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Monolithic CMOS pixel sensors: Ongoing developments in France

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- → Brief overview of French MAPS activities
- → 3 projects:

  MIMOSIS / OBELIX / CE-65 & stitching

MAPS contributors in France

3 laboratories currently involved

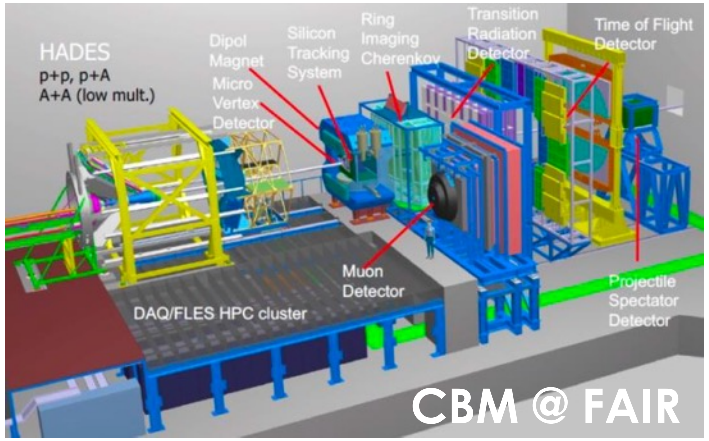
- **CEA-IRFU**, Saclay: CACTUS project, R&D for time resolution in few tens of ps range
  - Y. Degerli, F. Guilloux, P. Schwemling et al. DOI: 10.1088/1748-0221/15/06/P06011 (small proto few mm2)
- **IN2P3-CPPM**, Marseille: R&D for high-rate (>100 MHz/cm^2) and radiation tolerance of interest for HL-LHC, Belle II
  - Coordination: M. Barbero (scientific) & P. Pangaud (technical)
- **IN2P3-IPHC**, Strasbourg: applications to CBM, ALICE, Belle II
  R&D for granular (σ_{pos}~3 µm) and thin sensors (~0.1% X_0) for future Higgs factories

Structure @ IPHC

- Since 2019, **C4Pi** = core facility (~20 engineers for design and test + Docs and Postdocs)
  - Technical coordination C.Hu-Guo, deputy C.Colledani / Scientific coordination J.Baudot
- Physicist involved in R&D (5-6 people)
  - **PICSEL** group (A.Besson et al.) for future Higgs factory & spin-off applications
  - **Belle II** group (I.Ripp-Baudot et al.) for an upgrade of the vertex detector
  - **ALICE** group (C.Kuhn et al.) for Inner Tracking System (version 2 & 3) and ALICE 3 proposal

MIMOSIS project - Context

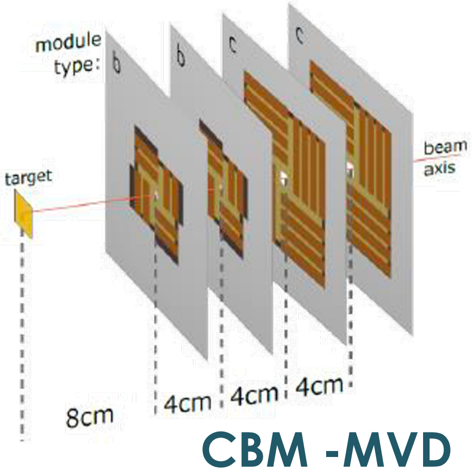
- **Goals & mean**
  - Match CBM vertex requirements & achieve steps forward / Higgs-Factories
    - combine low-power (<50 mW/cm²) & high hit-rate (>50 MHz/cm²)
  - Exploits known Tower-180 nm technology
    - Follows ALICE-ITS2/ALPIDE FEE & priority encoder matrix read-out



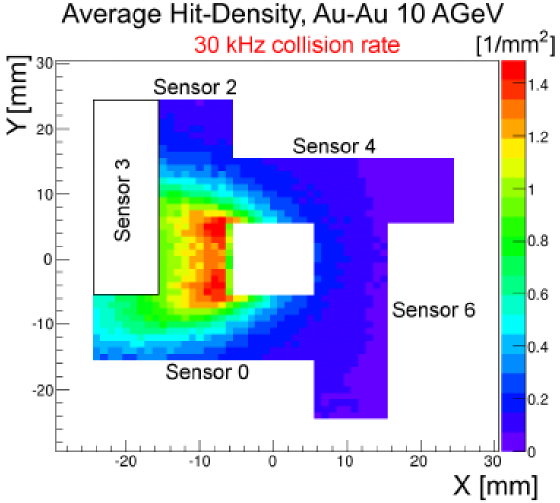
- **CBM Micro Vertex Detector (MVD)**
  - Collaboration: IPHC, IKFrankfurt, GSI, H2020-CREMLIN+
  - Collisions: 100 kHz Au+Au @ 11 AGeV and 10GHz p+Au @ 30 AGeV
    => large hit-rate fluctuation & operation in vacuum

Position resolution	~5 µm
Time resolution / continuous r.o.	~5 µs
Power dissipation	<100 - 200 mW/cm²
Hit rate (average/50 µs peak)	20/80 MHz/cm²
Material budget / layer	0.05 % X_0
Operation temperature	- 40°C to +30°C
Radiation* (non-ionizing)	~ 7×10^{13} n_{eq}/cm^2
Radiation* (ionizing)	~ 5 Mrad
Heavy Ions-tolerance	10 Hz/mm²

* No safety factor



J.Stroht Bormio 2018
M.Koziel, DPG 2017

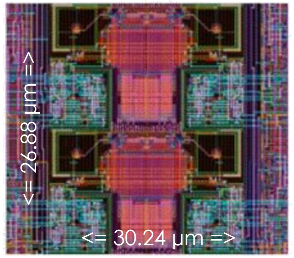


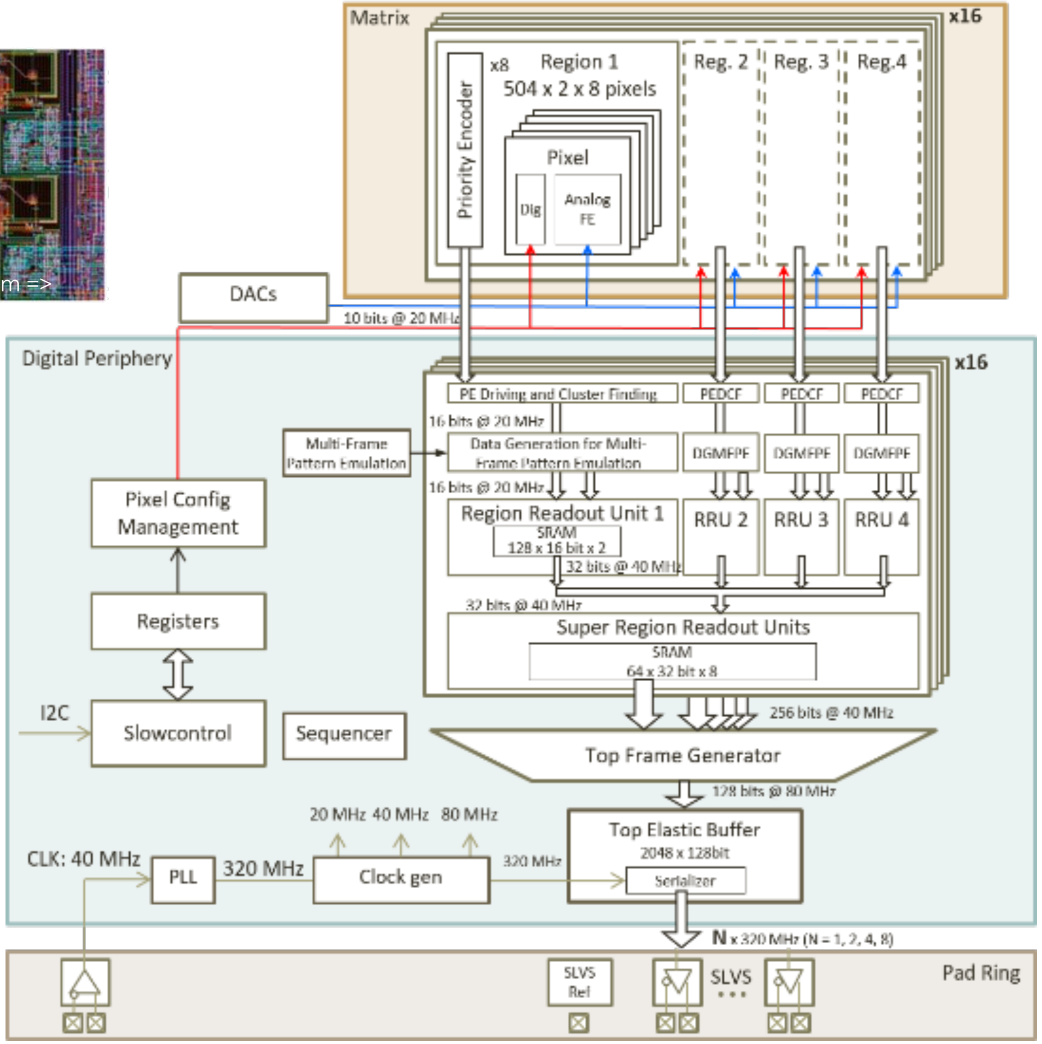
MIMOSIS sensor - architecture

- Pixel matrix
  - Pixel area = 26.88 x 30.24 µm^2
  - 504 x 1024 pixels
    structured in read-out regions (column groups)
  - Global shutter: 5 µs integration time
- Read-out
  - Elastic memory concept (9 events storage capacity)
  - 8 outputs (320 Mbps) for a total ~2.5 Gb/s
- Single-Event-Effects resilience
  - Triple Modular Redundancy in critical places
    + Error Correction Code (PhD. Y.Zhou)
- Power budget

Pixel/frame	1	640
Analogue (mW)	30	30
Digital (mW)	150	200
Total (mW/cm²)	**43**	**55**

https://indico.cern.ch/event/981823/contributions/4293566/
F.Morel TIPP 2021



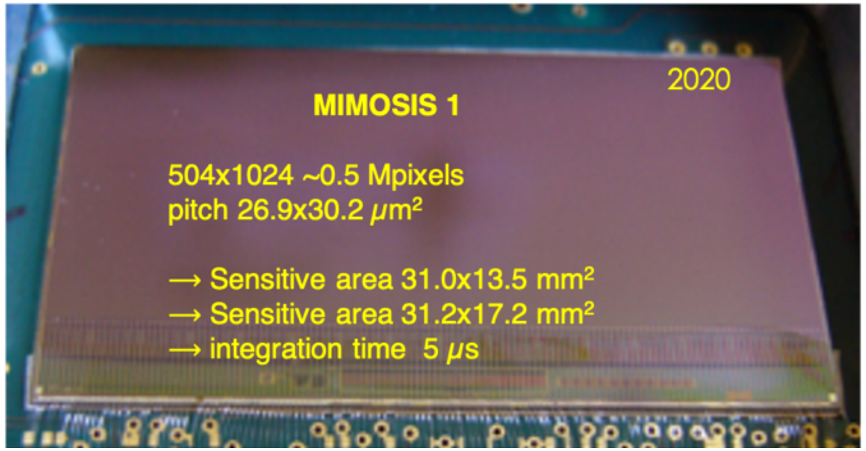


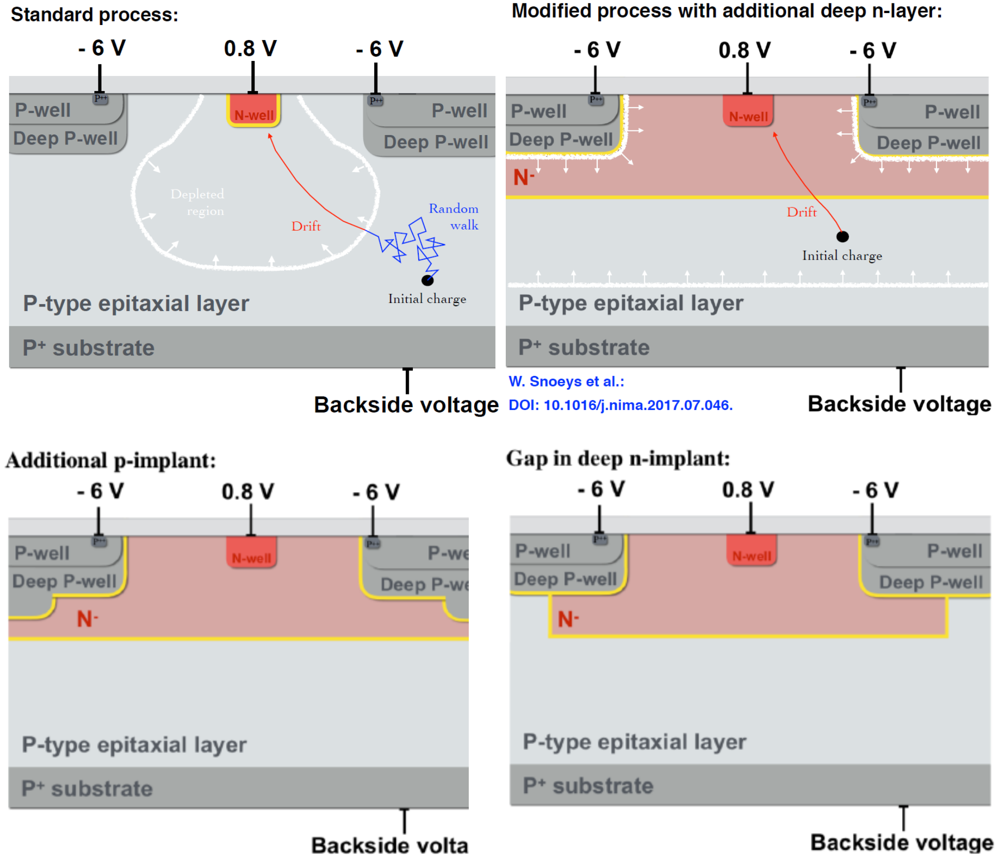
Archi. validated with MIMOSIS-0 (2018-19)
M.Deveaux et al.
https://doi.org/10.1016/j.nima.2019.162653

MIMOSIS sensor – process & sensing node

- Process: Tower 180nm
  - 2020: MIMOSIS-1 fabricated
  - 2021 (late): MIMOSIS-2 submission
  - >2022: final chip, MIMOSIS-3

- Sensing node
  - High resistive epitaxial layer (25 µm for MIMOSIS-1)
  - Benefits from process modification introduced by CERN
  - 2 Couplings collection node - Front-End
    - DC and AC for biasing > 20V (J.Heymes DOI: 10.1088/1748-0221/14/01/P01018)



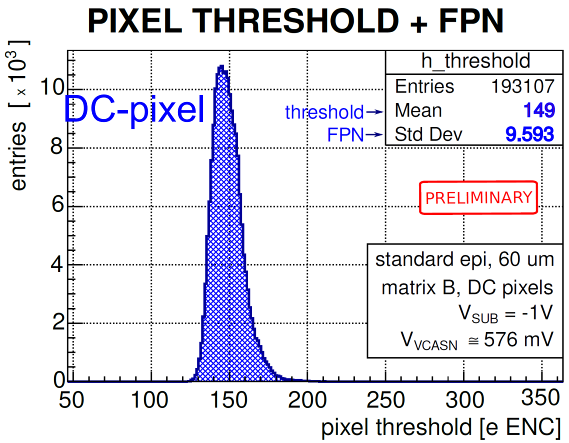


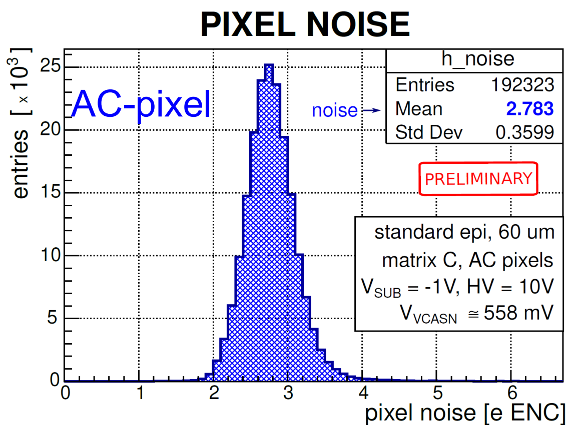
M.Munker et al. DOI: 10.1088/1748-0221/14/05/C05013
C.Bespin et al. DOI: 10.1016/j.nima.2020.164460

Key studies:
depletion role in trade-off position res. / radiation tolerance

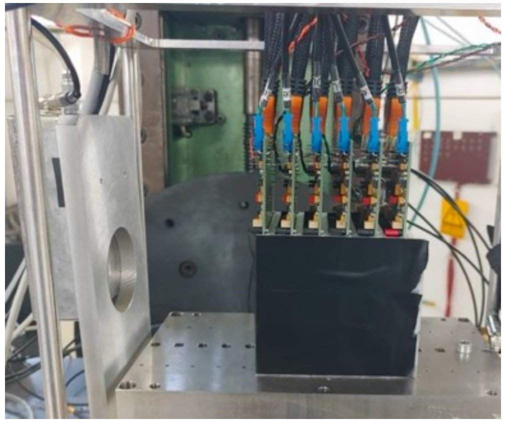
MIMOSIS sensor – on-going tests

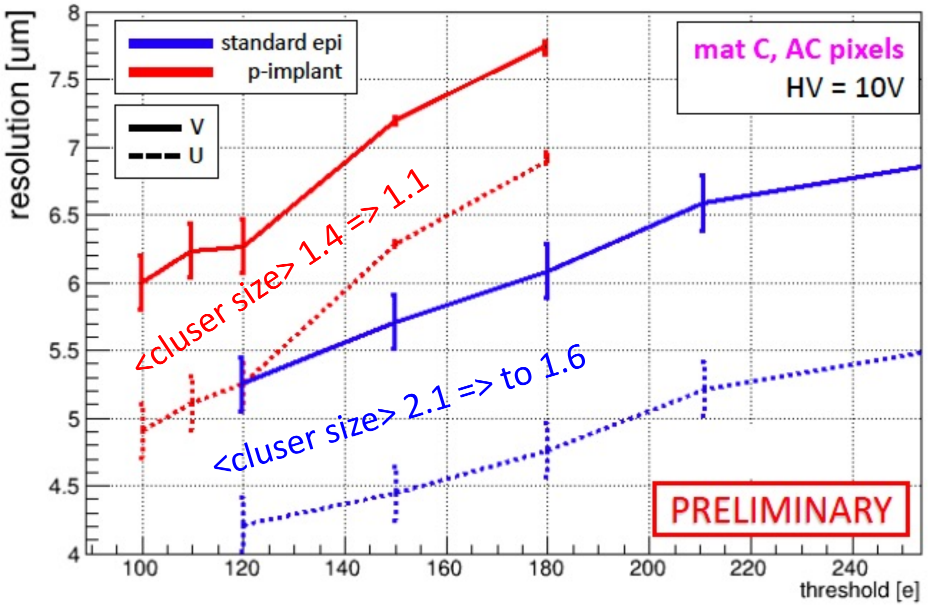
- Lab tests
  - DC pixel { Threshold 100-150 e-, FPN 5-10 e-, Pixel noise 3-5 e- }
  - AC pixel { Threshold 100-250 e-, FPN 10 e-, Pixel noise 3-5 e- }
- Radiation tolerance
  - Irradiations performed
  - Sensors tested in beam
- Beam tests
  - Sensors thinned to 60 µm => telescope = 6 x MIMOSIS
  - 3 campaigns @ DESY & CERN-SPS
  - Sensors @ room temperature
  - Various biasing conditions
  - Analysis still in progress
    - Detection efficiency > 99%





All results PRELIMINARY from R.Bugiel, TWEPP 2021





OBELIX project

Goal and mean

- Propose a sensor for an upgraded Belle II vertex detector
  - 5 to 6 layers fully pixelated
  - Readiness for ~2026

  => cf K.Nakamura talk earlier today
- Exploit similarity of ATLAS-ITK & Belle II requirements
  - Adapt existing TJ-MONOPIX2 sensor (J. Dingfelder Vertex 2021)

Belle II - VTX

- Collaboration for OBELIX:

  Bergamo Uni., Bonn Uni., CPPM, HEPHY, IFAE, IFIC, IPHC, INFN-Pavia/Pisa

Spatial resolution	<10 µm
Time resolution / trigger rate	25-100 ns
Trigger rate / delay	30 kHz / 5-10 µs
Hit rate* (inner layer)	<150 MHz/cm²
Material budget / layer	0.1 to 0.5 % X_0
Power dissipation	<100 - 200 mW/cm²
Operation temperature	room temperature
Radiation* (non-ionizing)	~ 10^{14} n_{eq}/cm²
Radiation* (ionizing)	<1 MGy

* x5 safety factor

- Technology Tower-180 nm
- Modified process for full-depletion
- Full scale sensor 2x2 cm2 fabricated in 2021
- Pixel matrix 512x512 with 33x22 µm² pitch
- Time resolution 25 ns
- Power dissipation 200 mW/cm²
- ENC, pixel 17 e-, FPN 5 e- (measured)
- Threshold 150 e- (measured)

Next step: full-size proto. OBELIX-1to be submitted in 2022
- Enlarge matrix size to 30 x 20 µm2
- Possibly increase pixel pitch up to 35-40 µm
- End-Of-Column logic adapted to Belle II trigger

CE-65 & stitching - Context

- **Technology switch every 10 years**
  - STAR-PXL built from 350nm process, R&D started ~2001
  - ALICE-ITS2 built from 180 nm process, R&D started ~2011

=> 2020 : 65 nm
  - smaller in pitch (< 20 μm) with HEP-useful hit-rates (>50 MHz/cm^2)
  - Time resolution down tp 10 ps range
  - Higher radiation tolerance (> 10^{15} n_{eq}/cm^2)
  - Lower power dissipation

- **Stitching as a way to the "ultimate thinness"**
  - Sensor area 30x10 cm^2 to reach 0.05% X_0/cylindric layer => cf M.Mager talk today

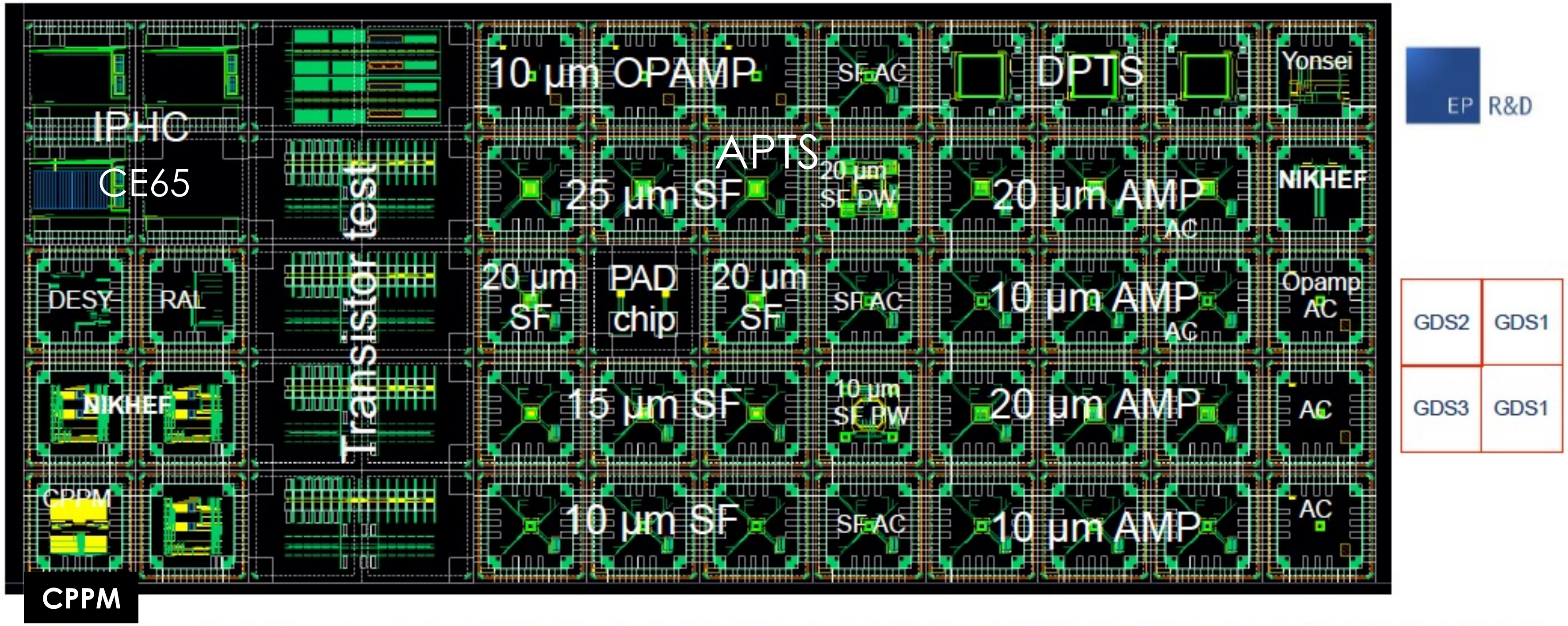
- **Tower-65nm process**
  - Accessed to TPSCo Foundry (Japan) through CERN for large international consortium (included also in AIDAinnova, Cremlin+)
  - Triggered by CERN EP R&D program, ALICE and ATLAS experiments
    - Firs application: ALICE-ITS3 (ALICE-PUBLIC-2018-013) for LHC-long shutdown 3
    - Obvious synergies with Higgs Factories requirements
  - Some details
    - 12" wafers
    - Very thin epitaxial layer
    - Doping profile optimised
    - Modified process (deep N-well blanket) possible

First submission in Tower 65 nm

- MLR run January 2021 (1.5x1.5 mm^2 dies)

1.5 mm

Presented by Walter Snoeys, CERN EP R&D roadmap WP1.2



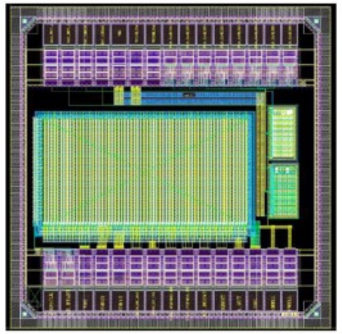
- IPHC: rolling shutter larger matrices, DESY: pixel test structure (using charge amplifier with Krummenacher feedback, RAL: LVDS/CML receiver/driver, NIKHEF: bandgap, T-sensor, VCO, CPPM: ring-oscillators, Yonsei: amplifier structures
- Transistor test structures, analog pixel (4x4 matrix) test matrices in several versions (in collaboration with IPHC with special amplifier), digital pixel test matrix (DPTS) (32x32), pad structure for assembly testing.
- After final GDS placement, GDS1 is instantiated twice.
- Converged with 4 splits of 3 wafers ← Standard and modified sensing node

CERN

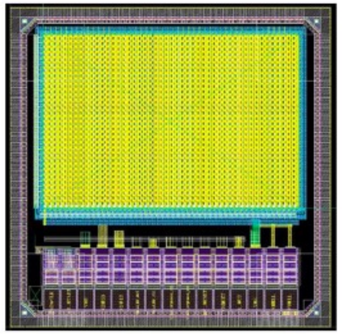
Back late Spring 2021
=> First test results are arriving
… promising but too early !

CE-65 sensors

- Small pixel matrices
  - Target: charge collection properties
  - Parameter space exploration
    - Pitch 15 & 25 µm
    - Front-ends: source-follower / amplifier
    - Collection diode with
    - Standard and optimised process

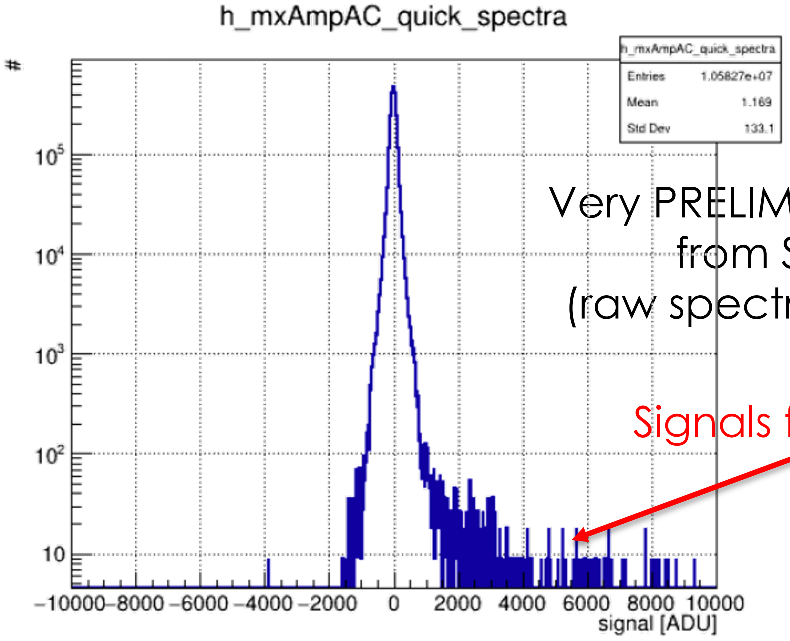


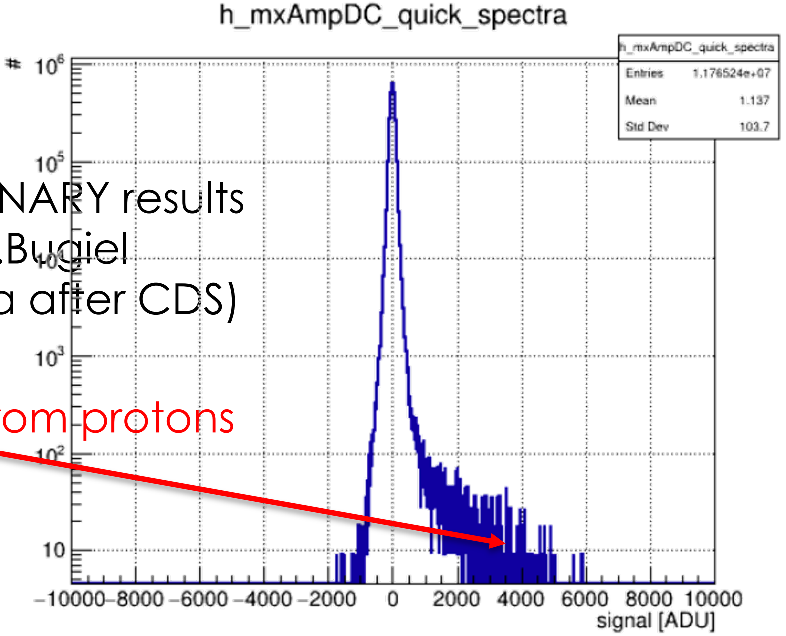
Variants A/B/C
64x32 pixels
15 µm pitch



Variant D
48x32 pixels
25 µm pitch

- Additional circuits
  - DAC (already validated)
  - Ring-oscillators from CPPM allowing radiation tolerance assessment





Very PRELIMINARY results
from S.Bugiel
(raw spectra after CDS)

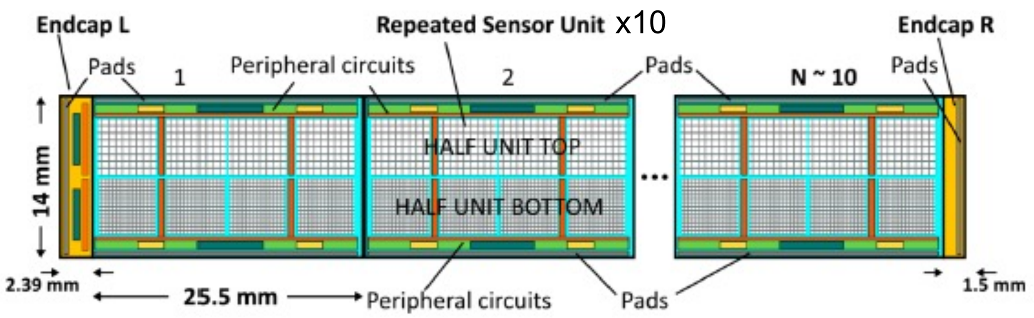
Signals from protons

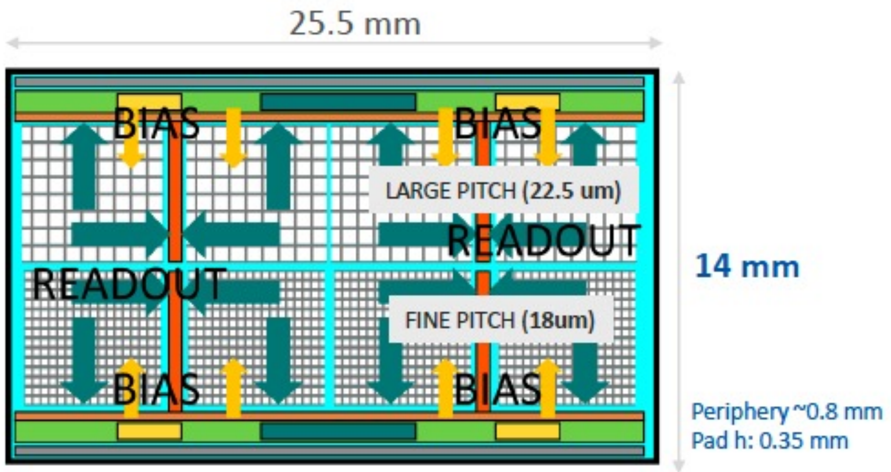
Preparing large stitched sensor

- Engineering run Q1 2022 in Tower-65 nm
- Pixel pitch 18 / 23 µm to be confirmed

MOSS Concept

(From G. Aglieri Rinella)





- Key aspects
  - Yield !
    - Power domain
  - Power dissipation
    - 66 pJ to transmit 1 bit over 30 cm

- Implement a large sensor abutting identical but functionally independent sub-units
  - Repeated Sensor Unit, Endcap Left, Endcap Right
  - Stitching used to connect metal traces for **power distribution** and **long range on-chip interconnect busses for control and data readout**

To conclude

- Strong MAPS activities in France with growing interest
  - **Dedicated core facility: C4Pi in Strasbourg**
- Main R&D lines
  - **Granular & thin sensors => CBM-MVD, ALICE-ITS3, Higgs Factories**
  - **High rate & radiation tolerant sensors => Belle II-VTX**
  - **Time resolution => targeting ~50 ps**
- Technologies
  - **Process under control: Tower 180 nm, LF 150 nm**
  - **Process under exploration: Tower 65 nm (also LAPIS-200 nm)**
  - **Skills under exploration: stitching**

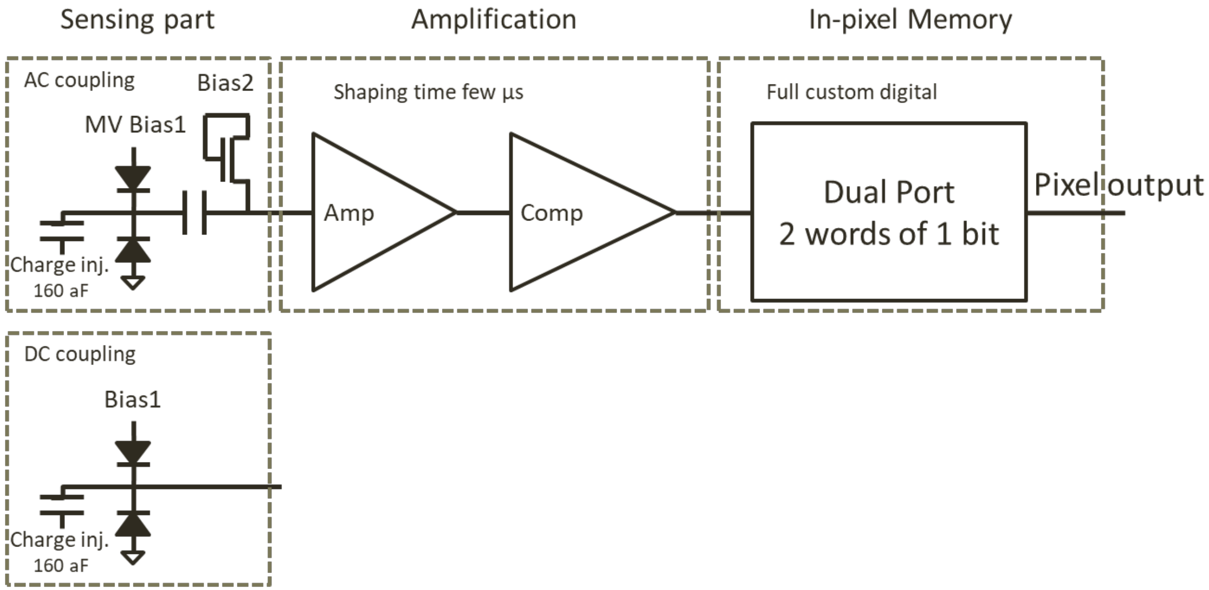
Thank you for your attention… …bonus slides start here

State-of-the-art / Needs

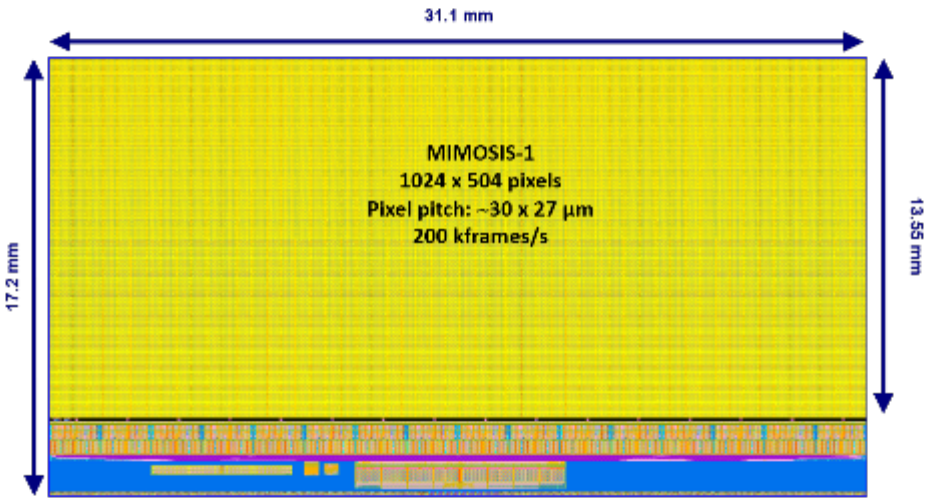
	STAR PXL	ALICE ITS2	HL-ATLAS ITK	CBM MVD	ALICE ITS3	Belle-II Lnom	ILC VTX	FCCee VTX	CLIC SiTrack	FCChh SiTrack
Position res. (µm)	< 10	~5	10	~5	~5	< 10	≲ 3	3 – 5	7	~10
Mat. budget (%X0)	0.37	0.35	<1	~0,3	0.05	0.15	0.15	0.15	~1	~2
Hit rate (MHz/cm²)	O(0.1)	O(1)	200	15-70	2x better / ITS2	100	20	O(20)	O(0.1)	
Time figure (ns)	200.10^3	5.10^3	25	5.10^3		~100	10^2-10^4	10^2-10^3	5	$5x10^{-3}$
Rad.hard. (kGy) (n_{eq}/cm^2)	2 10^{12}	30 $2x10^{13}$	800 10^{15}	30 /year < 10^{14} /y.		100 $5x10^{13}$	10 < 10^{12}	20 $5x10^{11}$	< 10 < 10^{12}	100 $5x10^{15}$
Sensor	**MIMOSA 28**	**ALPIDE**	**R&D MONOPIX MALTA**	**MIMOSIS**	**R&D MOSS**	**R&D OBELIX**	**R&D**		**R&D CLICtd**	
Techno (nm)	350	180	180 (150) modif.	180 modif.	65	180	180 / 65		180	
Pixel pitch (µm²)	20x20	28x28	33x33 36x36	27x30	target stitching	< 40x40	target 17x17		30x300	
Power (mW/cm²)	150	45	O(200)	< 55		target ~100	~3 Pow.Puls			

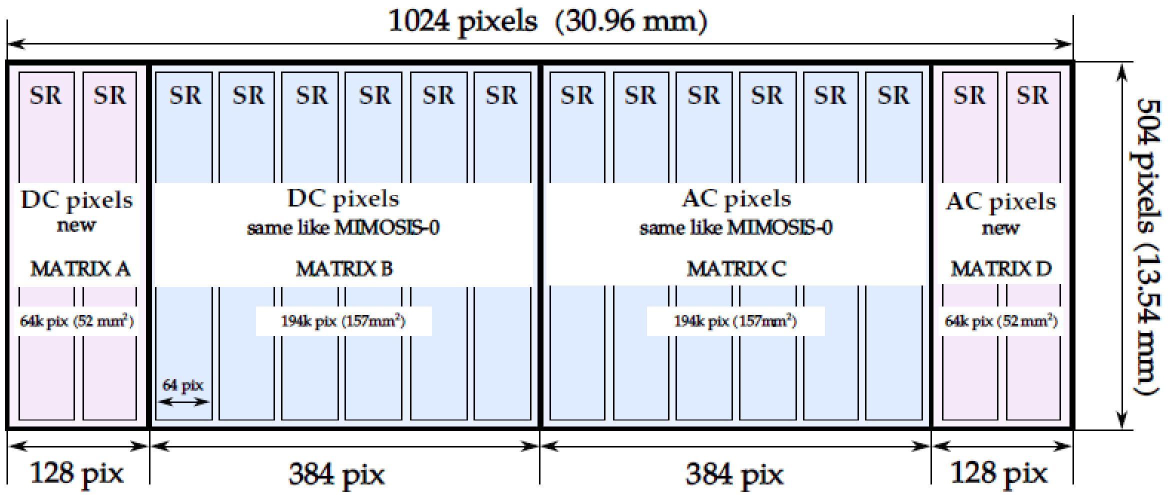
MIMOSIS details

- Pixel Front-End
  - Inherited from ALPIDE
  - Non-linear amplification
  - Clipping for large signals

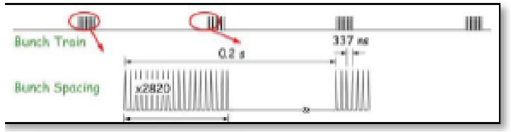


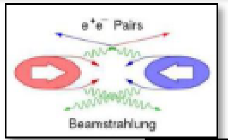
- Matrix





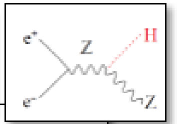
Scientific requirements: ILC - VTX





Reminder: ILC VXD requirements

$$\sigma_b < 5 \oplus \frac{10}{p\beta \sin^{3/2}\theta}\ \mu m$$



Physics
- ⇨ Flavour tagging
- ⇨ Low pT tracks

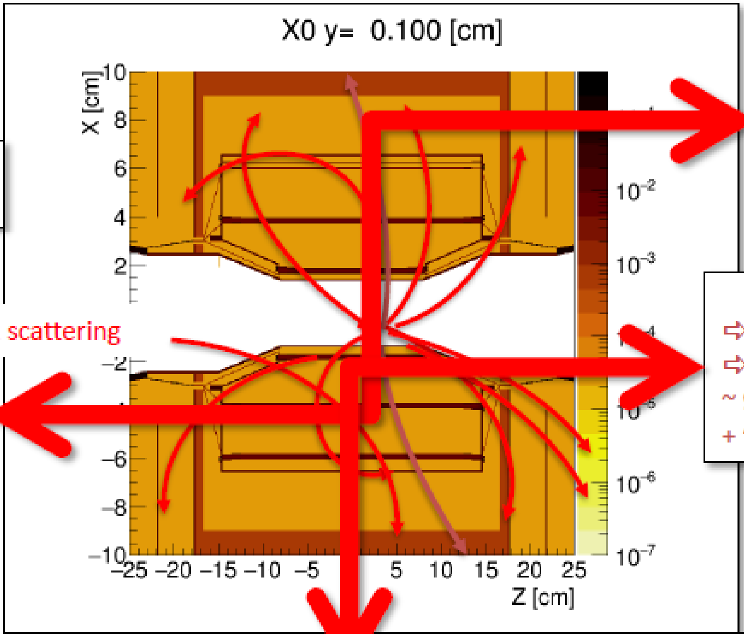
Physics (<Hz/cm²)

Beam background (~ 5 hits/BX/cm² on layer 0)

Beam background

Radiation hardness
O(100kRad/yr) & O(10^{11})n_{eq}/yr

Rad.Tol. devices



Back scattering

Vertex reconstruction
- ⇨ granularity
- ⇨ Pitch ~17 um
- ⇨ (σ_{sp} ~3 um)

Material Budget
- ⇨ ~ 0.15% X_0 / layer
- ⇨ < 1% X_0 for the whole VTX
- ~ 900 µm Si
- + ~0.14% X_0 for the beam pipe

Read-out speed
O(1-10 µs)

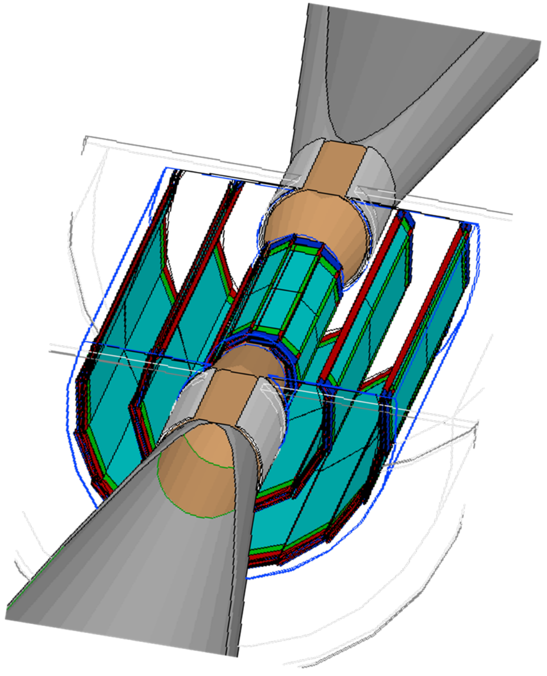
Power consumption
~< 50mW/cm²

Fast read-out & low Power architectures

Cooling
Stiffness / Alignment

Low material detectors & supports structures

Challenge : meet the requirements all together

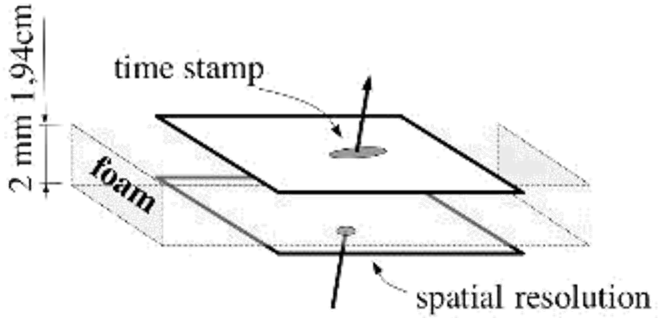


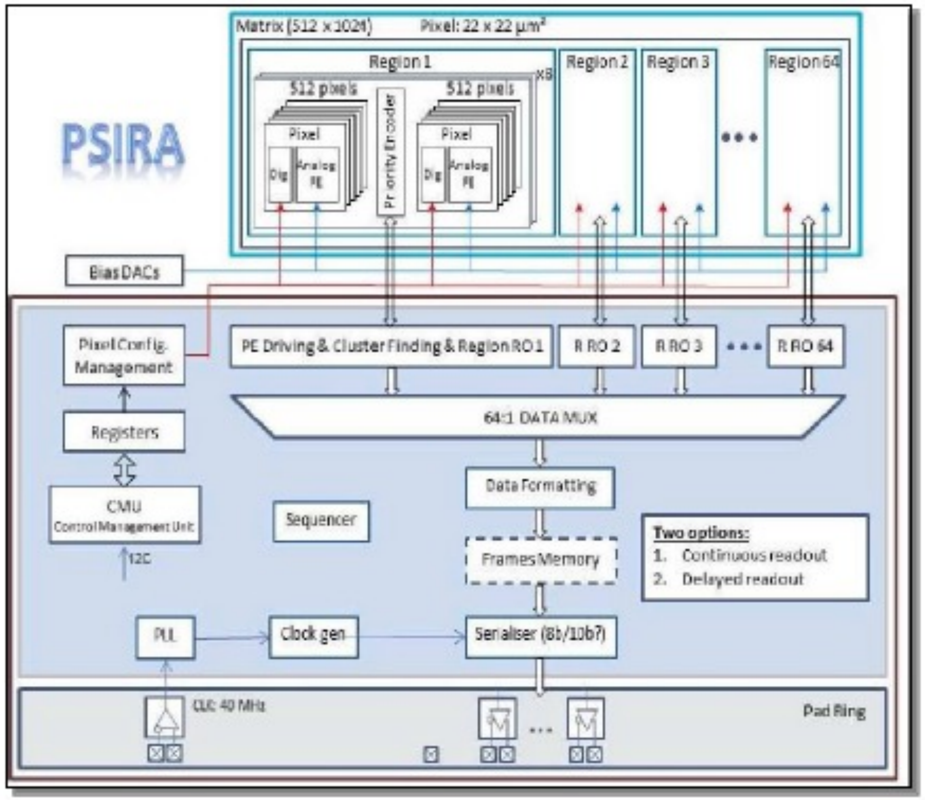
- CEPC / FCCee
  - Many similarities with ILC
    - ~ hit rates
    - granularity, mat.budget, rad.tol.
  - Main difference: time structure

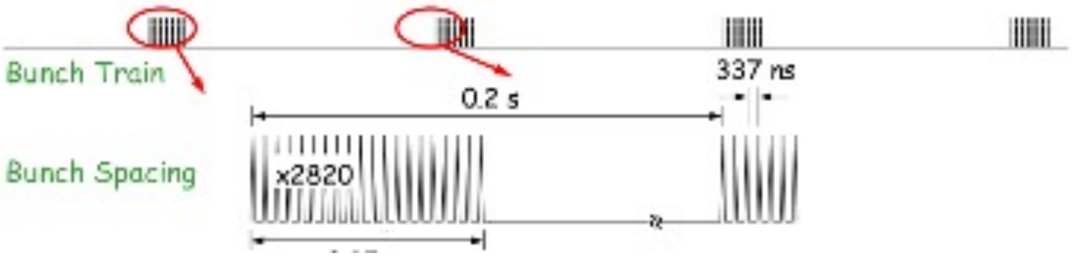
Need to control power without power pulsing

ILC – PSIRA, proposal by IPHC

- For Vertexing & SiTracker
  - Evolution of MIMOSIS
    - Hit-rate already demonstrated
    - Power pulsing to reach ~ 20 mW/cm^2
  - Position resolution < 3 µm
    - In 180 nm process: double-sided layers 4µm/√2
    - In 65 nm process: pitch 18x18 µm^2
  - Integration time ≲ 1 µs
    - Slight acceleration of MIMOSIS: OK
    - Bunch tagging closer to 300 ns:
      => doable but impact on power under study

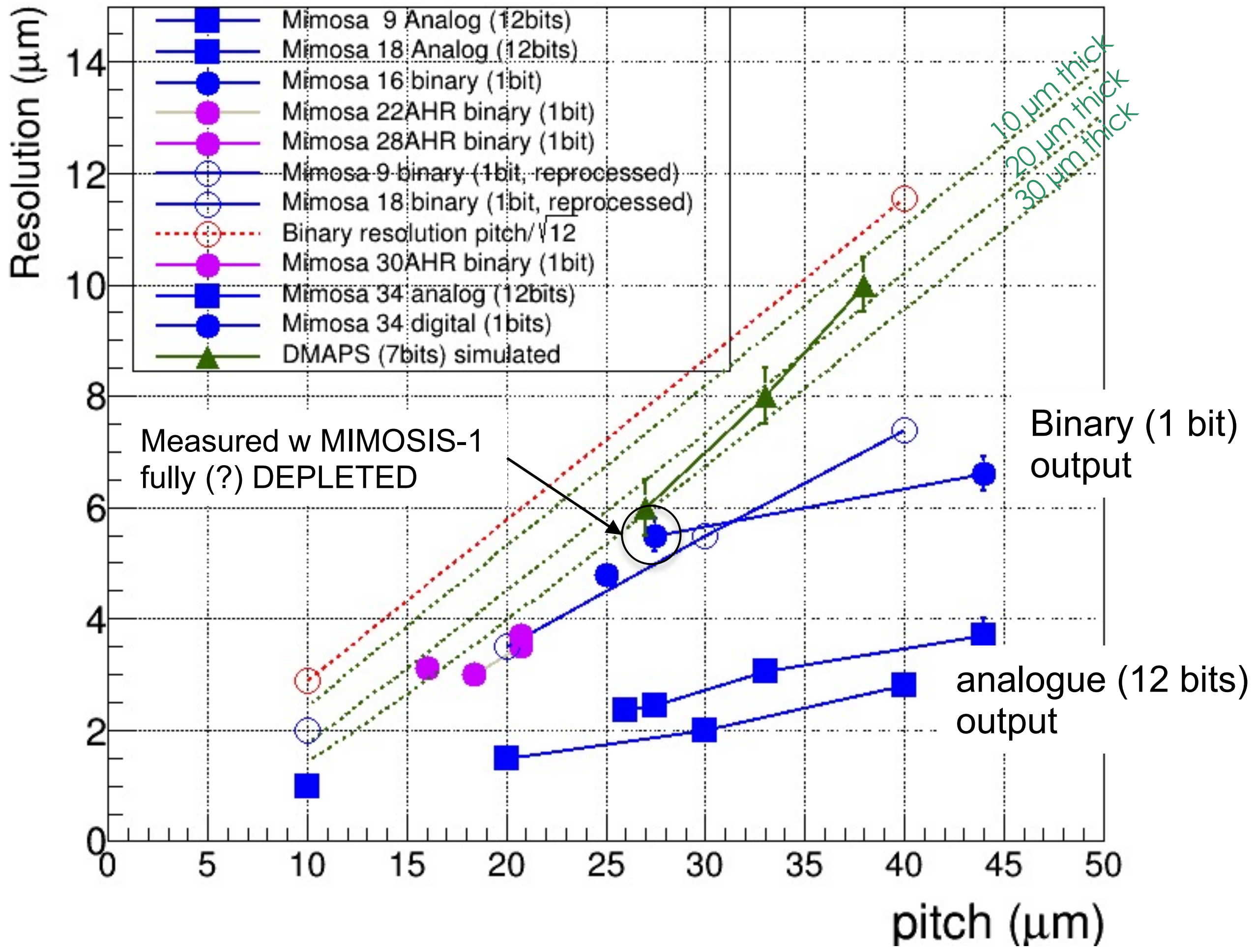






Position resolution

MAINLY from the MIMOSA series designed in Strasbourg with thin non-depleted sensitive layers



- Position derived from charge centroid
  - charge = 1 for binary output
- Resolution here = standard deviation of residuals = true – reconstructed pos.
  - For imaging ~ stdev of PSF

Key parameters

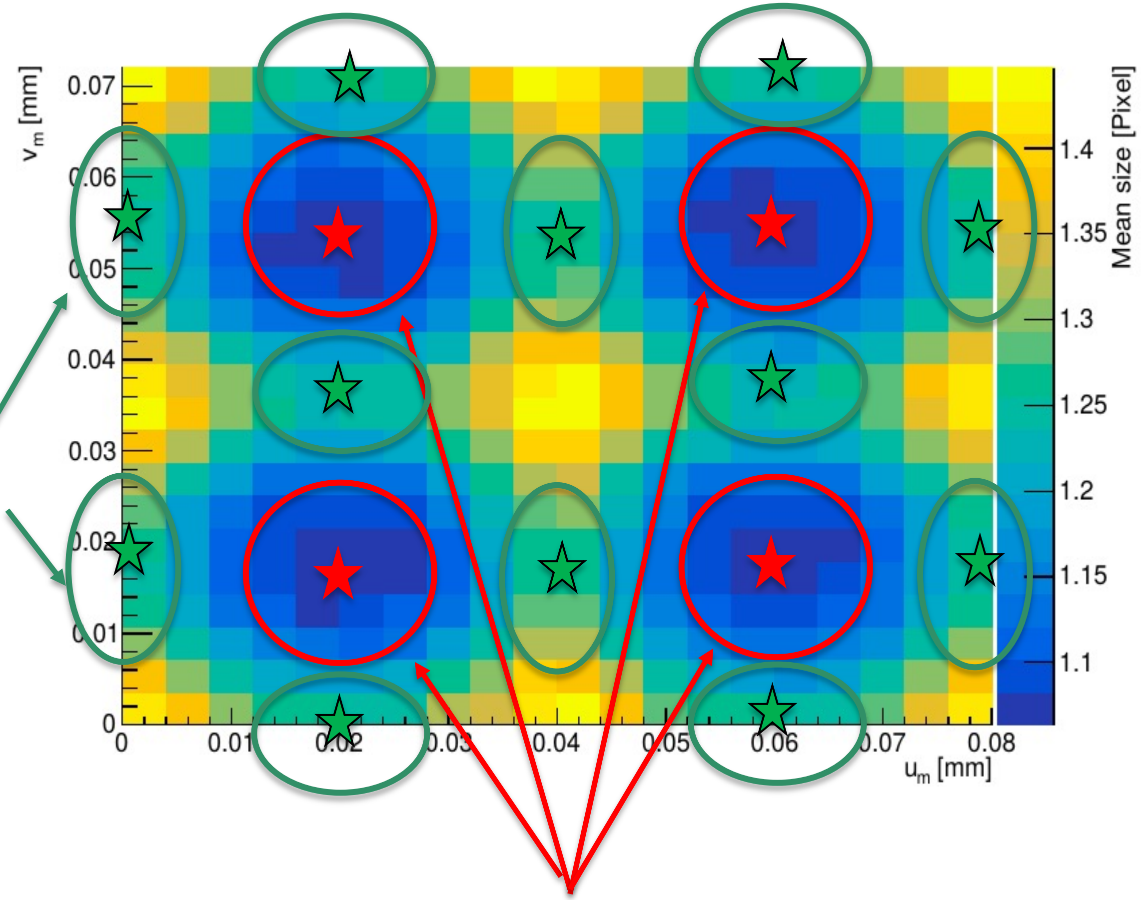
- Pixel pitch
- Charge digit precision
- Threshold for fired pixel detection
- Charge sharing, driven by $\sqrt{2D\frac{\text{distance}}{\text{velocity}}}$
  - Sensitive thickness (distance)
  - Level of depletion (velocity & distance)

Position resolution

- Resolution from binary sensors

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

Q-sharing regions
between 2 pixels



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