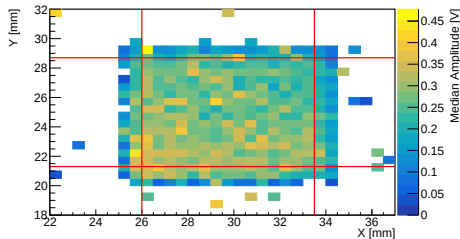


Red points: Median amplitude, excluding events below threshold or saturating the scope scale

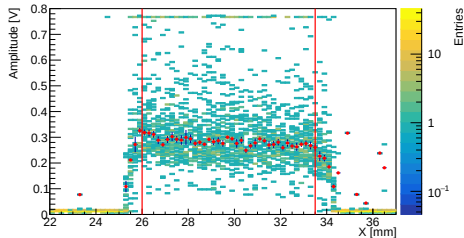
Improved uniformity over the detector

Metallized $8 \times 8 \text{ mm}^2$ APD, 1775 V, 100 GeV μ

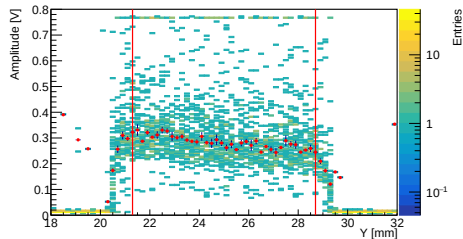
Median Amplitude



Section X (between horizontal lines)



Section Y (between vertical lines)



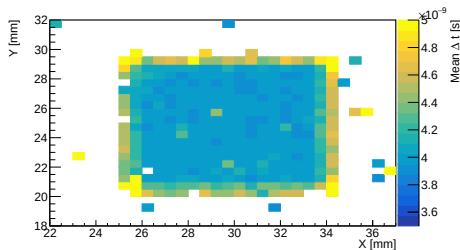
Red points: Median amplitude, excluding events below threshold or saturating the scope scale

Improved uniformity over the detector

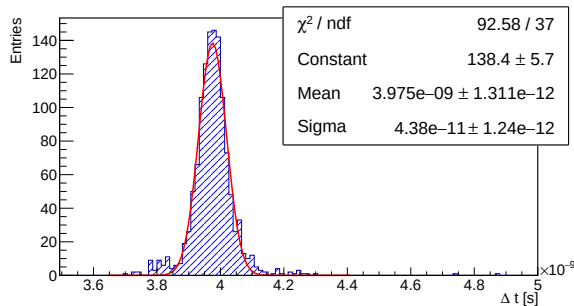
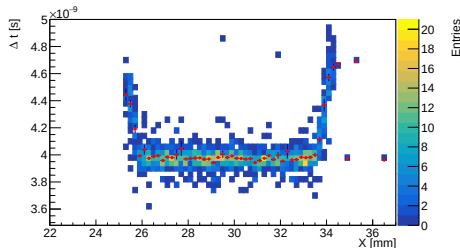
Metallized $8 \times 8 \text{ mm}^2$ APD, 1775 V, 100 GeV μ

Time of arrival Δt

Distribution (within geom. cuts)



Section X (between horizontal lines)



Red points: Average Δt

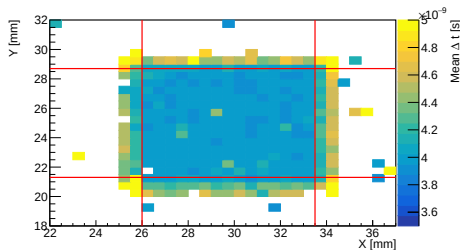
- Algorithm: CFD, 2 pt interpolation
- Uniform over the detector
- Tails at detector edges

**Time resolution of $44 \pm 1 \text{ ps}$
over a $8 \times 8 \text{ mm}^2$ detector**

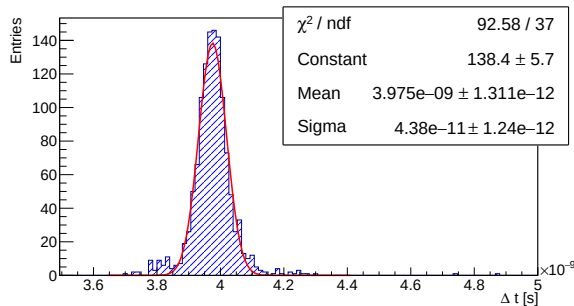
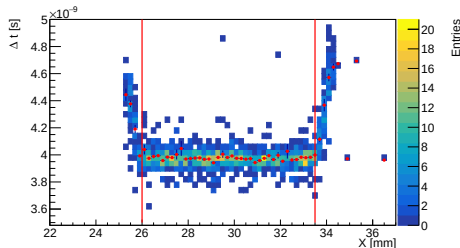
Metallized $8 \times 8 \text{ mm}^2$ APD, 1775 V, 100 GeV μ

Time of arrival Δt

Distribution (within geom. cuts)



Section X (between horizontal lines)



Red points: Average Δt

- Algorithm: CFD, 2 pt interpolation
- Uniform over the detector
- Tails at detector edges

**Time resolution of $44 \pm 1 \text{ ps}$
over a $8 \times 8 \text{ mm}^2$ detector**

Looking Back



[freepik]

- DD-APDs did not have the radiation hardness or granularity necessary for HL-LHC
- DD-APD demonstrated a time resolution of a few tens of ps in Si over a $\sim 1 \times 1 \text{ cm}^2$

Trento



[Wikimedia]

Tracking, Timing, X-ray Applications

A Change



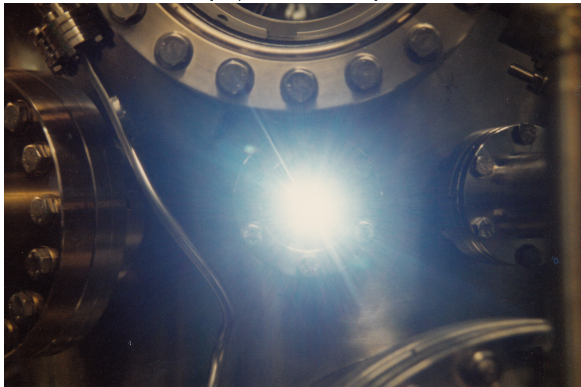
[La Repubblica 

- Sensor development and fabrication, both for research and industry
- Layout, simulation, fabrication
- Many sensors and projects: LGADs, pixels, strips, SDDs, 3D (with varying personal involvement)

In-depth characterization usually done by “costumers”

X-ray Detection

[Wikipedia CC BY-SA 2.0]



Advantages of LGADs demonstrated in:
[Andrae et al. J.Synchrotron Rad. 26 (2019)
1226-1237]

Development in collaboration with PSI
PAUL SCHERRER INSTITUT



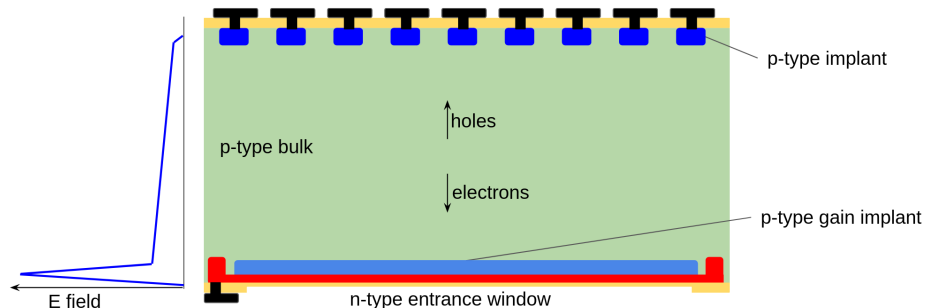
Detection of soft X-rays: 250 eV - 2 keV

- K-edges of bio elements
→ pharmaceuticals, cell imaging
- L-edges of 3d-transition metals
→ magnets, superconductors, quantum materials ...

Use LGADs:

- Gain to lower the detection limit of photon counting detectors
- Gain to improve SNR of integrating detectors
- Thin entrance window and gain structure must be developed

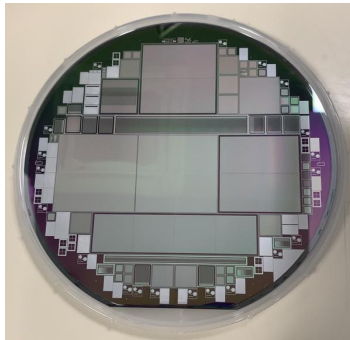
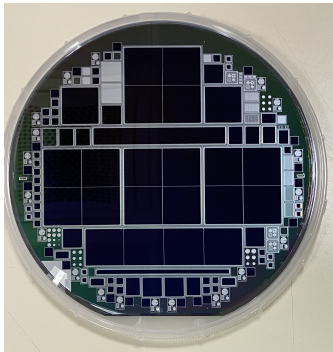
Double Sided (Inverted) LGADs



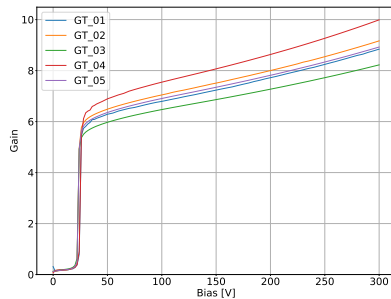
- Silicon detectors with charge multiplication, Gain ≈ 10
- **Improve SNR of the system** (when the sensor shot noise is not dominating)
- Continuous gain area in the active region $\Rightarrow$ 100% fill factor
- Double sided process $\rightarrow$ active thickness is the wafer thickness $\Rightarrow$ not optimal for timing

[G.F. Dalla Betta et al. NIM A 796 (2015) 154]

Double Sided LGADs for PSI

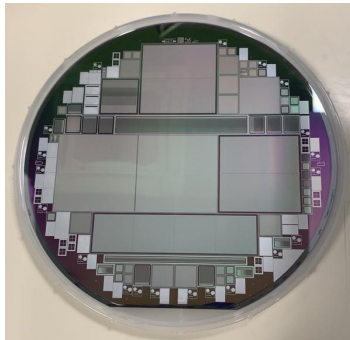
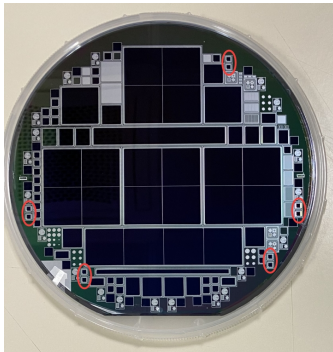


Gain with LED (STD gain structure)



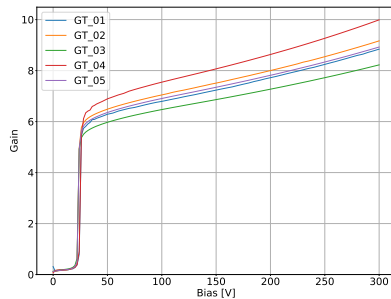
- Several pixel and strip geometries
- Thin entrance window
- Several gain structure designs → make as thin as possible
- Thickness 275 μm

Double Sided LGADs for PSI

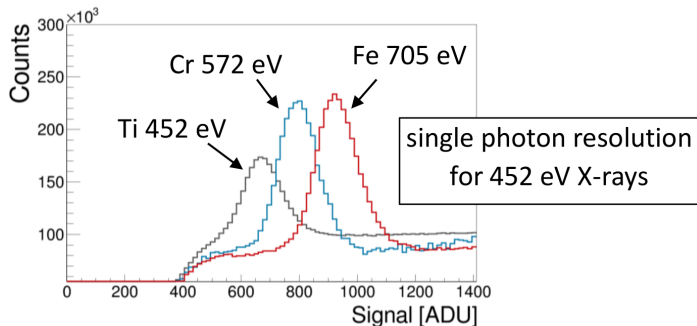


- Several pixel and strip geometries
- Thin entrance window
- Several gain structure designs → make as thin as possible
- Thickness $275\ \mu\text{m}$

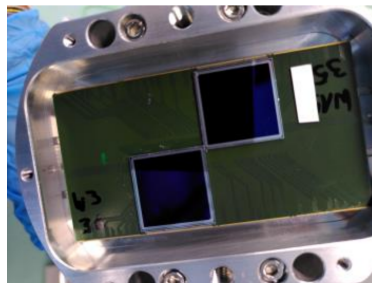
Gain with LED (STD gain structure)



Characterization at PSI

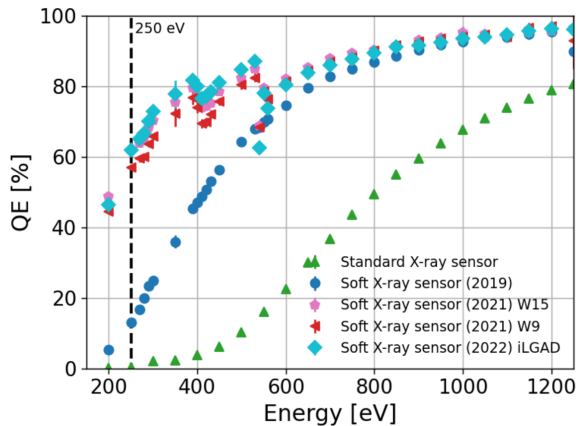


[V. Hinger et al. in publication JINST 2022]



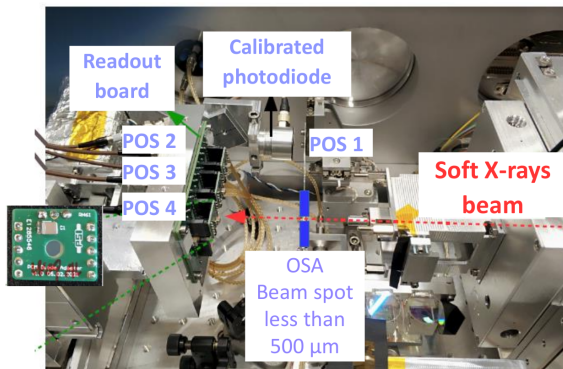
- X-ray tube with fluorescence targets
- Detector cooled to -22 C
- Jungfrau readout chip
- Single photon resolution with standard sensor ~ 800 eV

Characterization at PSI



[M. Carulla et al. IEEE 2022]

- Monochromatic x-rays from SLS
- 200-1250 eV
- QE $\sim$ 60% at 250 eV



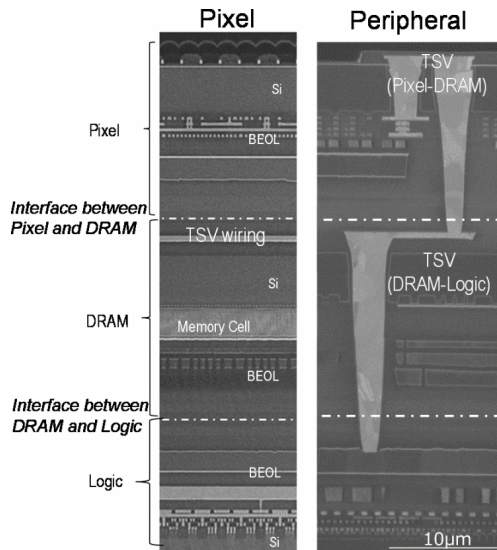
Future



[Tumblr]

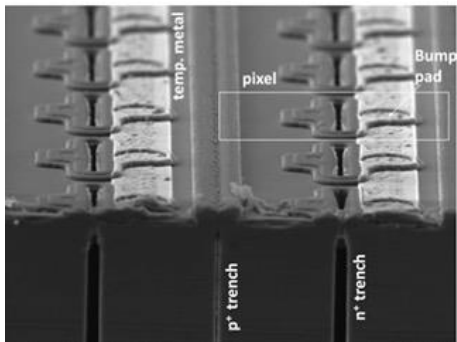
3D Integrated CMOS Sensors

- Many different technologies
- Wafer or chip level
- Add functionalities to sensor
- Separate domains or functions
- Some process similarity to 3D sensors

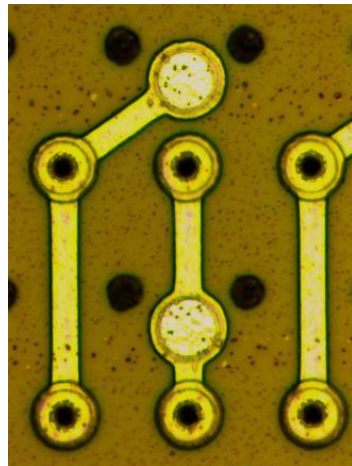


[H. Tsugawa et al. IEEE 2017]

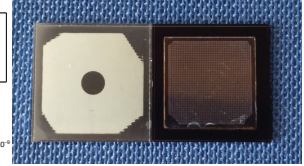
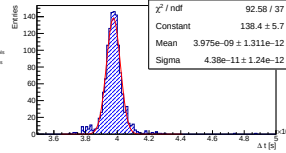
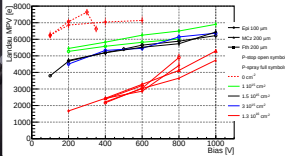
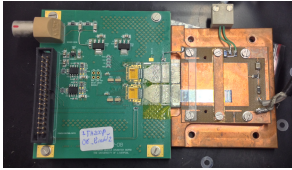
3D CMOS Sensors



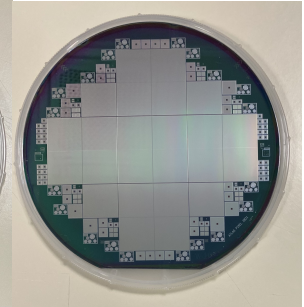
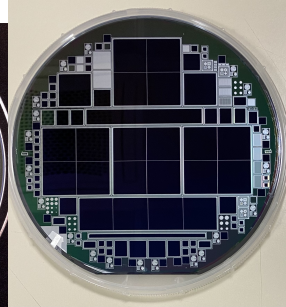
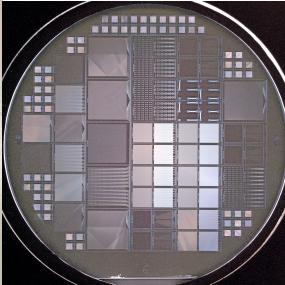
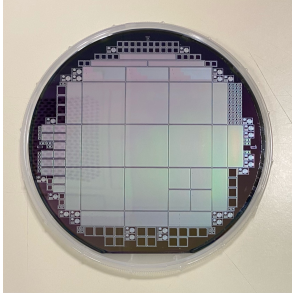
- Improve radiation hardness
- Tracking, timing
- Keep advantages of CMOS sensors



Light pixel sensor, tracking, timing
⇒ **applications outside HEP**



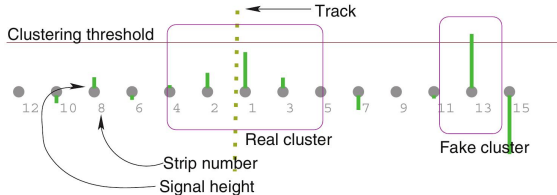
Thank you for your attention



Backup Material

Charge distribution

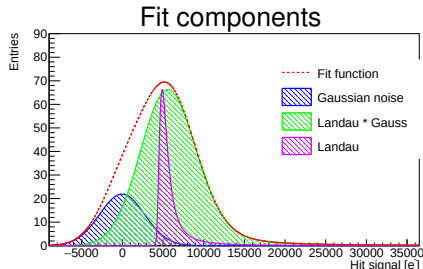
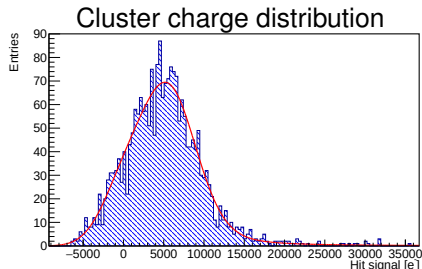
Cluster charge: Sum of the signal over 5 strips, centered on the hit one



Track information from telescope

No threshold used in the analysis

$$100\ \mu\text{m}, \Phi_{eq} = 1.3 \cdot 10^{16}\ \text{cm}^{-2}, 800\ \text{V}$$

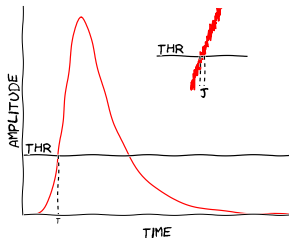


Landau MPV used to characterize the sensors

Timing

$$\Delta t = t_2 - t_1 \quad \sigma_{\Delta t}^2 = \sigma_{t_1}^2 + \sigma_{t_2}^2 \quad \sigma_t^2 = \sigma_J^2 + \sigma_{TW}^2 + \dots$$

Jitter



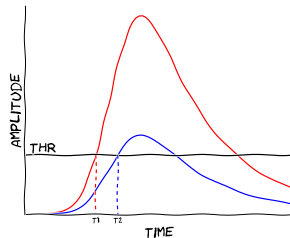
The noise influences the time at which the threshold is crossed

$$\sigma_J = \sigma_n / \frac{dV}{dt} \propto \frac{t_{rise}}{SNR}$$

Countermeasures:

- Reduce rise time
- Improve noise figure

Time walk

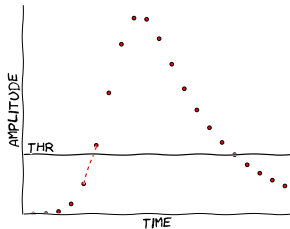


Variations in the amplitude influence the time at which the threshold is crossed

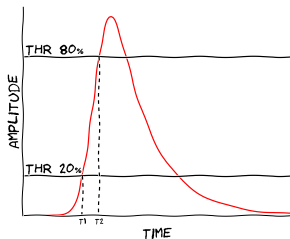
Countermeasures:

- Algorithm e.g. CFD

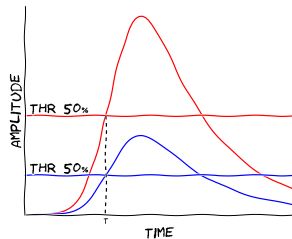
2pt interpolation



20-80% Rise time



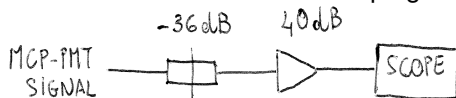
Constant Fraction Discrimination



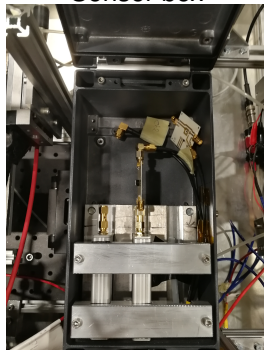
Beam Test Setup

- Sensor box placed downstream first tracking GEM
- Coating on detectors and PCBs to reduce discharges
- Amplifiers: CIVIDEC 2 GHz, 40 dB
- Data acquisition: Agilent 2.5 GHz, 10 Gs/s
 - Ch1: APD
 - Ch2: APD
 - Ch3: Telescope bit pattern (Trigger)
 - Ch4: MCP-PMT
- Temperature, bias, and current logged

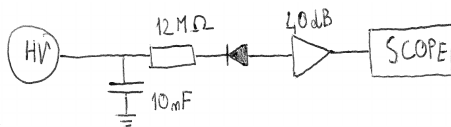
MCP-PMT readout and shaping



Sensor box



APD readout



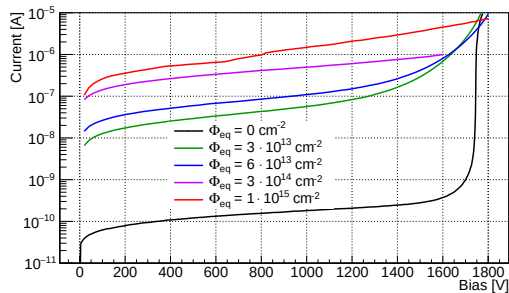
$2 \times 2 \text{ mm}^2$ APDs



- Packaged
- Irradiated in Ljubljana (reactor neutrons)
- Characterized using a pulsed infrared laser
- $\Phi_{eq} = 0, 3 \cdot 10^{13}, 6 \cdot 10^{13}, 3 \cdot 10^{14}, 10^{15} \text{ cm}^{-2}$
- Annealing of $\approx 70 \text{ min @ } 21^\circ\text{C}$
- Sensor irradiated to $\Phi_{eq} = 3 \cdot 10^{14} \text{ cm}^{-2}$ is quite unstable

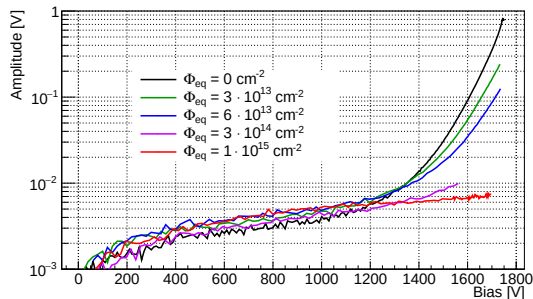
N-irradiated $2 \times 2 \text{ mm}^2$ APDs, -20°C

Dark Current



- Increase with irradiation
- Change of shape

Signal, IR laser, 15 MIPs

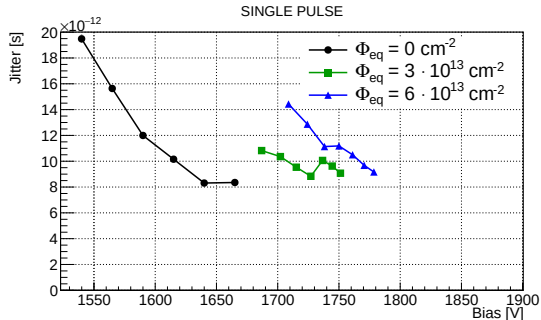


- Decrease with irradiation
- $\Phi_{eq} = 10^{15} \text{ cm}^{-2}$: little to no gain

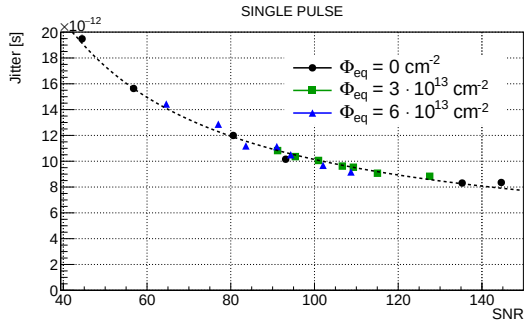
The gain is reduced by irradiation

N-irradiated $2 \times 2 \text{ mm}^2$ APDs, -20°C , IR Laser, 0.8 MIPS

Jitter vs Bias Voltage



Jitter vs Signal to Noise Ratio



- $\Phi_{eq} \leq 6 \cdot 10^{13} \text{ cm}^{-2}$: jitter of 8 - 10 ps

- $\Phi_{eq} = 10^{15} \text{ cm}^{-2}$: low SNR

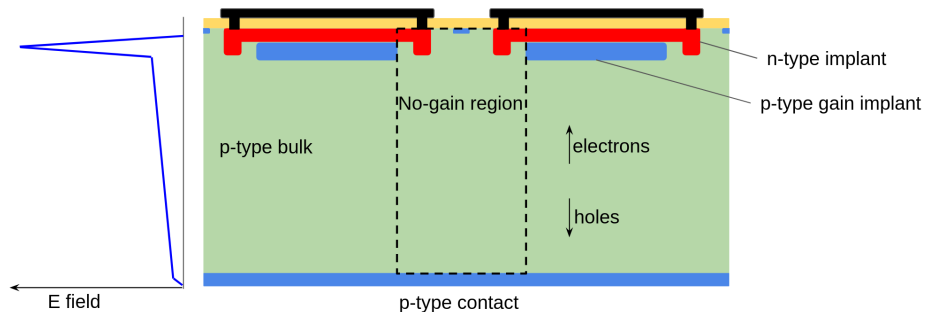
Jitter $\approx 0.5 \text{ ns}$

- Jitter scales as $1/\text{SNR}$

Time resolution maintained at least up to $\Phi_{eq} = 6 \cdot 10^{13} \text{ cm}^{-2}$, higher bias required

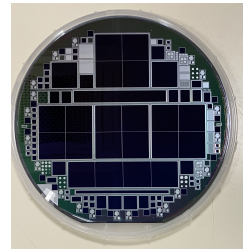
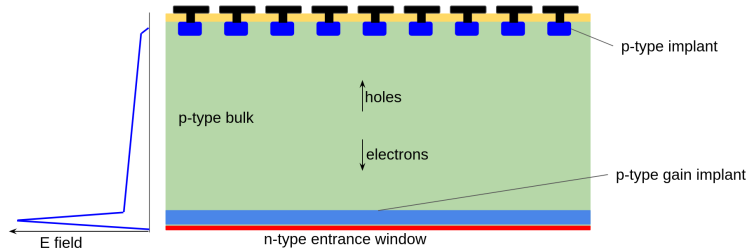
Radiation hardness estimated to be $\Phi_{eq} \approx 10^{14} \text{ cm}^{-2}$

(Standard) Low Gain Avalanche Diodes

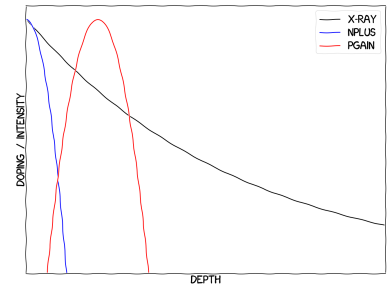


- Silicon detectors with charge multiplication
- Gain ≈ 10
- Gain layer provides high-field region
- No-gain region $\sim 30 - 80 \mu\text{m}$
- Time resolution $\sim 30 \text{ ps} \leftrightarrow$ thin $\sim 50 \mu\text{m}$ sensor
- **Improve SNR of the system**
(When the sensor shot noise is not dominating)
- Noise and power consumption
 $\Rightarrow$ low gain

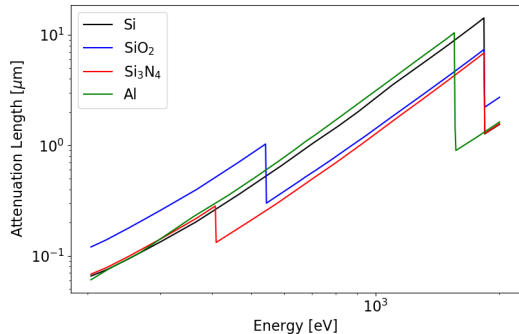
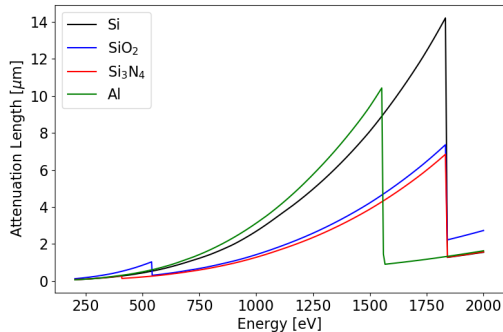
Double Sided LGADs for X-rays



- Optimization for x-rays
- One possibility: gain structure as narrow as possible
- Few variations in the batch



X-ray Attenuation Length



http://henke.lbl.gov/optical_constants/atten2.html