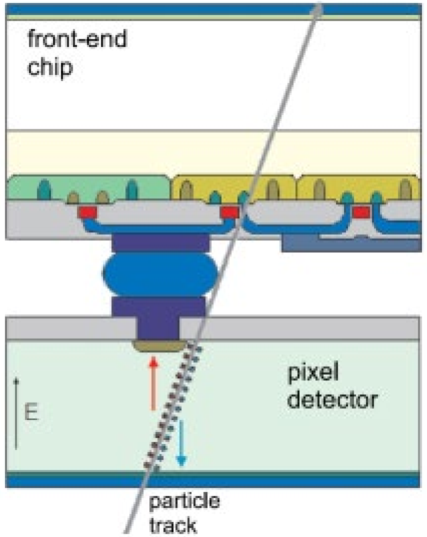
Rivelatori e Apparati

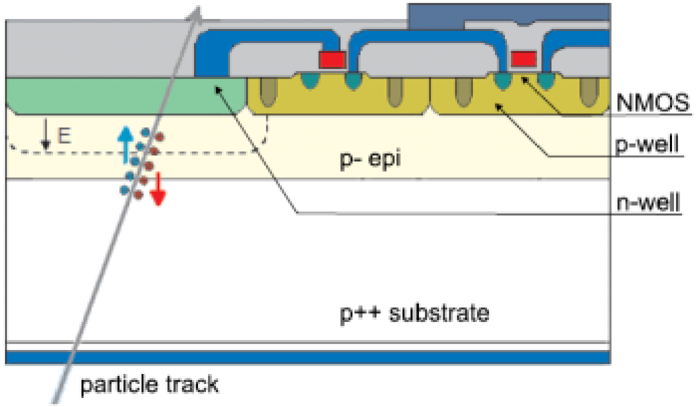
Slides_9 – MAPS, DMAPS, LGAD

giacomo.contin@ts.infn.it - RAFNeS_9 MAPS, DMAPS, LGAD

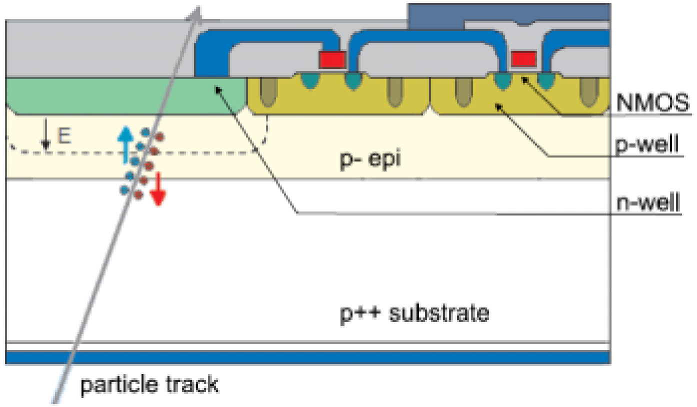
Hybrid Pixel Detectors



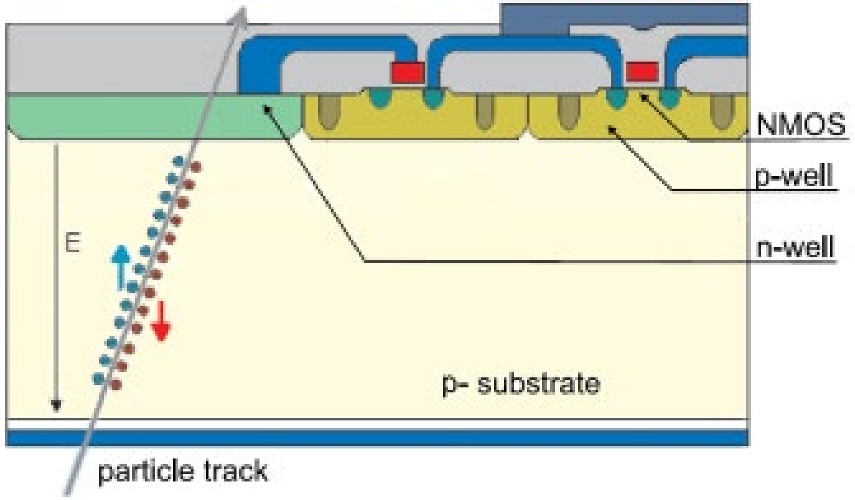
Monolithic Pixels



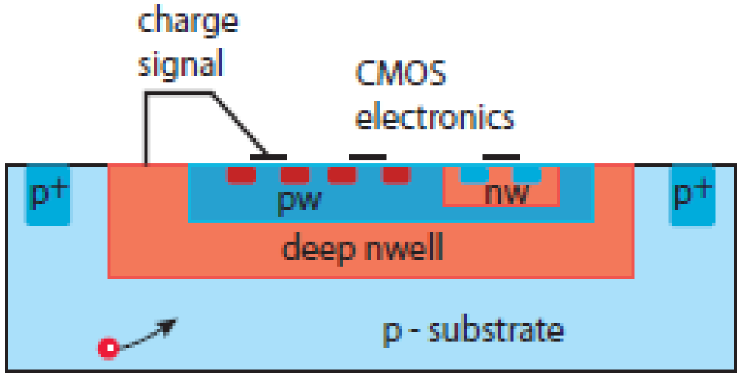
Monolithic Pixels



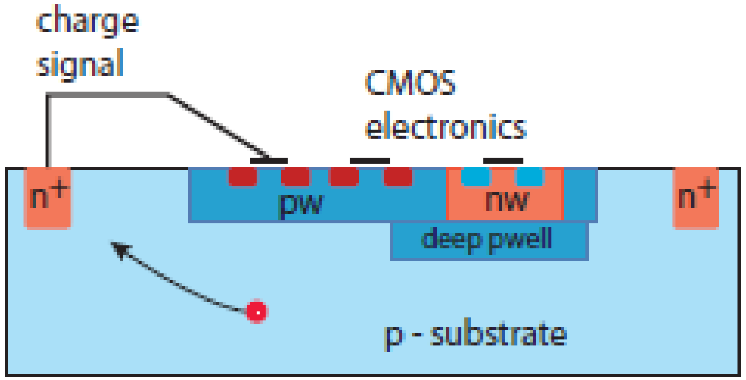
Depleted Monolithic Pixels



Fill factor

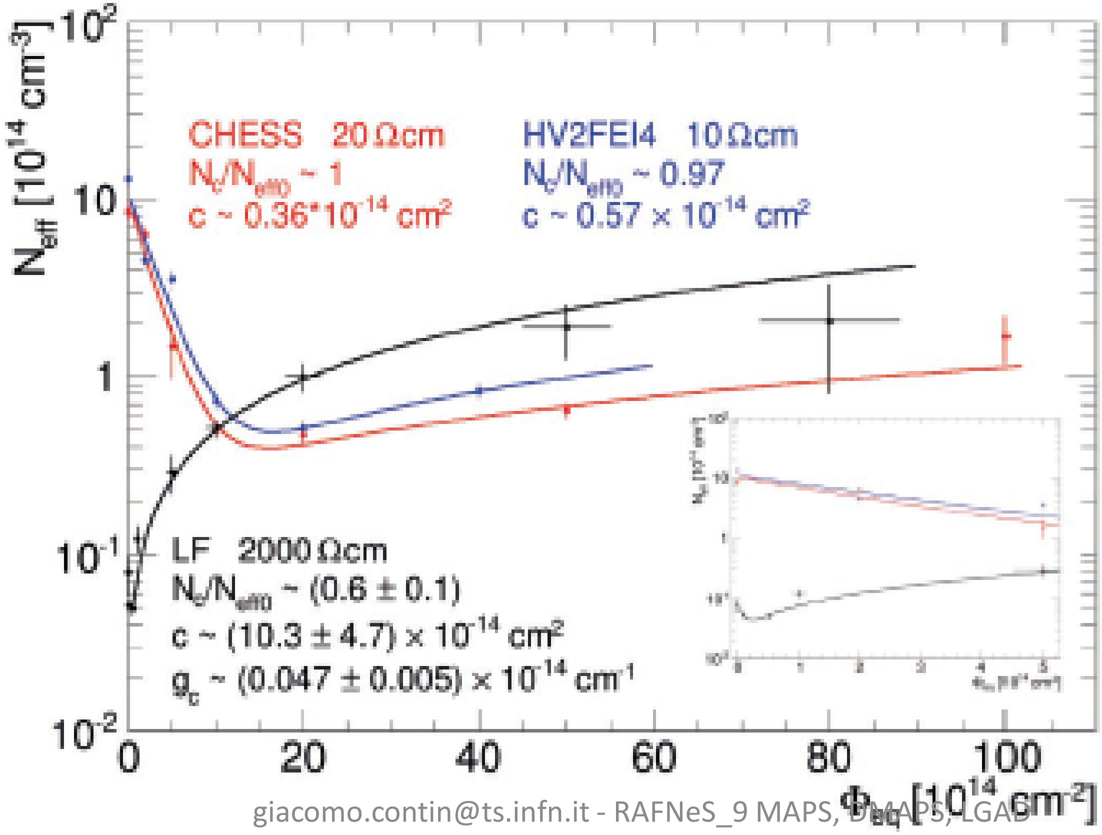


(a) Large fill-factor



(b) Small fill-factor

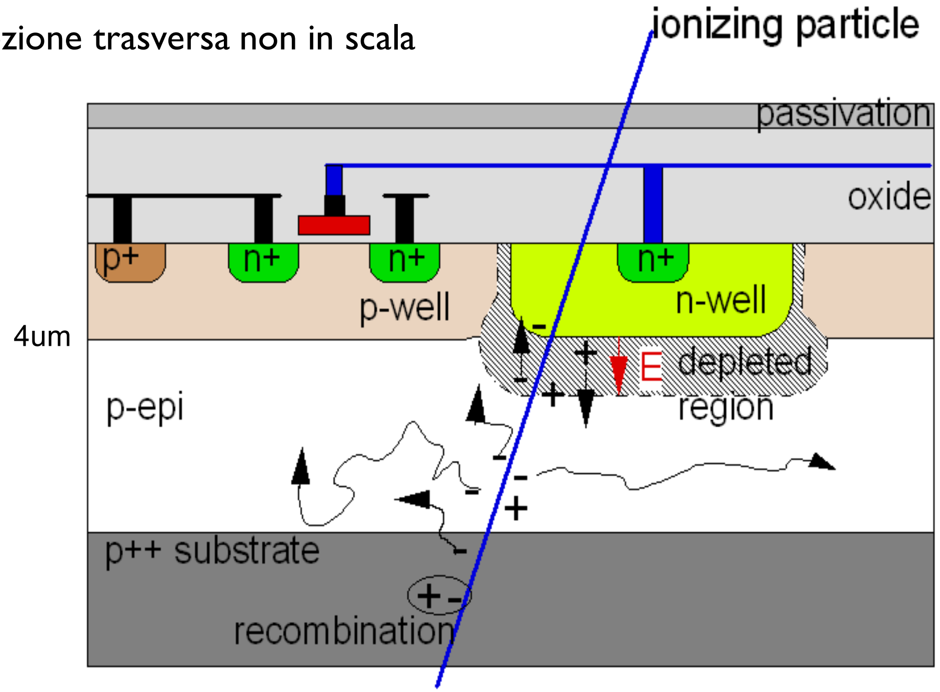
Resistivita' substrato



La tecnologia MAPS

Volume sensibile e logica CMOS di prima elaborazione del segnale nello stesso cristallo di silicio

Sezione trasversa non in scala



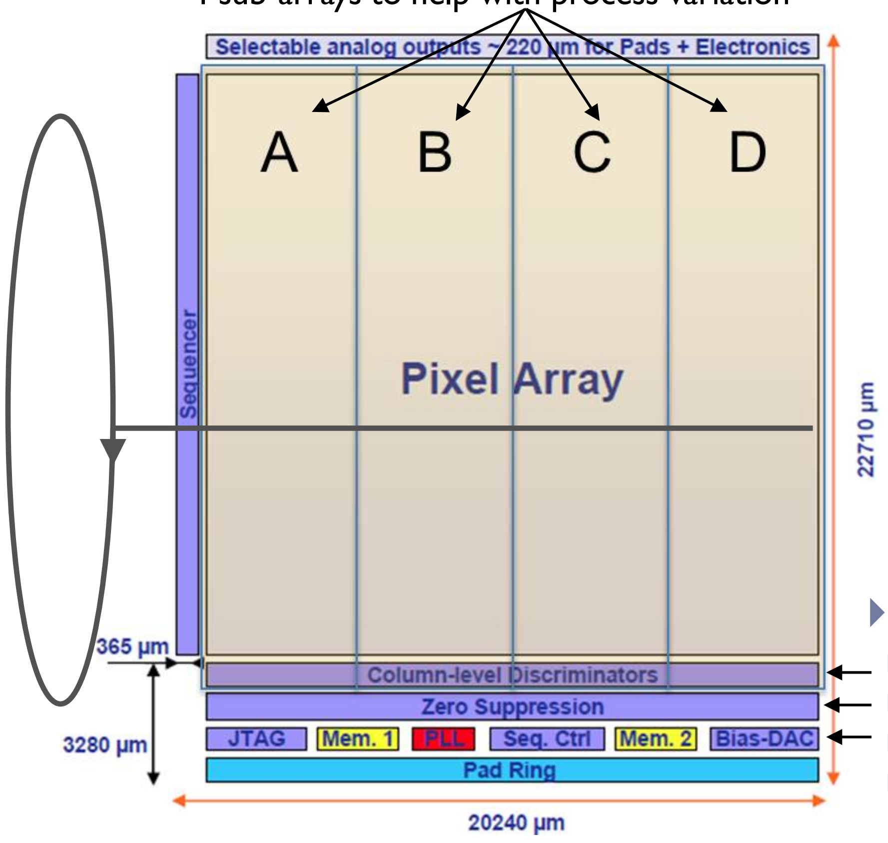
- Monolithic Active Pixel Sensor
- Tecnologia industriale standard CMOS
- **Room temperature** operation
- Sensore e processazione del segnale integrati nello stesso silicio
- Il segnale e’ creato nell’epitassiale (tipicamente ~10-15 μm) a basso drogaggio → segnale di un MIP limitato a <1000 elettroni
- La raccolta di carica avviene soprattutto per diffusione termica (lenta, ~100 ns), anche grazie ai confini “riflettenti reflective boundaries at p-well and substrate.
- Epitassiali ad alta resistivita’ per ottenere zone svuotate piu’ spesse → raccolta della carica piu’ efficiente, piu’ tollerante alle radiazioni
- 100% fill-factor

STAR HFT PXL sensor: Ultimate-2

- *Ultimate-2:* third generation sensor developed for PXL by the PICSEL group of IPHC, Strasbourg
- *Monolithic Active Pixel Sensor* technology, MIMOSA series

- High resistivity p-epi layer
  - Reduced charge collection time
  - Improved radiation hardness
- S/N ~ 30
- MIP Signal ~ 1000 e-
- **Rolling-shutter readout**
  - A row is selected
  - For each column, a pixel is connected to discriminator
  - Discriminator detects possible hit
  - Move to next row
- 185.6 μs integration time
- ~170 mW/cm² power dissipation

4 sub-arrays to help with process variation



Pixel matrix

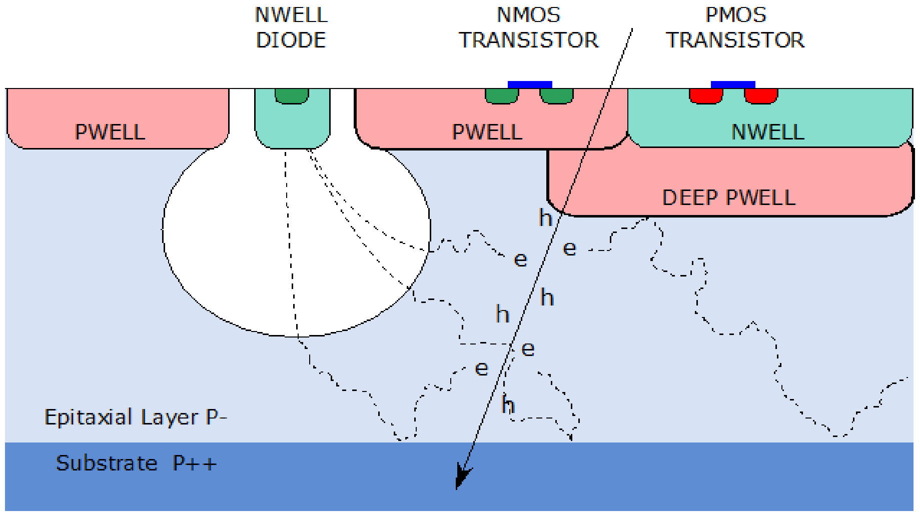
- 928 rows * 960 columns = ~1M pixel
- In-pixel amplifier
- In-pixel Correlated Double Sampling (CDS)

Digital section

- End-of-column discriminators
- Integrated zero suppression (up to 9 hits/row)
- Ping-pong memory for frame readout (~1500 w)
- 2 LVDS data outputs @ 160 MHz

ITS Pixel Chip – technology choice

CMOS Pixel Sensor using TowerJazz 0.18μm CMOS Imaging Process



ALPIDE sensor *(developed within ALICE)*

- ~28 μm pitch
- Integration time: < 20 μs
- Trigger rate: 100 kHz
- Read out up to 1.2 Gbit/s
- Power: 40 mW/cm^2
- Priority encoder - sparsified readout
- Rad. Tolerant: 700krad -10^{14} 1MeV n$_{eq}$/cm^2

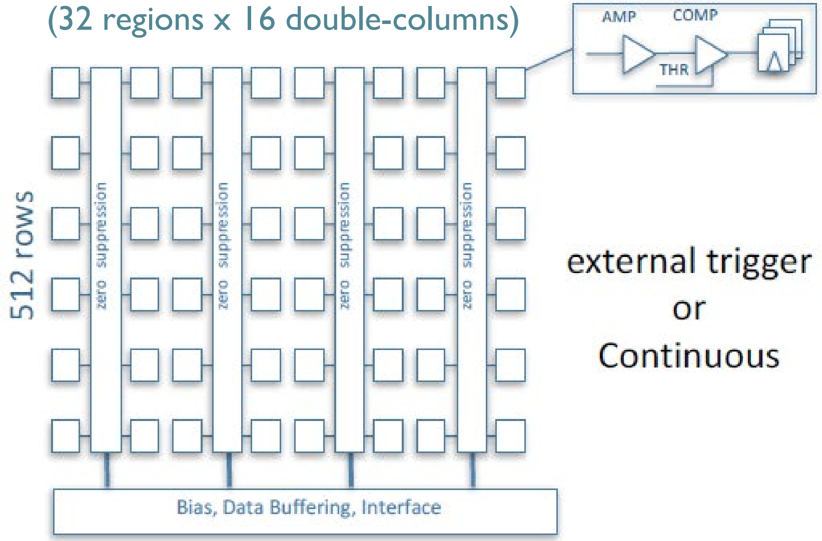
- High-resistivity (> 1kΩ cm) p-type epitaxial layer (20μm - 40μm thick) on p-type substrate
- Small n-well diode (2-3 μm diameter), ~100 times smaller than pixel => low capacitance
- Application of (moderate) reverse bias voltage to substrate can be used to increase depletion zone around NWELL collection diode
- Quadruple well process: deep PWELL shields NWELL of PMOS transistors, allowing for full CMOS circuitry within active area

ALICE ITS Upgrade sensor: ALPIDE

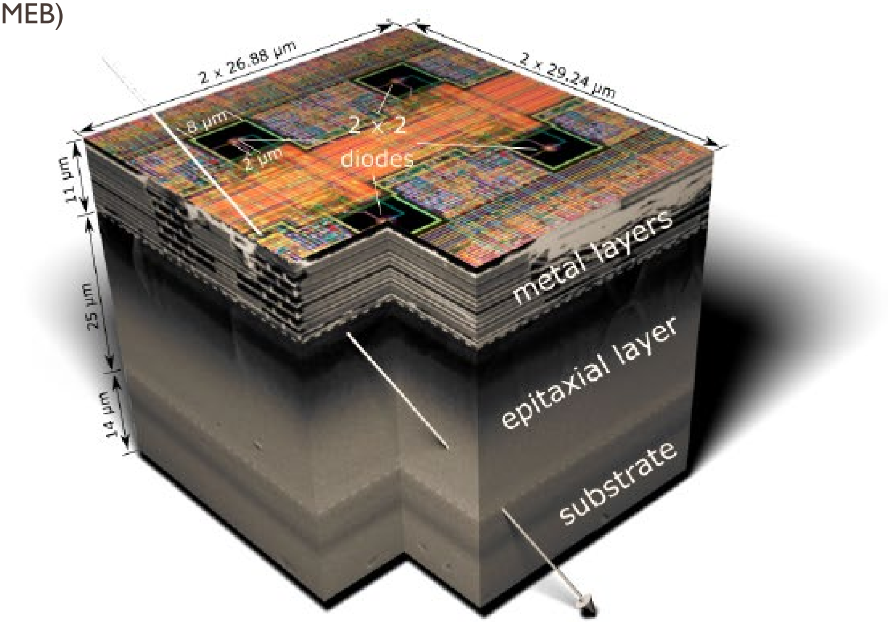
Priority Encoder (AE-RD)

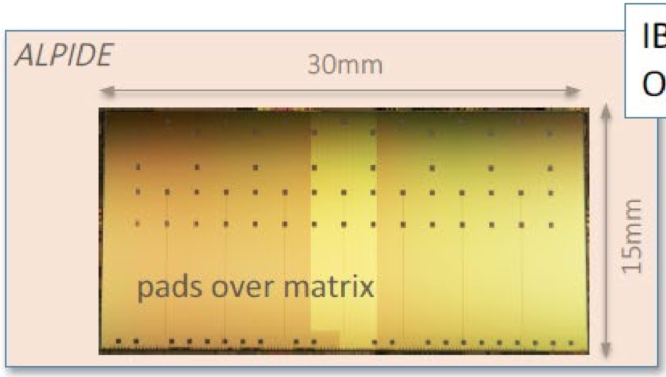
1024 pixel columns
(32 regions x 16 double-columns)

In pixel:
- Amplification
- Discrimination
- 3 hit storage registers (MEB)



external trigger
or
Continuous





IB: 50μm thick
OB: 100μm thick

Power: 40 mW/cm^2
Trigger rate: 100 kHz
Integration time: < 20 μs
Read out up to 1.2 Gbit/s.

130,000 pixels / cm^2 27x29x25 μm^3

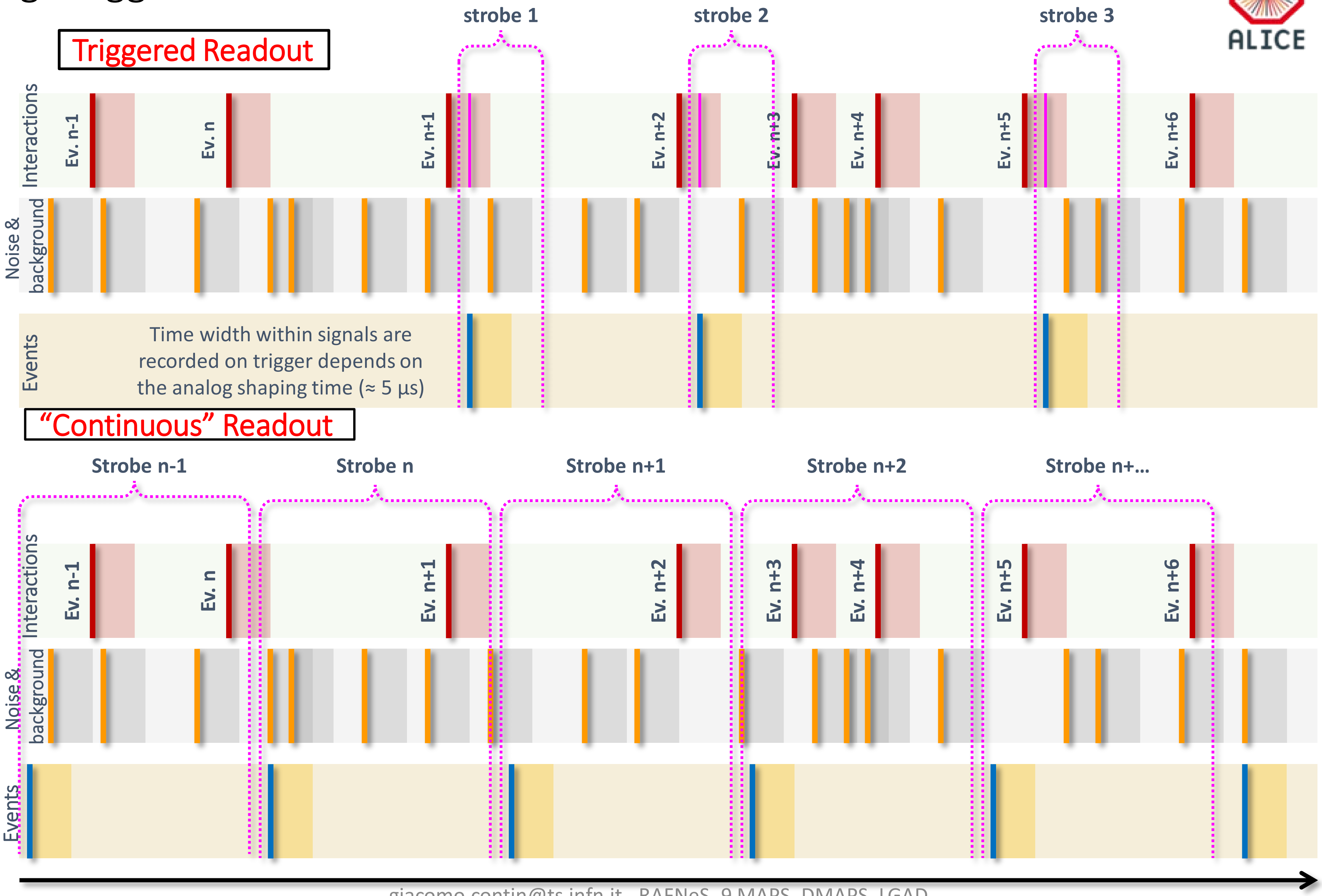
spatial resolution: ~ 5 μm (3-D)

Max particle rate: 100 MHz / cm^2

fake-hit rate: ~ 10^{-10} pixel / event

power : ~ 300 nW /pixel

ALPIDE Timing: Triggered & "Continuous" Readout



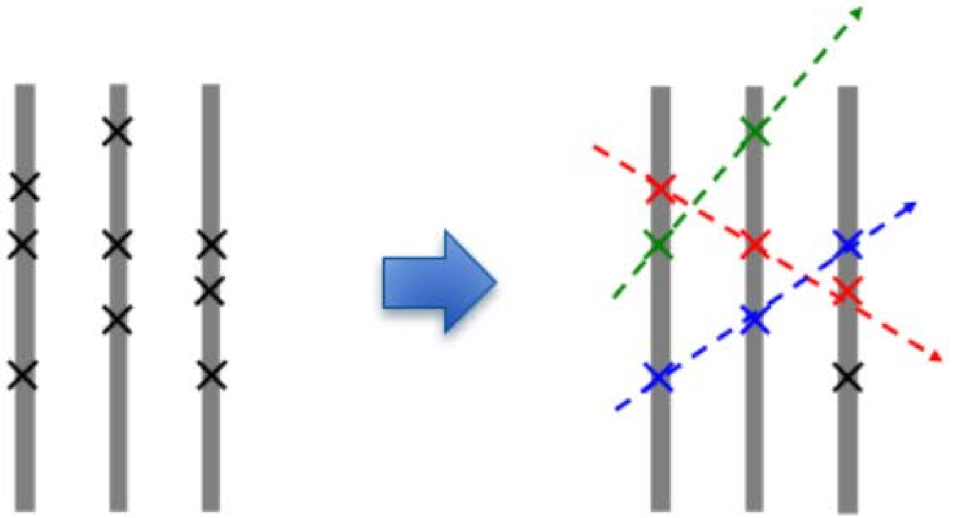
Time width within signals are recorded on trigger depends on the analog shaping time (≈ 5 µs)

Rivelatori al silicio per misure di tempo

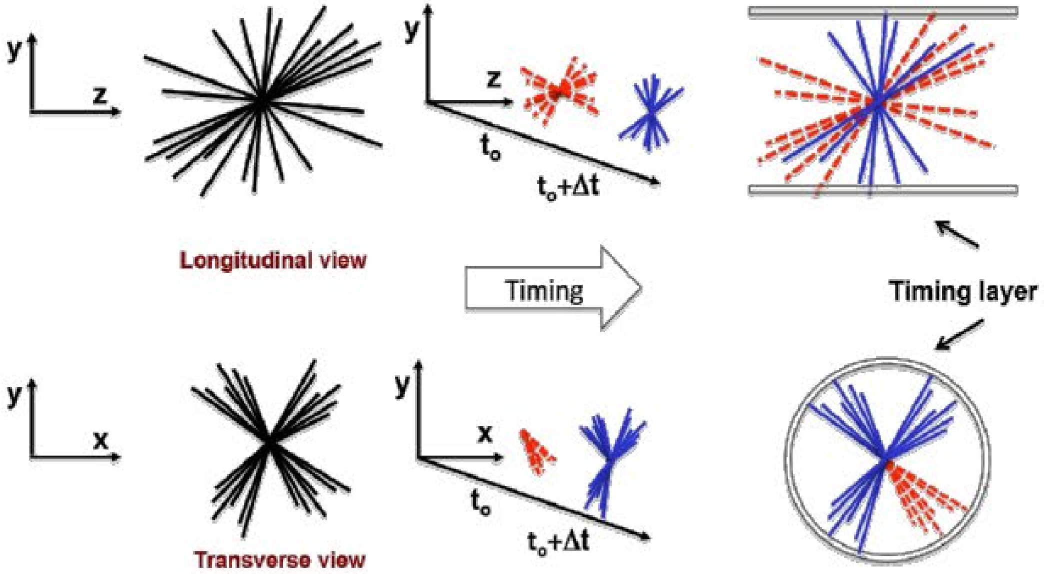
- Low Gain Avalanche Detectors (LGAD):
  - Rivelatori a valanga a basso guadagno
- SPAD
  - Single-photon avalanche photodiode: fotodiodo usato in regime valanga, come un interruttore seguito da una resistenza di quenching che spegne la valanga
- SiPM
  - Silicon Photo-Multiplier: matrici di SPAD in parallelo, non usato per imagine perche somma i segnali dalle diverse celle

Acquisition of timing information

- Time tagging at each point
  - LHCb Upgrade II (Run 5 ~2030)

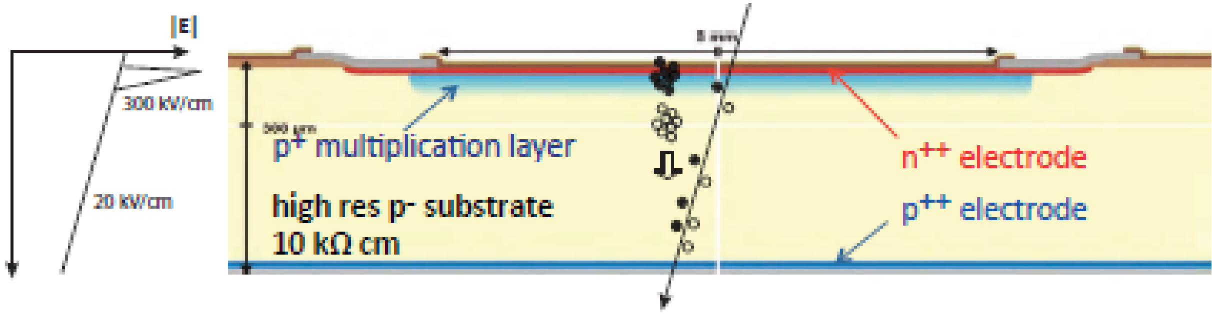


- Timing in the event reconstruction
  - HL-LHC: ATLAS and CMS

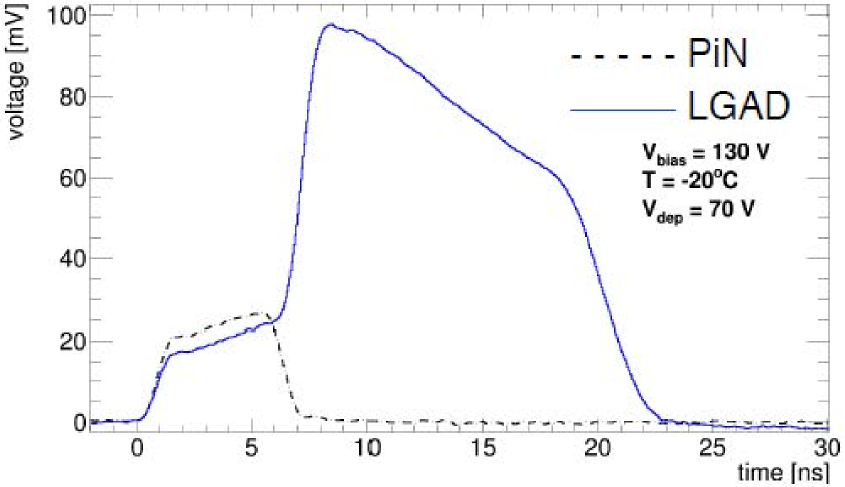


Gain mechanism in LGADs

- Planar silicon sensors (n+/p/p-)
  - n+ implant, p substrate
  - p-type multiplication layer

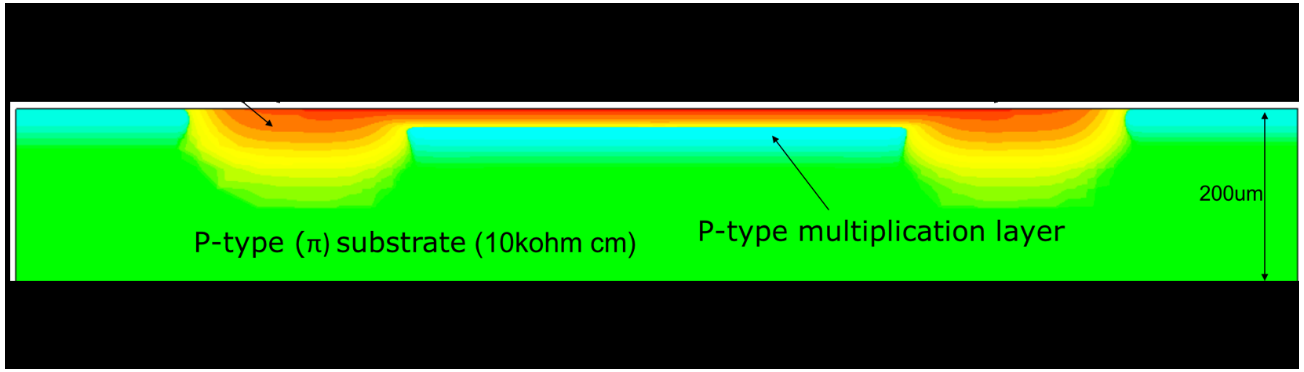


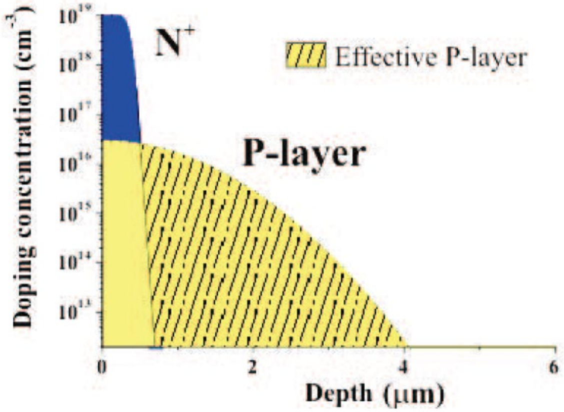
- **High electric field region in the multiplication layer**
  - Charges undergo impact ionisation
  - Gain depends on:
    - multiplication layer doping
    - bias voltage
    - temperature

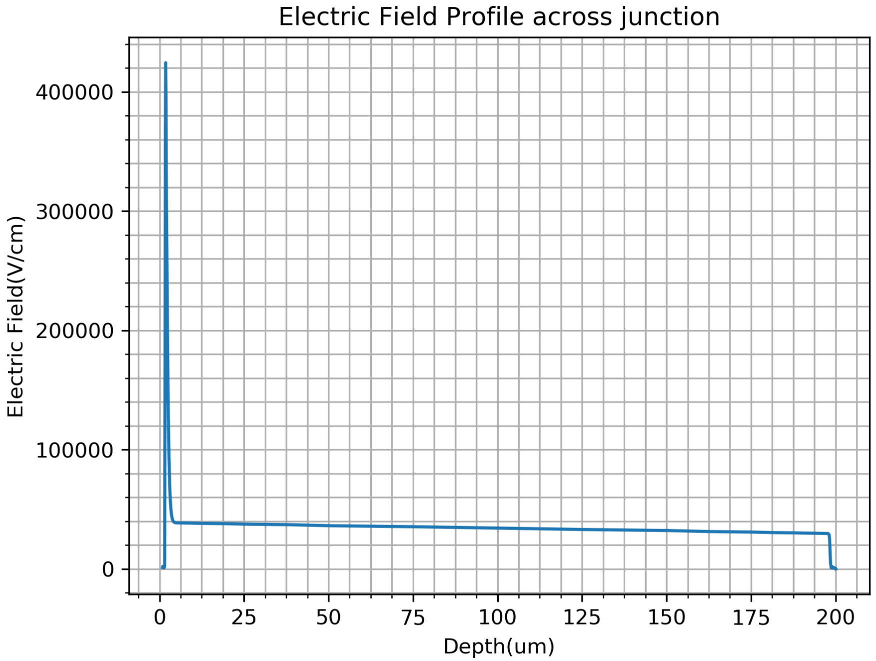


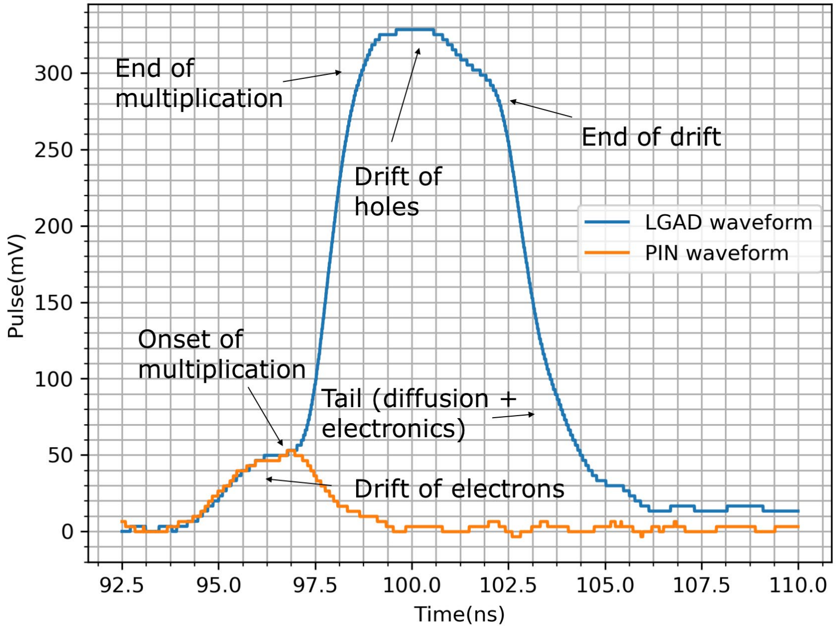
S. Otero Ugobono *et al.*, IEEE TNS (2018) vol. 6, no. 8, pp. 1667-1675

LGAD: simulazioni



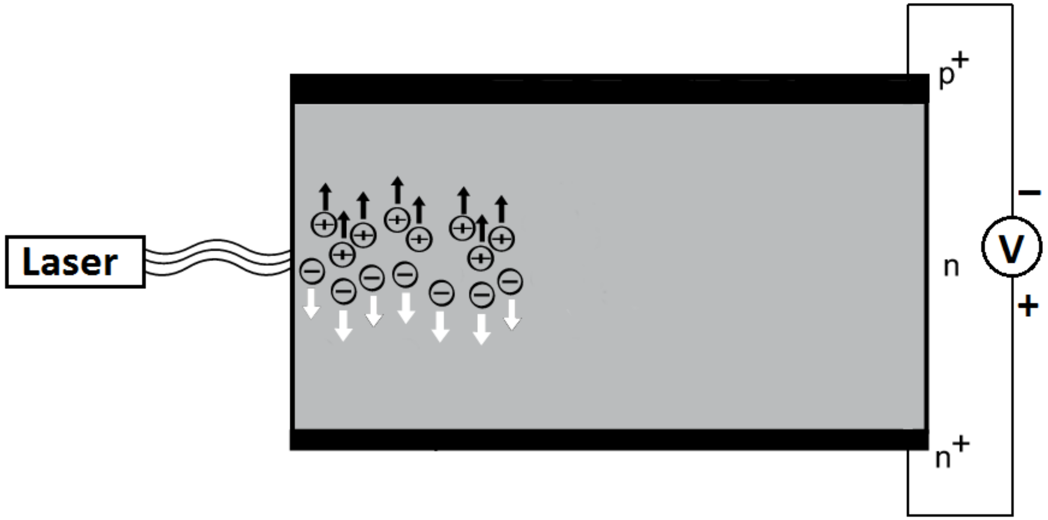




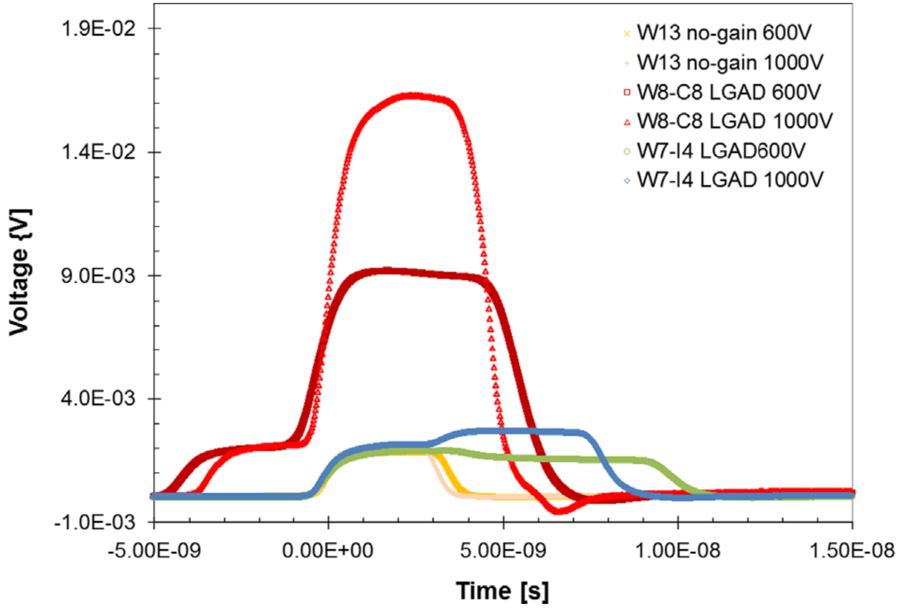


LGAD: misure TCT

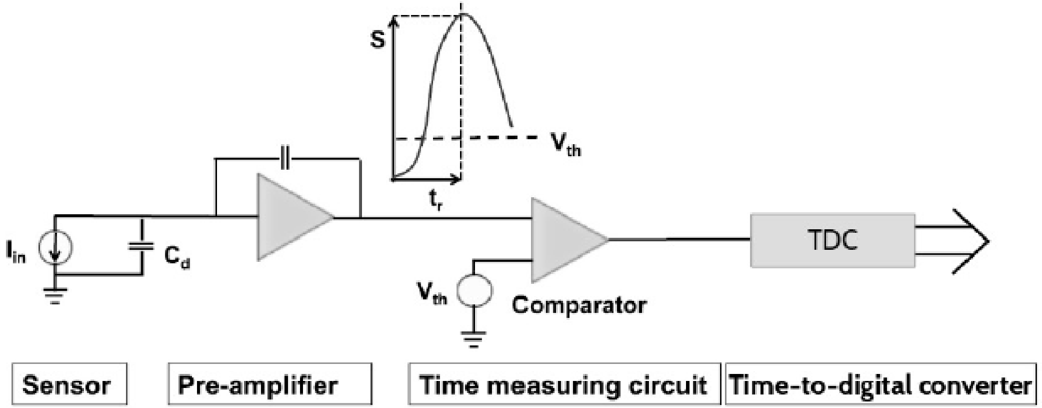
- Principio di funzionamento (Edge-)Transient Current Technique



- Misura TCT su LGAD con diversi Guadagni e a diverse Vbias



Time resolution



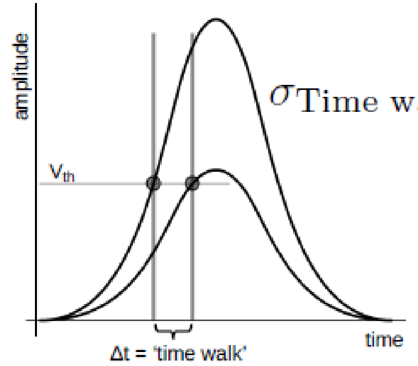
$$\sigma_t^2 = \sigma^2_{\text{Time walk}} + \sigma^2_{\text{Landau noise}} + \sigma^2_{\text{Jitter}} + \sigma^2_{\text{Distortion}} + \sigma^2_{\text{TDC}}$$

Time resolution is affected by:

- each step in the read-out process
- any effect that changes the shape of the signal

Time resolution

$$\sigma_t^2 = \boxed{\sigma^2_{\text{Time walk}}} + \sigma^2_{\text{Landau noise}} + \sigma^2_{\text{Jitter}} + \boxed{\sigma^2_{\text{Distortion}}} + \boxed{\sigma^2_{\text{TDC}}}$$



$$\sigma_{\text{Time walk}} \propto \left[\frac{N\sigma_n}{\mathrm{dV/dt}}\right]_{RMS}$$

- Variation in time of arrival due to different signal amplitudes
- Can be compensated by electronics

- Caused by inhomogeneous:
  - drift velocity
  - weighting field
- Solutions:
  - saturated drift velocity
  - optimised geometry

TDC: time-to-digital converter

$$\sigma_{\text{TDC}} = \Delta T/\sqrt{12}$$

comparator time bin width

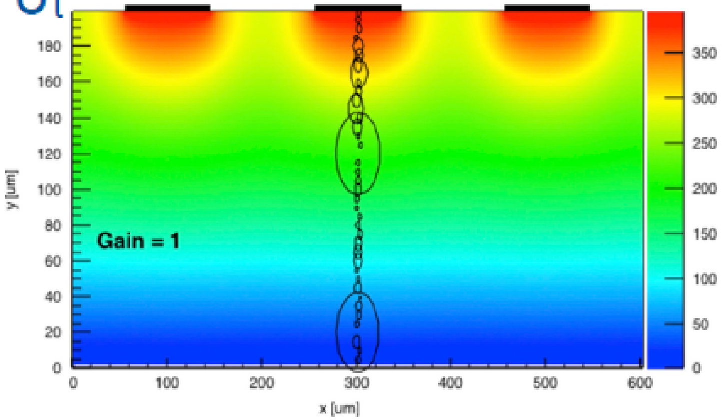
- Sub-picosecond ⇒ negligible

- V_{th}: threshold voltage to determine the time of arrival
- $N\sigma_n$: the threshold is usually expressed in multiples of the system noise

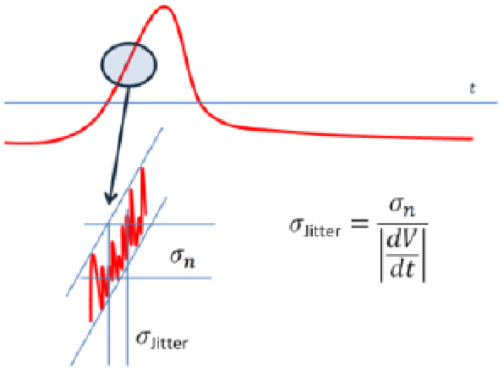
Time resolution

$$\sigma_t^2 = \sigma^2_{\text{Time walk}} + \boxed{\sigma^2_{\text{Landau noise}}} + \boxed{\sigma^2_{\text{Jitter}}} + \sigma^2_{\text{Distortion}} + \sigma^2_{\text{TDC}}$$

- Signal shape variations for MIPs
  - Non-uniform energy deposition per unit length
- Sets a physical limit to σ_t
- Can be minimised by:
  - setting a low V_{th}
  - using thin devices



- Variations in time of arrival due to signal noise



Jitter effect

- Can be minimised with:
  - low noise sensors
  - low noise electronics
  - fast slew rates

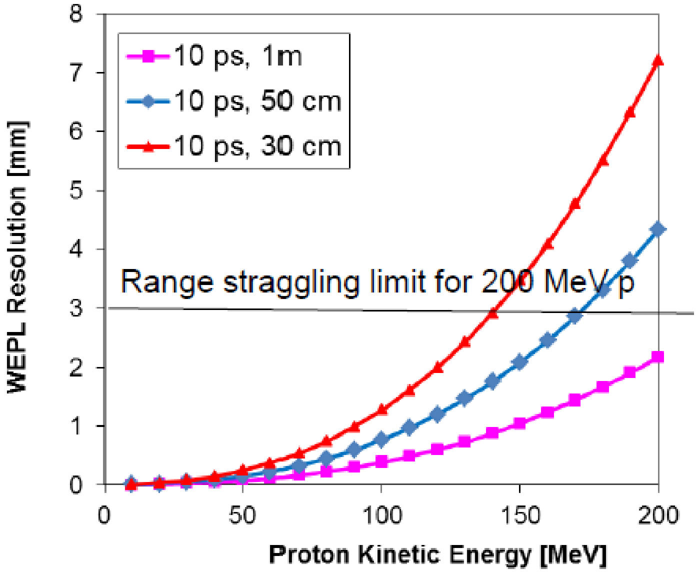
- V_{th}: threshold voltage to determine the time of arrival

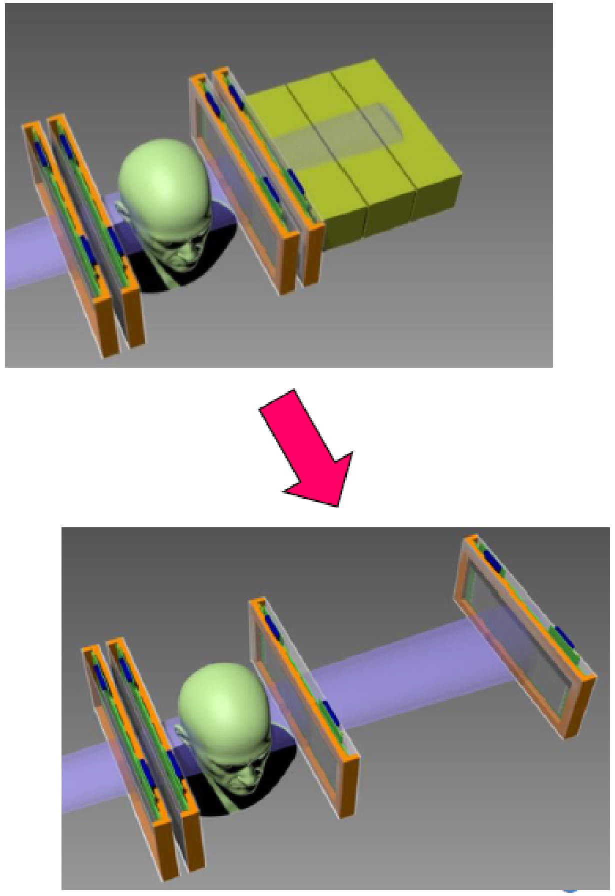
4-D Ultra-Fast Si Detectors in pCT

In support of Hadron Therapy, the relative stopping power (RSP) is being reconstructed in 3D.
The UCSC-LLU pCT scanner uses Si strip sensors to locate the proton and heavy scintillator stages to measure its energy loss (WEPL).

Protons of 200 MeV have a range of ~ 30 cm in plastic scintillator. The resulting straggling limits the WEPL resolution.

Replace calorimeter/range counter by UFSD:
Combine tracking with WEPL measurement where the ToF of the proton measures the residual energy., with comparable or better resolution than the scintillator.

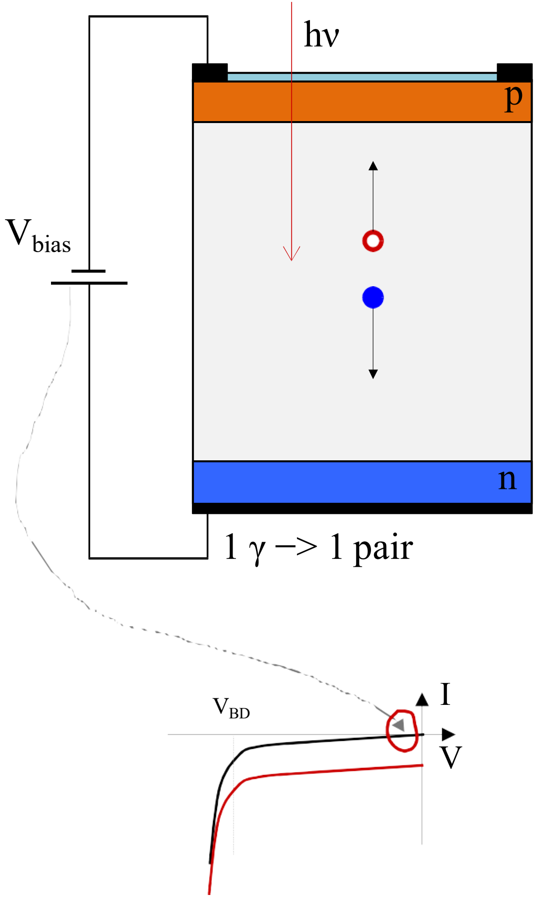




Light-weight,
all silicon
construction
ideal for
installation
Into the gantry

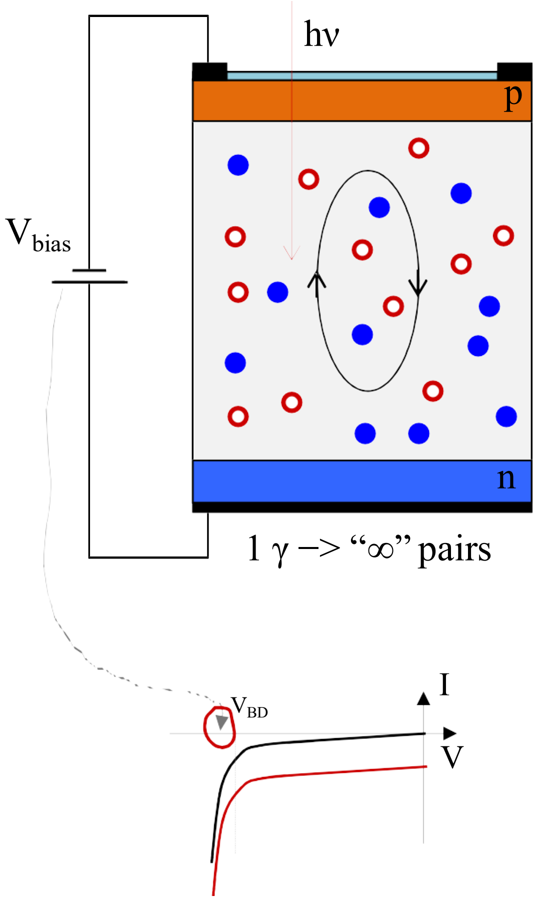
PD and SPAD

PD



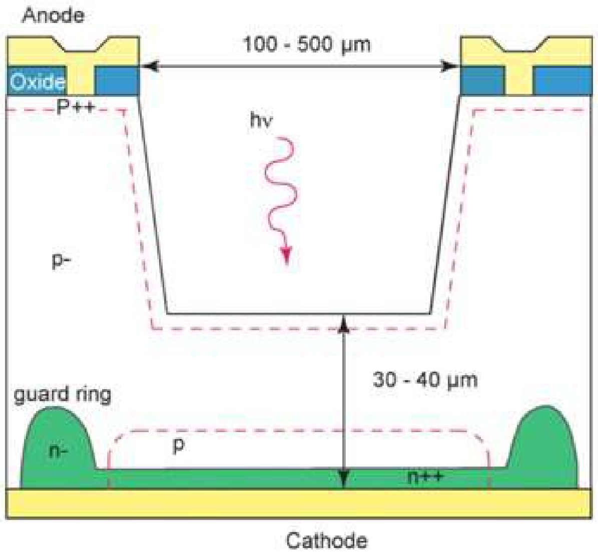
1 γ –> 1 pair

SPAD

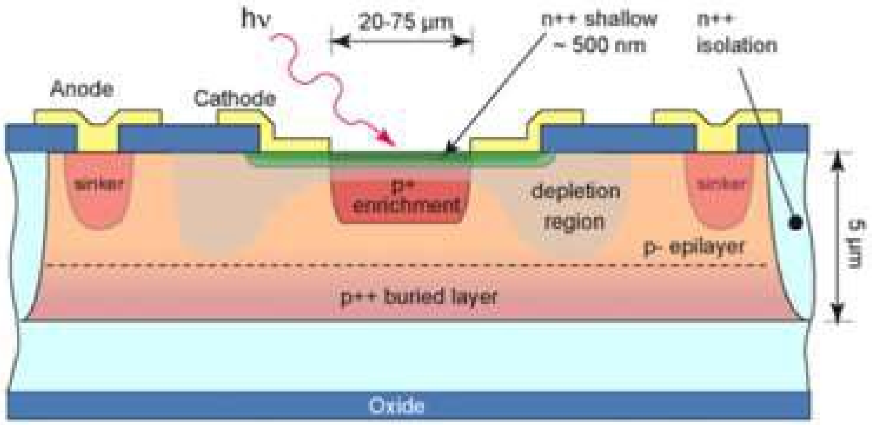


1 γ –> "∞" pairs

Structure of a SPAD



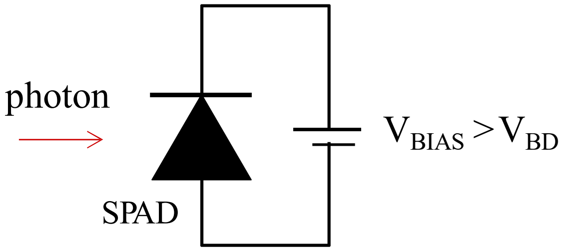
Structure of a *thick* SPAD

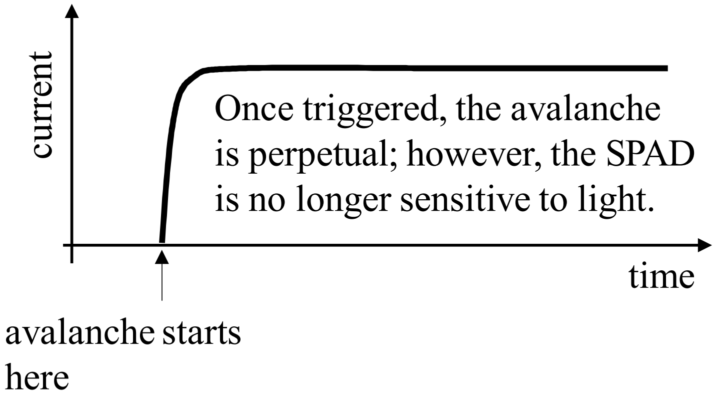


Structure of a *thin* SPAD. This structure is used in SPAD arrays.

Figures from Zappa et al. 2007

Operation of a SPAD

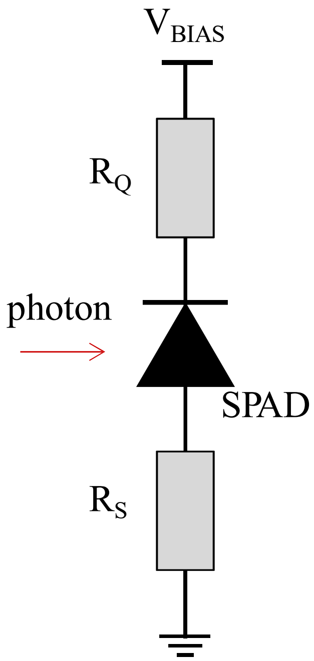




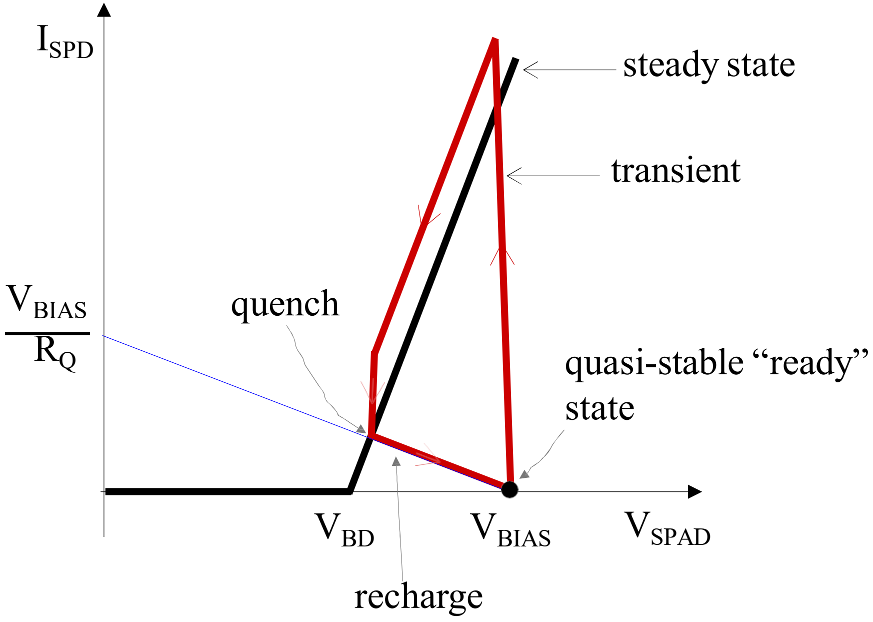
Once triggered, the avalanche is perpetual; however, the SPAD is no longer sensitive to light.

Without quenching, SPAD operates as a light switch.

Operation of a SPAD (passive quenching)

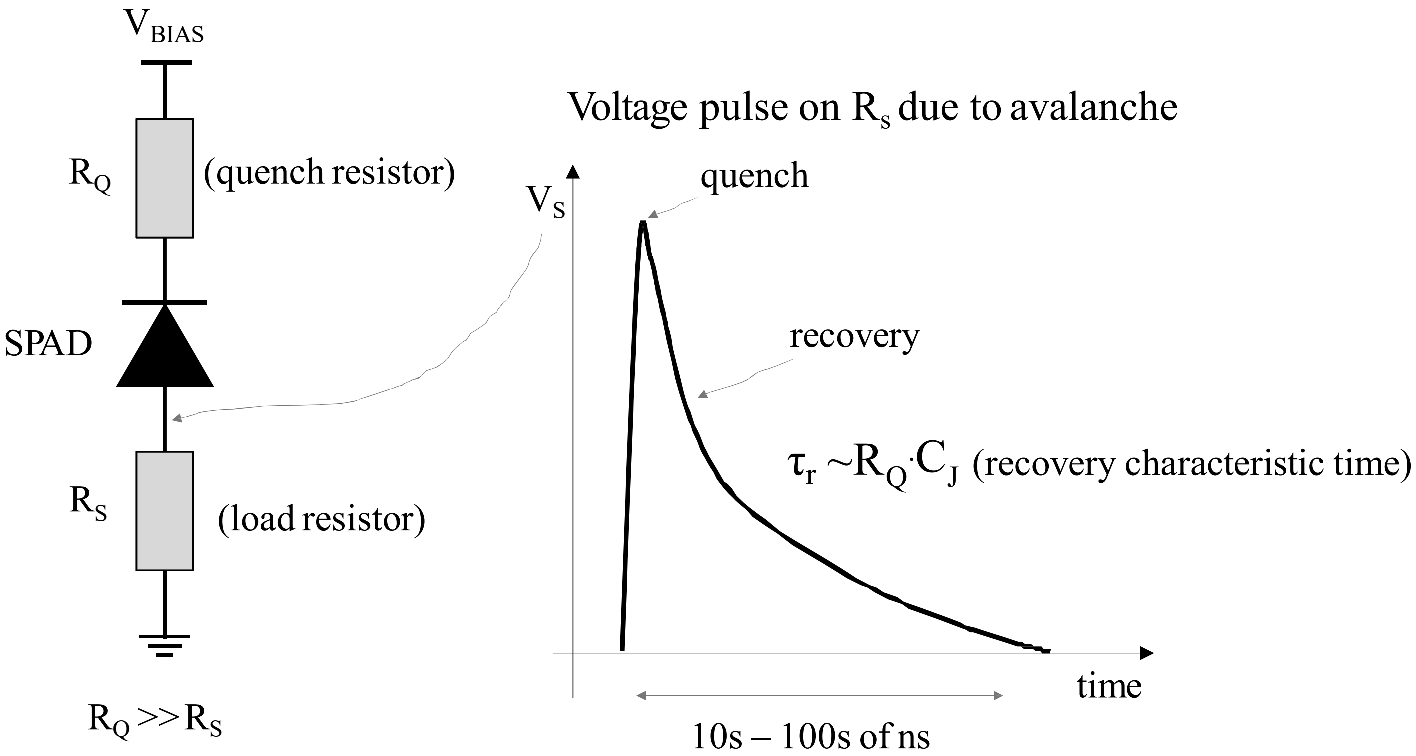


$R_Q >> R_S$



R_Q must be large enough to ensure quenching.

Operation of SPAD (passive quenching)

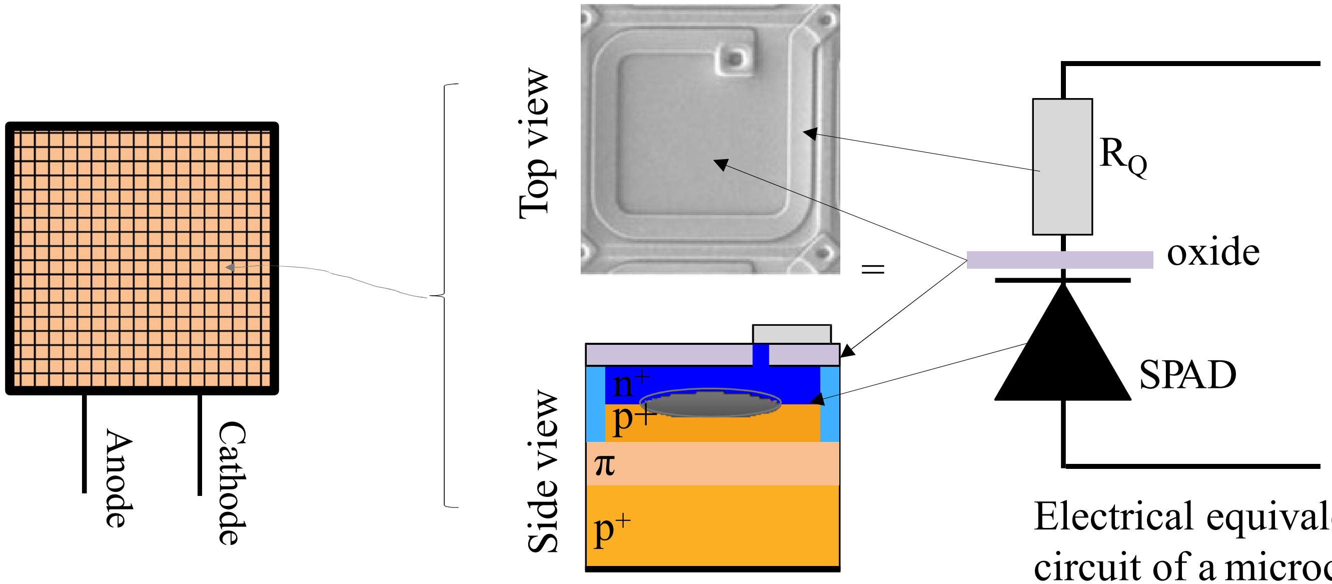


Voltage pulse on R_s due to avalanche

$\tau_r \sim R_Q \cdot C_J$ (recovery characteristic time)

$R_Q >> R_S$

Si-PM Silicon photomultiplier: structure

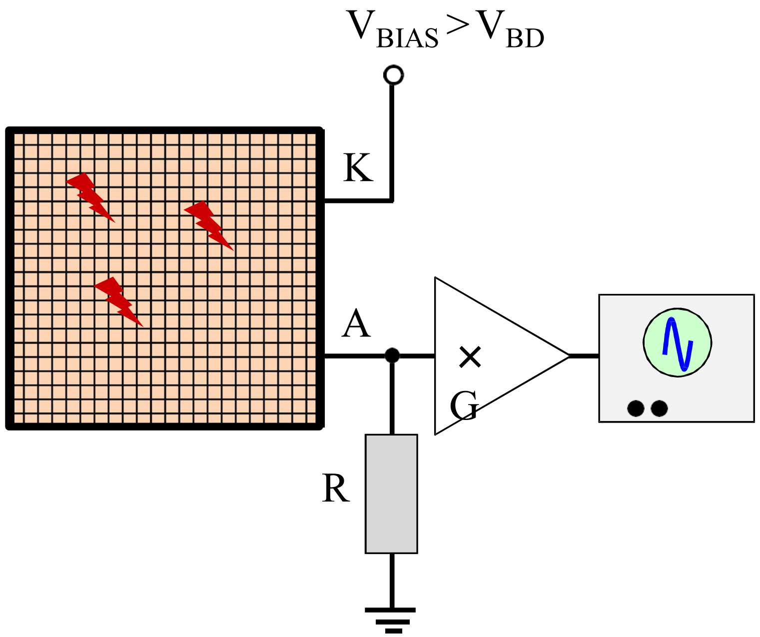


Single microcell

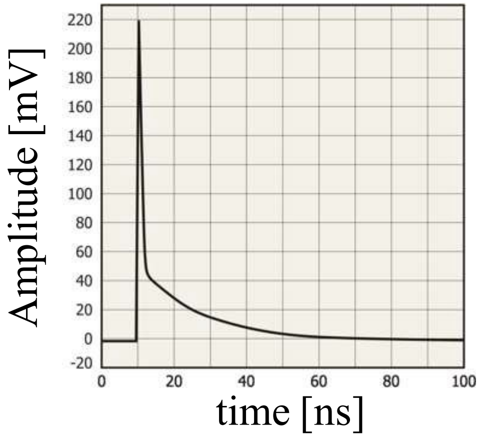
Electrical equivalent circuit of a microcell

Each microcell is a SPAD in series with a quench resistor. All microcells are connected in parallel. SiPM is **not** an imaging device because all microcells share a common current summing node.

Silicon photomultiplier: operation



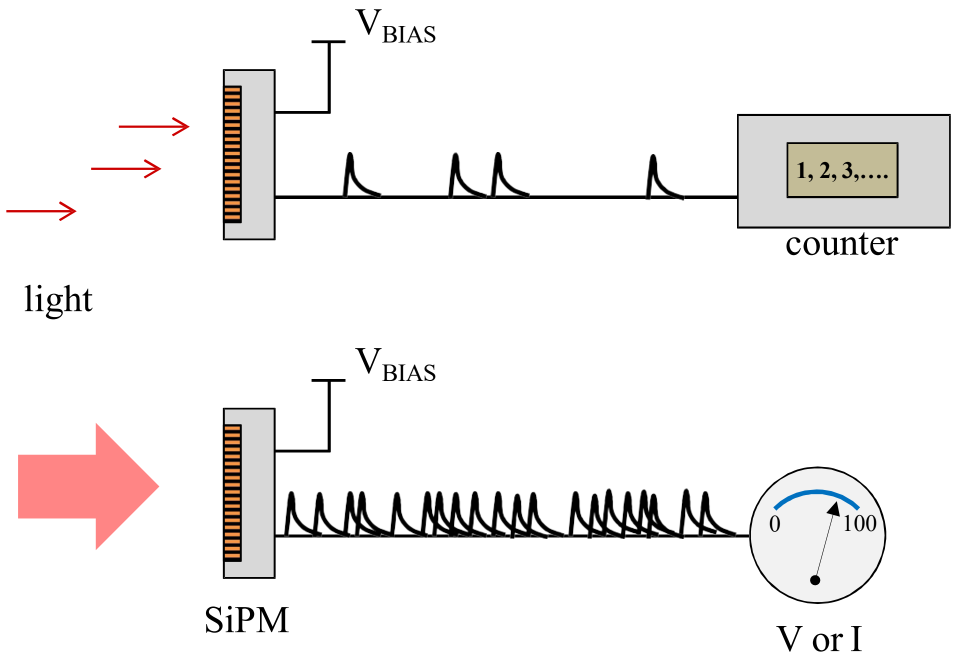
Overvoltage, $\Delta V = V_{BIAS} - V_{BD}$



Example of single-photoelectron waveform (1 p.e.)

Gain = area under the curve in electrons

Silicon photomultiplier: modes of operation



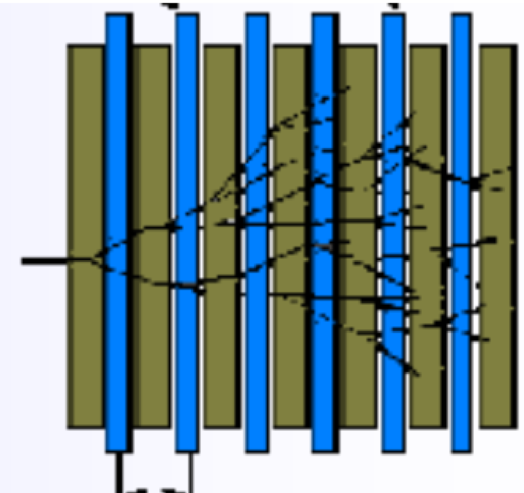
If the pulses are distinguishable, SiPM can be operated in a **photon counting** mode.

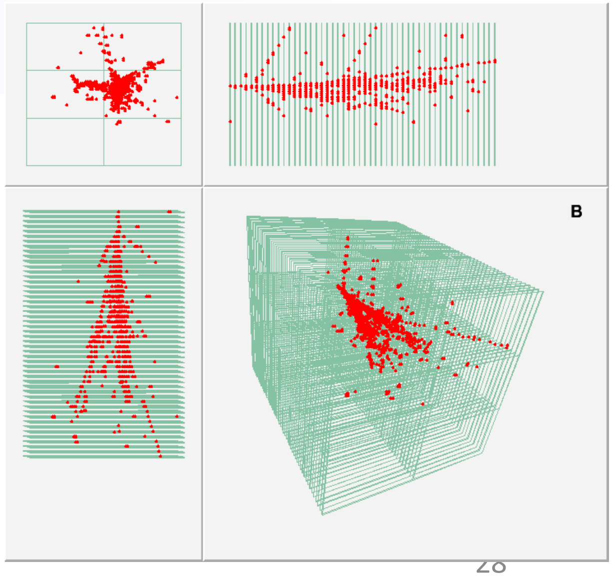
If the pulses overlap, the SiPM can be operated in an **analog mode**. The measured output is voltage or current.

- Applicazione rivelatori al silicio in calorimetria:
  - Calorimetri a campionamento

Sampling calorimeters

- Use different media
  - High density absorber
  - Interleaved with active readout devices
  - Most commonly used: sandwich structures ➔
  - But also: embedded fibres, ….
- Sampling fraction
  - $f_{\text{sampl}} = E_{\text{visible}} / E_{\text{total deposited}}$
- Advantages:
  - Cost, transverse and longitudinal segmentation
- Disadvantages:
  - Only part of shower seen, less precise

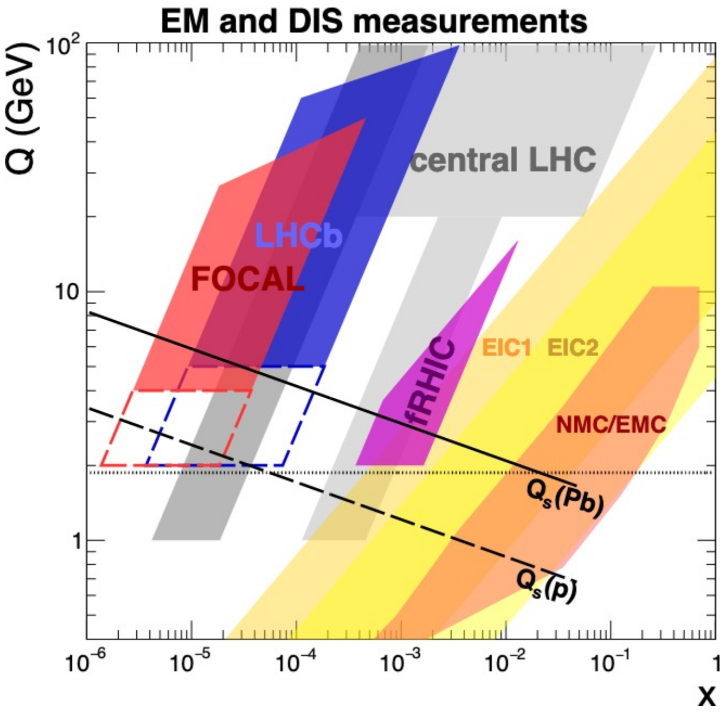


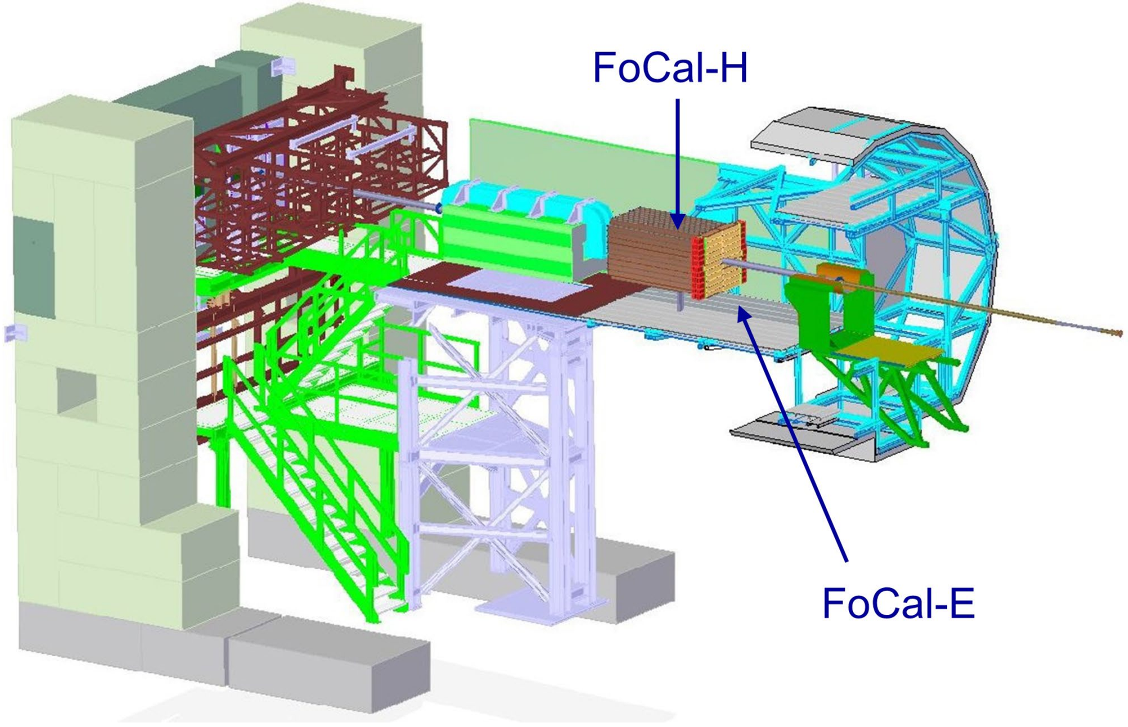


Forward Calorimeter

- Physics Goal: unravel nucleus structure at small-x
  - Unique capabilities to measure **direct photons** in pp and p-Pb
  - Study the **gluon distributions** at **small-x** scale and **low Q**

FoCal LoI - CERN-LHCC-2020-009





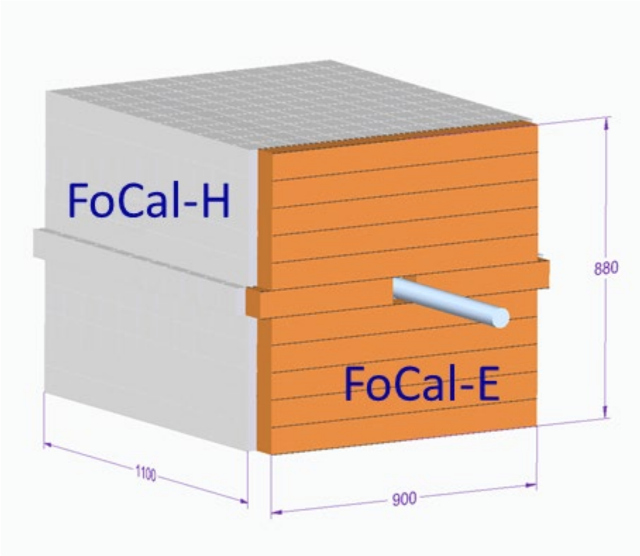
3.4 < η < 5.8
(baseline design @ 7 m from IP)

FoCal-H and FoCal-E

FoCal-H: Conventional sampling hadronic calorimeter (Cu + scintillating fibres)

- Providing γ isolation through direct detection of high energy hadrons

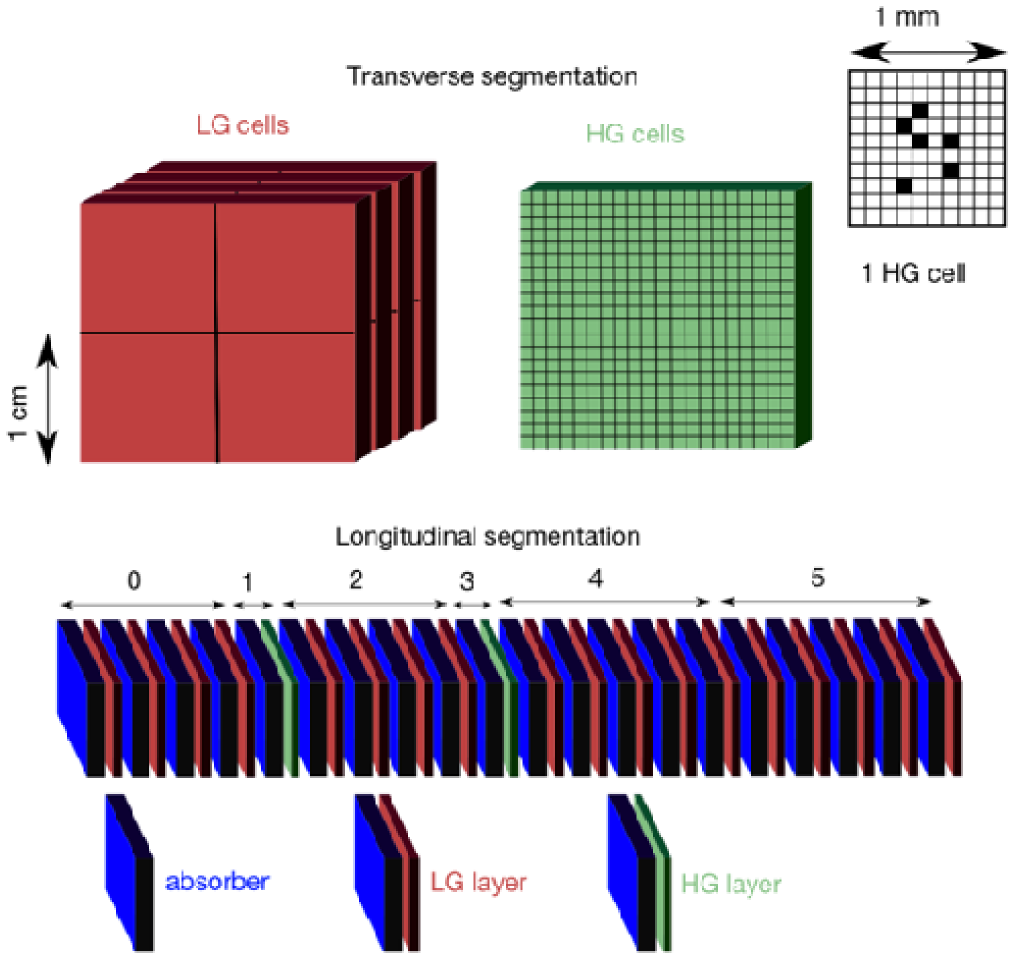
FoCal-E: high-granularity Si-W electromagnetic calorimeter for γ and π_0



- **Main challenge** for Focal-E**:** γ/π_0 separation at high energy
  - two photon separation from π^0 decay: ~2 mm
  - needs small Molière radius and high granularity readout

  ➔ Si-W calorimeter with effective granularity of ~1 mm^2

FoCal-E detector technologies

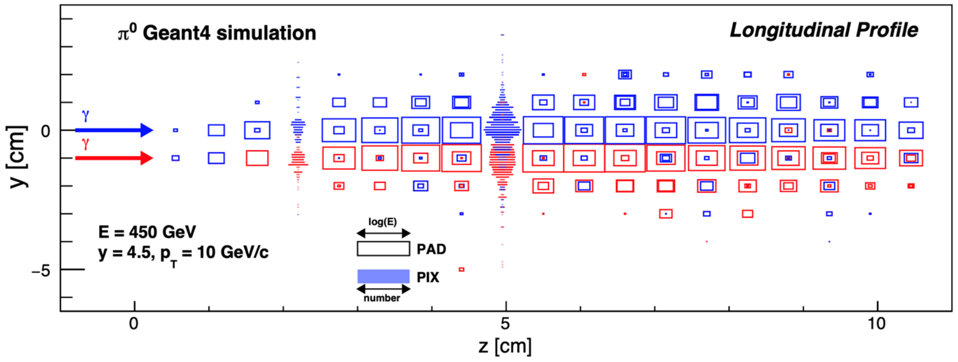


Studied in simulations: 20 layers

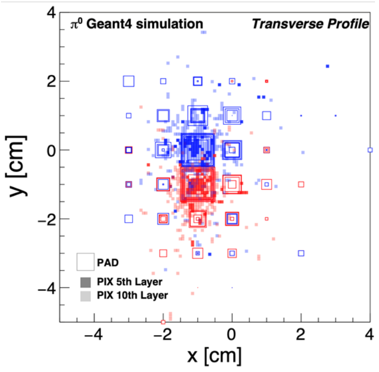
W (3.5 mm ~ 1X_0) + silicon

- 18 Pad layers
  - Low granularity (LG), provide shower profile and total energy
- 2 Pixel layers (ALPIDE)
  - High granularity (HG), provide position resolution to resolve overlapping showers

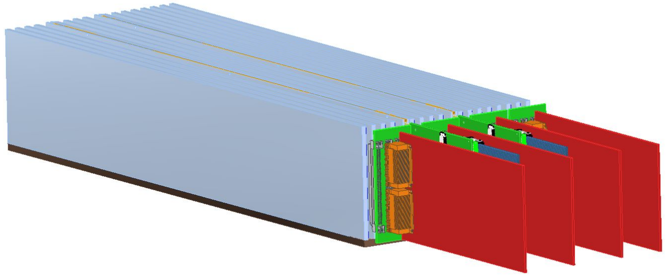
Longitudinal profile (2γ showers)



Trans. profile

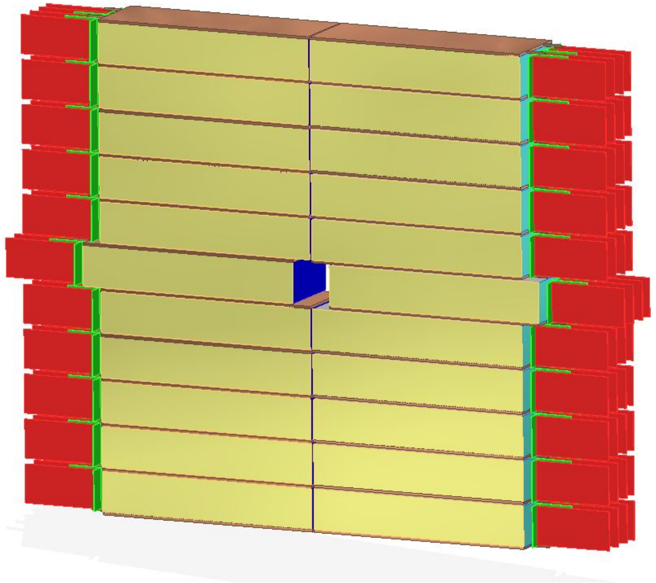


FoCal-E layout and prototypes

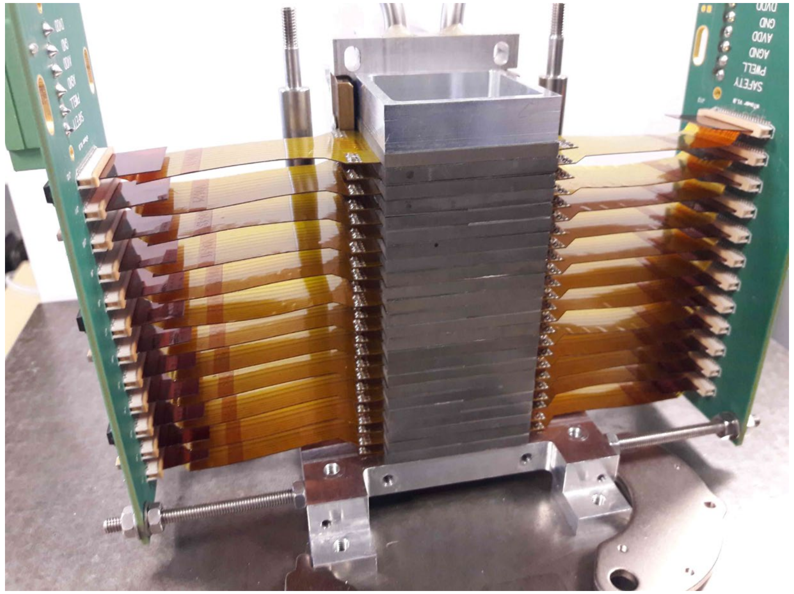


Module: 18 pad layers + 2 pixel layers

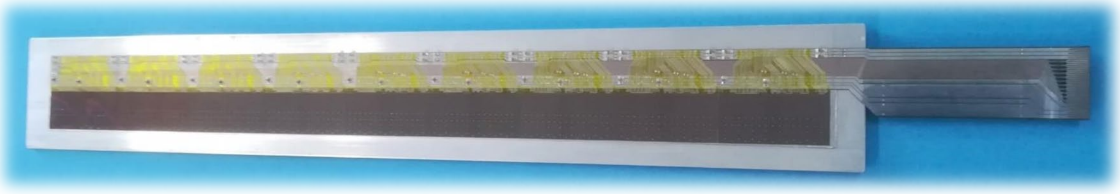
- Readout, power, cooling connected on one side



FoCal-E:
22 modules



EPICAL
all-pixel small E-cal



Pixel string prototype: 9x SpTAB bonded ALPIDE
Final pixel layer will have 3x 15-ALPIDEs strings