Review of MAPS detectors

for subatomic physics

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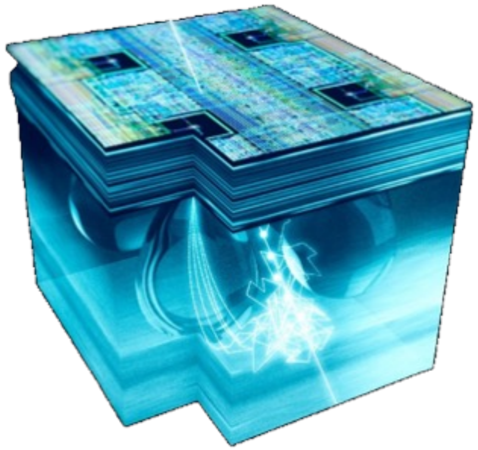
- → Concepts
- → About performances
- → Some sensors

CMOS Monolithic Active Pixel sensors
for subatomic physics



Sensing + signal amplification/conversion/treatment + matrix readout logic + data treatment/transmission

- Other "monolithic" technologies
  - CCD (SLD)
  - DEPFET (Belle II) *=> Not addressed here*
  - SOI (R&D)

- Introduced for vertex detectors at e+e- colliders
  - Genuinne attractiveness
    small pitch & low material budget & low power
- 1st applications at heavy ion colliders
  - STAR @ RHIC => PXL with MIMOSISA-28 sensor
  - ALICE @ LHC => ITS2 with ALPIDE sensor
- Extended range of applications
  - Trackers
  - Calorimeters
  - Time of Flight
  - Ion identification
  - Connected domains:
    - detectors in space
    - Scientific imaging

Concepts

- → Optimisations
- → Technologies
- → Charge collection
- → Read-out architecture
- → Stitching

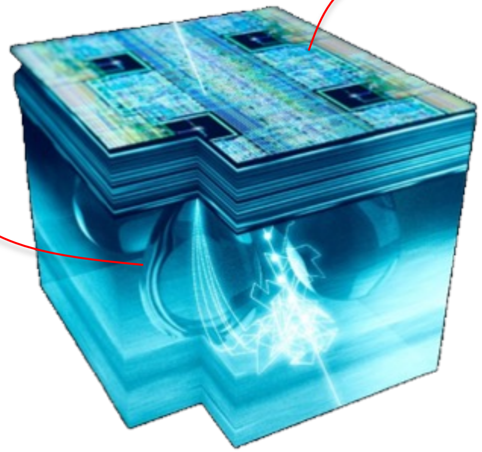
Intro to CMOS-MAPS R&D

Sensitive layer / Collection node

- Drive charge collection

=> defines collection pitch

- Modifications depends on techno.
- Optimised by R&D cycle:
  - TCAD simulation
  - prototyping
  - characterisation



In-pixel & in-matrix µ-circuits

(Above sensitive layer)

- Convert charge collection properties into actual performance

=> defines read-out pitch

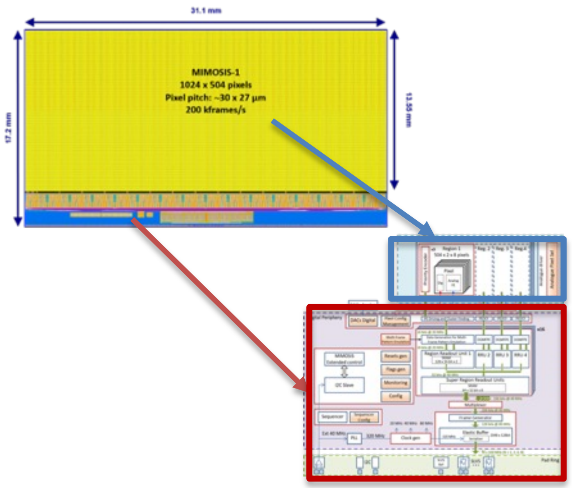
- Optimised by simulation & verification
  - prototyping still required to estimate for noise, pixel-to-pixel fluctuations, SEE

Periphery µ-circuits

- (Insensitive area, usually)

=> defines interface to outside world

  - Powering, configuration, signal transmission
- Optimised by simulation & verification
  - as complex as any large ASICS
  - Prototyping used to validate



Integration in det. modules

- Final sensor thickness, interconnection, geometrical arrangement

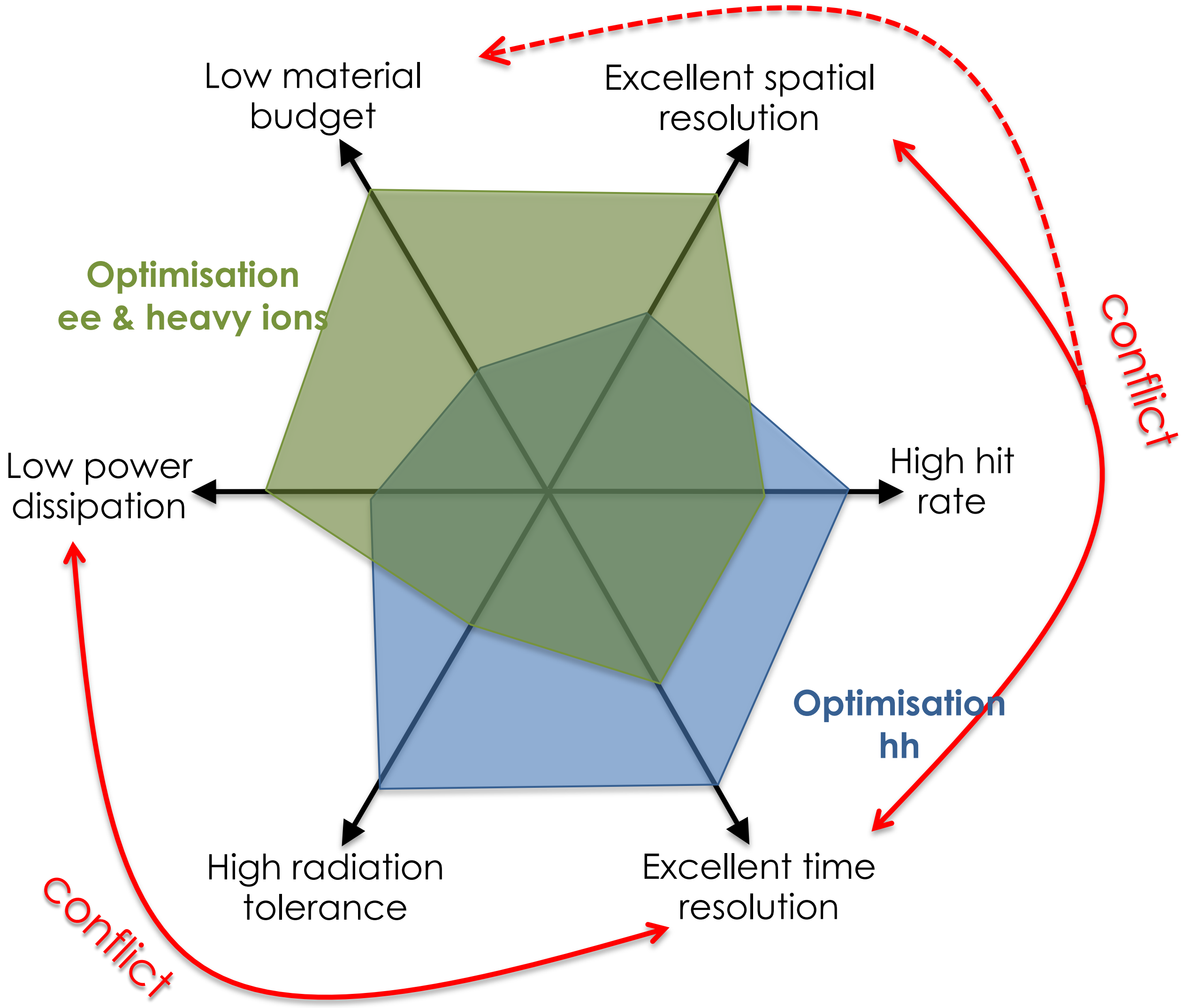
=> defines material budget & operability

- Optimised by iterative prototyping with increased complexity

The curse of the monolithic approach

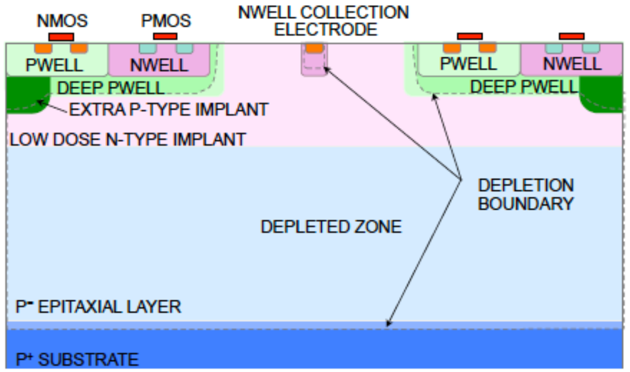
Stronger correlation between parameters than in other technologies

Any R&D is incomplete till all aspects addressed



CMOS-MAPS technological processes

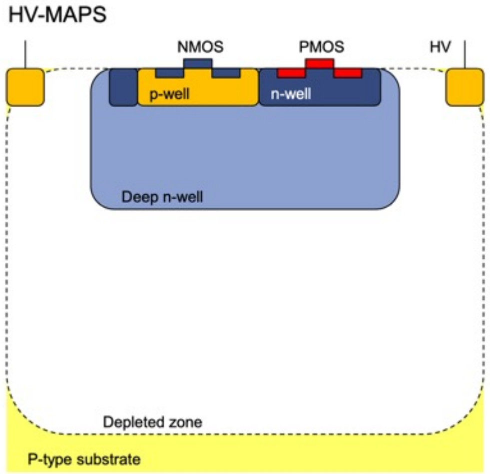
Small collection node (→ small det. capacitance)
- If depleted through High-Resistivity material



- Tower 180 nm
  - ALICE-ITS2 , ATLAS-ITK, Belle II , CEPC, CBM, CLIC, LHCb-UT, TIIX
- TPSCo 65 nm
  - ALICE-ITS3, ALICE3, FCCee

=> All techno in **ECFA-DRD3**-WG1 project
=> Tower-180/TPSCo-65/LF-110 in **DRD7**-WG6

Large collection node (→ large det. Capacitance)
- Depletion through High-Voltage allowed by process



- LF 150 nm
  - ATLAS ITK, RD50, CACTUS
- LF 110 nm
  - ARCADIA
- TSI 180 nm
  - Mu3e, LHCb-MT, ATLAS-ITK
- IHP 130 nm SIGe BiCMOS
  - Monolith, PicoAd, Faser

Context of MAPS R&D: the experiments

Attractive MAPS features for vertexing/tracking

=> small pitch, low mass & low power

- 1st applications
  - STAR-PXL@ RHIC 2014-16
    - MIMOSA-28 doi:10.1088/1748-0221/7/01/C01102
  - ALICE -ITS2 @ LHC (10 m^2) 2022-32
    - ALPIDE doi:10.1016/j.nima.2016.05.016
  - sPHENIX-MVTX @ RHIC 2023- (also ALPIDE)
  - Mu3e detector @ PSI 2023-
    - MuPix10 doi:10.1016/j.nima.2020.164441
  - MVD in CBM @ FAIR for late ~2028
    - MIMOSIS talk at Eurizon 2023 workshop

- Extended applications to higher radiation levels and/or hit rates
  - ATLAS-ITK @ LHC, successful R&D but not selected (yet)
    - MALTA, TJ-Monopix, LF-Monopix, ATLASPix
  - Belle II-VTX @ SuperKEKB upgrade project for late 20s
    - OBELIX talk at talk at AIDAinnova 2023 workshop

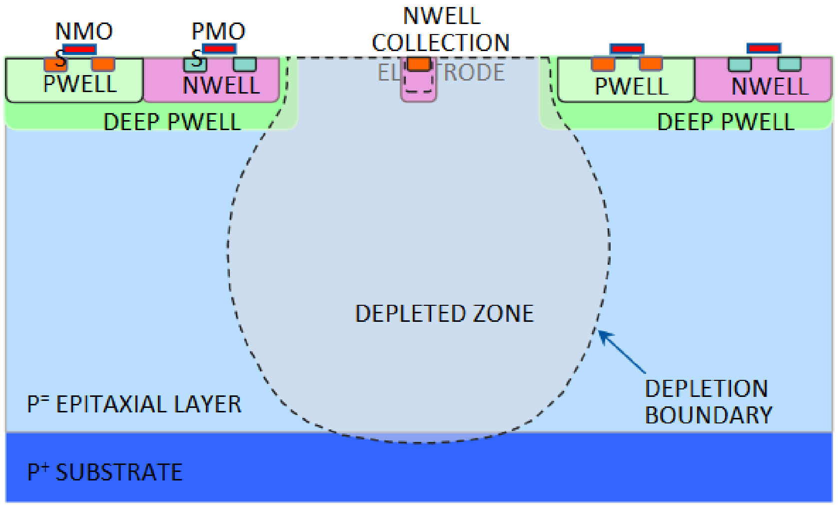
Pushing performances for more science

- Highly granular & light vertexing
  - ALICE-ITS3 XL-sensor (30x10 cm^2)
    - MOSS/MOST/MOSAIX doi: 10.1016/j.nima.2023.168018
  - All future e+e- colliders at high energy targetting spatial resolution $\lesssim$ 3 µm
    - JadePix, MIC, TaichuPix @ CEPC doi: 10.1016/j.nima.2023.168945
  - ALICE3 vertexing inside beam-pipe

- Tracking
  - Upgrades: Belle II @ SuperKEKB, LHCb @ LHC
    - OBELIX, MALTA
  - New systems: EIC @ eRHIC, ALICE3 @ LHC
Future e+e-/µµ/hh colliders

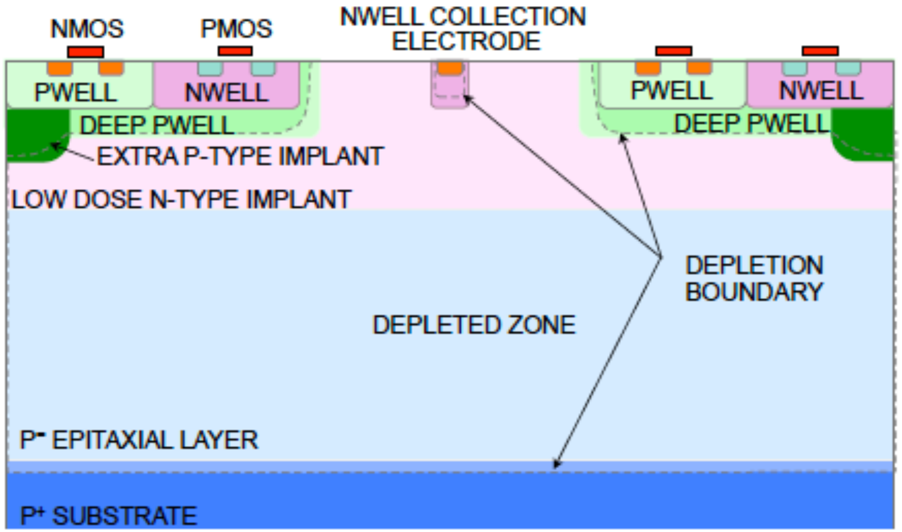
Charge collection: basic facts

Here on small collection node



- Fixed amount of charge generated by ionization in sensitive layer limited by substrate
  => all of it is collected over a cluster of pixels

- In **standard** process, **partial depletion**
  => charges move by diffusion and drift
  => sizeable charge sharing



- In **modified** process, close to or **complete depletion** (sometimes called DepletedMAPS)
  => drift strongly dominates
  => low charge sharing

Charge collection: basic facts

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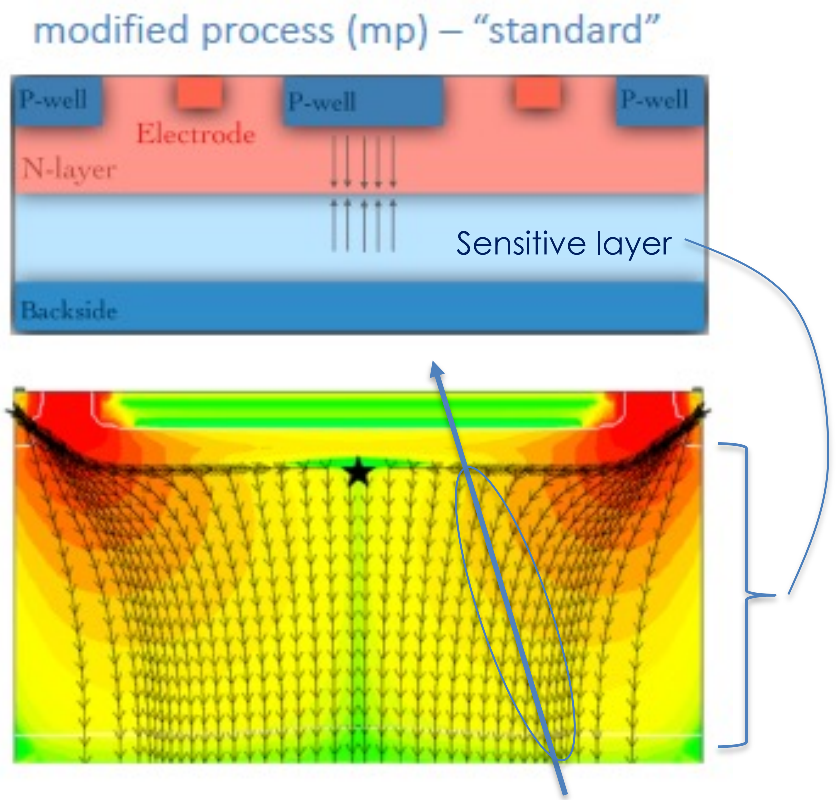
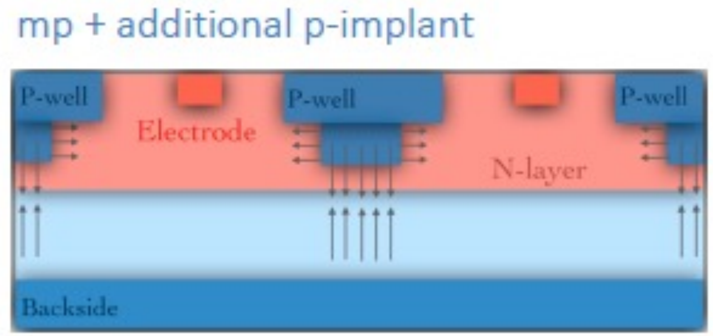


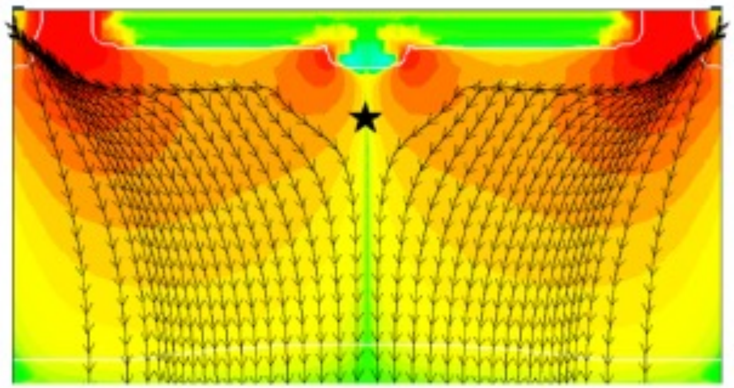
doi: 10.1016/j.nima.2017.07.046
doi: 10.1088/1748-0221/14/05/C05013

- Fixed amount of charge generated by ionization => all of it is collected over a cluster of pixels
- Electric field configuration & sensitive thickness drive charge sharing
- **Sizeable sharing** =
  - Lower charge on seed pixel ⟶ low threshold for high efficiency
  - Slow collection ⟶ unfavourable / tolerance to radiation
  - More information to reconstruct position
- **Low sharing** =
  - High charge on seed pixel ⟶ easy detection
  - Fast collection ⟶ beneficial for radiation tolerance & time resol.
    - Time resolution depends then on front-end
  - Detrimental to position resolution
- !! Sharing depends on impact position within pixel

Charge collection: basic facts

Here on small collection node





Field configuration driven by
(P/N)well geometries & doping

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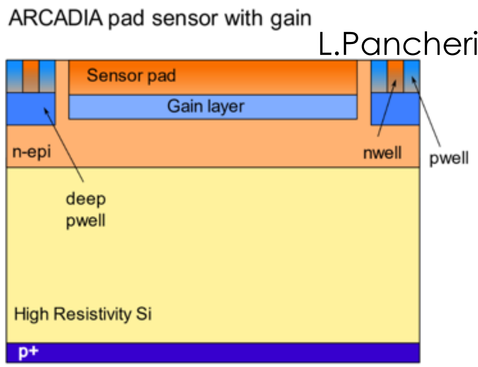
Charge collection: beyond basics

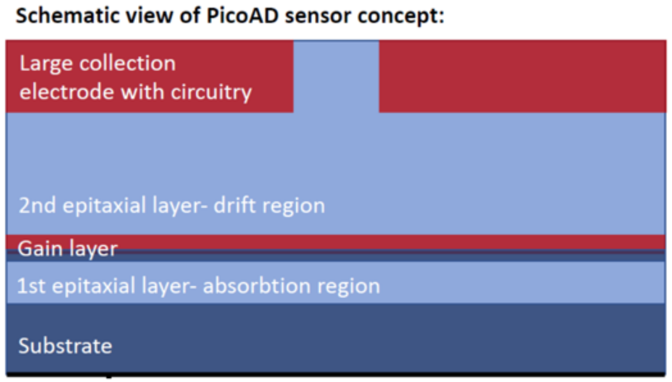
- Introduce amplification by impact in silicon
  - Stronger signal ⟶ better radiation tolerance (caveat about behaviour of additional layers with fluence)
  - Stronger signal ⟶ no need anymore for front-end: smaller pixels, lower power
  - Faster signal ⟶ better time resolution (but just one of the ingredients)

- Various current tentative
  - Mostly focused on timing (~10 ps) so far
    - ARCADIA project in INFN (LF 110 nm)
      doi: 10.22323/1.420.0017
    - SiGe BiCMOS in U.Geneva
      doi: 10.1088/1748-0221/17/02/P02019
  - Newcomers:
    - CERN starting with Tower 180 nm
    - French-APICS (IPHC, CPPM, ICube) starting with Tower soon

APD/LGAD-style
(⟶ future LGAMAPS ?)

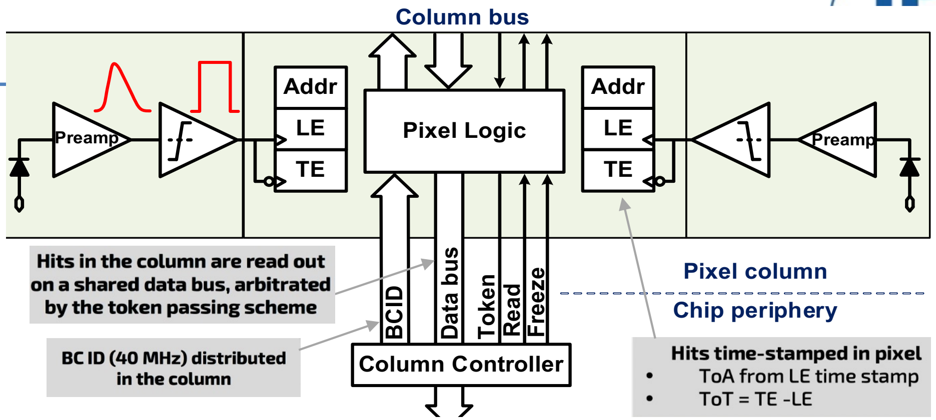


L.Pancheri 2022



M. Munker, Trento Workshop 2022

Read-out architecture



Column-drain doi: 10.1088/1748-0221/13/03/C03039
Priority encoder doi: 10.1016/j.nima.2015.02.063
Combination doi: 10.1016/j.nima.2022.167442

What we know

- Hit-rate capability & Power driven by
  - Front-end
  - Data-driven (position/charge/time) transmission out of the matrix
- ALICE/CBM/CEPC R&D (ALPIDE/MIMOSIS/TaichuPix)
  - ~50 MHz/cm^2 and ~50 mW/cm^2
- ATLAS-ITK/Belle II R&D (Monopix/Malta/AtlasPix/OBELIX)
  - >100 MHz/cm^2 and > 100 mW/cm^2

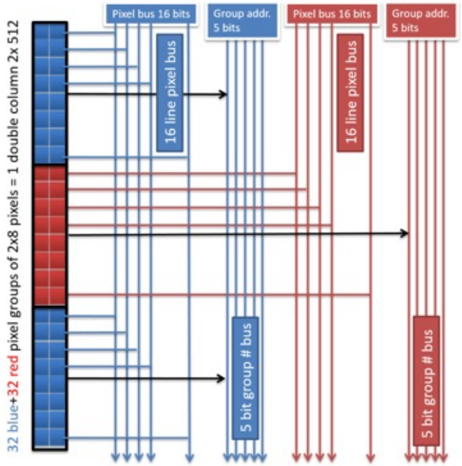
Beyond state-of-the-art need

- ITS3, ALICE-3, FCCee for power < 50 mW/cm^2
- LHCB UT-MT for hit-rate 200 MHz/cm2 & timestamping (25 ns)

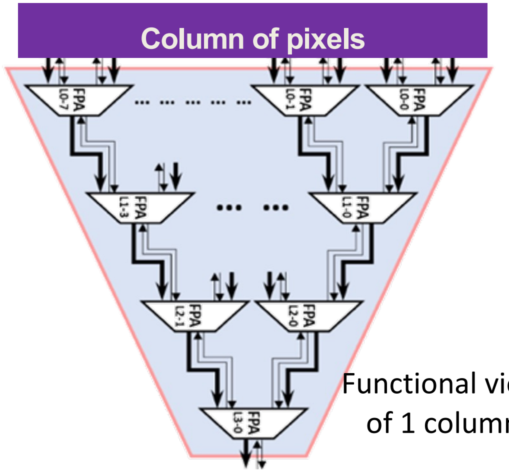
R&D topics

- Smaller CMOS process feature size
- Asynchronous logic, expected to save power
- Pixel 'multiplexing' to reduce granularity but keeping efficiency
  - 4:1 with 25x25 μm^2 50x50 μm^2
- In-pixel generation of time resolution <100 ps ?

Asynchronous bus
doi:10.1088/1748-0221/13/01/C01023
doi: 10.1088/1748-0221/18/03/C03013



Asynchronous arbiter
J. Soudier @ TREDI2023

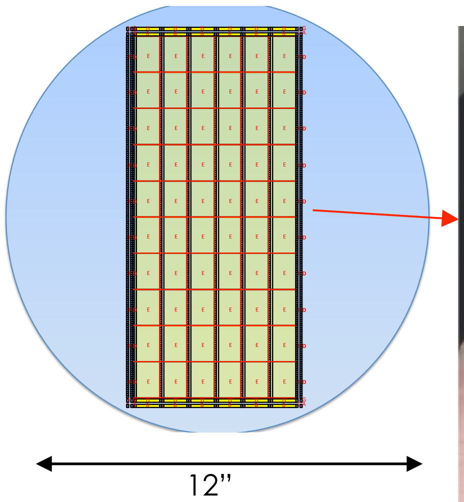


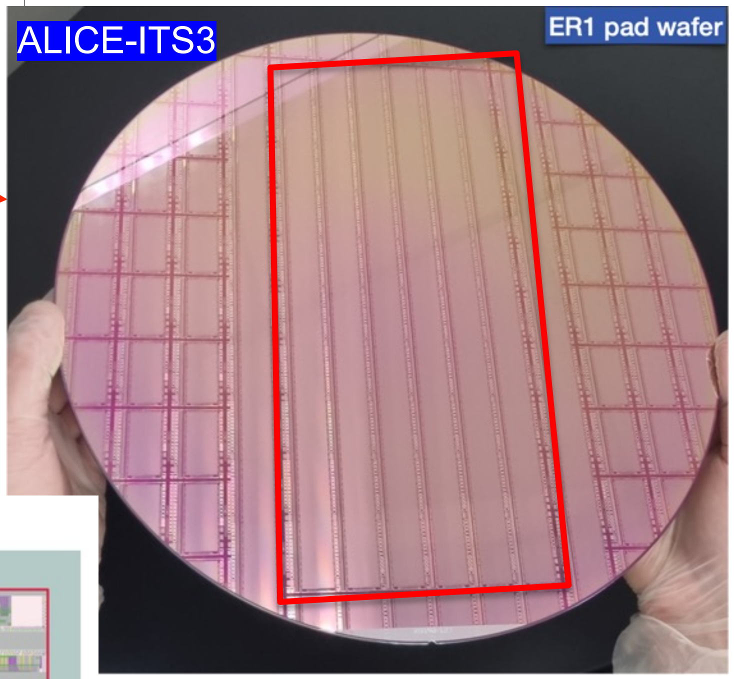
Functional view of 1 column

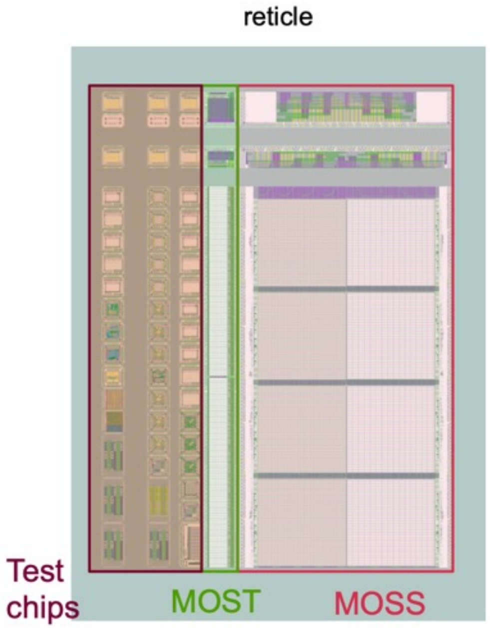
Note: 3D interconnection (hybridisation) might be needed

Stitching or not-stitching?

- **Benefits**
  - Material budget with a single bent crystal
  - System simplicity
- **Issues**
  - Yield => expecting first result from MOSS this year
  - Insensitive area to drain data out
- **Need**
  - Small area innermost layers: ALICE-ITS2 + ALICE3 + FCC
  - Large area => no go because of yield ?
- **R&D topic**
  - 1D stitching with ALICE
    - Power domain local-failure proof
  - 2D stitching?





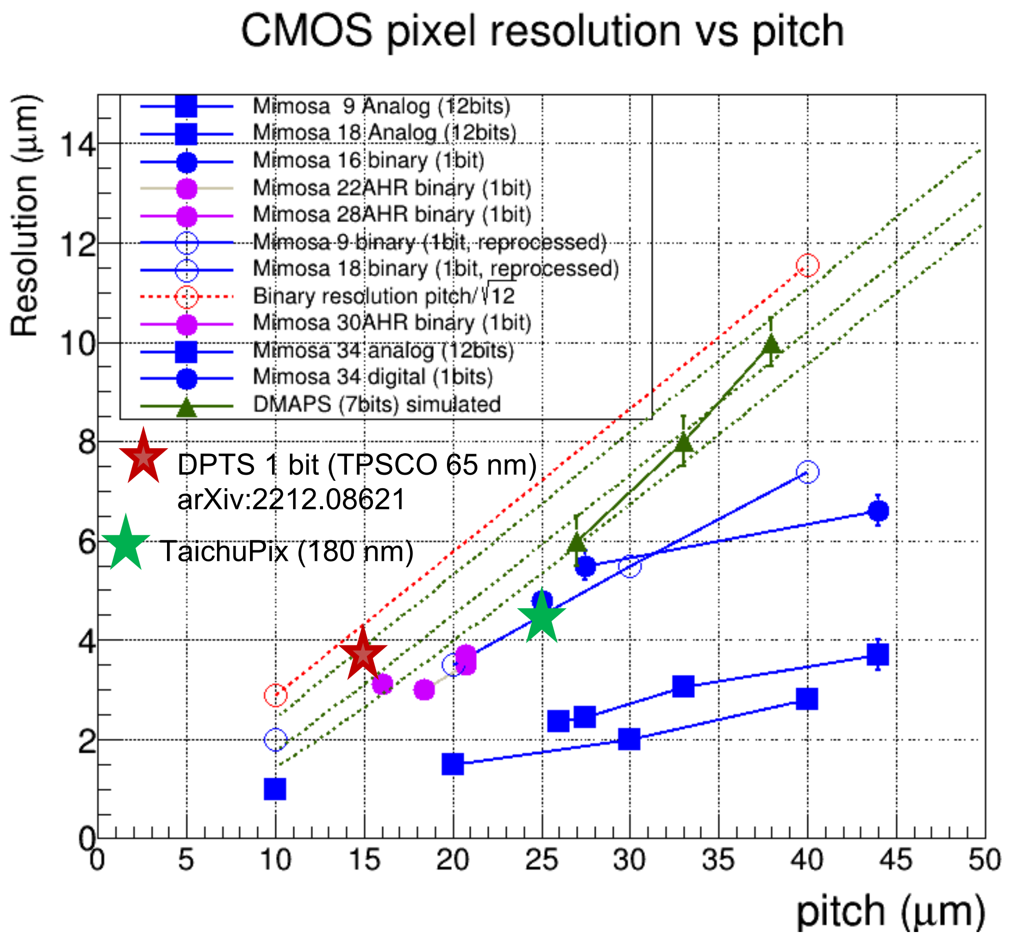


Discussion on performance

- → position resolution
- → time resolution
- → power dissipation
- → (radiation tolerance)
- → integration

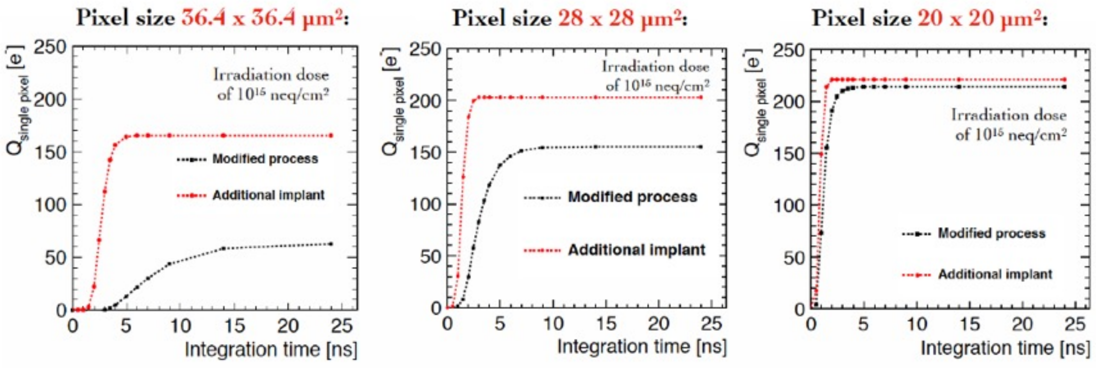
Position resolution

- **What we know**
  - Resolution driven by
    - Charge sharing
    - Pixel-signal encoding resolution
    - Detection threshold
  - Best today still the ‘slow’ MIMOSA-26/28
- **Beyond state-of-the-art needs**
  - ALICE 3 inner layers: 2.5 µm
  - Future lepton colliders: 3 µm
- **R&D topics**
  - CMOS process with smaller feature size ⟶ TPSCo 65 nm
    - But some work is still ahead of us
  - Removing front-end amplifier from pixel
    ⟶ requires amplification in silicon



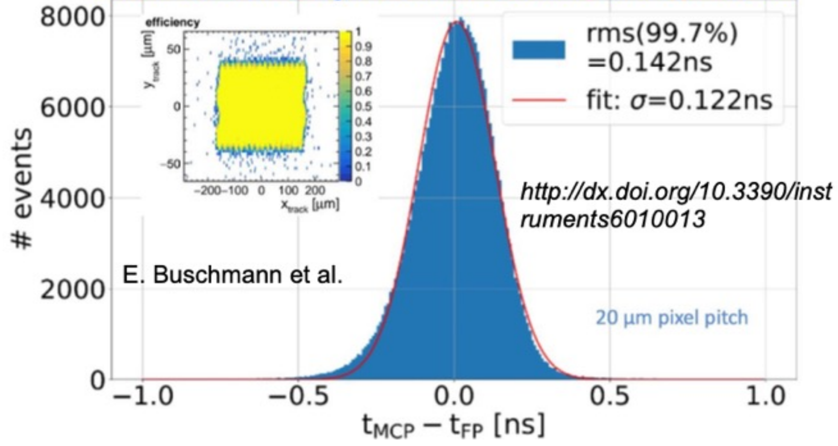
Time resolution

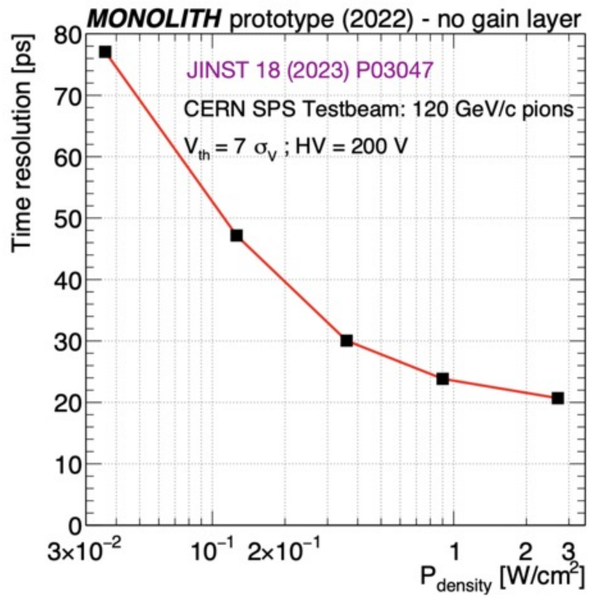
Simulations on 180 nm modified process



- What we know
  - Resolution driven by
    - Charge sharing
    - Time of arrival encoding
    - Time walk
  - Various ranges achieved:
    - Nanoseconds on large sensors (ATLAS-ITK R&D) (180 nm)
    - Sub-nanosecond on R&D sensors
      - Tower 180 nm & 65 nm
      - LF-150 nm: CACTUS doi: 10.1088/1748-0221/15/06/P06011
      - IHP SiGe BiCMOS 130 nm: Fastpix
  - **=> strong R&D on-going**

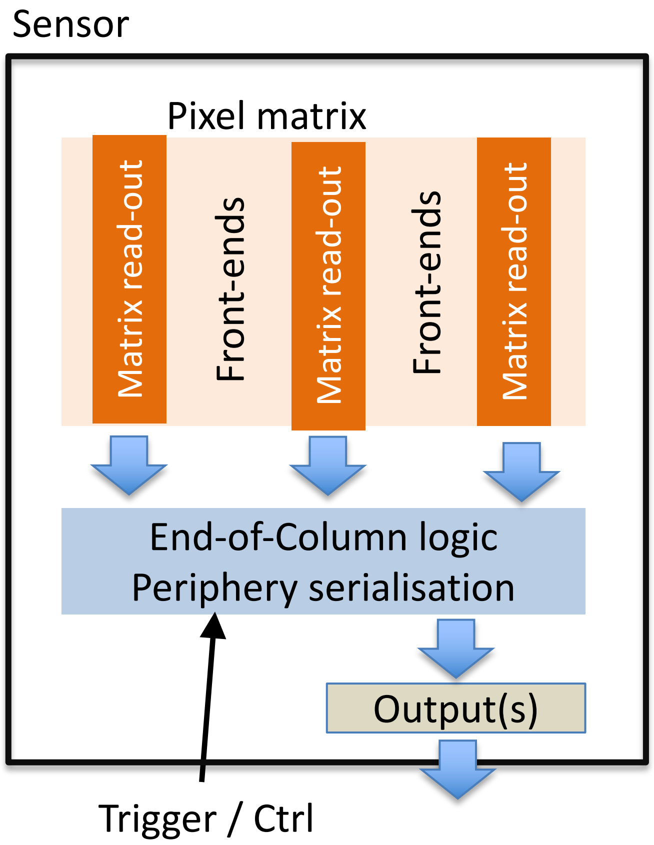
FASTPIX efficiency and time resolution in test beam





- Beyond state-of-the-art need
  - 4D-tracking
  - Time of flight for particle identification

Power dissipation



Usually main contributors

- **Front-end analogue power**
  - Proportional to $\left(\frac{Q}{C}\right)^{-2}$ doi: 10.1016/j.nima.2013.05.073
    - Benefit of small diode for collection node & depletion
  - Techno dependence
    - ALPIDE (180nm) 40 nW/pixel ⟶ MOSS (65nm) 10 nW/pixel @ same 5 µs
  - Speed dependence (timestamping)
    - Few 10s nW @ µs ⟶ few µW @ ns
- **Read-out & serialisation**
  - Data driven approach compulsory
  - Global signals (like clocks) detrimental
  - Of course increase with logic complexity
    - Triggering, handling occupancy fluctuations, …
- **Data transmission**
  - Depends of needed bandwidth
    - Close to analogue power for MIMOSIS
  - Much reduced for triggered sensor
    - See OBELIX but price in trigger logic

Sensor	MIMOSA28	ALPIDE	MIMOSIS-1	OBELIX	ATLASPix-3
Date	2008/10	2015-17	2021	2021	2019
Techno	AMS-350 nm	TJ-180 nm	TJ-180 nm	TJ-180 nm	TSI 180 nm
Pixel pitch (µm²)	20.7x20.7	29x27	30x27	33x33	150x50
Time Stamp (ns)	112/ x10³	5000	5000	25	25
read-out	Continuous	Continuous	Continuous	triggered	triggered
Bandwidth (Mbits/s)	180	1200	2400	320	1300
Power (mW/cm²)	**150**	**35**	**~50**	**200**	**150**
Hit rate (Mhz/cm²)	O(0.1)	10	15-70	>100	>100

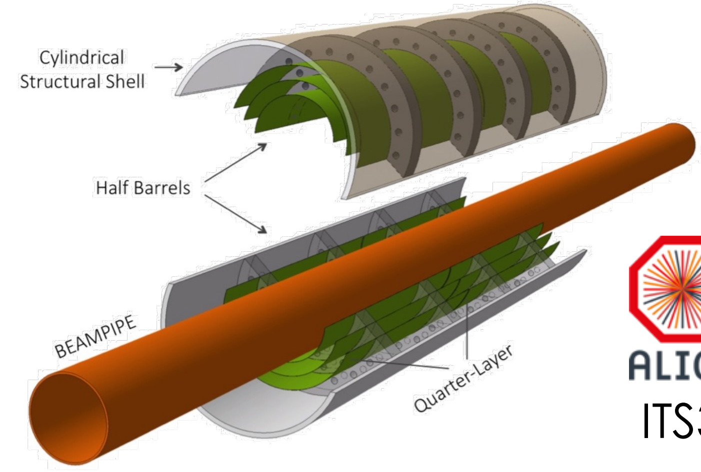
Integration:

- **Experience from**
  - STAR-PXL, PLUME, ALICE-ITS2, MALTA
  - FASER, MU3e, Belle II-VTX

PLUME: first double sided module
- 12 cm length, 8 Mpixels, 0.35 % X0

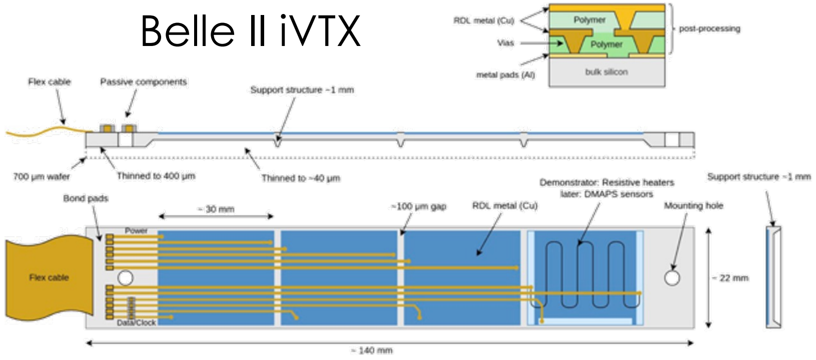
- Used in phase-2 SuperKEKB

- **R&D topics**
  - Stitching or pseudo-stitching
  - Connecting sensors on modules
    - For data and/or power
  - Regulating power



ALICE ITS3

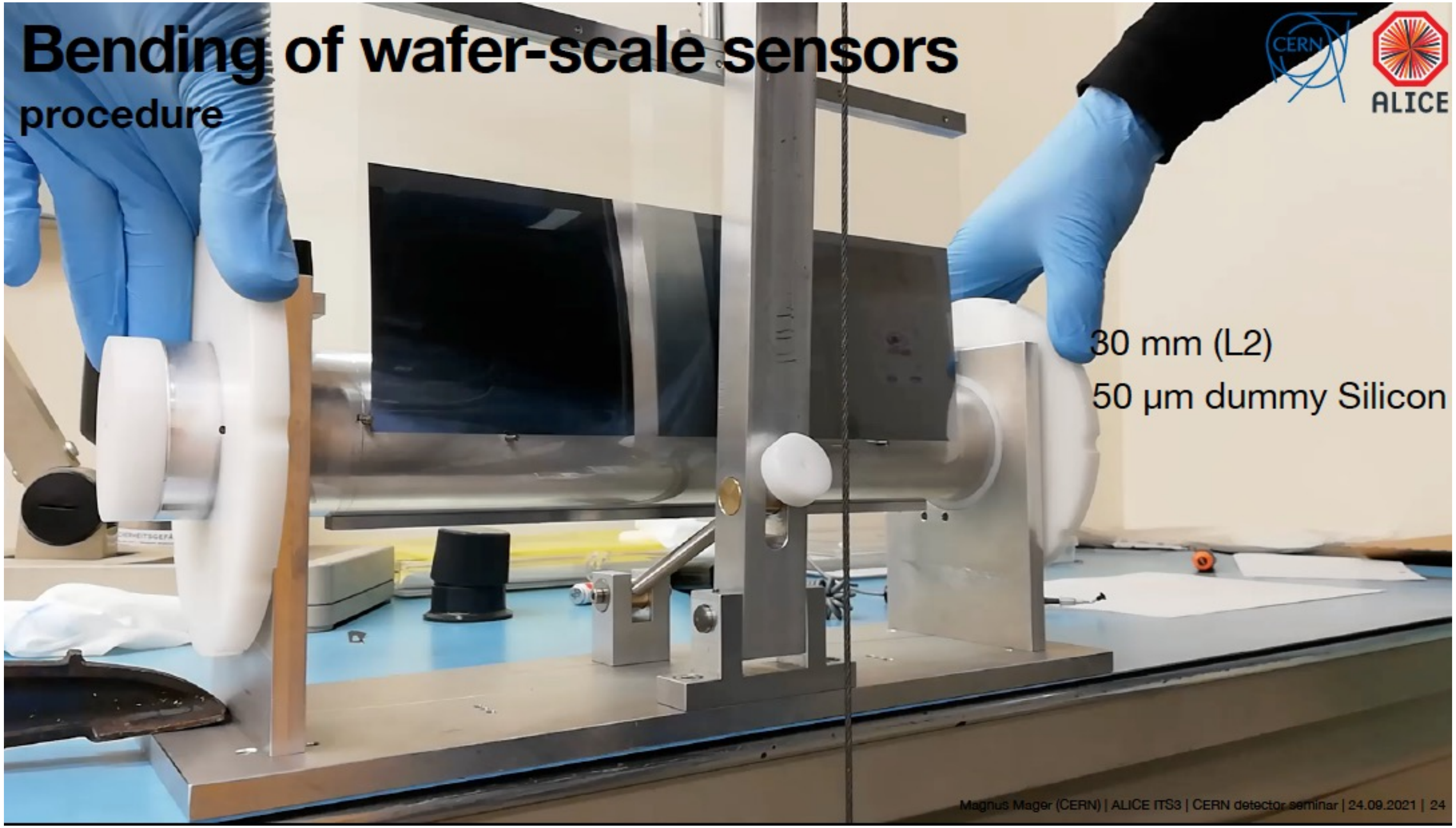
Belle II iVTX



Note: Quite difficult to have generic project
=> need an experiment to get practical

Bending large MAPS

From https://indico.cern.ch/event/1071914/

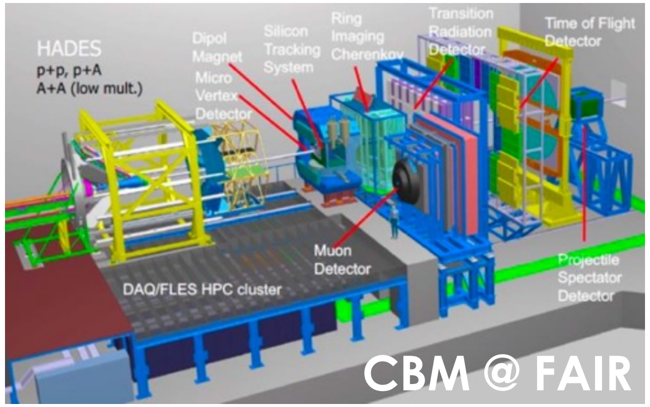


Some MAPS (a very selective choice)

MIMOSIS project (IPHC, Goethe Uni.Frankfurt, GSI)

Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

- **Goals & mean**
  - Match CBM vertex requirements & achieve step forward / Higgs-Factories
    combine position res. (~5µm) & low-power (<100 mW/cm²) & high hit-rate (>50 MHz/cm²)
  - Specificity of CBM collisions: 100 kHz Au+Au @ 11 AGeV and 10GHz p+Au @ 30 AGeV
    => large hit-rate fluctuation & operation in vacuum

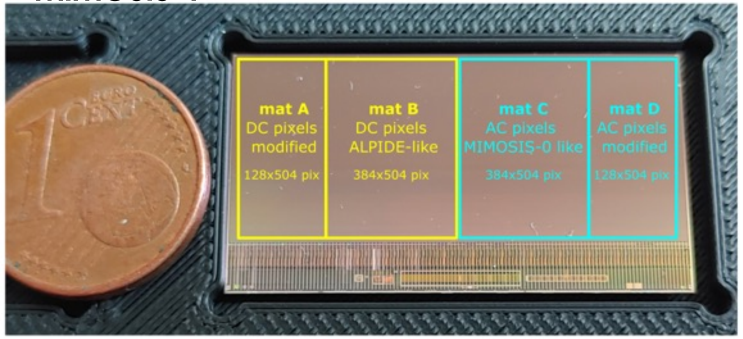


Full specs for MIMOSIS sensor

Position resolution	~5 µm
Time resolution / continuous r.o.	~5 µs
Power dissipation	<100 - 200 mW/cm²
Hit rate (average/50 µs peak)	20/70 MHz/cm²
Material budget / layer	0.05 % X_0
Operation temp in **vacuum**	- 40°C to +30°C
Radiation* (non-ionizing)	~ 7×10^{13} n_{eq}/cm^2
Radiation* (ionizing)	~ 5 Mrad
Radiation gradient	100 %
Heavy Ions-tolerance	10 Hz/mm²

* No safety factor

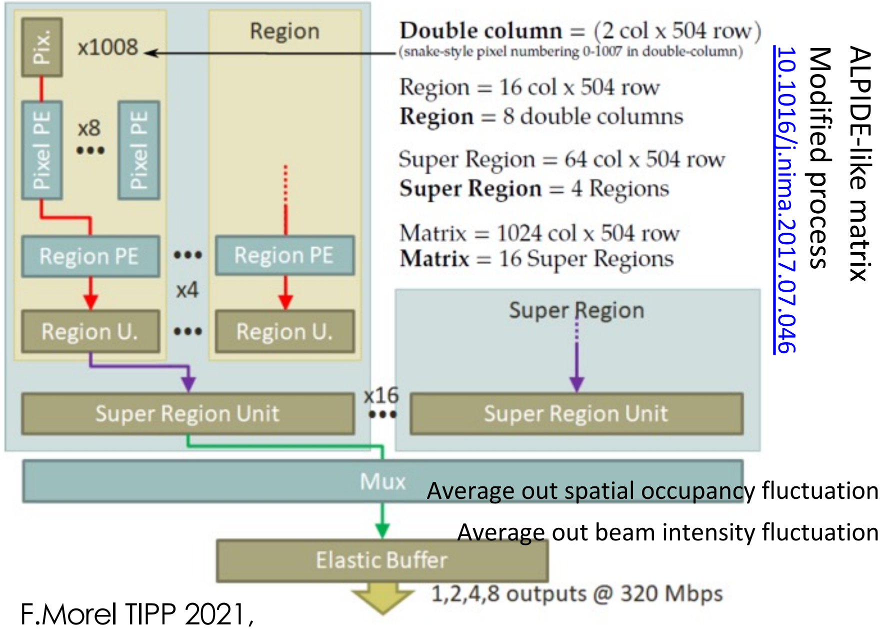
MIMOSIS-1



Parameter	Value
Technology	TowerJazz CIS 180 nm
Epitaxial layer	~25 µm thick, > 1kΩ·cm
Sensor thickness	300 µm or 60 µm
Pixel size	26.9 µm × 30.2 µm
Pixel array	1024 × 504 pixels
Sensitive area	≈ 4.2 cm²
Array readout time	≈ 5 µs
Power consumption	< 100 mW/cm^2

- **MIMOSIS sensors**
  - MIMOSIS-1 (2020)
  - MIMOSIS-2/2.1 (2022/2023)
  - Final MIMOSIS-3

Full digital on top design



ALPIDE-like matrix
Modified process
10.1016/j.nima.2017.07.046

F.Morel TIPP 2021,
https://indi.to/Vf5Vs

MIMOSIS-1 noise & threshold behaviour

- From laboratory tuning
  - Room temperature
  - Conversion factor 1 mV ~ 1-1.5 e-

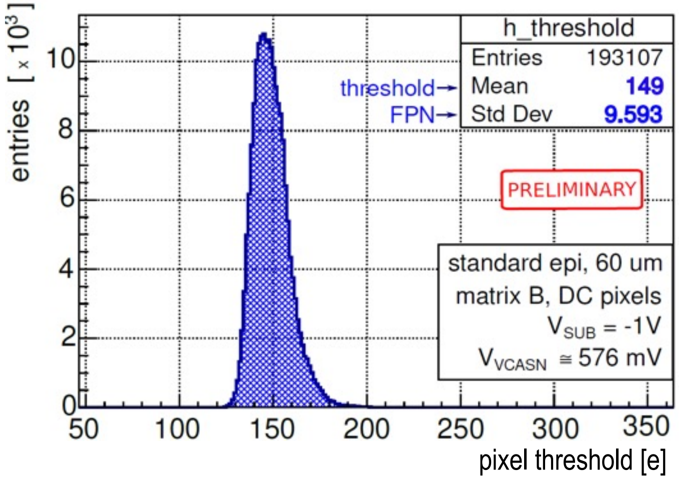
• Threshold range 100-250 e-

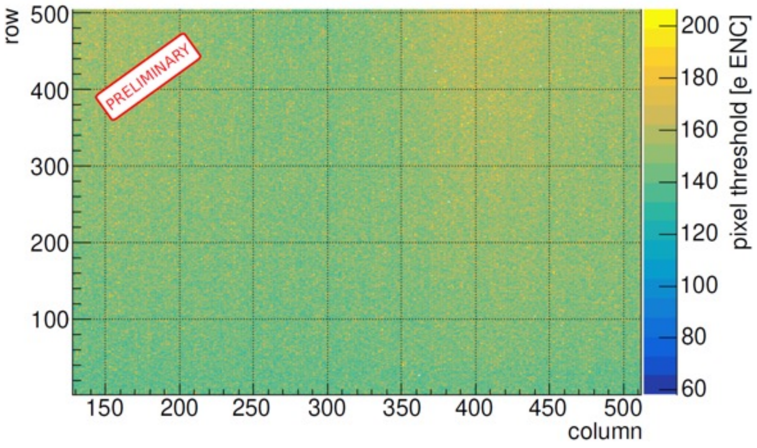
• Fixed pattern noise ~ 7-10 e-

• Temporal noise ~3-5 e-

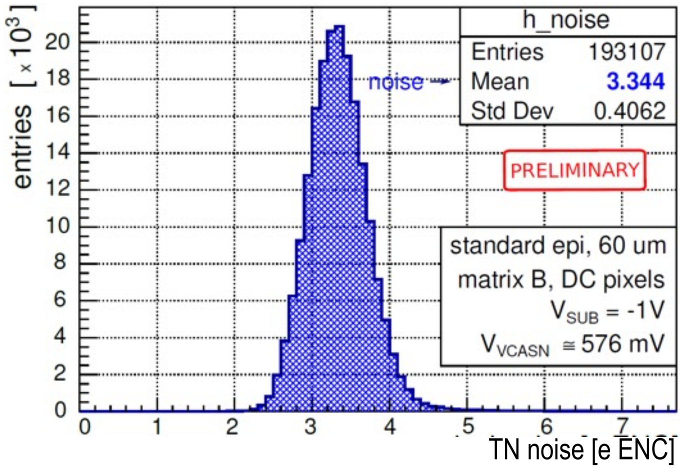
- Illustrative results for DC PIXELS (mat B)

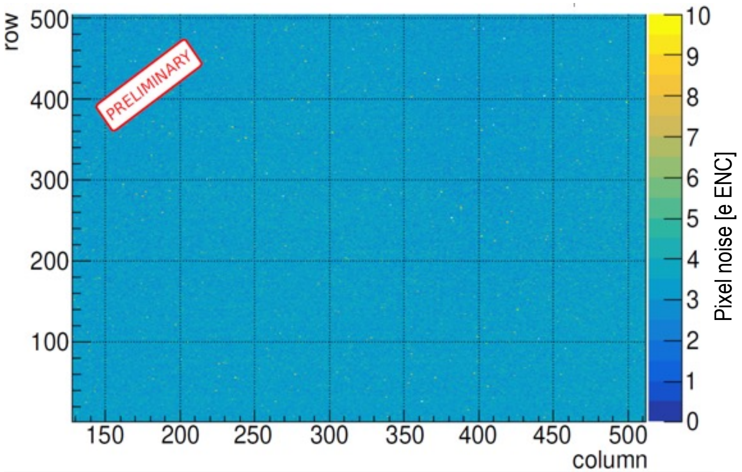
THRESHOLD DISPERSION





THERMAL NOISE

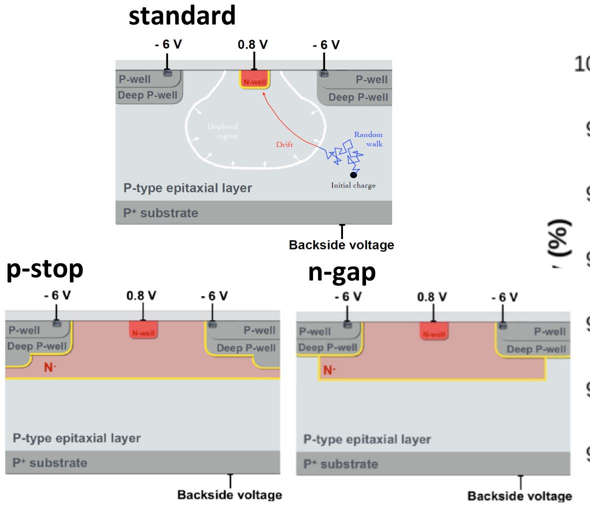


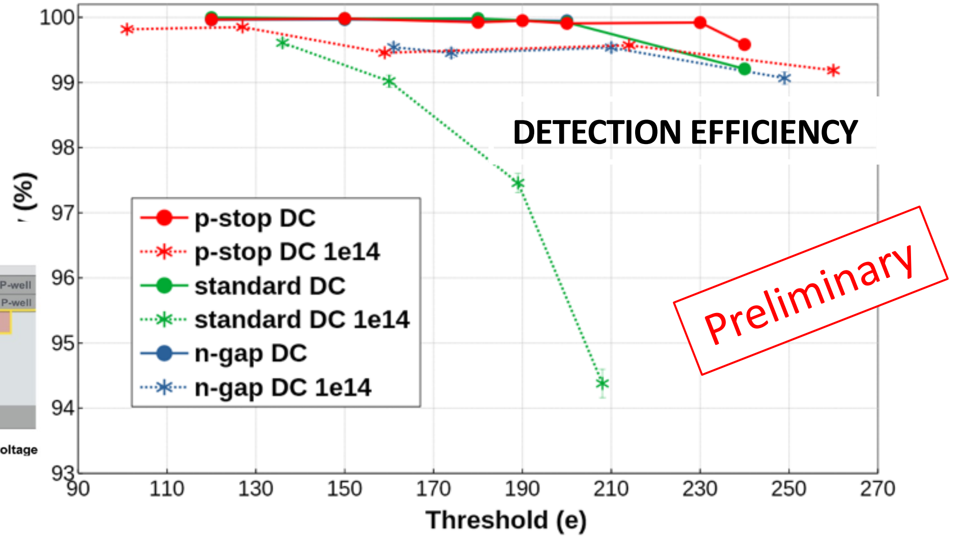


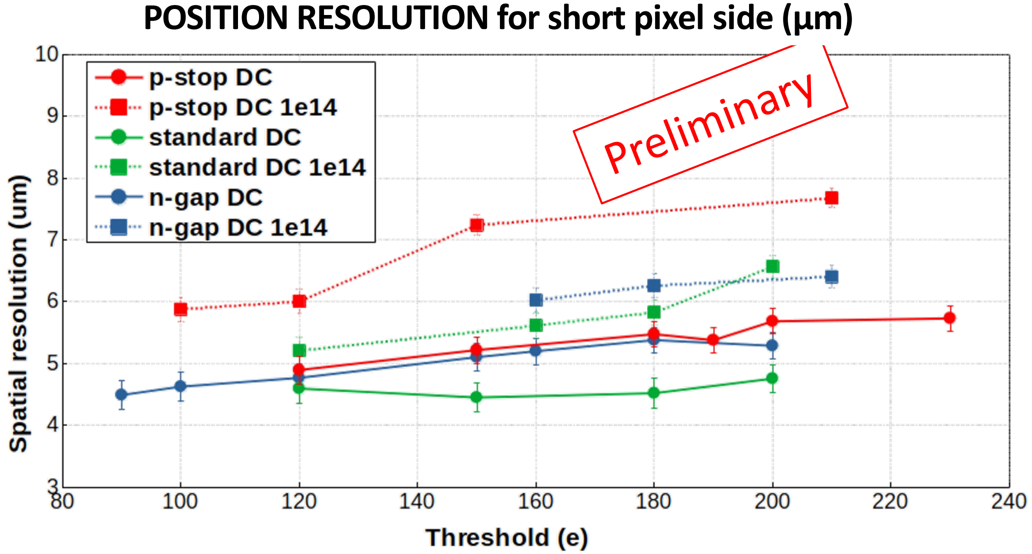
A.Dorokhov, VCI 2022, https://indi.to/vBJLx
R. Bugiel, Z.EL Bitar, NSS 2022, https://nssmic.ieee.org/2022

MIMOSIS-1 efficiency and position resolution

- From Beam test
  - Telescope made of 6 MIMOSIS-1 sensors
    - 5 GeV e from DESY II
    - 120 GeV π from SPS-CERN
    - Room temperature
  - Fake rate (not shown) 10^{-7} /pixel/frame(5 μs) after NIEL fluence and for all thresholds
  - Detection efficiency stable after NIEL for modified process
  - Correlation resolution and charge-sharing as expected
  - Resolution mildly degraded by NIEL fluence
    - Bulk damages reduces cluster size

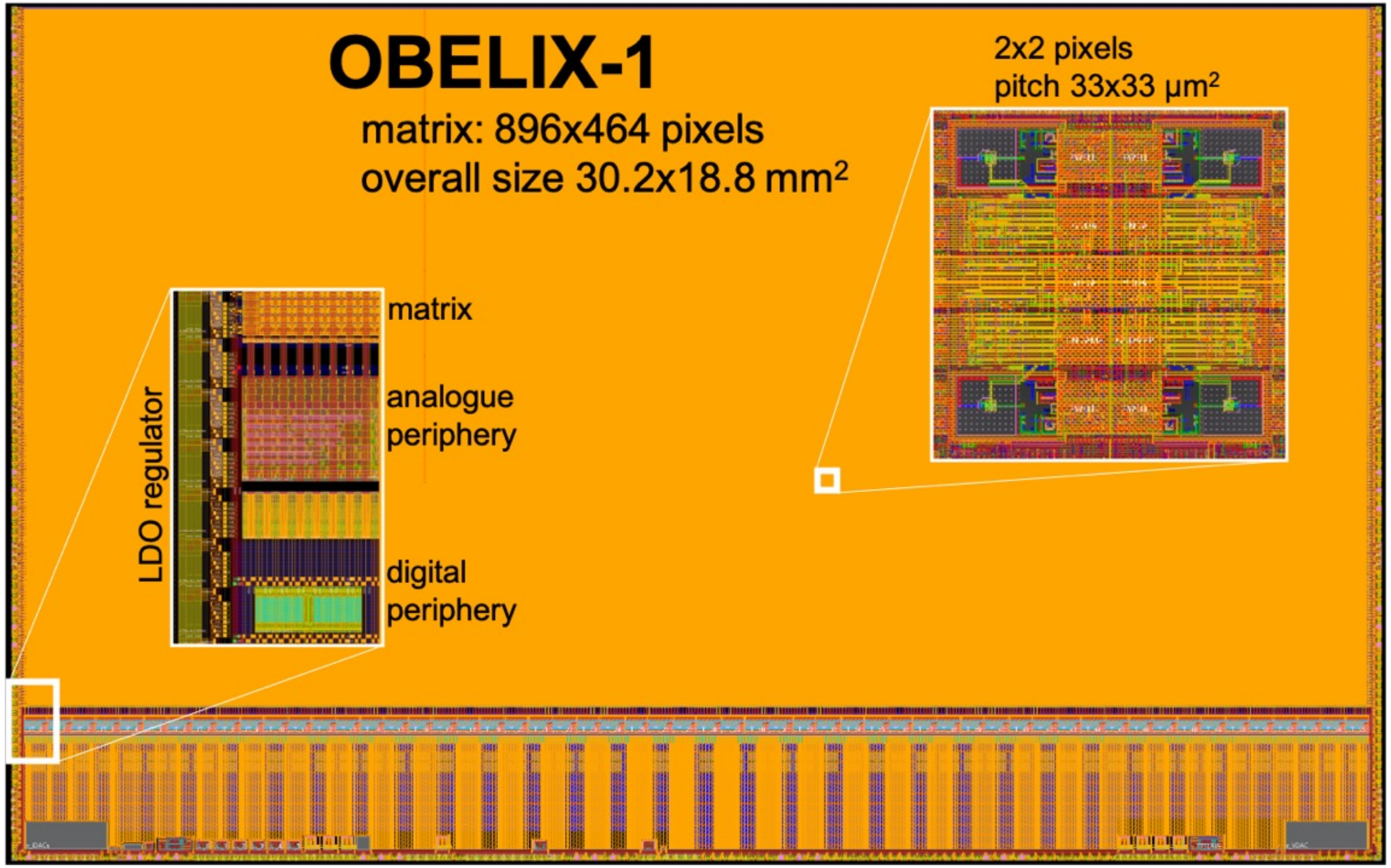






A.Dorokhov, VCI 2022, https://indi.to/vBJLx
R. Bugiel, Z.EL Bitar, NSS 2022, https://nssmic.ieee.org/2022

Belle-II / OBELIX-layout



DOI: 10.1016/j.nima.2023.168015

Submission in Q1-2024

	OBELIX
Pitch	33 µm
Signal ToT	7 bits
Integration time	50 To 100 ns
Time stamping	~5 ns for hit rate < 10 MHz/cm²
Hit rate max for 100% eff.	120 MHz/cm²
Trigger handling	30 KHz with 10 µs delay
Trigger output	~10 ns resolution with low granularity
Power (with hit rate)	120 to 200 mW/cm² (1 to 120 MHz/cm2)
Bandwidth	1 output 320 MHz

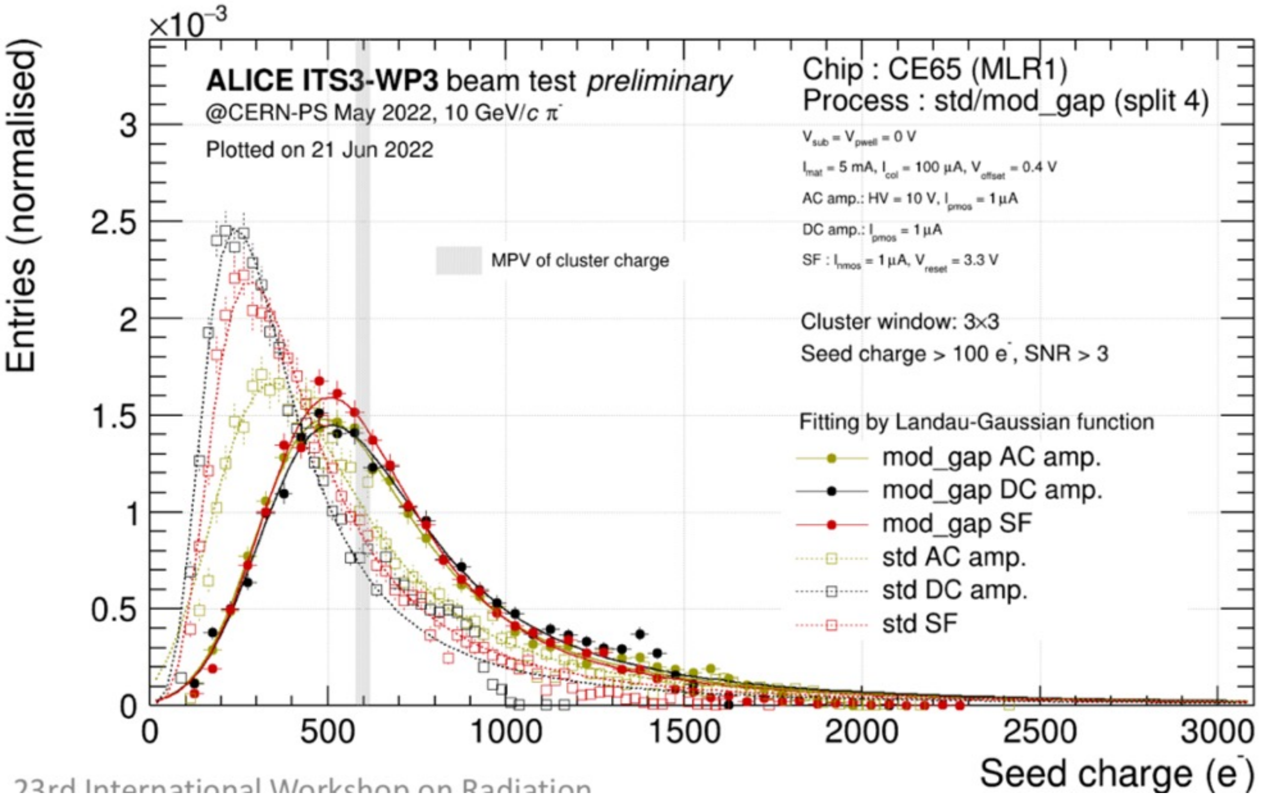
Belle-II OBELIX key features & status

1. Pixel matrix with **detection efficiency** proven at hit rates & radiation levels expected
   - Low threshold (250 e-) established
   - Time-walk compatible with 25 ns 98% in-time efficiency
   - Radiation-tolerance validated during July 2023 beam test
2. Handling of Belle II **trigger rate & delay**
   - Implementation of trigger logic (TRU) in digital design
   - Verified by simulation
3. Robust handling of **trigger veto** during injection
   - No specific mode required in TRU
   - Tolerance up to 800 MHz/cm2 for 0.5 µs verified in simulation
4. Power dissipation adapted to **air cooling** (inner layer) and **water cooling** (outer layer)
   - Demonstrated in simulations & test beam
   - Digital logic power with hit rate known
5. Simple system integration: **power regulation** on-chip, low data bandwidth
   - LDO layout on-going, but require full simulation
   - Low bandwidth confirmed
6. Providing **fast input to trigger** (~100 ns) with coarse granularity (8 areas)
   - Parallel read-out (/ main path) implemented (TTT)
   - Not yet checked at detector system level
7. **Integration time** within 50-100 ns range, option for **finer time stamping** (≲10 ns)
   - BCID mechanism adapted
   - Additional mechanism (PTD) simulated with ~6 ns resolution
8. Monitoring of internal biases and temperature
   - ADC architecture proposed
   - Independent integration in OBELIX-1 (no risk)

TPSCo 65 nm: current status

- From 1st submission in TPSCo 65 nm
  - Based on APTS, CE-65, DPTS: talks at IWoRiD2022, TREDI 2023, ULTIMA 2023, PSD 2023
  - Variety of pixel pitches: 10-25 µm
  - Successful sensitive layer depletion
    - From modified process

doi: 10.1016/j.nima.2022.167213
doi: 10.48550/arXiv.2309.14814
doi: 10.1016/j.nima.2023.168478



- Large consortium
  - CERN-EP R&D roadmap WP1.2 + ALICE-ITS3 project
  - France(Strasbourg,Marseille, Saclay), Italy(Bari, Torino, Catania, Cagliari, Salerno, Trieste), NIKHEF, Germany (DESY, Heidelberg, Munich) HEPHY-Vienna, EPFL, Zürich STFC-RAL, Oxford, Birmingham CCNU, Yonsei, Bolu, Talinn, Zagreb

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  - Successful sensitive layer depletion
  - Promising radiation tolerance

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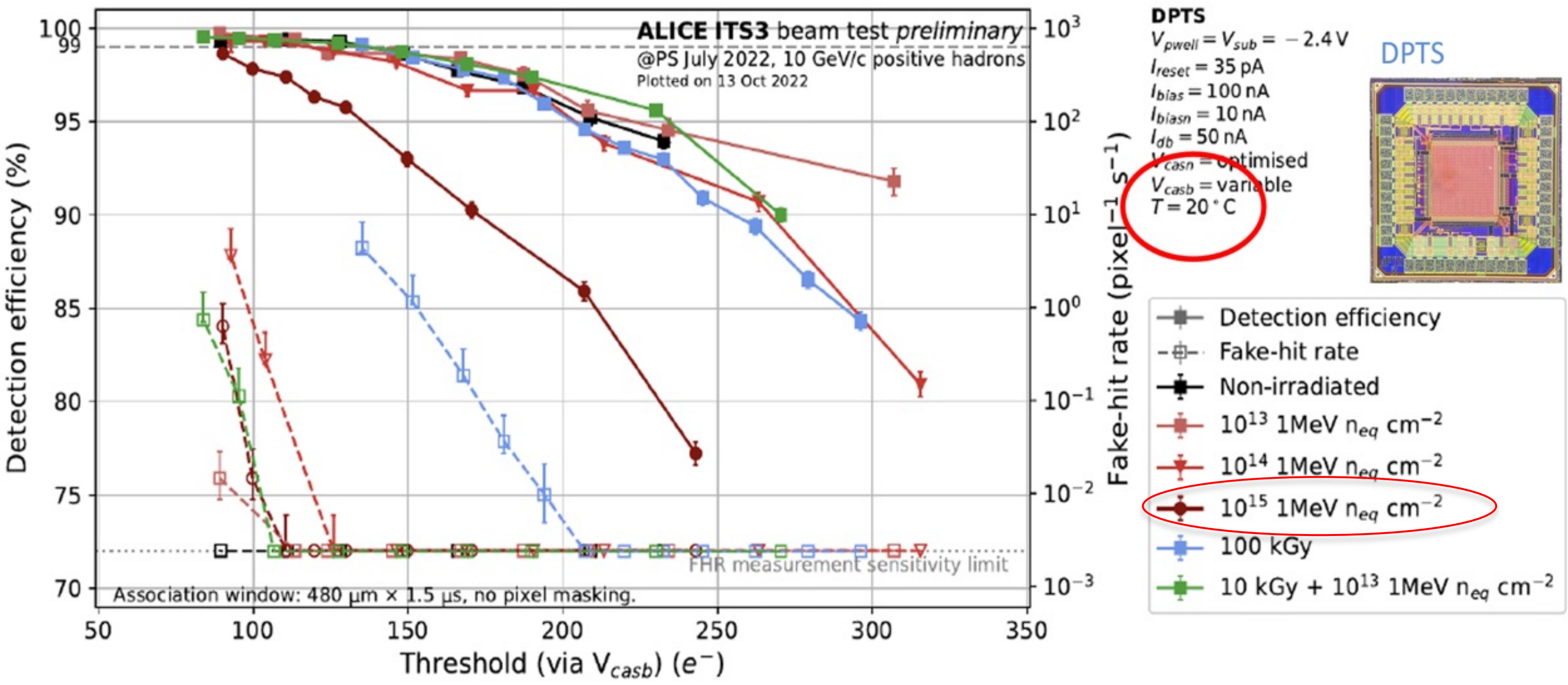

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  - Successful sensitive layer depletion
  - Promising radiation tolerance
  - Promising time resolution

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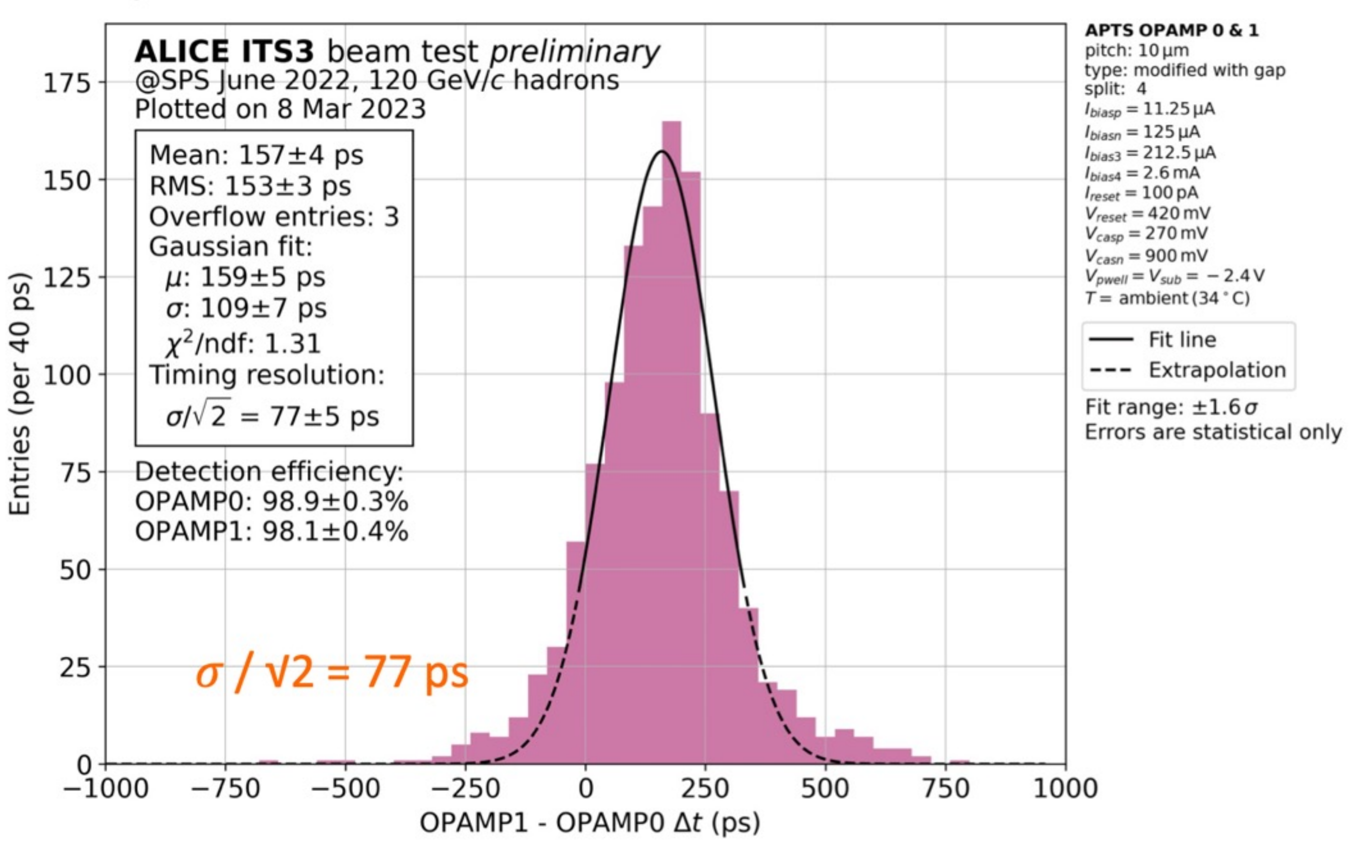


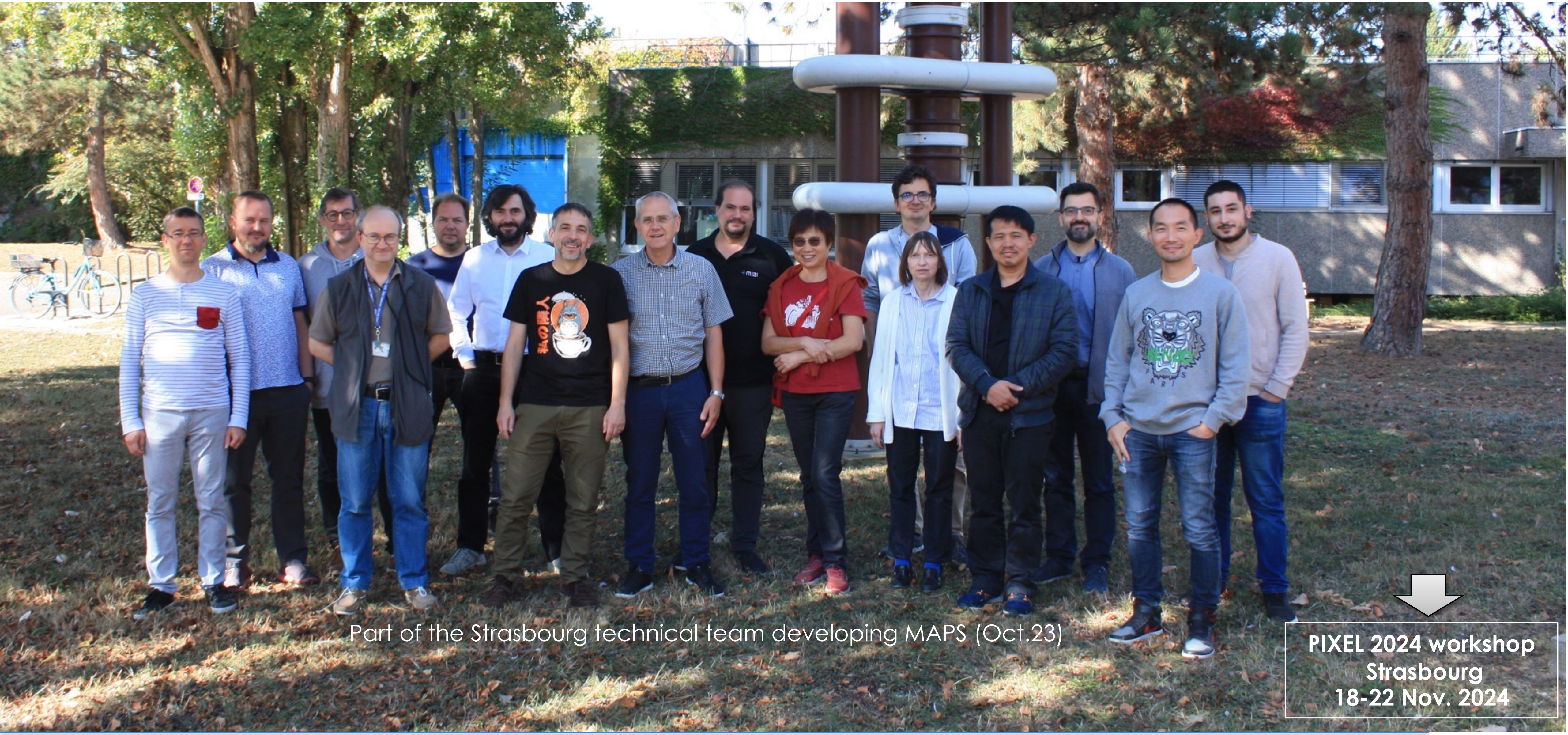
Conclusions for a review on MAPS

- Already a large choice of various optimisations

- A very active R&D world-wide pushing for (among others)
  - 3 μm position resolution with fast readout and low-power (~20 mW/cm^2)
  - Sensors adapted to tracking: low granularity but high-rate (>100 MHz/cm^2) & ~nanosecond timing
  - Gigantic sensor (>100 cm^2)
  - Sub-nanosecond resolution on large sensors

… Sorry if I missed your favourite topics!

Thank you for your attention…backups from here on

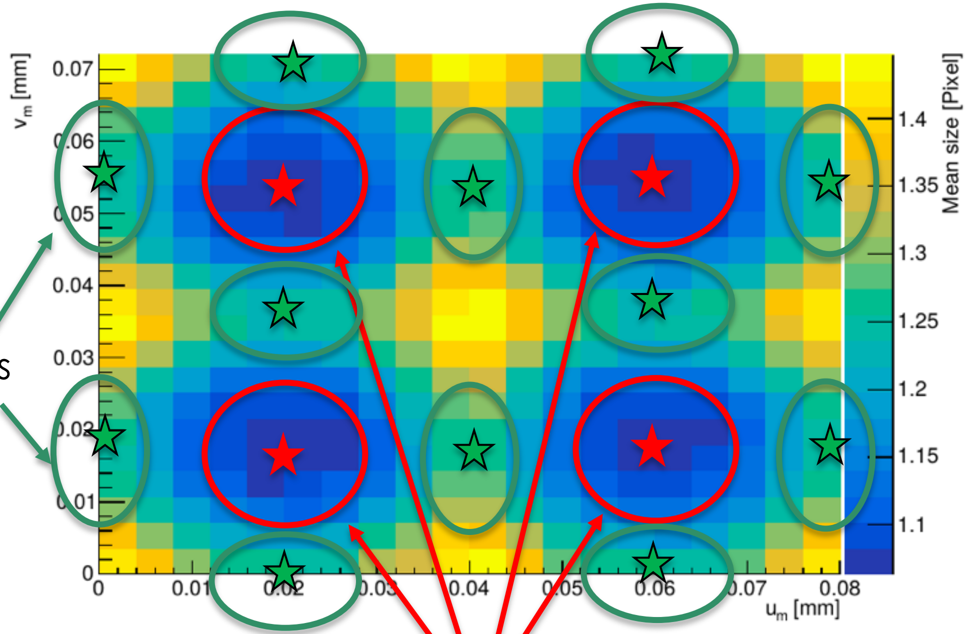


Part of the Strasbourg technical team developing MAPS (Oct.23)

PIXEL 2024 workshop
Strasbourg
18-22 Nov. 2024

Charge sharing & resolution

2x2 pixel (40x36 μm²) area
(TJ-Monopix1 result, ©Bonn Uni.)

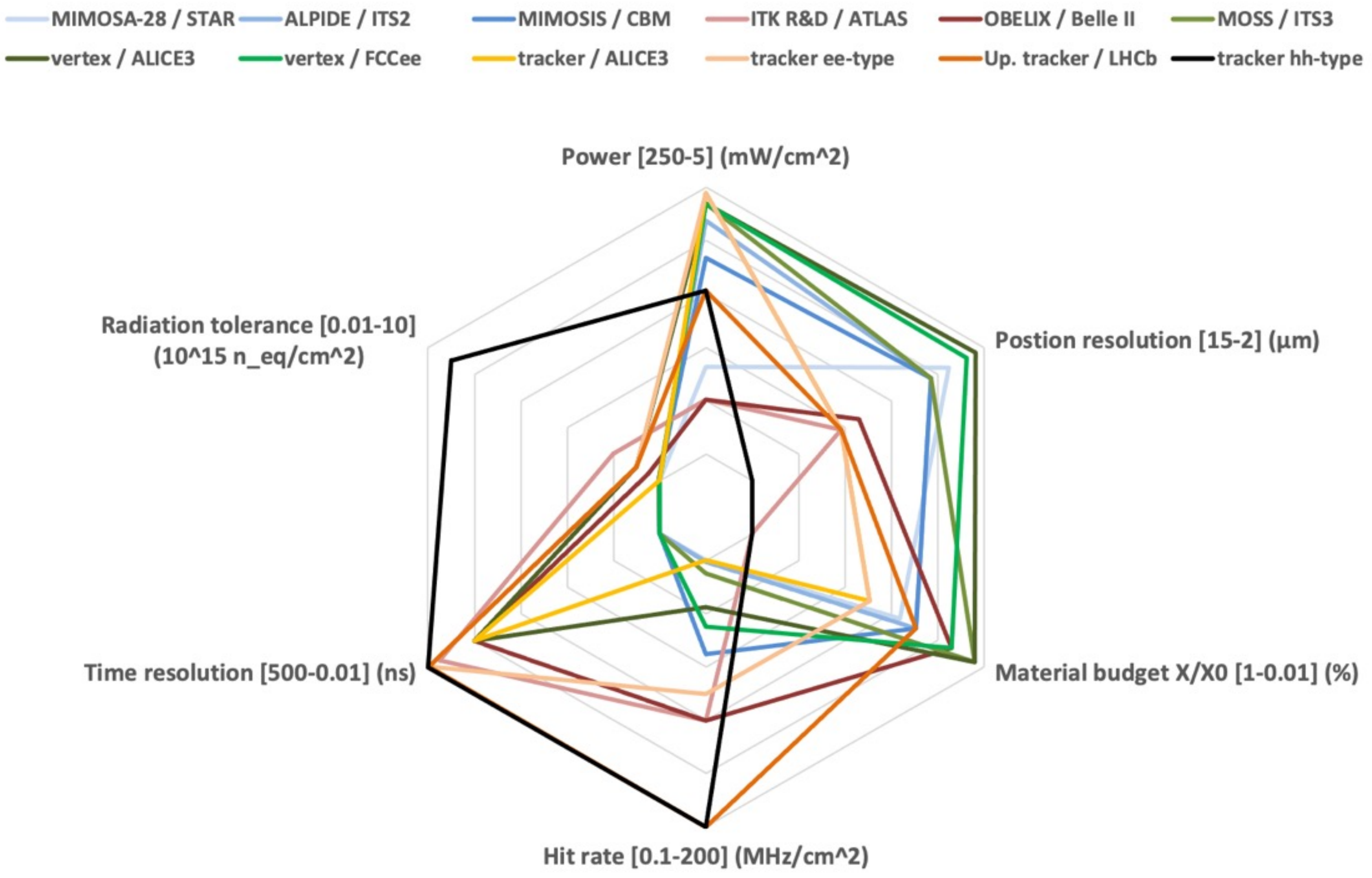


Q-sharing regions
btween 2 pixels

True binary resol. region
=> effective pitch < physical pitch

	STAR PXL	ALICE ITS2	HL-ATLAS ITK	CBM MVD	ALICE ITS3	Belle-II VXD	ALICE3 VTX	ALICE3 tacker	EIC tracker	LHCb UT	FCCee VTX	FCChh tracker
Data taking in	2014	2020	(2035)	2026	2029	2028	2035	2035	203?	2035	>2040	>2050
Total area (cm^2)												
Spatial res. (µm)	< 10	**~5**	10	**~5**	**~5**	< 10	**2.5**	10	pitch 10	O(10 µm)	**3** – 5	~10
Mat. budget (%X0)	0.37	0.35	<1	~0,3	**0.05**	**0.15**	**0.15**	0.3?	0.05-0.55	0.3?	**0.15**	~2
Hit rate (MHz/cm^2)	O(0.1)	O(1)	**200** triggered	15-70	~20	**100** triggered	35	0.005	?	20Gb/s	O(20)	
Time figure (ns)	200.10^3	5.10^3	**25**	5.10^3	5.10^3	~100	100	100	100 (?)	**O(1)**	10^2-10^3	**$5x10^{-3}$**
Trigger rate (kHz)						30			500			
Rad.hard. (kGy) (n_{eq}/cm^2)	2 10^{12}	30 $2x10^{13}$	800 10^{15}	30 /year < 10^{14} /y.	<100 <10^{14}	100 $5x10^{13}$	- $1.5x10^{15}$ /year	-	- 10^{15}	**2400 $3x10^{15}$**	20 $5x10^{11}$	100 **10^{16}**
nb of layers	2	7				5-6			5 + 5d			
radii (cm)	3-8					1.2-13.?						
bunchX (ns)			25		25	4			10			

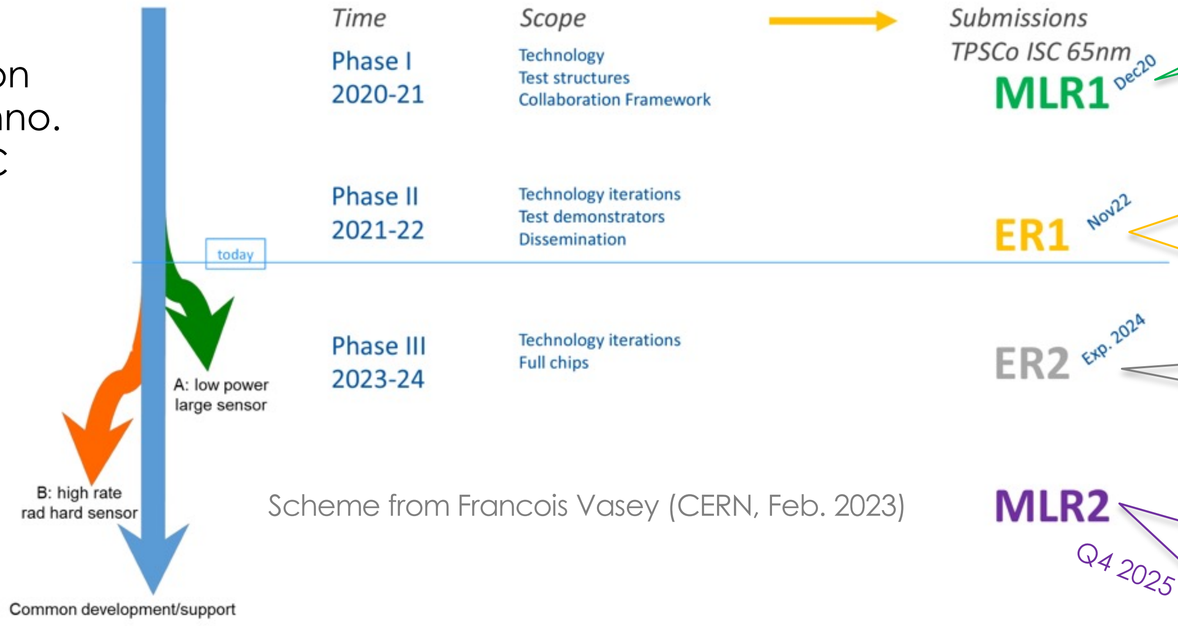
Specifications (normalized to 0-100% score)



ECFA-DRD3/7

The new horizon: TPSCo 65 nm ?

- Foundry located in Hokuriku, Japan
- Large consortium lead by CERN exploring the techno.
- Strong connection with 180 nm techno. operated @ IPHC

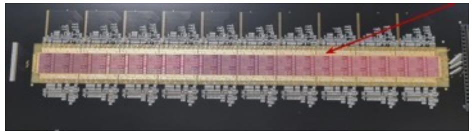


Scheme from Francois Vasey (CERN, Feb. 2023)

- initial functional blocks
- 1st sensors (APTS, CE-65, DPTS)
- Structures to qualify techno

- Optimised sensors (APTS, CE-65, DPTS)
- Complementary functional blocks
- 1st stiched (1D sensors)

1.4x26 cm



- Optimised stiched sensor ALICE-ITS3
- Some chiplets for R&D

- **Start of the R&D program**

process modifications

position $\sigma \lesssim 3$ µm

power $\lesssim 20$ mW/cm^2

timing 10 -100 ps

LGAD in MAPS

hit rate > GHz/cm^2

new architectures

tolerance > 10^{16} n_{eq}/cm^2

My understanding about TPSCo submission

LS2		Run 3				LS3			Run 4				LS4	
2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034

MLR1 ER1 ER2 ER3 **=> ALICE/ITS3**

- Significant R&D in MLR1 & ER1
- Few R&D in ER2
- None in ER3 (?)

Update ESPP

MPR2 MPR3 MPR4 … **=> FCCee**

R&D within CERN & ECFA
- critical role of DRD3 WG1 for scientific program
- critical role of DRD7 WG6 for submission organisation

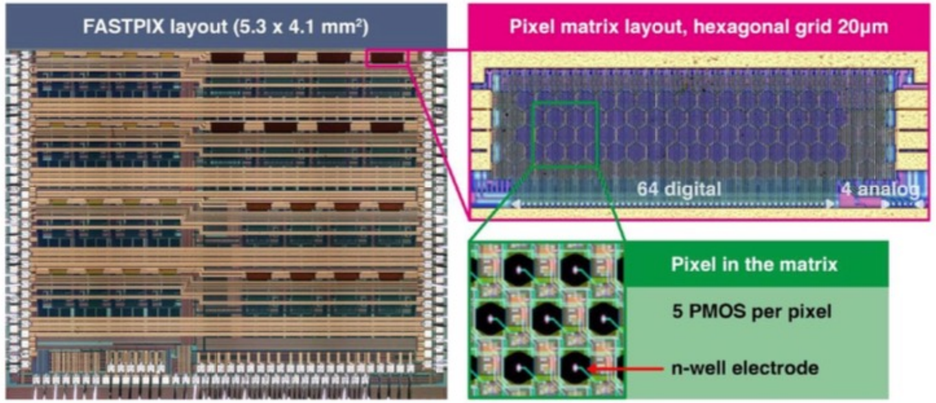
Intermediate projects
- ALICE 3, vertex & tracker
- LHCb tracker
- Belle II tracker

=> Delicate transition switch from generic R&D to experiment-oriented dvpmt

FASTPIX

FASTPIX technology demonstrator for sub-ns timing

- Modified 180 nm CMOS imaging process, design optimisations for fast charge collection
- Small hexagonal pixels (8.66 to 20 µm pitch)
- Time resolution of ~140 ps achieved in test beam



doi: 10.3390/instruments6010013

FASTPIX efficiency and time resolution in test beam