Recent advances in CMOS pixel sensors: towards more applications

Lab. Nat. Frascati
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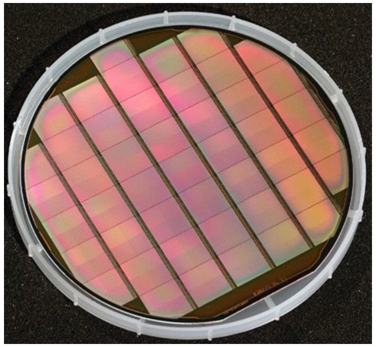
J. Baudot
(jerome.baudot@iphc.cnrs.fr)

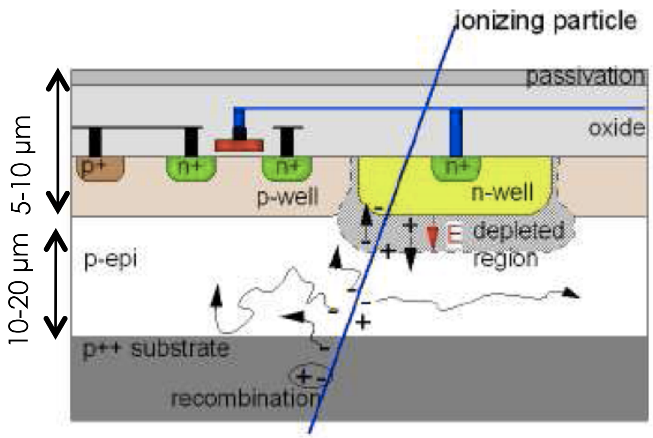
- Basics of CMOS pixels
- Projects in HEP: sensors & systems
- Tracking at low energy
- Non-tracking projects

Basic of CMOS pixel sensors

- → *The technology*
- → *Signal & Noise*
- → *Architectures*

Main features





Useful thickness: 30 µm

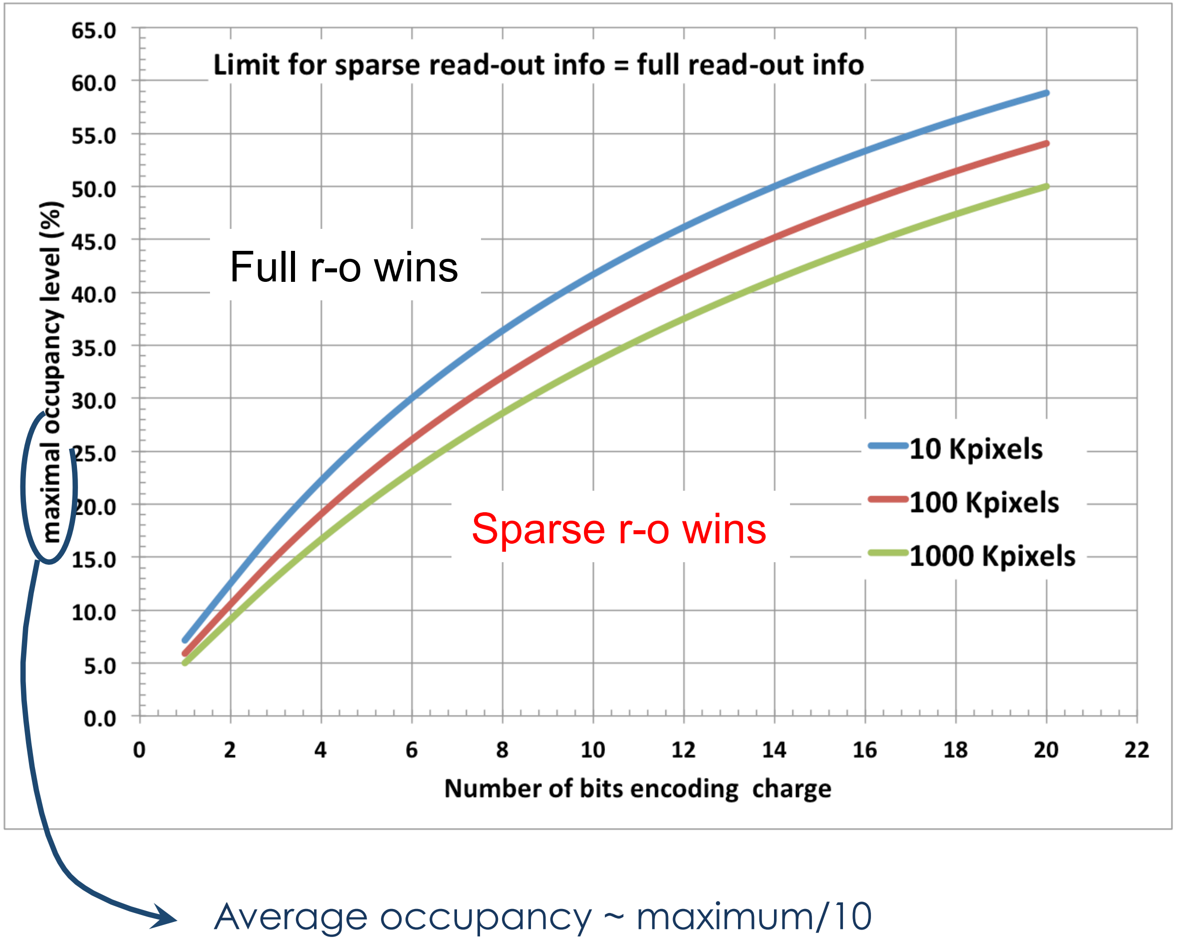
- Industrial technology
  - Integrated circuits (chips)
  - Lithography feature size ≪ 1µm ↘
  - Reticule limits ≈ 25x30 mm² ↗
  - } constantly improving
- Main features
  - Small pixel size possible down to few µm²
  - Signal processing on chip
    - In-pixel amplification → high SNR: "active"
    - No additional FEE readout: "monolithic"
  - Sensitive layer
    - Thin
    - Resistivity (10 to 10³ Ω.cm) → drives charge collection
    - } possibly adapted to radiation type
  - Operation at room temperature
- Invention of CMOS sensors for light
  - Early works late 60's
  - 1993 paper by E.Fossum

Speeding up the architecture

Tracking (4D-pattern recognition) works with very low occupancy
Basic idea = send less information

- Definitions:
  - **Full** read-out = all pixel signals sent out
  - **Sparse** read-out = only pixel with "high" signal sent out

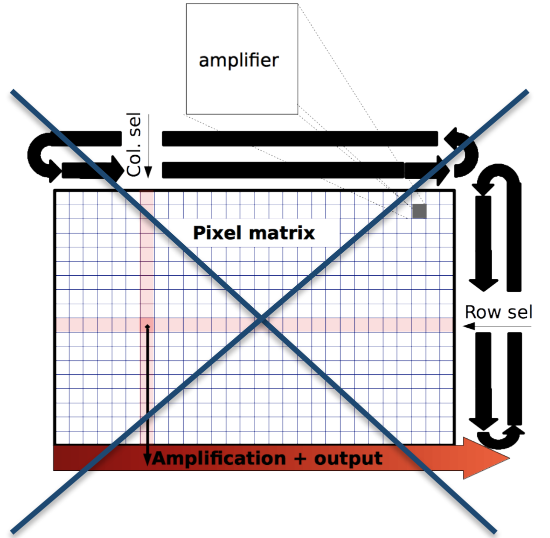
  → need discrimination (thresholding)



Basic of read-out architectures

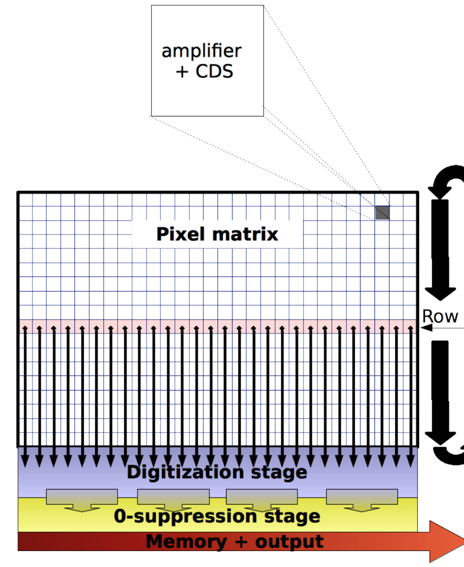
(obviously over-simplifying)

- **Synchronous**
  - Integration time = frame time
  - Size efficient /pixel pitch
- **Asynchronous**
  - Integration time = amplifier properties
  - Frame time = data stored * output speed
  - Time-stamping friendly

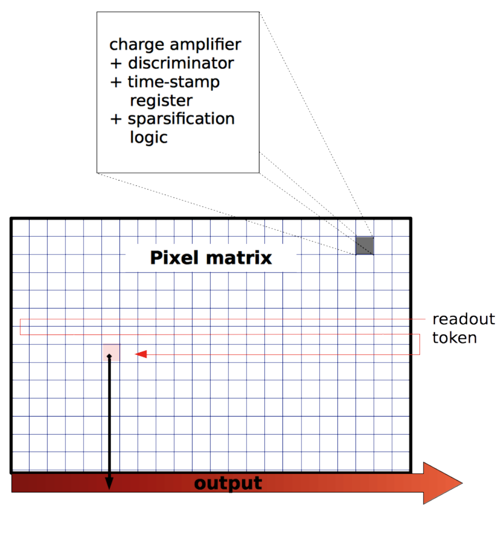


Impracticable / tracking

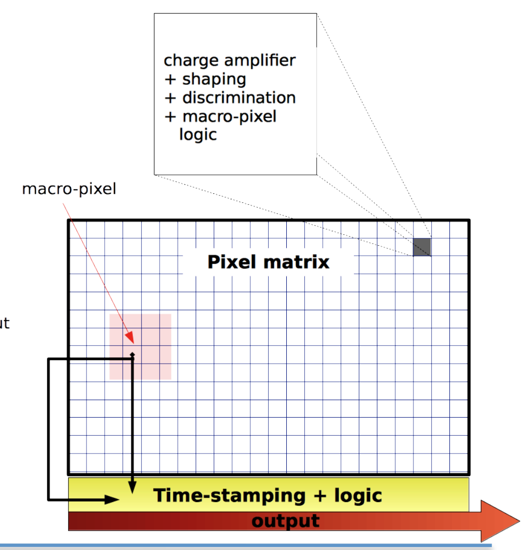
a)



b)



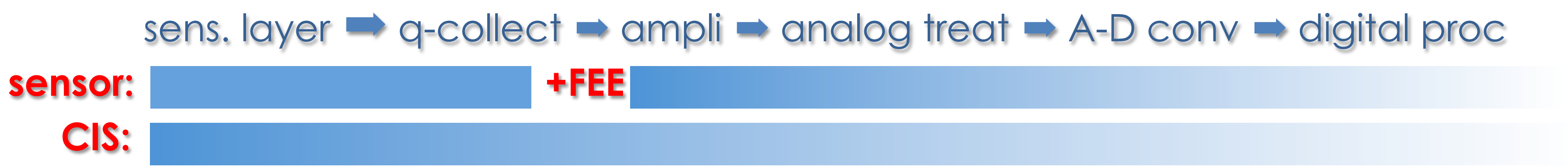
c)



d)

Initial pros & cons

- Full detection chain

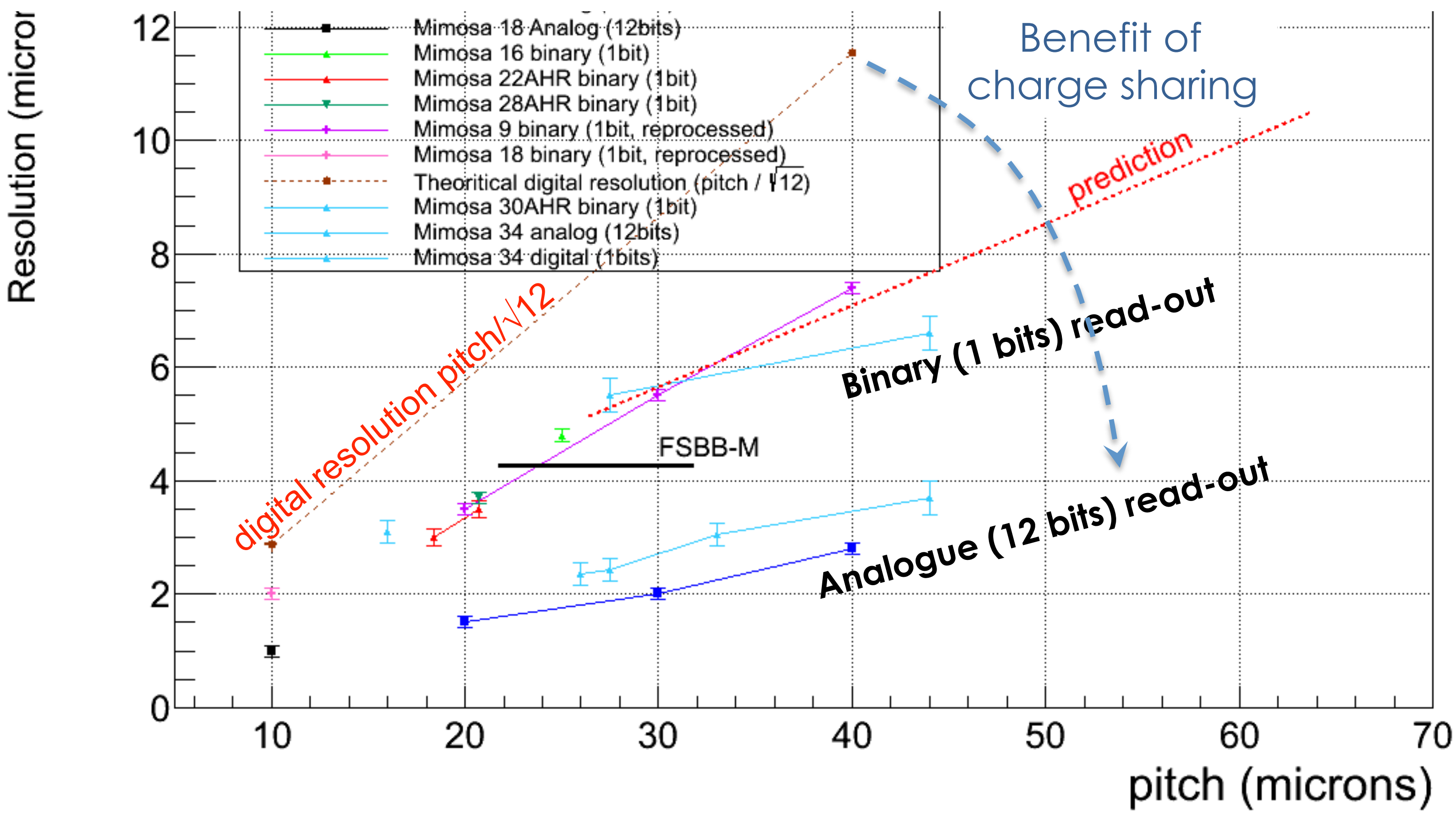


- Obvious advantages
  - Early ampli
    - → high sensitivity
  - Smartness
    - → limit data throughput
  - Complete system on a chip
    - → easy to integrate
  - Low fabrication cost

- Some limitations
  - Conflicting design parameters
    - – ex: granularity vs speed
  - 1 sensor = 1 system
    - → no further optimization after fab.
  - Development cost not small
  - Same technology for all functions
    - – Mitigated by 3D integration

Spatial resolution performances

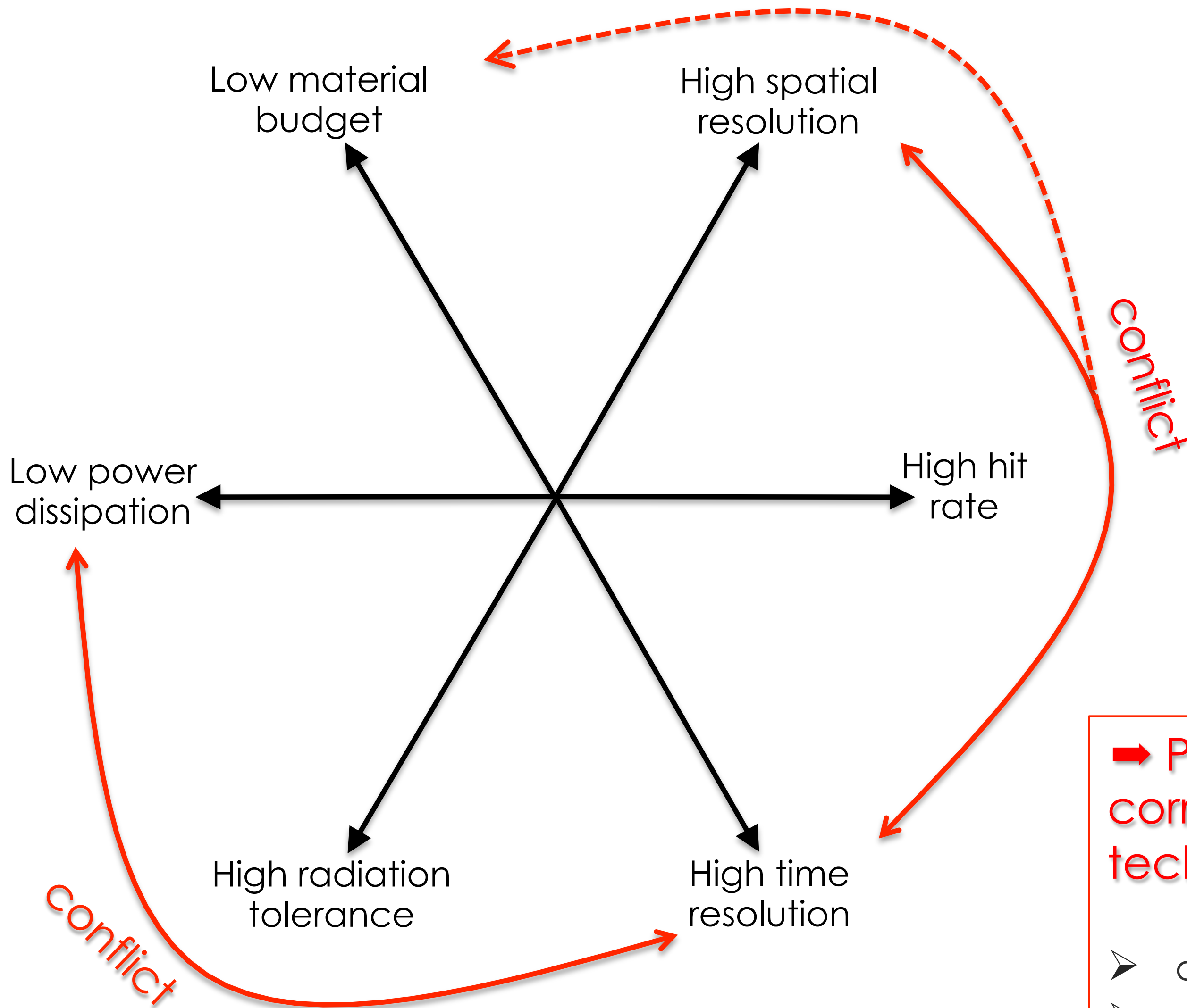
From many prototypes, the MIMOSA series from Strasbourg
(for thin non-depleted sensitive layers)



Tracking in High Energy Physics

	SLD	CMS LHC	STAR	CBM	ALICE	Belle-II	ILC	CLIC	ATLAS HL-LHC
Collision system	$e^+ + e^-$	p+p	A+A p+p	A+A	A+A p+p	e^+e^-	e^+e^-	e^+e^-	p+p
Spatial resolution (µm)	**2**	13	< 10	**~5**	**~5**	< 10	**≲ 3**	≲ 3	
Material Budget (% X0)	0.4	~2	**~0.3**	**~0,3**	**~0.3**	**~0.2**	**≲ 0.2**	**≲ 0.3**	<1
Hit rate (10^6 $s^{-1}cm^{-2}$)		**O(20)**	O(0,1)	O(1-10)	O(1)	**100**	O(0,2)	O(1)	O(200)
Time figure	0,2 s	25 ns	200 µs	~10 µs	<30 µs	**~1 µs**	O(10)µs	10 ns	25 ns
Radiotolerance (Mrad) (n_{eq}/cm^2)	-	**100 < 10^{15}**	O(0,2) O(10^{12})	**O(30) < 10^{14}**	O(0.7) O(10^{13})	O(20) < 10^{13}	O(0,1) < 10^{12}	O(20) < 10^{14}	500 <10^{17}
Power dissipated (W/cm^2)	-		**0.1**	1-2	~0.3	~2	**0.1**	**0.1**	

Requirements on sensing layers



➡ Parameters correlated within one technology

- optimisation required…
- …or going to 3D

Tracking in HEP: Sensors

- *Heavy-ion collisions*
- *p+p @ LHC*
- *$e^+ + e^-$ colliders*

Heavy-ion collisions

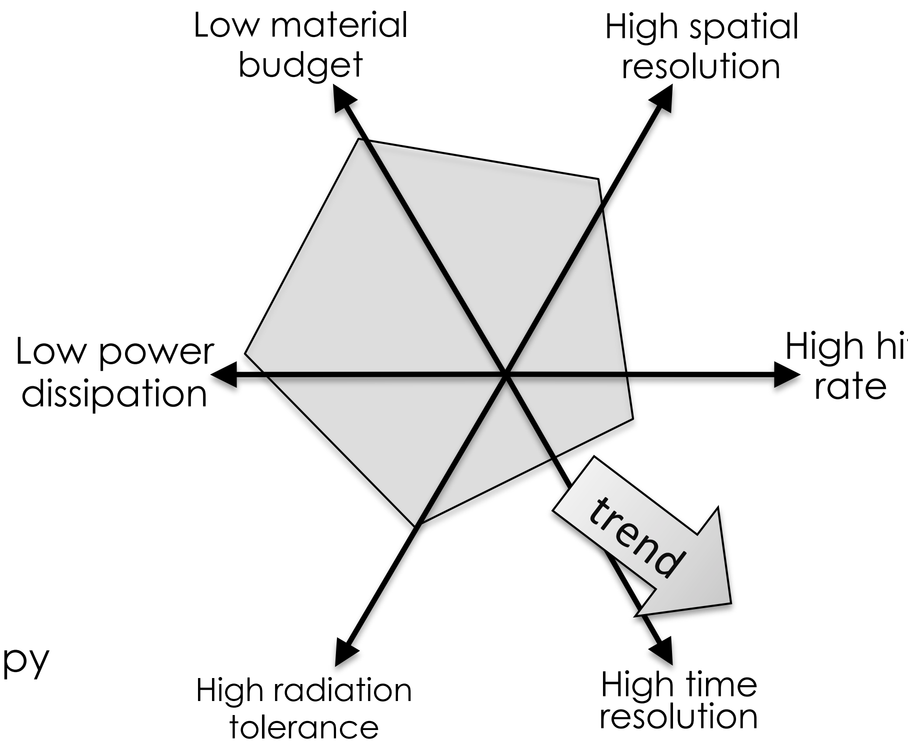
- STAR @ RHIC (2014)
  - Material budget ~ 0.4 % X_0
  - Single point resolution $\sigma_{point} \lesssim 10\ \mu m$
  - Only vertexing

- ALICE @ LHC (2021)
  - Higher rate ⇒ σ_{time}~10 µs
  - Single point resolution $\sigma_{point} \lesssim 5\ \mu m$
  - Vertexing & **tracking** (newITS)
    - Large surface → cost

- Fixed target experiments
  - Measurement of Xsections / hadrontherapy
  - FIRST (GSI 2011-2012)
  - FOOT (Italy, Germany, France)

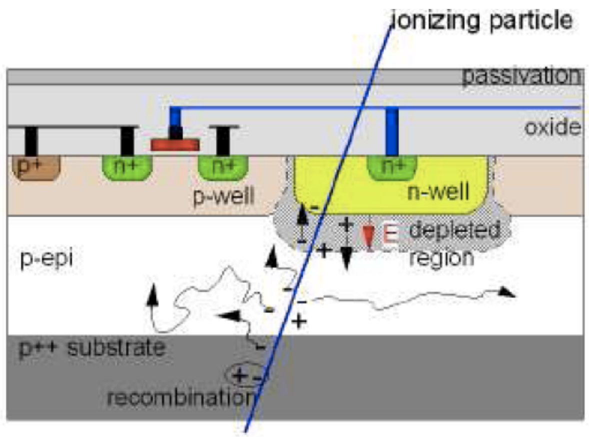
  → See Eleuterio's talk

- EIC (?)



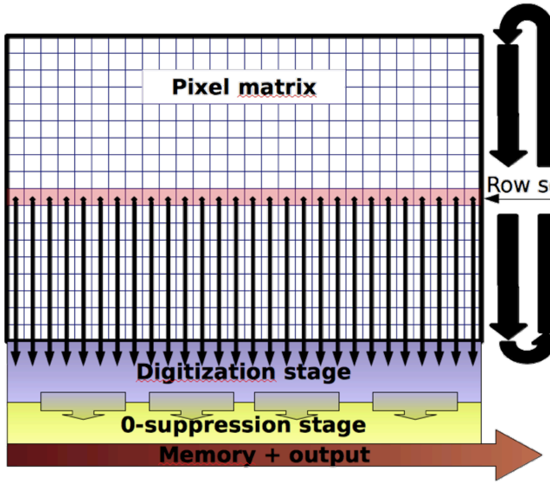
Technical choice
⇒ hybrid (current ALICE-ITS)
⇒ monolithic

STAR – MIMOSA-28



- **Technology:**
  AMS 0.35 µm
- **Sensitive layer:**
  400 Ω.cm

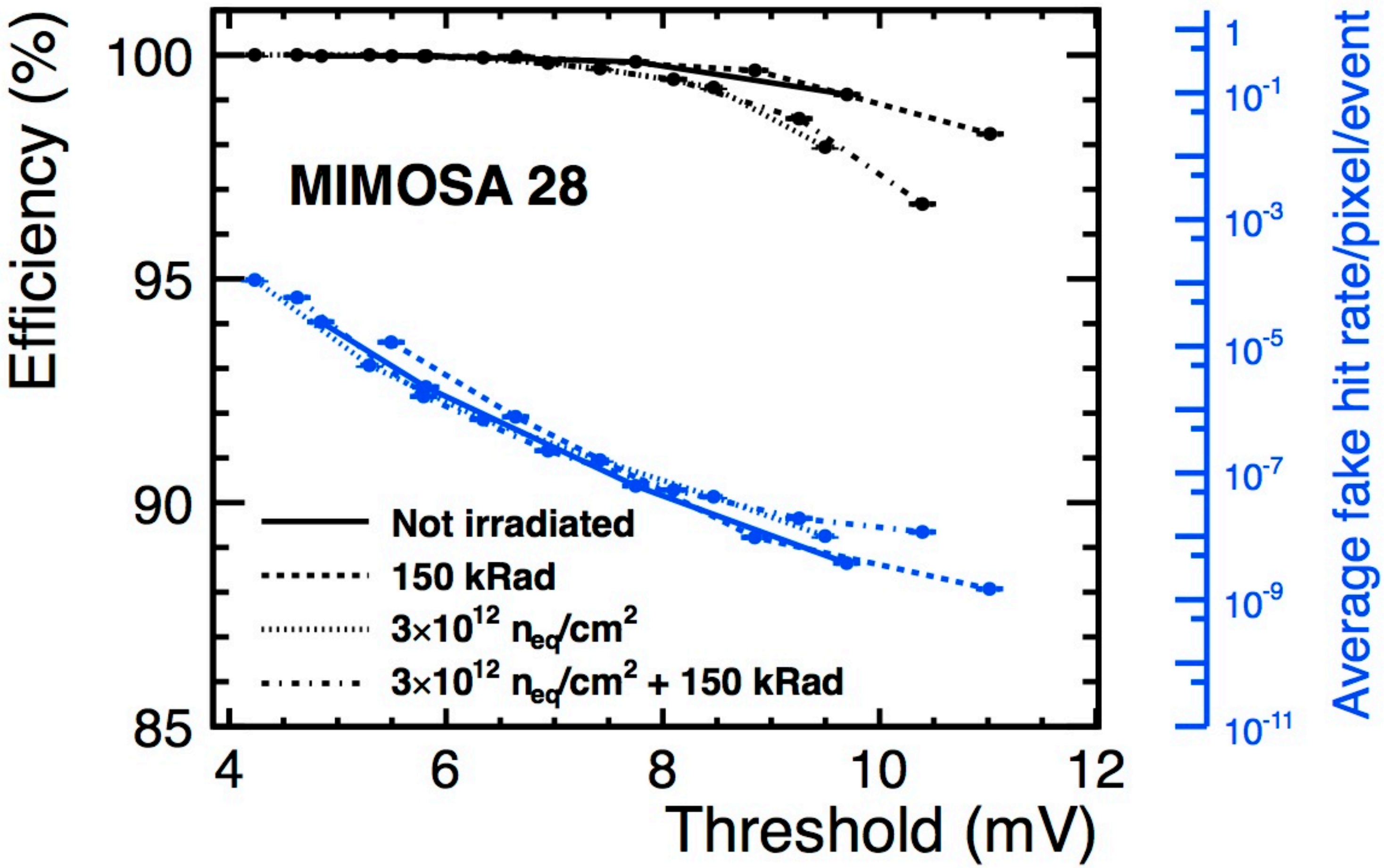
- Key elements
  - In-pixel CDS ➙ discri possible
  - Column // read-out
    BUT one row at a time
  - Synchronous digitization
    - discriminator (1bit)
  - Synchronous zero-suppression
    - address pixels per group



- Distinct features
  - Read-out time = integration time
  - Insensitive area aside the pixel matrix
  - Counting rate ⬅ size and speed zero-supp. stage

➡ Counting rate: > 10^6 hits/cm²/s

MIMOSA-28 performances

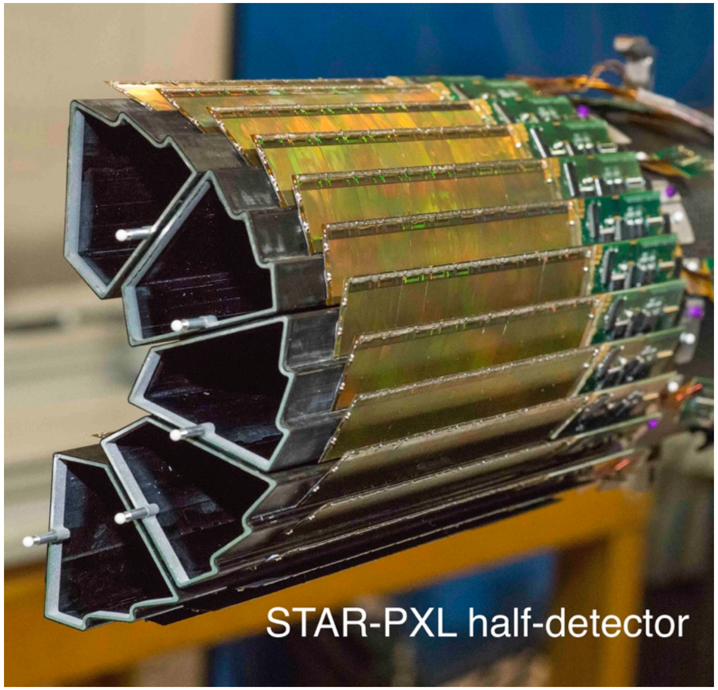


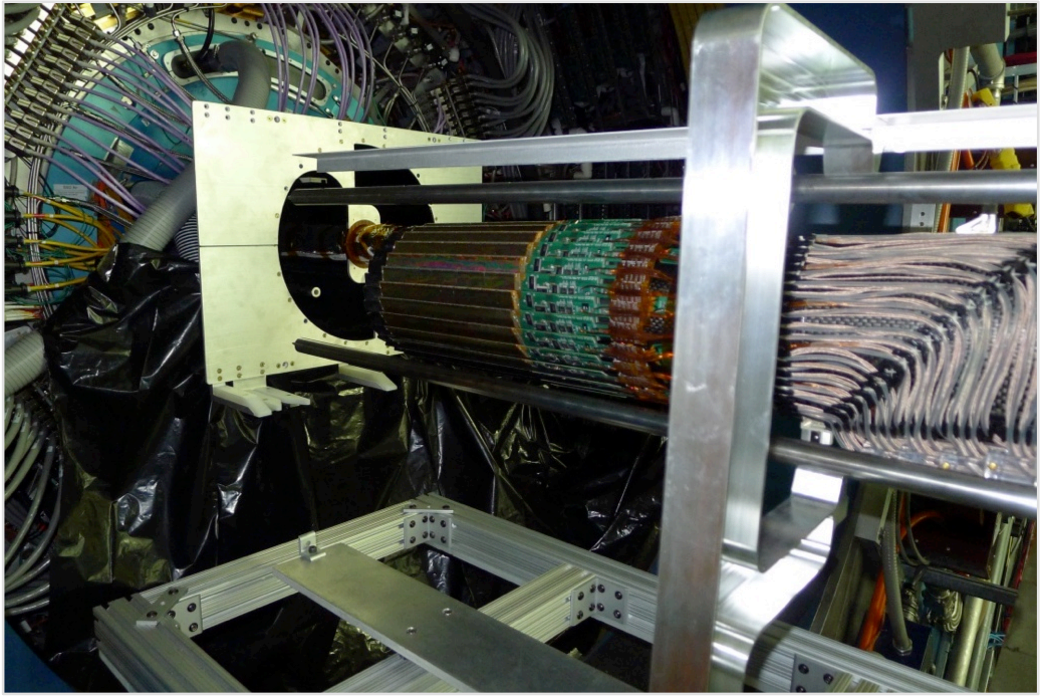
STAR-PXL = the first MAPS detector

- 400 MIMOSA-28 sensors
- 360 10^6 pixels
- Air flow cooling $T_{op} \lesssim 35^{\circ}C$
- $\sigma_{s.p.} \simeq 4$ µm
- mat. budget = 0.39 % X_0 / layer
- Read-out time ~ 190 µs

➞ operated from 2014 to 2016

Detector developed by LBNL, U.Texas, CCNU





Cantilever support

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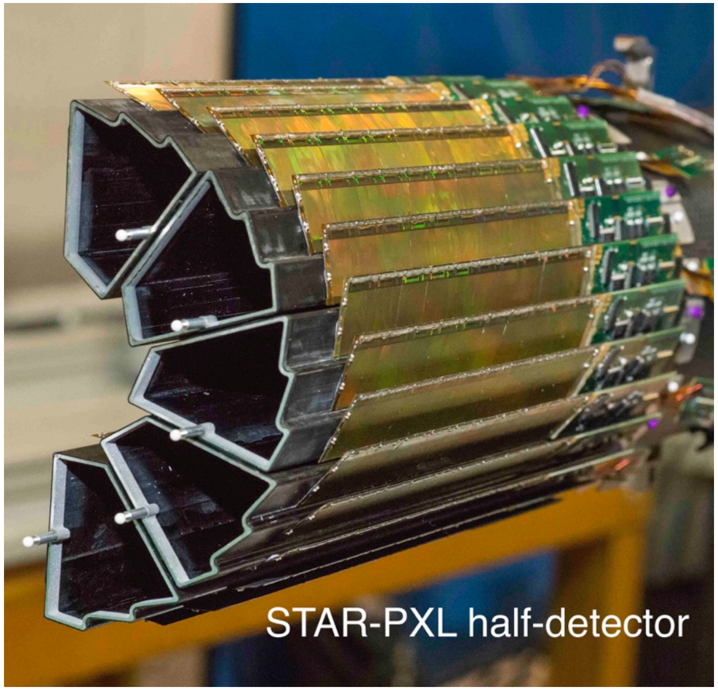
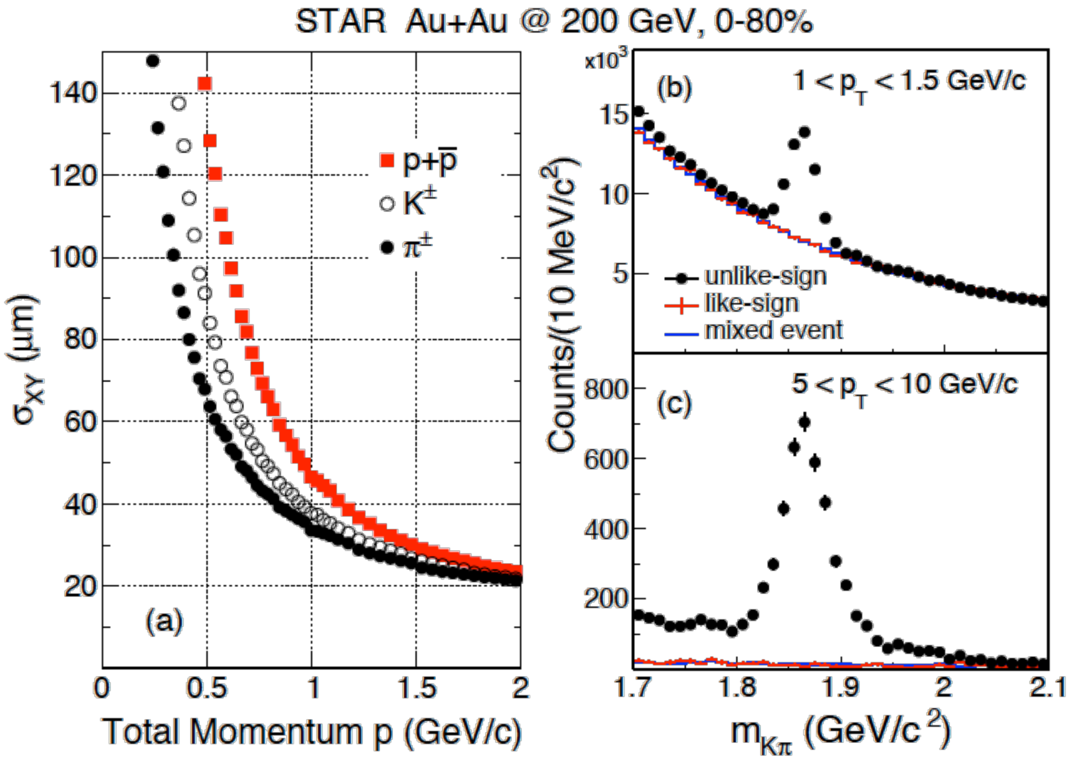
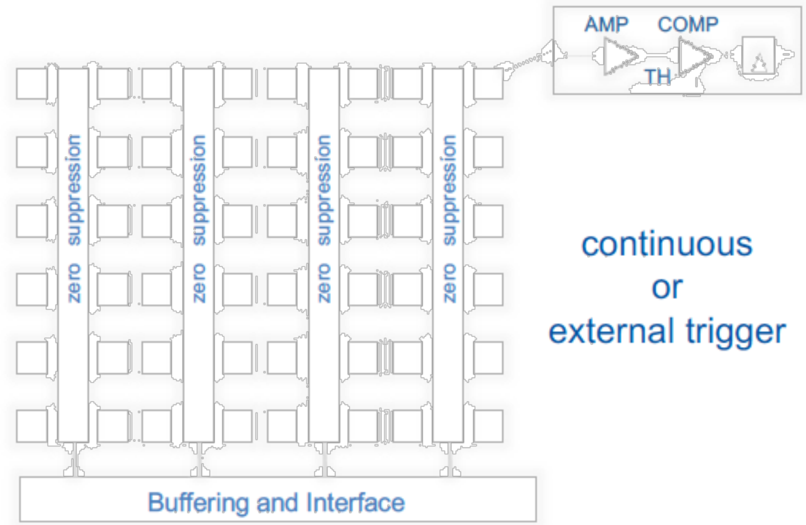




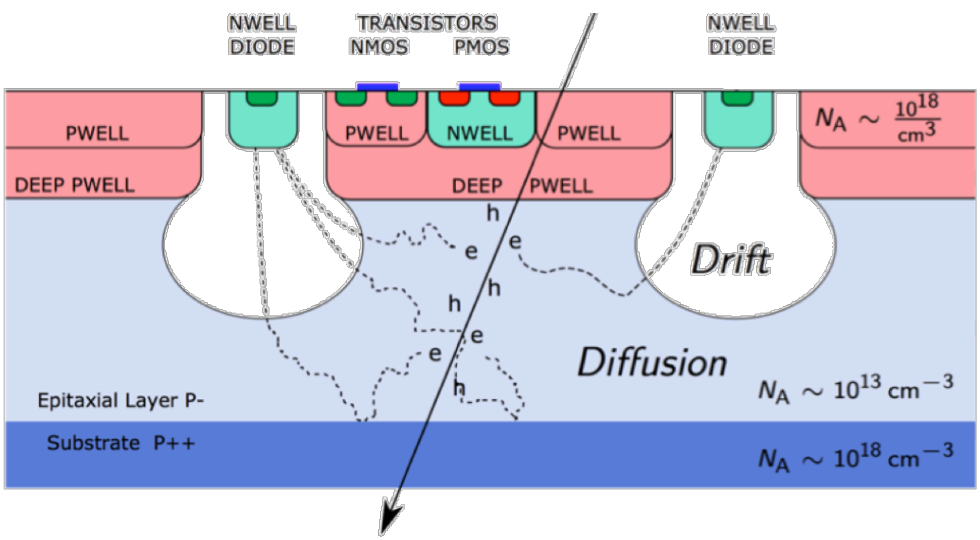
ALICE - ALPIDE

M.Mager, Nucl.Instr.Meth. A824 (2016) 434-438

- New technology, new architecture
  - Developped @ CERN with many contributors
  - Pixel size 29x27 μm^2
  - 30x15 mm^2
  - Spatial resolution 5 µm
  - Integration time ~5 µs
  - Power dissipation 40 mW/cm^2



continuous
or
external trigger



- **Technology:**
  TowerJazz 0.18 µm
- **Sensitive layer:**
  > 1 kΩ.cm
  → some depletion / back-bias

ALICE - newITS

Based on high resistivity epi layer MAPS

3 Inner Barrel layers (IB)
4 Outer Barrel layers (OB)

Radial coverage: 21-400 mm

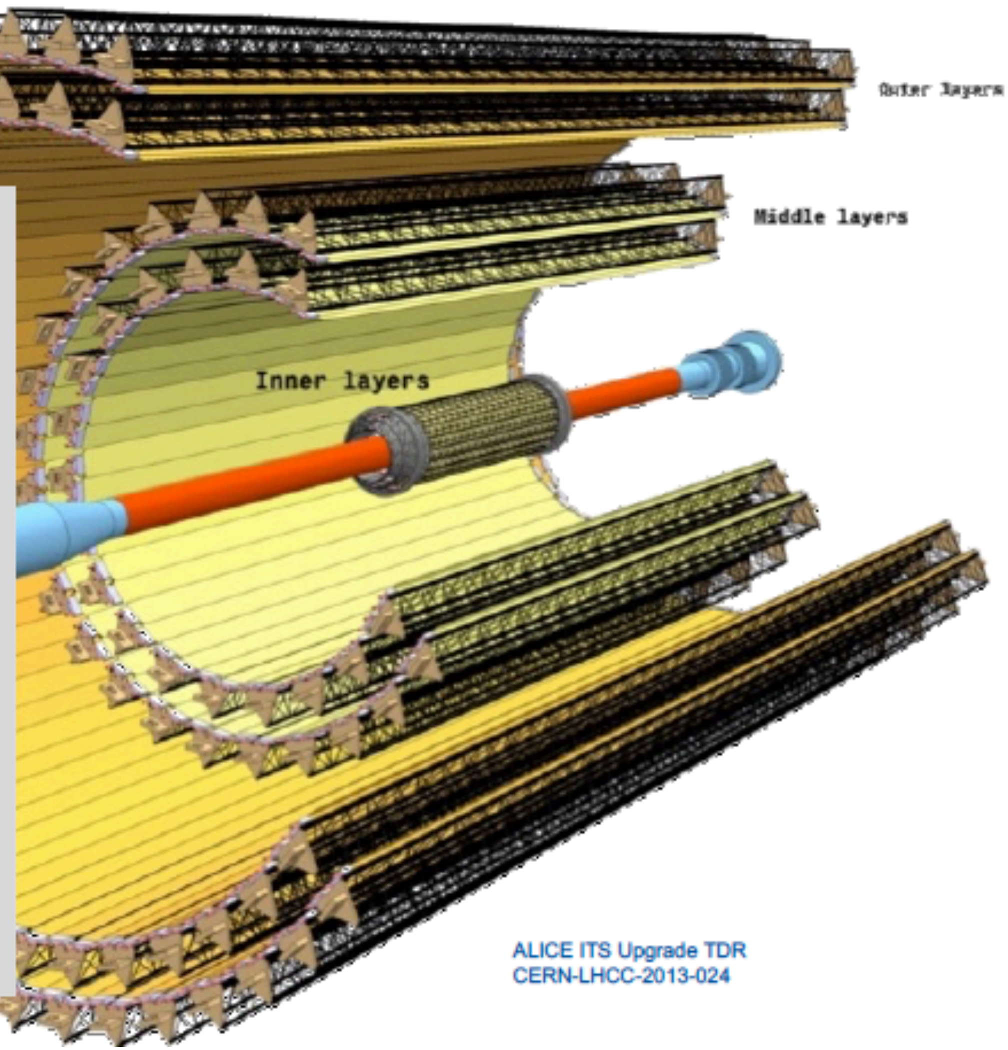
~ 10 m^2 **12.5 Gpixels**

|η|<1.22 over 90% of the luminous region

0.3% X_0/layer (IB)
0.8 % X_0/layer (OB)

Radiation level (IB, layer 0): TID: 2.7 Mrad, 1.7 x 10^{13} 1 MeV n_{eq} cm^{-2}

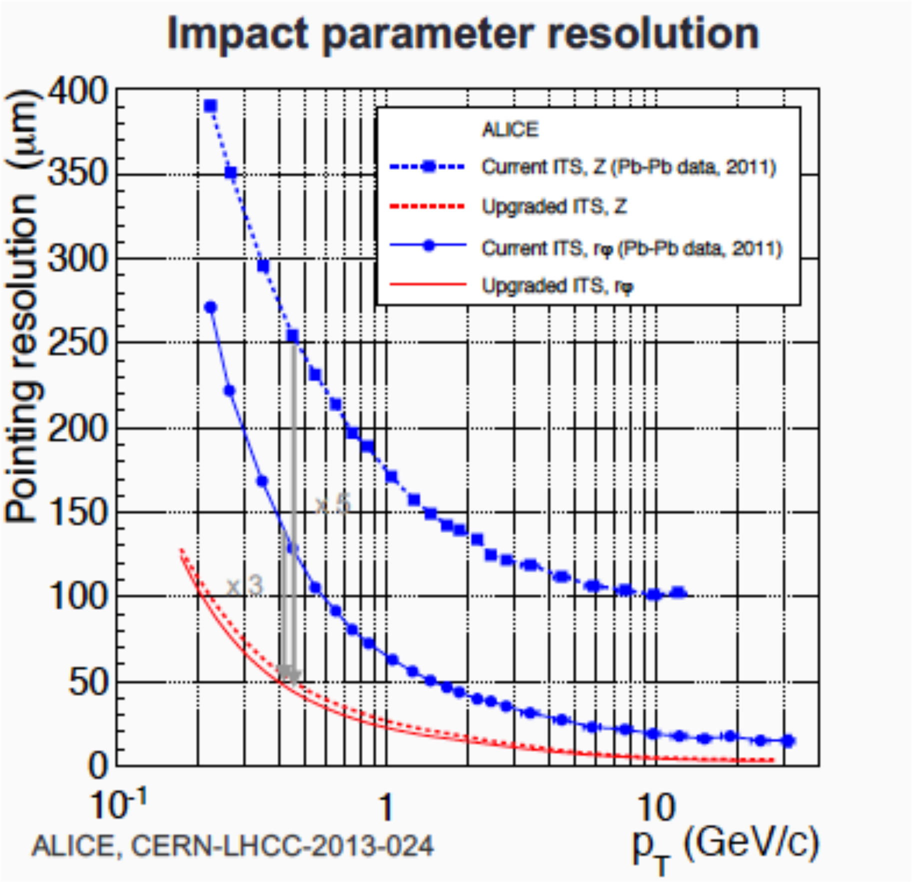
Installation during LS2



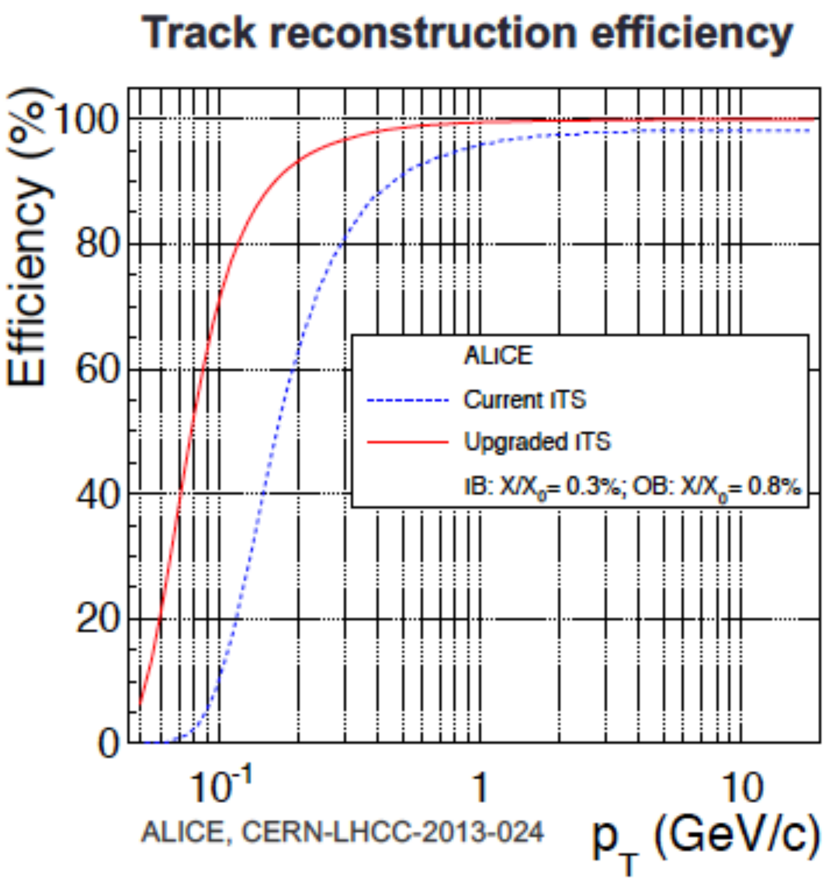
ALICE ITS Upgrade TDR
CERN-LHCC-2013-024

ALICE - newITS

Expected tracking performances, from simulations



Improved impact parameter resolution

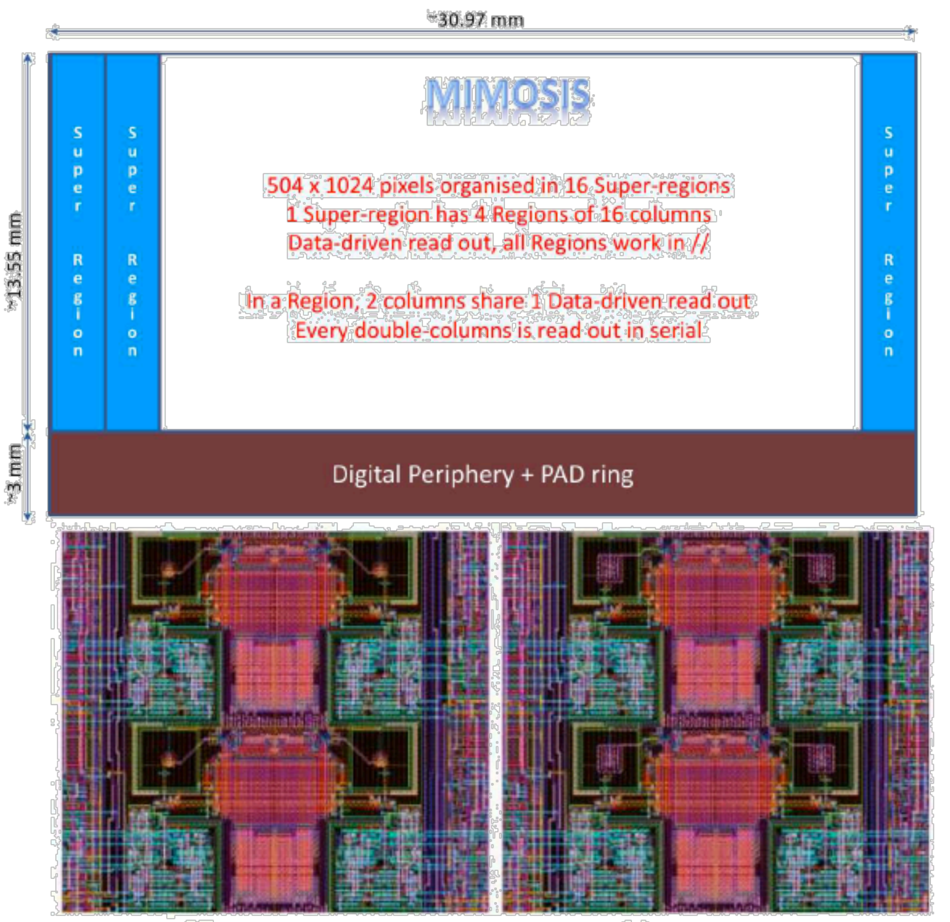


High standalone tracking efficiency

CBM - MIMOSIS

- **Objective: Sensor equipping Micro-Vertex Detector (MVD) of heavy-ion CBM expt at FAIR/GSI**
  - 4 double-sided stations equipped with 50 μm thin CPS, operated in vacuum at $T_{op} \sim -40^{\circ}C$
  - MIMOSIS sensor: asynchronous read-out architecture derived from ALPIDE sensor (ALICE-ITS)
- **Sensor target performances:**
  - Spatial & Time resolutions $\lesssim$ 5 μm & 5 μs
  - Radiation tolerance $\gtrsim$ 3 MRad $\oplus$ $3 \cdot 10^{13} n_{eq}/cm^2$
  - Power: 200-350 mW/cm^2 (depending on distance to target)
  - Hit/Data rate capability: $1.5\text{-}7 \cdot 10^5/mm^2/s \Rrightarrow$ 1.6 Gbits/cm^2/s

- **Technology:**
  TowerJazz 0.18 µm
- **Sensitive layer:**
  > 1 kΩ.cm



DC coupling

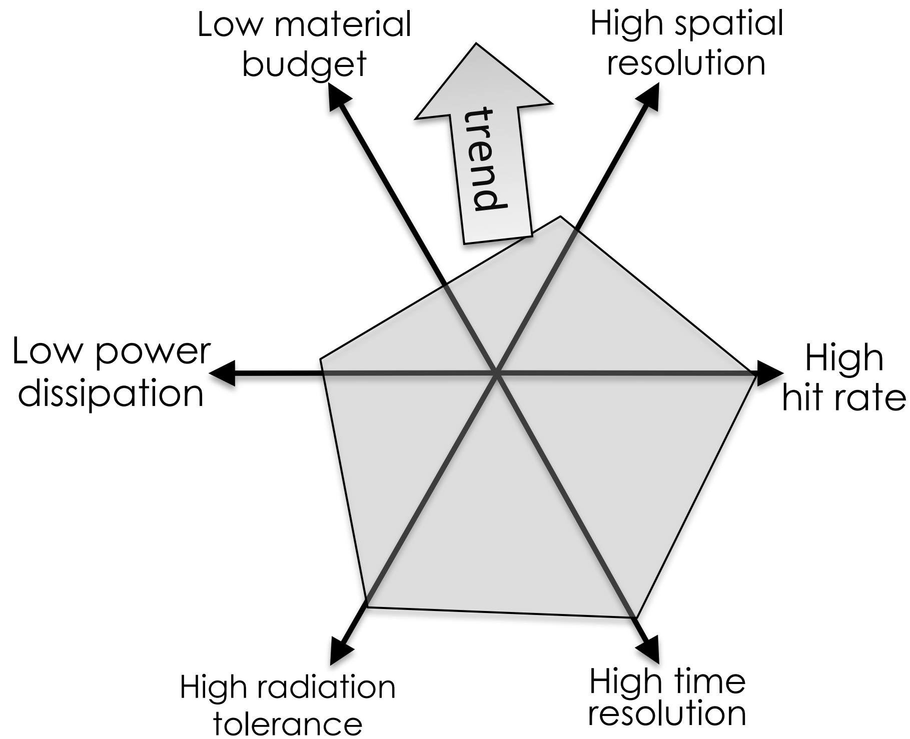
AC coupling (for depletion see later)

- First small proto in 2017, engineering runs for 2018,19,**20**

Hadron colliders (ATLAS, CMS, LHCb)

- Current LHC (2008-21)
  - Beam-crossing every 25 ns
    - 40 collisions / beam crossing
    - Few 1000 tracks / event
  - Radiation at 4-5 cm
    - 500 kGy / year
    - few 10^{14} n_{eq}(1 MeV)/cm^2

- High-luminosity LHC (>2024)
  - Instantaneous lumi x10
    - Pile-up of 200-400 p+p collisions
  - Radiation
    - 15 MGy / year
    - few 10^{16} n_{eq}(1 MeV)/cm^2
  - Improved track param. resolution
    - material budget ~ % X_0
    - Single point resolution σ_{point} ~ 10 μm



Technical choices
⇒ hybrid in inner layers
(⇒ monolithic in outer layers)

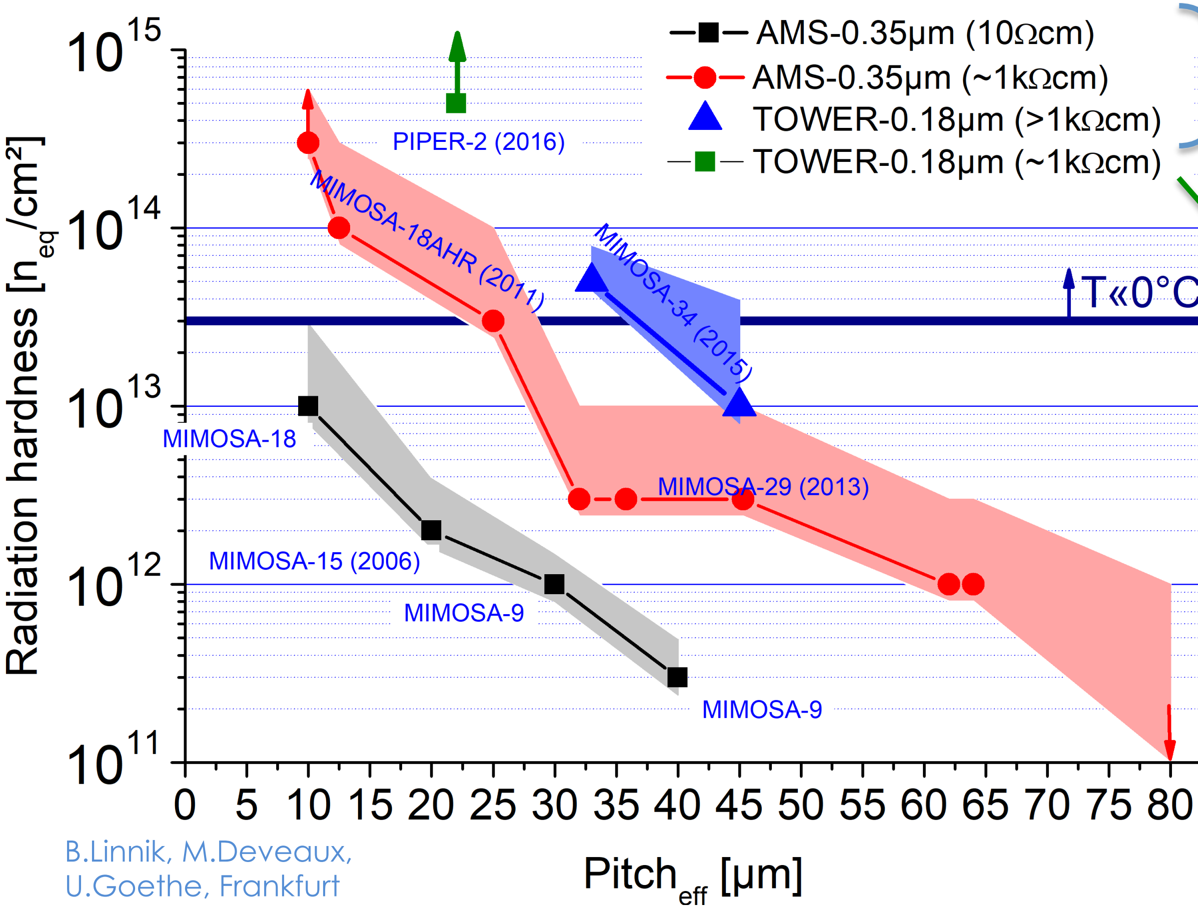
Intermezzo / sensing layer engineering

Toward higher radiation tolerance

- **Impact of radiations**
  - Total Ionising Dose (TID)
    - Charges trapped at oxide/Si surfaces
    - Randomly released (I_{leak}) → higher noise
    - Change transistor behaviours
      - Not sensor specific
  - Highly ionising particle
    - Various Single Event Effects
      - Overcurrent, logic defaults…
    - Not sensor specific
  - Non Ionising Energy Loss (NIEL)
    - Damage Si crystal
    - Trap charges → lower signal
    - Increases I_{leak} → higher noise

- **Potential cures**
  - Specific design rules
    - Not sensor specific
  - Lower temperature
    - Mitigate leakage current (I_{leak})
  - Focus charges on lower number of pixels
    → Increases signal
    - With denser collection nodes
      ⇐ smaller pixels
    - With drift field
      ⇐ depleted sens. volume

NIEL mitigation



B.Linnik, M.Deveaux,
U.Goethe, Frankfurt

<u>undepleted sensors:</u>
Thermal diff. > drift
collection time > 100 ns
large charge sharing

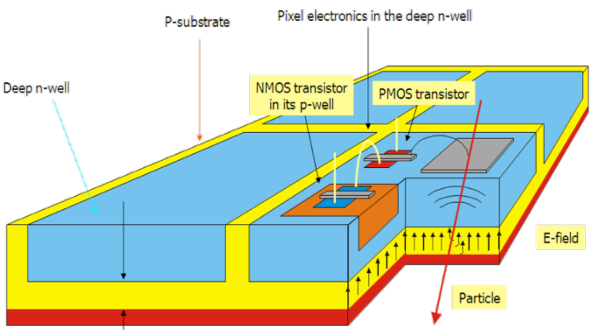
depleted sensors
mostly drift
collection time few ns
~no charge sharing

<u>Similar impact for TID:</u>
- Undepleted ~ 300 kRad
- Depleted ~ 1 GRad

Three ways to deplete MAPS

Depletion depth $\propto (V_{bias} \times \rho)^{\alpha}$ with $\alpha \lesssim 1/2$

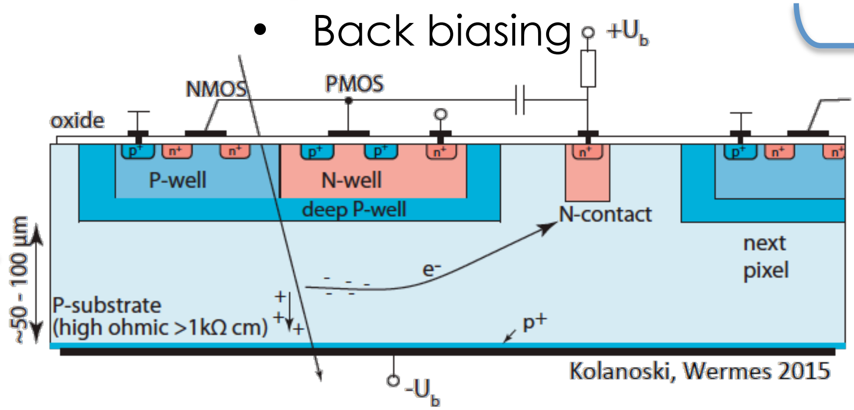
- **High Voltage**



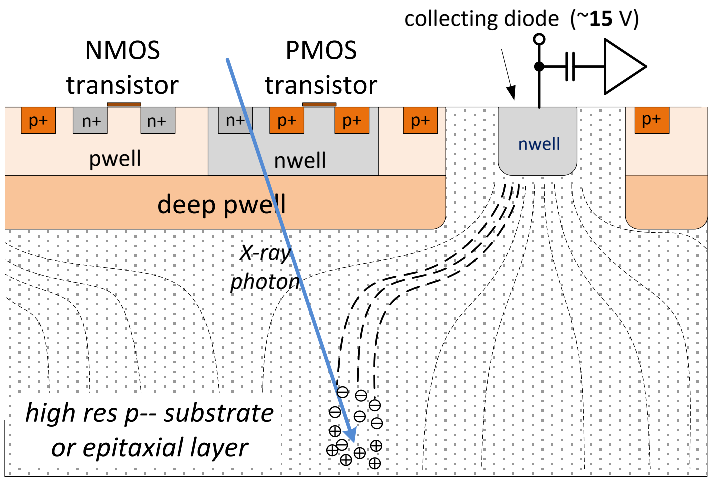
I.Pieric 2010

Target fast timing

- **High Resistivity**
  - Back biasing



- **High Resistivity**
  - Top biasing



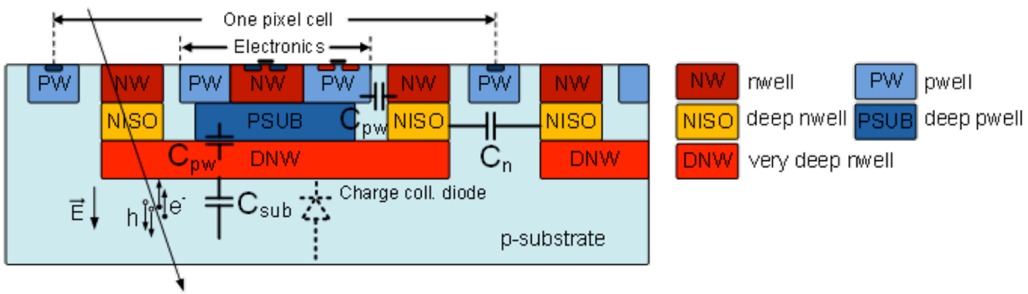
M.Kachel 2013

Target small pixels

✷ All with multiple wells CMOS process:
Remember hybrid tech. offers natural shielding

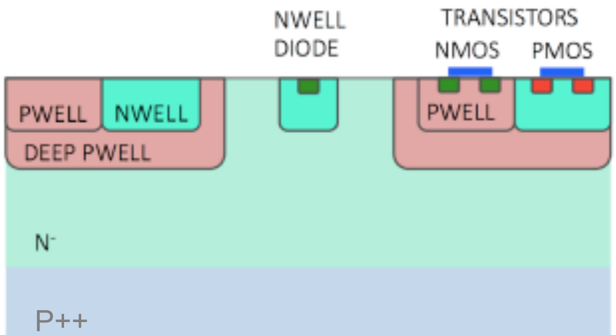
ATLAS – MAPS: full-depletion

- Monopix
  - L-Foundry 150 nm
    - High-res, Vbias ~100-300 V
  - "large fill factor" diode
  - Pixel size 250x50 μm^2
    - 36 μW/pixel for 25 ns read-out



U.Bonn, CPPM, IRFU

- MALTA
  - Tower Jazz 180 nm
  - "small fill-factor"
  - Derived from ALPIDE with process modif / depletion



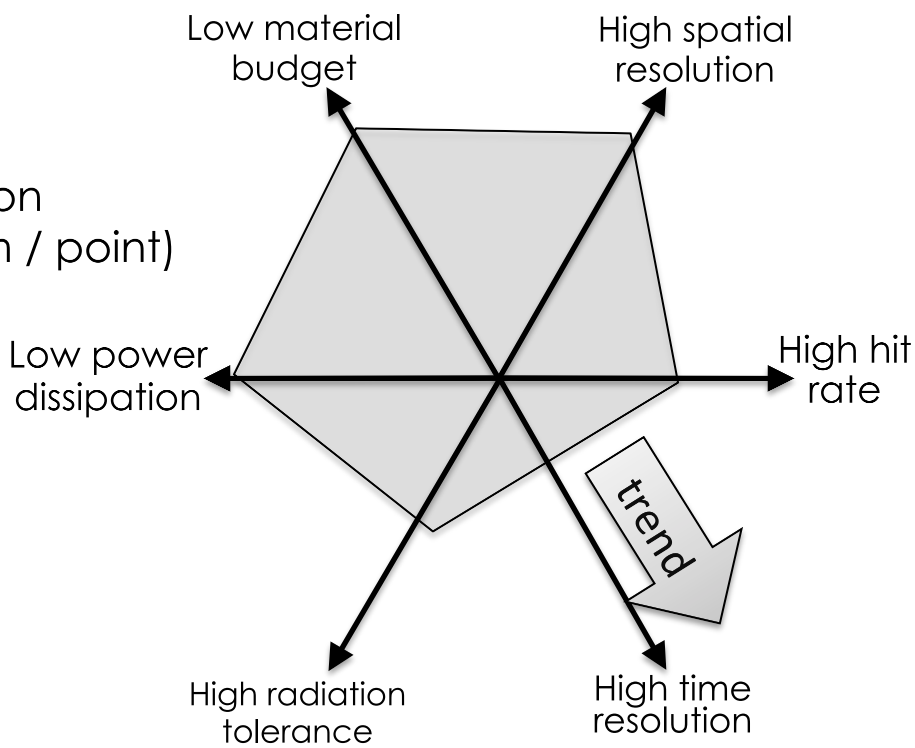
W.Snoeys et al., CERN

- HV-CMOS
  - Not discusses here, see Mu3e

- Currently
  - At the proto (1 cm^2) level
  - Demonstrated
    - Full depletion O(100) μm
    - Tolerance up to few 10^{15} n_{eq}/cm^2

Leptonic e+e- collisions

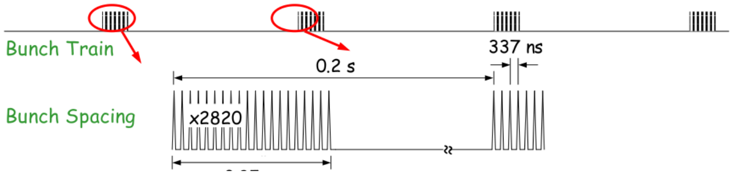
- History (20th century <2010)
  - **SLD** had the first and only CCD-based vertex detector
  - **LEP** introduced strips and pixel hybrid
  - **B-factories** most precise vtx det. so far
  - ~10-20 tracks /event, almost no radiation
    BUT need for tracking precision (~10 µm / point)
- SuperKEKB / Belle II (2018)
  - x100 luminosity ⇒ σ_{time}~10 ns
- Next linear colliders (~2030)
  - > 100 tracks / event
  - Single point resolution $\sigma_{point} \lesssim 3$ µm
  - Material budget 0.1 - 0.2 % X_0
  - Separating primary collision
    - ILC needs σ_{time}~100 ns
    - CLIC needs σ_{time}~10 ns



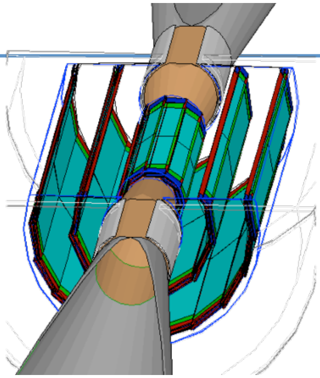
Technical choice
⇒ monolithic
⇒ hybrid if few ns required

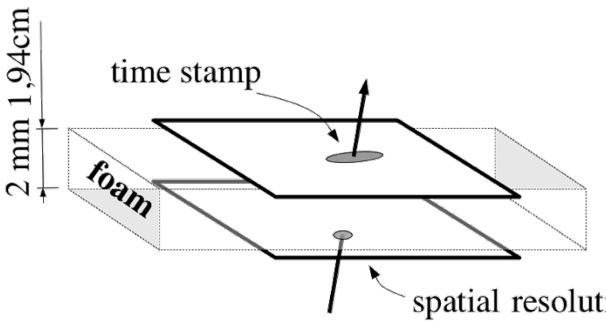
ILC – PSIRA

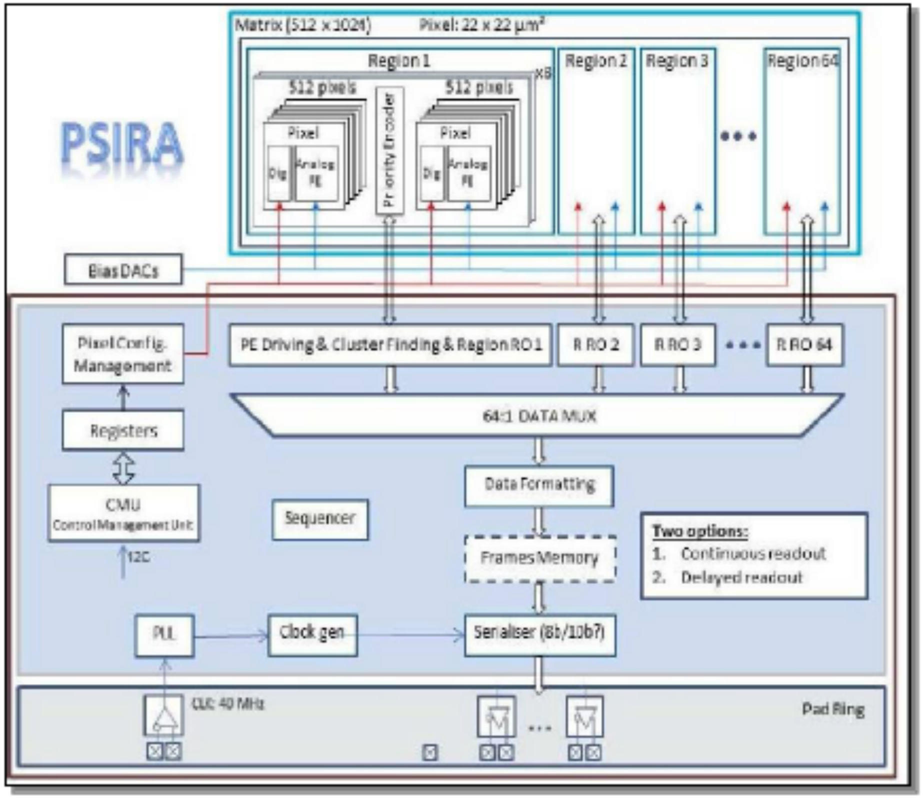
- For Vertexing & SiTracker
  - Evolution of MIMOSIS
    - Spatial resolution < 3 µm pitch 18x18 µm²
    - Power pulsing to reach ~ 30 mW/cm²
  - Vertexing: $T_{integration} \lesssim 1$ µs
  - Tracking: $T_{Integration}$ 2-4 µs



- Target sensor readiness by 2025
  - Probably smaller feature-size 180 → 110 nm
  - Potentially other foundries than Tower-Jazz







CLIC Silicon tracker

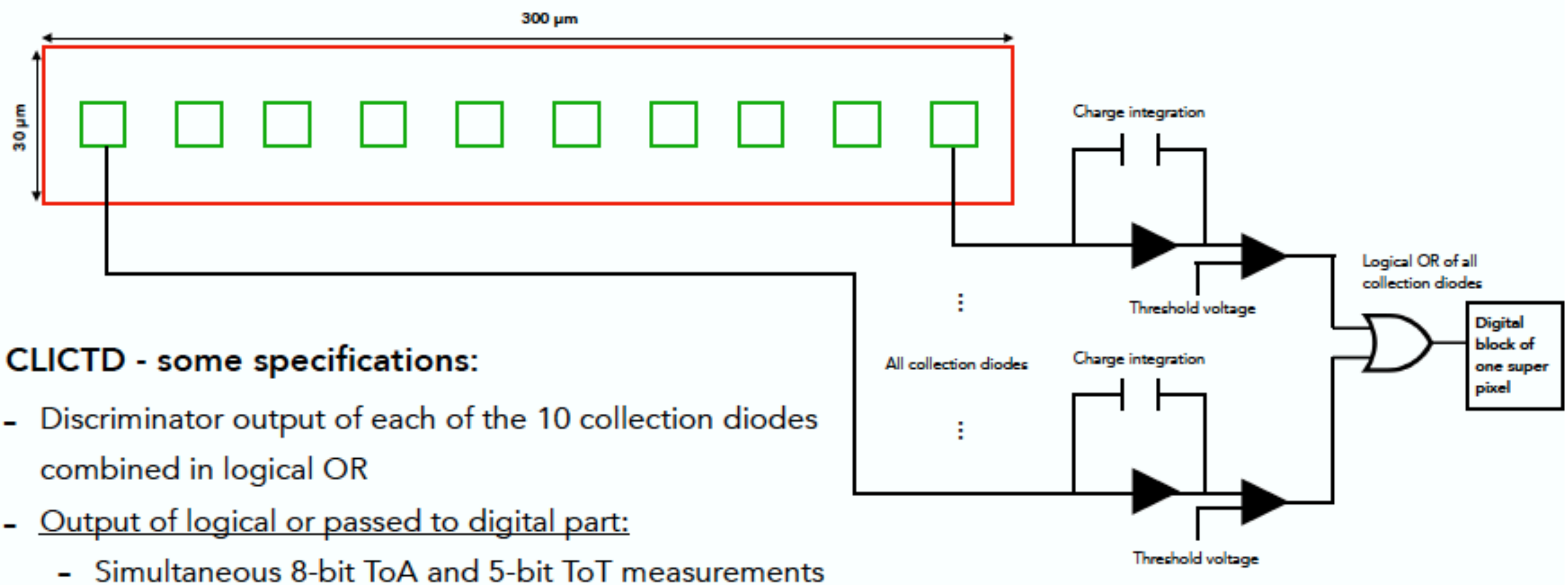
M.Munker, LCWS 2017, Strasbourg

Motivation:

- Promising performance of studied HR-CMOS technology with respect to requirements of CLIC tracker
- Technology used in next phase of R&D to design a fully integrated chip for the CLIC tracker

CLIC Tracker Detector (CLICTD) - main idea/concept for elongated pixels/small strips:

- Design super pixel structures to maintain advantages of small collection diode (prompt and fully efficient charge collection) while reducing digital logic

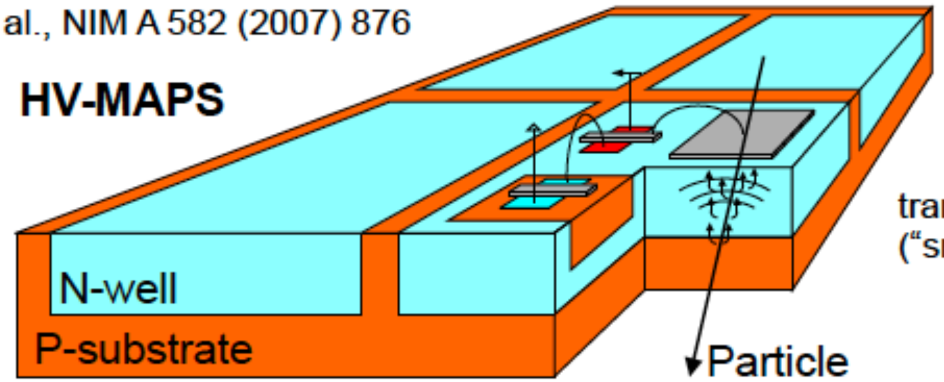


CLICTD - some specifications:

- Discriminator output of each of the 10 collection diodes combined in logical OR
- <u>Output of logical or passed to digital part:</u>
  - Simultaneous 8-bit ToA and 5-bit ToT measurements
  - 100 MHz clock to achieve 10 ns time slicing

Mu3e - MuPix

I.Peric, et al., NIM A 582 (2007) 876



MuPix7 (2016)
- few mm^2

MuPix8 final
- 2x2 cm^2

High Voltage - Monolithic Active Pixel Sensor (HV-MAPS)

- **active sensor → hit finding + digitisation + zero suppression + readout**
- high precision → pixels 80 x 80 µm^2
- low noise ~ 40 - 50e → low threshold
- small depletion region of ~ 10 µm → thin sensor ~50 µm (~ 0.0005 X_0)
- standard HV-CMOS process, 60 - 90 V → low production costs
- continuous and fast readout (serial link) → online reconstruction

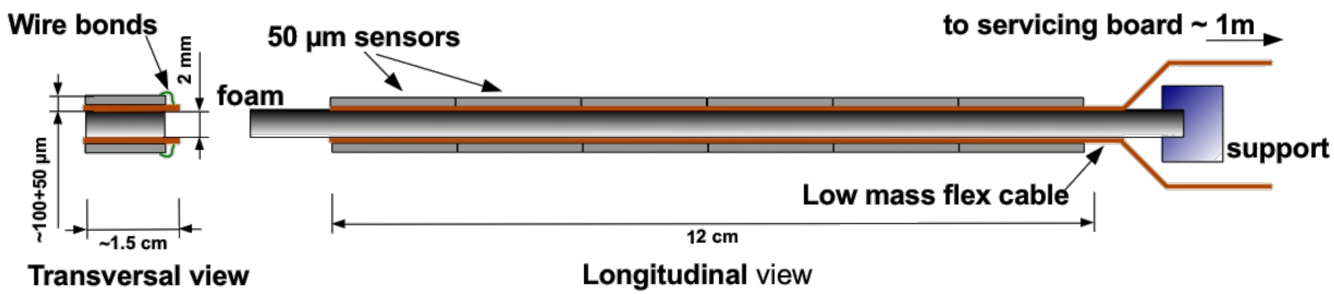
André Schöning, Heidelberg (PI) 27 Vertex2016, September 27, 2016

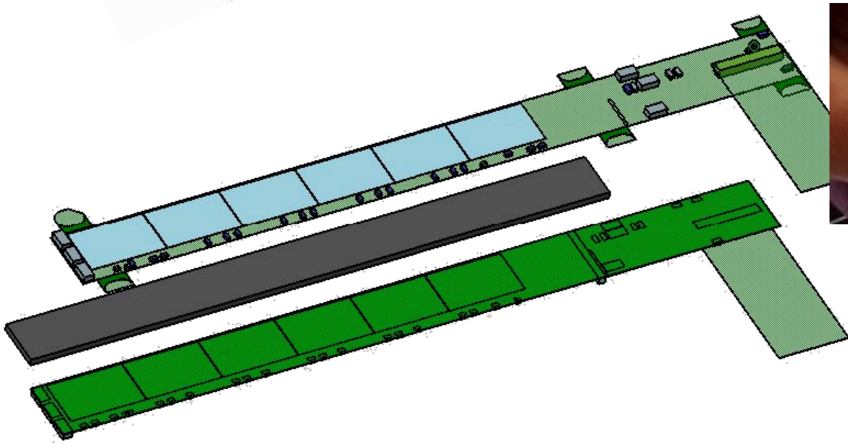
Tracking in HEP: Systems

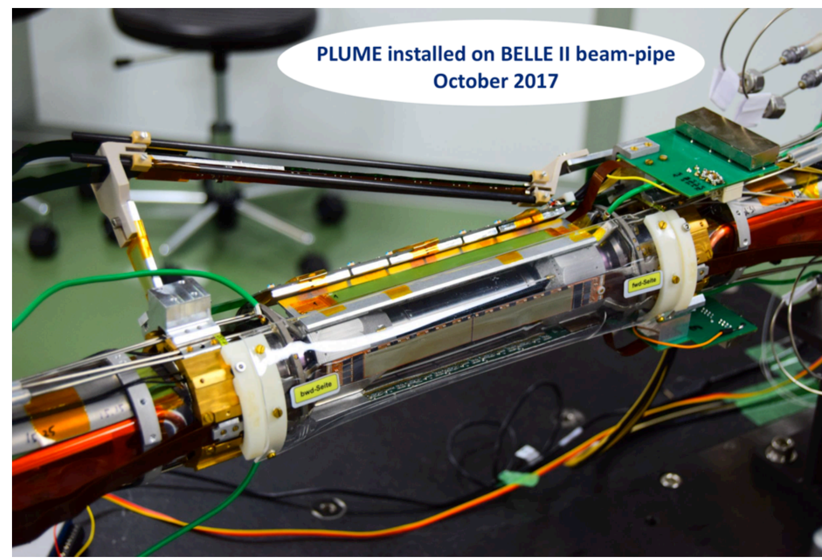
Proof that MAPS are easily integrated

Layers for the ILC-vtx

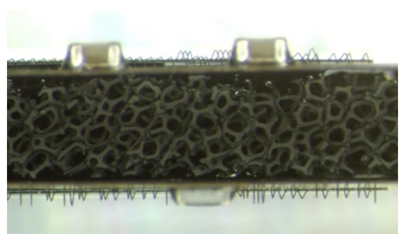
- PLUME project
  - DESY-Hambourg, Uni. Bristol, IPHC







Two position measured
Thickness 2 mm
8 Mpixels, 100 µs, 10 g
9 Watts (air cooled)

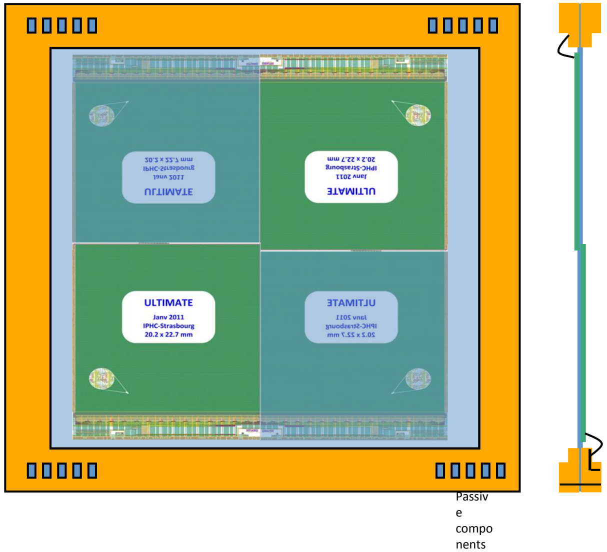


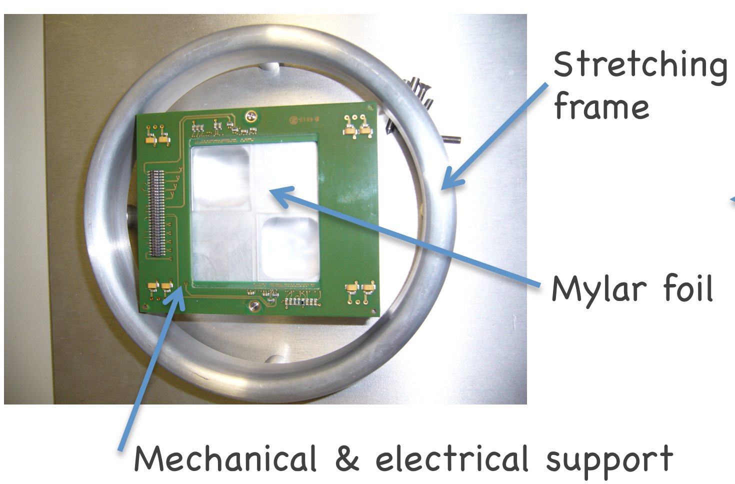
Side view

Single Arm Large Area Telescope

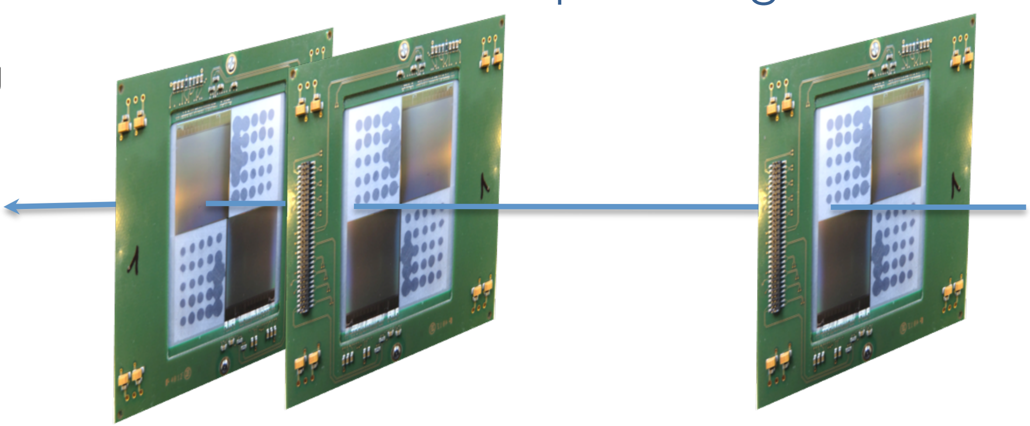
- [Basic sensor]
  - MIMOSA-28 thinned to 50 µm
- [Assembly]
  - stretching 50 µm-thin Mylar foil
  - gluing 2 staggered sensors on each side
- [Basic numbers]
  - 3.6 Mpixels over 15.3 cm^2
  - 190 µs integration time
  - cracks = central vertical band about 100 µm

Sensing area = 4x 3.8 cm^2





Telescope configuration

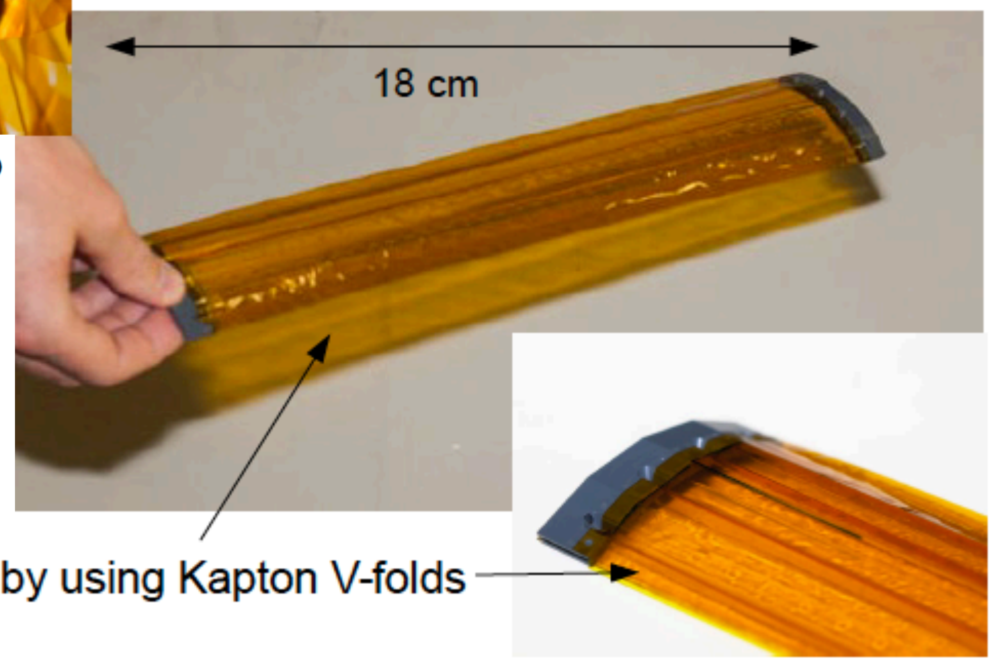


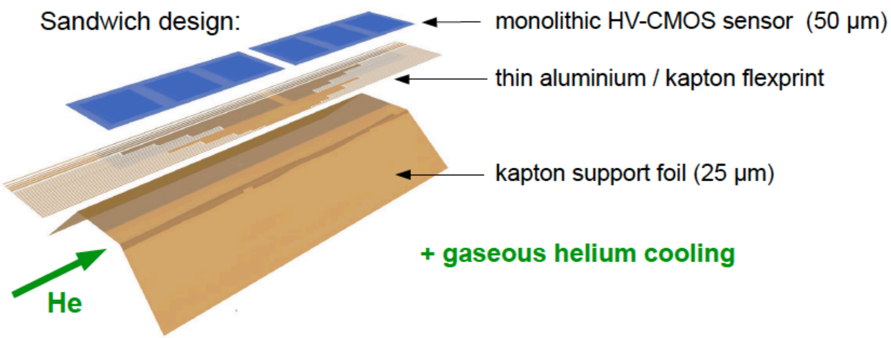
Mu3e – VTX concept

Ultra-thin mechanical mockup:

- sandwich of 25 µm Kapton®
- here 50 µm glass (instead of Si)

Even larger stable structures possible





$X \leq 0.1\%\ X_0$ per layer possible

by using Kapton V-folds

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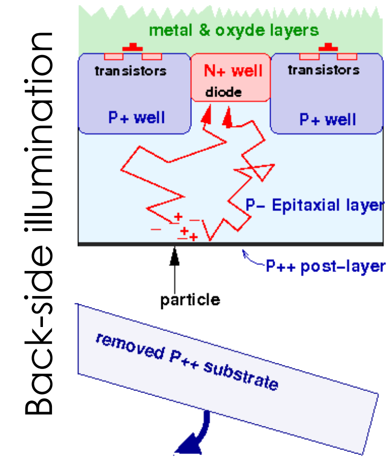
Non tracking applications

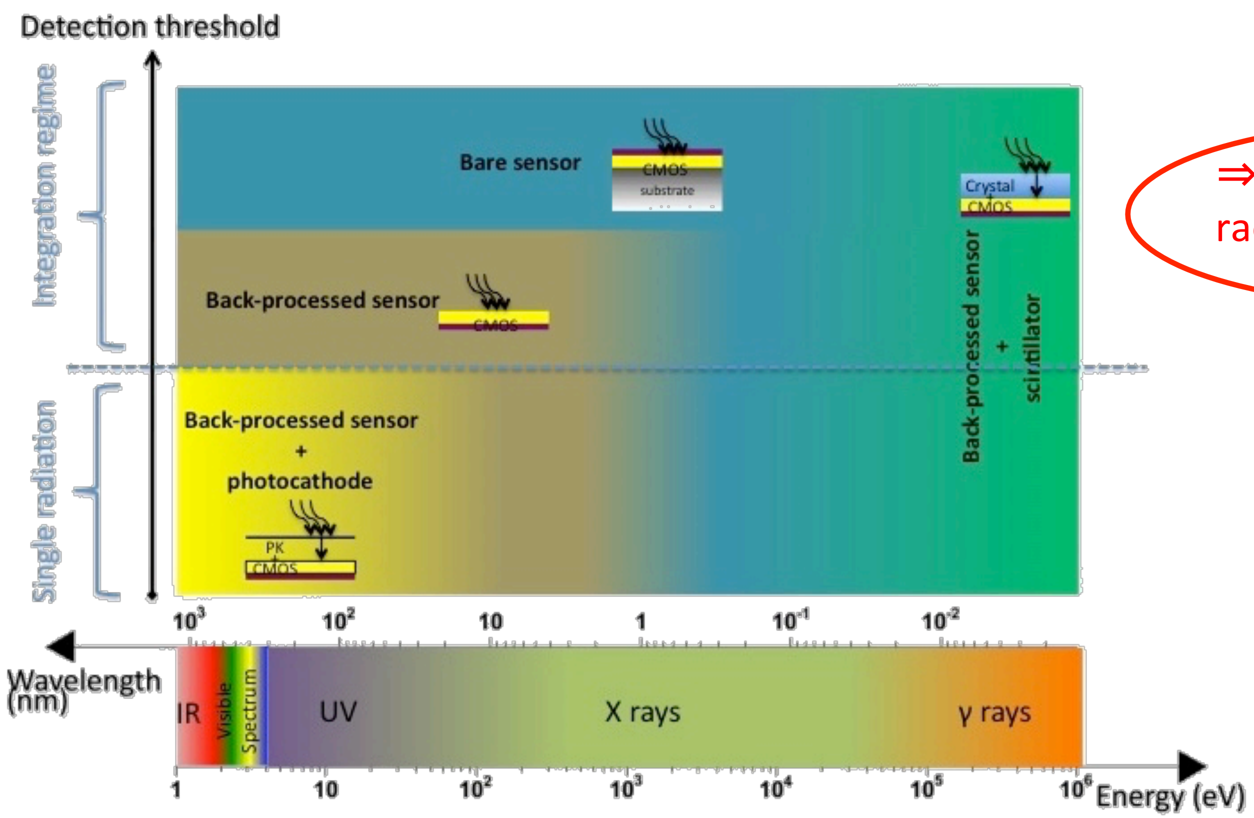
- *Calorimetry !*
- *Molecular imaging*
- *X-ray counting & spectrometry*
- *Autoradiography*

Sensitivity to radiations

- **Charged particles**
  - Low ENC → easy detection for E_{loss} ~ keV
  - Sensitivity to all spectrum
    - Limitation to low penetrating part. (e- of few keV, α)



- **Photons**



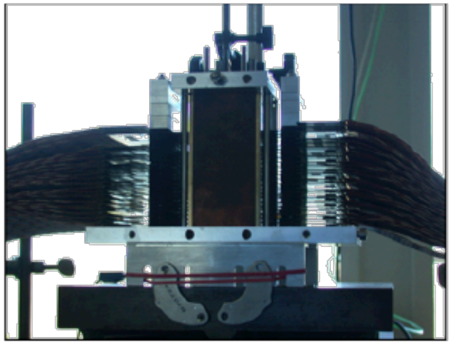
⇒ Sensitivity depends on radiation stopping power

FOCAL

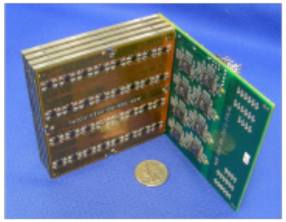
T.Peitzman et al., arXiv:1708.051

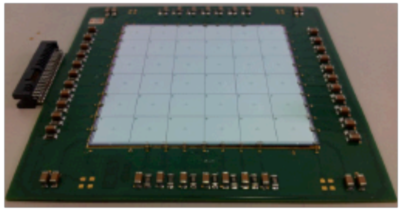
- High-Granularity digital electromagnetic calorimetry
  - Stack of (tungsten + MAPS) layers

24 layer pixel detector



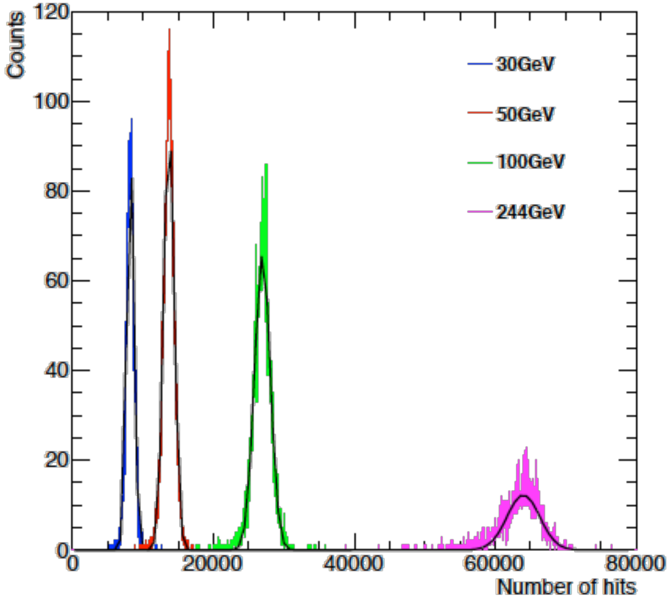
Pad layer integration





Several groups involved:
  Full prototype with pixel detectors
  CMOS (MIMOSA) 39M pixels,
  30μm pitch
    use synergy with R&D for ALICE ITS upgrade
  Full prototype with pad readout

Performed systematic tests:
  Test beam data from 2 to 250 GeV (DESY, PS, SPS)
  Cosmic muons



- response to electrons from SPS test beam

- calculated from per-event hit density distributions

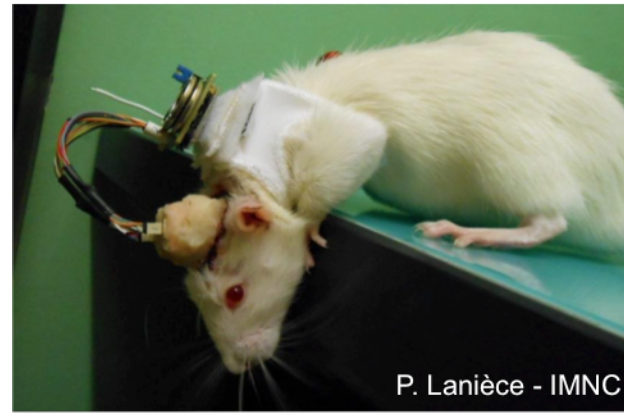
Utrecht/Nikhef (Netherlands),
Bergen (Norway),

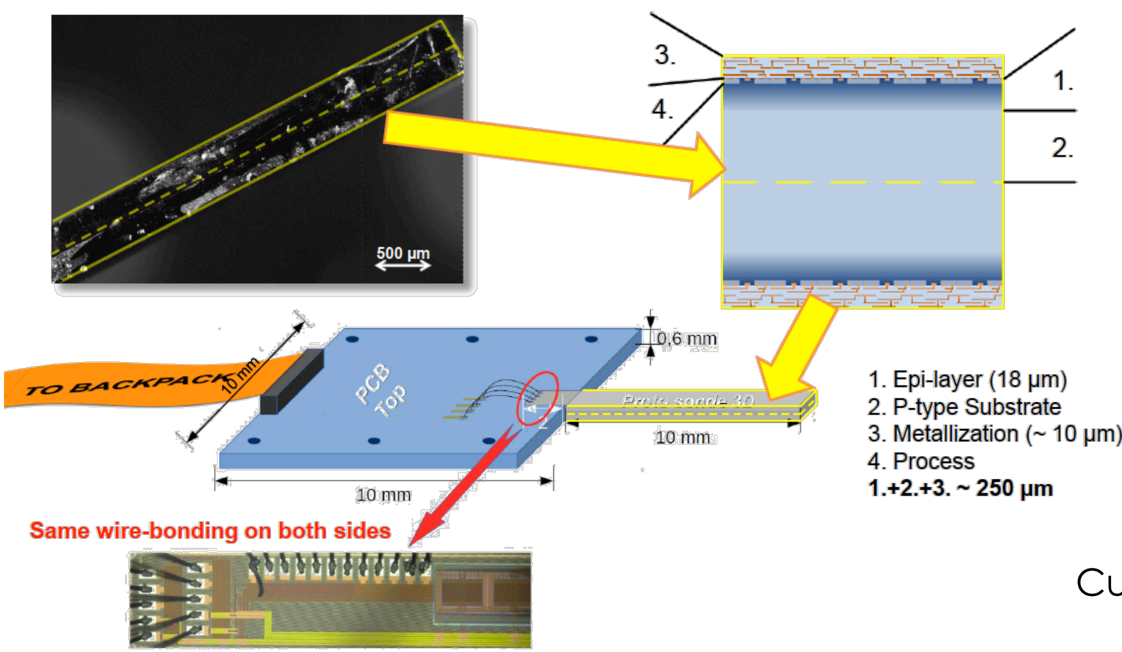
Tsukuba, Nara, Hiroshima (Japan),
ORNL (US)
VECC Kolkata,
BARC Mumbai (India)

R&D Activities with Si-pad/W Calorimeter Prototypes (Japan/ORNL, India) not covered here

Charged particles dosimetry

- Molecular imaging with β+ emitters in moving rodent
  - MAPSSIC: extreme integration in specific environment
    - Constraint on size and power dissipation
    - IMNC, IPHC, CPPM, CERMEP, NeuroPSi
  - Exploit CMOS sensors derived from ALICE
    - One active probe = 160 µW
    - For few counts / s
    - Wireless connection



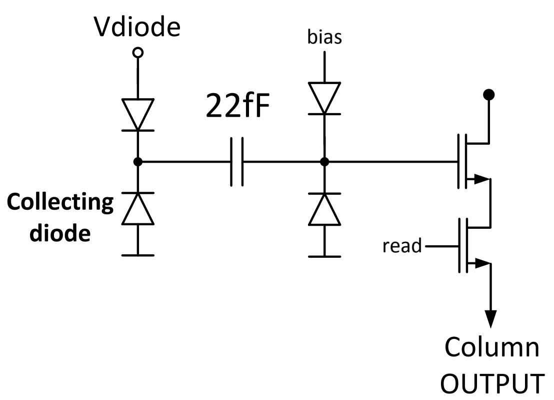


probe in the brain :
- section ~500x500 µm²
- sensitive volume (18 um) immune to γ

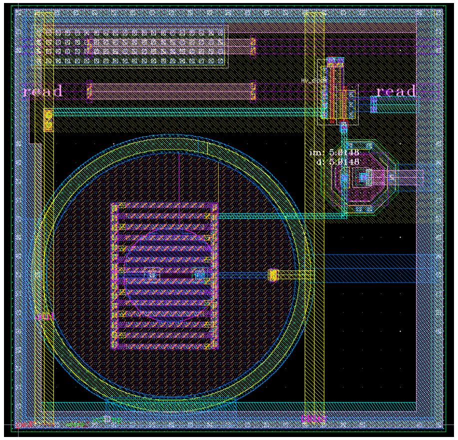
Currently integrating prototype sensor …

Depletion on prototype sensors

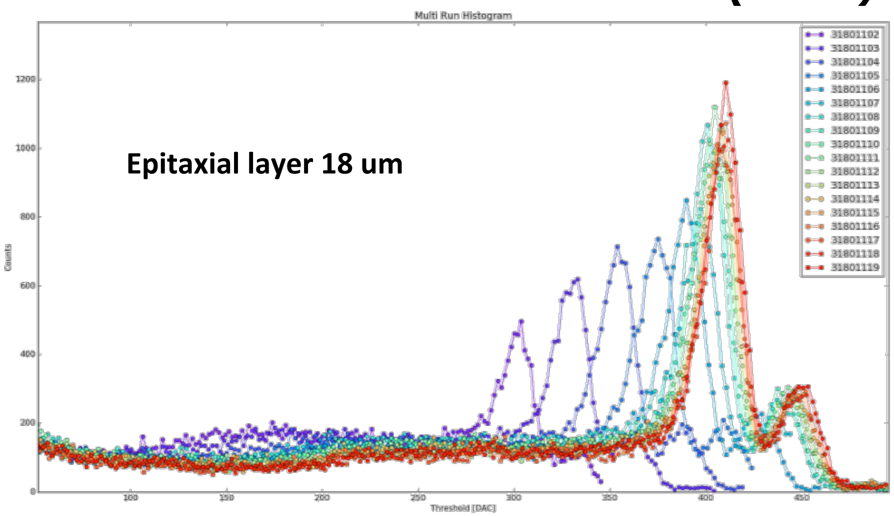
- PIPPER-1 (2014), PIPPER-2 (2016), PIPPER-3 (2017)



- Prorotype chip 32 x128 pixels
- Analog outputs
- Pixel size 22x22 µm
- AC coupled collecting diode
- Produced on two substrates:
  - Epitaxial layer 18µm
  - Czochralski substrate



^{55}Fe irrad. function of diode bias (1-19V)



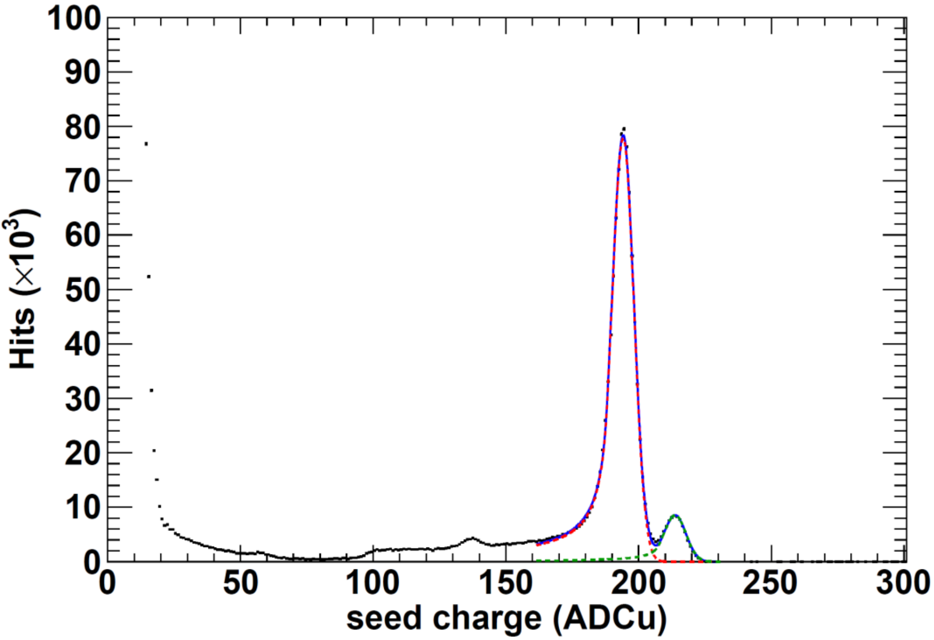
Energy resolution

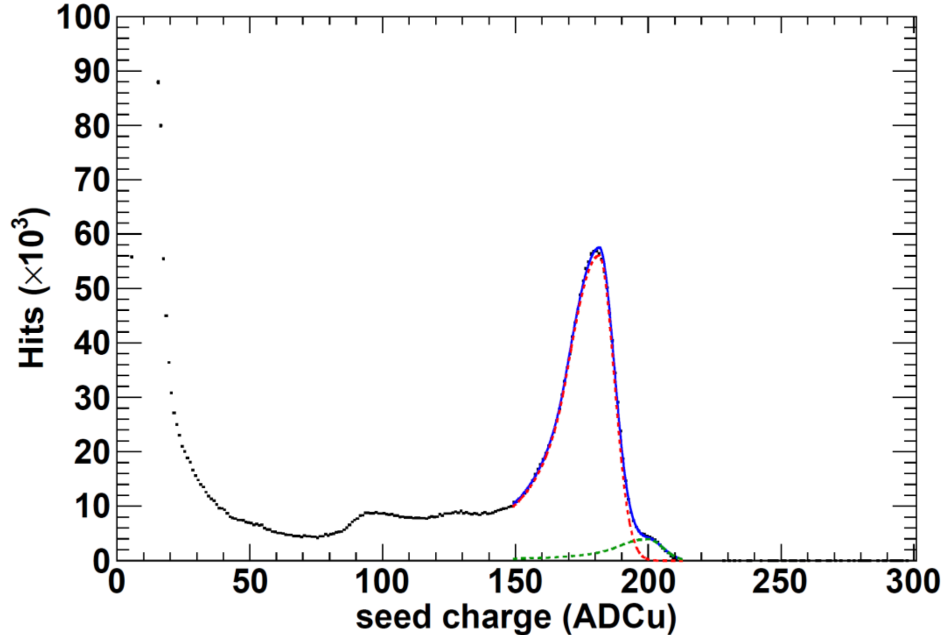
After clustering → Seed pixel distribution

- Energy resolution dominated by collection fluctuation on charge coll. (full thickness sensor)

- **HR-18**
  - ENC = 24 e^- (eq to FWHM ~200 eV)
  - FWHM (5.9 keV) = 298 eV
  - 30.38 eV/ADCu
  - Si escape peak visible (138 ADCu)
  - 75 % charges collected on the seed pixel

- **CZ**
  - ENC = 26 e^-
  - FWHM (5.9 keV) = 686 eV
  - 32.51 eV/ADCu
  - Mn-Kα and Mn-Kβ merging
  - 68 % charges collected on the seed pixel

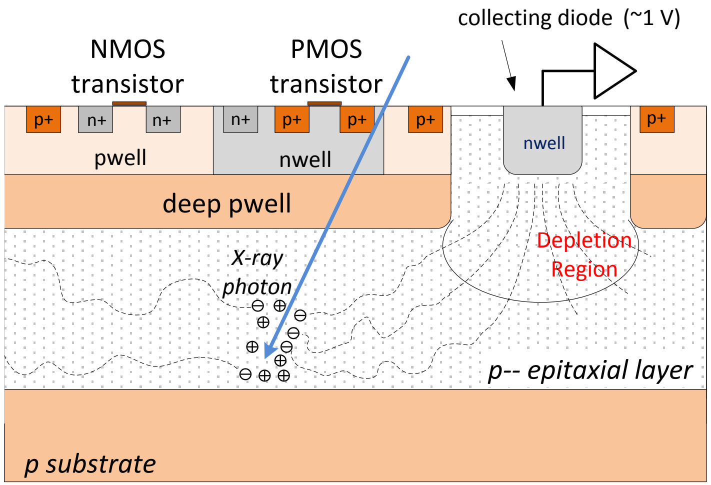




Pipper-2 measurements (presc. 2, $T°_{cool}$=7 °C, V_{diode}=30V) ^{55}Fe irradiation – 400000 frames

Engineering the sensitive layer

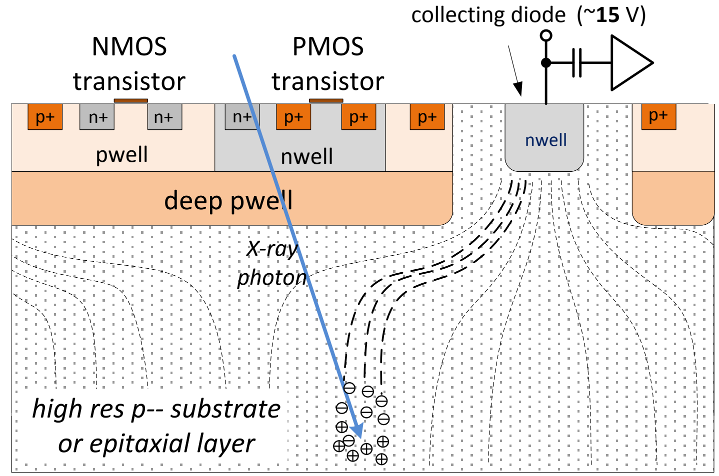
Low-resistivity layer
(the std old way)



Charges move MOSTLY from therm. diffusion

- Long (~100 ns) collection time
- Important charge sharing

Depleted MAPS
(the new way)



Charges move MOSTLY from E drift

- Short (< 10 ns) collection time
- Low charge sharing

Back-side illumination

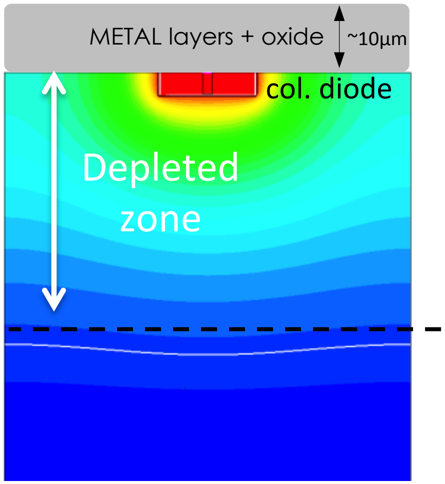
- Substrate removed (50 µm easy in industry)

- Sensors too thin (~20 µm) ➡ front support
- Complex connexion (costly)

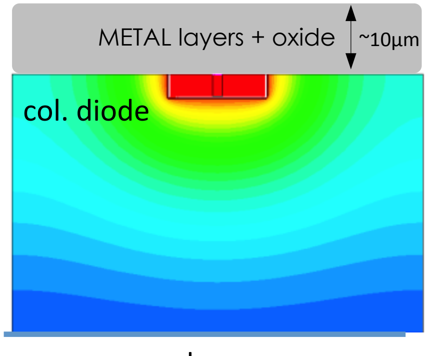
- Could stay thick ➡ no complexity

Back Side Processing

- Goal: « costless » BSI sensor

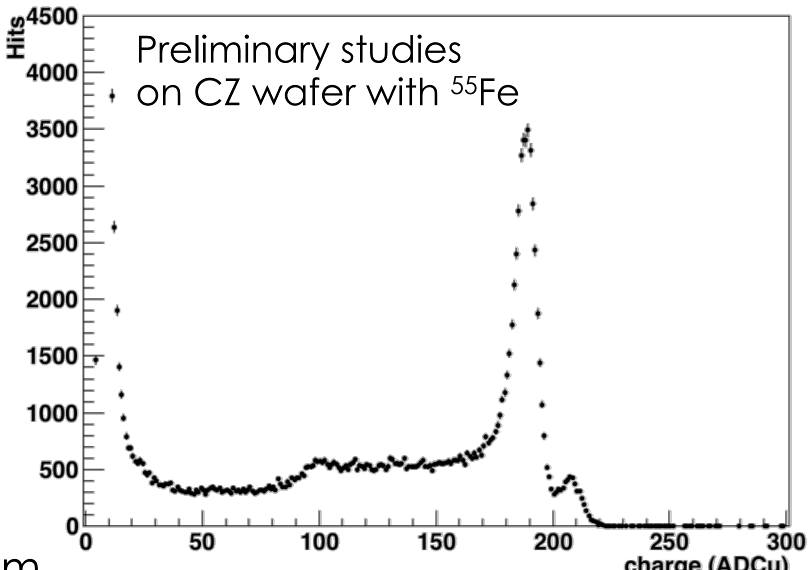


[J. HEYMES]



- **Thinning 50 µm**
- **Ion implant**
- **Annealing**

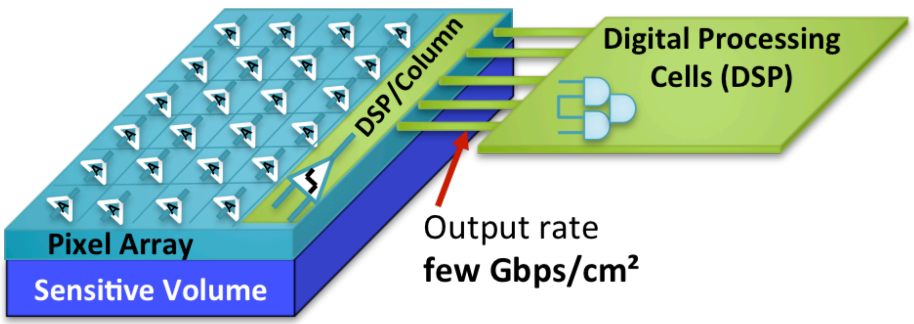
Post processing done in Jan 2017



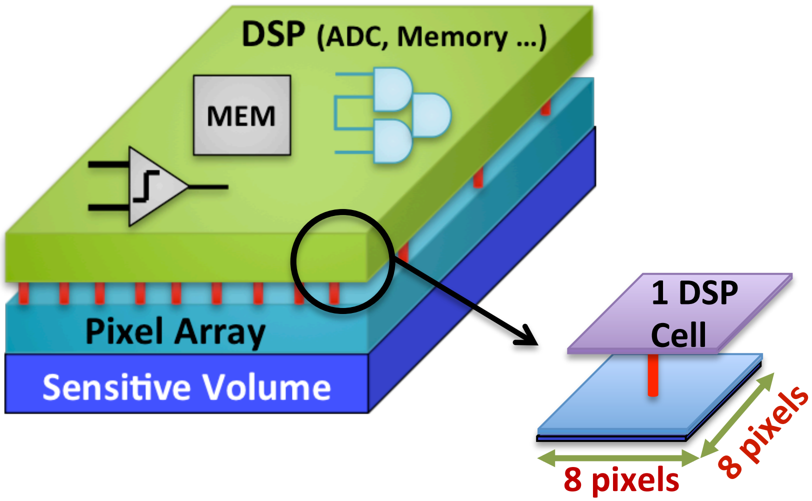
➡ Depletion depth under investigation: 25-40 µm

Photon counting?

- 2D architecture
  - 1 sensor = **SYNAPS-2D**
  - Rolling shutter with // columns analogue signal readout
    - 100-200 ns readout per row
    - About 512 rows
  - Digitization (binary) at column end with energy window
  - Dynamic range 1-2x10^4 photons/pixel/s



- Mid-term → 3D architecture
  - 1 sensor + 1 DSP chip = **SYNAPS-3D**
  - Local rolling-shutter within submatrix
    - 1 µs readout per submatrix
    - ~10 photons (5 keV) dynamic per pixel
  - Digitization + Memory in DSP
  - Dynamic range 1-10^7 photons/pixel/s



Prototype small pixel X-ray counter

- Counting Low energy X-ray - Mimosa 22SX

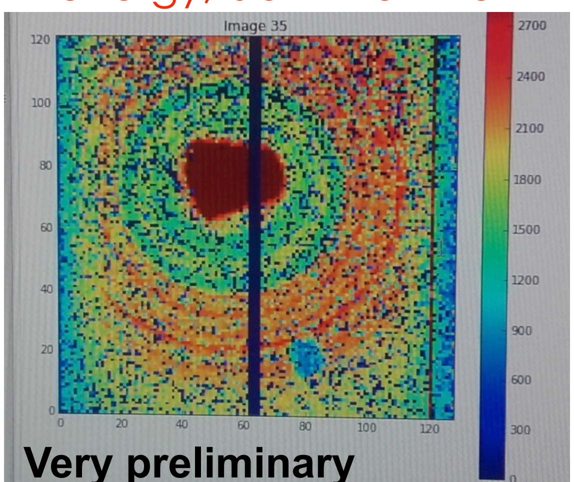
SOLEIL SYNCHROTRON

Requirements:

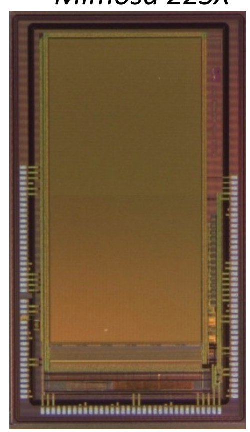
- X-Ray Energy Range [**few 100 eV – 5 keV**] with 100% QE
- Counting Dynamic [1-10^7] ph/pix/s
- High Spatial Resolution (pixel pitch ~ 20 µm)

Test at HERMES beam-line

- F.Orsini *et al.*
- Simple pin-hole diffraction
- Low energy, down to 1 keV

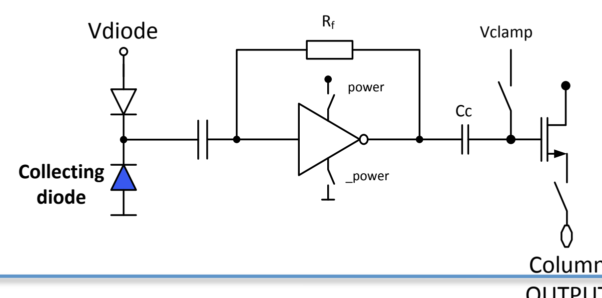


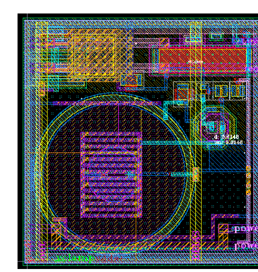
Mimosa 22SX



First 2D prototype specs

- Tower Jazz 180 nm CIS
- 128 x 256 pixels with 22µm pixel pitch
- Collecting diode AC coupled to the amplifier
- Discriminator with 2 thresholds
  → energy windowing
- Binary outputs
- 16 mm² of active area





A spin-off application for M22SX

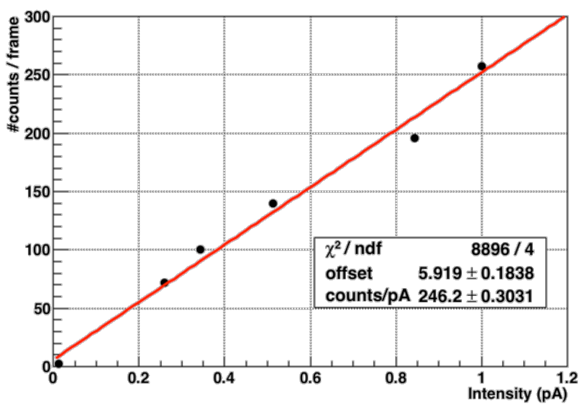
- Dose Monitoring by counting

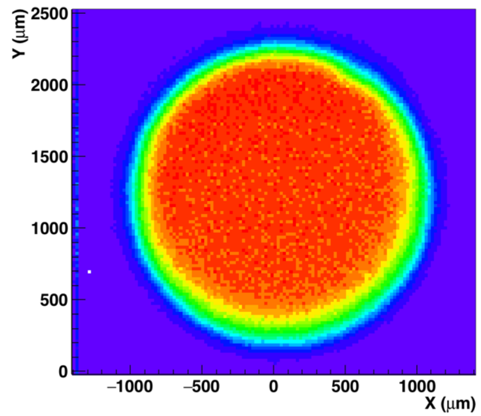
CYRCé Cyclotron at IPHC:
- 24 MeV protons
- Millimetre beam size for small animal proton therapy

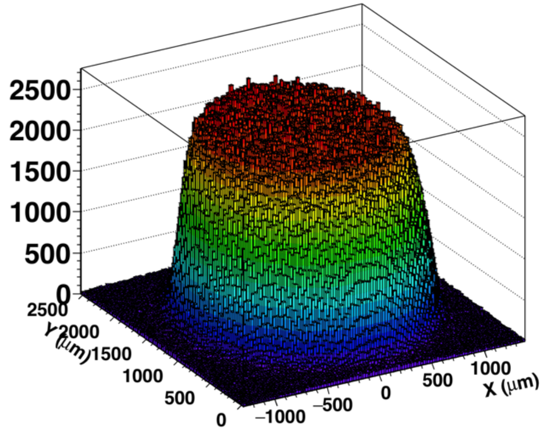
CYRCé
Cyclotron pour l'enseignement et la recherche

Motivation:
Monitor dose for small beam size (problematic with current detector)

First tests with Mimosa 22SX
- Linear behaviour in the measured fluence range
- At least 1000 protons/pix/s possible

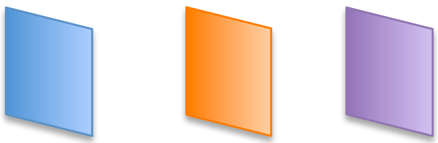






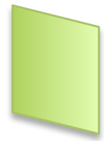
DREAM of electronic emulsion

- Let's stack!

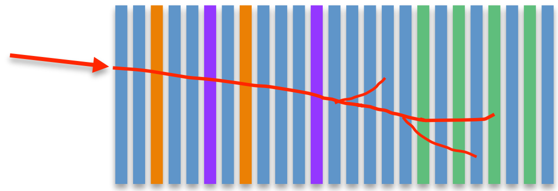


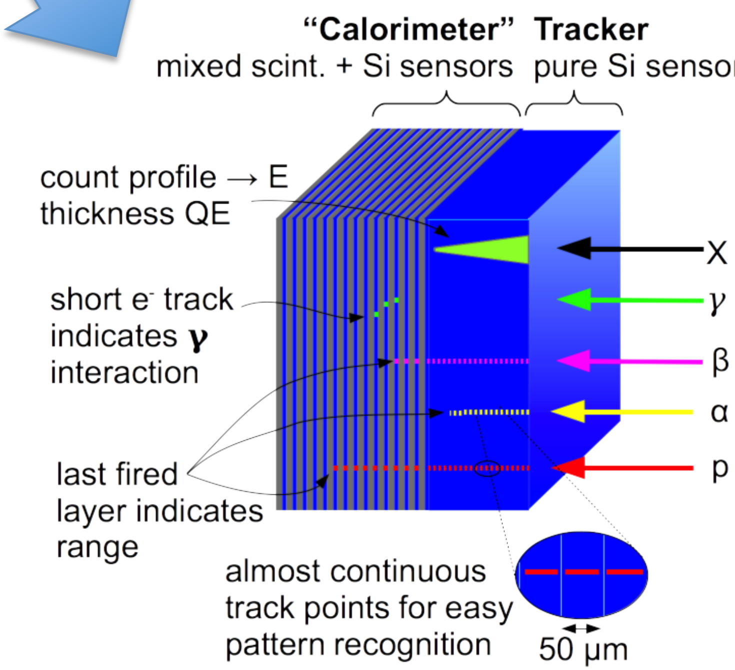
σ_{space} σ_{energy} σ_{time}

CMOS pixel flavours with sense layer ~ 100 % thickness



scintillator /converter





➡ **Fast electronic equivalent of a nuclear emulsion**

- **8D measurements**
  - 3D position + 3D direction
  - 1D time
  - 1D energy (range / sampling)
- **Adjustable performances**
  - Stack re-shaping (~~sensor redesign~~)

Conclusion

- Historical perspective
  - CMOS Image sensors started ~60 years ago
    ➡ customisation into the Si sensor world
  - Scientific version of CIS (sCMOS) started ~ 20 years ago
  - CMOS pixel sensors (MAPS) for charged particle tracking started ~ 20 years ago
    - Very few labs in the high-energy physics community
- Currently a lot of activities
  - CMOS processes are evolving quickly
    + corresponding integration technologies
  - Many labs and design companies are pushing various performances
    - Ex: spectrometry, electron multiplying CMOS, …
  - In Strasbourg, 2 architectures emerging:
    1. Fast binary outputs
    2. Energy deposited measurement outputs
- Outlooks
  - More applications to be expected
  - Complex landscape, time to know what you want (cost, specs, …)

ADDITIONAL SLIDES

CMOS Image Sensor (CIS)

- Main markets
  - Customers (camera, smartphone, …)
  - Industry (machine, automotive,…)
  - Medical imaging

Pixel size 1-2 µm
Frame rate ~ video
Integration camera (~~single quanta~~)

➡ Main markets = technology drivers

- CCD vs CMOS

$$\frac{CMOS}{CMOS+CCD}$$

20% in 2012 → 99% in 2020

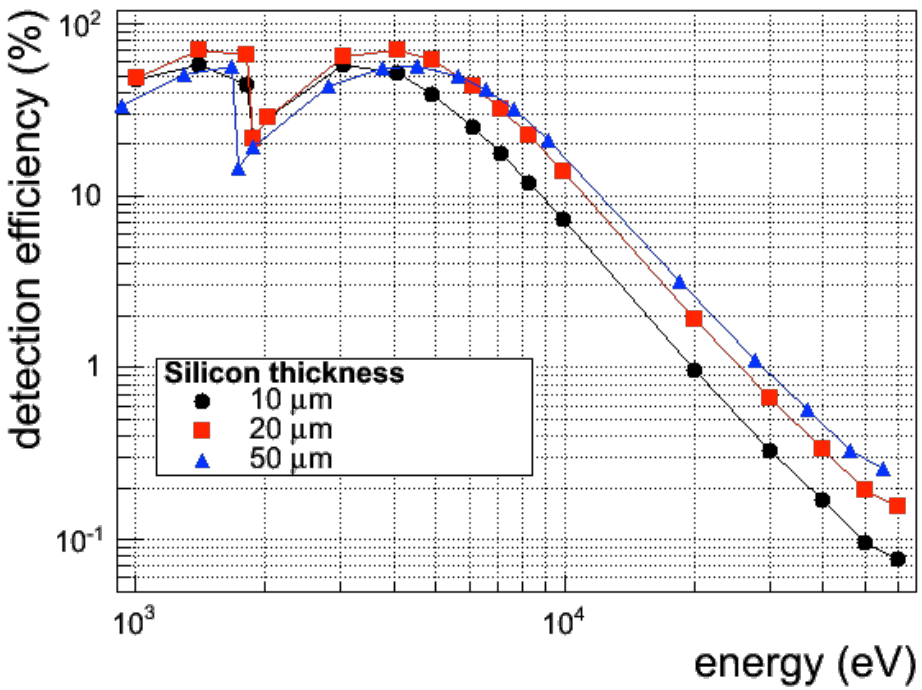
- CMOS camera yield > few billions/year
- Main reason: cost and now performances

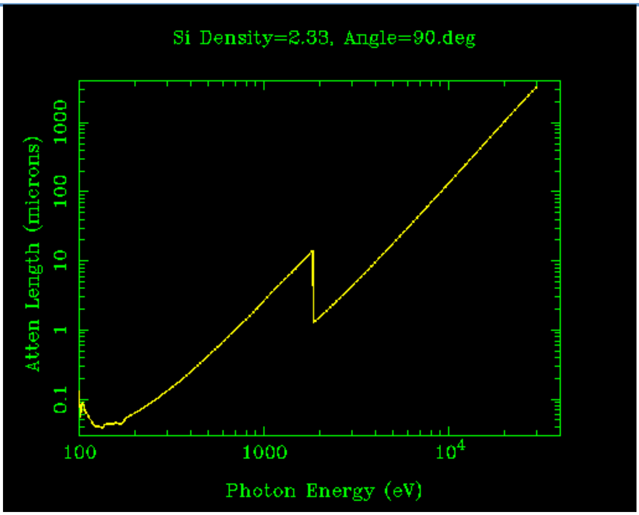
- Foundry examples
  - **SONY**
    - Main world player
    - Ex: Backside illuminated sensor "stacked" camera (sensor + readout)
    - 60000 wafers / month
  - **Tower-Jazz**
    - Small & very focused player
    - Ex: Medical application sensor
    - Few 1000 wafers / year

X-ray detection

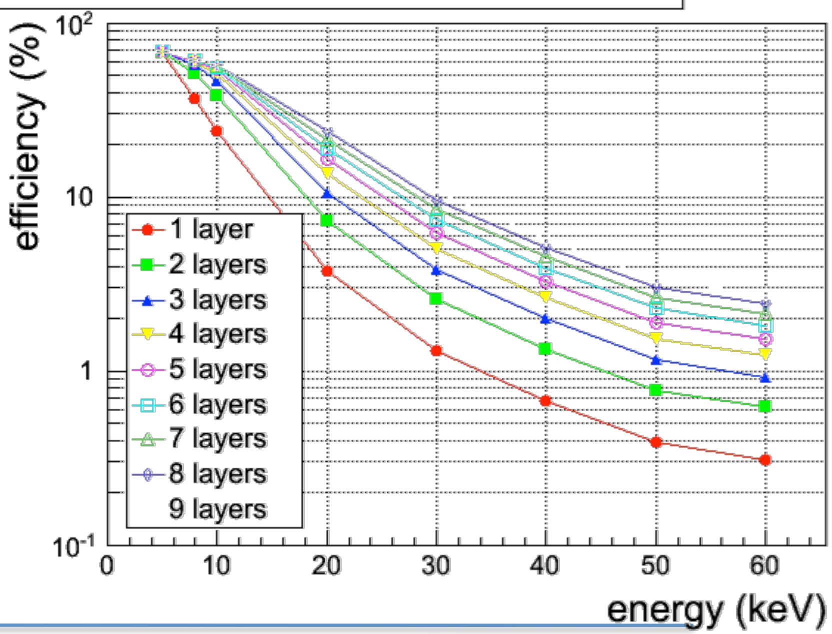
- [Silicon weak point]
  - μ drops quickly with E

Beer-Lambert law: $1-e^{-\mu x}$



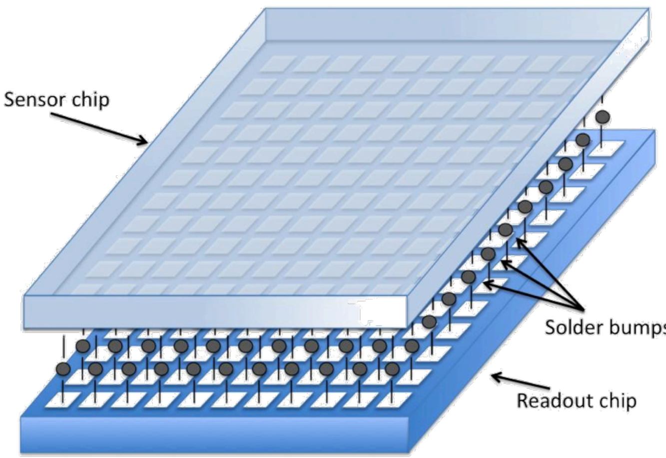


Efficiency wrt energy for 40 µm thick layer



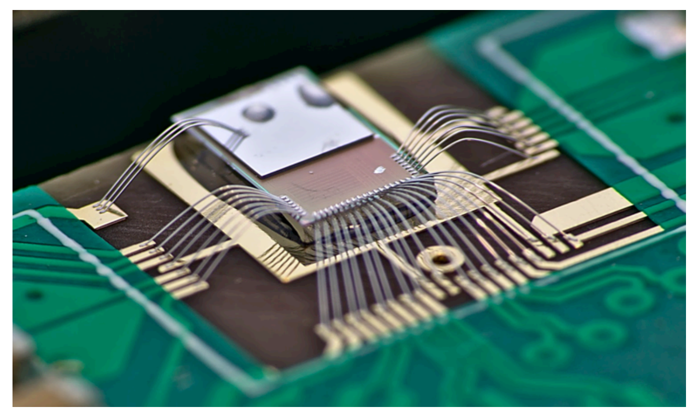
Hybrids (strips & pixels)

- THE standard approach in HEP
  - Implement powerful processing
    - Pre-ampli + shaper ⇒ time & energy resol.
  - Radiation hardness
    - Si type adapted
    - 3D sensors
  - Recently edgeless sensors



- "limitations" / pixels
  - Relatively large pixel size
    - Limited by bump-bonding & processing
    - Current ATLAS 50x250 μm^2, CMS 100x150 μm^2
  - Relatively thick ⇐ 2 thickness of silicon
  - Sensitivity to low ionizing particles
    - Typical minimal threshold ~1000 e-

- Developments / CLIC
  - targets pitch 25x25 μm^2
  - with thickness 50 μm (ASIC) + 50 μm (Sensor)
  - Some functional prototypes

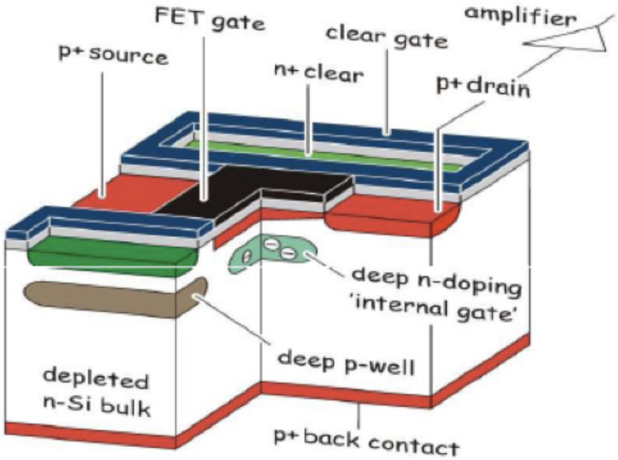


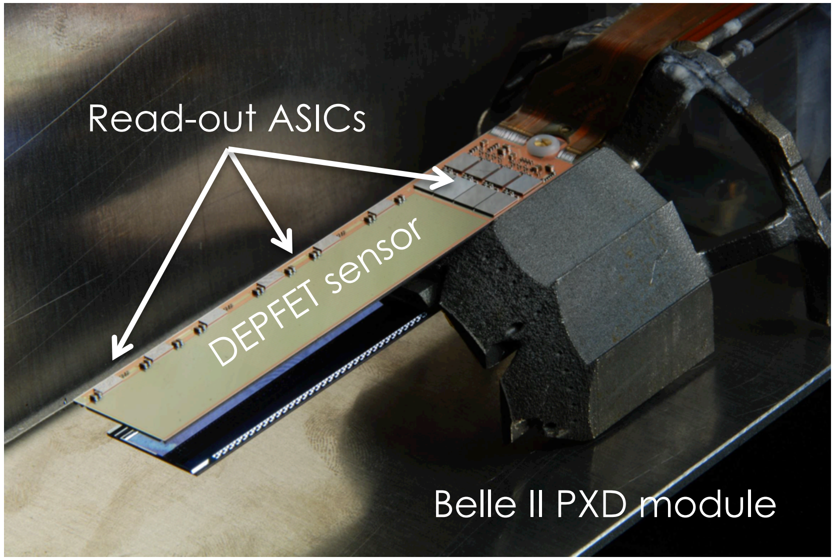
DEPFET

- A "monolithic" approach
  - Driven by imaging (X-rays, electrons)
  - Amplification in-pixel but no processing
  - Fully depleted volume
    300 to 50 µm (thinned)

- First detector for HEP in 2018
  - Belle II vertex detector (PXD)
  - The thinnest detector 0.18 % X_0 / layer
  - Pitch not crucial: 70 µm
  - 20 µs integration/read-out time

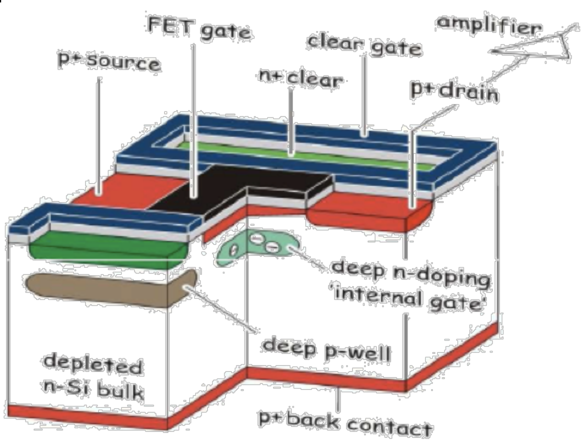
- Toward ILC
  - Smaller pixel 20 µm



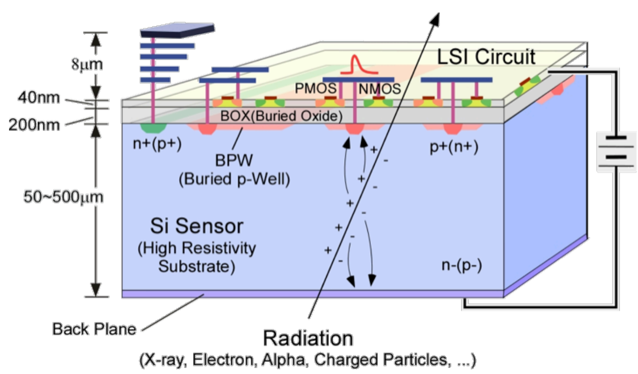


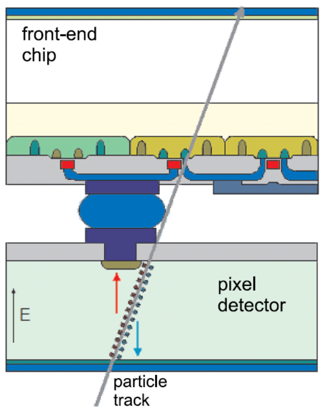
Pixel detectors in HEP (except MAPS)

- CCD
  - Very seldom used
  - Too slow & weak / TID, NIEL
- DEPFET
  - First application on-going
  - Small pixels possible
  - Fully depleted sens. Layer
  - Internal amplification BUT
    - needs read-out chipS
    - speed limited
  - Production site limited



- Silicon On Oxide (SOI)
  - Never used yet
  - Small pixel possible
  - Fully depleted sens. Layer
  - Embed processing
  - Sens volume decoupled from processing layer
  - TID issue solved (?)
  - Costly (?) process

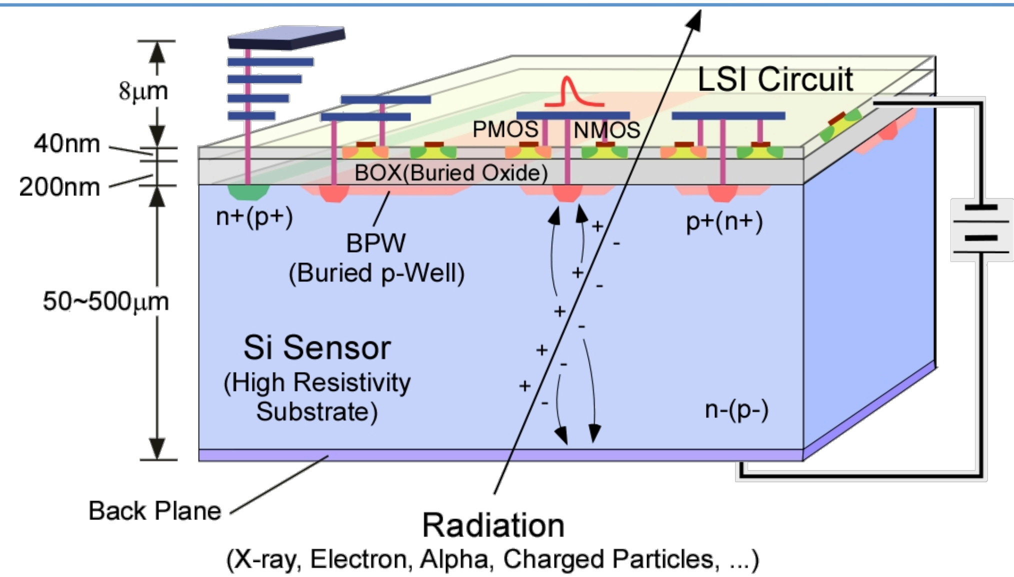




- Hybrid pixel
  - THE standard way
  - Small pixel hardly possible
  - Fully depleted sens. Layer
  - Sens volume decoupled from processing layer
    - Sensitivity limited
  - FEE on top of sensor
    - Increased mat. budget
    - BUT powerful processing ⇒ FAST
  - Bump bonding costly

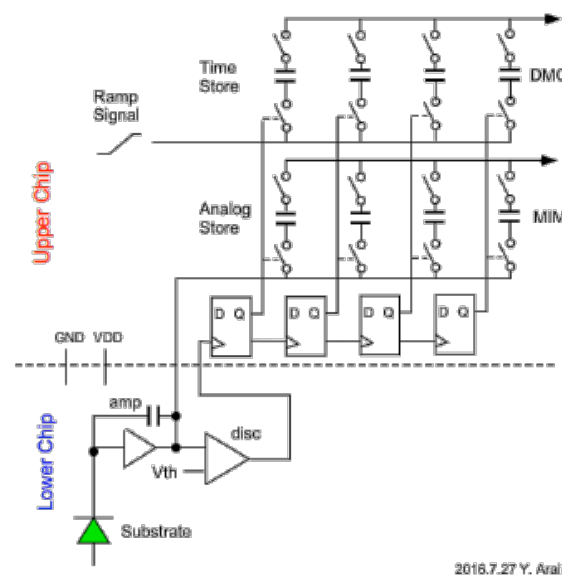
SOI

- A monolithic-hybrid ?
  - Includes fully depleted sensitive layer 50-700 µm
  - Includes processing power
    - less constraint / CMOS sensors
  - Large SNR
  - Relatively weak to radiation
    - thick oxide

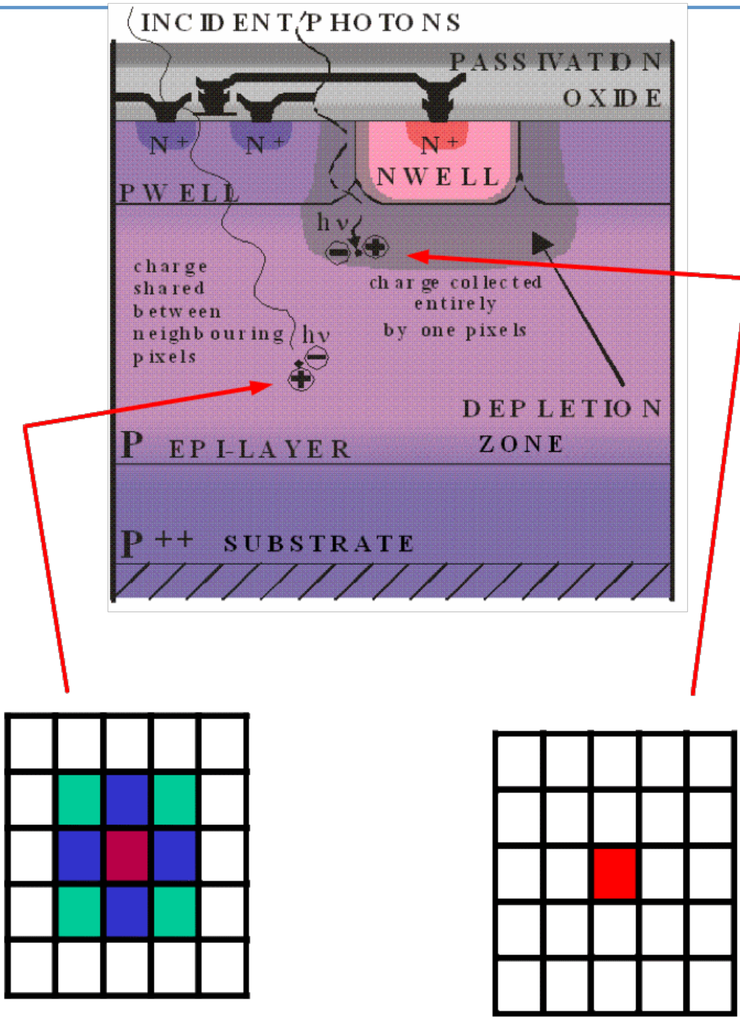


- Current usage
  - Mostly for imaging (X-rays)
    - Synchrotron, medical, astronomy, …

- Project in HEP: ILC
  - Enhanced signal treatment within 20 µm pixel
    - Spatial & time resolution
  - Still prototyping



Non depleted MAPS

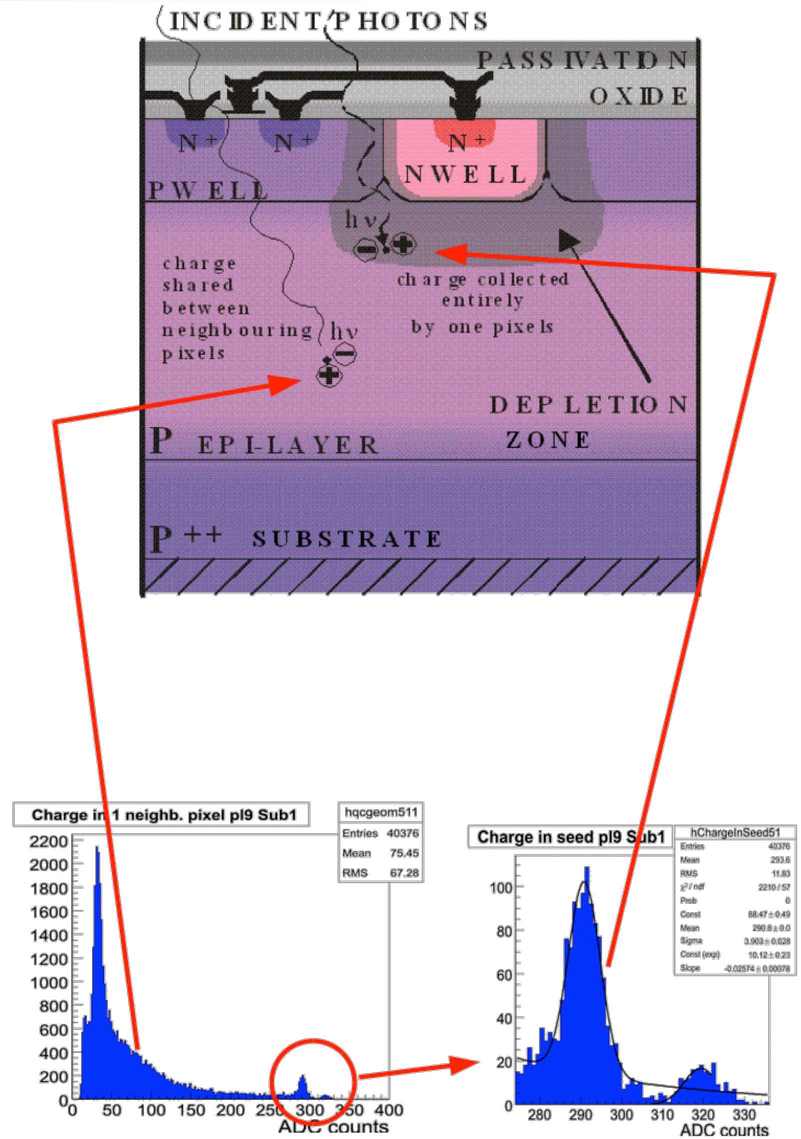


Cluster of hit pixels:

Σsignals ~ all X-ray energy
& low signal on central pixel

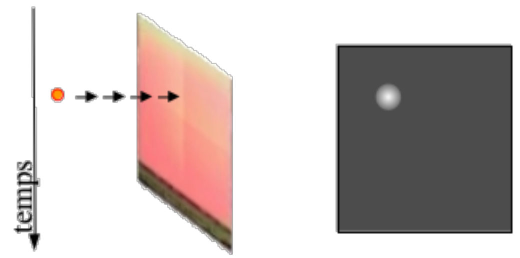
Single hit pixel:

Signal = all X-ray energy
(**calibration**)

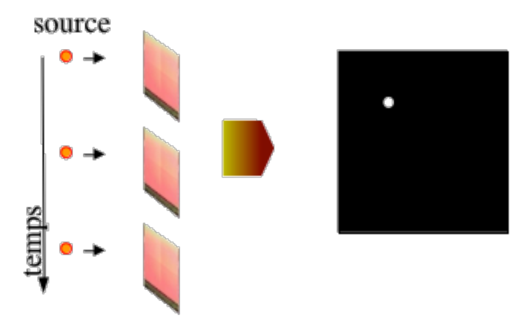


Preliminary remark: read-out

- Std imaging sensors ⇔ usually INTEGRATION
  - One channel signal = several quanta of radiations
  - Key parameters:
    - dynamic (full well), point spread function, noise
  - Single frame ~100% occupied
    - read-out relatively slowly (~video rate)



- Tracking sensors ⇔ COUNTING single particles
  - One quanta = several channels
  - Key parameters:
    - resolution (E, t, position), SNR, dark count
  - Single frame ≲1% occupied
    - read-out @ high-frequency (< 10 kHz)



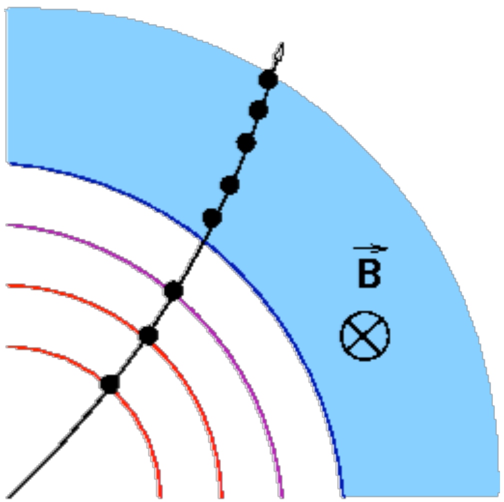
➡ Both can build image…with various qualities
  - Strong impact on read-out electronic design

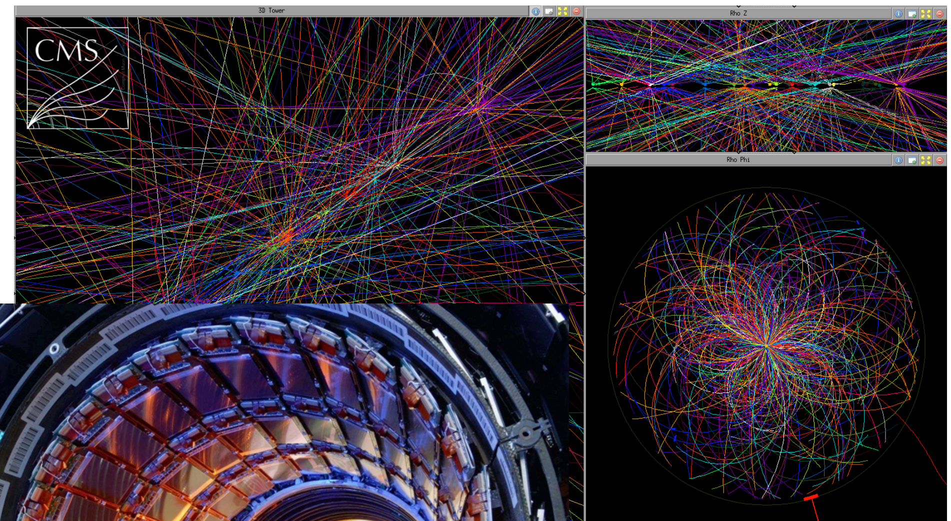
Tracking in High Energy Physics

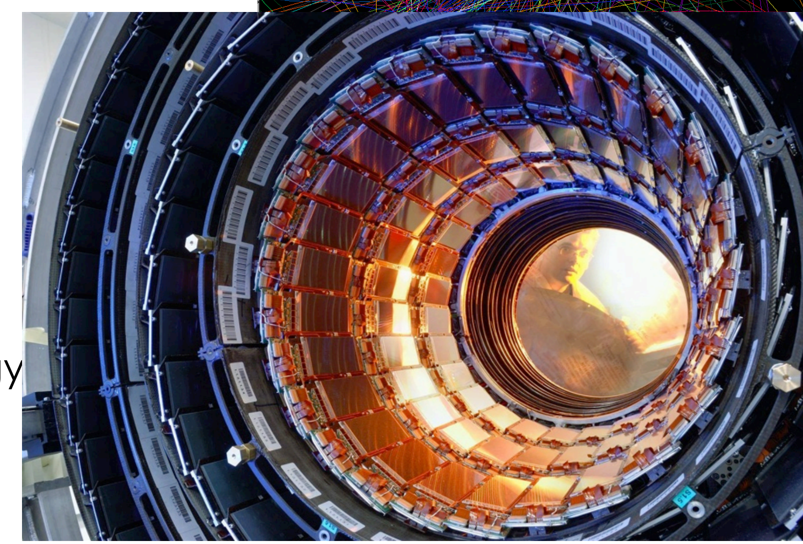
- Multi-layers are needed
  - Material budget (thickness) to be limited ≪ 1 % radiation length(X_0)
  - Power dissipation is a problem

- Events are complex…
  - Spatial resolution (2-20 µm)
  - Time resolution (ns to µs)

… BUT (almost) EMPTY wrt sensors







- LHC-CMS tracker
  - Full silicon technology
  - 210 m^2
  - 9.6 x 10^6 channels
  - few 10 Tbits/s

sCMOS versus MAPS

- Scientific CMOS (sCMOS)
  - Improved CIS
  - Essentially integrating detectors
    - Increased dynamic (full well)
  - Target generic applications

  - Keep small pixels (few µm pitch)
  - Speed up to 1000 kframes/s
  - Sensitivity
    with equivalent noise ~ few e-

- MAPS
  - Monolithic Active Pixel Sensor
  - Only counting detectors
    - single quanta
  - Target specific experiment

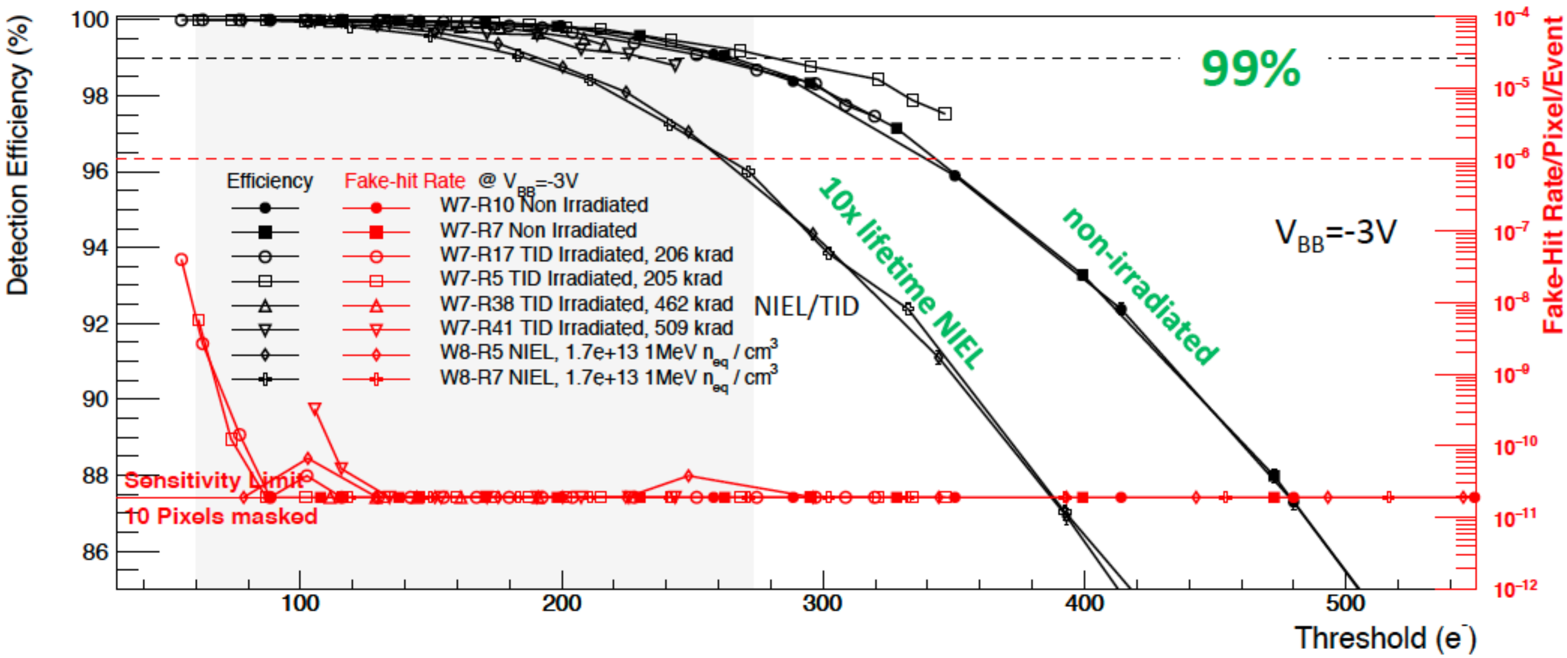
  - Pixel size adapted
    to desired resolution
  - Speed adapted to
    occupancy
  - Equivalent noise ~ 10-30 e-

Signal & Noise build-up

- Signal
  - Nb of charges on coll. diode depends on
    - Sensitive thickness
    - Potential distribution
  - Conversion factor (capa)
- Noise
  - Capacitance
  - Leakage current

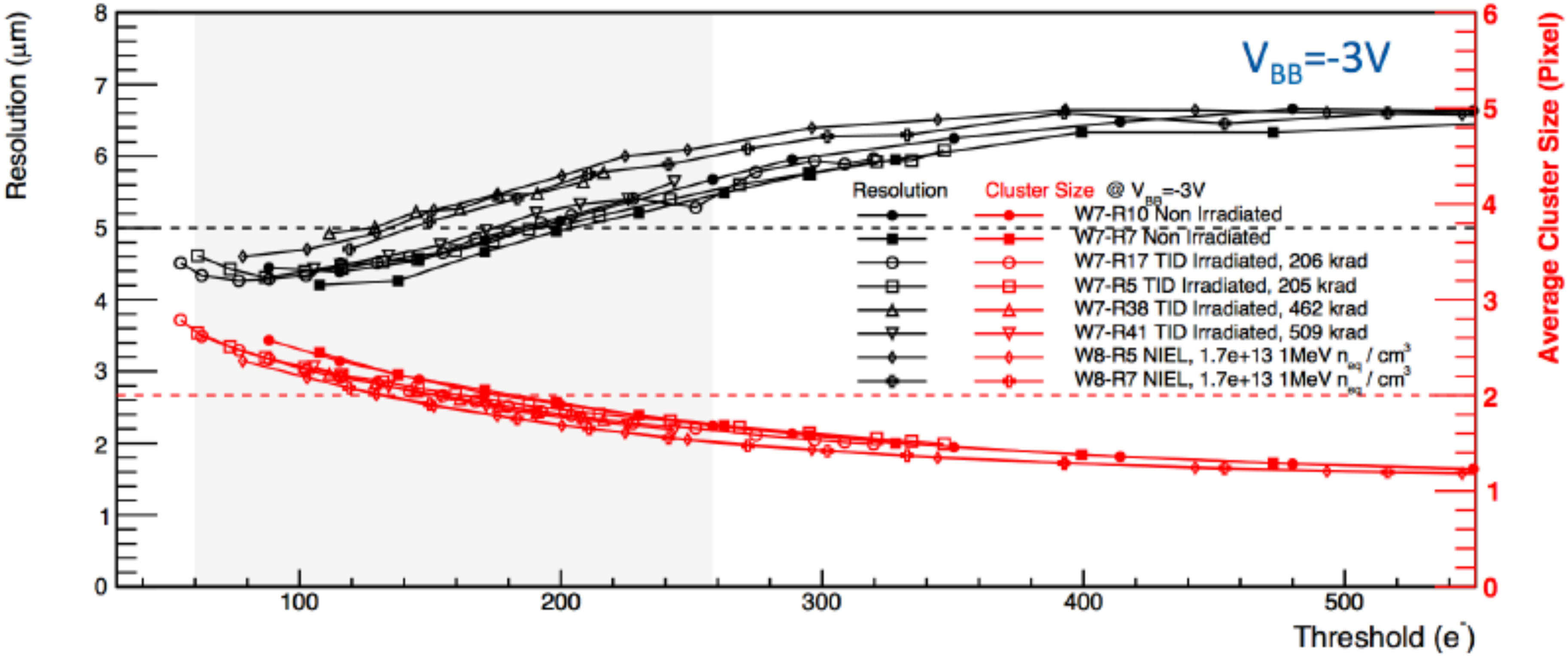
TID mitigation

ALICE - ALPIDE



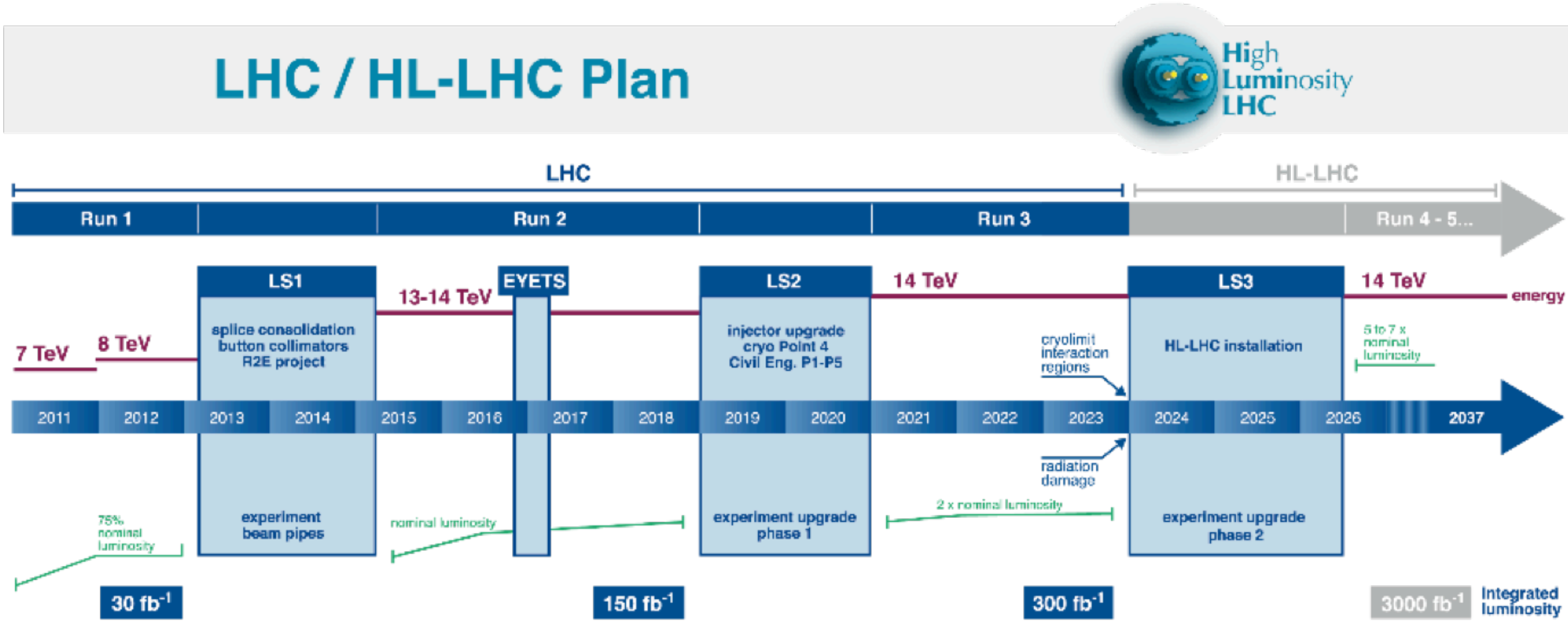
6 GeV/c π^-

ALICE - ALPIDE



6 GeV π^-

LHC timeline



The PICSEL group in Starsbourg

General web site: iphc.cnrs.fr/picsel

- Complementary expertise
  - Physicists: 4 staffs, 1 post-doc, 3 PhD students
  - Micro-electronics design: 11 staffs, 1 Post-docs, 2 PhD students
  - (Micro-)electronic test : 5 staffs

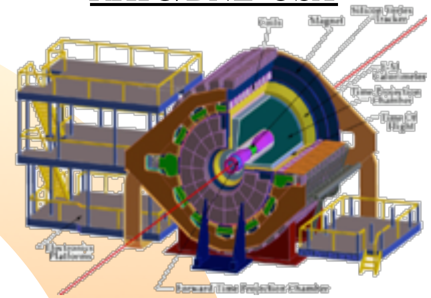
- Scientific production since 1998
  - ~70 publications, ~50 proceedings, ~14 PhD defended
  - ~50 CMOS Pixel Sensors (CPS) designed and characterized

- Partners
  - Academics:
    - CERN, , KEK (Japan), DESY (Hamburg), LNF (Frascati) USA (Berkeley, Brookhaven), IHEP in China, many University groups
  - CMOS foundries:
    - AMS (Austria), Tower-Jazz (Israel), TSMC(Taiwan), STM (France), ESPROS (Switzerland)

Scientific drivers for the PICSEL group

EUDET 2006/2010
CERN, DESY, …

STAR 2014
RHIC/BNL-USA

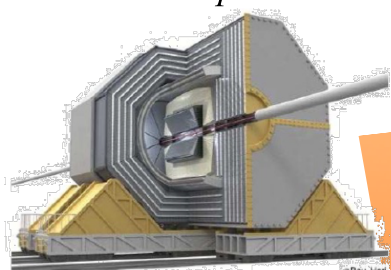


Tracking of charged particles
- *Subatomic Physics*
- *Hadrontherapy*

Imaging
- *Detection of ß, low energy electrons*
- *Detection of X-rays*
- *Dosimetry*
- *Hybrid photo-detector*
- *bio-inspired vision*

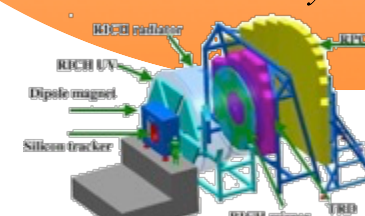
Belle II 2018
SuperKEKB-Japan

ILD ~2030
ILC-Japan

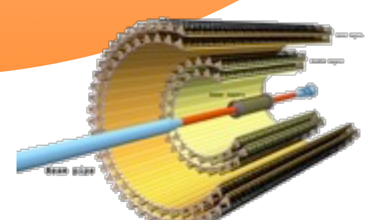


SOLEIL 2018
France

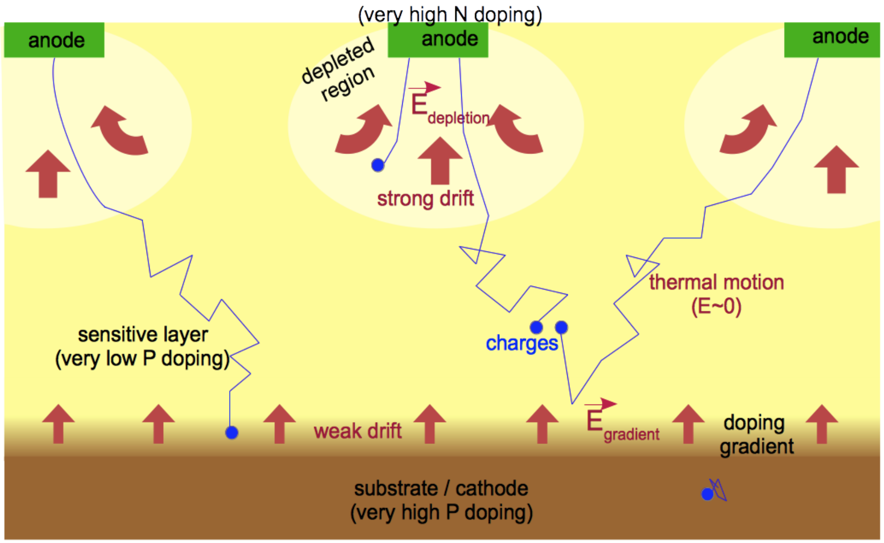
CBM >2019
FAIR/GSI-Germany

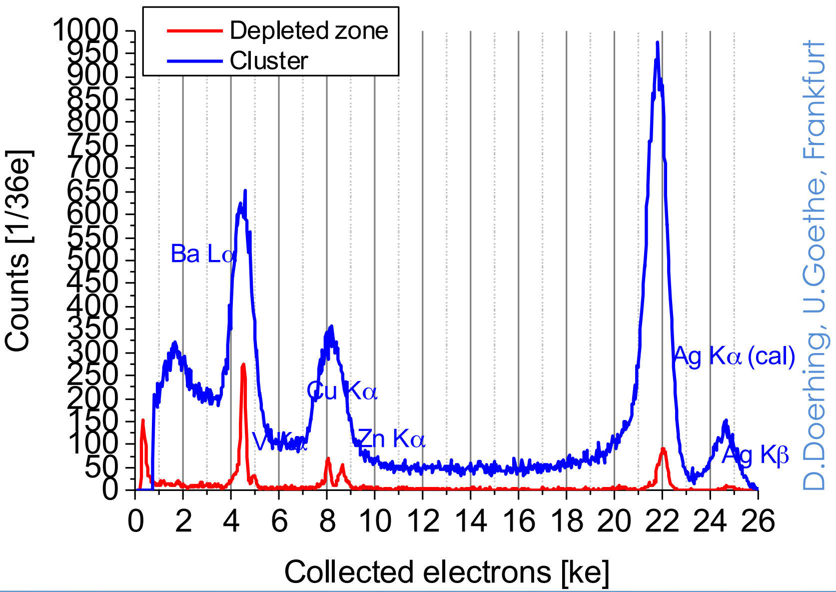


ALICE 2019
LHC/CERN

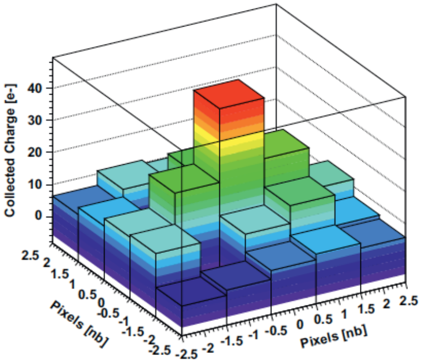


Standard "undepleted" MAPS



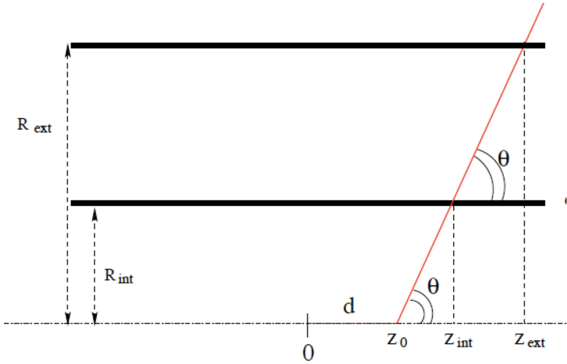


- **3 different E-field zones**
  - Zone extensions driven by
    - anode dimensions & spacing
    - anode/cathode potentials
- **Depletion drives performances**
  - Deeper depletion ➡
    - Shrinks charge sharing / pixels
    - Increases signal/Noise per pixel
  - Optimization required /
    - Detection sensitivity
    - Detection efficiency
    - Impact counting
    - Spatial resolution (or PSF)
    - Energy resolution

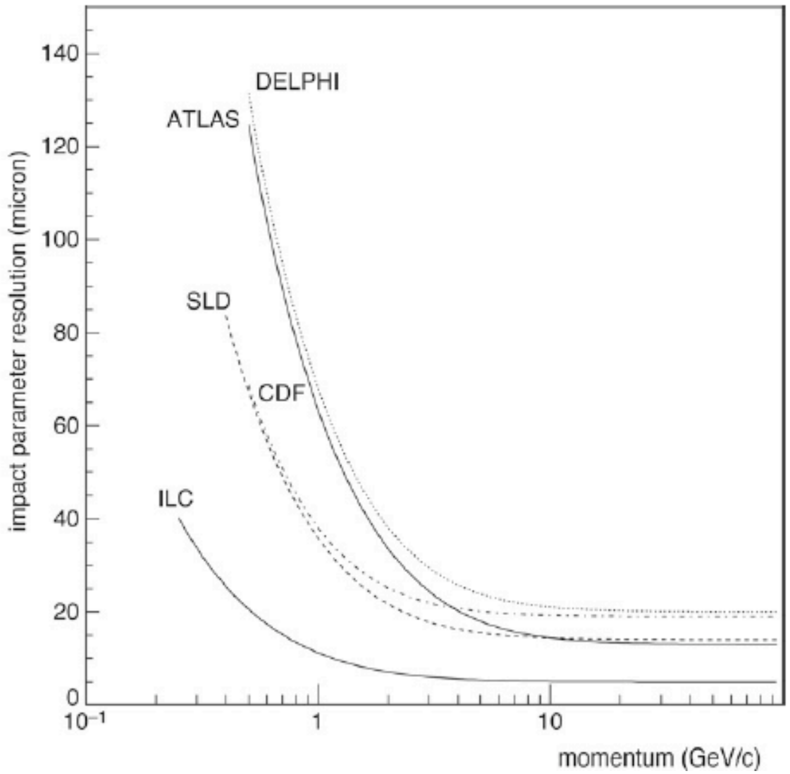


Charge cluster example (few keV electrons)

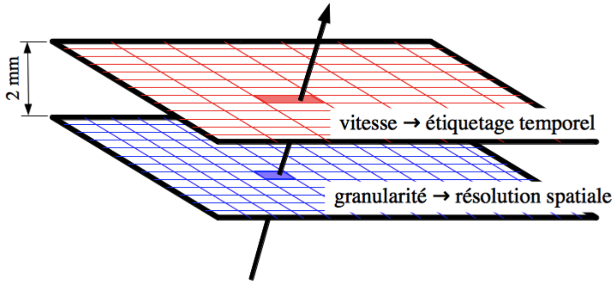
Impact parameter resolution

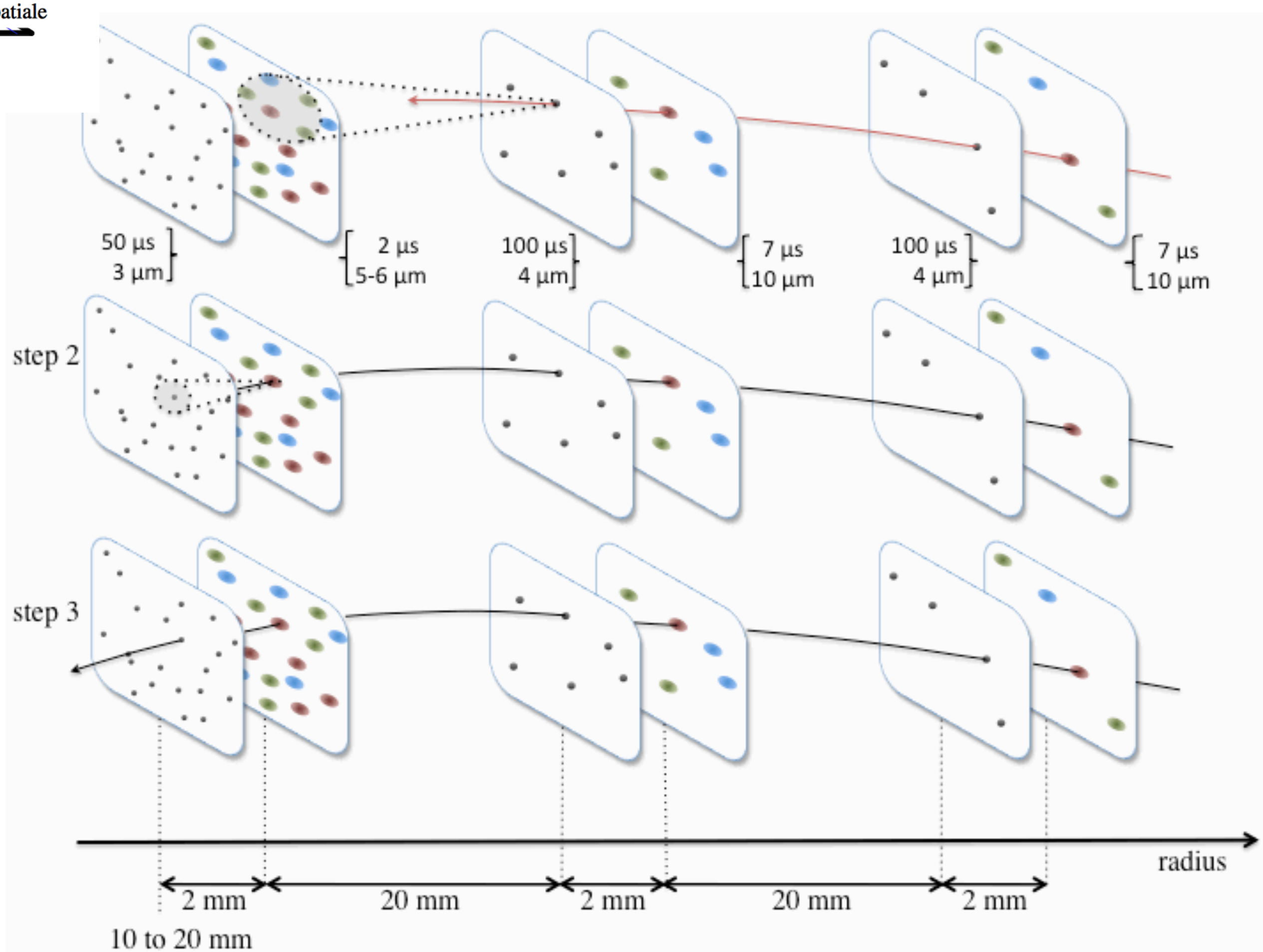


$$\sigma_{IP} \propto \frac{\sqrt{R_{\text{ext}}^2\sigma_{\text{int}}^2 - R_{\text{int}}^2\sigma_{\text{ext}}^2}}{R_{\text{ext}} - R_{\text{int}}} \oplus \frac{R_{\text{int}}\sigma_{\vartheta(\text{ms})}}{p\sin^{3/2}(\theta)}$$



Tracking with doublets





MAPS are foldable !

B.Guenter et al., https://doi.org/10.1364/OE.25.013010

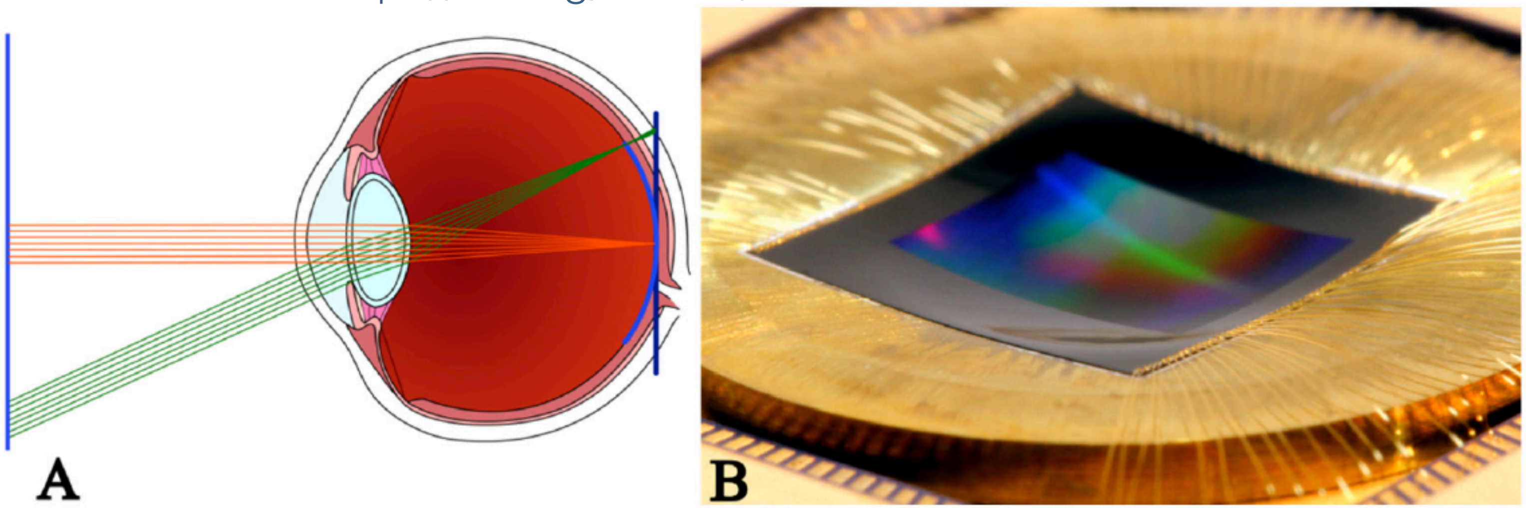


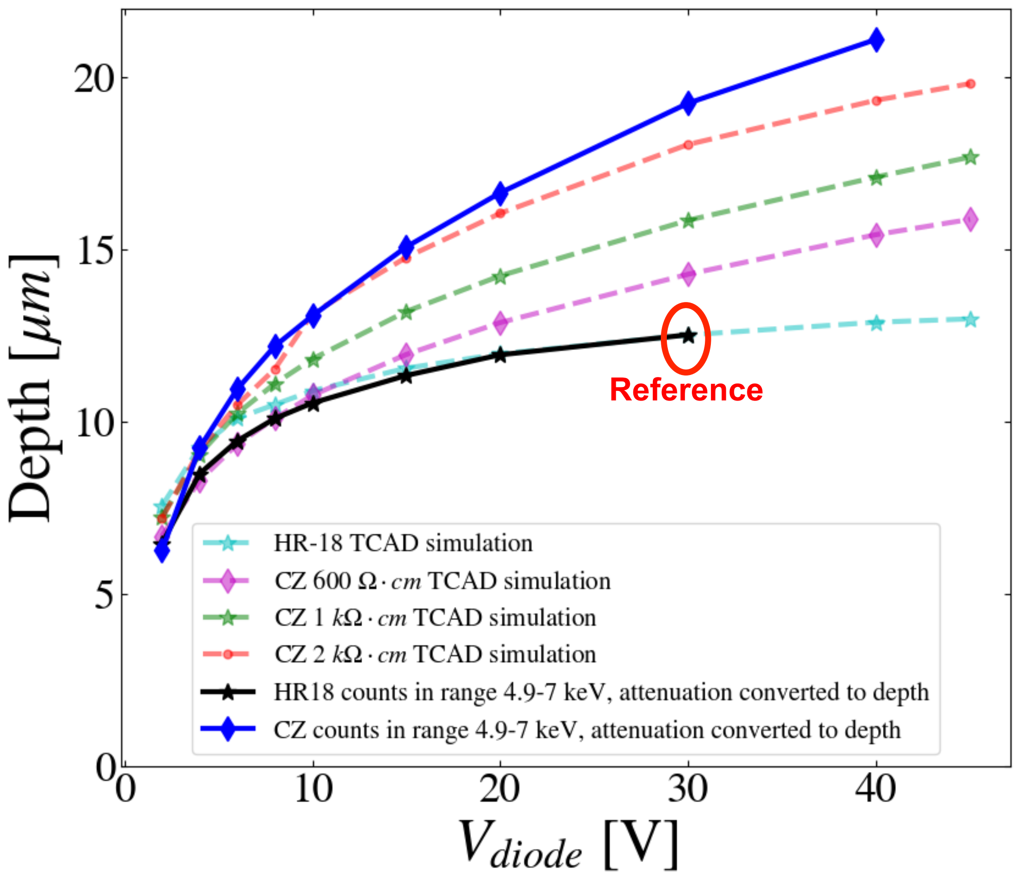
Fig. 1. A) The eye focuses onto photosensitive cells arranged along the curved focal surface inherent of a thick lens. Typical optical lenses require more elements and complexity to focus on flat focal planes and correct the aberrations these compensating elements introduce, losing performance compared to a curved focal plane. B) Functional, 18 megapixel (1/2.3" 7.6 mm x 7.7 mm die) BSI CMOS curved image sensor bonded to a precise 18.74 mm curved mold surface.

Own trial (IPHC, CERN)

Determination of the depletion depth

Using the ^{55}Fe calibration peaks – HR-18 vs. CZ

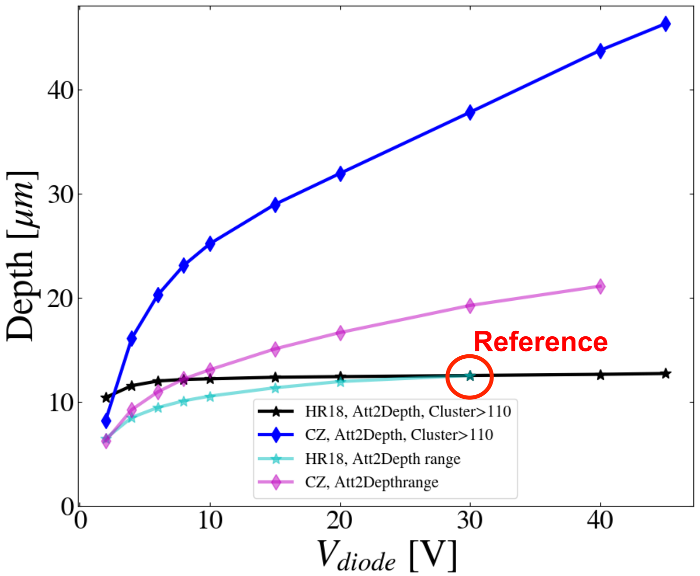
- Counts in range 4.9 keV – 7 keV
  - Depth determined from relative attenuation of HR-18 at 30 V
  - Maximum depleted depth 21 µm
  - Compared to TCAD simulations
    - Resistivity of 2 kΩ·cm



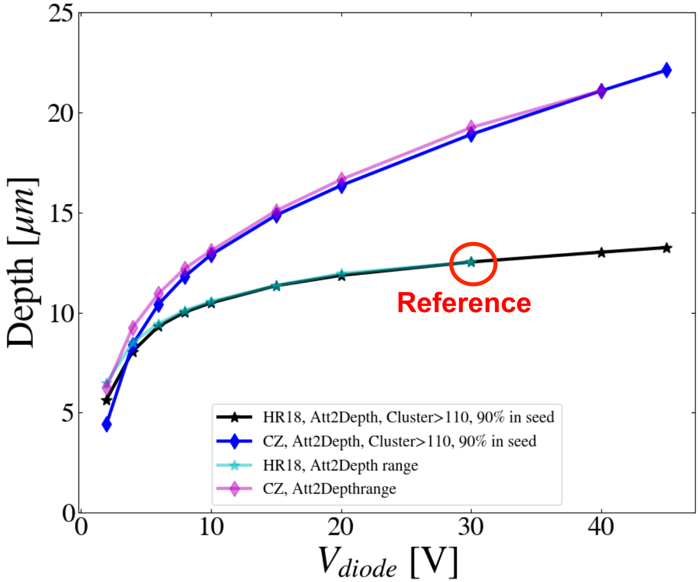
Determination of the depletion depth

Using the ^{55}Fe spectrum

- Total counts in spectrum after selection of hits in clusters > 110 ADCu
  - Depth determined from relative attenuation to HR-18 at 30 V
  - HR18: Quick saturation around 12.5 µm
  - CZ: Depth increasing up to 46 µm (81 % attenuation for Mn-K α)
  - ➔ Reaching the limit of sensitivity of ^{55}Fe

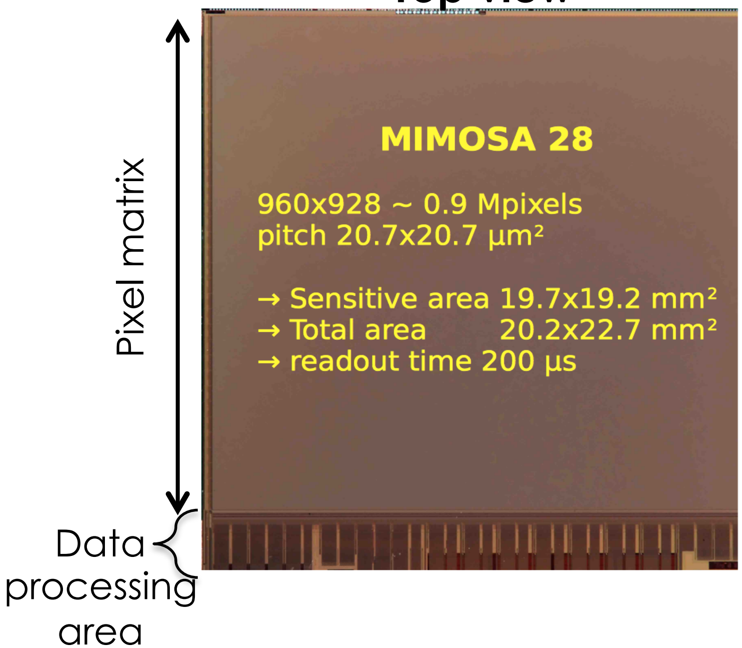


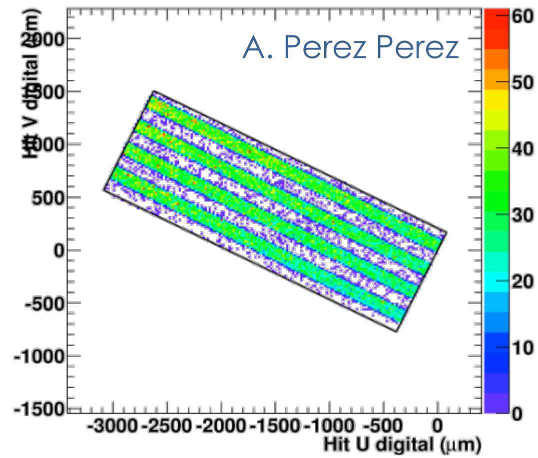
- Total counts in spectrum after selection of hits in clusters > 110 ADCu and with 90 % of the charge on seed pixel
  - Depth determined from relative attenuation to HR-18 at 30 V
  - Same behavior than 4.9-7 keV method
  - ➔ HR18: depth reaching 13.25 µm
  - ➔ CZ: depth reaching 22 µm



X-counting trial with previous tech.

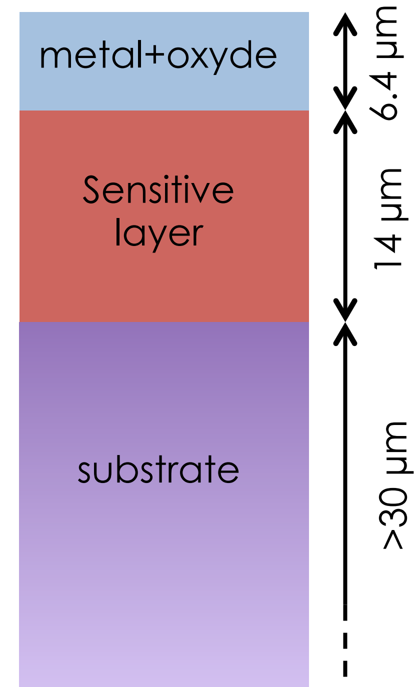
Top view



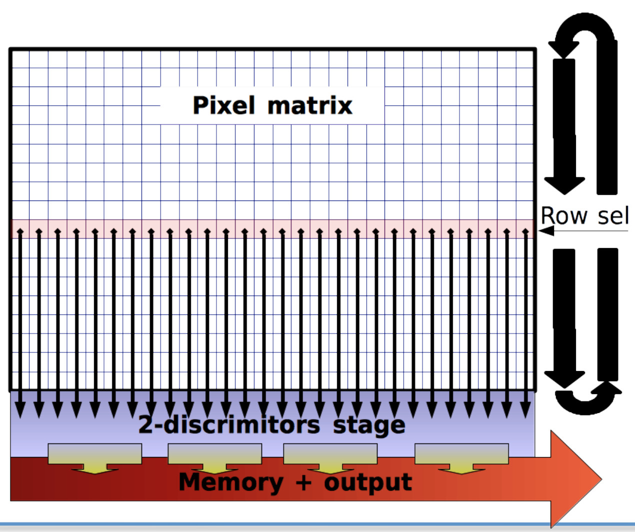


Test @ SOLEIL, E_X = 6 keV
with similar sensor (pitch 18.4 µm)
➡ Spatial resolution ~ 4 µm

Front (= illuminated side)



Side cut



Readout architecture
⬇
single photon counting