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Future of Low Mass Pixel Systems with MAPS

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Les deux infinis

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- Specifications for different experiments
- MAPS, standard performances & challenges
- 2D or planar CMOS technologies
- Integration technologies
- 3D integrated circuit technologies
- Conclusion

Why low mass + high granularity ?

- Charm hadrons
  - STAR, ALICE, CBM
- Charm jet tagging
  - ILC, CLIC, (superB)
- B decay length
  - SuperB
- Beam background
  - ILC, CLIC, SuperB, CBM
- Low momentum tracks
  - STAR, ALICE

Charm hadrons cτ ~ 100 µm

Low $\beta\gamma_B \sim 0.28 \rightarrow \sigma(\Delta z) \sim 60\mu m$

$P_\perp$ down to 100 MeV/c

Impact parameter resolution:
(2 layers hypothesis)

$$\sigma_{I.P.} \approx \boxed{\sigma_{sing.pt.}} \frac{\sqrt{r_1^2+r_2^2}}{r_2-r_1} \circ \frac{\boxed{\sqrt{x/X_0}}\, r_1}{p \sin^{3/2}\theta} \times cst$$

Specification summary

- For the most demanding layer (1st out of 2 to 6)
  - ✗ Orders of magnitude, no security factor, subject to modification
  - ✗ Apply to one layer only

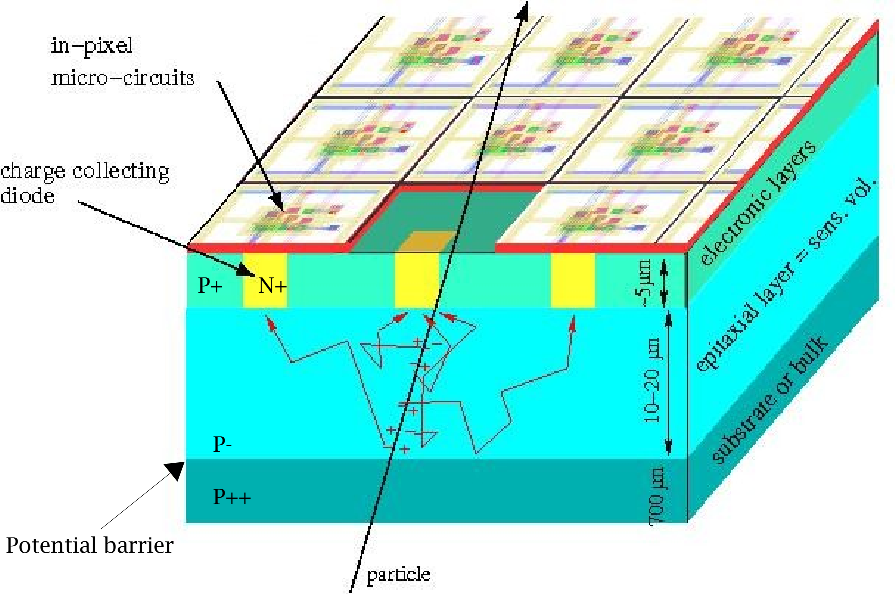
	STAR	CBM	ALICE	ILC 500GeV	CLIC 3TeV	SuperB
spatial resolution (µm)	< 10	~5	~ 5	< 3	~ILC	~15
Material budget (% X0)	< 0.3	0.3	0.3	< 0.3	~ILC	<1.0
Hit rate (x10^6/s/cm^2)	*O*(0.1)	*O*(1-10)	*O*(1)	*O*(0.2)	*O*(1)	*O*(20)
Radiation / year (Mrad) (n_{eq}/cm^2)	*O*(0.2) *O*(10^{12})	*O*(30) <10^{14}		*O*(0.1) *O*(10^{11})	x10/ ILC	*O*(3) ?
Power dissipation (W/cm^2)	0.1	1-2		0.1		1-5

<u>Notes:</u> 10^6 hits/s/cm^2 over 20x20 µm^2 pixels ⟺ 0.04% occupancy @ 100 µs readout
BUT sparse data~70 Mbits/s over 1 cm^2

ILC, CBM r.o. time~10µs / CLIC timestamp~10ns

MAPS, the basics

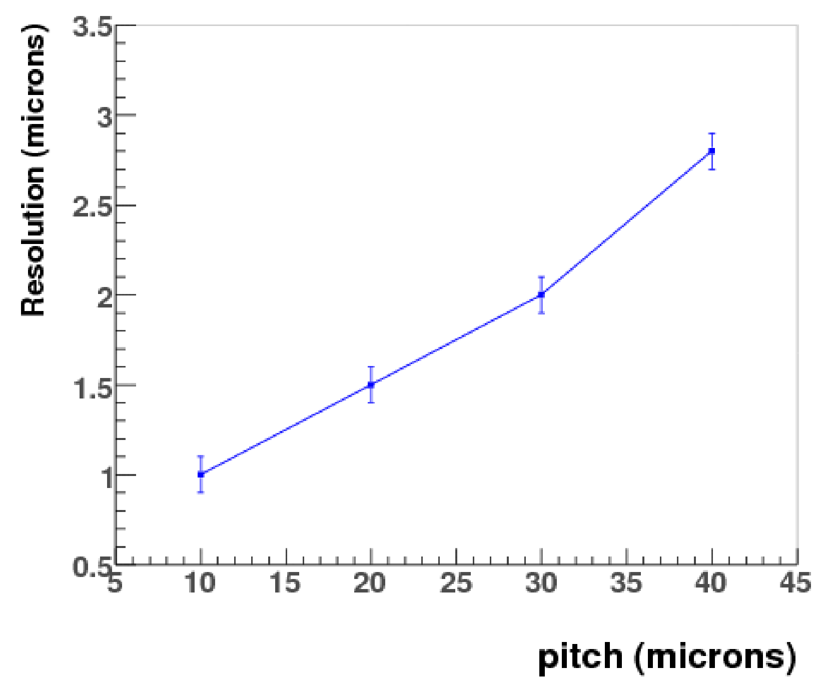
- Technology
  - Industry standard for ICs
  - All processes not optimized
    - Epitaxial layer thickness
    - # metal layers
    - Nwell – Psubstrate junction



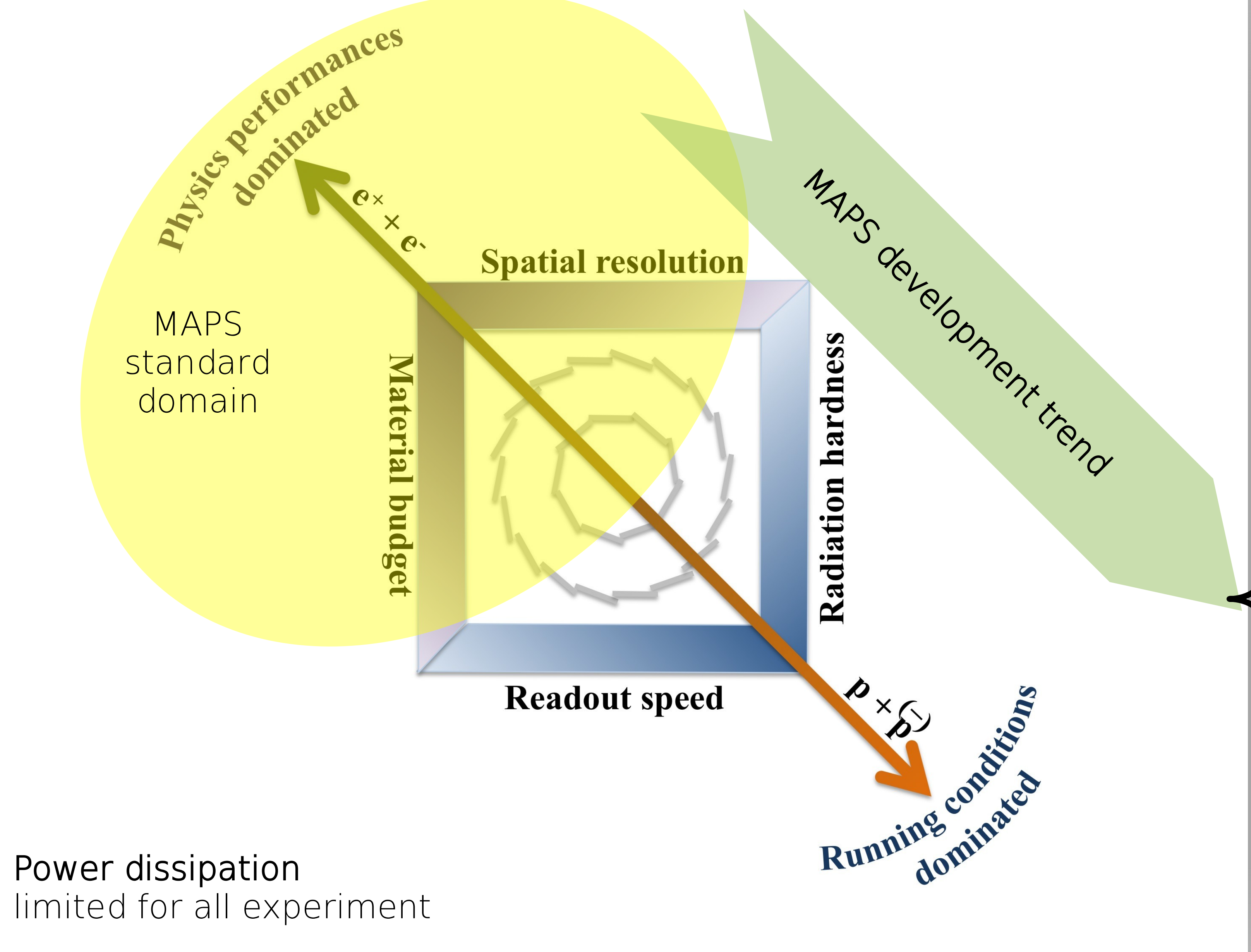
- Intrinsically thin sensors
  - sensitive layer ~10-20 µm
    - Small MIP signal, few 100 e- per pixel → requires low pixel noise *O*(10 e-)
  - Substrate almost useless
    - Few µm enough, total thickness could reach 20 µm
  - Monolithic & active
    - No external IC required in vicinity

MAPS, standard performances

- From the MIMOSA family
  - ✗ Developed at IPHC-Strasbourg
  - ✗ AMS 0.35 µm process, ~11 µm epitaxial layer
  - ✗ 3 transistors pixel - Sequential analogue readout
  - ✗ Performances assessed also @ 50 µm thickness
    - ➔ Thinning routinely achieve by industry
- Hit rate
  - ✗ With parallel analog outputs
  - ✗ 1Mpixels ~ 1ms r.o, time
- Radiation tolerance
  - ✗ Ionizing: ~Mrad
  - ✗ Non-ionizing: few 10^{12} n_{eq}/cm^2
  - ✗ Integration time and temperature dependant



Maps, the challenges

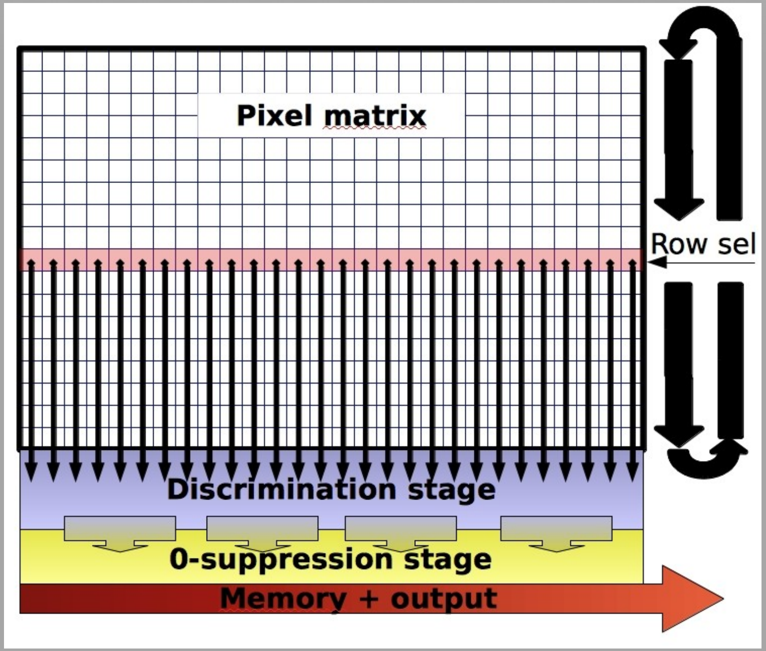


Power dissipation
limited for all experiment

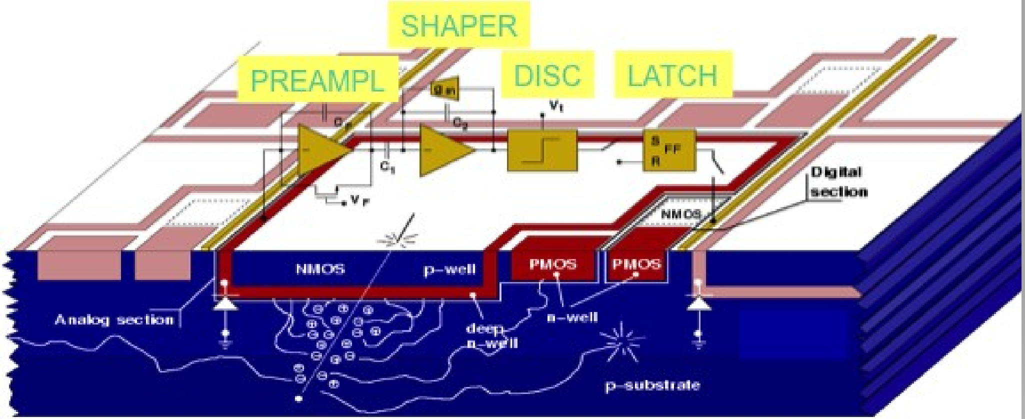
- 2D process
- Integration tech.
- 3D process

2D (planar) process

- Increasing the hit rate
  - ✗ Basic idea: zero-suppression



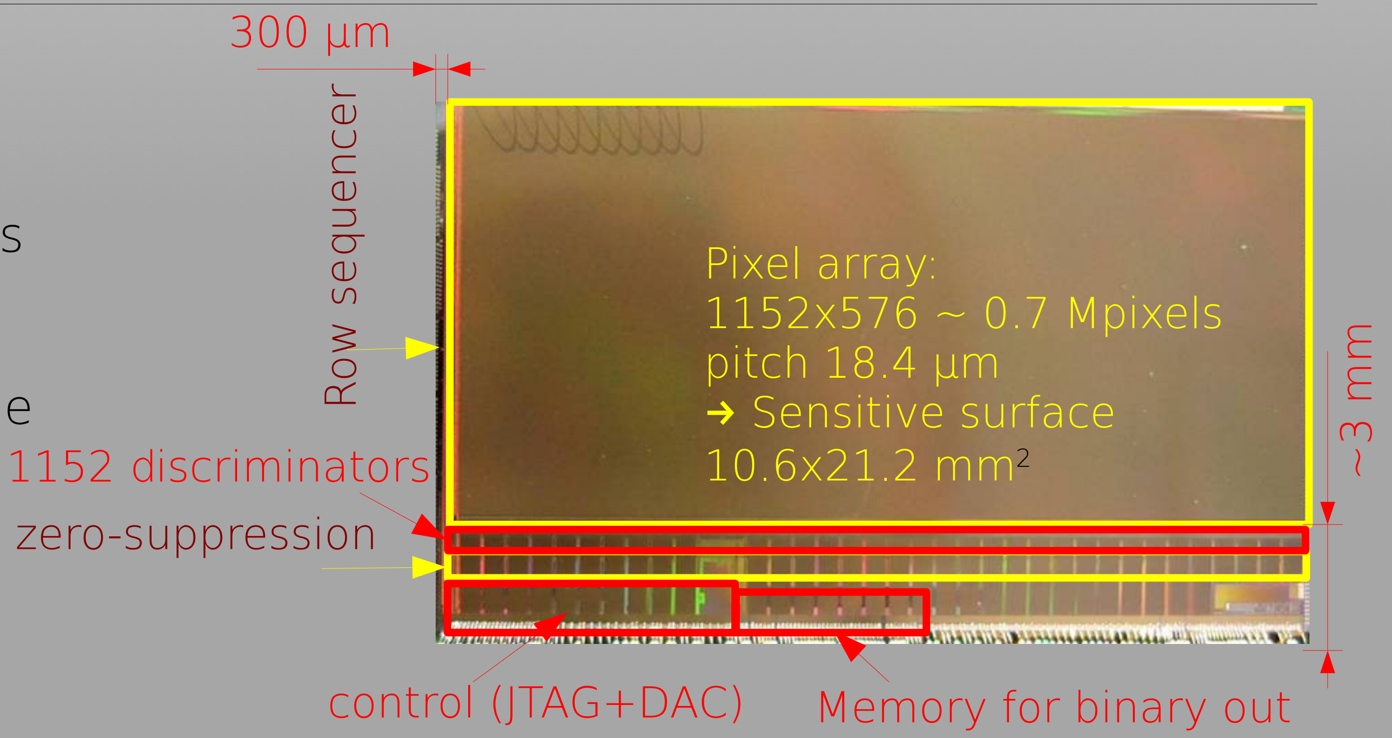
- Strategy 1:
  - ✗ Peripheral discrimination
  - ✗ Increasing the readout speed
  - ✗ IPHC(Strasbourg)+IRFU(Saclay) groups



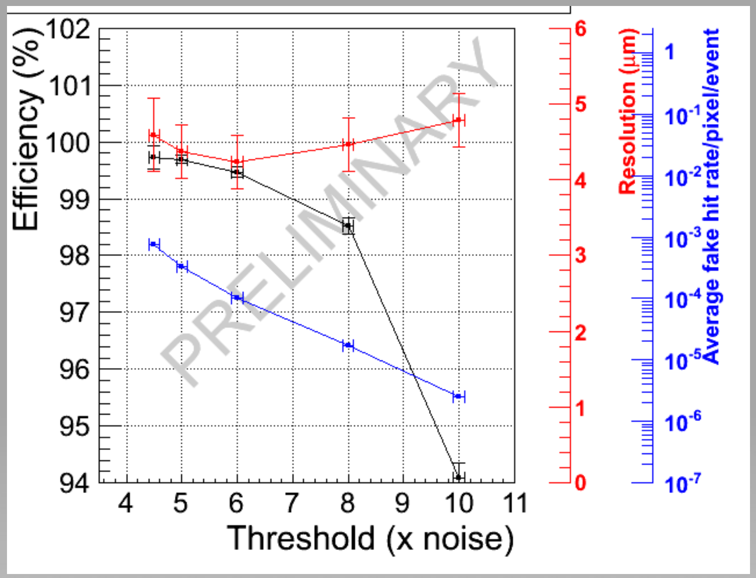
- Strategy 2:
  - ✗ In-pixel discrimination
  - ✗ Data-driven r.o. mode with time-stamp @ periphery
  - ✗ SLIM5 collaboration (INFN+Italian Universities)
  - ✗ Also INMAPS process @ RAL

2D – peripheral discrimination

- MIMOSA 26
  - ✗ Fabricated end 2008
    AMS 0.35 µm process
  - ✗ Binary output
  - ✗ ~100 µs readout time
  - ✗ >10^6 hits/cm²/s



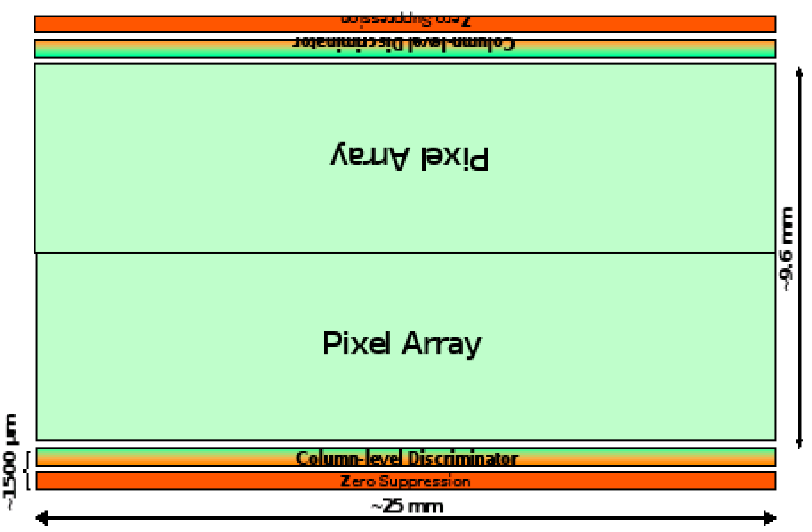
- First applications
  - ✗ EUDET beam telescope
    (running since 2009)
  - ✗ FIRST experiment
    (2011, GSI)
  - ✗ Forerunner of final sensor for STAR (2013)
    - ➔ Talk by M.Szelezniak
      "MAPS based vertex detector at STAR",
      Thursday 17h30



2D – peripheral discrimination

- Further applications, r.o. Time ~10 µs
  - ILC, CBM
    - Talk C.Schmidt "FAIR Silicon Tracking Detector System", Thursday 17h

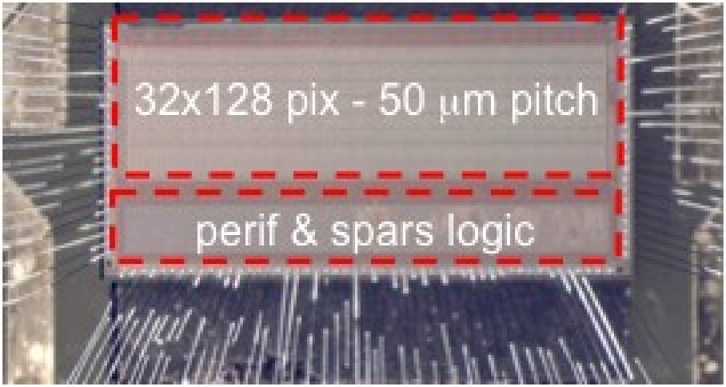
- Extrapolate MIMOSA26 architecture
  - Move to 0.18 µm process (ex. INMAPS techno. introduced by RAL)
    - Higher internal clock
    - Lower power dissipation
    - Reduced insensitive area
  - Double-sided readout
    - readout time / 2
  - Stretched pixels with ADC
    - Similar spatial resolution
    - Readout time / 4-5

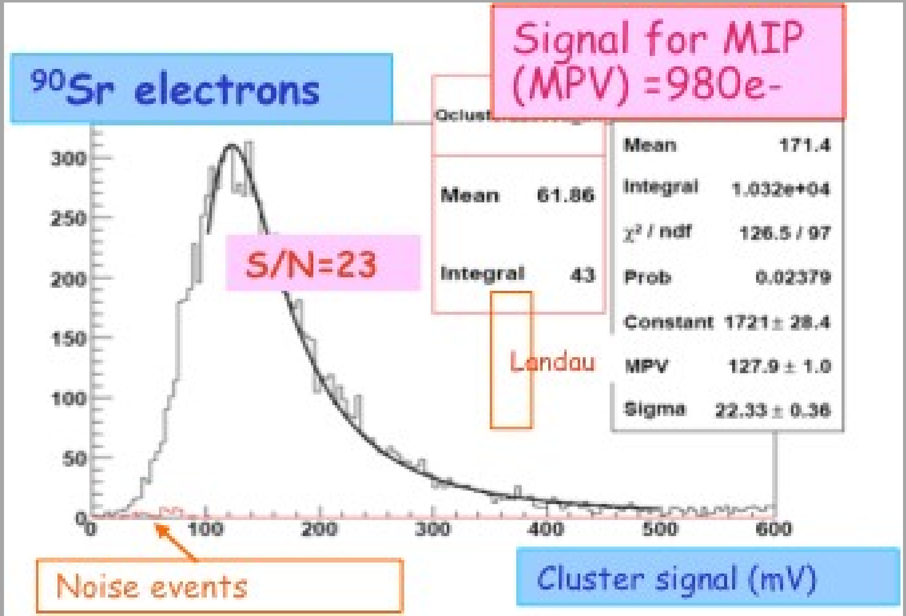


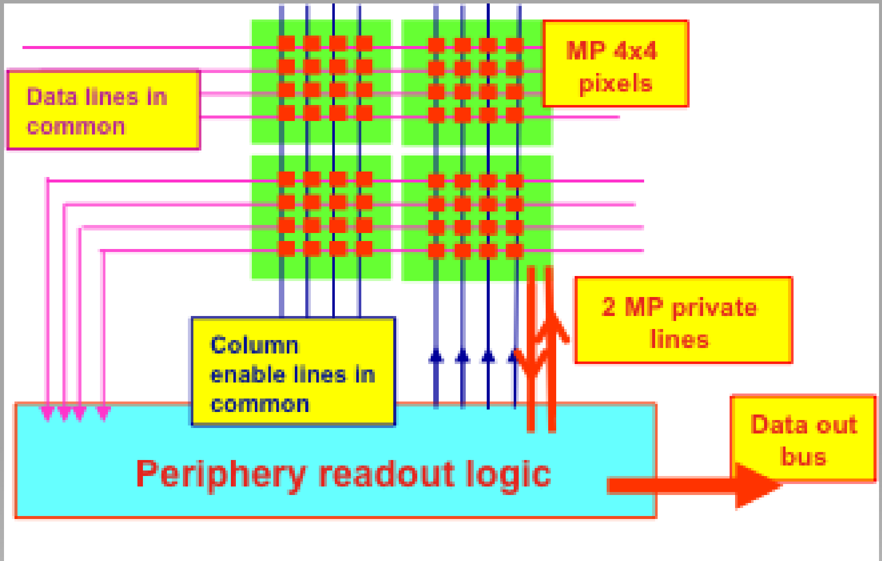
2D - In-Pixel discrimination

- APSEL family
  - ✗ Techno. STM .13 µm,
  - ✗ APSEL4D → APSEL5T
    - ➔ Pixel 50x50 µm² → 40x40 µm²
    - ➔ Amplification scheme "smaller"
  - ✗ Read-out through MacroPixel
    - ➔ Using dedicated logic
    - ➔ Optimized for 100.10⁶ hits/cm²/s

APSEL 4D, fab. Early 2008

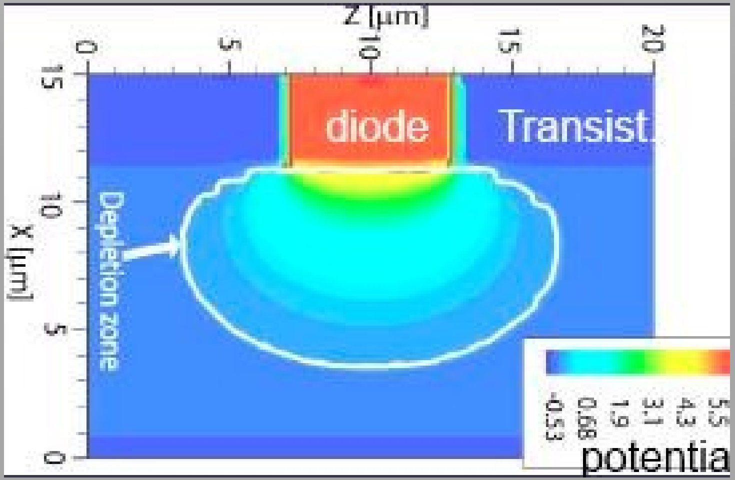




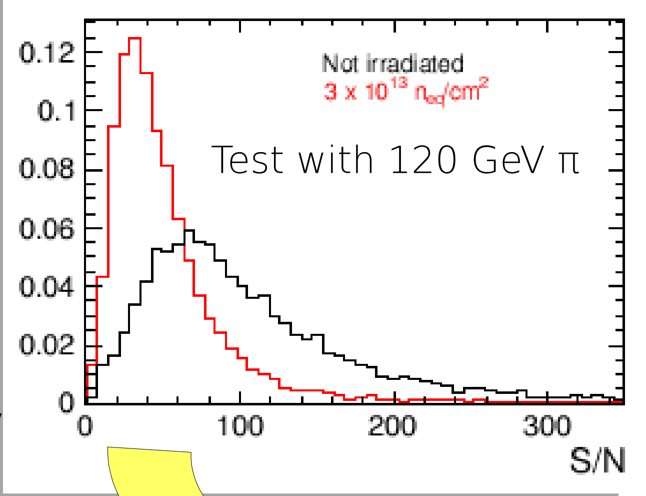


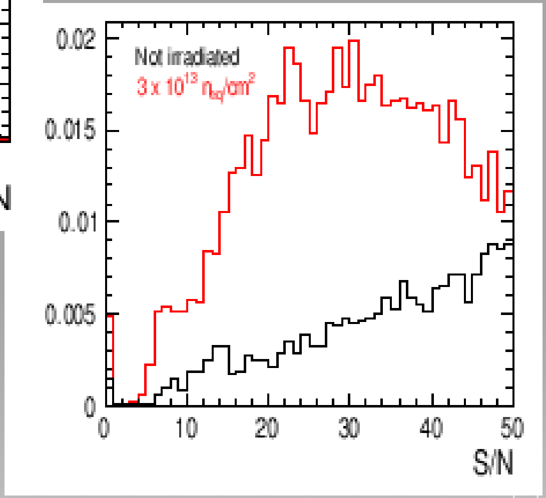
(non-ionizing) Radiation hard 2D process

- High resistivity epitaxial layer
  - ✗ Allow some level of depletion
  - ✗ Faster collection
    → lower sensitivity to crystal defects
    → lower signal spread over pixels
- Prototypes @ IPHC
  - ✗ MIMOSA 25, fab 2008
    - ➔ XFAB 0.6 µm, 1000 Ω.cm
    - ➔ 20 µm pitch
    - ➔ 80 µs analog read-out
  - ✗ MIMOSA 26HR, fab end 2009
    - ➔ AMS 0.35µm, 400 Ω.cm
    - ➔ 10, 15 & 20 µm epitaxial lay
    - ➔ In beam test,
      up to 3.10^{13} n$_{eq}$/cm^2
  - ✗ Also provided by
    INMAPS process (RAL) & IBM LePIX (CERN)



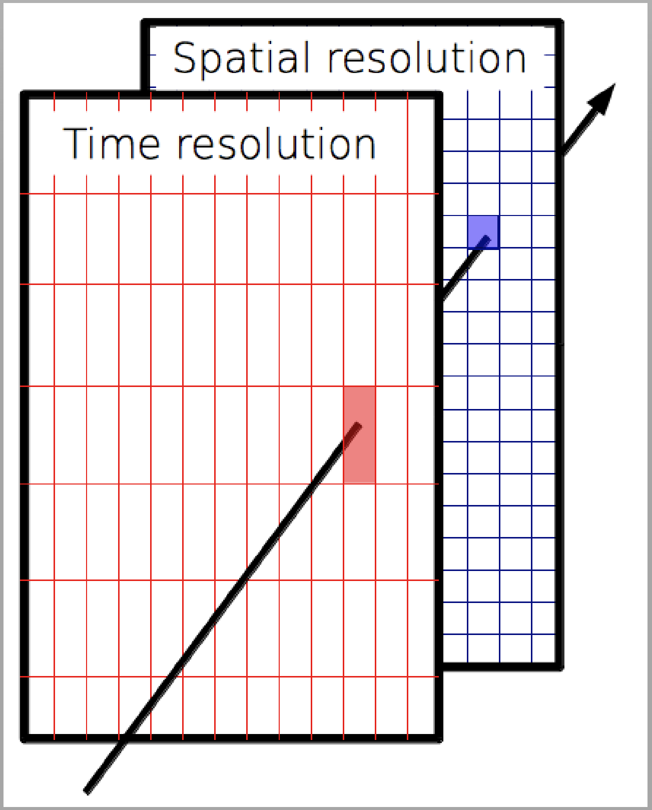
TCAD simulation by A.Dorokhov IPHC





Integration technologies

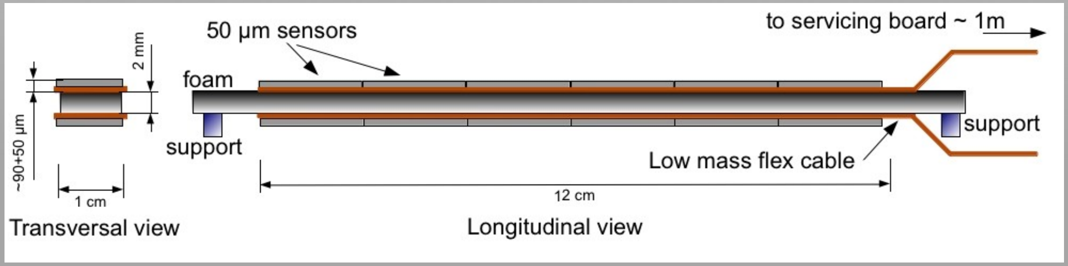
- “Smarter” AND still thin
  - ✗ Basic idea: multi-points in a single layer
  - ✗ Possible with
    - ➔ Thin sensors
    - ➔ Thin support material
    - ➔ thin cables
  - ✗ Benefits
    - ➔ Tracklets for pointing res. or triggering
    - ➔ Mixing ≠ granularity/speed compromises



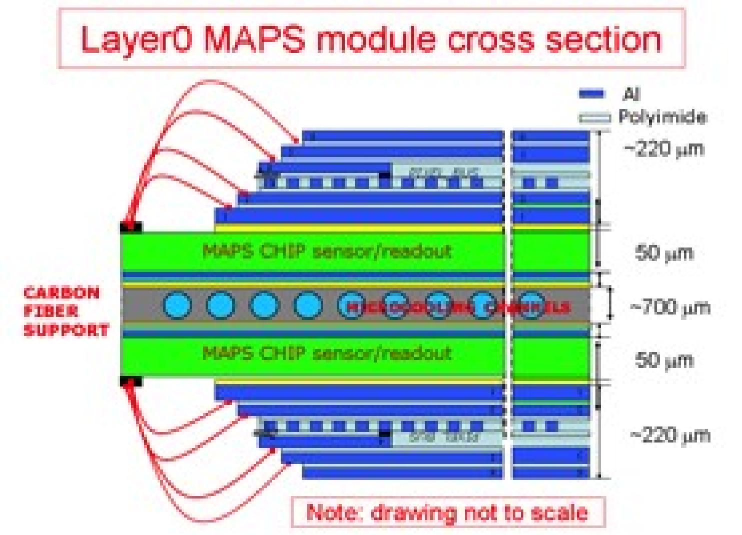
- MAPS advantages
  - ✗ Already thin
  - ✗ No additional IC required
  - ✗ ~30°C operation possible
    - ➔ Active cooling avoidable

Double sided ladders

- The PLUME project
  - ✗ Double sided ladder @ 0.4% X0
  - ✗ Passive cooling: air flow
  - ✗ Power pulsing
  - ✗ Bristol U., DESY, Oxford U., IPHC
  - ✗ Several iterations over 2009-2012
    - ➔ Current proto @ 0.6%X0



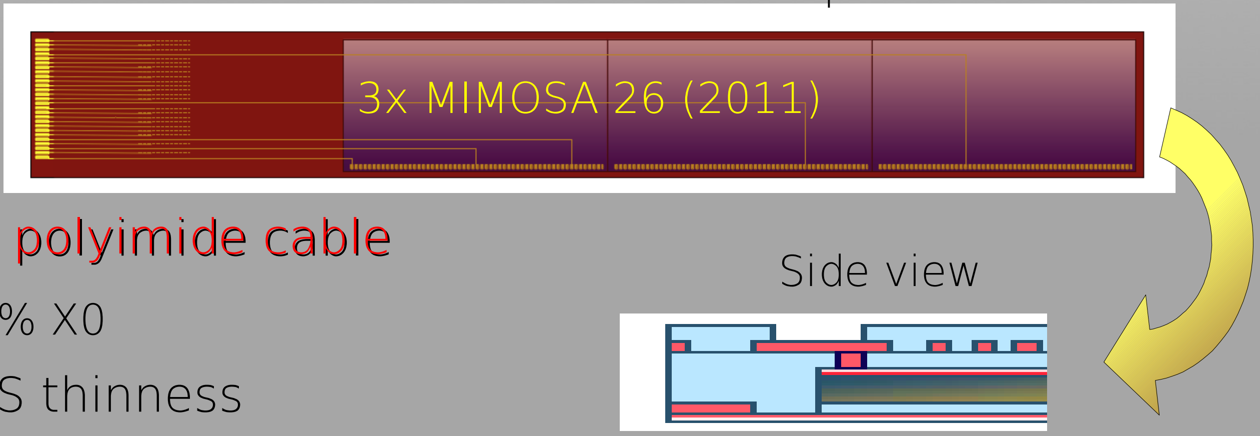
- The SuperB project
  - ✗ Few W/cm^2 → Active cooling required
  - ✗ Support from carbon fiber µtubes
    - ➔ 0.15%X0
  - ✗ INFN and Italian Universities groups



From integration to embedding

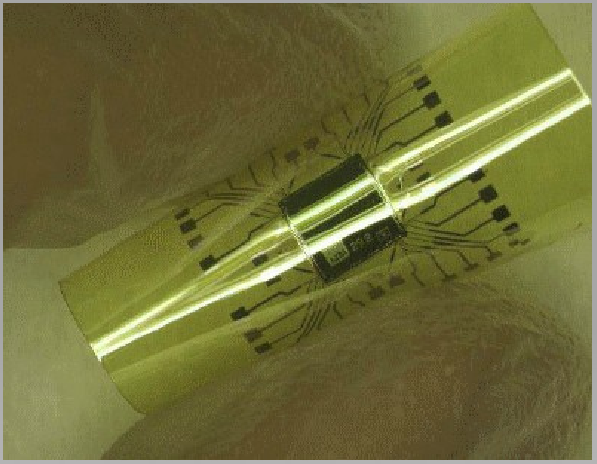
Top view

Side view

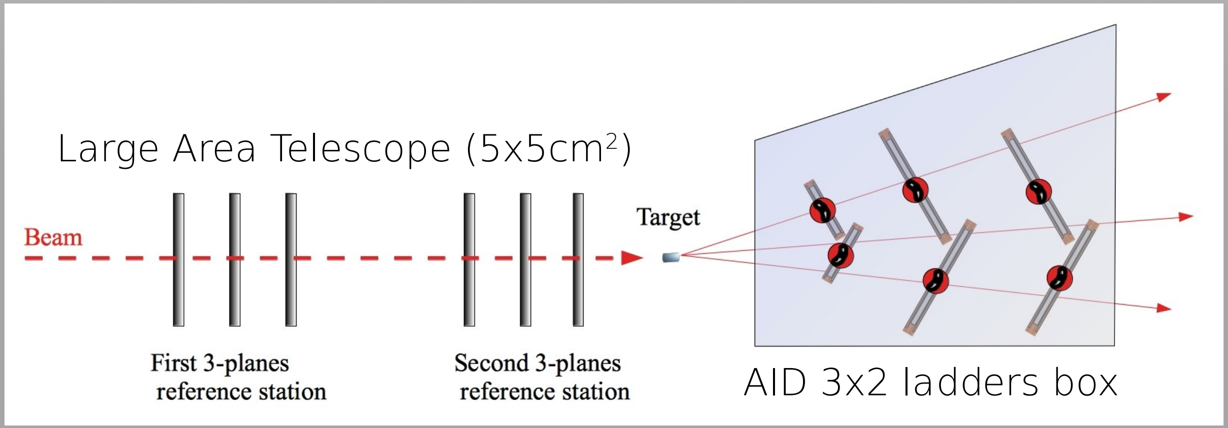


- The SERWIETE project
  - ✗ Embed sensors inside soft polyimide cable
    - ➔ Cable with traces ~< 0.1% X0
  - ✗ Benefit fully from the MAPS thinness
    - ➔ Sensors < 30 µm
  - ✗ IKF-Frankfort+IPHC+IMEC
  - ➔ Adaptable to the support shape
    - ➔ Beam pipes, detector edges, ...
- More "embedding"
  - ✗ Stitching sensors (proposed by several foundries)
    - ➔ reduce metal traces & support
  - ✗ Opto-couplers
    - ➔ High data-thoughput
      with limited additional material

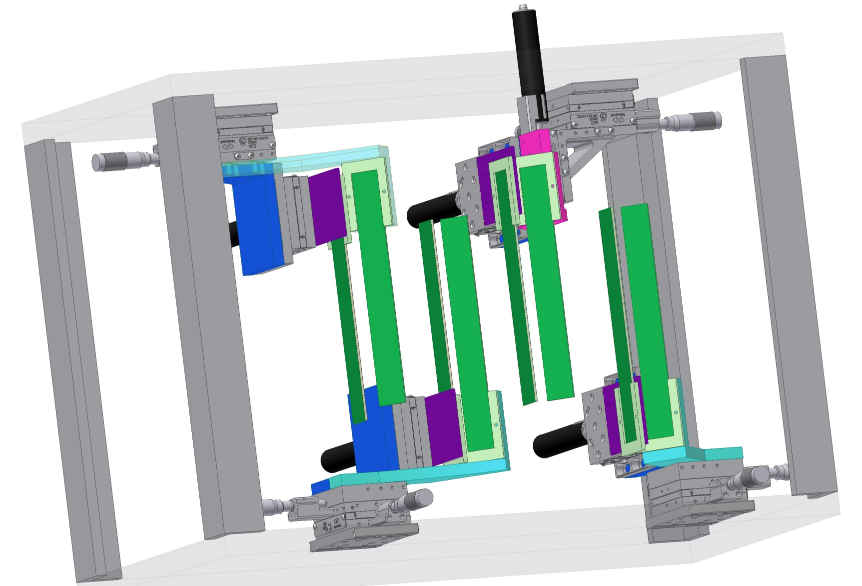
IMEC-Leuven, Belgium examples:



Testing, evaluating



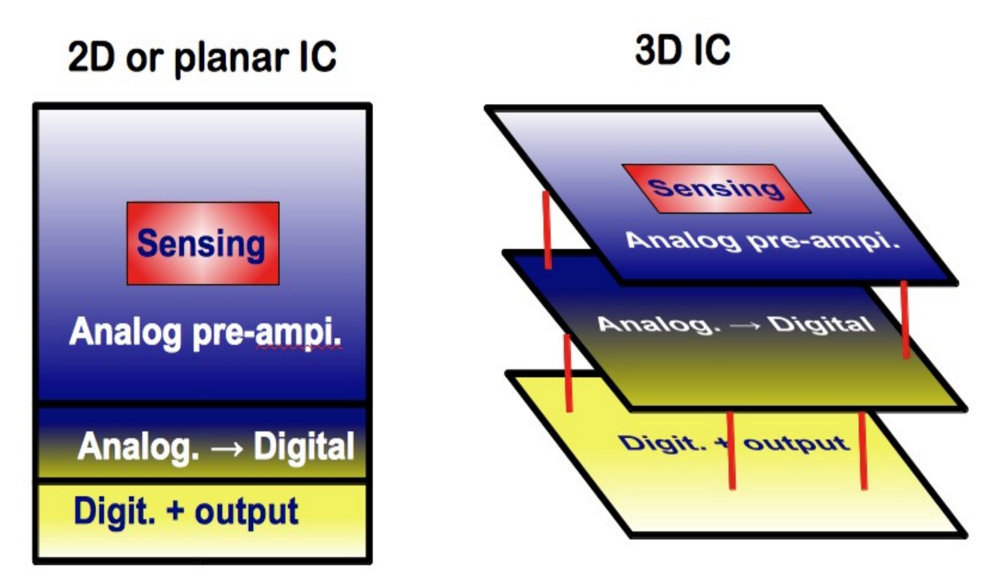
- The AIDA project
  - ✗ EU-FrameProg.7, 2011-2014
  - ✗ Worpackage 9.2
    - ➔ Alignment studies
    - ➔ Power extraction
    - ➔ Mechanical stability
    - ➔ Power pulsing (ILC)



Mechanical design by S.Yang, Oxford U.

3D process

- Combining functionalities & technologies
  - ✗ Best prepared for readout (optical link)
  - ✗ Overcome 2D process limitations
    - ➔ Smallest feature size
    - ➔ rad.tol. sensitive layer
    - ➔ Integrate more intelligence
    - ➔ Geometrically effective
  - ✗ Road to r.o. time ~ µs level



- International 3D consortium
  - ✗ Lead by FNAL (pioneering work)
  - ✗ First circuits expected in 2010 (many different approaches)
  - ✗ More info on Thursday session
    - ➔ G.Traversi, "3D consrtium", 9h
    - ➔ R.Yarema "The Via Revolution", 11h

Conclusion

- On the roads offered by different technologies for MAPS
- Challenge I: higher hit rate
  - ✗ Deep sub-micron 2D processes, ~10µs
  - ✗ Advanced integration technologies: compact multi-layer systems
  - ✗ Most promising: 3D processes, ~µs read-out >2015
- Challenge II: higher radiation tolerance
  - ✗ High resistivity epitaxial layer for non-ionizing rad.
- System challenge: data transmission & storage bottleneck
  - ✗ Advanced integration

- Impact on imaging systems
  - ✗ From multi-layers & data throughput
  - ✗ Intelligent imagers (definition, scene detection,...)
  - ✗ Multi-type radiation detection (dosimetry, veto function,...)

Backups

Thanks for your attention

- Acronyms helper
  - ✗ AID=Alignment Investigation Device
  - ✗ AIDA=Advanced European Infrastructures for Detectors at Accelerators
  - ✗ CBM=Compressed Baryonic Matter at FAIR, GSI
  - ✗ EUDET=EUropean DETector R&D towards the International Linear Collider
  - ✗ INMAPS=Isolated N-wells, or INtelligent MAPS
  - ✗ MALT=Monolithic Active Liquid Tranquillizer
  - ✗ MIMOSA=Minimum Ionizing MOS Active pixels sensor
  - ✗ PLUME=Pixelated Ladder with Ultra-low Material Embedding
  - ✗ SERWIETE=SEnsor Row Wrapped In Extra-Thin Envelope
  - ✗ STAR=Solenoid Tracker At Rhic, BNL