

Journée Thématique du réseau R&D semi-conducteurs
Effets des irradiations dans les détecteurs semi-conducteurs
June 16th 2016

Radiation Effects on CMOS Pixel Sensors

Alejandro Pérez Pérez
PICSEL group IPHC Strasbourg



CENTRE NATIONAL
DE LA RECHERCHE
SCIENTIFIQUE



Outline

- **Introduction to CMOS Pixel Sensors (CPS)**
- **Radiation Effects on CMOS Pixel Sensors**
- **CPS State of the Art: STAR-PXL detector**
- **Next generation of High Precision Vertexing & Tracking systems using CPS**
- **Current trends to improve radiation tolerance of CPS**
- **Summary**

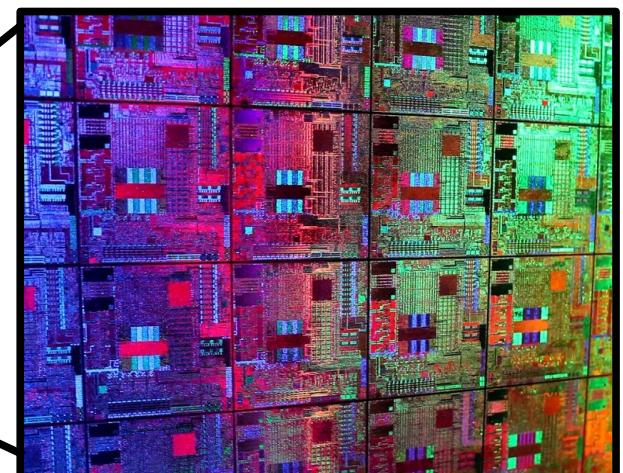
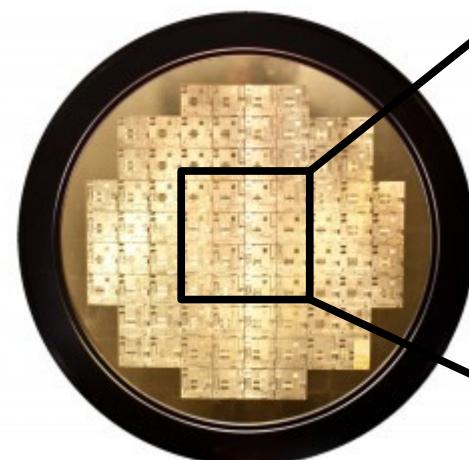
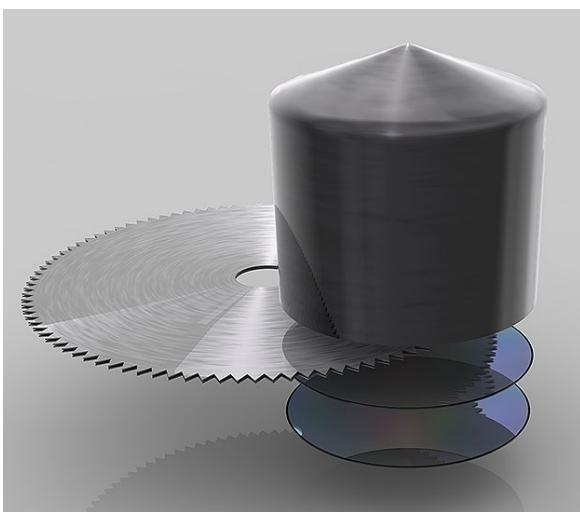
Introduction to CMOS Pixel Sensors (CPS)

CMOS Technology

- CMOS ≡ Complementary Metal-Oxide-Semiconductor
- CPS exploit the fabrication processes used in industry for mass production of IC
 - Micro-processors, micro-controller, RAM, ...
 - Cell phones, lap tops, cars, ...



- CMOS fabrication mode
 - Micro-circuit lithography on a substrate sliced from a Si crystal ingot
 - Process through reticules (e.g. 21×33 or 25×32 mm²) organized in wafers

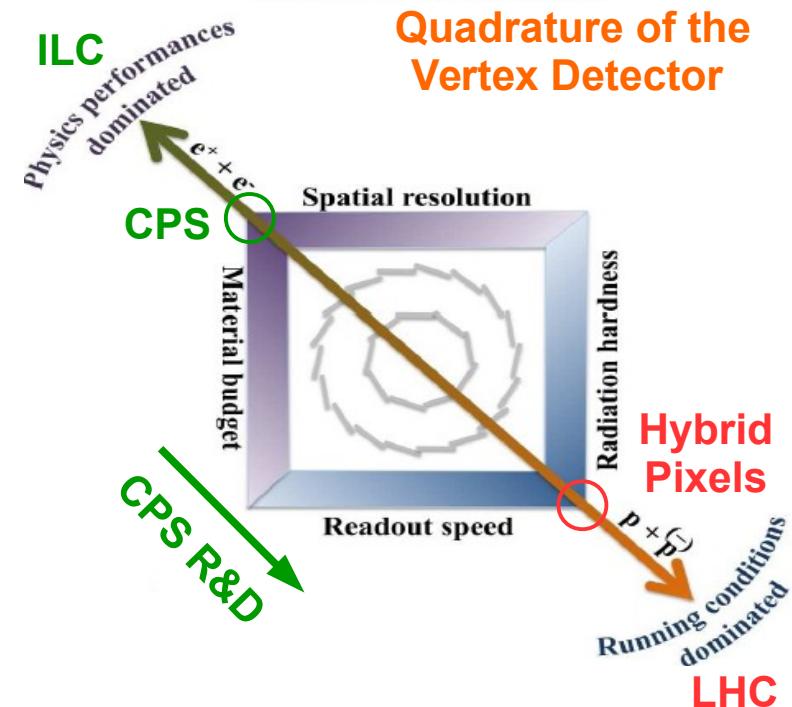


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, June 16th 2016

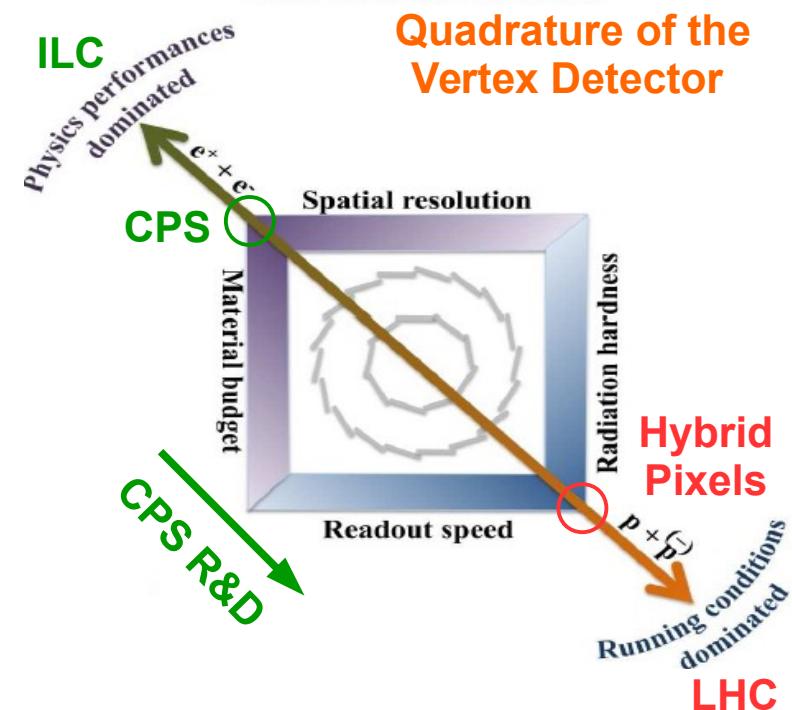
CPS: Development motivation

- CPS triggered by the need of very granular and low material budget sensors
- CPS applications exhibit milder running conditions than at pp/LHC
 - Relaxed readout (r.o.) speed & rad. tolerance

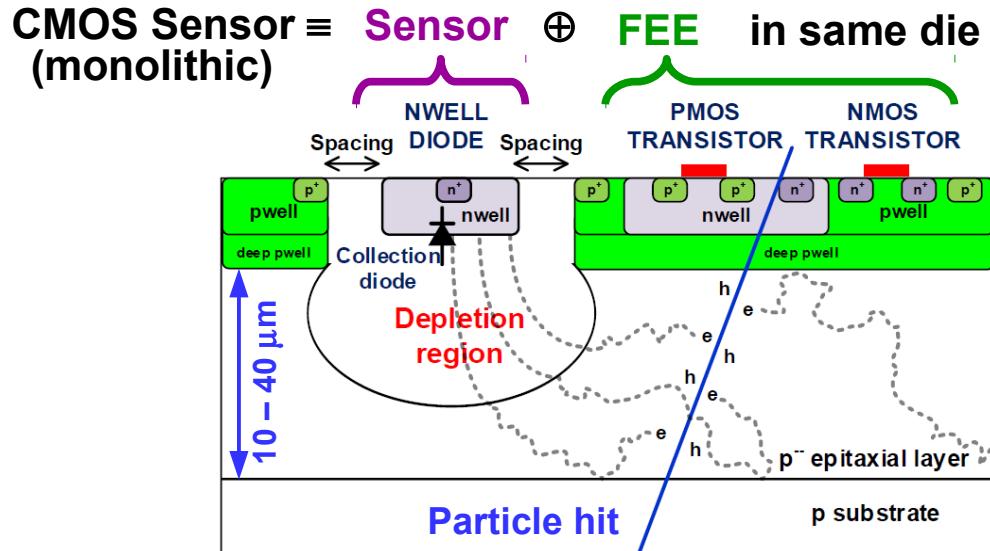


CPS: Development motivation

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- Application domain widens continuously (existing/foreseen/potential)
 - Heavy-ion collisions \Rightarrow STAR-PXL, ALICE-ITS, CBM-MVD, NA61...
 - e^+e^- collisions \Rightarrow BES-III, ILC, Belle II (BEAST II)
 - Non-collider experiments \Rightarrow FIRST, NA63, Mu3e, ...
 - High-precision beam-telescopes \Rightarrow EUDET-BT (DESY, CERN, ...) & BTF-BT (Frascati)



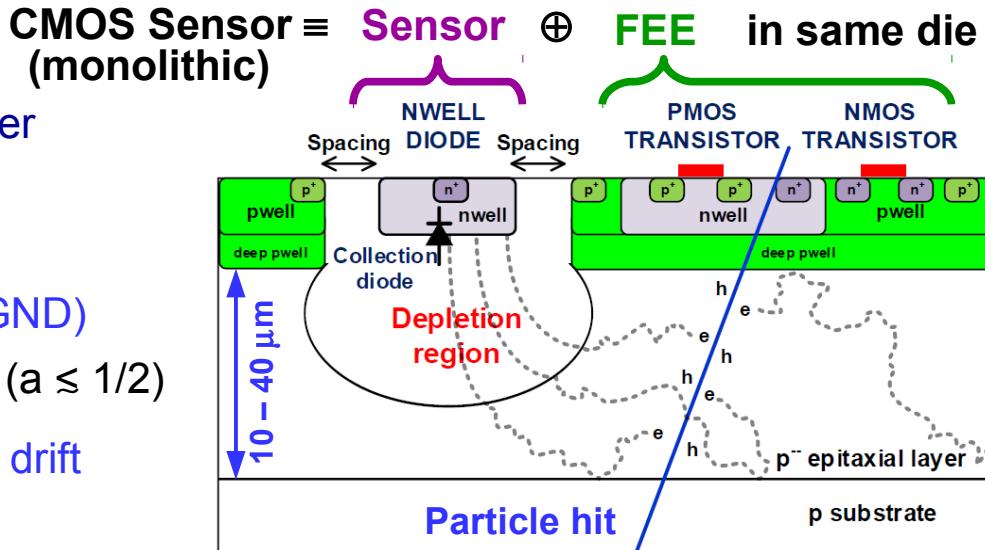
CPS: Main features



CPS: Main features

Working principle

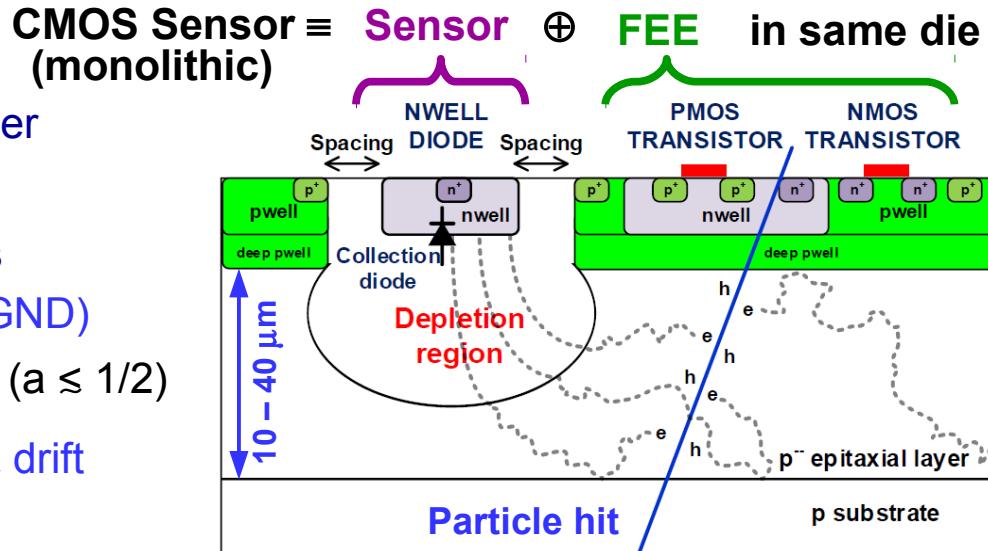
- Secondary charges generated in epi-layer
 - $Q \sim 80 \text{ e-h}/\mu\text{m} \Rightarrow \text{signal } O(1000\text{e}^-)$
- Charges transport driven by 3 potentials
 - P-well/N-well/P++ (GND/few volts/GND)
- Epi not fully depleted: $d_{\text{dep}} \sim (\rho_{\text{sub}} \times U_{\text{bias}})^a$ ($a \lesssim 1/2$)
 \Rightarrow transport is mix of thermal diffusion & drift



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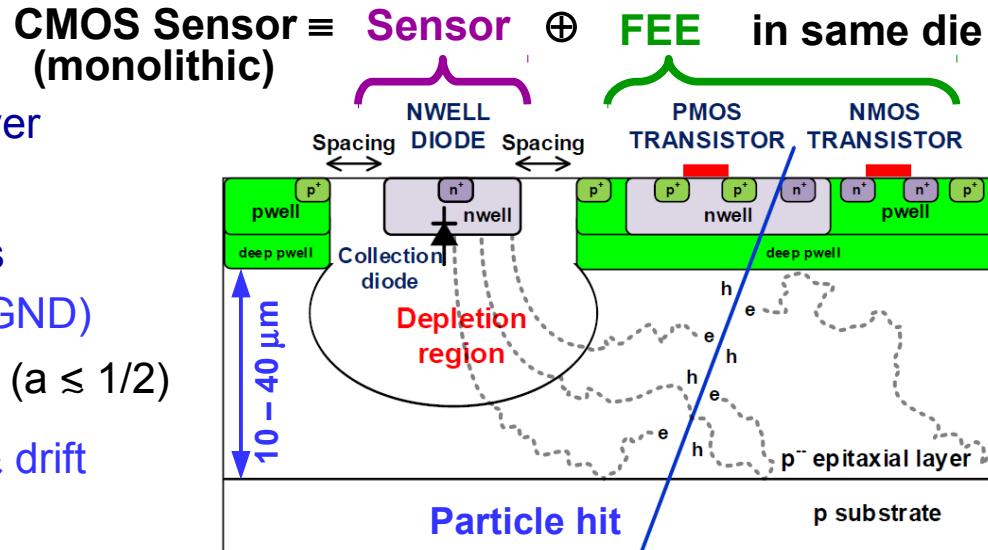
Prominent features

- FEE integrated on sensor substrate \Rightarrow downstream electronics & syst. integration
- High granularity \Rightarrow excellent spatial resolution (few μm)
- Thin epi-layer \Rightarrow usual thinning down to 50 μm total thickness
- T_{room} operation \Rightarrow simple cooling, further material budget reduction
- Standard fabrication process \Rightarrow low cost & easy prototyping, many vendors, ...

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CPS technology developments

- Mainly driven by commercial applications \Rightarrow Not fully optimized for particle detection
- R&D largely consists in exploiting as much as accessible industrial processes

CPS: Optimization Process

Sensor performance are evaluated in terms of

- Noise \Leftrightarrow Dark hit rate
 - Charge Collection & Signal/Noise \Leftrightarrow Detection efficiency (ε_{det})
 - Cluster multiplicity (CM) \Leftrightarrow Spatial resolution (σ_{sp})
- Radiation tolerance**
- 
- Depend on construction parameters**

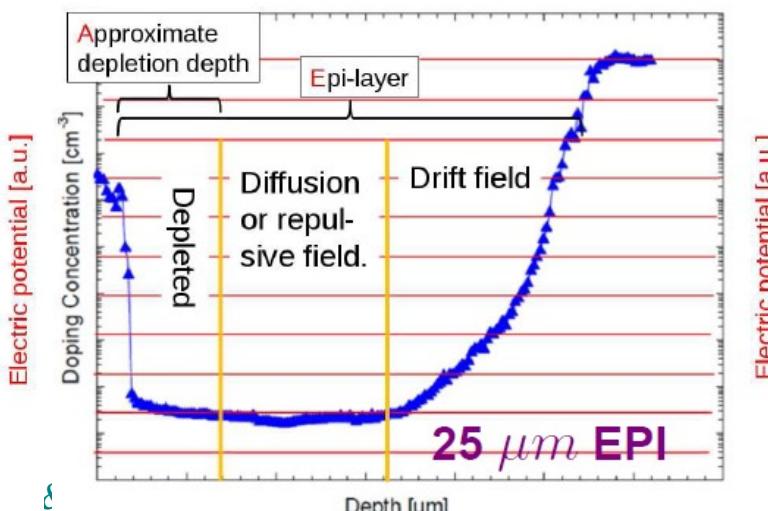
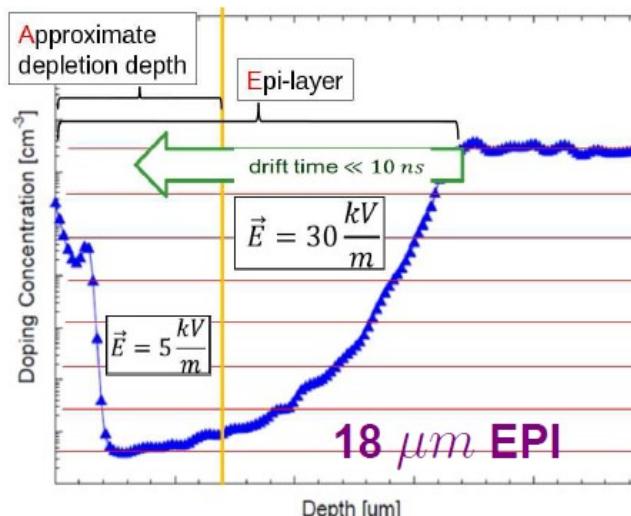
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E.g.: Role of epitaxial layer

- Q_{signal} : thickness & doping profile
- ε_{det} & NIEL tolerance: depletion depth vs thickness
- CM & σ_{sp} : pixel pitch / thickness, depletion depth, ...



CPS: Optimization Process

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Application-specific multiparametric trade-off to be found,
based on exploratory prototypes rather than on simulations

Radiation Effects on CMOS Pixel Sensors

What is radiation Hardness?

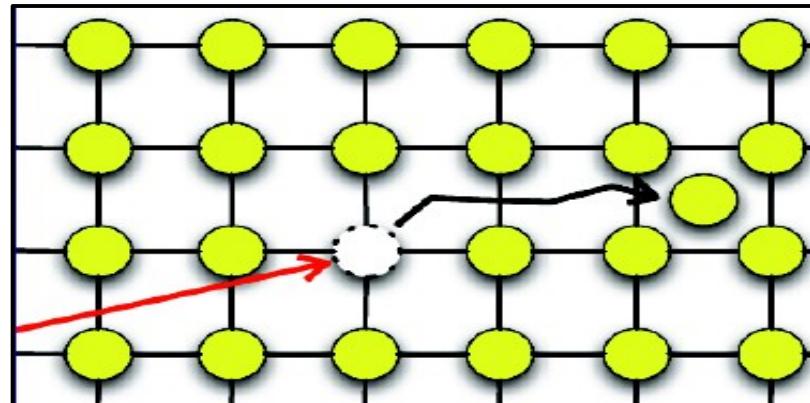
Degradation of sensor properties with radiation is a steady process

- Decide if sensor is still functional depends on application requirements
- E.g., in tracking applications ϵ_{det} and dark rate are most important properties
 - Radiation degrades Q_{coll} and increases noise $\Rightarrow Q_{\text{coll}}/\text{Noise}$ is figure-of-merits

Radiation damage

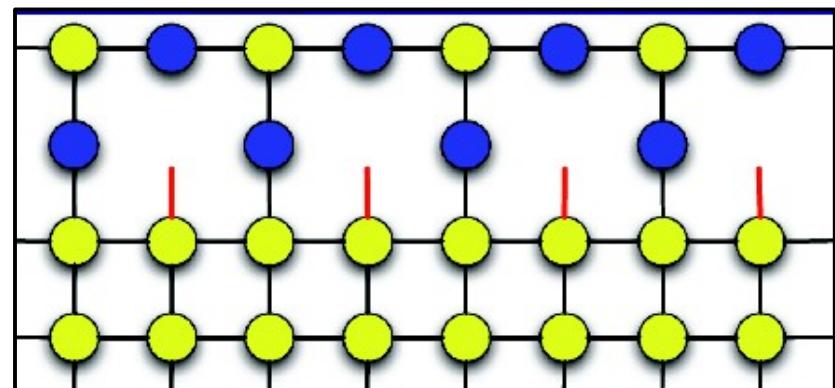
Damage due to non-ionizing E-loss (NIEL)

- Atomic displacement caused by massive particles (p, n, π)
- Affects mainly sensitive volume



Damage due to ionizing E-loss

- Prop. E-loss/mass (1 rad = 0.01 J/Kg)
- Trap of ionization induced holes at Si-SiO₂ interface
- Affects both detector and electronics



Radiation effects on Epitaxial layer: Bulk Damage

■ **NIEL hypothesis:** bulk damage proportional to total KE imparted to displaced Si atoms

■ **Conventional to use 1 MeV n⁰ as benchmark**

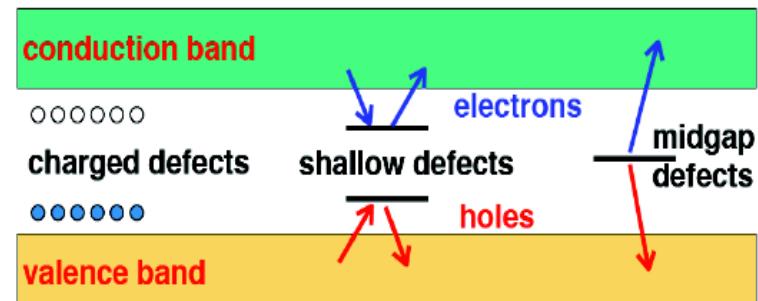
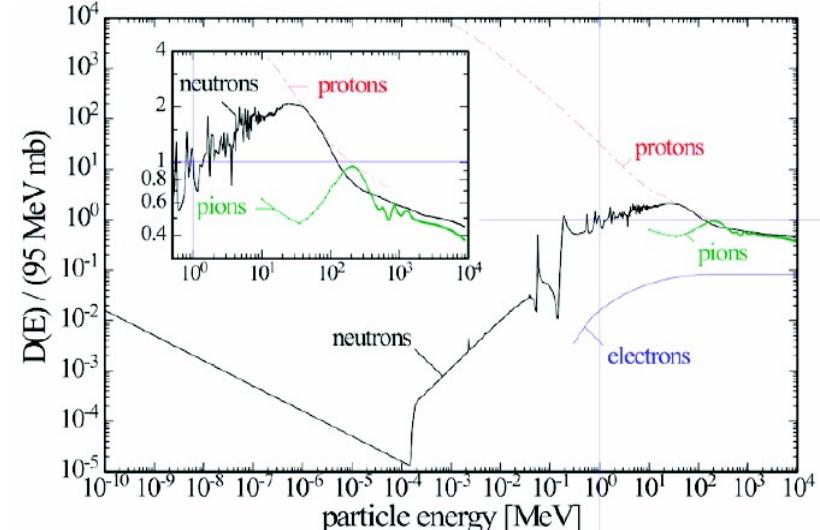
- Convert any particle flux Φ_{phys} to equivalent flux Φ_{eq} of 1 MeV n⁰ producing same NIEL

■ **Radiation damage due to NIEL**

- Charged donors/acceptors -like defects
 - Increase (decrease) $N_{\text{eff}} = N_D - N_A (\rho_{\text{res}})$
 - ⇒ reduced $d_{\text{dep}} \sim (\rho_{\text{sub}} \times U_{\text{bias}})^a$
- Shallow defects trap and detrap e- and holes
 - Degrade charge collection efficiency
- Mid-gap defects effectively reduce E_g
 - Increase leakage current ⇒ Thermal noise
- **All these effects prop. to Φ_{eq}**

KERMA = Kinetic Energy Released in Matter

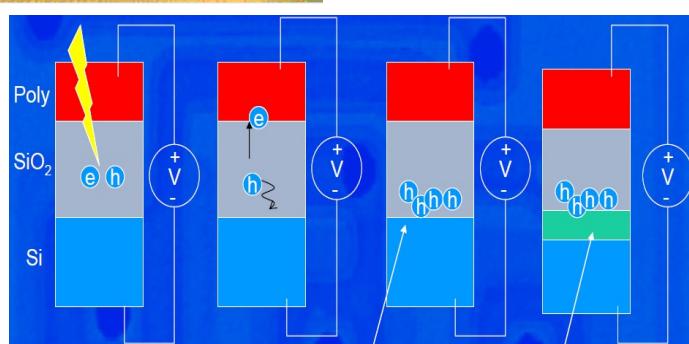
$$KERMA(\text{MeV}) = D(\text{MeV mb}) \times \phi \left(\frac{\#}{\text{cm}^2} \right) \times (\# \text{Si}) \times \left(\frac{10^{-27} \text{ cm}^2}{\text{mb}} \right)$$



Radiation effects on FE & RO electronics: Ionization Damage

Radiation damage due to ionizing radiation

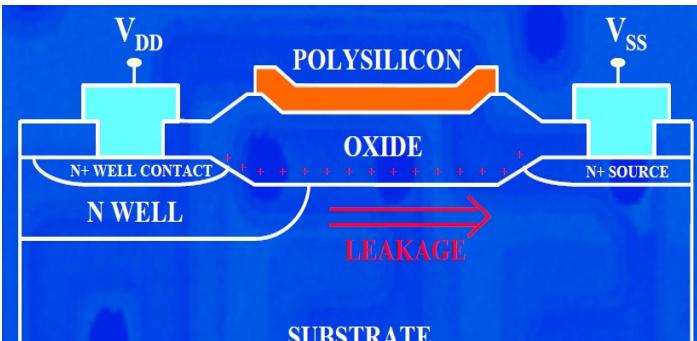
- SiO_2 no structure \Rightarrow insensitive to atom displacement
- Ionizing radiation produces e-h in SiO_2
- Holes drift to interface and are trapped



Transistor V_{th} variation \Rightarrow oxide charges increase

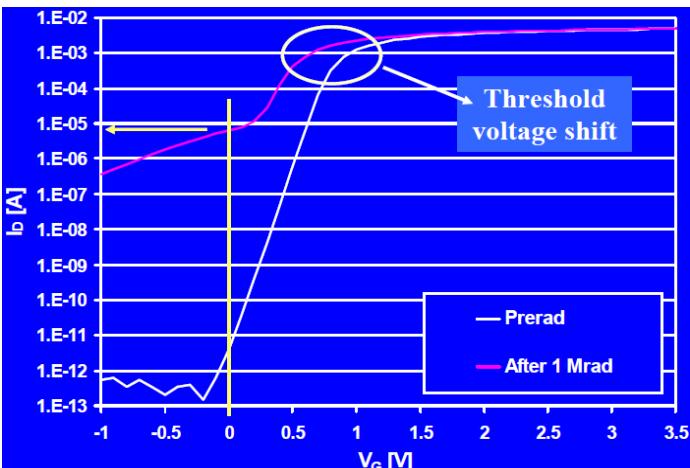
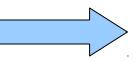
Increased I_{leak} (S – D, between devices)

- trapped charges in oxide decrease V_{th} of MOS structure, and p-substrate can be inverted even without E-field



These effects are strongly dependent on oxide thickness (t_{ox})

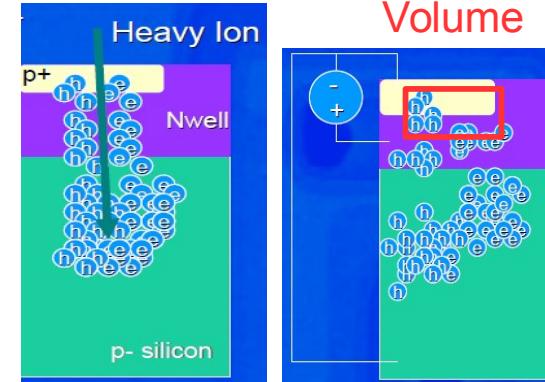
- Significant for 0.7 μm techno ($t_{ox} = 17 \text{ nm}$)
- Negligible for 0.35 μm ($t_{ox} = 7 \text{ nm}$) and 0.18 μm ($t_{ox} = 3 \text{ nm}$) CMOS processes



Single Event Effects (SEE)

SEE

- E-deposition by single particle in precise instant in time
- Only charge in sensitive volume (SV) contributes to SEE, e.g. in appropriate circuit node in relevant amount of time
- Density of e-h in SV determines if SEE takes place

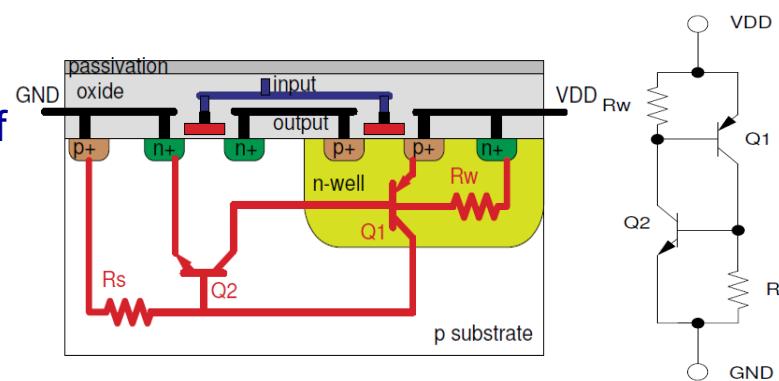


Single Event Upset (SEU)

- Particle produces e-h collected by junction part of circuit where logic level is stored (0 or 1)
- Can induce “flip” of the stored logic level \Rightarrow “upset” of “soft error”
- **Consequences:** data corruption and misconfiguration
- **Solution:** periodic circuit reset

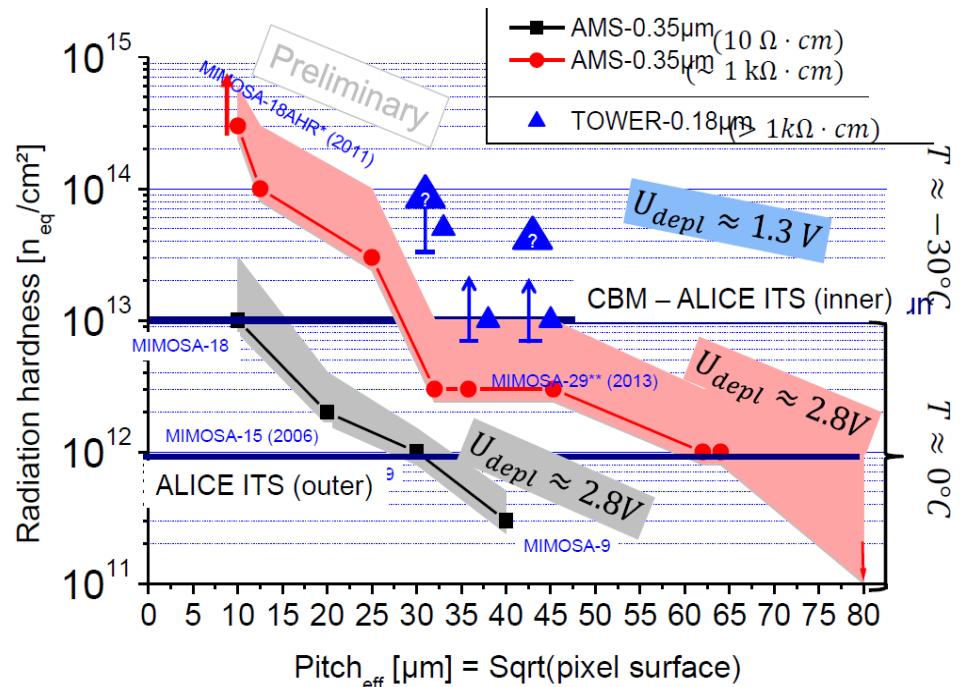
Single Event Latch-up (SEL)

- Sudden short circuit between power-supply rails of components that trigger thyristor-like structure
- SEL can be triggered by ionizing particle
- **Consequences:** damage bond wires, melting due to localized overheating
- **Solution:** power down circuit



CPS Radiation Tolerance

- Technology rad. tolerance still evolving: CMOS industry parameter evolution
- Expected to tolerate high TID: Doses (>> 10MRad), @ < 0°C & short $t_{r.o.}$
- Concern is Non-ionizing radiation: Relies on thick & depleted sensitive volume
- Influence of pixel pitch
 - High density collection diodes (\equiv small pitch) \Rightarrow improves non-ionizing radiation tolerance (smaller travel distance)
- Influence of epitaxial layer
 - e.g.: $400 \Omega \cdot \text{cm}$ & $V_{\text{dep}} \sim O(1 \text{ V})$
 - Trend: $\gtrsim 1 \text{k}\Omega \cdot \text{cm}$ & $V_{\text{dep}} \gg 1 \text{ V}$
 - **Tolerance to $\geq 10^{14-15} n_{\text{eq}}/\text{cm}^2$ not excluded**



CPS @ PICSEL - IPHC: A long term R&D

- Main objective: ILC, with staged performances

- CPS applied to other applications with intermediated requirements

running

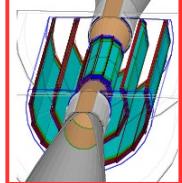
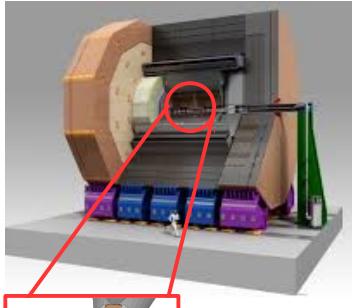
EUDET 2006/2010

Beam Telescope



ILC > 2025

International Linear Collider



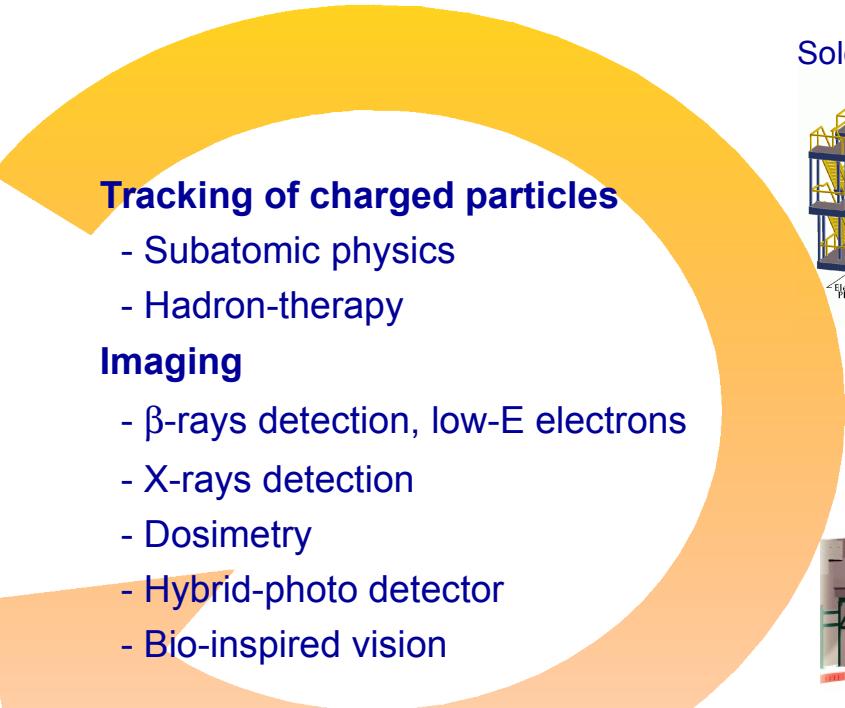
On-going R&D

Tracking of charged particles

- Subatomic physics
- Hadron-therapy

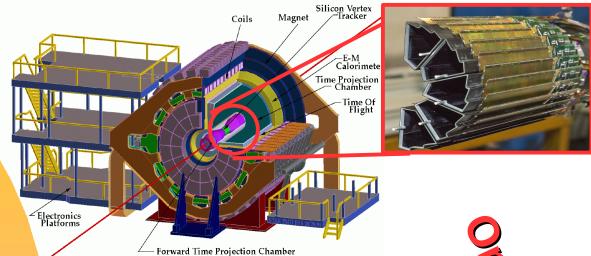
Imaging

- β -rays detection, low-E electrons
- X-rays detection
- Dosimetry
- Hybrid-photo detector
- Bio-inspired vision



STAR 2013

Solenoidal tracker @ RHIC



running

ALICE 2018

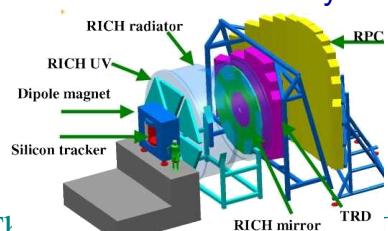
A Large Ion Collider Experiment



On-going R&D

CBM > 2019

FAIR/GSI - Germany

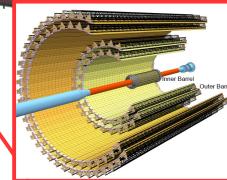


SOLEIL 2017

CMOS for X-ray detection



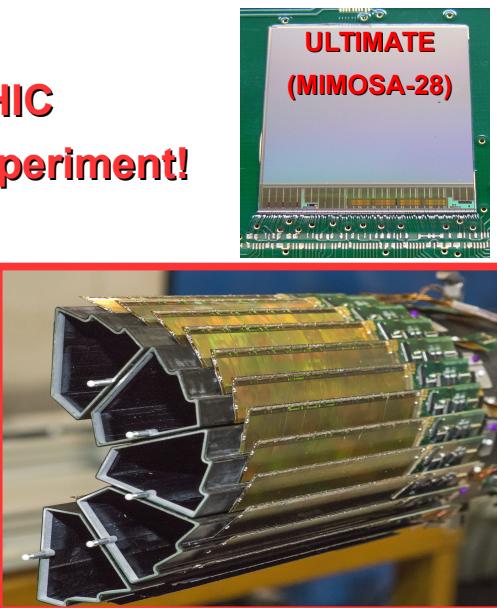
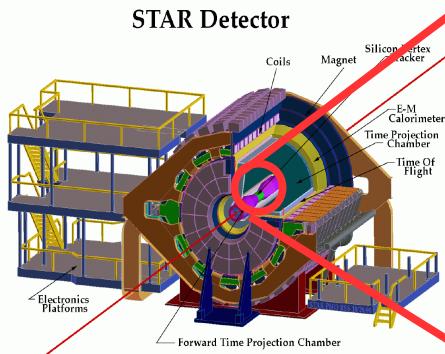
On-going R&D



CPS State-of-the-Art: STAR-PXL detector

STAR-PXL @ RHIC

1st CPS @ a collider experiment!



ULTIMATE Sensor (MIMOSA-28)

- Rolling shutter r.o. ($t_{r.o.} \lesssim 200 \mu\text{s}$)
- $T_{op} = 30 - 35^\circ\text{C}$, Power $\lesssim 150 \text{ mW/cm}^2$
- $\epsilon_{det} \gtrsim 99.9\%$ $\sigma_{sp} \gtrsim 3.5 \mu\text{m}$ & $f_{rate} \lesssim 10^{-5}$
- Validation up to 150 kRad $\oplus 3 \times 10^{12} n_{eq}/\text{cm}^2$

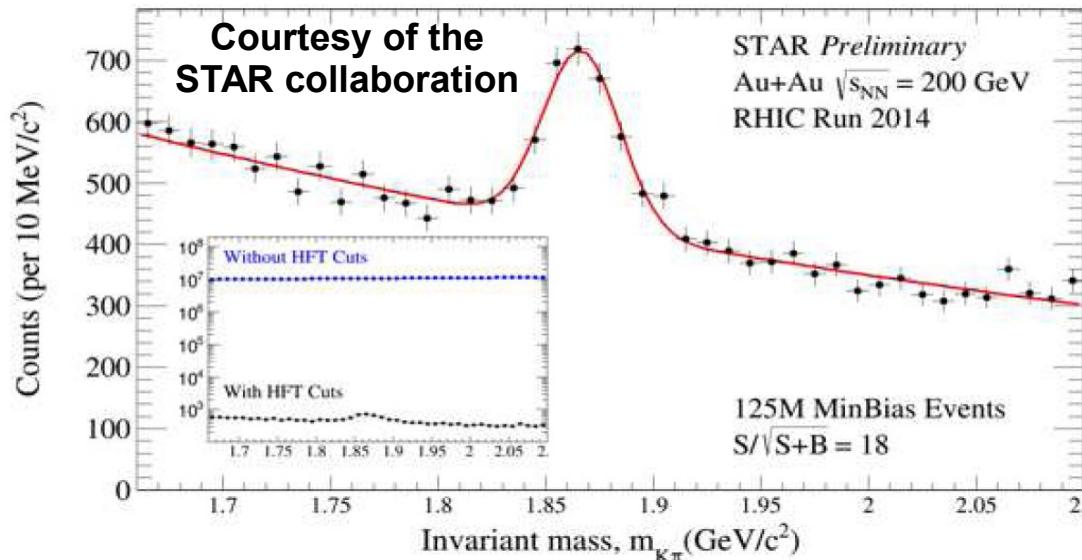
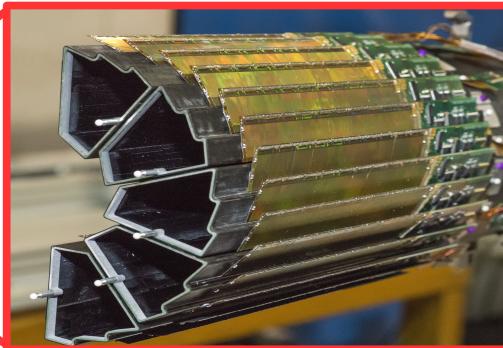
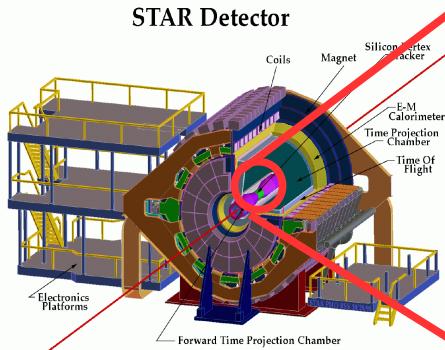
STAR-PXL (360M pixels)

- 2 layers @ $r = 2.8, 8 \text{ cm}$
- 40 ladders (10 sensors/ladder) ($0.37\% X_0$)

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Several Physics-runs

- 1st / 2nd run in 2014 & 2015
- Currently in 3rd run (Jan. 2016)
- $\sigma_{ip}(p_T)$ matching requirements
 $\sim 40 \mu\text{m}$ @ 750 MeV/c for K^\pm

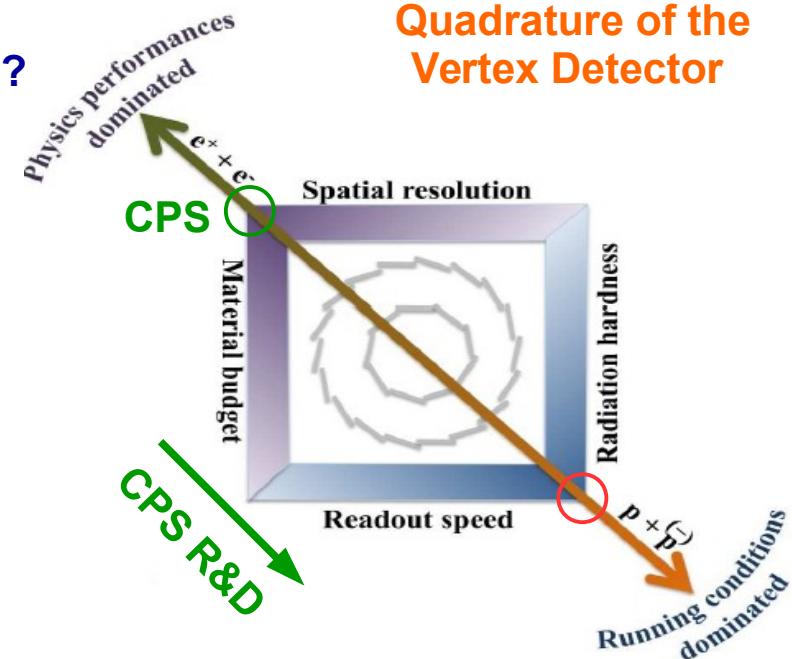
Observation of D^0 production

- STAR: peak significance = 18
- ALICE: peak significance = 5

CPS: Improving Speed & Radiation Tolerance

How to improve r.o. speed and rad. tolerance while preserving σ_{sp} ($3\text{-}5 \mu\text{m}$) and material budget ($< 0.1\% X_0$)?

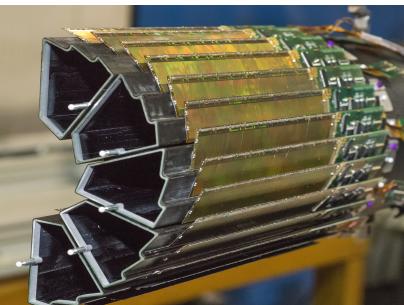
Quadrature of the Vertex Detector



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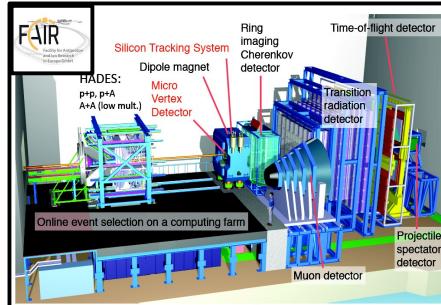
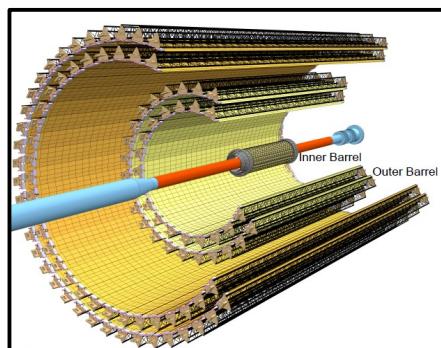
$$t_{r.o.} \sim O(10^2) \mu\text{s}$$



EUDET/STAR-PXL

2010/2014

$$t_{r.o.} \sim O(10) \mu\text{s}$$



ALICE/CBM

2018/2020

Physics performances
dominated

CPS

Quadrature of the
Vertex Detector

Spatial resolution

Material budget

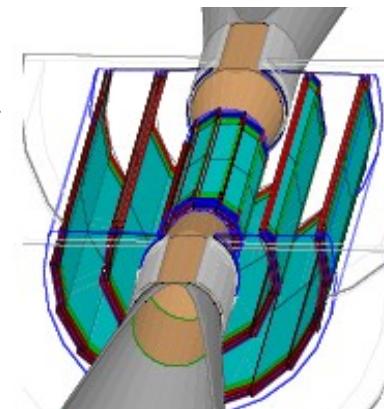
CPS R&D

Radiation hardness

Readout speed

$p + (\bar{p})$
Running conditions
dominated

$$t_{r.o.} \sim O(1) \mu\text{s}$$

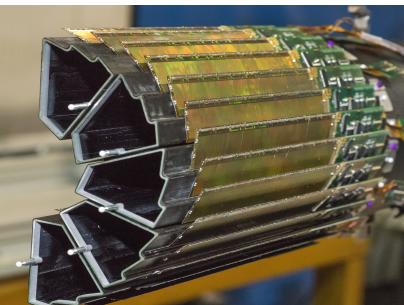


ILC > 2025

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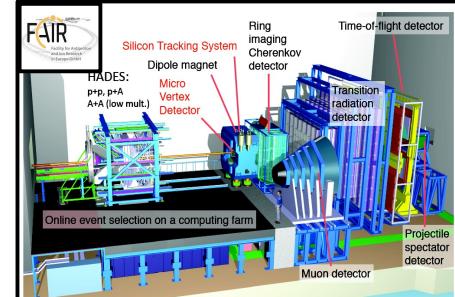
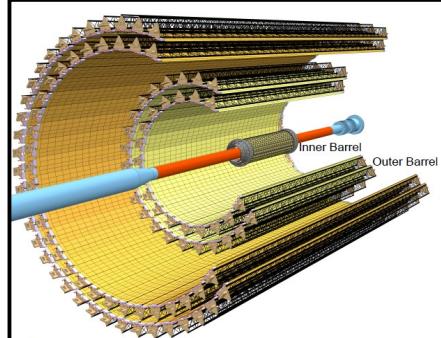


EUDET/STAR-PXL

2010/2014

We are currently here!

$$t_{r.o.} \sim O(10) \mu\text{s}$$



ALICE/CBM

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Quadrature of the
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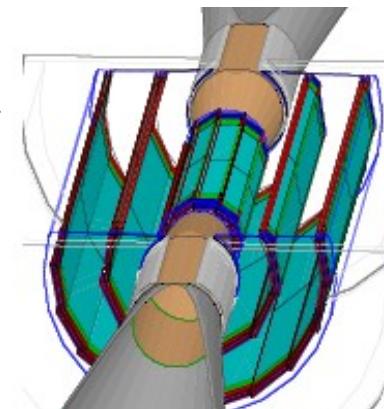
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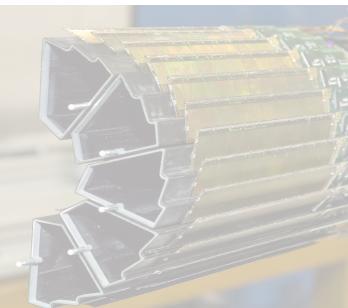


ILC > 2025

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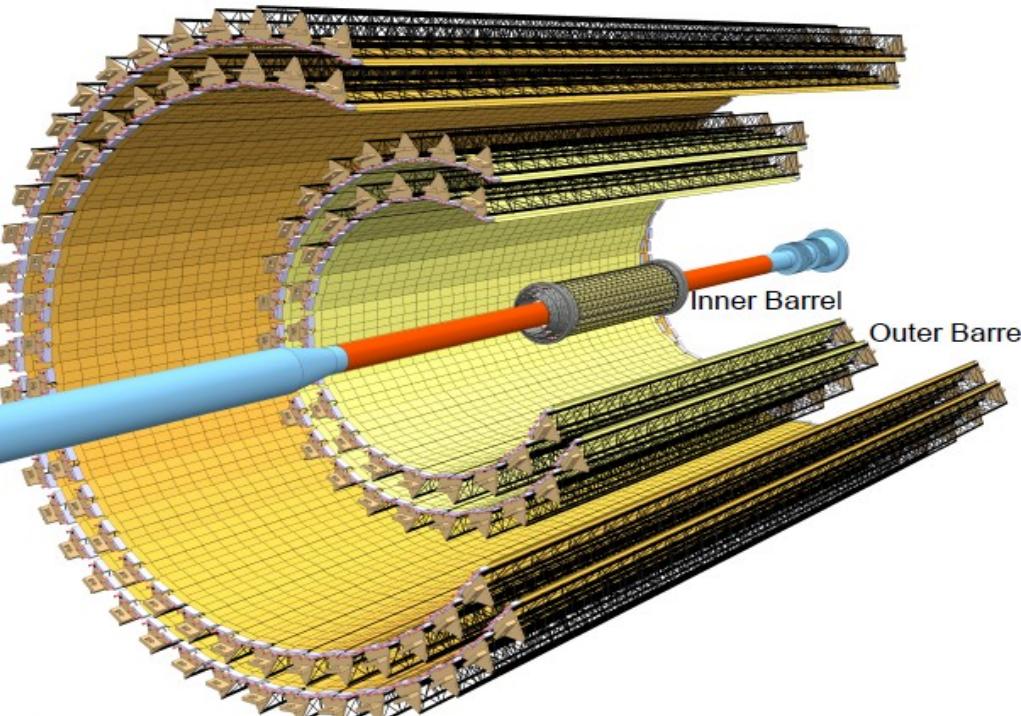
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EUDET/STAR-PX

2010/2014

Forthcoming Device: ALICE-ITS Upgrade



ALICE/CBM
2018/2020

ILC > 2025

physics performances
dominated

Quadrature of the
Vertex Detector

spatial resolution

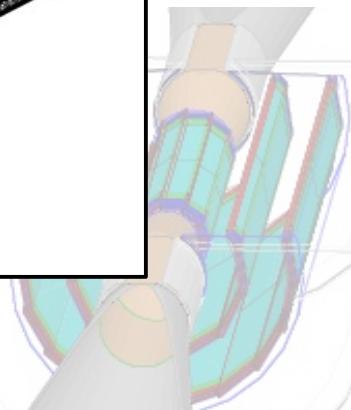
Readout speed

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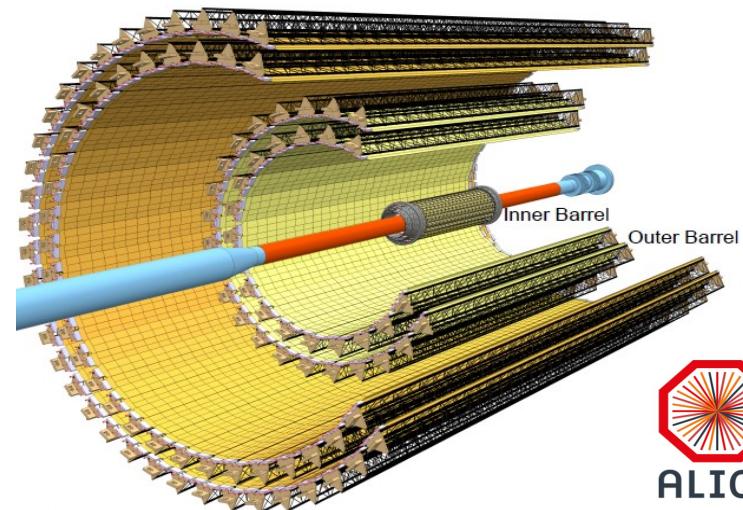
$O(1) \mu\text{s}$



Forthcoming Device: ALICE-ITS upgrade

Upgraded ITS entirely based on CPS

- Present detector: 2xHPD/2xDrift-Si/2xSi-strips
- Future detector: 7-layers with CPS (25k chips)
⇒ 1st large tracker (~ 10 m²) using CPS



ALICE

Requirements for ITS inner & outer layers (comparison with STAR-PXL chip)

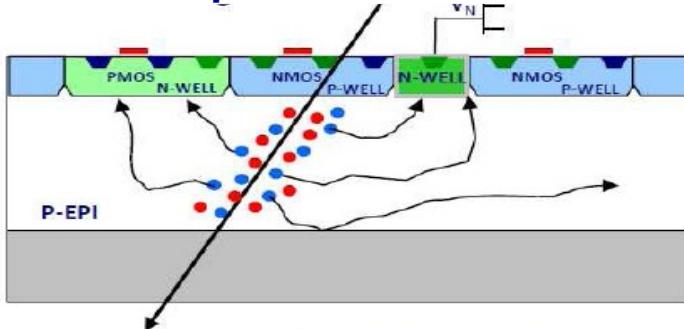
	σ_{sp}	$t_{r.o.}$	Dose	Fluency	T_{op}	Power	Active area
STAR-PXL	< 4 μm	< 200 μs	150 kRad	$3 \cdot 10^{12} n_{eq}/cm^2$	30-35 °C	160 mW/cm ²	0.15 m ²
ITS-in	$\lesssim 5 \mu m$	$\lesssim 30 \mu s$	2.7 MRad	$1.7 \cdot 10^{13} n_{eq}/cm^2$	30 °C	< 300 mW/cm ²	0.17 m ²
ITS-out	$\lesssim 10 \mu m$	$\lesssim 30 \mu s$	100 kRad	$1 \cdot 10^{12} n_{eq}/cm^2$	30 °C	< 100 mW/cm ²	$\sim 10 m^2$

⇒ 0.35 μm CMOS process (STAR-PXL) marginally suited to this r.o. speed & rad. hardness

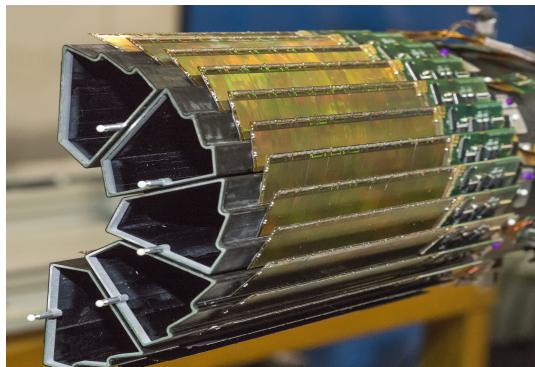
- Transition to new CMOS process for improving readout speed and radiation hardness
⇒ Tower-Jazz 0.18 μm CIS

CMOS Process Transition: STAR-PXL → ALICE-ITS

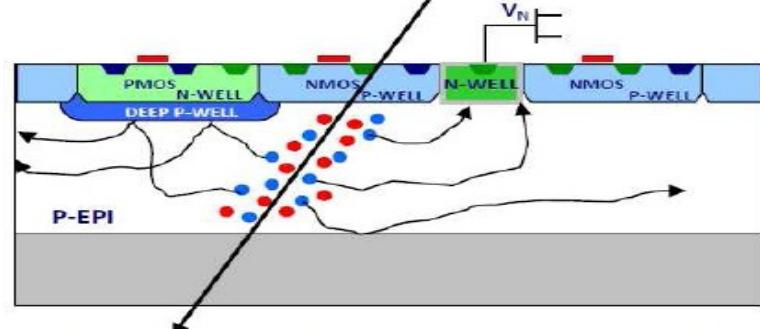
Twin well process: 0.6-0.35 um



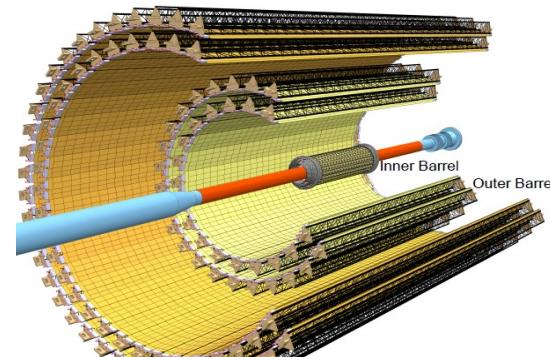
- Use of PMOS in pixel array not allowed
⇒ parasitic q-collection of additional N-well
- Limits choice of readout architecture strategy
- Already demonstrated excellent performances
 - **STAR-PXL:** Mi-28 (AMS 0.35 μm process)
⇒ $\epsilon_{\text{det}} > 99.5\%$, $\sigma_{\text{sp}} < 4\mu\text{m}$



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



- N-well of PMOS transistors shielded by deep P-well
⇒ both types of transistors can be used
- Widen choice of readout architecture strategies
 - **New ALICE-ITS:** 2 sensors R&D in || using TowerJazz CIS 0.18 um process (quadr. well)
 - **Synchronous Readout R&D:**
proven architecture ⇒ safety
 - **Asynchronous Readout R&D:** challenging



ALICE-ITS: advantages of the new technology

■ New fabrication process (TowerJazz CIS 0.18 μm)

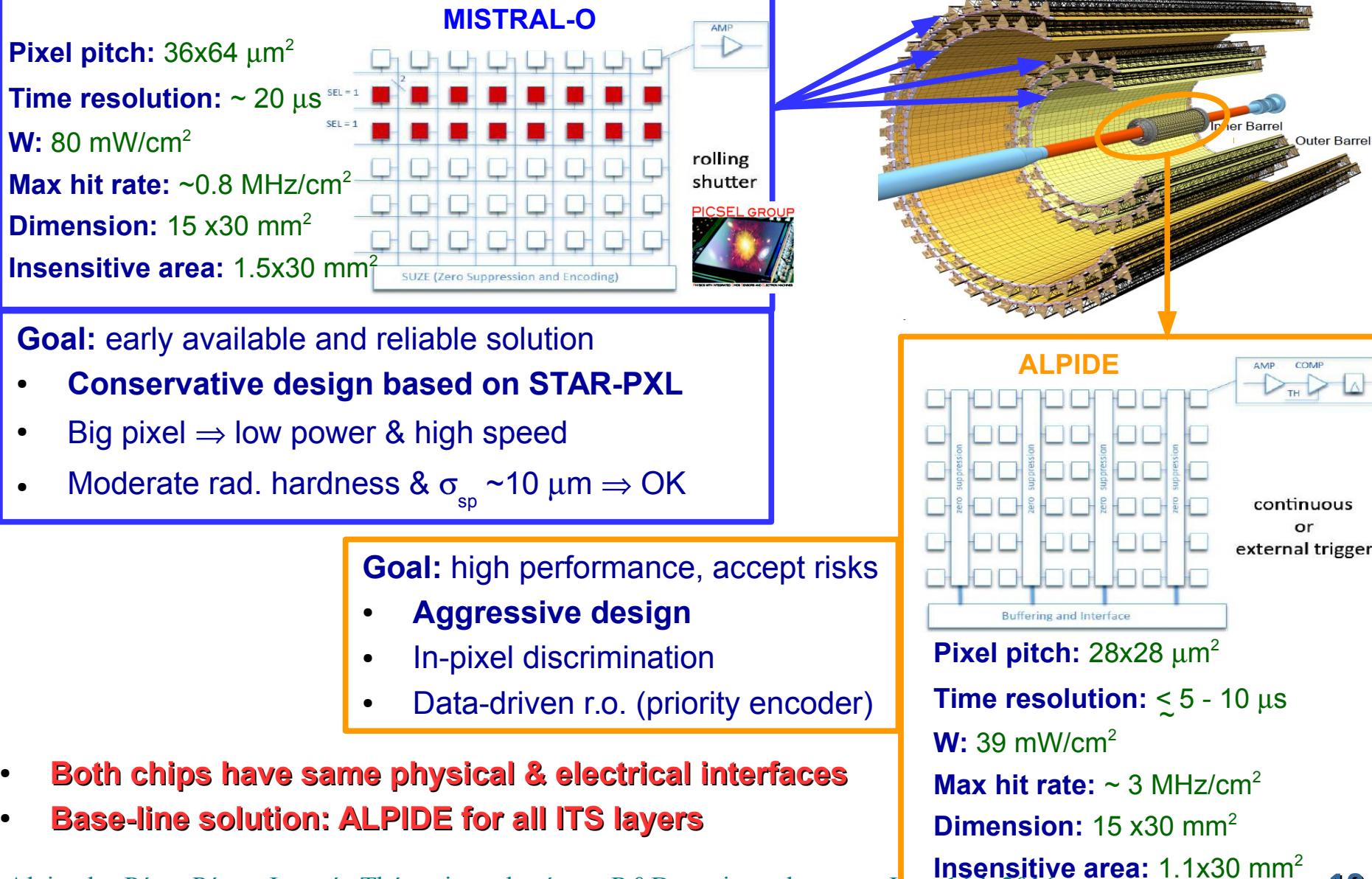
- Expected improvement of ration tolerance
- Expected to allow for fast enough r.o.
- Larger reticule: ~ 25 x 32 mm²

STAR-PXL	ALICE-ITS	added-value
$0.35 \mu m$	$0.18 \mu m$	speed, TID, power
4 ML	6 ML	speed, power
twin-well	quadruple-well	speed, power
EPI 14/20 μm	EPI 18/40 μm	SNR
$EPI \gtrsim 0.4 \text{ k}\Omega \cdot cm$	$EPI \sim 1 - 8 \text{ k}\Omega \cdot cm$	SNR, NITD

■ Drawback of smaller feature size

- 1.8 V operative voltage (instead of 3.3 V)
⇒ reduced dynamics in signal processing circuit & epi-layer depletion voltage
- Increase risk of Random Telegraph Signal (RTS) noise

ALICE-ITS: Two Architectures for the pixel chip

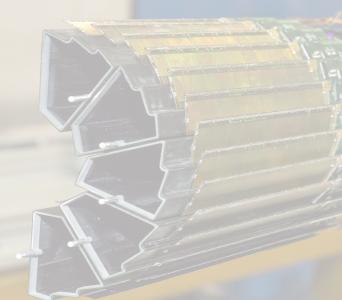


CPS: Improving Speed & Radiation Tolerance

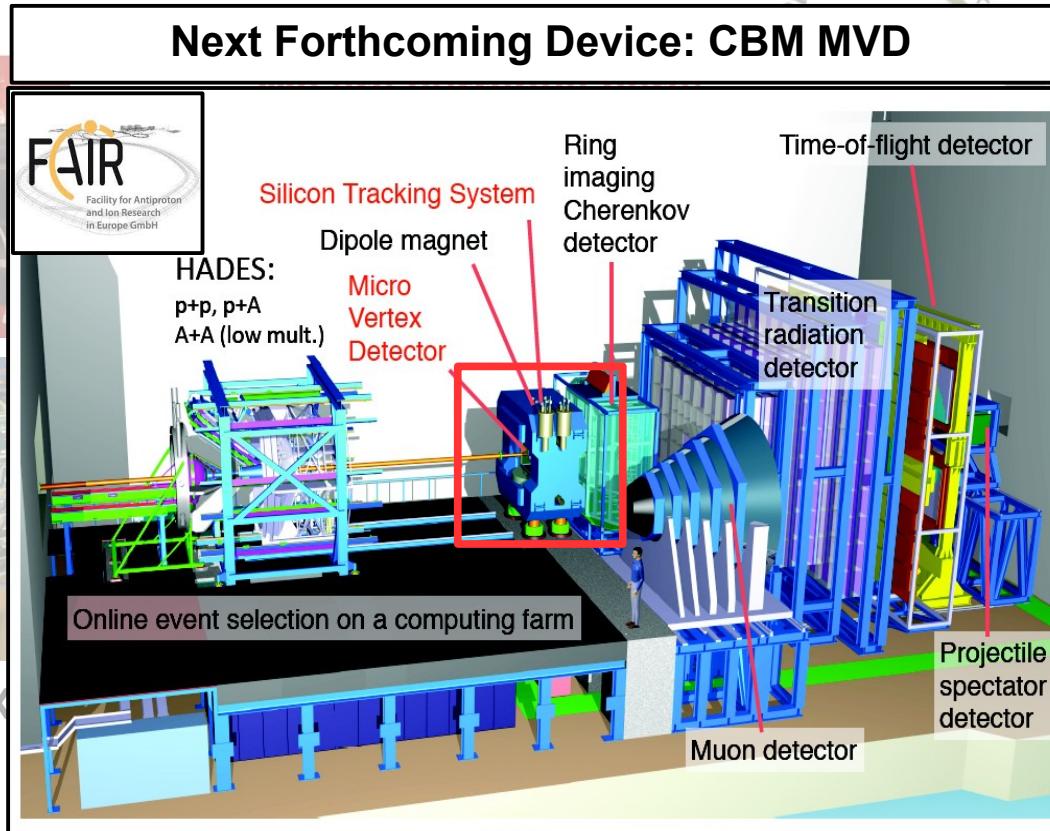
How to improve r.o. speed and rad. tolerance while preserving σ_{sp} ($3-5 \mu\text{m}$) and material budget ($< 0.1\% X_0$)?

Quadrature of the Vertex Detector

$t_{r.o.} \sim O(10^2) \mu\text{s}$



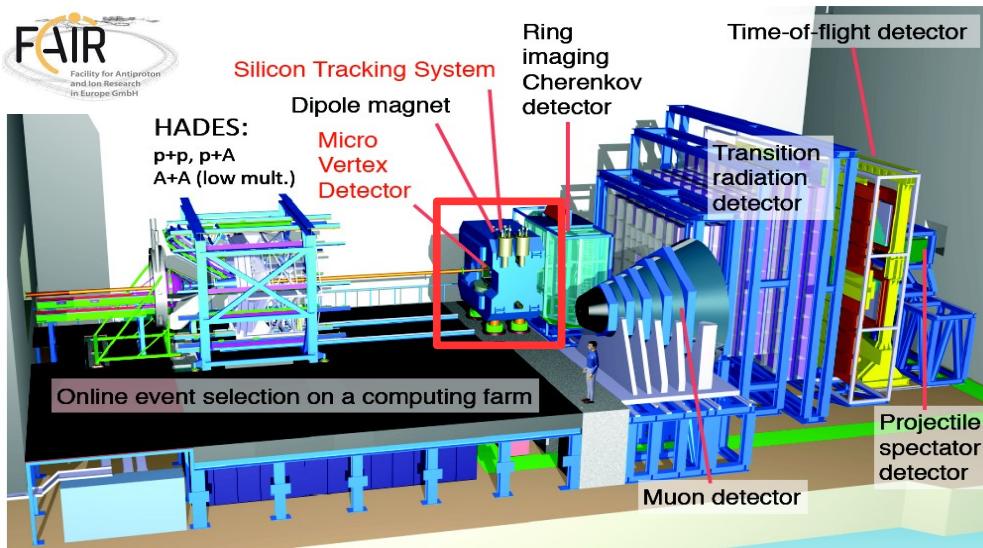
EUDET/STAR-PX
2010/2014



ALICE/CBM
2018/2020

ILC > 2025

Next Forthcoming Device: CMB Micro-Vertex Detector



Micro Vertex Detector (MVD)

- **Layout**
 - 4 stations of (partial double-sided) pixels sensors
- Factor 10 improvement in rad. tolerance
- Vacuum compatible
- Operation @ negative Temp & vacuum

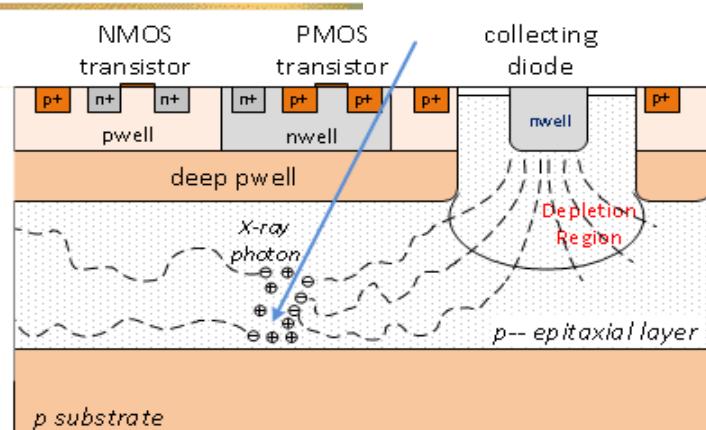
Sensor properties	FSBB	ALPIDE	MIMOSIS-100 (prelim)
Active surface (mm ²)	9.2×13.7	13.9×30	$\sim 10 \times 30$
# pixels (cols × rows)	416×416 (173k)	512×1024 (524k)	1500×300 (450k)
Pixel pitch (μm)	22×33	28×28	22×33
Integration time (μs)	40	5 – 10	2.5 – 10 (likely 5)
Data rate (Mbps)	2×320	1×1200	$> 6 \times 320$
NIEL ($10^{13} n_{\text{eq}}/\text{cm}^2$)	$\gtrsim 1$	$\gtrsim 1.7$	3 (*)
TID (MRad)	$\gtrsim 1.6$???	3 (*)
$T_{\text{operation}}$ ($^{\circ}\text{C}$)	+30	+30	-20 in Vacuum

(*) per year of operation
= 8 weeks

Improving sensitive layer depletion

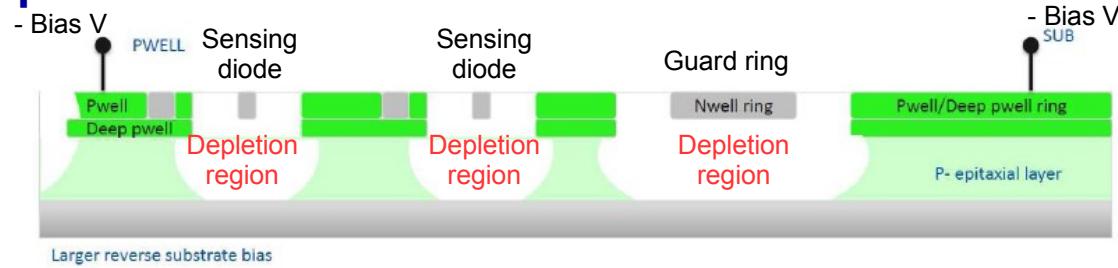
Motivations

- **HEP:** Faster signal \Rightarrow better tolerance to NIEL
- **X-Ray detection**
 - Thicker sensitive volume (Beer-Lambert law)
 - Uniformity of ϵ_{det} across active area
 - Spectroscopy

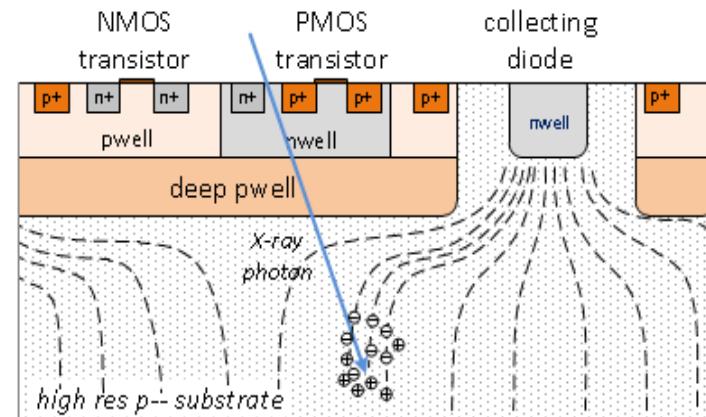
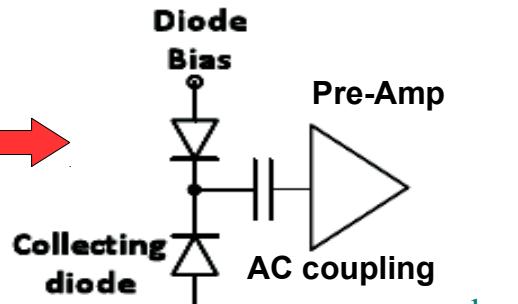
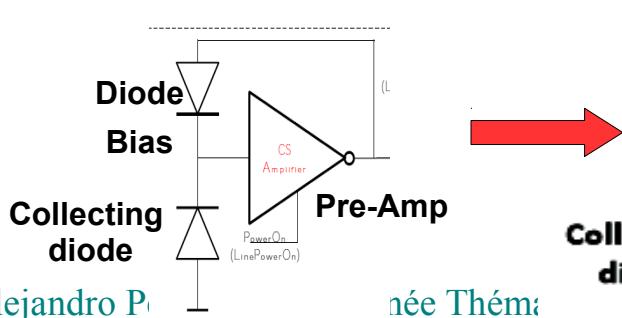


Alternatives for depletion improvements

- Substrate reverse bias
E.g. ALPIDE on P-wells



- Sensing diode front bias: AC coupling with FEE



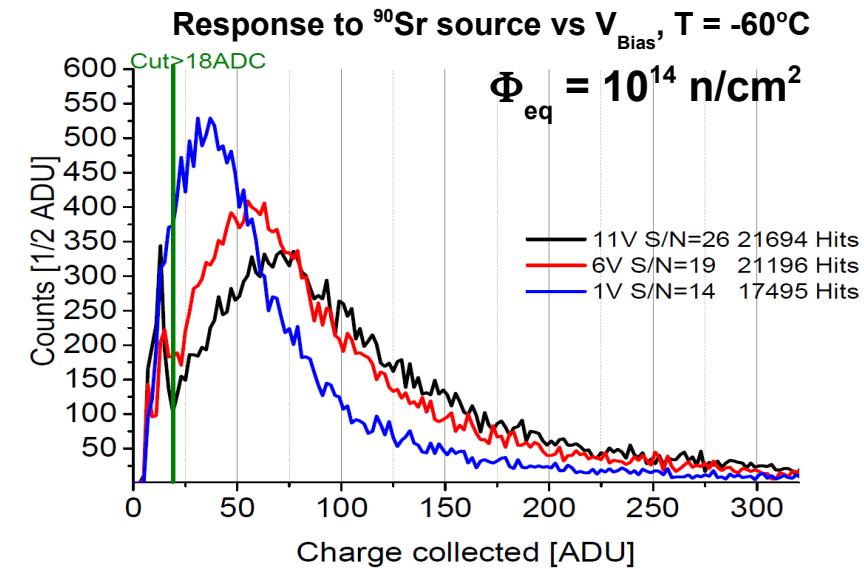
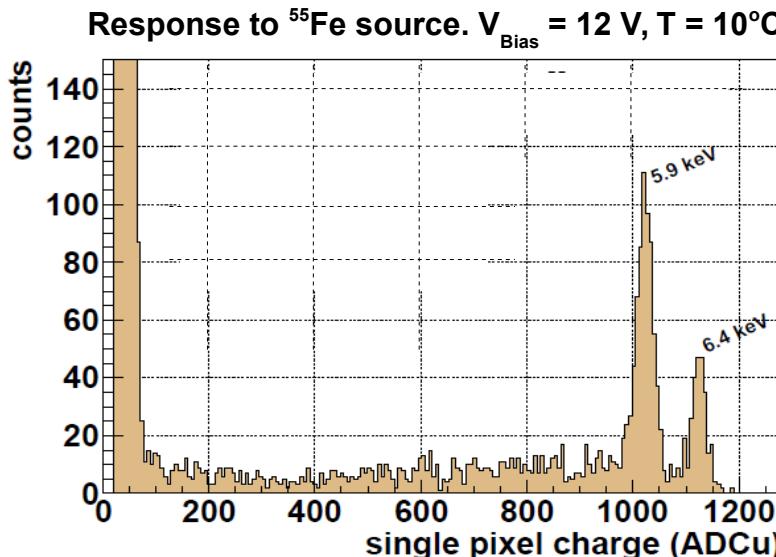


SYNchrotron Active Pixel Sensors

- High granularity/counting-rate CPS for soft X-ray (0.1 - 5keV) detection
⇒ $10^4 - 10^6$ photons/pixel/s

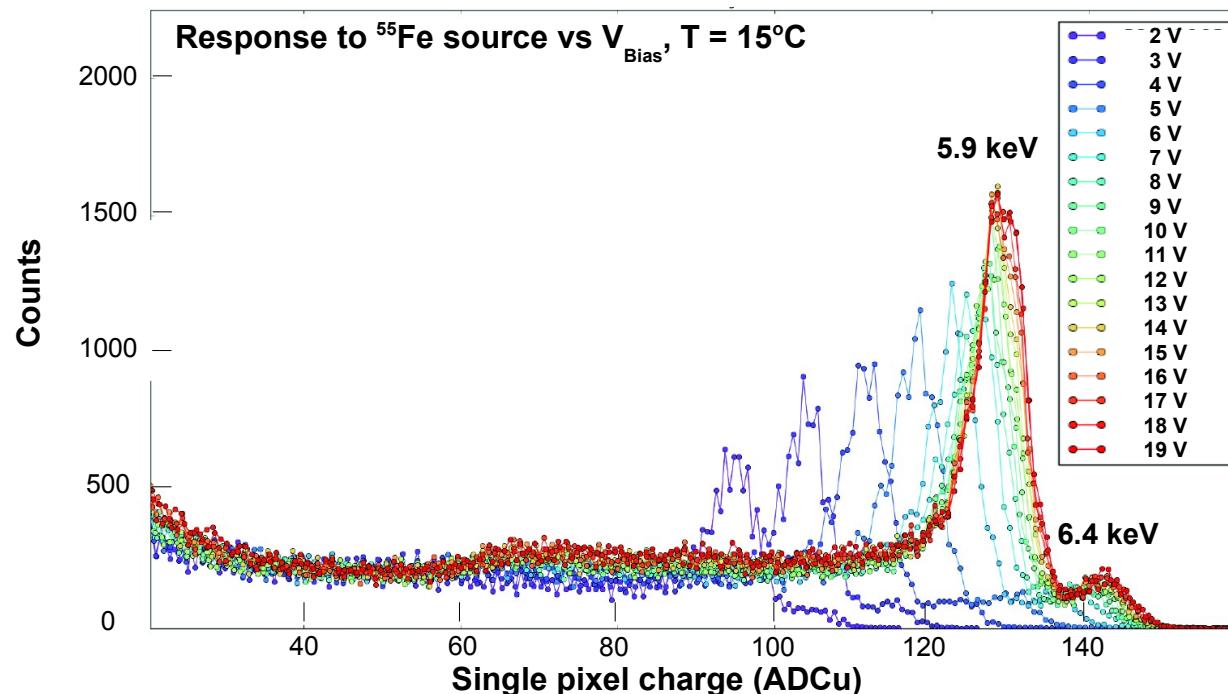
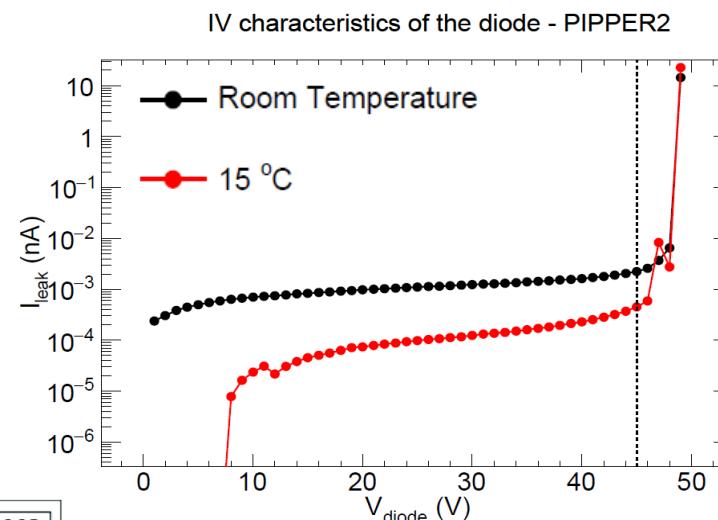
PIPPER-1 prototype (Tower-Jazz 0.18 μm CIS)

- 56×8 square pixels ($25 \mu\text{m}$ pitch)
- epi-layer = $18 - 30 \mu\text{m}$ ($> 1 \text{ k}\Omega \text{ cm}$) & CZ = $50 \mu\text{m}$ ($\sim 700 \Omega \text{ cm}$)
- $T_N \approx 16 \pm 1 \text{ e}^- \text{ ENC}$ @ 10°C
- Metal-Insulator-Metal (MIM) capa for AC-coupling to Pre-Amp, $V_{\text{Bias}} = 0 - 15 \text{ V}$



PIPPER-2 prototype (Tower-Jazz 0.18 μm CIS)

- 128 x 8 square pixels (25 μm pitch)
- Collection system: 1 diode 3, 5 μm \varnothing , 4 diodes 4 μm \varnothing
- epi-layer = 18 μm ($> 1 \text{k}\Omega \times \text{cm}$) & CZ = 50 μm ($\sim 700 \Omega \times \text{cm}$)
- TN $\approx 10 - 15 \text{ e}^- \text{ ENC}$ @ 15°C
- Fringe capa for AC-coupling to Pre-Amp, V_{Bias} up to 45 V



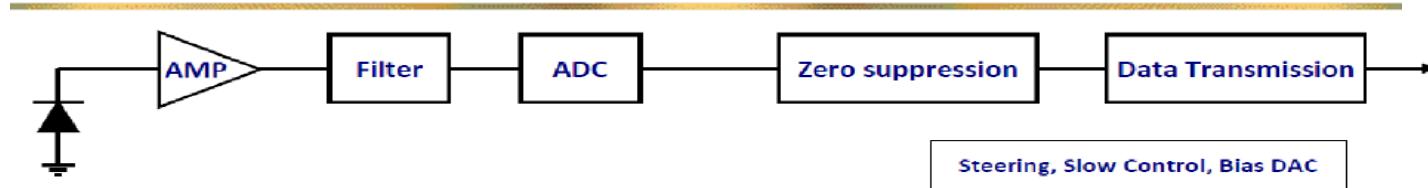
Summary

Summary and outlook

- **CPS development triggered by applications needing high precision and low material budget (relaxing t_{r.o.} and radiation hardness). Many applications**
 - High precision beam-telescopes: multi-GeV → sub-GeV beams (CERN, DESY, LNF)
 - Vertex detectors for flavour tagging (STAR-PXL, FIRST)
 - Pixelated Tracker for low momentum tracks (ALICE)
- **Constant CMOS technology developments enlarge the toolbox to improve radiation hardness (and r.o. speed) of CPS**
 - Smaller feature size \Rightarrow improved tolerance to ionizing radiation (TID >> 10MRad)
 - Epi-layer (thickness & p_{sub}) \Rightarrow improved tolerance to non-ionizing radiation (main concern)
- **Outlook**
 - Fully depleted sensitive volume ($p_{sub} > 1 \text{ k}\Omega\text{cm}$) with relatively low V_{Bias} (up to 45 V)
 - Collection diode AC-coupled to in-pixel Pre-amplifier

A large, three-dimensional word "BACKUP" is displayed in a dark green color with a marbled texture. The letters are thick and slightly slanted, creating a sense of depth. The background is plain white.

Main components of signal processing chain



Typical readout (r.o.) components

- **AMP:** in-pixel low noise pre-amplifier
- **Filter:** in-pixel filter
- **ADC** (1-bit \equiv discriminator): may be implemented at end-of-column (usual) or in-pixel
- **Zero suppression** (SUZE): only hit pixel info is retained and transferred
 - Implemented at sensor periphery (usual) or inside pixel array
- **Data transmission:** O(Gbps) link implemented at sensor periphery

r.o. alternatives

- Rolling shutter (synchronous): || column r.o. reading N-lines at the time (usually $N = 1-2$)
 - Simpler design ($t_{r.o.} \gtrsim 20 \mu\text{s}$)
- Data-driven (asynchronous): only hit pixels are output upon request
 - Better r.o. speed but much more complex design ($t_{r.o.} \gtrsim 1 \mu\text{s}$)

CPS: Optimization Process

Sensor performance are evaluated in terms of

- Noise \Leftrightarrow Dark hit rate
- Charge Collection & Signal/Noise \Leftrightarrow Detection efficiency (ε_{det})
- Cluster multiplicity (CM) \Leftrightarrow Spatial resolution (σ_{sp})

Radiation tolerance

Depend on construction parameters

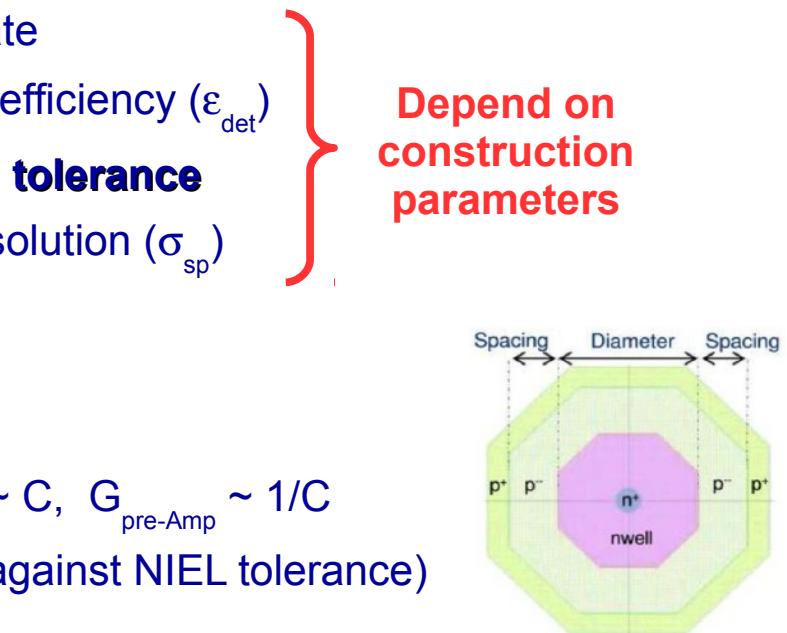
E.g.: Sensing node vs FEE

Sensing node should be

- Small: $V_{\text{signal}} = Q_{\text{signal}}/C$; Noise $\sim C$, $G_{\text{pre-Amp}} \sim 1/C$
- But no too small: $Q_{\text{signal}} \sim \text{CCE}$ (important against NIEL tolerance)

Pre-amp connected to sensing node

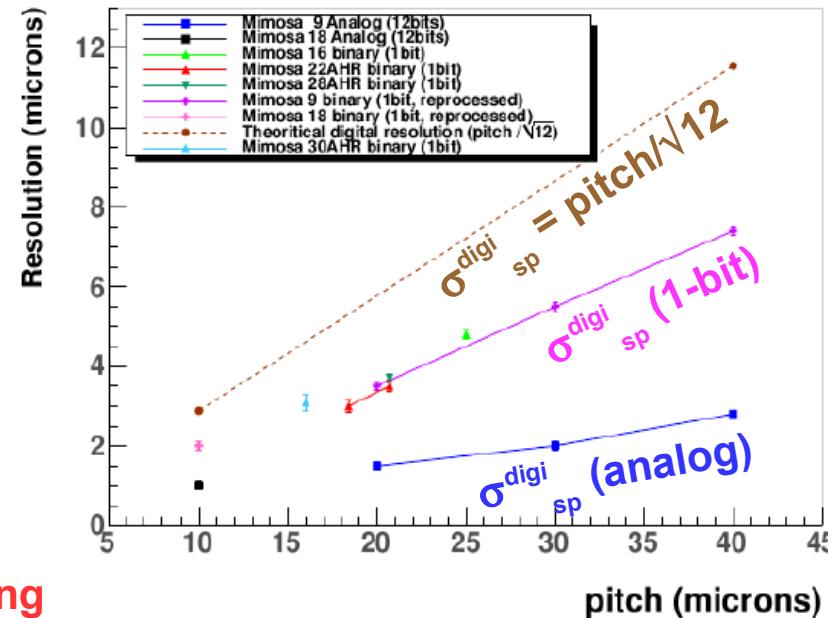
- High enough $G_{\text{pre-Amp}}$
- Input transistor with minimal noise
- Close to sensing node (minimize line C)



Example of CPS performance: σ_{sp}



- σ_{sp} is multiparametric function
 - Pixel pitch
 - Epi-layer: thickness & doping profile
 - Sensing node: geometry & electrical properties
 - Sensing node pattern: density, staggering
 - Signal-encoding: Nb of bits
- Significantly better σ_{sp} than σ_{sp}^{digi} \Rightarrow charge sharing
- Pixel pitch: linear relation with σ_{sp}
- Signal-encoding resolution: significantly improves σ_{sp}



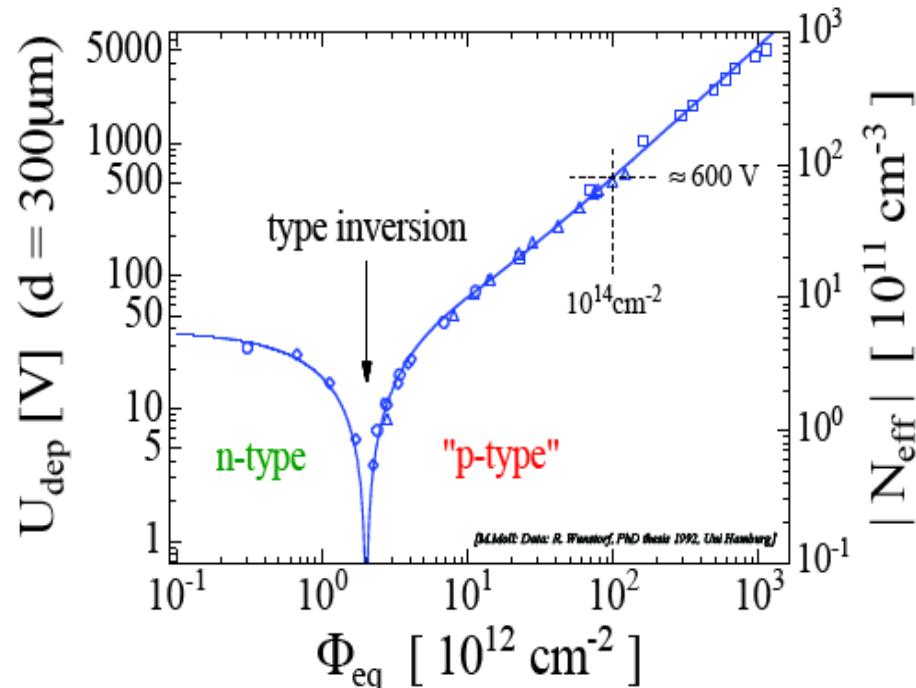
σ_{sp} vs signal-encoding (pitch = 20 μm)

Nb of bits	12	3-4	1
Data	measured	reprocessed	measured
σ_{sp}	$\lesssim 1.5\mu\text{m}$	$\lesssim 2\mu\text{m}$	$\lesssim 3.5\mu\text{m}$

Radiation effects on Epitaxial layer: Bulk Damage (2/3)

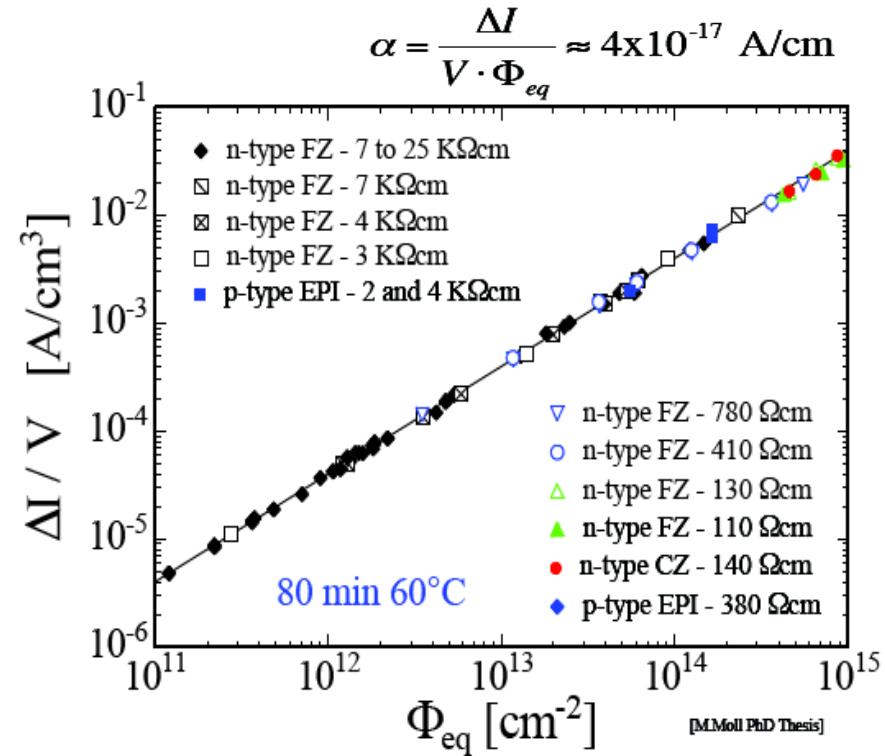
■ Reduction of depleted volume

- Reduction of epi-layer ρ_{res} (prop 1/Neff)
- Reduction of $d_{\text{dep}} \sim (\rho_{\text{sub}} \times U_{\text{bias}})^a$
- Deteriorate charge collection



■ Increase of leakage current (I_{leak})

- Thermal noise increase
- Strong temperature dependence
- $I_{\text{leak}} \text{ prop. exp}(-E_g/2kT)$
- Improvement by cooling down



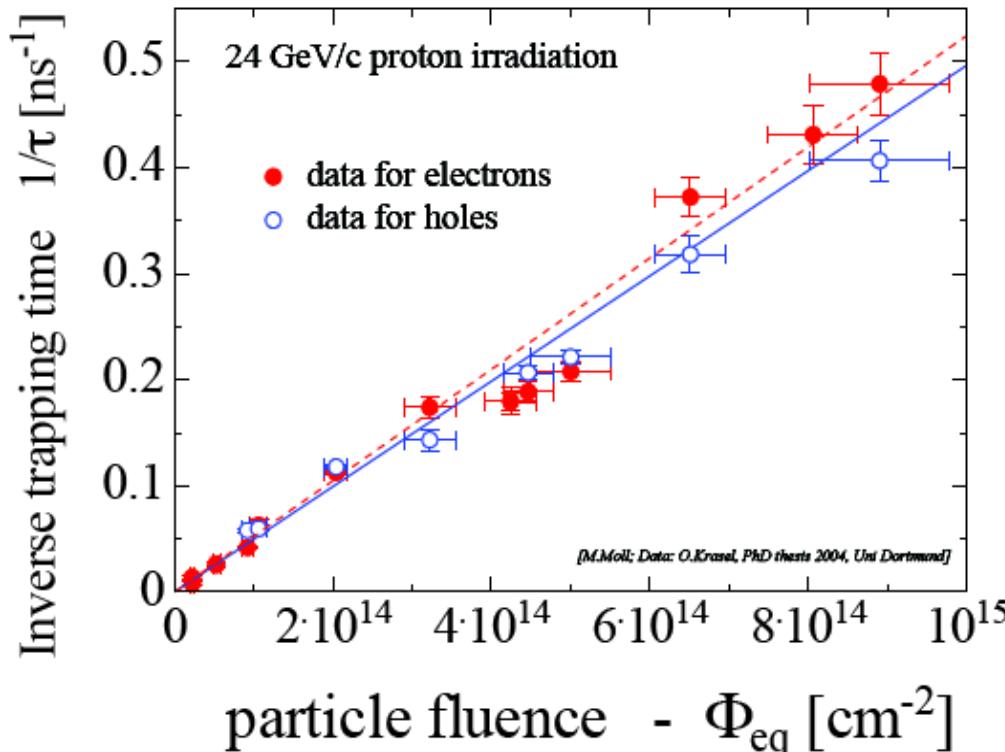
Radiation effects on Epitaxial layer: Bulk Damage (3/3)

- Deterioration of charge collection efficiency by trapping
- Trapping characterized by effective trapping time ($\tau_{\text{eff } e,h}$) for e^- and holes

$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{\text{eff } e,h}} \cdot t\right)$$

where

$$\frac{1}{\tau_{\text{eff } e,h}} \propto N_{\text{defects}} \propto \Phi_{eq}$$

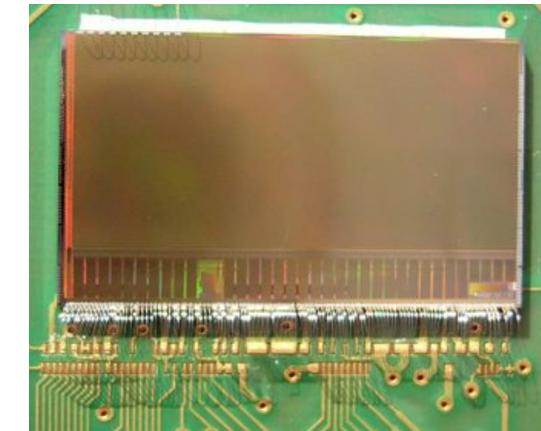


MIMOSA-26 sensor: Established architecture

Main characteristics

- 0.35 μm process with high- ρ epi-layer ($\gtrsim 1\text{k}\Omega\cdot\text{cm}$)
- Rolling shutter r.o. with in-pixel CDS & amplification
- End-of-column discriminator (1-bit) followed by SUZE
- 1152x576 pixels of 18.4 μm pitch (active area: $21.2\times10.6\text{ mm}^2$)
 - $\sigma_{\text{sp}} \sim 3 - 3.5\text{ }\mu\text{m}$
- $t_{\text{r.o.}} = 115\text{ }\mu\text{s}$ ($\sim 10^4$ frames/s \Rightarrow Rate $> 1\text{MHz/cm}^2$)
- $T_{\text{op}} = 30 - 35\text{ }^\circ\text{C}$, Power $\sim 250\text{ mW/cm}^2$

MIMOSA-26



2 arms of 3 MIMOSA-26 sensors

EUDET Beam Telescope

- Sensors thinned down to 50 μm total thickness
- Few μm pointing resolution
- Adapted to medium/low energy e^+ beams
- Several copies around the world
 - CERN-PS/SPS (3), DESY (2), Bonn (1), SLAC (1)

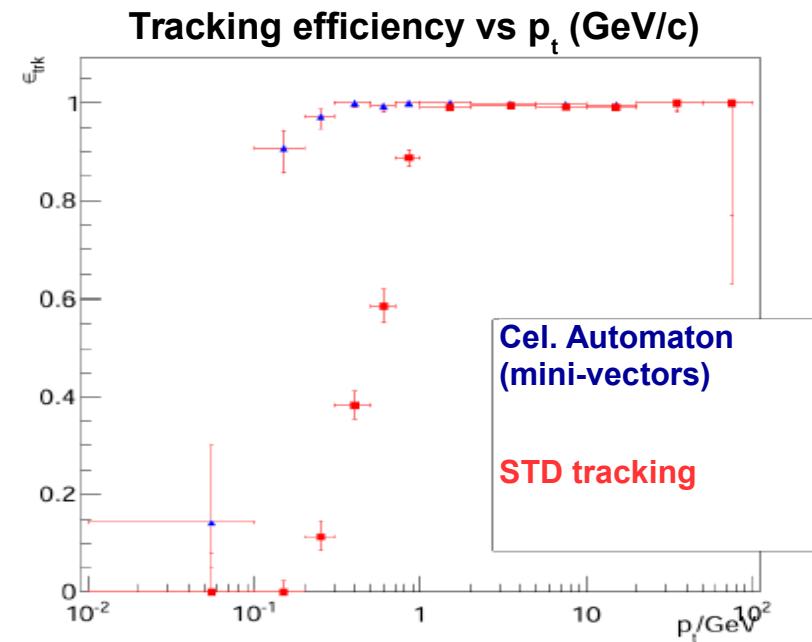
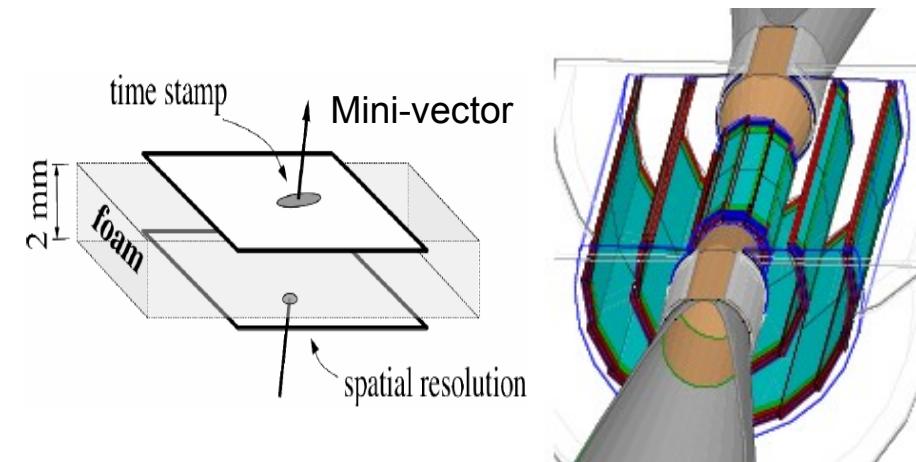


Other MIMOSA-26 applications: VD demonstrators, NA63, NA61, FIRST, dosimetry, ...

MIMOSA-26 sensor: Integration in Ultra-Light devices

- ILC vertex detector triggered R&D on ultra-light double-sided ladder

- Alignment & tracking improvement
- 1-support/2-layers (material budget)

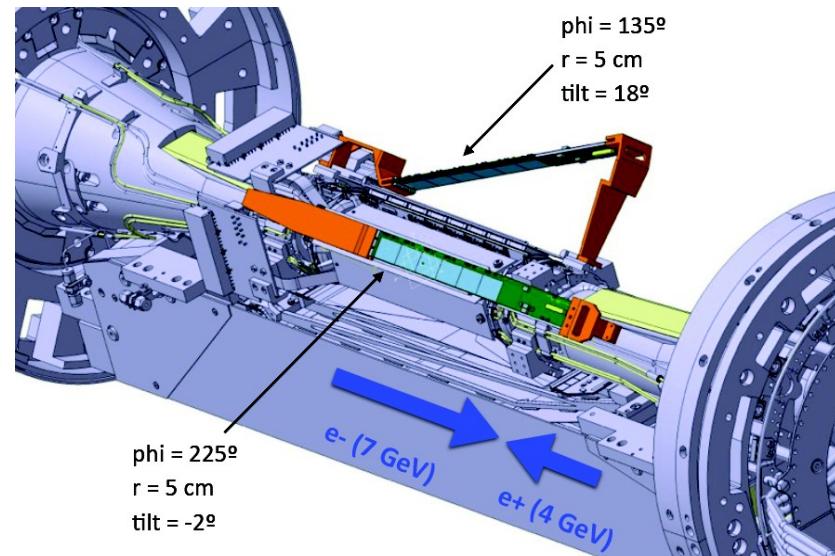
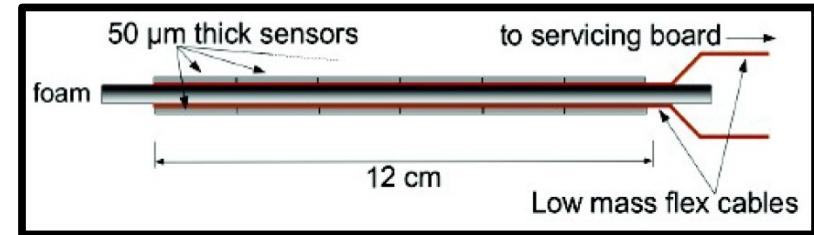


MIMOSA-26 sensor: Integration in Ultra-Light devices

- ILC vertex detector triggered R&D on ultra-light double-sided ladder
 - Alignment & tracking improvement
 - 1-support/2-layers (material budget)

- PLUME collaboration (Bristol, DESY, IPHC)
 - 2x6 MIMOSA-26 (50 μm) on 2mm SiC foam
 - PLUME 01 prototype in 2012 (0.6% X_0)
 - Validated on beam @ CERN
 - PLUME 02 (0.35/0.42% X_0) in production

- PLUME 02 most recent application
 - BEAST-II @ SuperKEKb (**data taking 2017**)
 - 2 PLUME 02 ladders equipping IP region
 - Characterize beam related backgrounds
 - Use mini-vectors \Rightarrow rate & properties



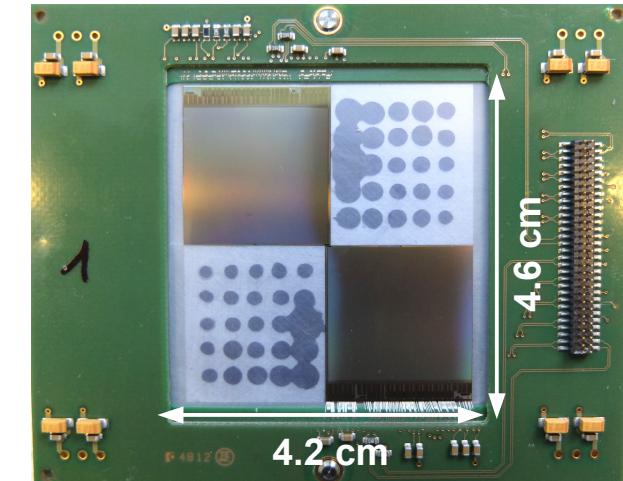
Other applications of MIMOSA-28/ULTIMATE

- Beam Telescope for hadron-therapy (e.g. GSI)
- Beam Telescope @ Frascati BTF ($0.05\% X_0/\text{plane}$)

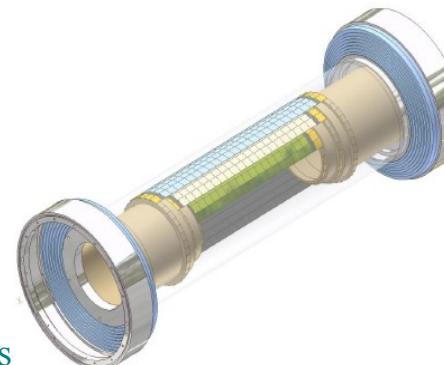
- Adapted to 450 MeV/c electrons
- Becoming part of BTF equipment



- AIDA (EU-FP7)
 - Single Arm Large AREA Telescope (SALAT)
 - SALAT plane: 4 MIMOSA-28 glued to stretched Mylar foil
 - $<< 0.1\% X_0/\text{plane}$



- Prototype for an inner tracker
 - Reference requirement: BESIII upgrade
 - 3 detection layers
 - 120 sensors thinned down to 50 μm

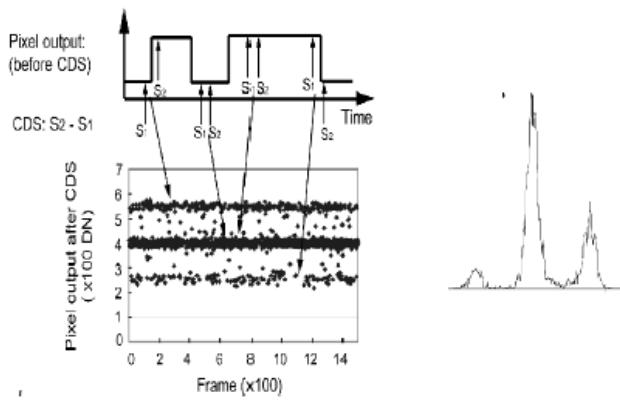


- STEPS VALIDATED IN 2012 :

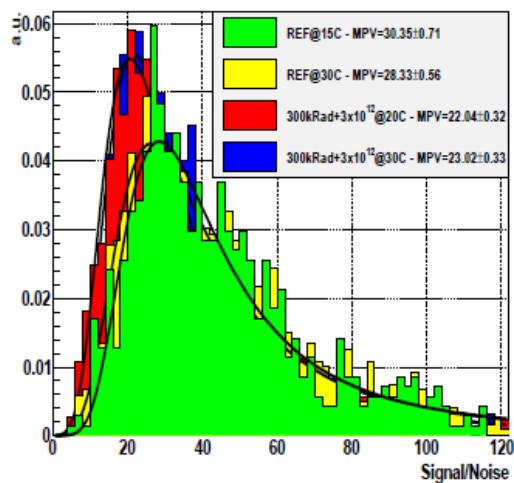
- * Several in-pixel amplifier variants lead to satisfactory SNR & det. eff. ($20 \times 20 \mu\text{m}^2$) incl. after 1 MRad & $10^{13} \text{n}_{eq}/\text{cm}^2$ at 30°C
- * Results pres. at VCI-2013 (J. Baudot)

- CALL FOR IMPROVEMENT :

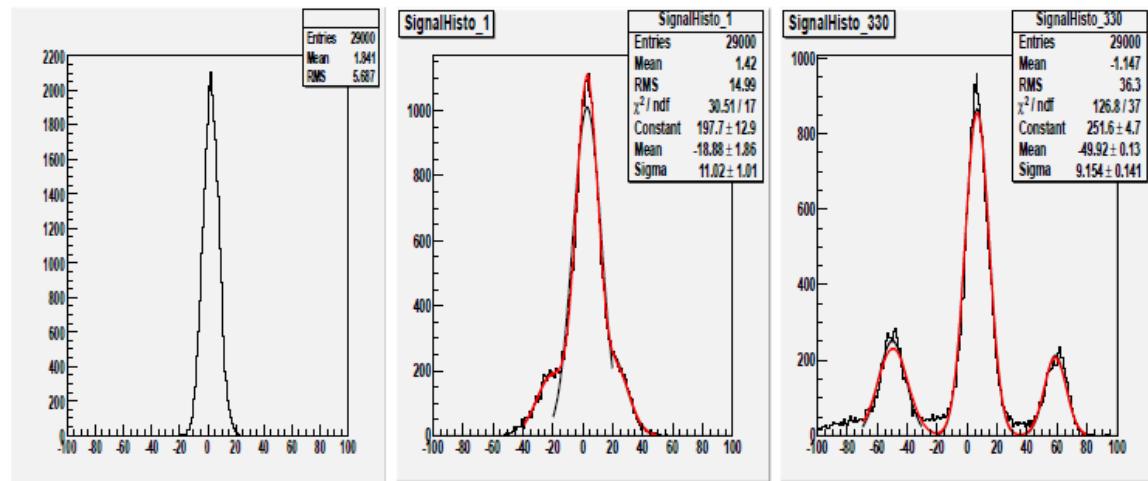
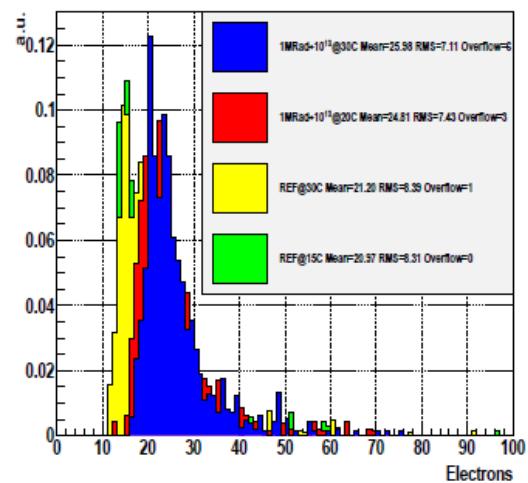
- * Pixel circuitry noise :
 - tail due few noisy pixels
 - attributed to RTS noise
 - ⇒ required optimising T geometries



Signal/Noise ratio for P25



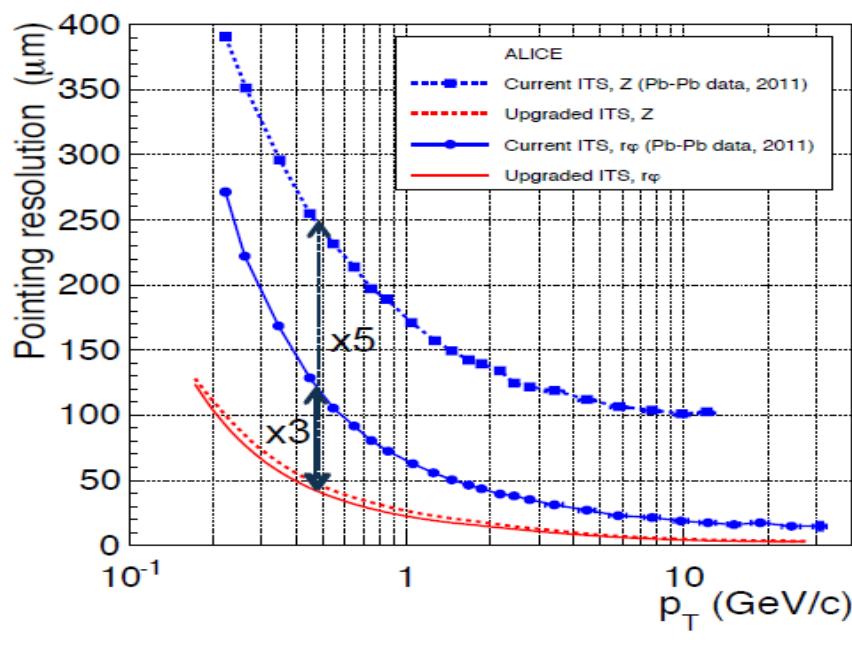
Noise for P25



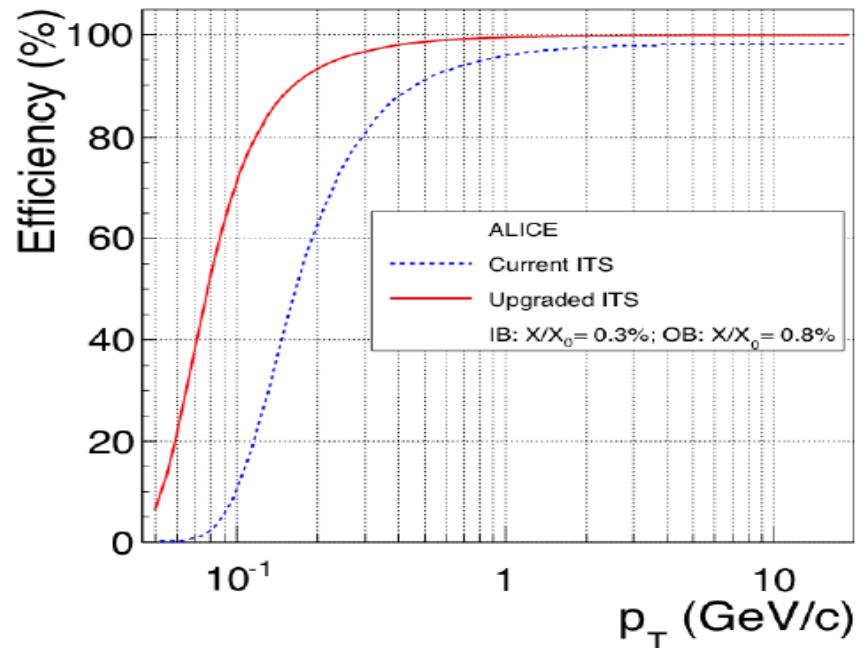
Forthcoming Device: ALICE-ITS upgrade

- **ALICE Inner Tracking System (ITS) foreseen to be replace during LS2/LHC**
 - Higher luminosity & improved charm tagging
- **Expected improvement in pointing resolution and tracking efficiency**

Impact parameter resolution

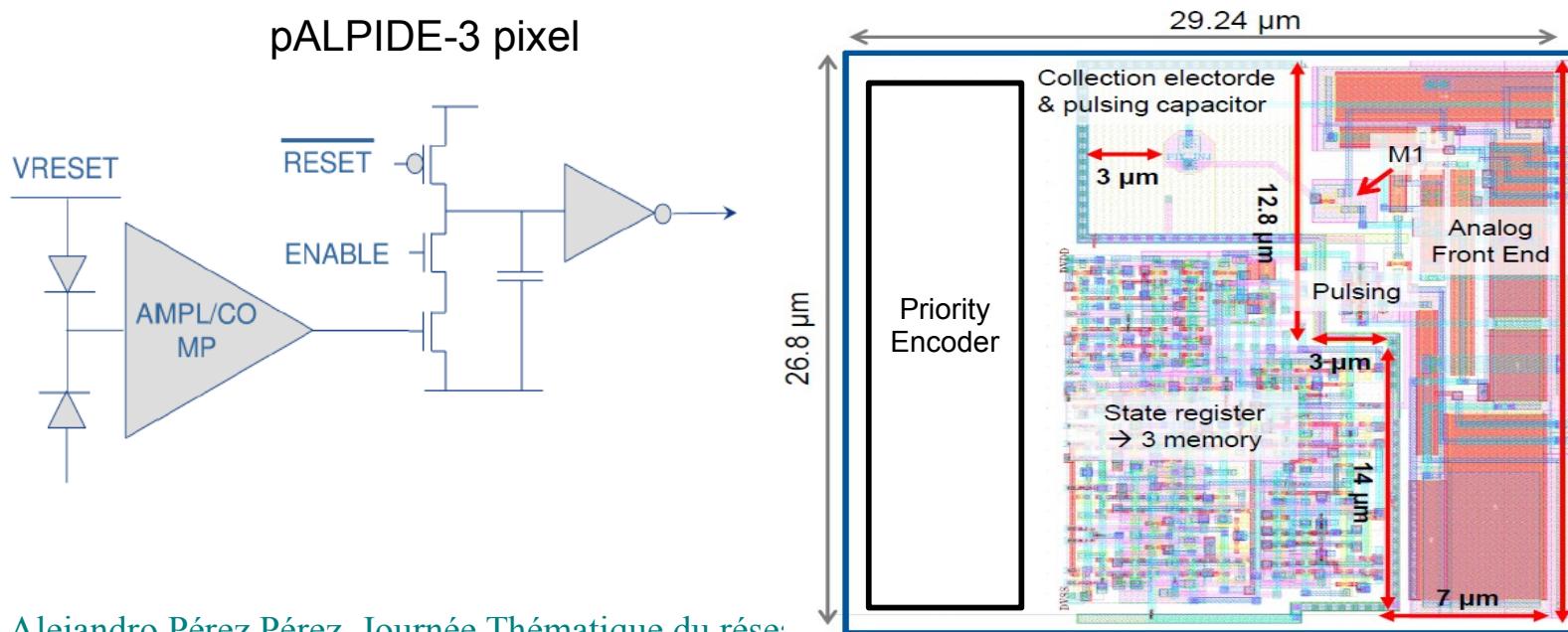


Tracking efficiency (ITS standalone)



Asynchronous r.o. architecture: ALPIDE

- Concept similar to hybrid pixel r.o. architecture
- Continuously power active in each pixel
 - FEE: single stage amplifier ($G \sim 100$) + shaping (peaking $\sim 5 \mu\text{s}$) / current comparator
- Storage element for hit information (3 in-pixel memories \Rightarrow multi-event)
- Data driven r.o.: only zero-suppressed data transferred to periphery \Rightarrow Priority Encoder



Rolling Shutter r.o. architecture: MISTRAL-O

Power vs speed in rolling shutter r.o.

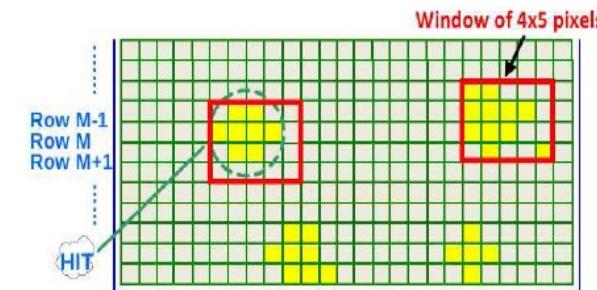
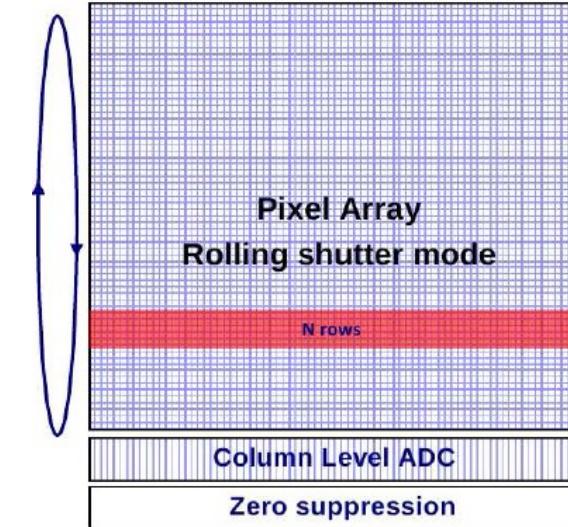
- **Power:** only the selected rows ($N = 1, 2, 3 \dots$) to be readout
- **Speed:** N rows of pixels are readout in ||
 - Integration-time (t_{int}) = (Row r.o. time) x (# Rows) / N

Why large pixels ($36 \times 64 \mu\text{m}^2$)?

- Lower # of rows & columns for same sensitive area
⇒ improved speed & reduced power
- Pixel staggered layout ⇒ improve sensing node uniformity
- BUT degraded σ_{sp} ($\sim 10 \mu\text{m}$) & rad. tolerance
 - OK for relaxed requirements of ALICE-ITS outer layers

Design addressing

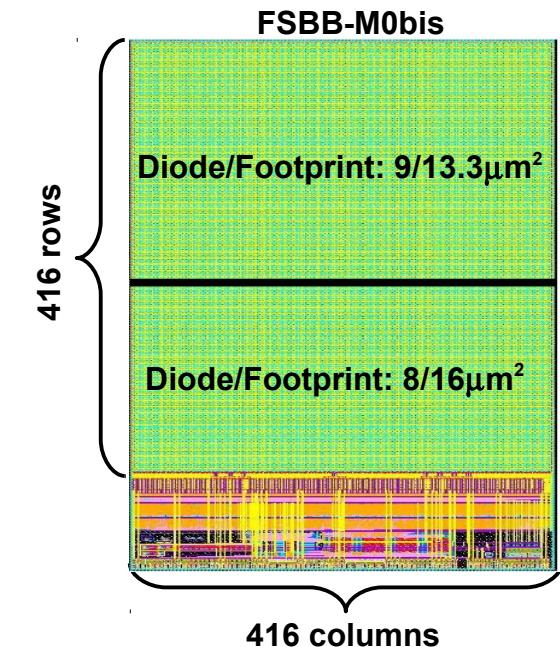
- Large pixels ⇒ sensing node + Pre-Amp optimization
- Rolling shutter r.o. addressing 2 neighbour rows
- 2D sparsification: 4x5 pixels windows
(evolution from 1D sparsification on MIMOSA-28)



MISTRAL-O: prototypes tested on beam

Full Scale Building Block (FSBB) sensor

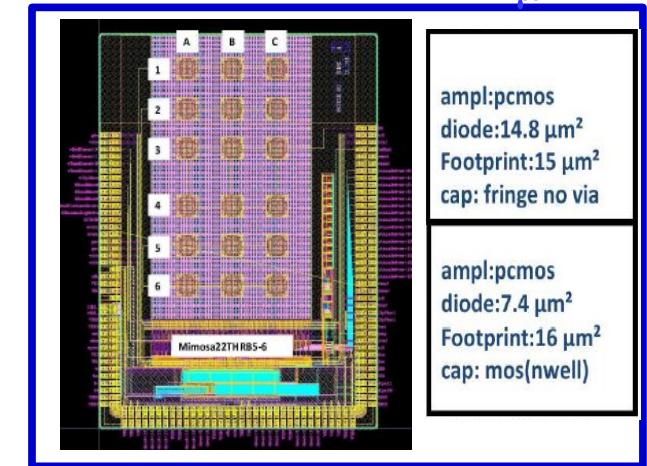
- Full 2-row r.o. chain & 2D sparsification $t_{r.o.} = 40 \mu\text{s}$
- Sensitive area ($\sim 1 \text{ cm}^2$) \approx final building bock
- Similar Nb of pixels ($\sim 170\text{k}$) to final chip
- Epi-layer: high- ρ 18 μm thick
- **BUT:** small pixels ($22 \times 32.5 \mu\text{m}^2$) & sparsification circuitry is oversized (power!)
- **Goal:** validation of r.o. architecture in new CMOS process
- **Tested in 2015: DESY (5 GeV e^-) & CERN (120 GeV π^-)**



Large-pixel prototype (MIMOSA-22THRb)

- Two slightly different large pixels
 - $36 \times 62.5 \mu\text{m}^2$ & $39 \times 50.8 \mu\text{m}^2$
- Pads over pixel (3ML used for in-pixel circuitry)
- Epi-layer: high- ρ 18 μm thick
- **BUT:** only $\lesssim 10 \text{ mm}^2$, 4k pixels & no sparsification
- **Goal:** validation of large pixel design
- **Tested @ Frascati BTF (450 MeV e^-) in 2015**

Mi22-THRb6: $36 \times 62.5 \mu\text{m}^2$



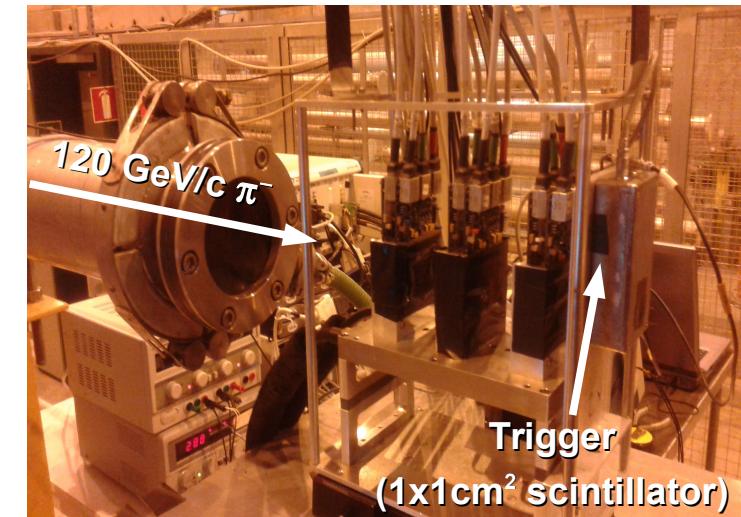
FSBB BT @ CERN-SPS (Oct. 2015)

■ Experimental set-up

- 3 pairs of FSBB planes on T4/H6 (120 GeV/c π^-)
- Particle flux: trigger rate \sim 4, 25 & 100 kHz/cm²
- $T_{\text{coolant}} = 30^\circ\text{C}$

■ Goals: validation of full r.o. chain

- Measure ε_{det} , σ_{sp} & dark rate (R_{dark})
- Rad. Tolerance relevant to ALICE-ITS inner layers
- Impact of operation parameters on performances



FSBB BT @ CERN-SPS (Oct. 2015)

■ Experimental set-up

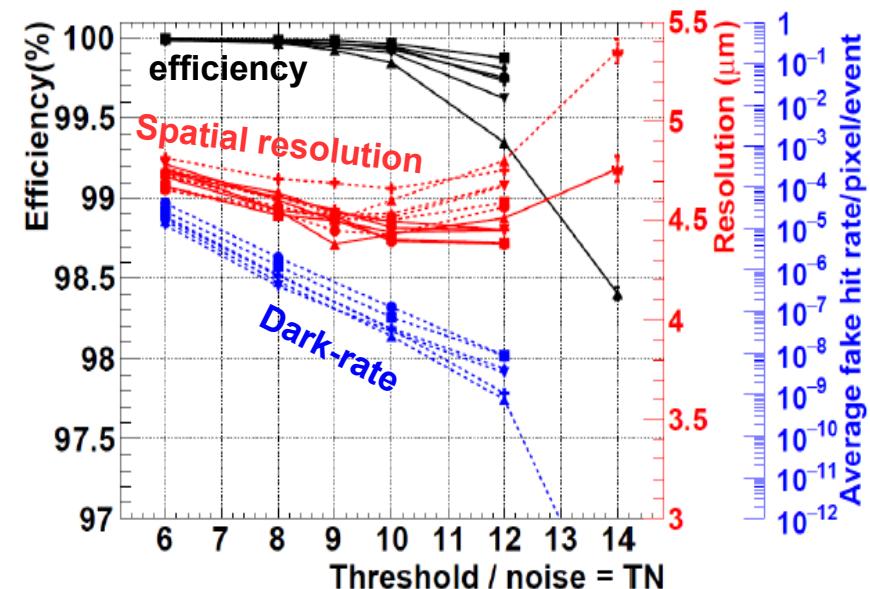
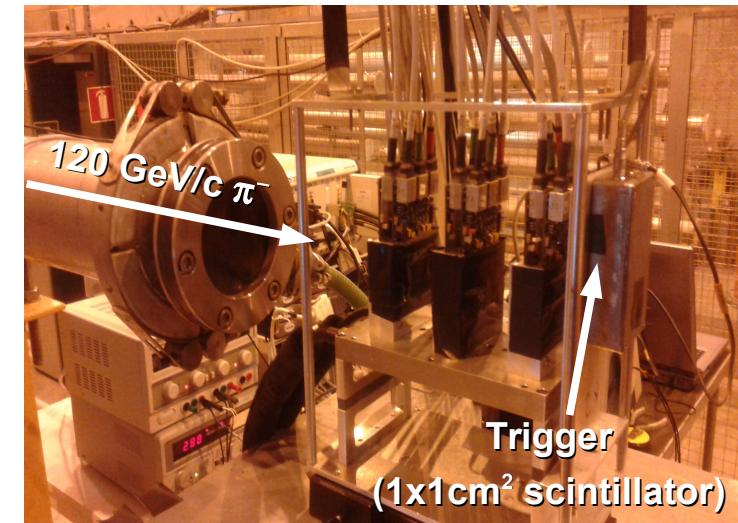
- 3 pairs of FSBB planes on T4/H6 (120 GeV/c π^-)
- Particle flux: trigger rate $\sim 4, 25 \text{ & } 100 \text{ kHz/cm}^2$
- $T_{\text{coolant}} = 30^\circ \text{C}$

■ Goals: validation of full r.o. chain

- Measure ε_{det} , σ_{sp} & dark rate (R_{dark})
- Rad. Tolerance relevant to ALICE-ITS inner layers
- Impact of operation parameters on performances

■ Measured performances

- Excellent performances for all sensors
 - $\varepsilon_{\text{det}} > 99\%$, $R_{\text{dark}} < 10^{-6}$ for Thr/Noise < 12 & moderate pixel masking (10^{-3})
 - $\sigma_{\text{sp}} < 5 \mu\text{m}$
- Validation for doses relevant to ITS-in
 $1.6 \text{ MRad} \oplus 1.0 \times 10^{13} n_{\text{eq}}/\text{cm}^2$



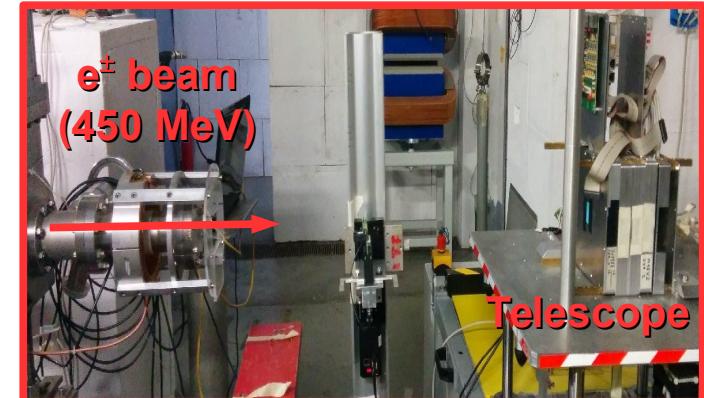
MIMOSA-22THRb BT @ Frascati BTF (May 2015)

■ Experimental set-up

- **Telescope:** 2xMi28 ($\sigma_{\text{sp}} \sim 3.5 \mu\text{m}$) & 4xMi18 ($\sigma_{\text{sp}} \sim 1-2 \mu\text{m}$) sensors thinned to 50 μm
- **Trigger:** beam injection (few ns) \Rightarrow synchronisation

■ Goals: validation of large pixel design

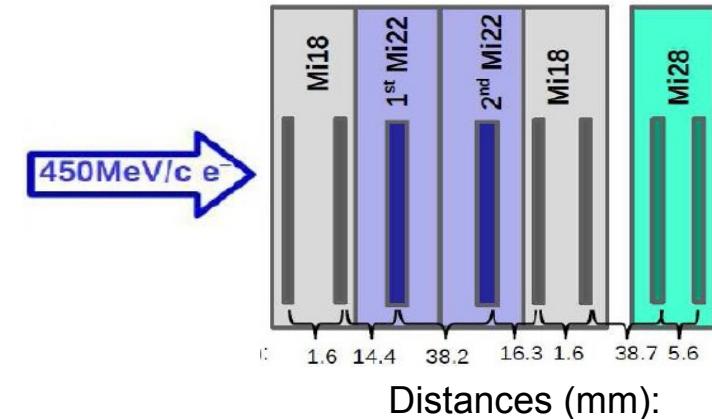
- Measure ε_{det} , σ_{sp} & dark rate (R_{dark})
- Rad. Tolerance relevant to ALICE-ITS outer layers



MIMOSA-22THRb BT @ Frascati BTF (May 2015)

■ Experimental set-up

- **Telescope:** 2xMi28 ($\sigma_{sp} \sim 3.5 \mu m$) & 4xMi18 ($\sigma_{sp} \sim 1-2 \mu m$) sensors thinned to 50 μm
- **Trigger:** beam injection (few ns) \Rightarrow synchronisation

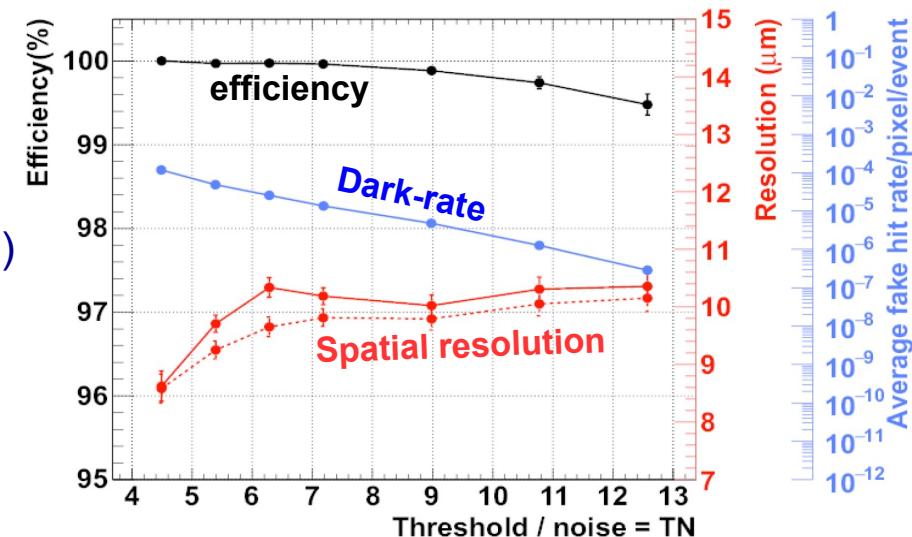


■ Goals: validation of large pixel design

- Measure ε_{det} , σ_{sp} & dark rate (R_{dark})
- Rad. Tolerance relevant to ALICE-ITS outer layers

■ Measured performances

- Excellent detection performances
 - $\varepsilon_{det} > 99\%$ & $\sigma_{sp} \lesssim 10 \mu m$ (as expected)
- Validation for doses relevant to ITS-out
 $150 \text{ kRad} \oplus 1.5 \times 10^{12} n_{eq}/cm^2$

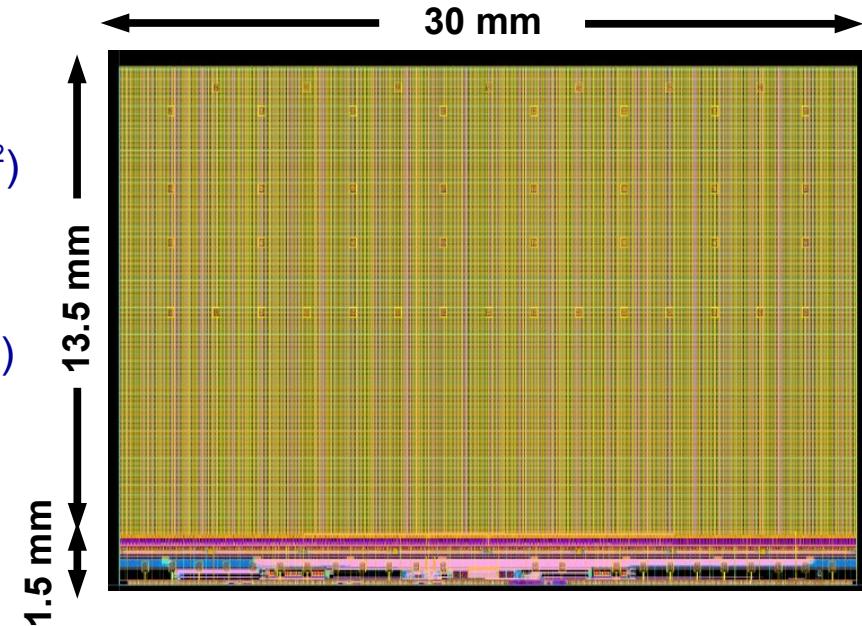


Final Sensor: MISTRAL-O

Combination of 4 FSBB-M0 with MIMOSA-22THRb7 pixels

Main characteristics

- 832 columns of 208 (160k) pixels ($36 \times 65 \mu\text{m}^2$)
- In-pixel Pre-Amp & clamping (fringe capa)
- End-of-column signal discriminator
- Discriminator's output 2D sparsification (SUZE)
- Pixel masking circuitry
- Fully programmable control circuitry
- Pads over pixel array



Typical performances (based on FSBB-M0 & MIMOSA-22THRb tests)

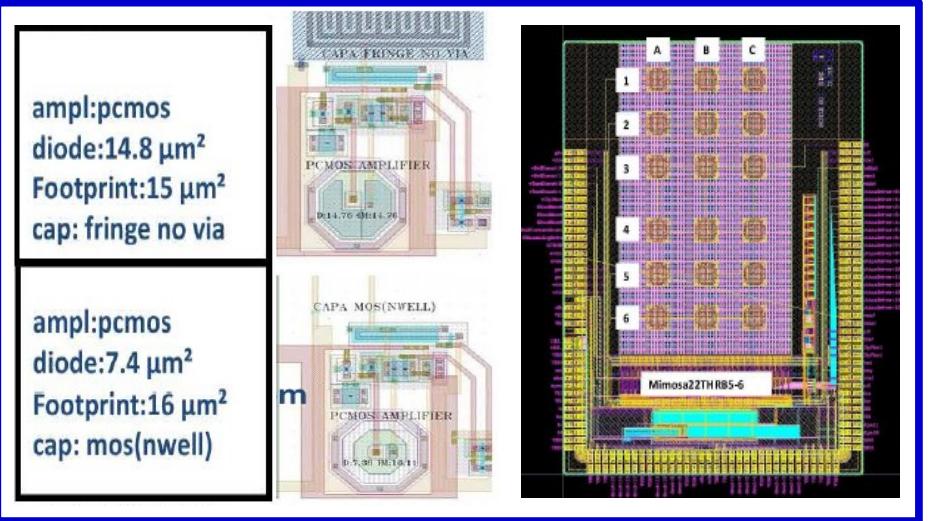
- $t_{r.o.} \sim 20 \mu\text{s}$; $\sigma_{sp} \sim 10 \mu\text{m}$; Power consumption $\lesssim 80 \text{ mW/cm}^2$
- Rad. Hardness $\gtrsim 150 \text{ kRad} \oplus 1.5 \times 10^{12} n_{eq}/\text{cm}^2$ @ $T \gtrsim 30^\circ\text{C}$

MIMOSA-22THRb6/7: characteristics

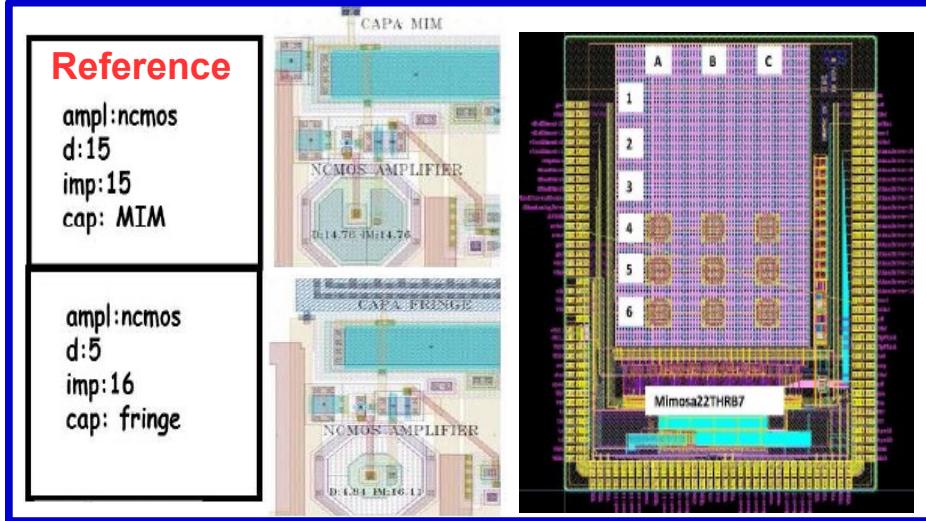
Design features

- 64x64 pixel array (staggered): 56 columns ended with discri. and 8 with analog output
- Readout $\approx 5\mu\text{s}$ (100MHz clock)
- Epitaxial layer: HR18

Mi22-THRb6: $36 \times 62.5\mu\text{m}^2$



Mi22-THRb7: $39 \times 50.8\mu\text{m}^2$



Purpose of the chip

- Validate pads over pixels
- Validate in-pixel circuitry concentrated on $\approx 3\text{ML} \Rightarrow$ modified clamping capacitor
- Validate large pixel performances w.r.t. TDR requirements on layers 3 – 6

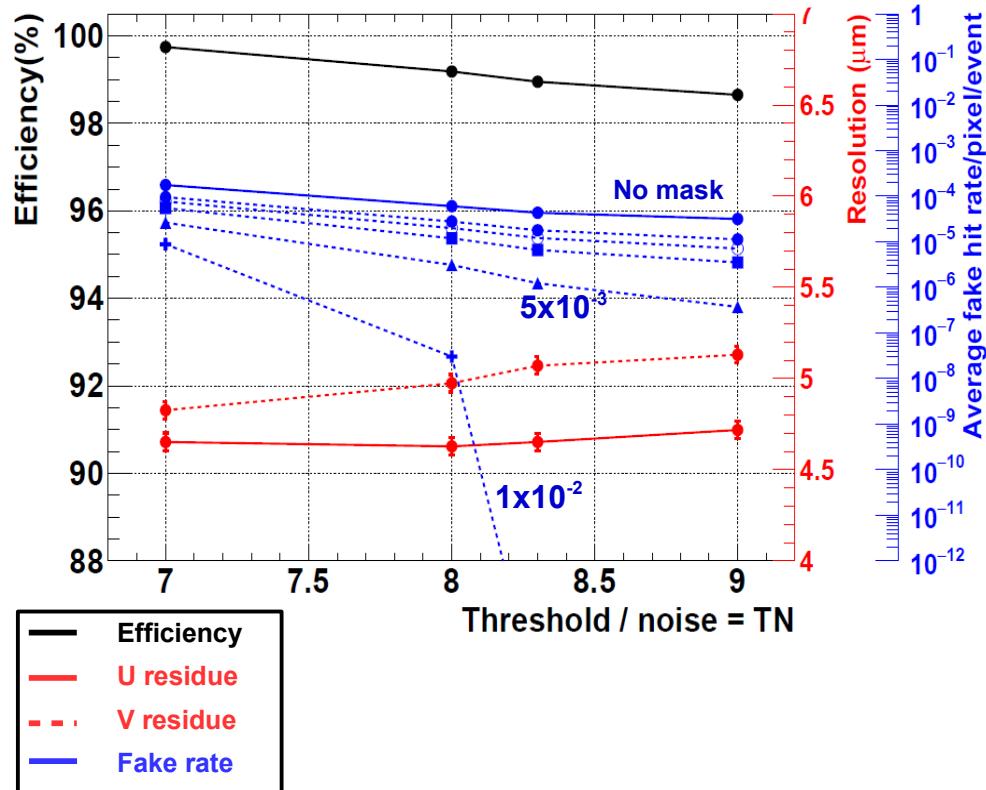
⇒ MISTRAL-O

Main FSBB-M0 detection performances (2/2)

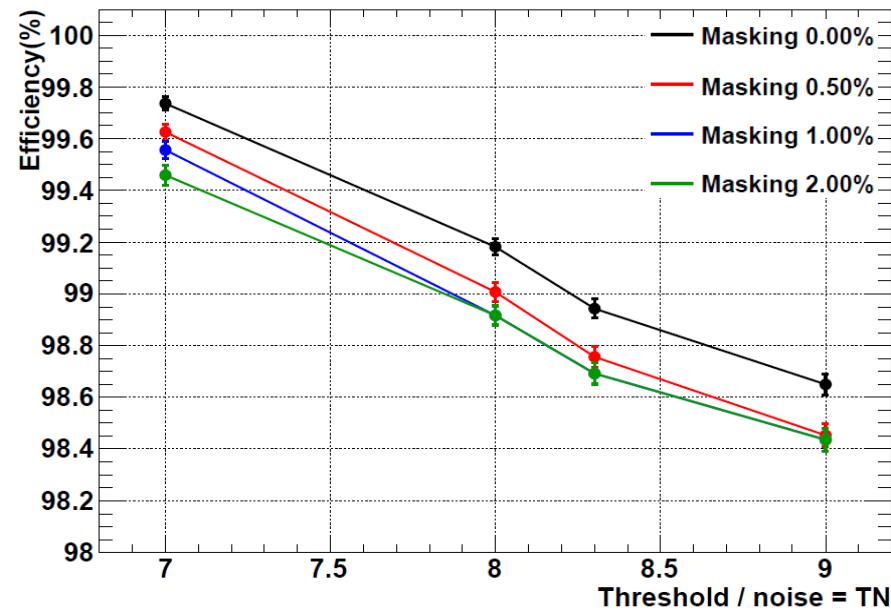
- Study of rad. tolerance @ $T \geq 30$ °C: loads relevant to ALICE-ITS inner layers
 - Load: $1.6 \text{ MRad} \oplus 10^{13} \text{n}_{\text{eq}}/\text{cm}^2$

Diode/Footprint: $9/13.3 \mu\text{m}^2$

ϵ_{det} , σ_{sp} & fake-rate vs Discr. Threshold



ϵ_{det} vs Discr. Threshold vs pixel masking

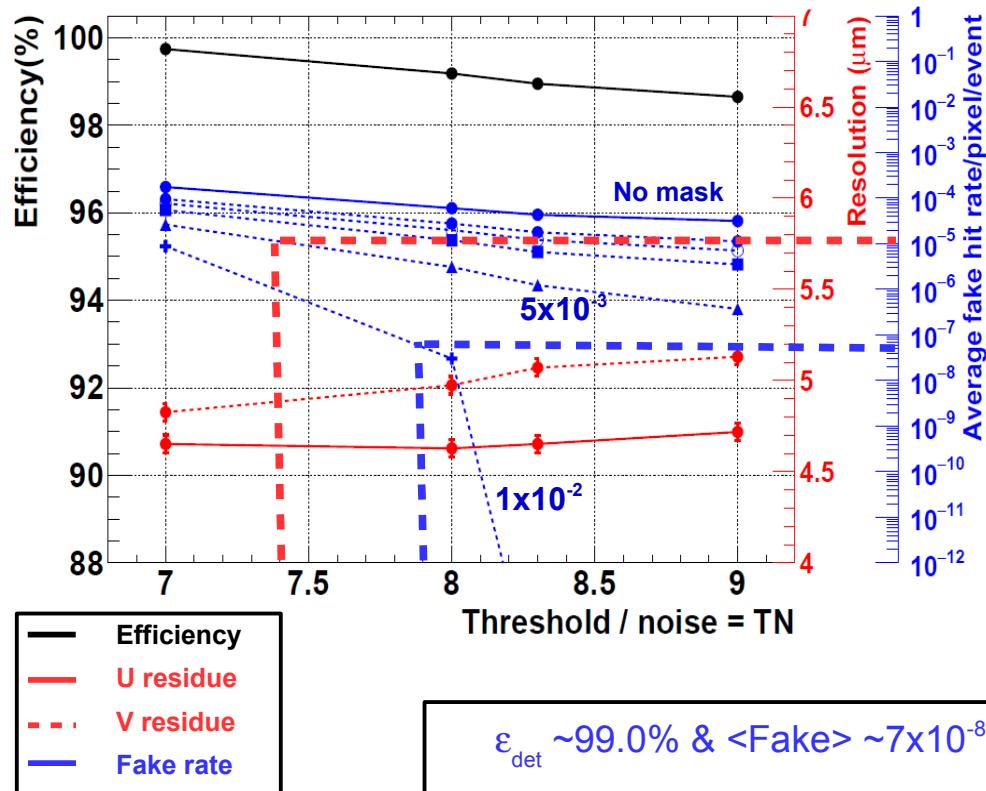


Main FSBB-M0 detection performances (2/2)

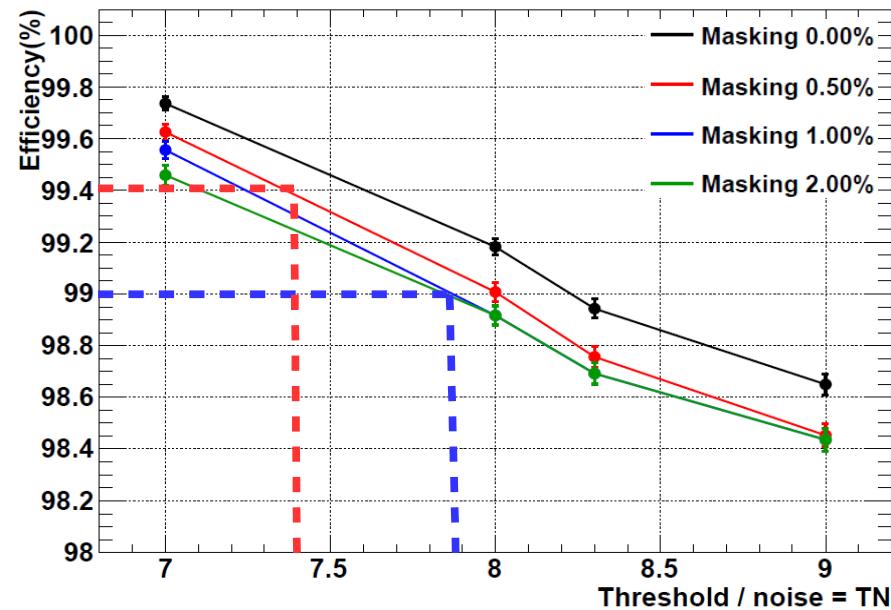
- Study of rad. tolerance @ $T \geq 30$ °C: loads relevant to ALICE-ITS inner layers
 - Load: $1.6 \text{ MRad} \oplus 10^{13} \text{n}_{\text{eq}}/\text{cm}^2$

Diode/Footprint: $9/13.3 \mu\text{m}^2$

ϵ_{det} , σ_{sp} & fake-rate vs Discr. Threshold



ϵ_{det} vs Discr. Threshold vs pixel masking

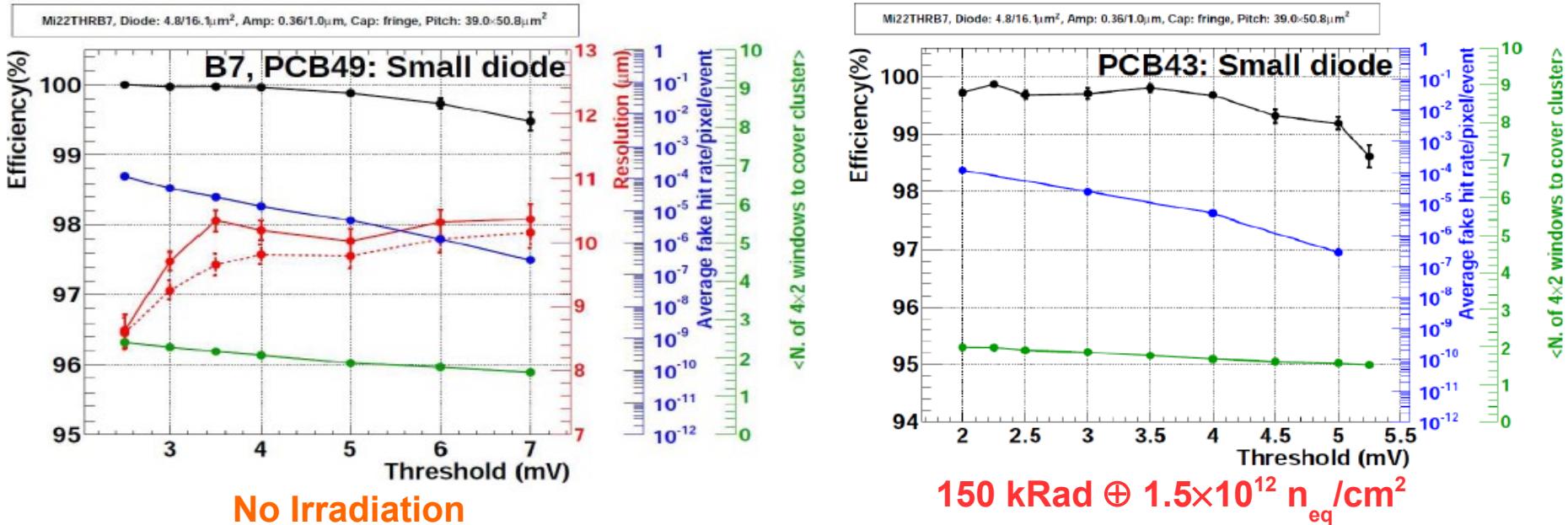


$\epsilon_{\text{det}} \sim 99.0\% \text{ & } \langle \text{Fake} \rangle \sim 7 \times 10^{-8}$ (1.0% masking) @ Thr = $7.9 \times \sigma_{\text{TN}}$

$\epsilon_{\text{det}} \sim 99.4\% \text{ & } \langle \text{Fake} \rangle \sim 1 \times 10^{-5}$ (0.5% masking) @ Thr = $7.4 \times \sigma_{\text{TN}}$

Main MIMOSA-22THRb detection performances

Pixel type	Pixel dim.	Diode/Footprint	Pre-Amp T.	Clamping capa.	Integ. time
MIMOSA-22THRb7	$39 \mu\text{m} \times 50.8 \mu\text{m}$	$5/16 \mu\text{m}^2$	N-MOS	MOS (N-well)	$5 \mu\text{s}$



- Efficiency
- U residue
- - - V residue
- Fake rate
- # Suze Windows

Excellent detection performances

- $\varepsilon_{\text{det}} > 99\%$ & $\sigma_{\text{sp}} \sim 10 \mu\text{m}$ (as expected)
- Good performances for radiation load relevant for outer ALICE-ITS

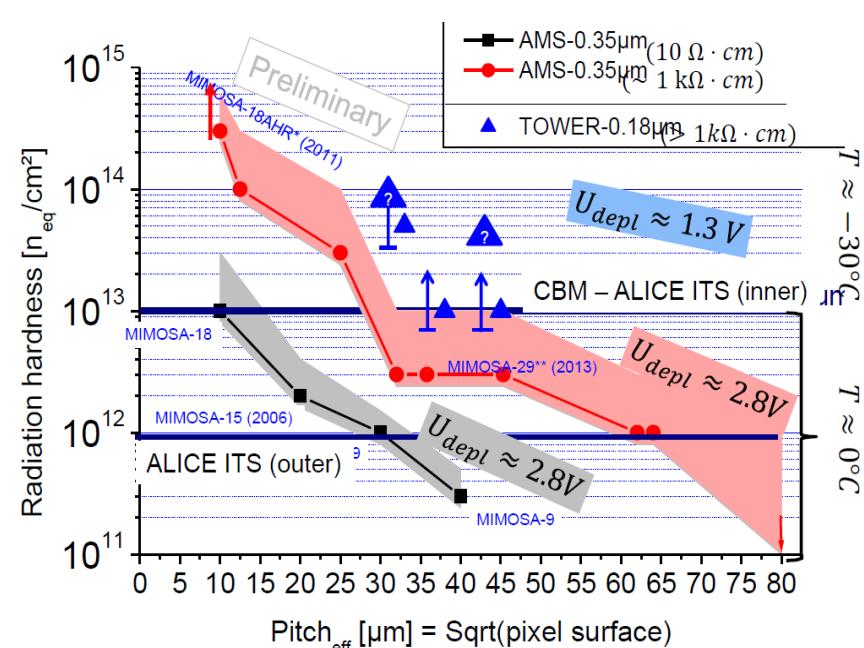
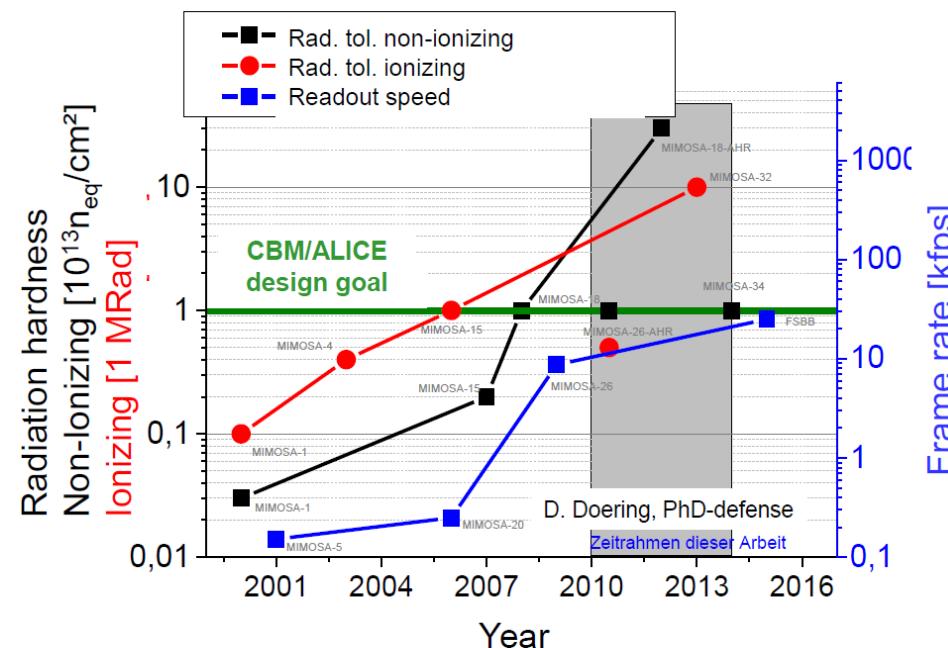
Validation of large pixel design for the outer layers of the ALICE-ITS!

CPS Radiation Tolerance

- 15 years of experience of PICSEL group in developing CPS
- Strong collaboration with ADMOS group at Frankfurt
- r.o. speed evolution
 - Factor of ~ 50 improvement in 15 years of research



- Radiation tolerance
 - Significant improvement with time
 - Validation up to $10 \text{ MRad} \oplus 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$



PIPPER-2 prototype (Tower-Jazz 0.18 μm CIS)

- 128 x 8 square pixels (25 μm pitch)
- Collection system: 1 diode 3, 5 μm Ø, 4 diodes 4 μm Ø
- epi-layer = 18 μm ($> 1 \text{k}\Omega \times \text{cm}$) & CZ = 50 μm ($\sim 700 \Omega \times \text{cm}$)
- TN $\approx 10 - 15 \text{ e}^- \text{ ENC}$ @ 15°C
- Fringe capa for AC-coupling to Pre-Amp, V_{Bias} up to 45 V

I_{leak} vs V_{Bias} & breakdown V for MIM & Fringe

	MIM	Fringe
Leakage@10V	21 pA	2.1 fA
Leakage@20V	42 nA	3.1 fA
Leakage@30V	42 μA	5.6 fA
Breakdown Voltage	~30 V	> 40V

