Monolithic Active CMOS Pixel Sensors: ASICs with Integrated High Precision Particle Detection

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LHCb Workshop / LAPP / 22 mars 2018

Contents

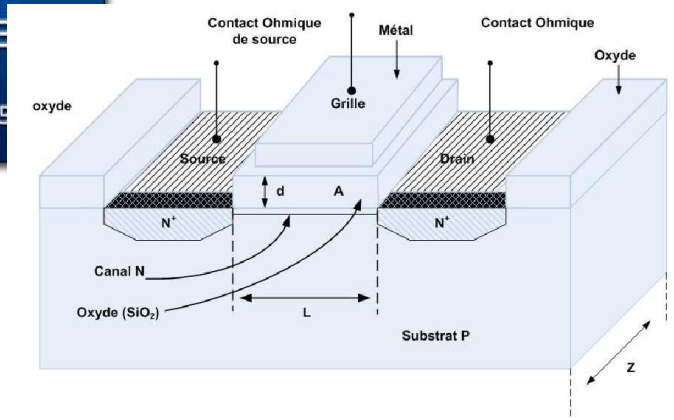
- *Introduction on Monolithic* **CMOS Pixel Sensor (CPS)**
- *On-going R&D relevant for high luminosity pp collisions*
- *Remarks/Questions addressing the specific case of the LHCb tracker*
- *Summary & Outlook*

SOURCES : Talks at TWEPP-17, Hiroshima-17, CERN Workshop on Instrument. Techno. (16.03.18), LHCb meeting (16.03.18)

SLIDES : Ch. Parkes, M. Needham, W. Snoeys, T. Kugathasan, D. Wiedner, H. Pernegger, ...

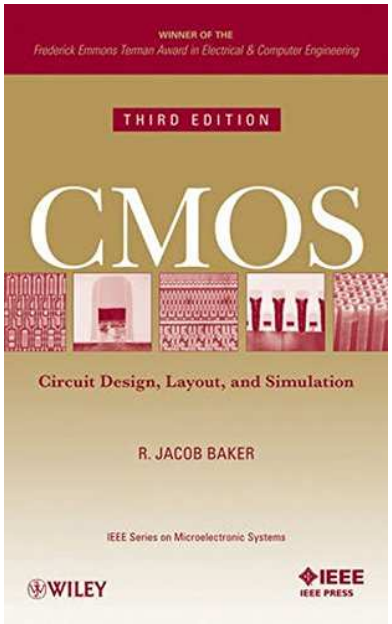
Origin of CMOS Pixel Sensors

- **CMOS Pixel Sensors are derived from ASICS**
  - **≡ Application-Specific Integrated Circuits**
    - ASICs populate every day's life: e.g. credit cards, PC, cell-phones, cars, washing machines, ...
      ⇛ industrial mass production item
      (world revenue ∼ several 100 billions USD/year)
    - key element: MOSFET transistors & conductive traces printed in **Silicon** (usually)



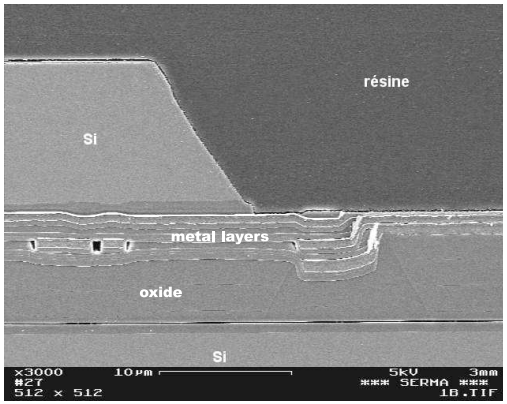
Substrat type P pour MOSFET canal N
Substrat type N pour MOSFET canal P

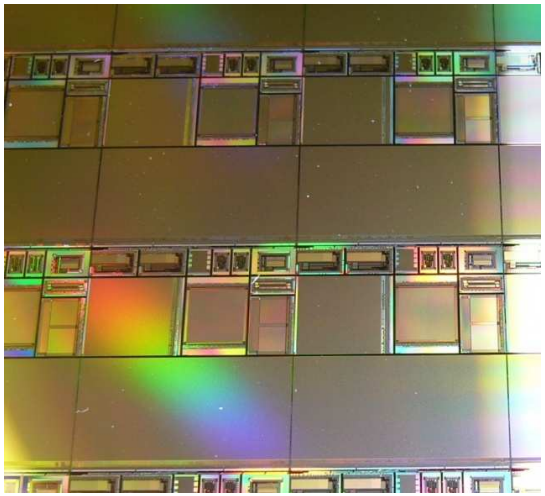
- **C.M.O.S. ≡ Complementary Metal Oxyde Semi-conductor**
  - widespread technology for constructing integrated circuits used in microprocessors, microcontrollers, memories, etc.

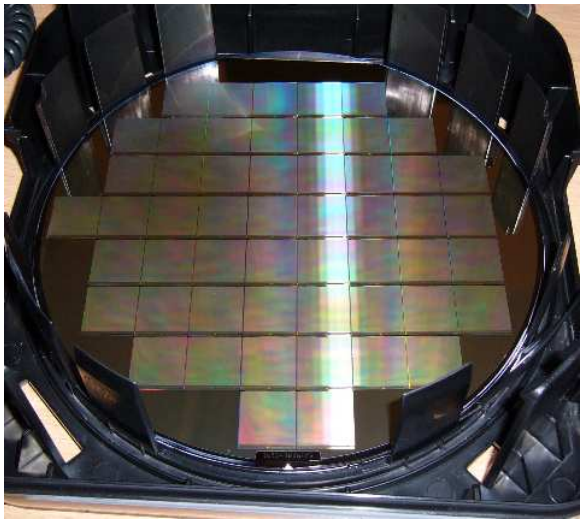


CMOS Technology

- **CMOS fabrication mode :**
  - μcircuit lithography on a substrate sliced from a crystal ingot (or *boule*)
  - proceeds through reticules (e.g. 21x23 or 25x32 mm^2) organised in wafers



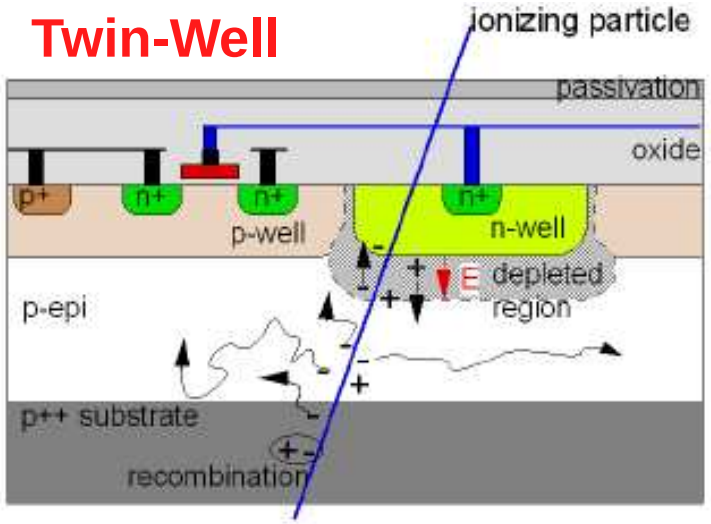




CMOS Pixel Sensors: Main Features

- **Prominent features of CMOS pixel sensors :**
  - high granularity $\Rightarrow$ excellent (micronic) spatial resolution
  - signal generated in (very) thin (15-40 μm) epitaxial layer
    - $\hookrightarrow$ resistivity may be $\gg$ 1 k$\Omega \cdot cm$
  - signal processing μ-circuits integrated on sensor substrate
    - $\Rightarrow$ impact on downstream electronics and syst. integration ($\Rightarrow$ cost)

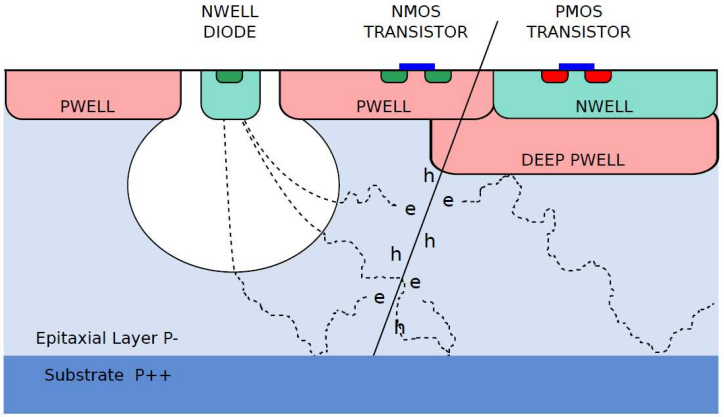
Twin-Well



- **CMOS pixel sensor technology has the highest potential :**

  $\Rightarrow$ R&D largely consists in trying to exploit potential at best with accessible industrial processes

  $\hookrightarrow$ manufacturing param. not optimised for particle detection: wafer/EPI characteristics, feature size, N(ML), ...



Quadruple-Well

- **Read-out architectures :**
  - 1st generation : rolling shutter with analog read-out (twin-well)
  - 2nd generation : rolling shutter with // read-out & end-of-column discrimination (twin-well)
  - 3rd generation : data driven read-out with in-pixel discrimination (synchronous/asynchronous)

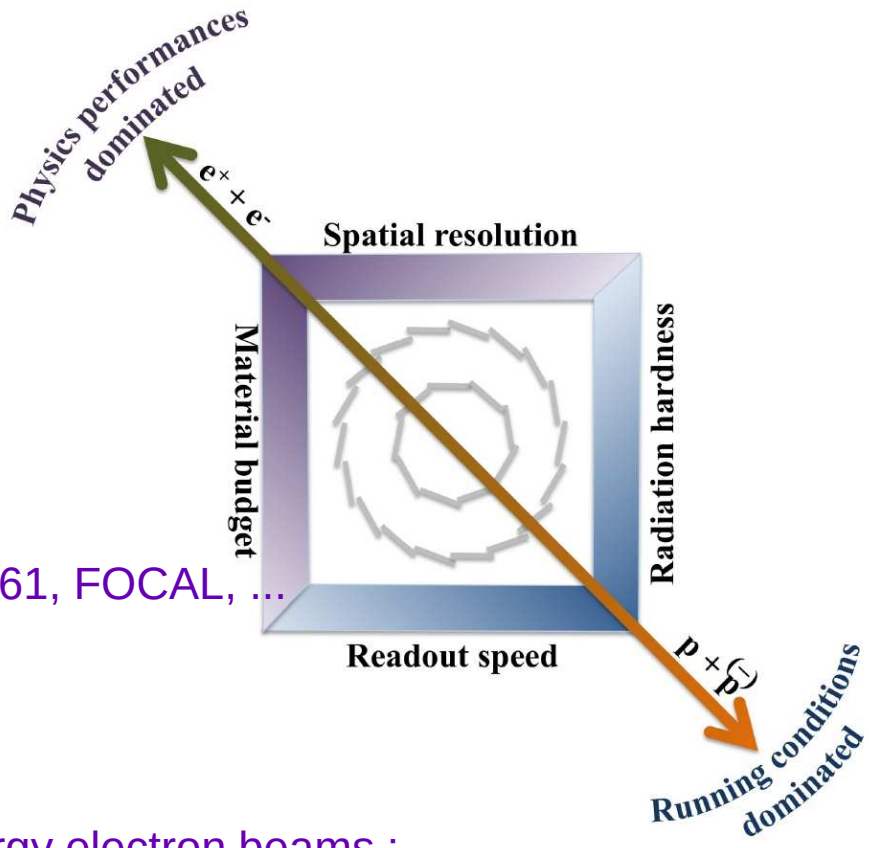
Motivation for Using CMOS Pixel Sensors

- **CPS development triggered by need of**
  very high granularity & low material budget

- **Applications exhibit(ed) much milder running conditions than pp/LHC**

⇒ **Relaxed speed & radiation tolerance specifications**

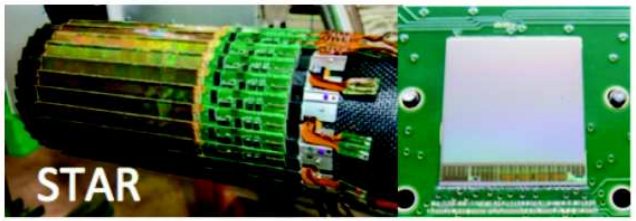
Quadrature of the Vertex Detector



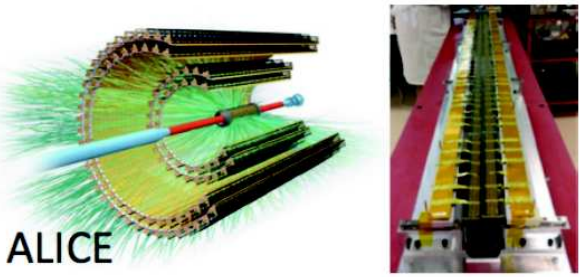
- **Increasing panel of existing, foreseen or potential application domains :**
  - **Heavy Ion Collisions :** STAR-PXL, ALICE-ITS, CBM-MVD, NA61, FOCAL, ...
  - **e^+e^- collisions :** ILC, BES-3, ...
  - **Non-collider experiments :** FIRST, NA63, Mu3e, PANDA, ...
  - **High precision beam telescopes** adapted to medium/low energy electron beams :
    ↪ few μm resolution achievable on DUT with EUDET-BT (DESY), **BTF-BT (Frascati)**, ...
  - **RECENTLY: high rate pp collisions** ⇒ addressing the pb of speed and radiation hardness

Evolution of Radiation Tolerance and Hit Rate Capability

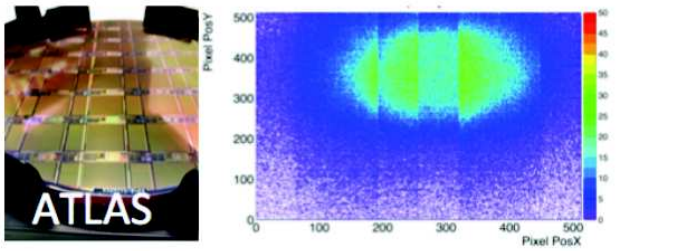
	RHIC STAR	LHC - ALICE ITS	CLIC	HL-LHC Outer Pixel	HL-LHC Inner Pixel	FCC pp
NIEL [n_{eq}/cm^2]	10^{12}	10^{13}	$<10^{12}$	10^{15}	10^{16}	10^{15}-10^{17}
TID	0.2Mrad	<3Mrad	<1Mrad	80 Mrad	2x500Mrad	>1Grad
Hit rate [MHz/cm^2]	0.4	10	<0.3	100-200	2000	200-20000



Ultimate Sensor



Alpide Sensor



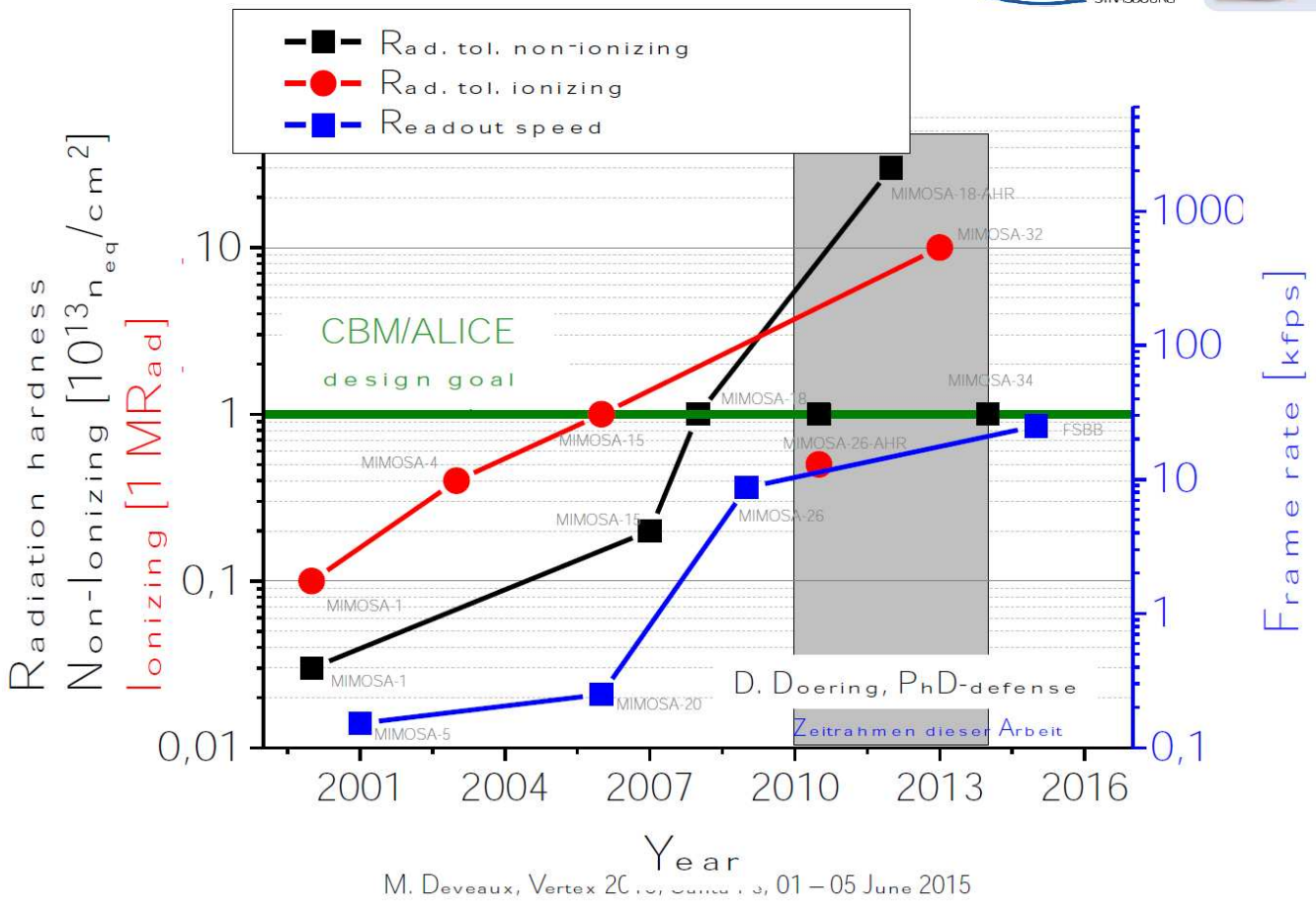
MALTA & Monopix & AtlasPix Sensor

- **Evolution of process characteristics:**
  - starting material: epitaxy thickness and resistivity
  - doping profile: from twin-well to quadruple well with burried N-doped brane
  - feature size and nb of Metal. Layers
- **Today's accessible CMOS processes allow considering pp collisions at LHC**
  - ↪ **market drives CMOS technology in a direction complying with HEP needs**

Radiation Tolerance Achieved by 2013 (AMS-0.35 process)

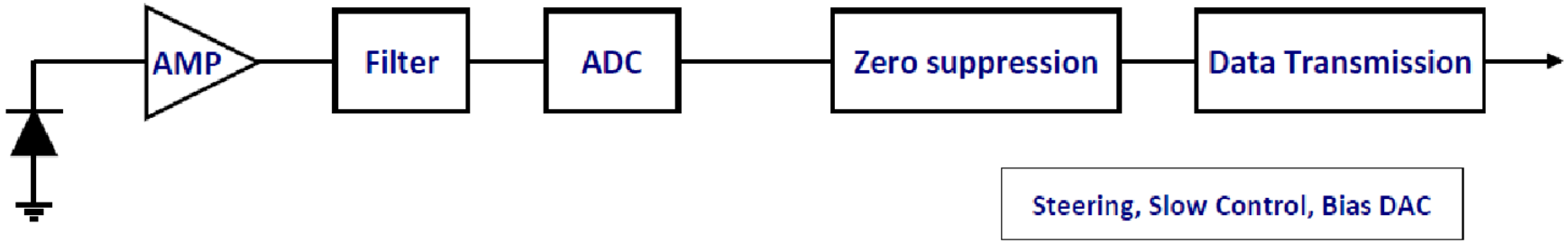
Material budget: 0.05% X_0

Spatial resolution: ~ 3-5 µm



- **Reminder:** radiation tolerance may be enhanced in various ways: sensing node density (≡ pixel pitch), operating temperature, epitaxy resistivity & depletion, signal processing speed, etc.

Main Components of the Signal Processing Chain



- **Typical components of read-out chain :**
  - **AMP :** In-pixel low noise pre-amplifier
  - **Filter :** In-pixel filter
  - **ADC :** Analog-to-Digital Conversion : 1-bit ≡ discriminator
  - **Zero suppression :** Only hit pixel information is retained and transfered
  - **Data transmission :** O(Gbits/s) link implemented on sensor periphery
- **Read-Out in general data-driven:**
  - **Synchronous:** clock distributed over pixel array ⇛ Power consumption !
  - **Asynchronous :** no clock running over pixel array ⇛ increased design complexity ?
- **Trade-off between conflicting parametres:**

  ↪ pixel dimensions (precision, sensing node density), speed and power, ...

  ↪ exploit relaxed constraints to privilege the most demanding ones !
- **Thin sensitive volume ⇛ small signal ⇛ VERY LOW NOISE signal processing circuitry**

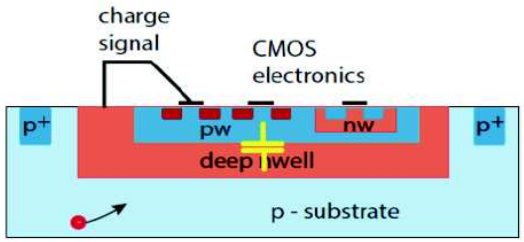
Various In-Pixel Circuitry Approaches

- **Monolithic CPS integrate the complete signal creation and processing chain :**

  ⇒ **SPECIFIC GLOBAL OPTIMISATION** for each dedicated application

- **Sensing Node ≡ key element**

• Large electrodes

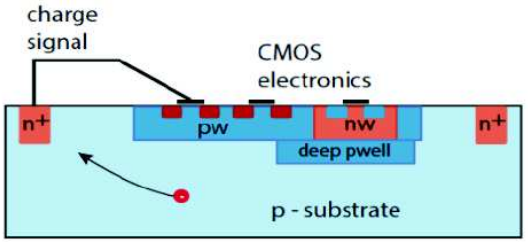


+ μ-circuits inside coll. well
+ shortened drift distance
+ extended lateral depletion
- sensing node capacitance

⇒ ENC, gain, signal rise, power

- risk of X-talks betw. digital & analog μC

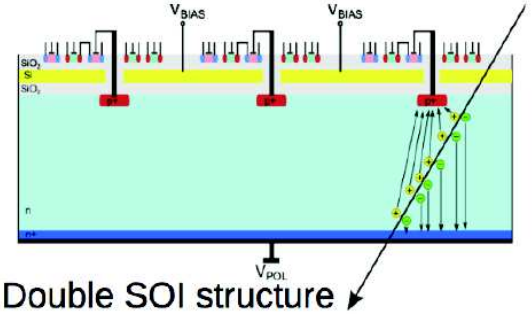
• Small electrodes



+ μ-circuits outside coll. well
+ small capa. ⇒ high SNR, fast signal
+ separate ana. & digi. μcircuits
- sizeable drift distance

⇒ calls for process modif. (rad. tol.)

• "Burried" electrodes (SOI)

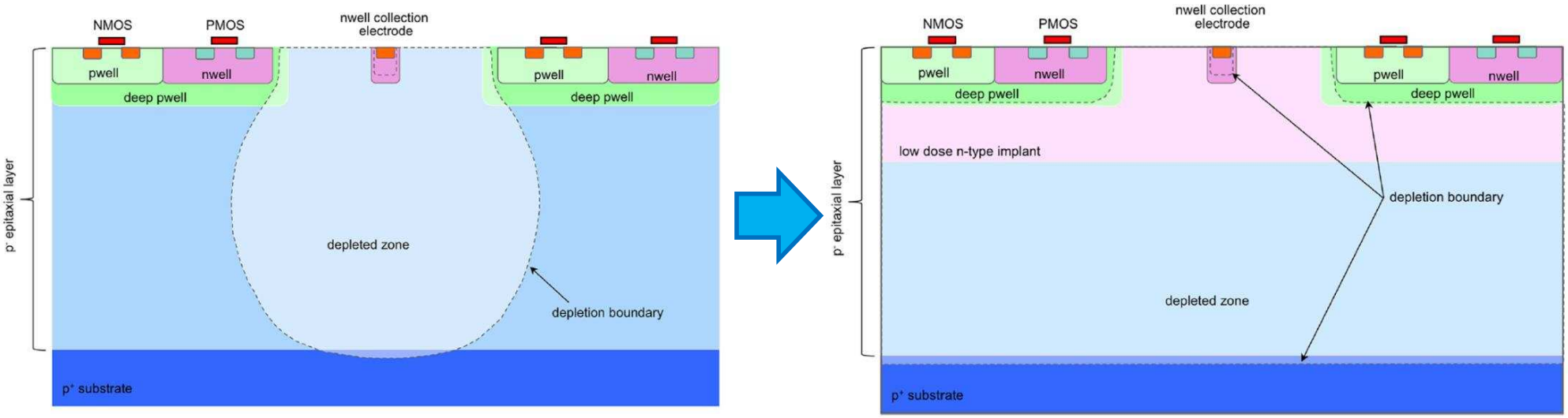


+ μ-circuit & sensing node in separate layers
+ adaptable sensitive vol.

⇒ special design to overcome radiation induced charge build up at interfaces

TowerJazz 180 nm Modified Process

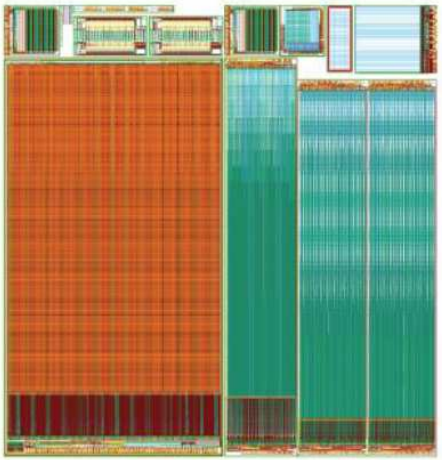
- Modified process developed in collaboration of CERN with TJ foundry, originally developed in context of ALICE ITS
- Adding a planar n-type layer significantly improves depletion under deep PWELL
  - ✓ Increased depletion volume → fast charge collection by drift
  - ✓ better time resolution reduced probability of charge trapping (radiation hardness)
  - ✓ Possibility to fully deplete sensing volume with no significant circuit or layout changes



Granular Monolithic CPS for LHC pp Running Conditions

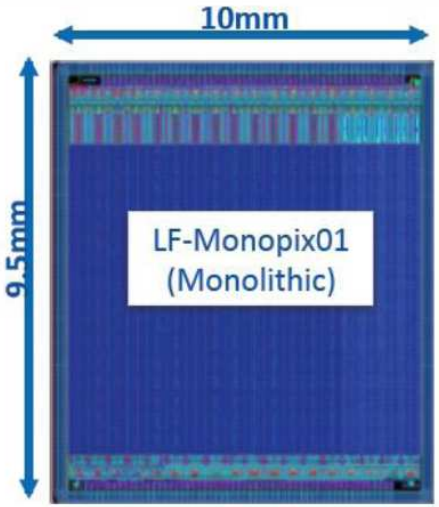
Chip name	Technology	CE Size*	Pixel size [µm^2]	R/O architecture	Staust
aH18	AMS 180nm	Large	56 × 56	Asynchronous	Measurements
Malta	TowerJazz 180nm	Small	36 × 36	Asynchronous	Submitted
TJ Monopix		Small	36 × 40	Synchronous	
LF Monopix	LFoundry 150 nm	Large	50 × 250	Synchronous	Measurements
Coolpix		Large	50 × 250	Synchronous	
LF2		Large	50 × 50	Synchronous	

* CE Size = Collection Electrode Size



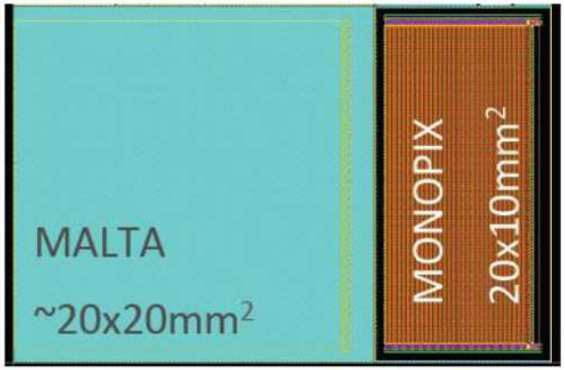
ATLAS Pix & MuPix

AMS 180 nm



MONOPIX, LF2 & COOLPIX

Lfoundry 150 nm



MONOPIX & MALTA

TowerJazz 180 nm

ATLAS Inner Tracker Upgrade Phase 2

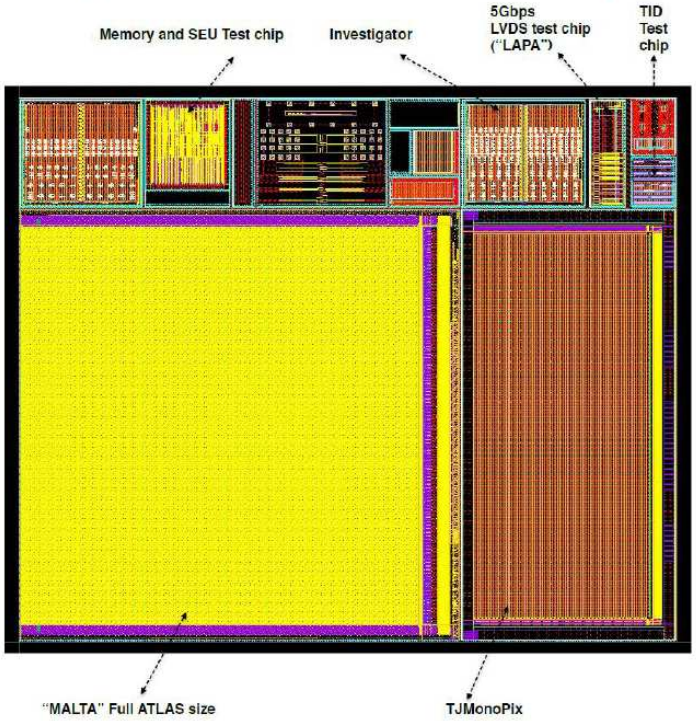
Specifications for the ATLAS Inner Tracker Upgrade Phase 2 (HL-LHC)

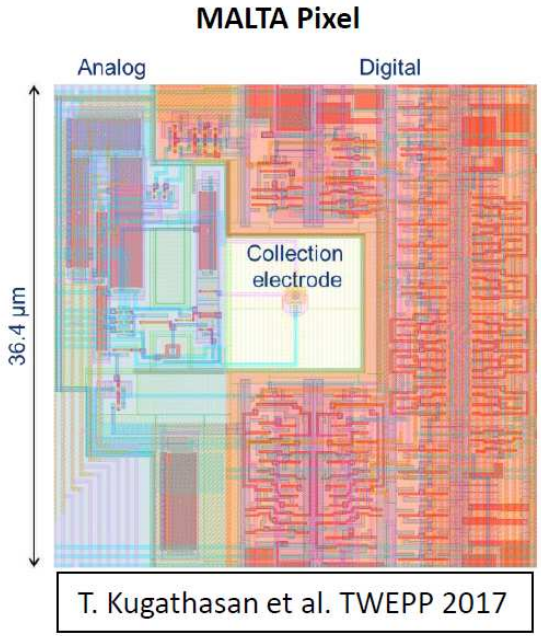
	ALICE-LHC	ATLAS-HL-LHC	
		Outer	Inner
Required Time Res. [ns]	20 000	**25**	
Particle Rate [kHz/mm^2]	10	**1000**	10 000
Fluence [n_{eq}/cm^2]	>10^{13}	**10^{15}**	10^{16}
Ion. Dose [Mrad]	0.7	**50**	1000

- ✓ Time resolution: fast collection by drift (<< 25 ns) ➔ larger depletion
- ✓ High particle rate: short dead time (< 1 us)
- ✓ Tolerance to non-ionizing radiation (displacement damage):
  fast collection by drift to decrease signal charge trapping probability ➔ larger depletion
- ✓ High Q/C for power optimization:
  - High Q : less charge sharing (small cluster) ➔ larger depletion
  - High Q : less charge sharing (small cluster) ➔ larger depletion

Large CPS Fabricated Recently for the ATLAS Inner Tracker

- Design of two full-scale demonstrators to match ATLAS specifications for outer pixel layers :MALTA & TJ-Monopix





T. Kugathasan et al. TWEPP 2017

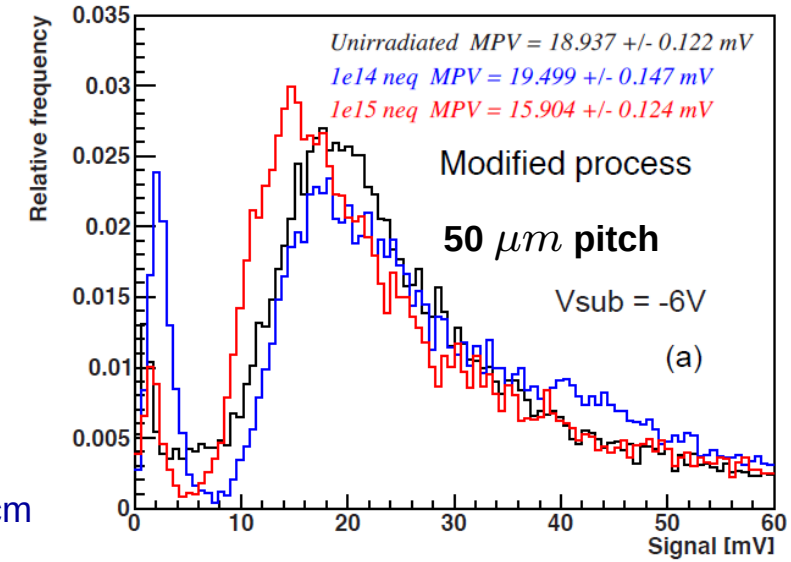
- **MALTA**
  Asynchronous readout architecture to reduce digital power consumption and increase hit rate capability in the matrix.
  No clock distribution over the pixel matrix - (power reduction)

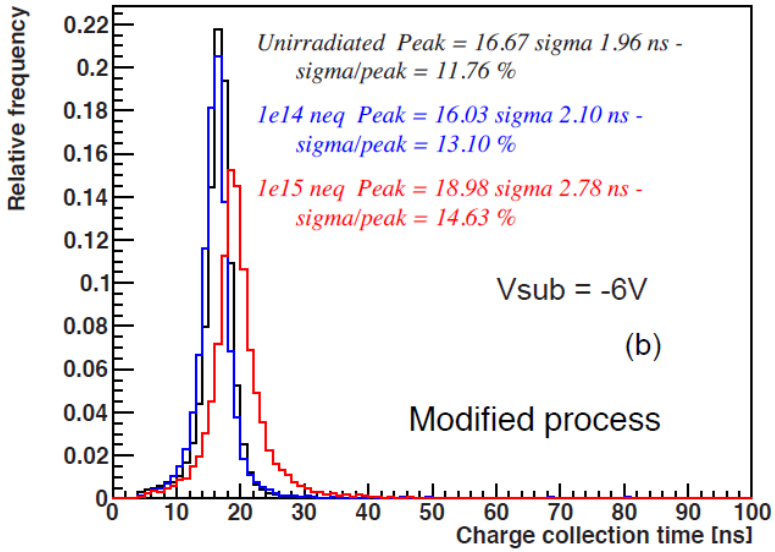
  ? Dead time ?

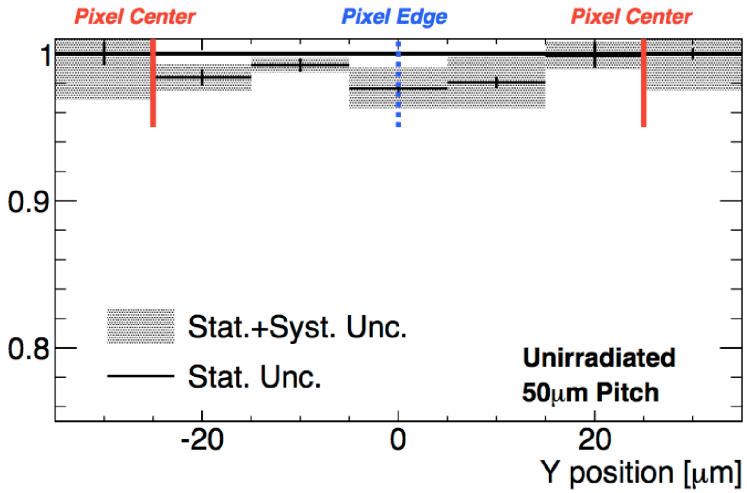
- **TJ-Monopix**
  Synchronous readout architecture. Uses the well-established column drain readout architecture (experience from LF-Monopix design)

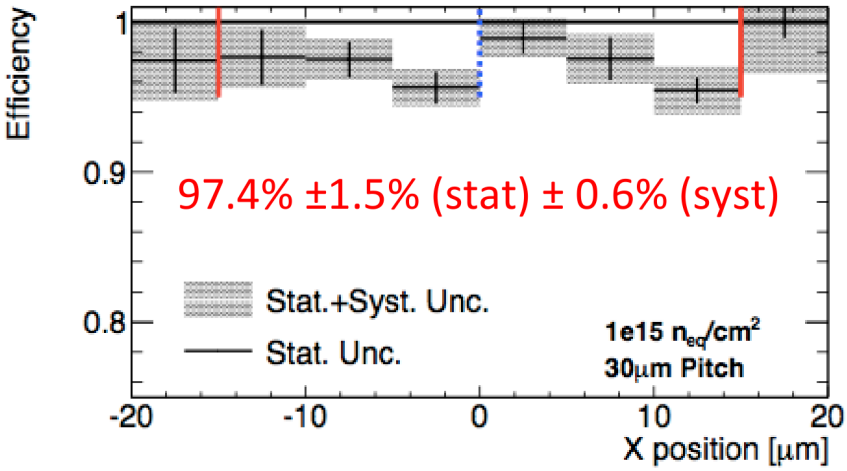
Test Results of Investigator Pixel Array Prototype

- **Investigator prototype: explores impact of sensing node param.**
  (H. Pernegger et al., JINST 12 P06008)
  - process: Tower-Jazz 180 nm standard & modified
  - epi: 25μm thick, $\rho \gg 1$ kΩ·cm
  - square pixel pitch: 25, 30, 50 μm
  - sensing node $\oslash$: 3 μm
  - spacing: 3 - 18 μm
  - fluence: 10^{14} n_{eq}/cm^2 & 10^{15} n_{eq}/cm^2,
  - T_{op} = - 15°C
  - response to Sr^{90} source (top) and 180 GeV pions (bottom)



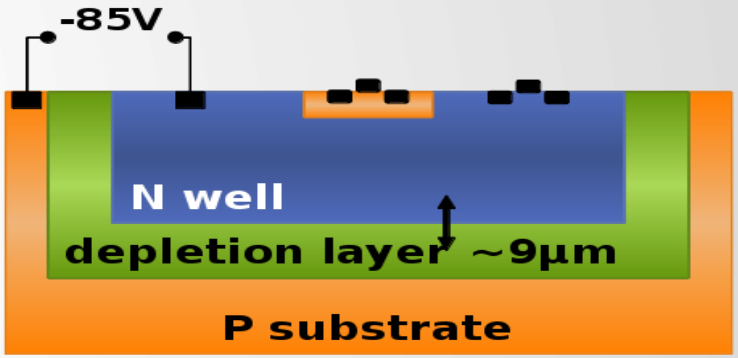




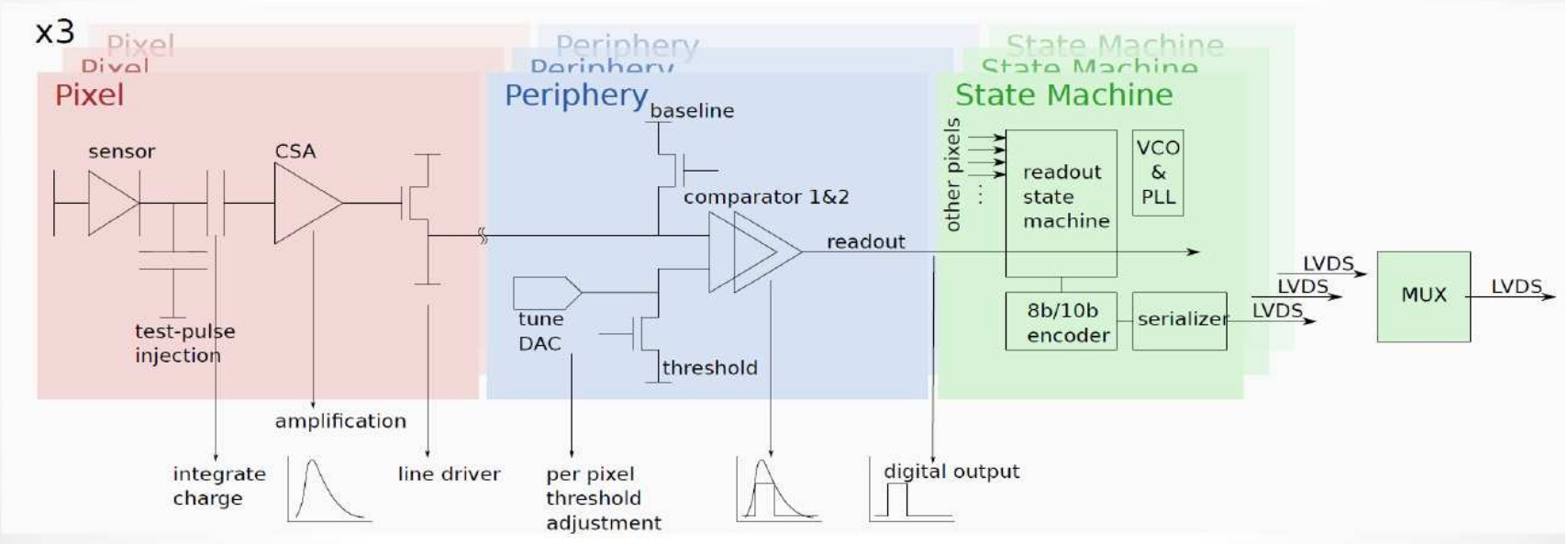


High-Voltage Monolithic CMOS Pixel Sensor

- High Voltage Monolithic Active Pixel Sensors
- HV-CMOS technology
- N-well in p-substrate
- Reversely biased ~85V
  - Depletion layer
  - Charge collection via drift
    - ➢ Fast <1 ns charge collection
  - Thinning to < 50 µm possible
- Integrated readout electronics



by Ivan Perić
I. Perić, A novel monolithic pixelated particle detector implemented in high-voltage CMOS technology Nucl.Instrum.Meth., 2007, A582, 876



HV-CMOS: Test Results of MuPix-7 and -8

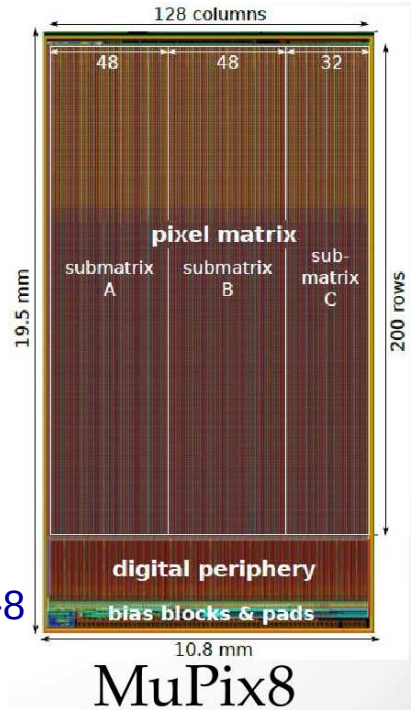
- **First large scale sensors :**

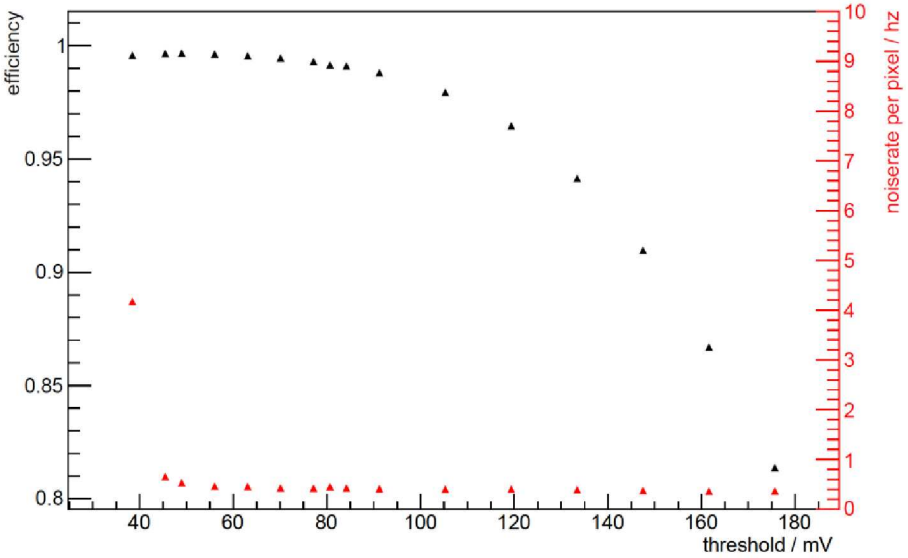
  MuPix-7 and MuPix-8:

  - process: AMS-H18
  - triple well, no epitaxy
  - thinned to 50 μm
  - light doping substrate:

    $\rho \sim$ 20/80 Ω·cm for MuPix-7/-8
  - depletion depth: $\simeq$ 9/15 μm for MuPix-7/-8
  - pixels : 80 x 81 μm^2
  - fluence: 1.5·10^{15}p/cm^2 (CERN-PS)
  - $T_{op} \sim 10^{\circ}$C ????
  - response to 4 GeV e^+ (DESY)
  - non-ion. radiation tolerance

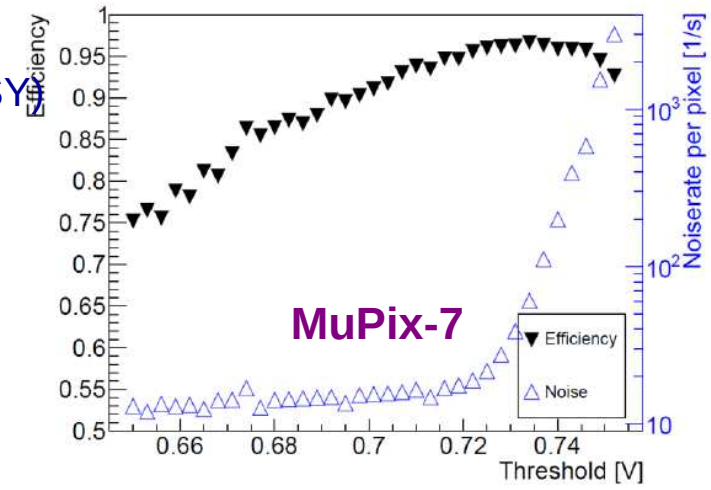
    after 1 yr of anealing

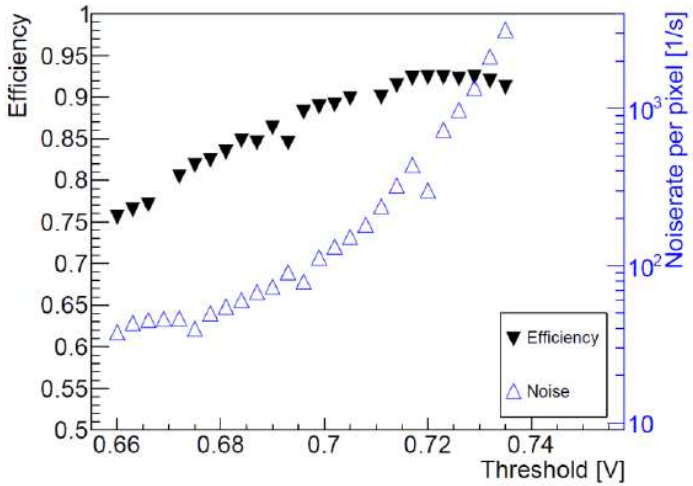




Non irradiated

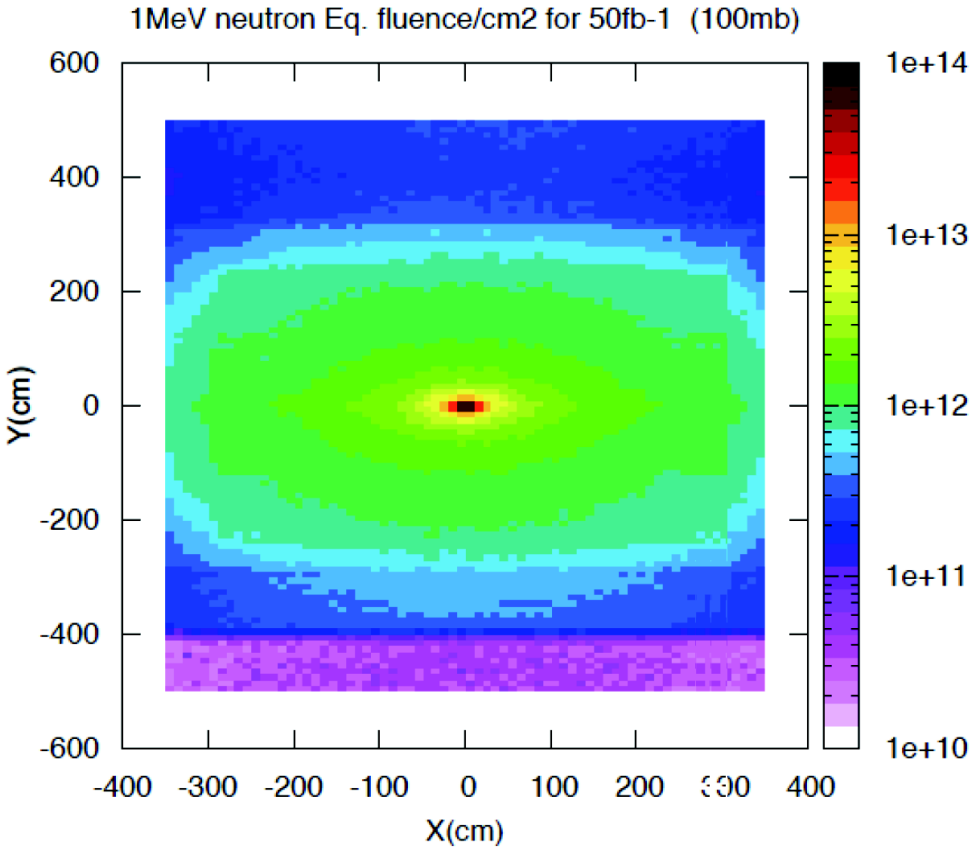
PS proton irradiated 1.5 × 10^{15} p/cm^2



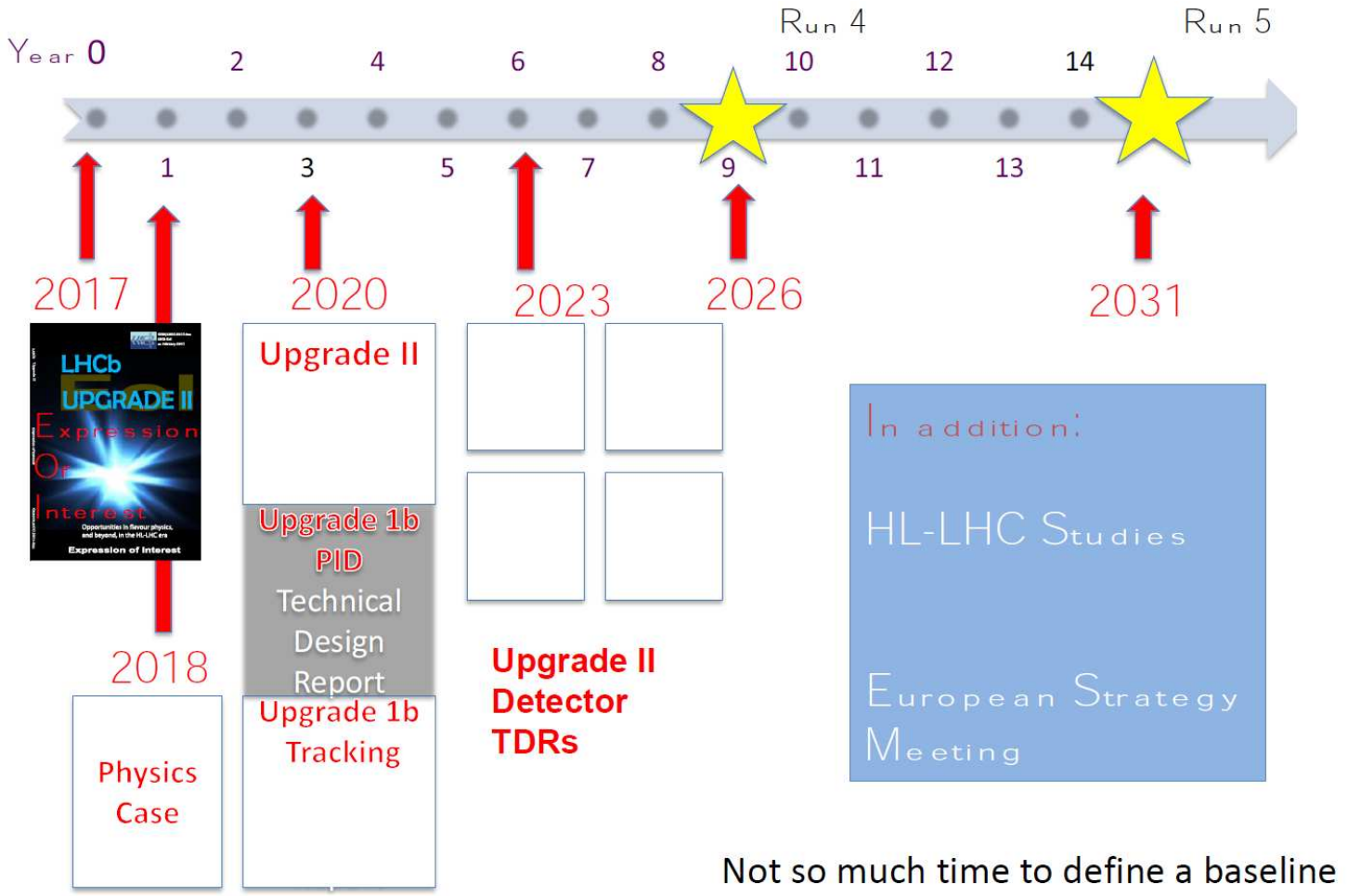


LHCb Tracker: Non-Uniform Radiation Load over Detection Area

- **Smallest radii:**
  - radiation hardness is a priority
  - ATLAS oriented CPS may be appropriate
- **Medium and Large radii:**
  - radiation hardness is much less demanding
  - how to exploit this relaxed requirement ?
  - power saving becomes the priority:
    - pitch $> 50\ \mu m$ complying with good det. eff.
      (small pixels may be grouped in larger super-pixels)
    - reduce in-pixel current ?
    - etc.



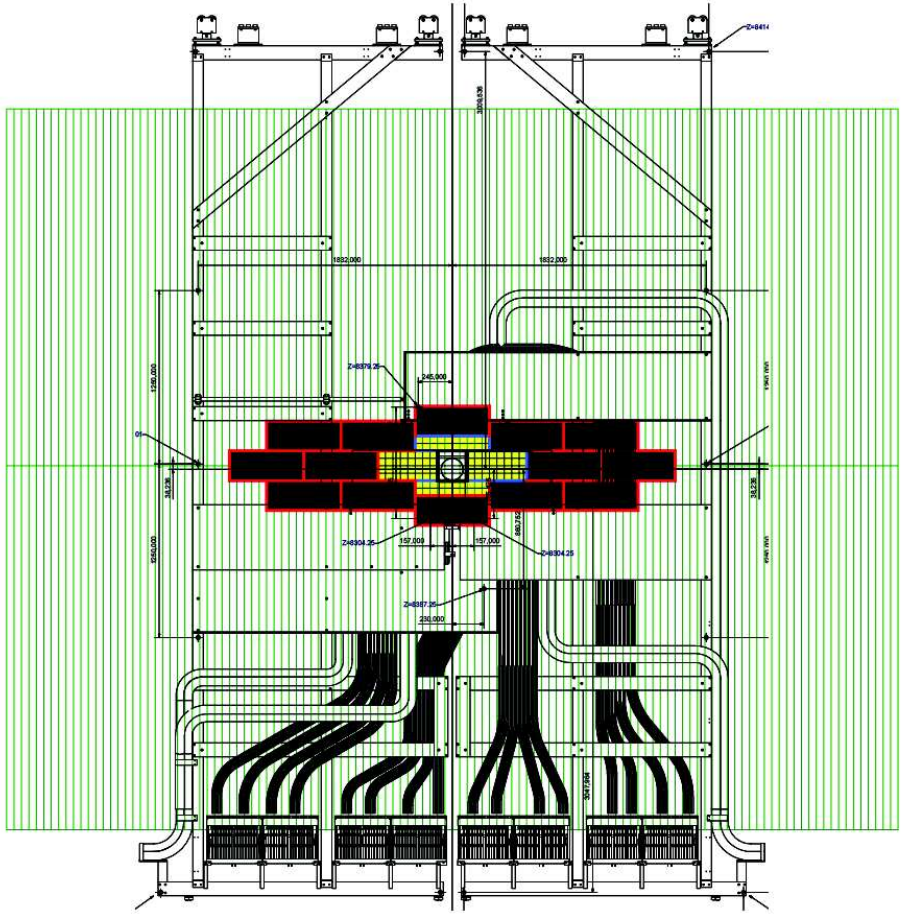
Time Remaining for Dedicated Sensor Realisation



- **2 different time scales**
  - for 2026 : how much can one depart from designs currently under development ?
  - for 2031 : time sufficient to develop a specific sensor, possibly based on new CMOS technology & concept

System Integration Aspects

- **Prominent performances driving parametres for high-resolution trackers**
  - track finding in dense environnement
  - track momentum reconstruction (impacts track origin rec.)
  - track origin (esp. for high P), if material budget low
  - rejection of secondaries from interactions in det. material (esp. if detector material shrinks with new tracker)
    $\longmapsto$ detector radiography
  - track pointing to ECAL (electron-photon separation) and HCAL (neutral hadron showers)



- **Double-sided detection modules**
  - improves track reconstruction (against ghosts), pointing resolution (upstream and downstream), momentum reconstruction, station spatial resolution (30 %) and alignment
  - redundancy alleviates impact of detection inefficiencies (esp. after irradiation)
  - possibility to combine two different sensors ($<$ 1 ns timestamping ?)
  - BUT: doubles power consumption and increases moderately (true ?) the material budget

CONCLUSION and OUTLOOK

- $\sim$ 20 yrs of Monolithic CMOS Pixel Sensors development for charged particle detection

$\rightarrowtail$ achieved maturity allows addressing very demanding running conditions & large detection areas

$\Rrightarrow$ **relevant technological approach for pixelated trackers of O(100) m$\hat{2}$ (R&D still needed !)**

- **Each application calls for specific design(s),** guided by realistic, comprehensive, MC simulations, accounting for global yield & system integration aspects

- **On-going R&D expected to establish the possibility to realise monolithic CPS combining**

$<$ 10 μm resolution, timestamping $<$ 25 ns & high rad. tol. (10^{15}n$_{eq}$/cm^2, 100 MRad)

  - Are these sensors suited to the most exposed parts of the LHCb tracker ? $\Rrightarrow$ MC simulations should tell
  - Which benefits would follow from relaxing the rad. tol. requirement on the design, to derive a sensor optimised (power !) for less exposed & largest surface of the tracker ?
  - Reduced material budget associated to CPS $\rightarrowtail$ double-sided stations may be of significant advantage

- **Perspectives:**
  - smaller feature size $\Rrightarrow$ faster & more complex (low power) circuitry for signal conditionning & transmission
  - stacked layers incorporating $\geq$ 3 CPS / station module ($\equiv$ mini-tracker)

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