3rd Journées Collisionneur Linéaire, 1 Dec. 2014

CMOS Pixel Technologies R&D state of the art

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PICSEL GROUP

Physics with Integrated Cmos Sensors and ELectron machines

Outline

- Motivations for developing CMOS Pixel Sensors (CPS) beyond STAR-PXL
- Main characteristics of the real scale sensor FSBB-M fabricated in 2014
- Beam test based performance assessment of the FSBB-M sensor
- Summary and outlook

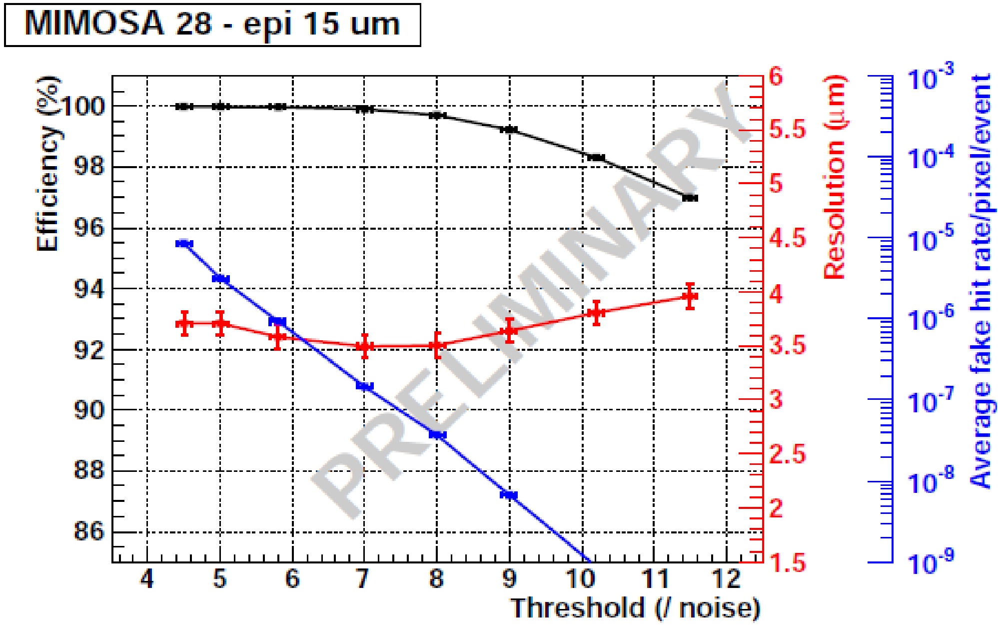
State-of-the-Art: STAR-PXL (The Sensor)

ULTIMATE main characteristics

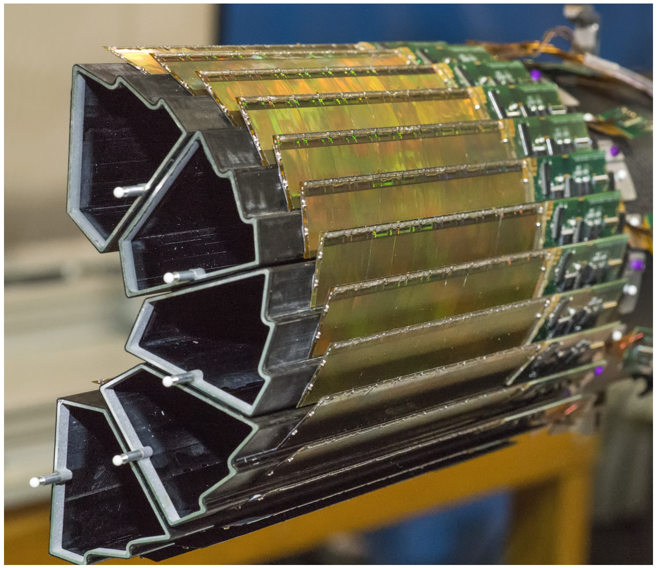
- CMOS sensor (0.35µm AMS) high-resistive Epi-layer-15µm
  Sensor thinned to 50µm (total thickness)
- Column || architecture with in-pixel CDS & amplification
- End-of-column discriminator & binary charge encoding, followed by ∅-suppression
- 960x928 (columns x rows): pitch 20.7µm (19.9x19.2 mm^2)
- $t_{r.o.} \lesssim$ 200µs (~5x10^3 frames/s) ⇒ suited to > 10^6 part./cm^2/s
- 2 outputs @ 160 MHz
- Power consumption ~150mW/cm^2
- Running at room temp. (T = 30C^o)

ULTIMATE Performances

- $\sigma_{sp} \gtrsim$ 3.5µm
- Efficiency $\lesssim$ 99.9%
- Fake rate $\lesssim$ 10^{-5}



State-of-the-Art: STAR-PXL (I)

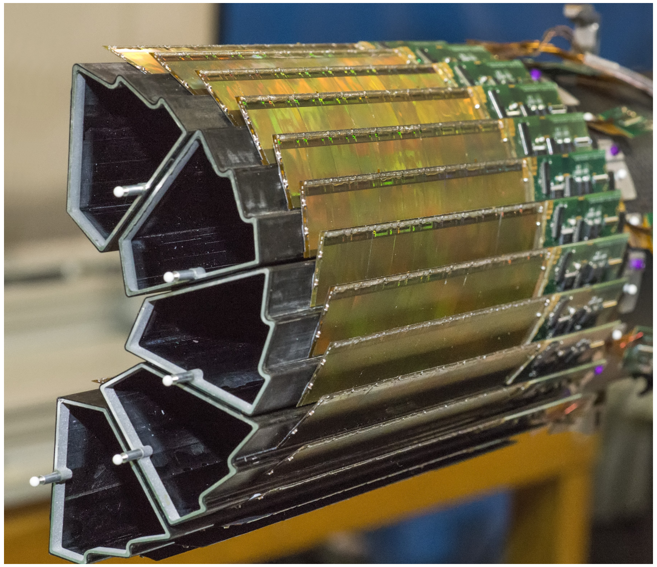


STAR-PXL HALF-BARREL

- 2 layers: 20 ladders (0.37% X_0)
- 200 sensors
- 180×10^6 pixels
- Air flow cooling: T < 35°C
- $\sigma_{sp} < 4\mu m$
- Rad. Load 150kRad + 3×10^{12} n.e.q (Full life-time)
- $t_{o.r.} < 200\mu s$

1st CMOS Pixel Sensor in a collider experiment !

State-of-the-Art: STAR-PXL (II)



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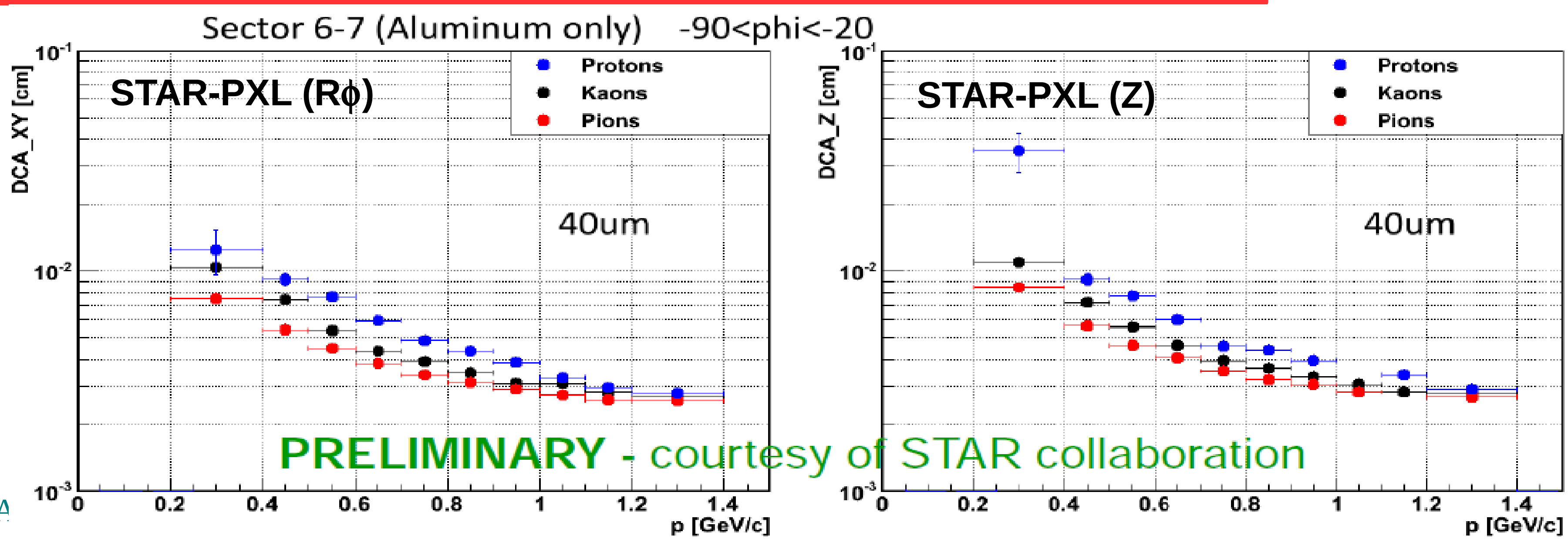
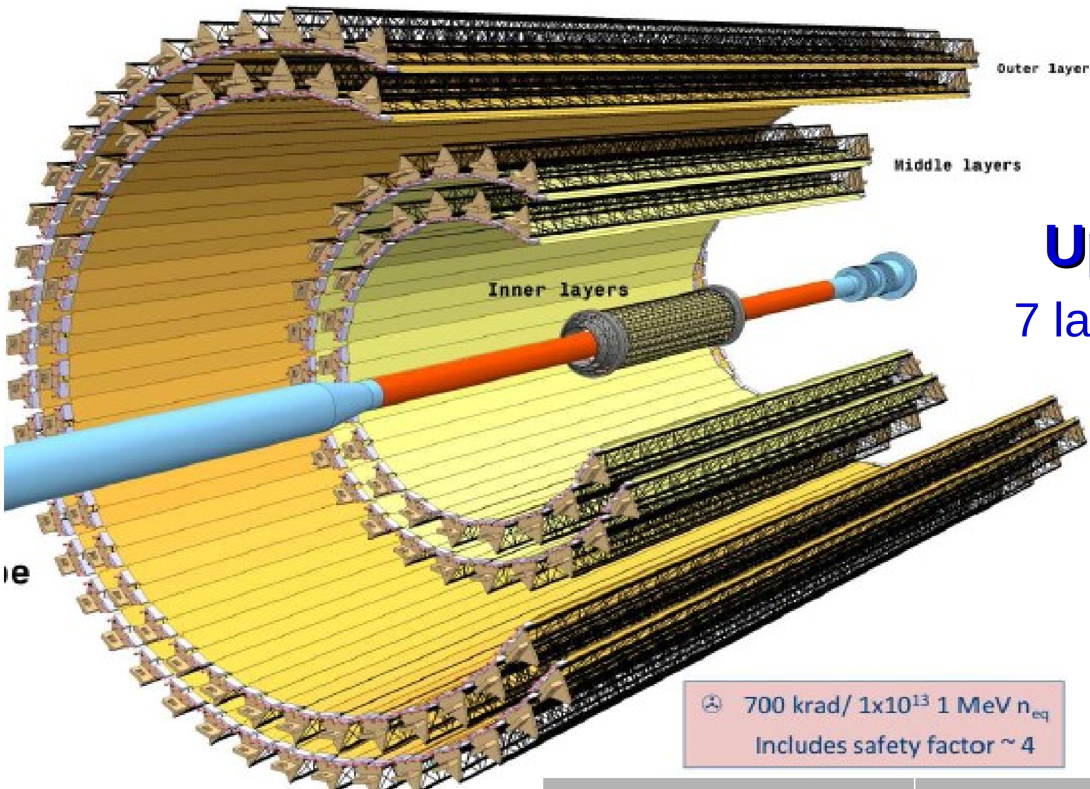


Next generation of High Precision
Tracking & Vertexing Devises
⇓
FASTER and MORE RADIATION TOLERANT
CMOS Pixel Sensors (CPS)

Forthcoming device: New ALICE Inner Tracking System (ITS)



Upgrade of ALICE-ITS at LHC

7 layers > $10 m^2$ active area (>> 10^4 CPS)

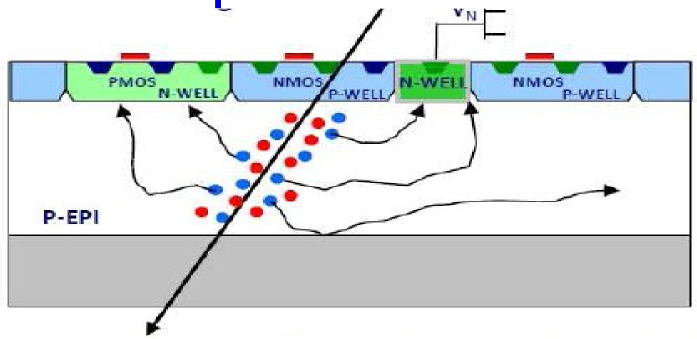
- $\sigma_{sp} \lesssim 5(10)\mu m$ inner (outer) layers
- ~ 0.3 % X_0 / layer

700 krad/ 1×10^{13} 1 MeV n_{eq}
Includes safety factor ~ 4

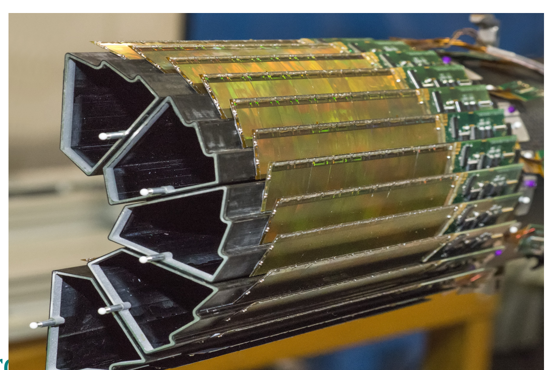
Parameter	Inner Barrel	Outer Barrel
Max thickness (μm)	50	50
σ_{sp} (μm)	5	10
Chip dims. (mm^2)	15x30	15x30
Max power (mW/cm^2)	300	100
Max t_{int} (μs)	30	30
Radiation load	250kRad + $2.5\times10^{12} n_{eq}/cm^2$	15kRad + $5\times10^{11} n_{eq}/cm^2$

CMOS Process Transition: STAR-PXL → ALICE-ITS

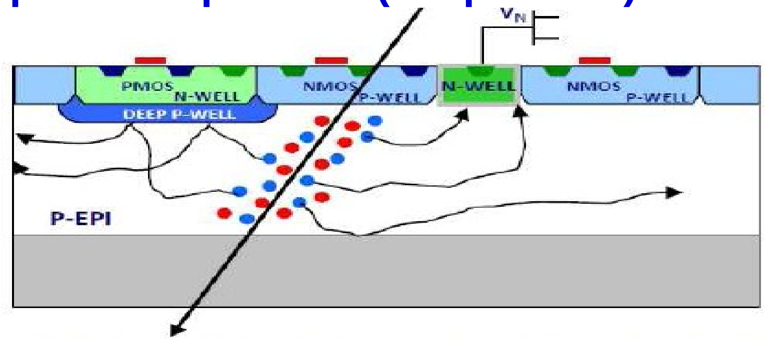
Twin well process: 0.6-0.35 um



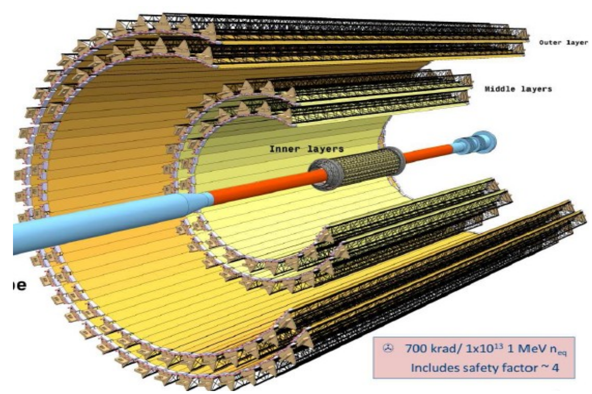
- Use of PMOS in pixel array not allowed because any additional N-well hosting PMOS would compete for charge collection with sensing node
- Limits choice of readout architecture strategy
- Already demonstrate excellent performances
  - STAR-PXL: Mi-28 designed in AMS-0.35µm process ⇒ $\varepsilon_{det} > 99.5\%$, $\sigma_{sp} < 4\mu m$
  - 1st CPS detector at collider experiment



Quadrupole well process (deep P-well): 0.18 um



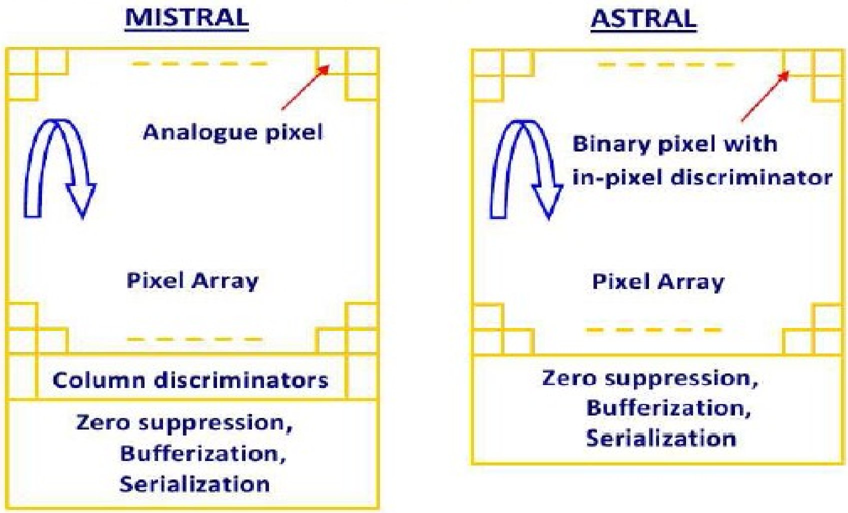
- N-well hosting PMOS transistors is shielded by deep-P-well ⇒ both types of transistors can be used
- Widens choice of readout architecture strategies
  - Ex. ALICE-ITS upgrade: 2 sensors R&D in || using TOWER CIS 0.18um process (quadrupole well)
    - Synchronous Readout R&D: proven architecture ⇒ safety
    - Asynchronous Readout R&D: challenging

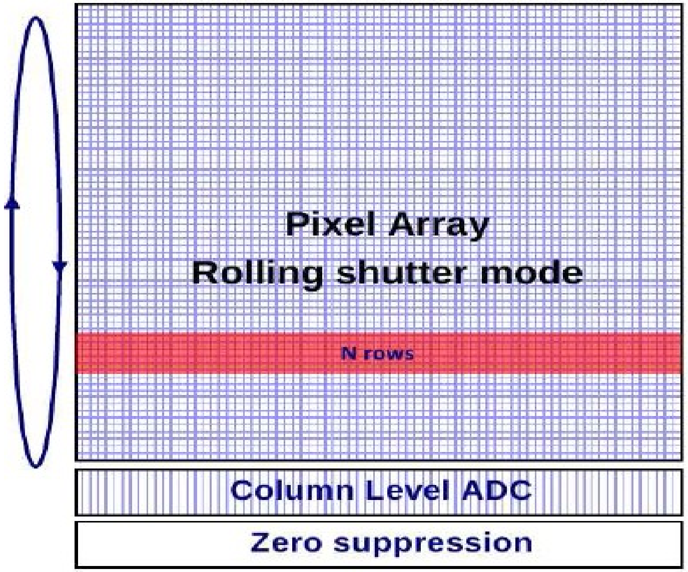


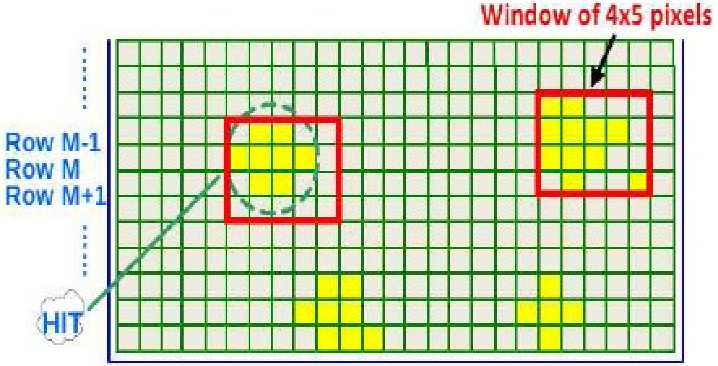
ALICE

Synchronous readout Architecture: Rolling Shutter Mode

- Design addresses 3 issues
  - Increasing S/N at pixel-level
  - Analogue to Digital Conversion
    - At end of column ⇒ **MISTRAL**
    - Inside pixel ⇒ **ASTRAL**
  - Zero suppression (SUZE) at chip edge

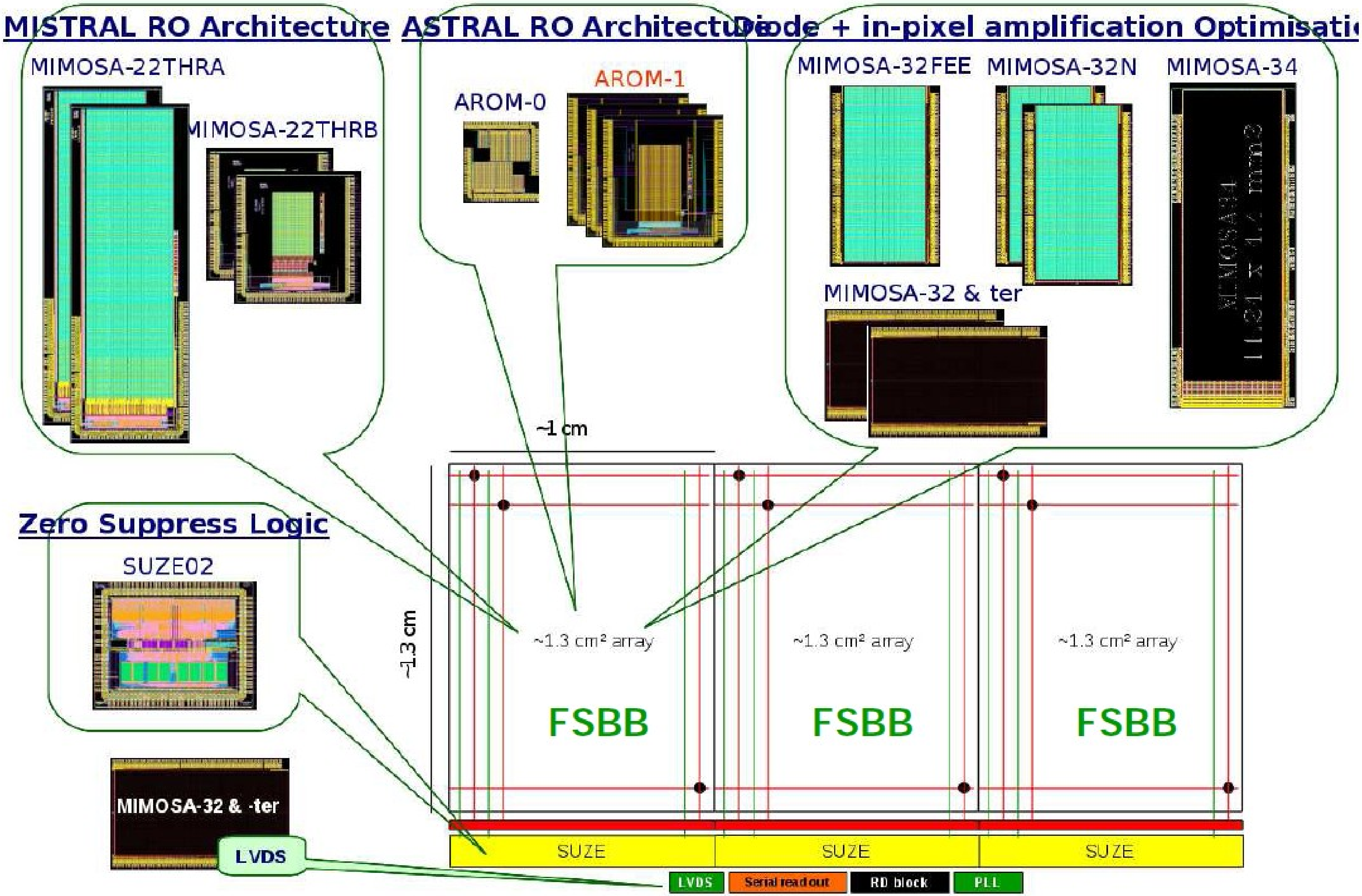






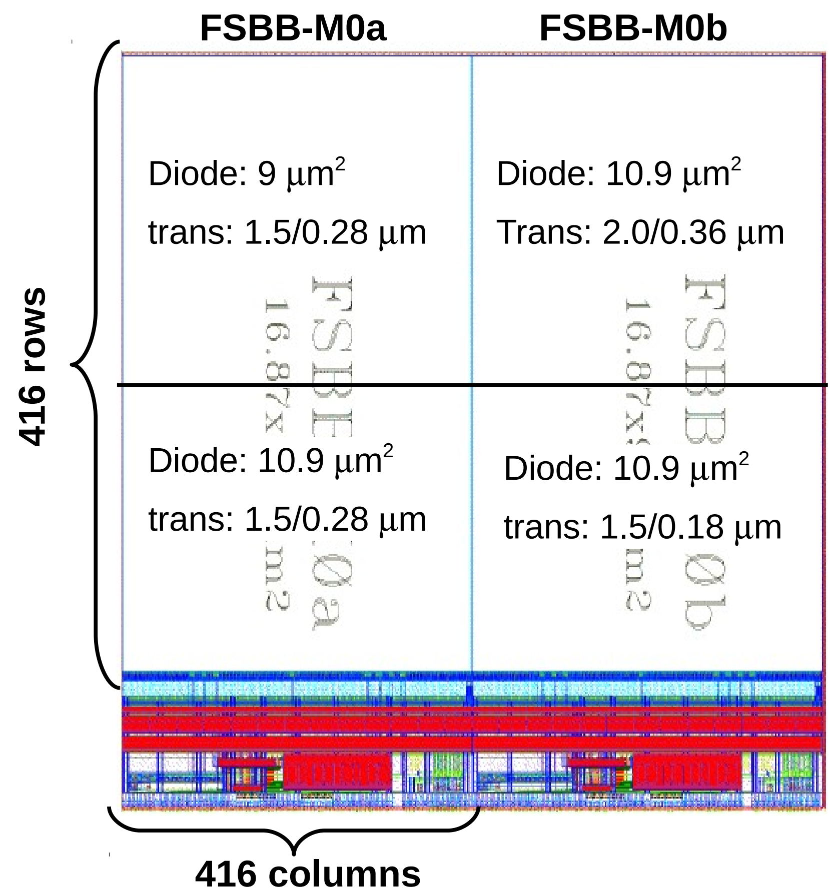
- Power vs Speed
  - Power: only the selected rows (N=1,2,3 …) to be readout
  - Speed: N rows of pixels are readout in ||
    - Integration-time (t_{int}) = frame readout time ⇒ $t_{int} = \frac{(Row\ readout\ time) \times (No.\ of\ Rows)}{N}$

Prototypes Fabricated to Explore the Full Sensor Chain



FSBB-M0 (≡ MISTRAL) Fabricated in Spring 2014

- TJsc-0.18 CIS process, HR (~1kΩcm) 18μm epitaxy, thinned to 50μm
- Staggered pixel: 22x33 μm^2 including pre-amplification and clamping with 6 metal layers (ML)
- 416x416 of Columns x Row of pixels ended by discriminator (8-cols with analogue output)
- Double-row readout at 160MHz clock frequency ⇒ t_{int} = 40μs
- On-chip 3-stage sparsification: SUZE-02
- 4 Memories of 512x32 bits
- 2 output nodes at 320Mbits/s (used only one for TB)
- Integrated JTAG and regulators
- Sensitive area ~ 1.2cm^2
- Two versions fabricated (FSBB-M0 a & b)
  - FSBB-M0a: sensing node size variation
  - FSBB-M0b: input transistor of in-pixel pre-amplifier
- Design not optimized in terms of
  - Pixel dimensions
  - Power consumption
  - Readout speed
  - ITS layer, layout
  - In-pixels circuitry and discriminator
  - Epitaxy parameters



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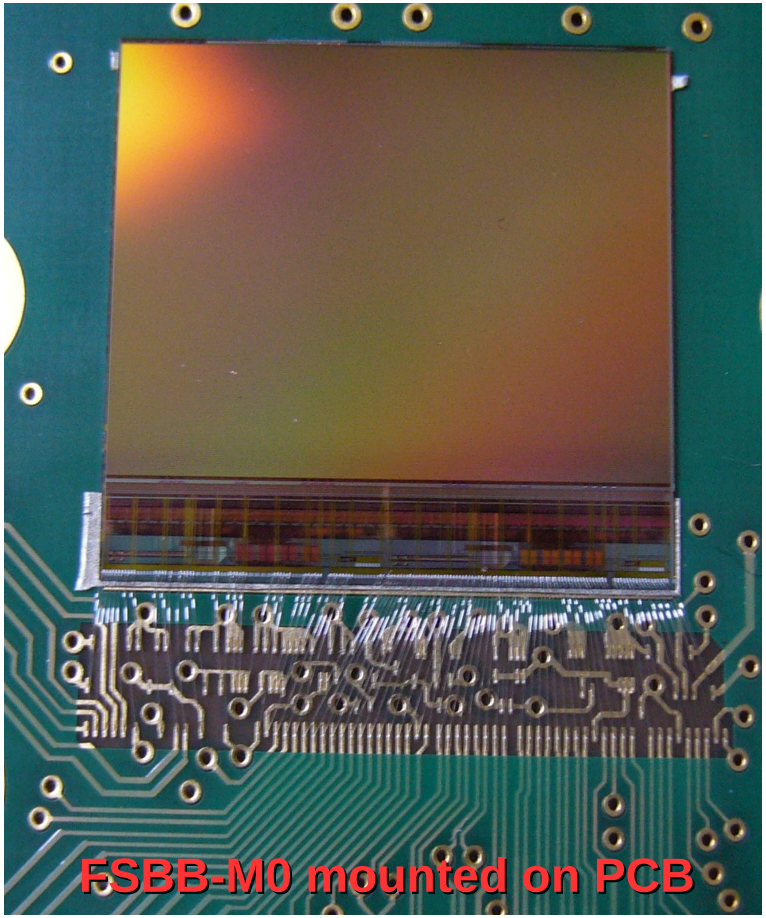
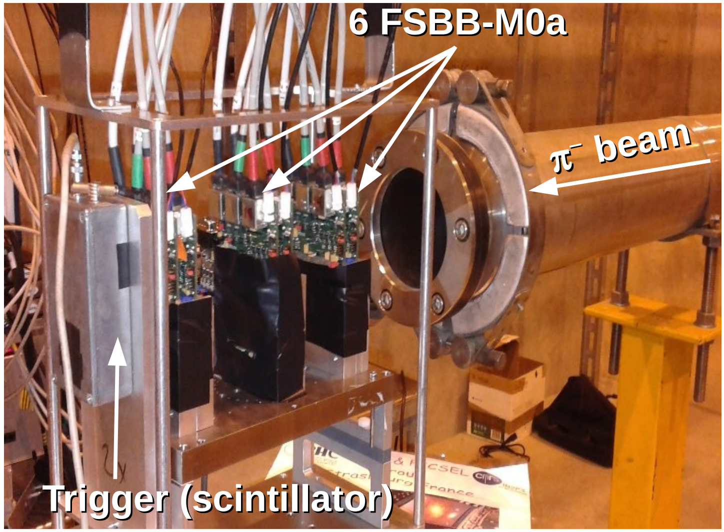


Beam-Test: Experimental conditions and set-up

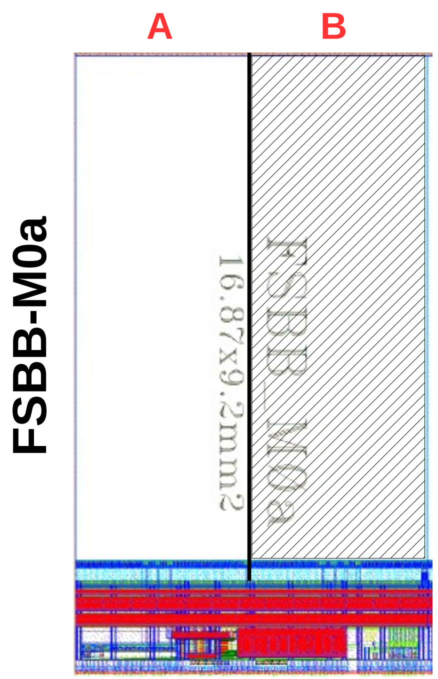
Beam conditions at CERN on Oct. 2014

- SPS H6A area
- 120 GeV π^-
- Particle flux: trigger rate ~2.5 to 100 kHz / 5x10 mm^2



Device used for the tests

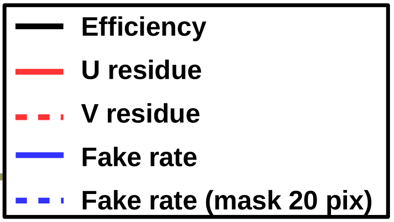
- 6 FSBB-M0a thinned to 50µm
- Most of the measurements with sub-array B (80k pixels), less cross-couplings than sub-array A



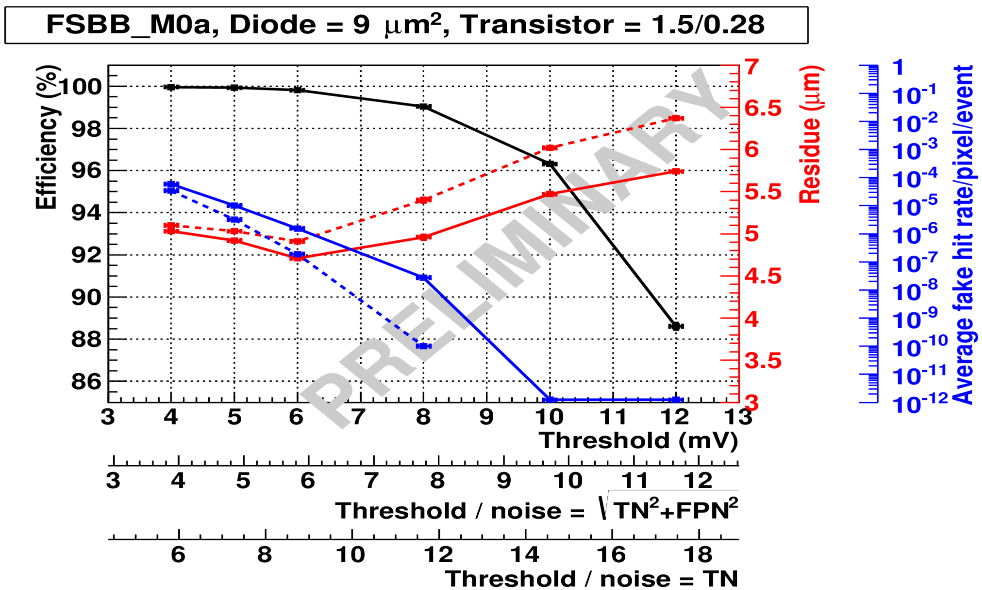
Data Collected (mainly on October 18-19th)

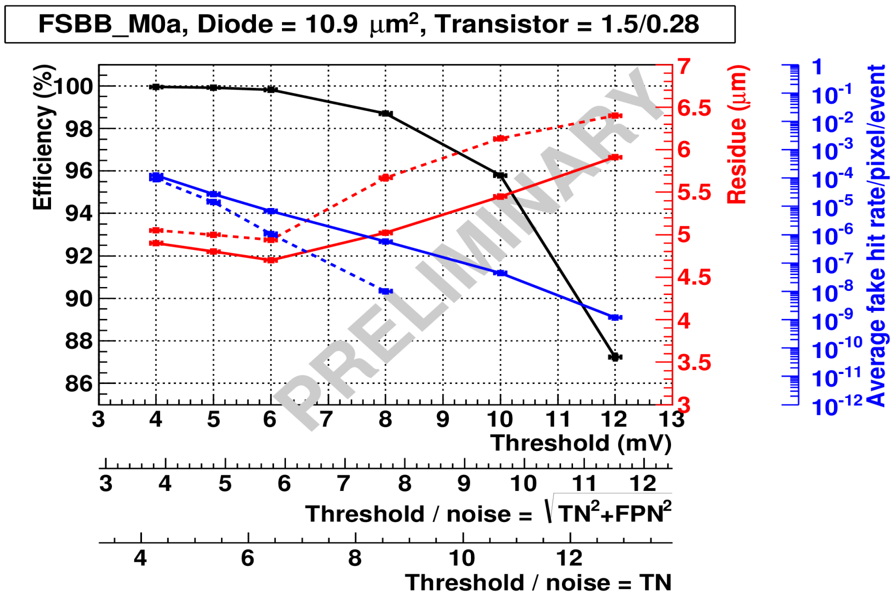
- 3.7×10^6 triggers collected with beam
- Reconstructed tracks for performances assessment
  - 11µm^2 diode: ~400k
  - 9µm^2 diode: ~300k
- 8.5×10^6 frames collected without beam for noise determination ⇒ fake rate studies
- All measurements performed at T_{op} = 30°C

Beam-Test: Detection Performances



- ε_{det}, **fake rate,** σ_{res} **vs discriminator threshold** **(Noise averaged over 11 thinned sensors)**





Diode size (µm²)	$\varepsilon_{det} \gtrsim 99.8\%$	$\varepsilon_{det} \gtrsim 99.5\%$	$\varepsilon_{det} \gtrsim 99.0\%$	fake $\lesssim 10^{-5}$
11.0	$\lesssim$ 6.0 mV	$\lesssim$ 6.5 mV	$\lesssim$ 8.0 mV	$\gtrsim$ 6.0 mV
9.0	$\lesssim$ 6.0 mV	$\lesssim$ 7.0 mV	$\lesssim$ 8.0 mV	$\gtrsim$ 5.0 mV

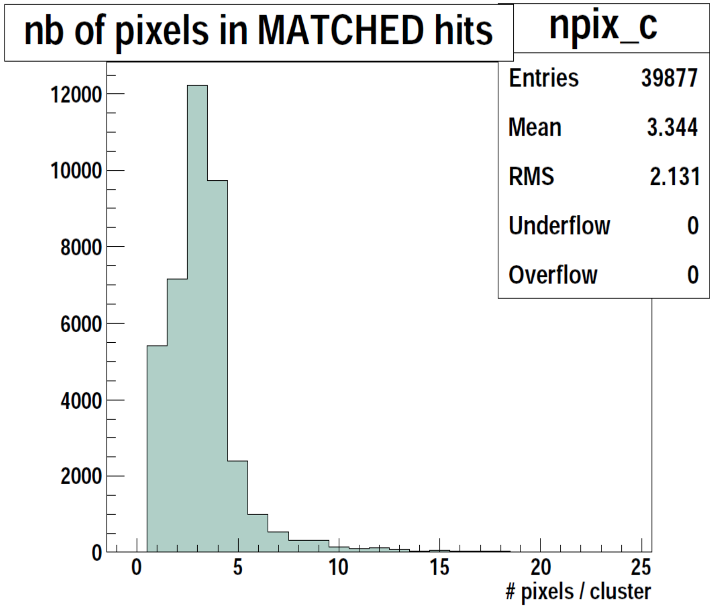
Discriminator Thresholds

- **Residue on DUT:** $\sigma_{res} \approx (4.7 \pm 0.1)$ µm (U) & (4.9 ± 0.1) µm (V) at 6mV for both diode sizes
- **Expected resolution:** $\sigma_{sp} \approx 4.5$ µm (tbc)

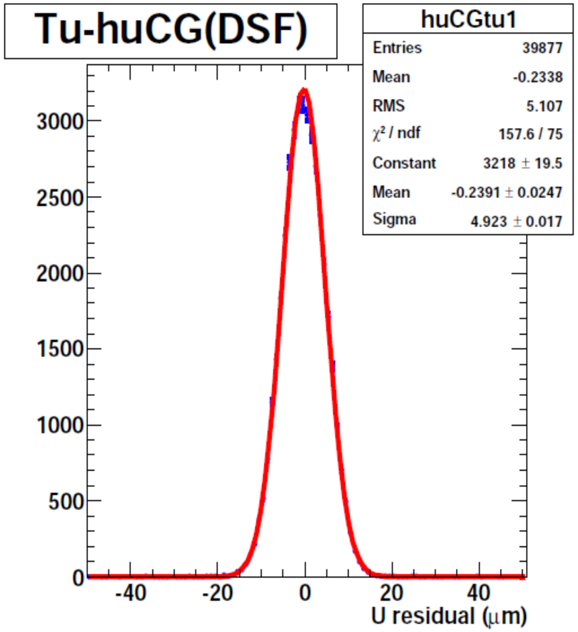
Beam-Test: Spatial resolution vs cluster multiplicity

- Multiplicity depends on where the track hits the sensor with respect to the collection diode
  $\Rightarrow$ resolution is then a function of multiplicity

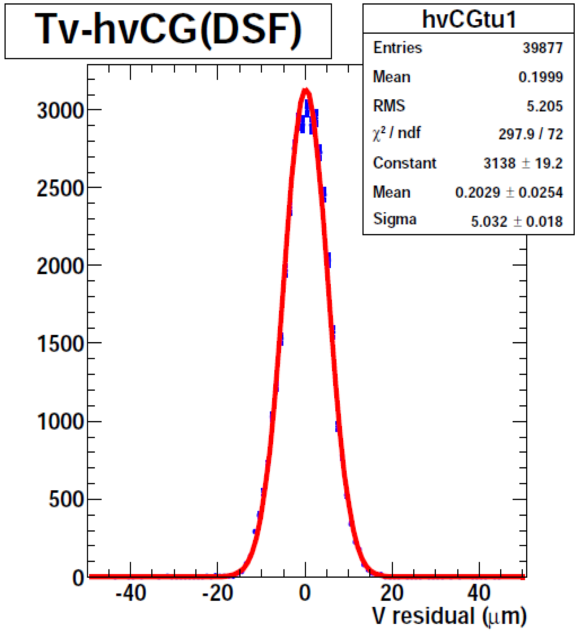
- **9 µm² diode:** threshold at 5mV



Residue distribution U



Residue distribution V



Beam-Test: Spatial resolution vs cluster multiplicity

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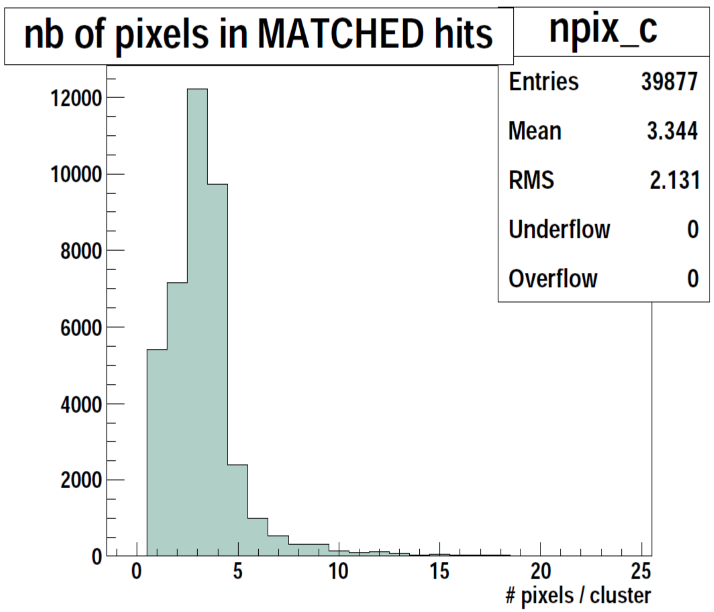
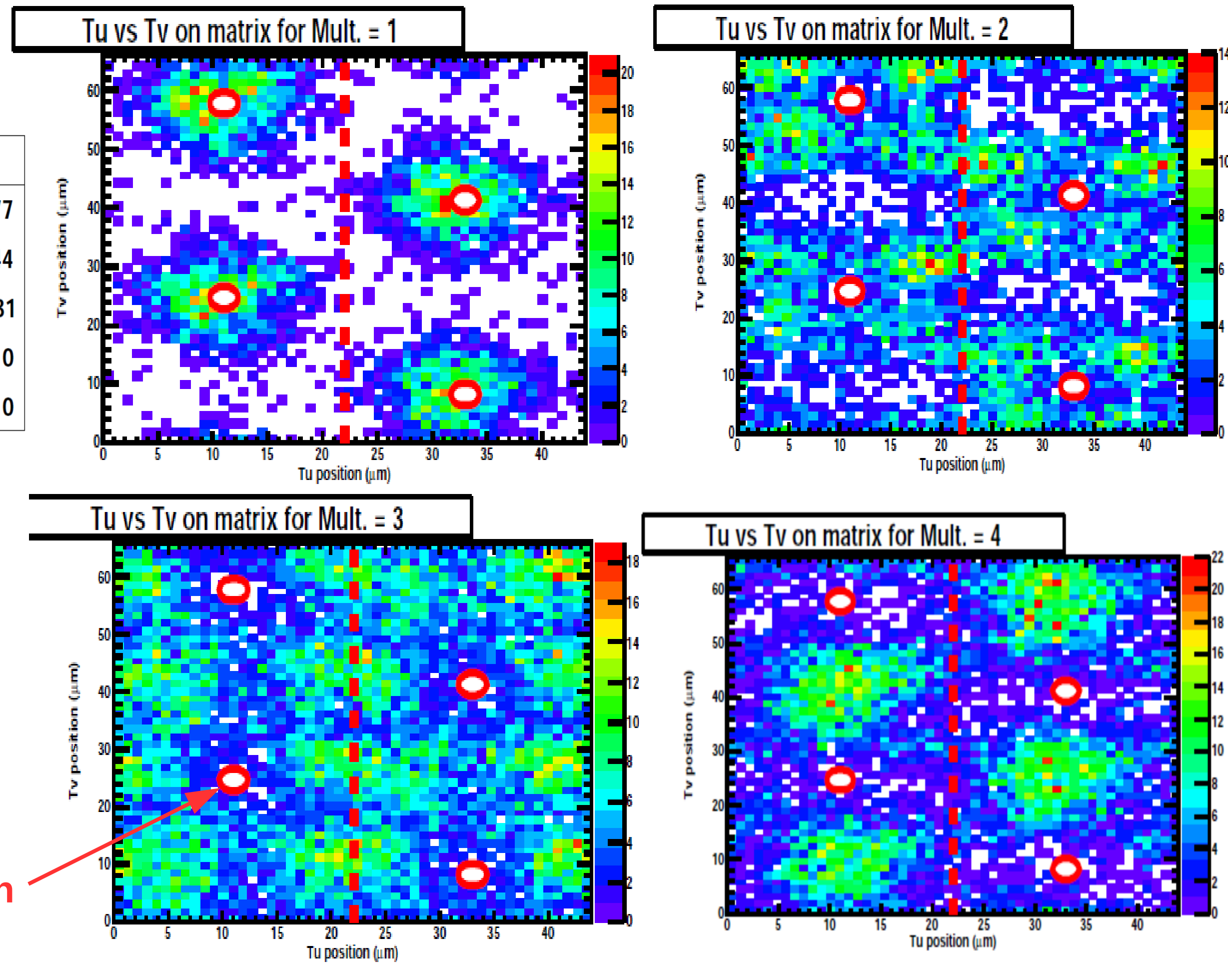
- **9 μm^2 diode:** threshold at 5mV



Track position distribution vs associated hit multiplicity



Collection diode position

Beam-Test: Spatial resolution vs cluster multiplicity

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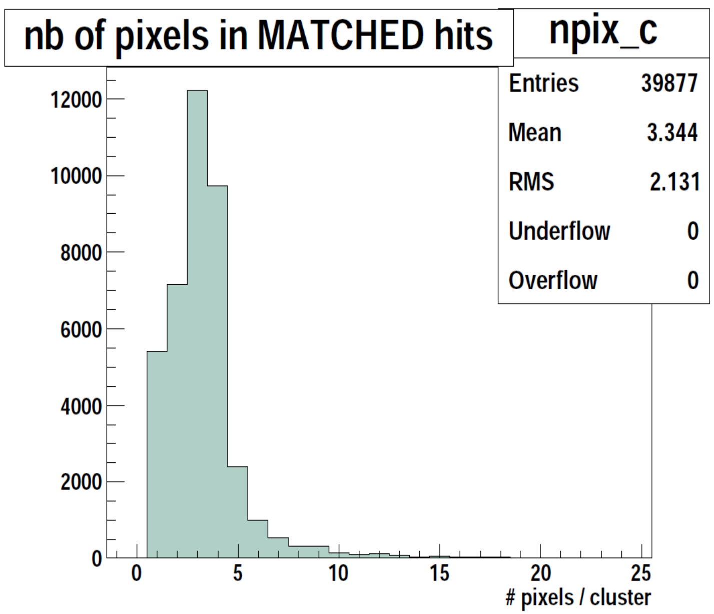

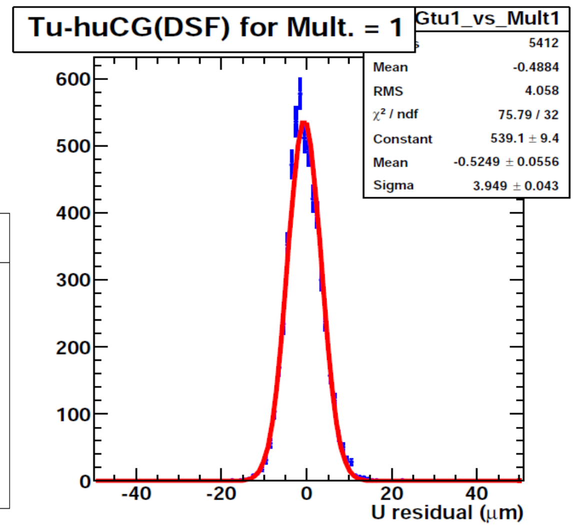

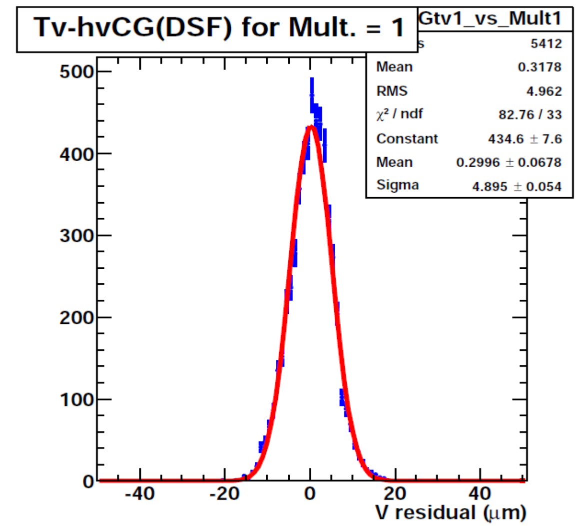

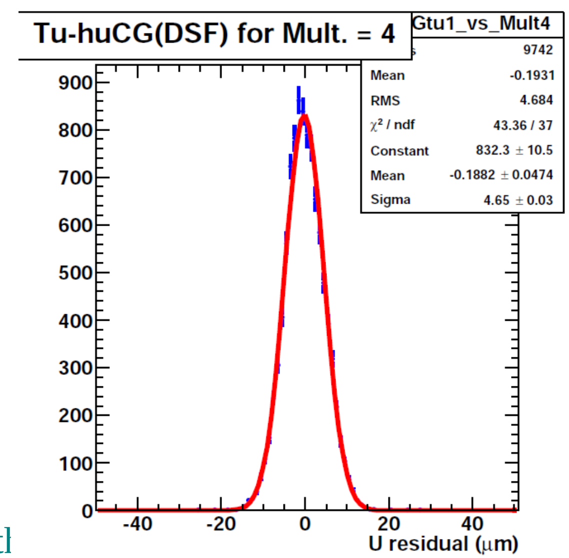

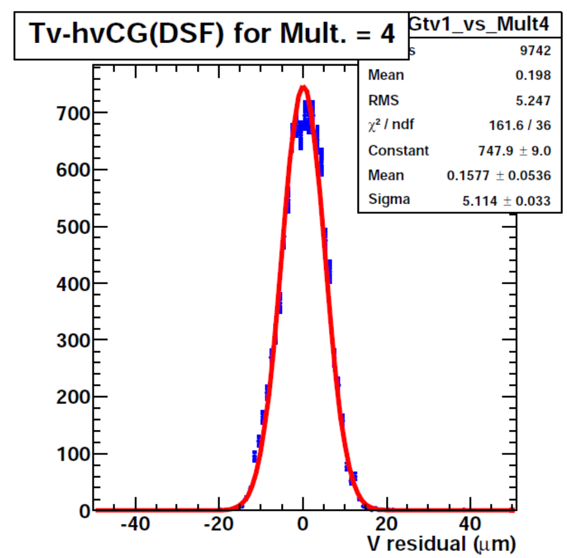

Beam-Test: Spatial resolution vs cluster multiplicity

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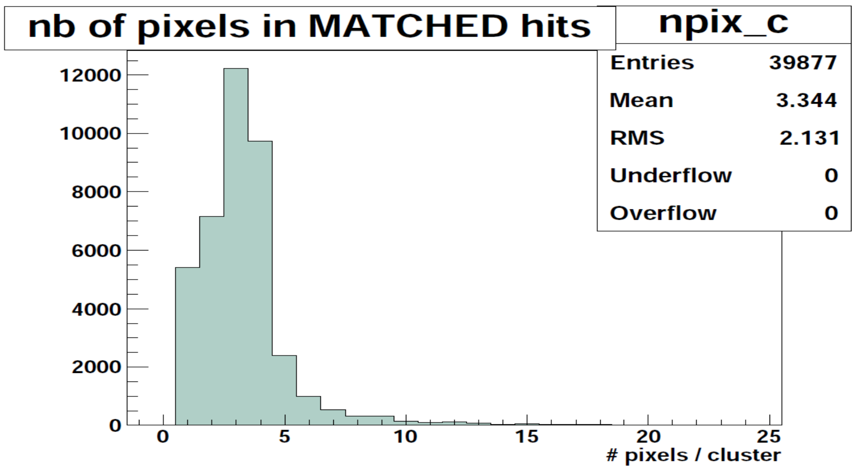
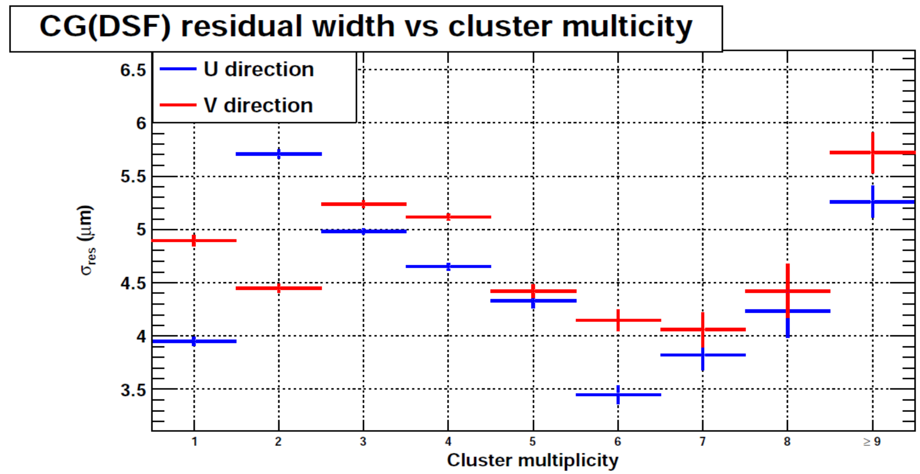
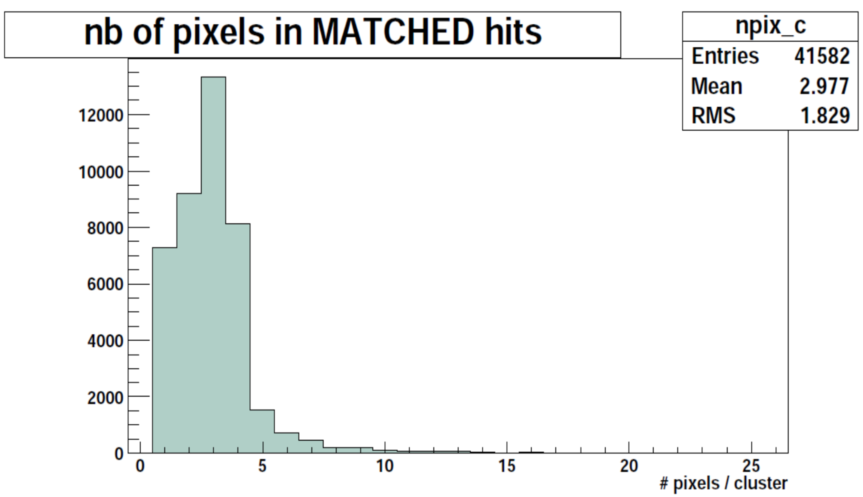
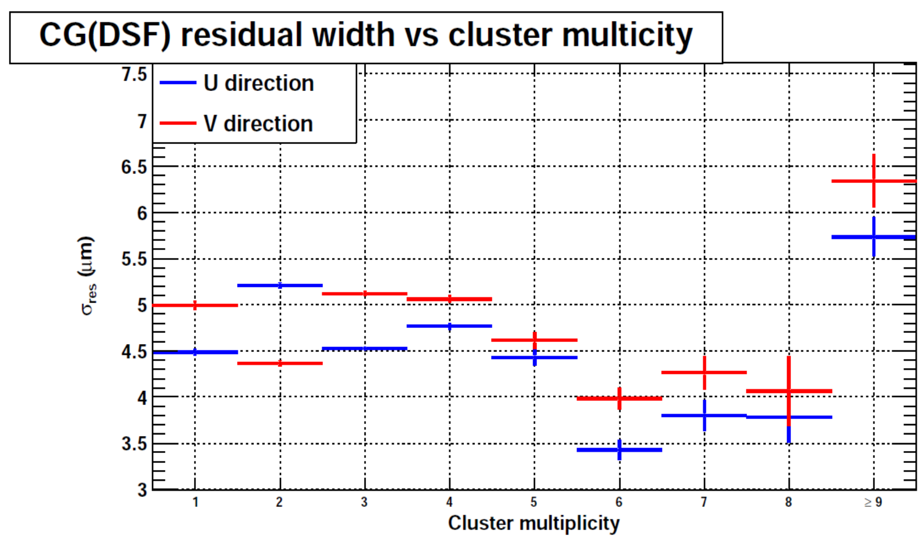




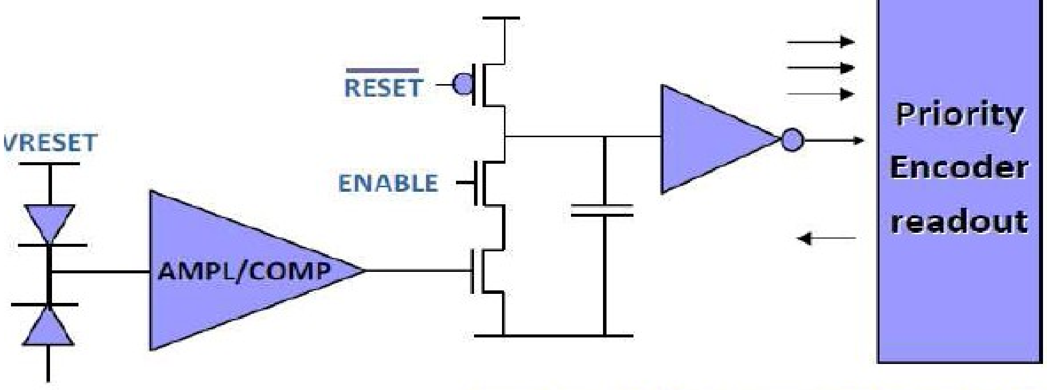
- **11 μm^2 diode:** threshold at 5mV



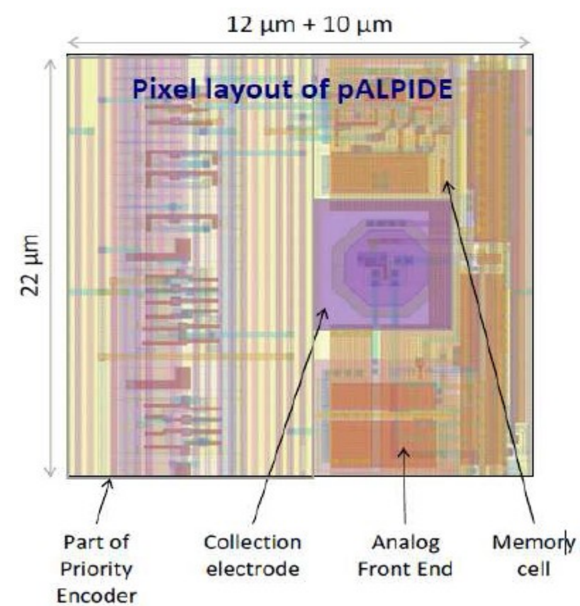


Asynchronous readout Architecture
ALPIDE (Alice Pixel DEtector)

- Concept similar to hybrid pixel readout architecture
  - Tower CIS quadrupole well process: both N & P MOS can be used
- Continuously power active in each pixel
  - Low power consumption analogue front-end (< 50nW/pixel) based on single stage amplifier with shaping / current comparator
    - High gain ~100
    - Shaping time few µs
  - Dynamic memory cell, ~80fF storage capacitor which is discharged by an NMOS controlled by the front-end
- Data driven readout of the pixel matrix, only zero-suppressed data transferred to periphery

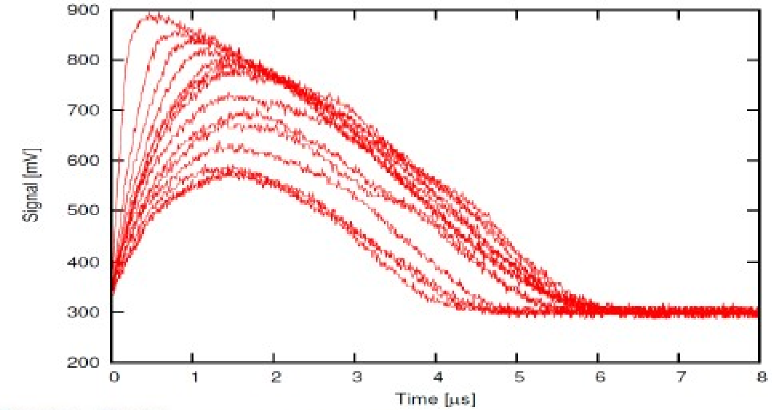


Courtesy of W. Snoeys / TWEPP-2013

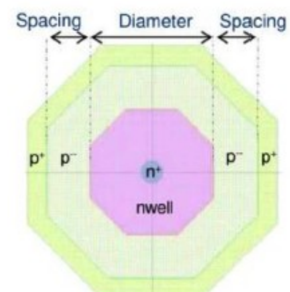


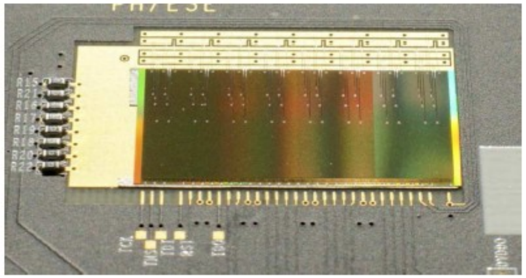
ALPIDE Architecture Validation

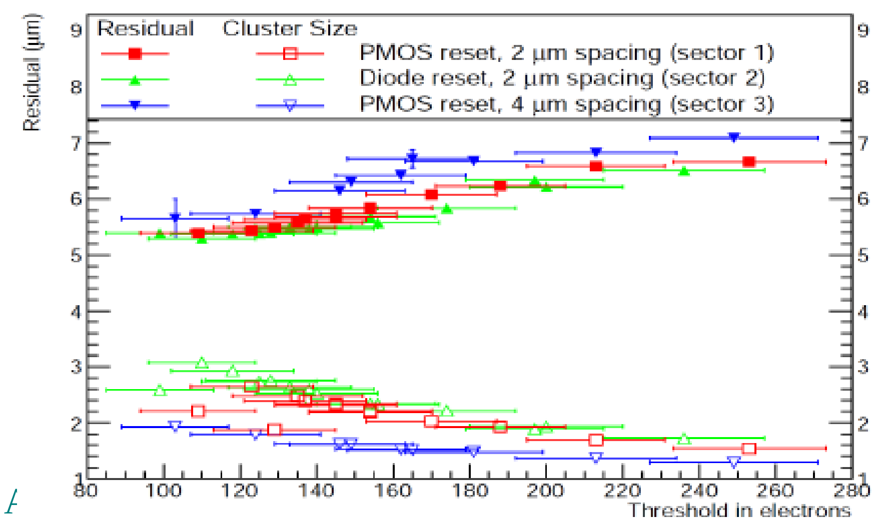
- **1^{st} step:** pALPIDE to validate fast pixel readout
  - 64x512 columns x rows ($22 \times 22\ \mu m^2$)
  - Analog output of one pixel tested with ^{55}Fe source $\Rightarrow$ expected time resolution

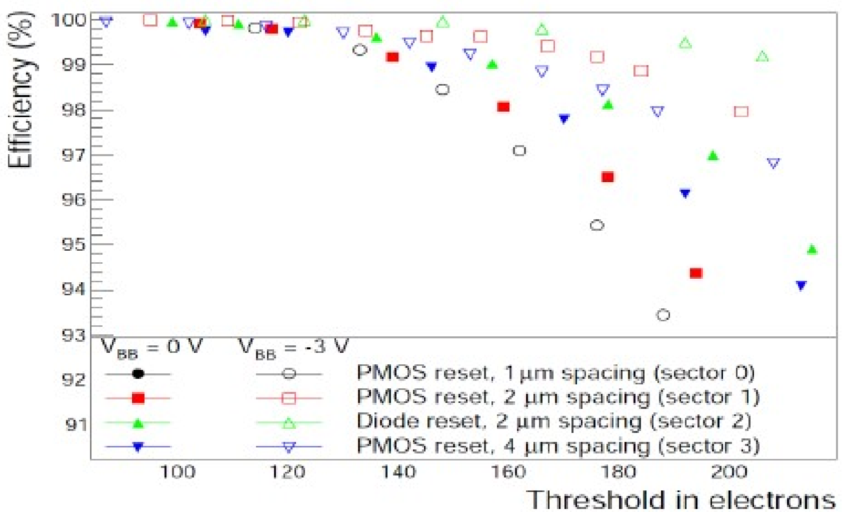


- **2^{nd} step:** full scale ALPIDE
  - Final sensor dimensions: $15 \times 30\ mm^2$
  - ~ 500k pixels of $28 \times 28\ \mu m^2$
  - 4 different sensing node geometries
  - Possibility of reverse biasing the substrate







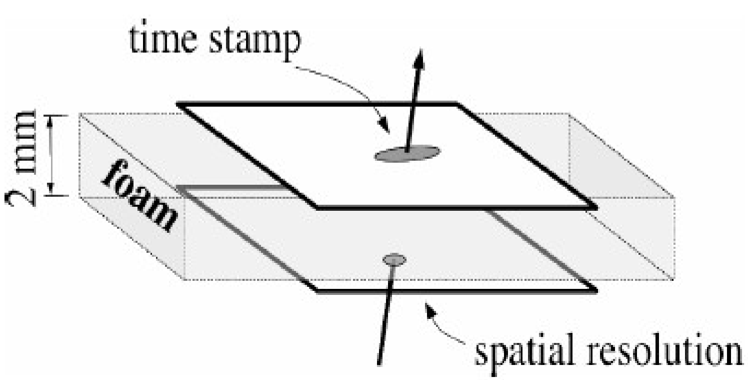


Summary and outlook

- 1^{st} FSBB ($1.2cm^2$ sensitive area) composing MISTRAL sensor ($4.2cm^2$ sensitive area) fabricated & successfully (but not completely) assessed on beam at T = 30°C
  - ε_{det} ~ 99.8% for fake rate < 10^{-6}
  - σ_{sp} < 5µm with 22x33 um^2 pixels
- Some layout shortcomings observed (e.g. x-couplings in peripheral circuitry)
  - Corrections implemented in FSBB-M0bis, submitted to foundry

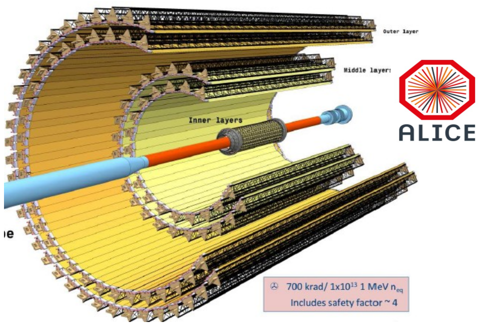
- Next steps
  - 2015: fabrication of full scale MISTRAL prototype ALICE-ITS outer layers

- Potential of FSBB-M/MISTRAL architecture well suited for ILD-VXD. E.g.
  - 17x17 μm^2 pixels: σ_{sp} < 3µm & t_{int} ~ 30-40µs (tbc)
  - 17x102 μm^2 pixels: σ_{sp} < 6µm & t_{int} ~ 5µs (tbc)
  - **See A. Besson's talks for more on perspectives for ILD-VXD**



Back up Slides

Next Forthcoming device: CBM Micro-Vertex Detector (MVD)

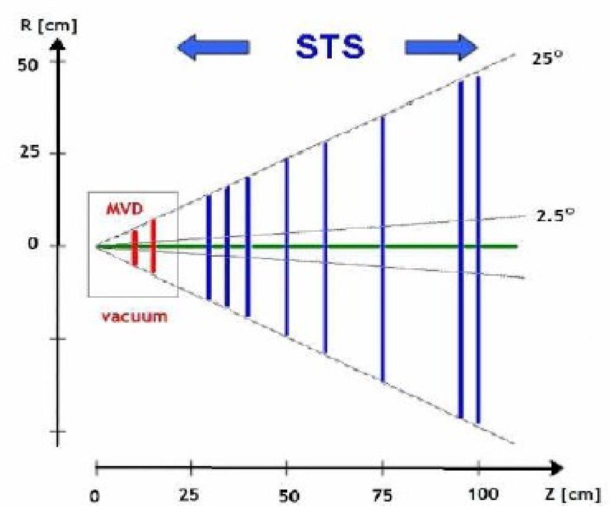


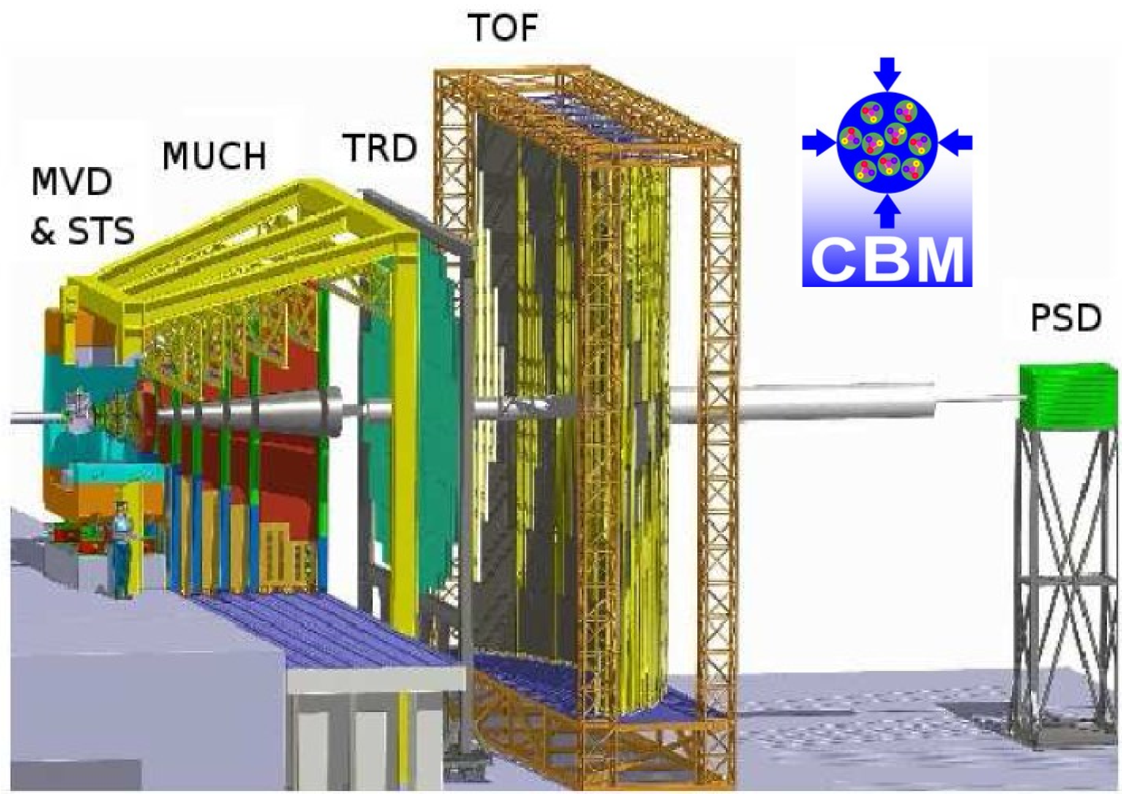
ALICE-ITS 2018/19

CBM-MVD at FAIR/GSI

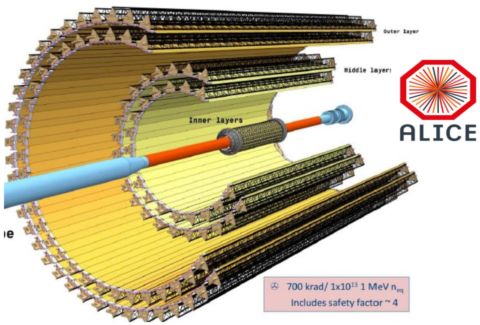
3 double-sided stations in vacuum at T < 0°C

- $\sigma_{sp} \lesssim 5\ \mu m$
- ~ 0.5 % X_0 / station
- Radiation load: $\gtrsim 10^{13} n_{eq}/cm^2$

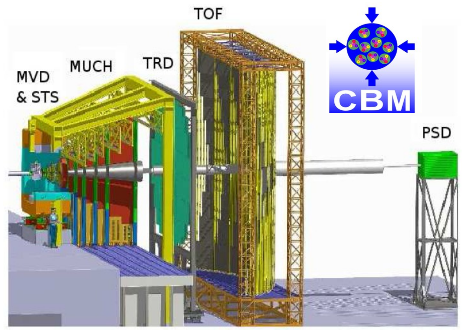




Device under Study: ILC Vertex Detector



ALICE-ITS 2018/19

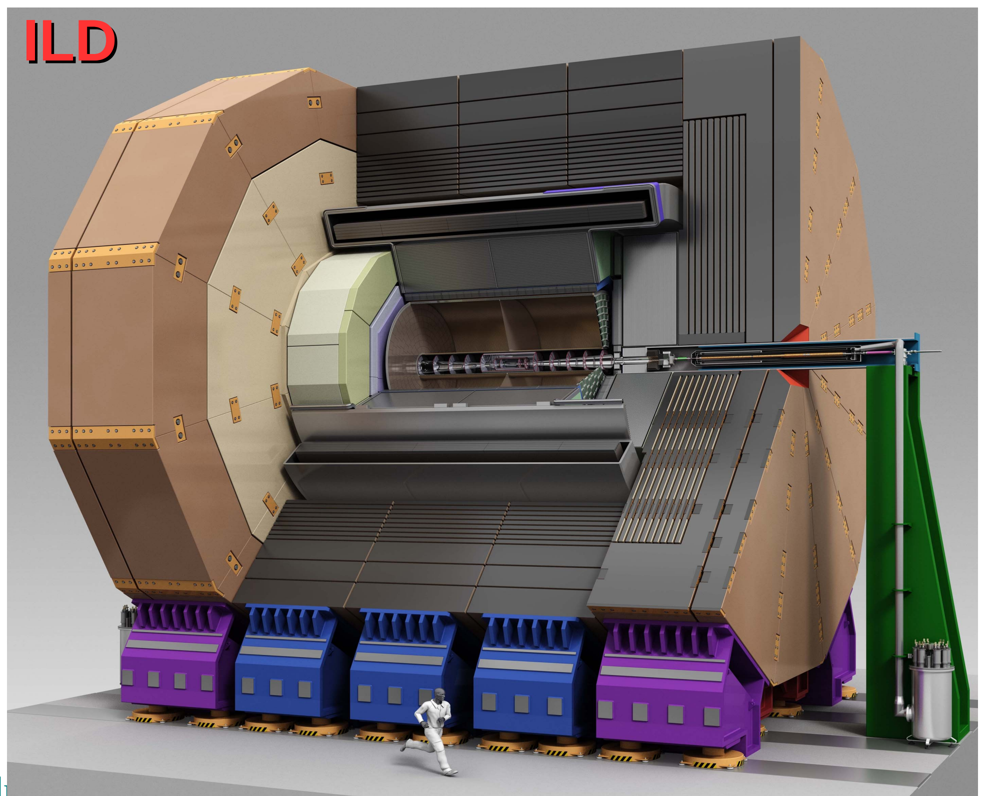


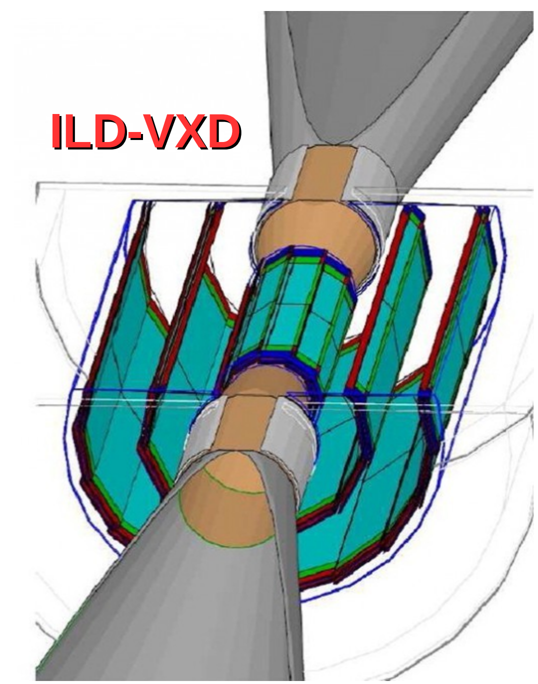
CBM-MVD > 2020

ILD-VXD at ILC

3 double-sided layers

- $\sigma_{sp} \lesssim 3\ \mu m$
- ~ 0.3 % X_0 / layer
- Radiation load: O(100) kRad + O(10^{11}) n_{eq}/cm^2 (1yr)

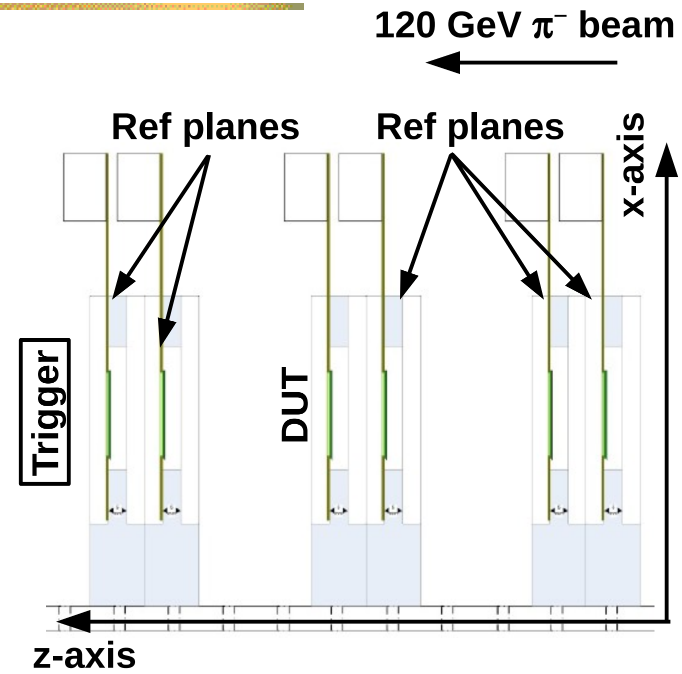


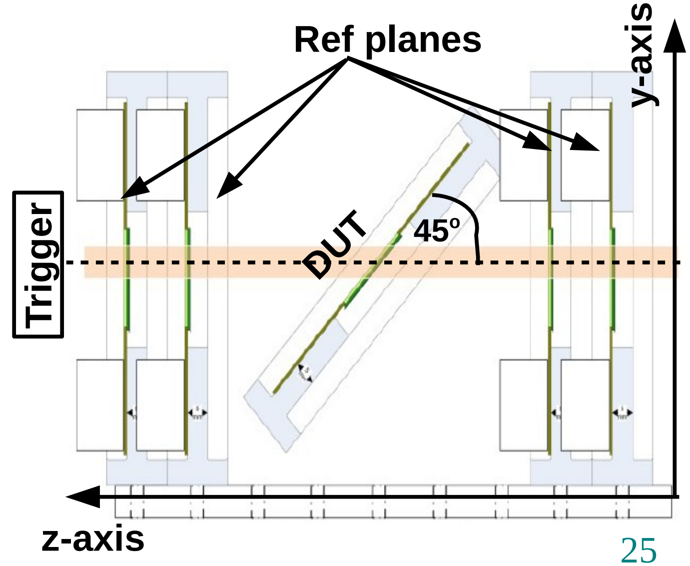


Beam-Test: Main goals and data collected

- **Main goals (mainly with sub-array B)**
  - Validate pixel geometry for σ_{sp} ~ 5µm
  - Determine detection efficiency (ε_{det})
  - Determine working range with
    - ε_{det} > 99%
    - Fake hit rate < 10^{-5}
  - Study impact of present cross-coupling effects

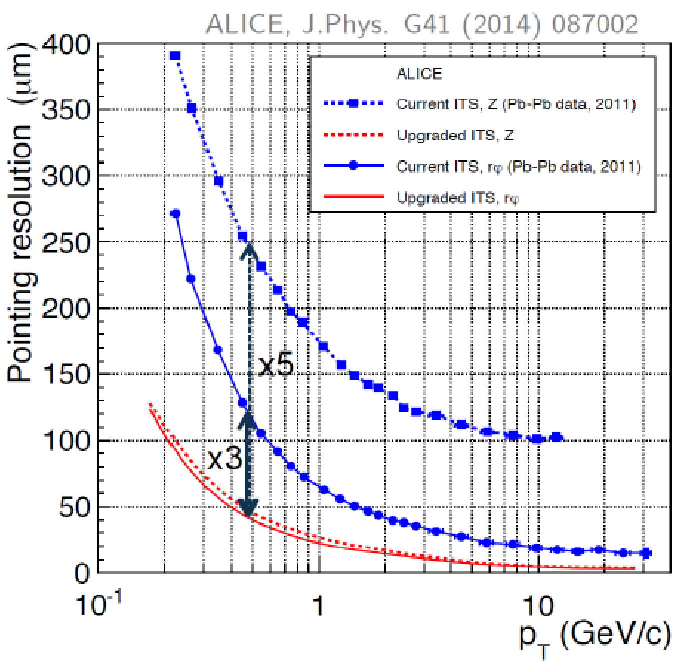
- **Running parameters varied**
  - Discriminator thresholds: 4 → 12 mV
  - Beam flux: 0.78 → 11.6 hits/cm^2/frame (average value)
  - Incidence angle of beam particle on DUT: 0 or ~45^o (ITS maximum peudo-rapidity ~ 55^o)
  - Comparison of sub-array A to sub-array B
  - V_{REF}(discri.): external (cable on chip) vs internal (SDS)



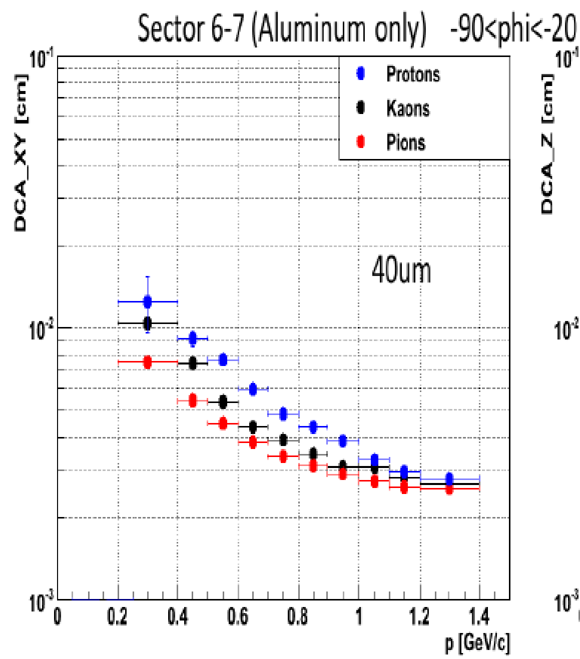


FSBB-M0 inspired from STAR-PXL Chip

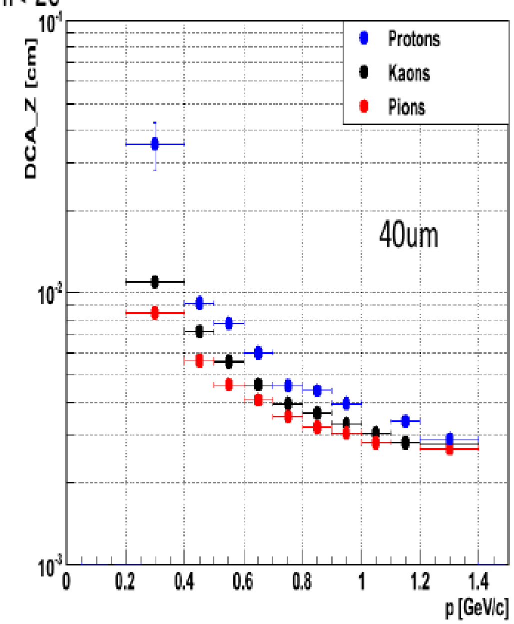
- **STAR-PXL PRELIMINARY results (courtesy of STAR collaboration) :**
  - Data collected with low luminosity (clean TPC environment)
  - Tracks traversing the ladders equipped with Al traces ↦ resolution on DCA



ITS-TDR



STAR-PXL ($R\Phi$)



STAR-PXL (Z)

$\Rightarrow$ **40/35 μm obtained for 700-800 MeV/c $K^{\pm}/\pi^{\pm}$ in both directions**

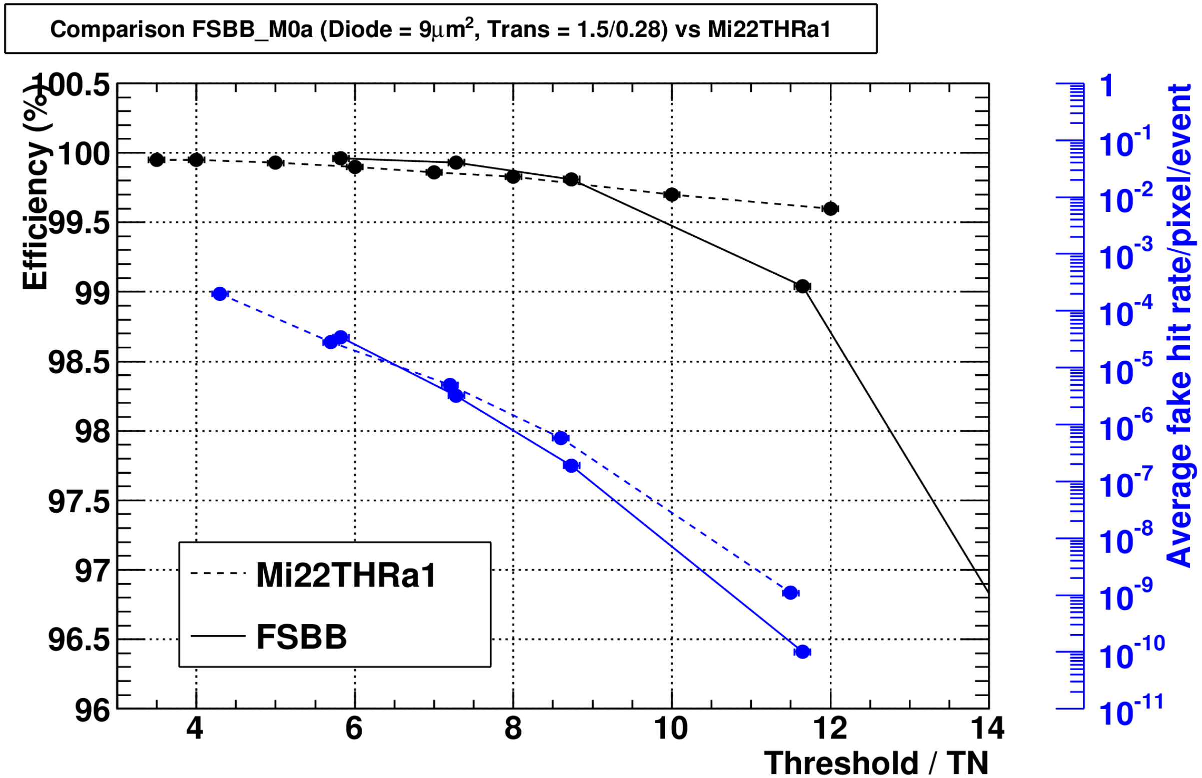
↦ **very similar to ITS objectives**

12

Comparison of Small Diode to MIMOSA-22THRa1

- **MIMOSA-22THRa1:** 4.4 GeV e⁻ beam
  - HR (~2kΩcm) 20μm epitaxial layer
  - 128 columns of 320 pixels
  - No SDS, thresholds dispersion ignored
  - Pixel dimensions: 22x33μm² (11μm² diode)
  - Pixel amp input Trans: L/W = 0.36/1 μm

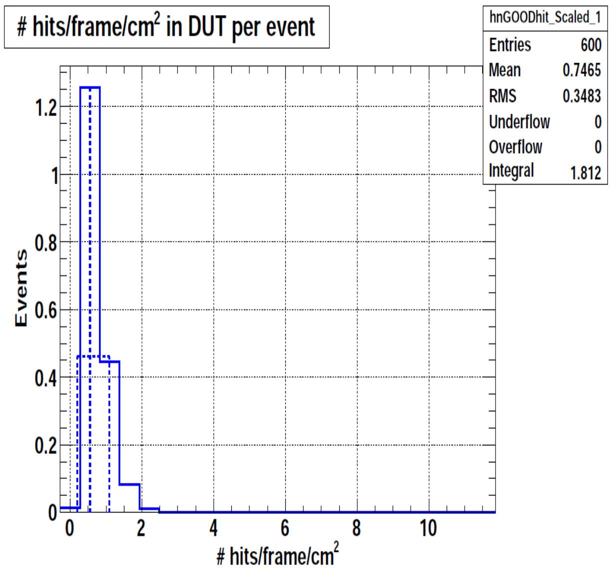
- **FSBB-M0a (small diode):** 120 GeV π⁻ beam
  - HR (~1kΩcm) 18μm epitaxial layer
  - 2x208 columns of 416 pixels
  - Discri. outputs processed with SDS
  - Pixel dimensions: 22x33μm² (9μm² diode)
  - Pixel amp. input Trans: L/W = 0.27/1.5 μm
  - **Noise increased by cross-coupling (mainly FPN)**



Beam-Test: Detection Performances vs Trigger Rate

- Data taken at different trigger rates: 2.5 (default value), 25 and 100 kHz
- Measurements performed with high threshold settings: 8mV

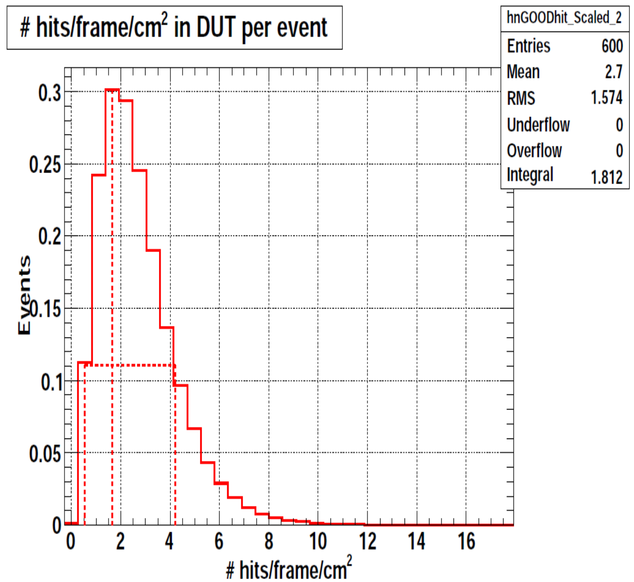
2.5 kHz



$\#$ hits/cm^2/frame = 0.75

Occupancy ≈ 0.12×10^{-4}

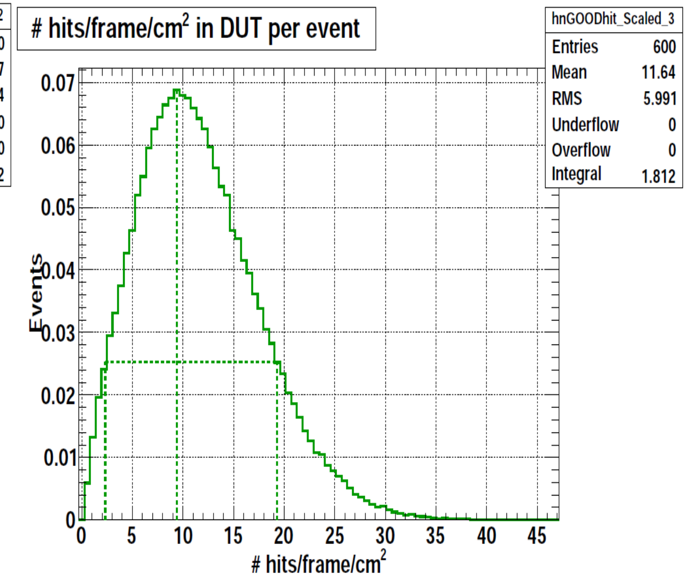
25 kHz



$\#$ hits/cm^2/frame = 2.70

Occupancy ≈ 0.45×10^{-4}

100 kHz

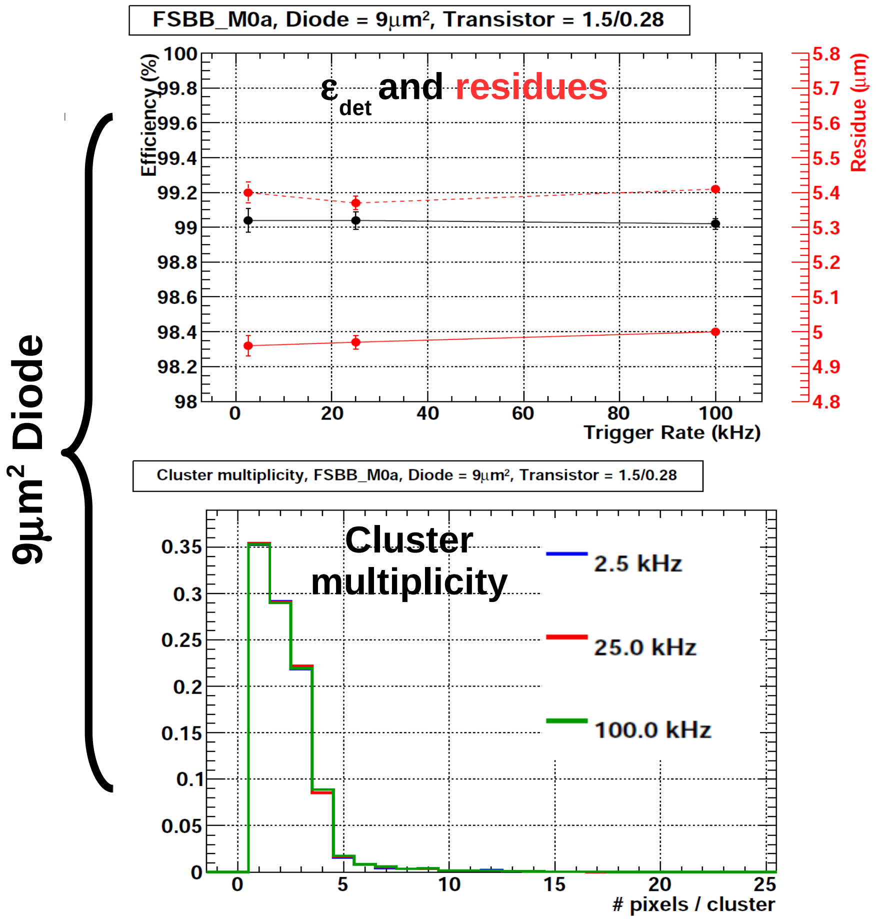


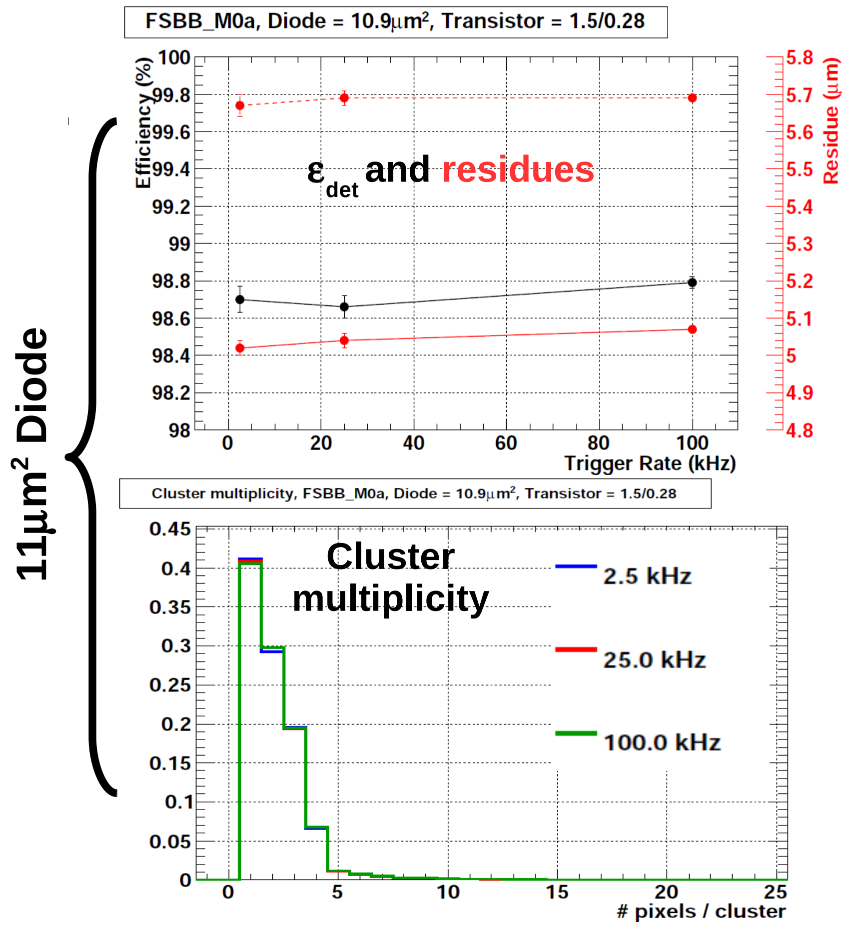
$\#$ hits/cm^2/frame = 11.64

Occupancy ≈ 1.95×10^{-4}

Beam-Test: Detection Performances vs Trigger Rate

- Data taken at different trigger rates: 2.5 (default value), 25 and 100 kHz
- Measurements performed with high threshold settings: 8mV



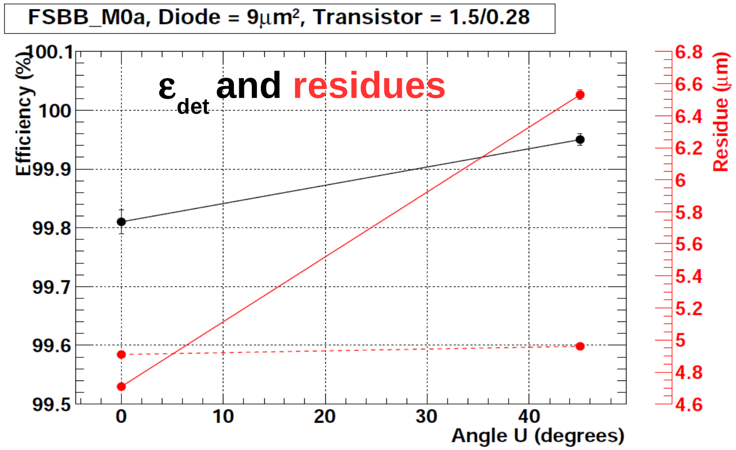


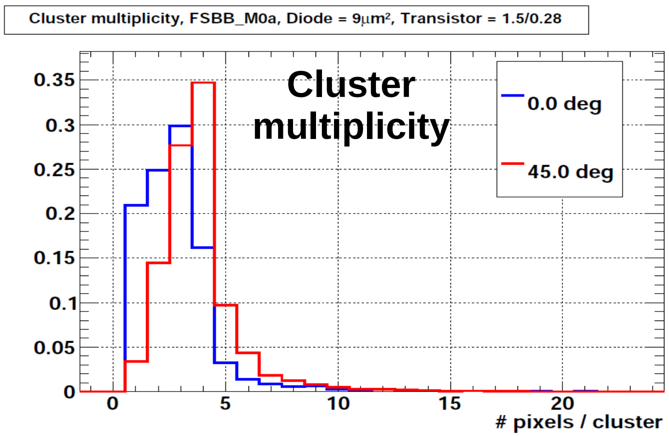
- **No sensitivity to hit rate observed** (deeper analysis under way)

Beam-Test: Detection Performances at High Incidence Angle

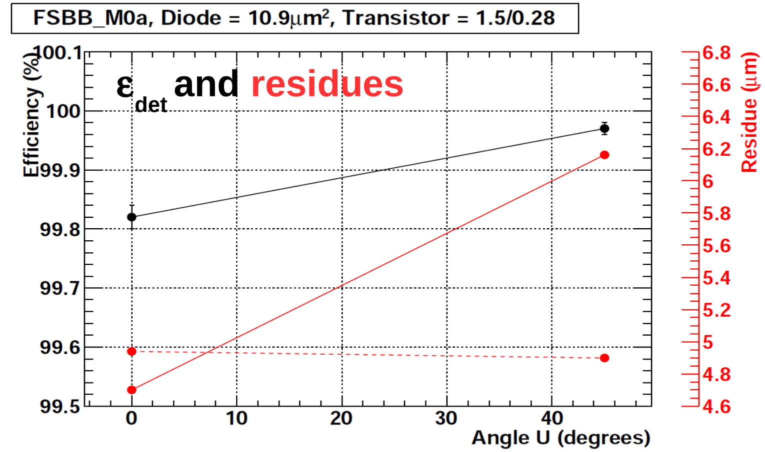
- Data taken with trigger rate of 2.5 kHz and 6mV threshold

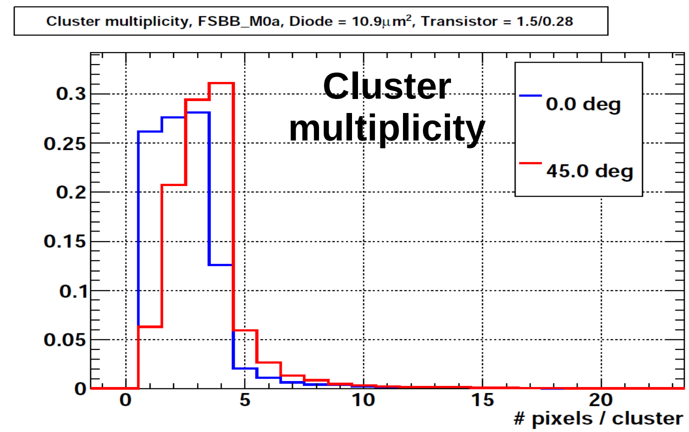
$9\mu m^2$ Diode





$11\mu m^2$ Diode





- Increase in ε_{det} and multiplicity at high angles
- Increase in U-residue mainly due to the increase in multiplicity in this direction
- No change in V-residue as expected