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Radiation Experiments, SLAC, USA, 3-6 April 2006

CCLRC
Rutherford Appleton Laboratory

CMOS Monolithic Active Pixel Sensors (MAPS)

for future vertex detectors

... but not just

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CCLRC - Technology

Outline

Introduction. MAPS for charged particle detection

Results so far

- **3T-pixel**
- **Pipeline pixels**
- **Digital sensors/pixels**

MAPS in an experiment

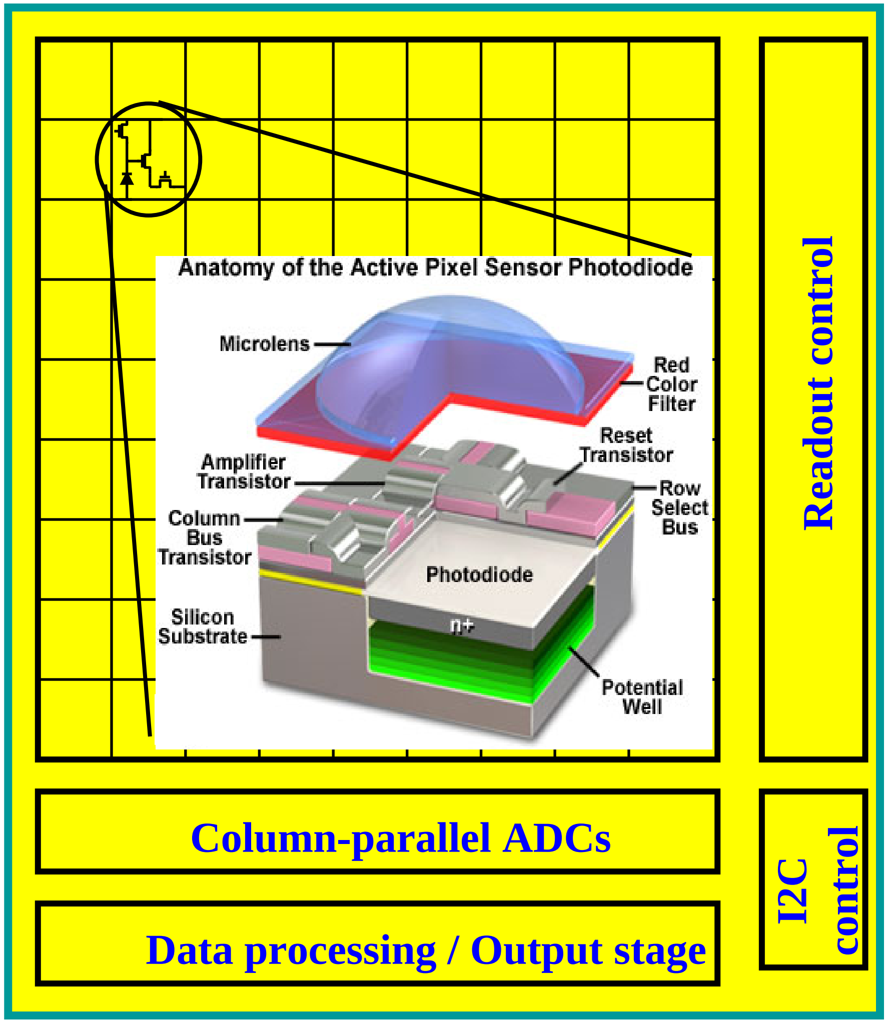
- **STAR**
- **Belle**
- **ILC: vertex and calorimetry**

Conclusion

CMOS Monolithic Active Pixel Sensor (MAPS)

(Re)-invented at the beginning of '90s: JPL, IMEC, …

- **Standard CMOS technology**
- **all-in-one detector-connection-readout = *Monolithic***
- **small size / greater integration**
- **low power consumption**
- **radiation resistance**
- **system-level cost**
- **Increased functionality**
- **increased speed (column- or pixel- parallel processing)**
- **random access (Region-of-Interest ROI readout)**



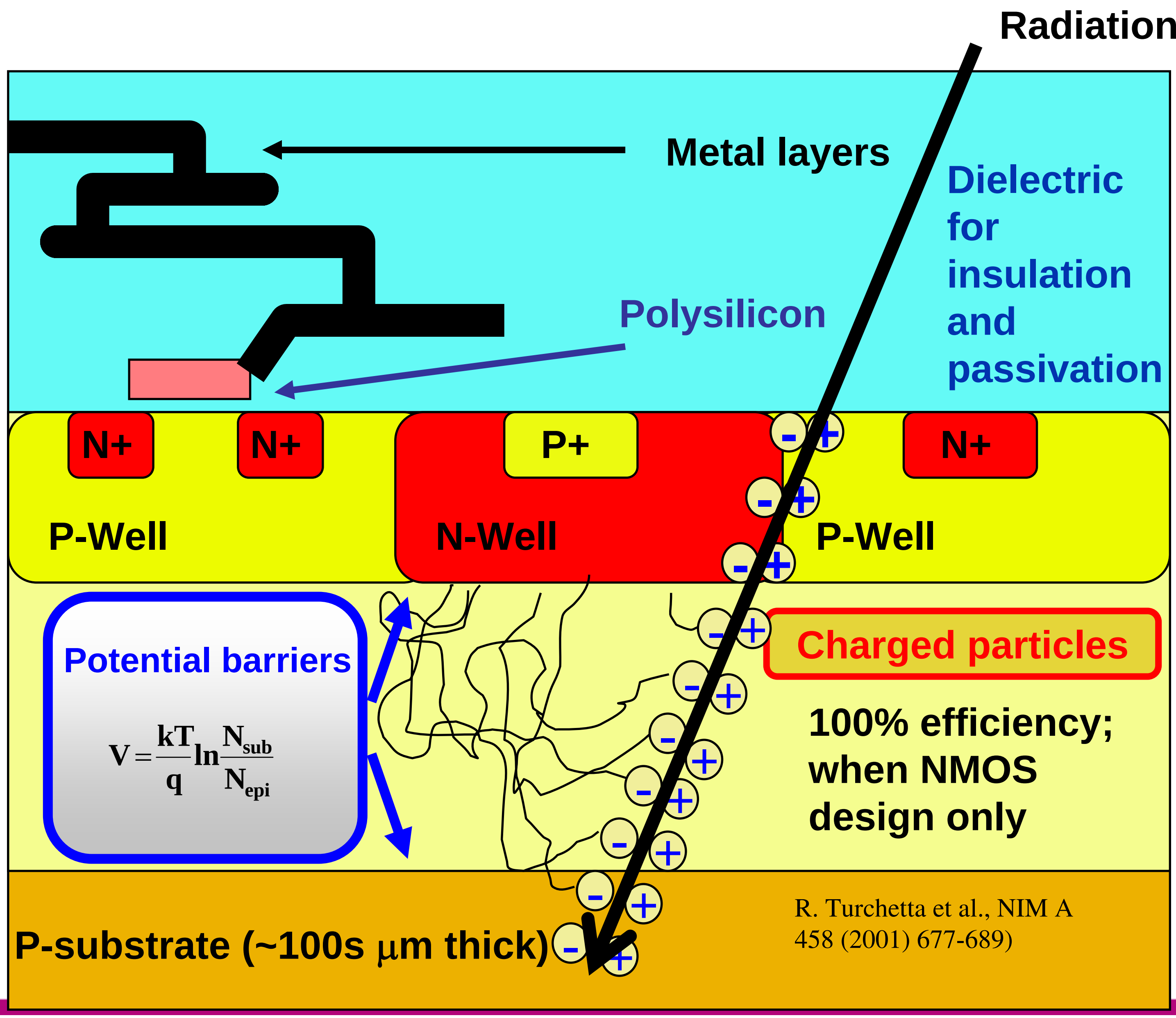
CMOS sensors in digital cameras

Digital intraoral imaging

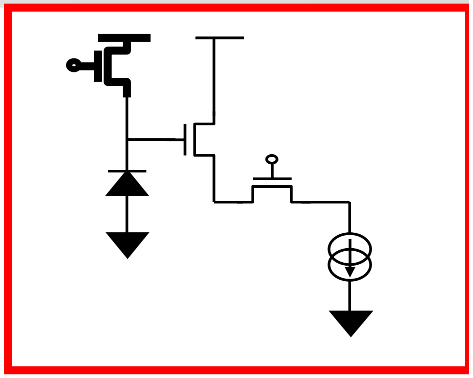
Consumer/prosumer
Digital cameras

Digital mammography

MAPS for charged particle detection



3T pixel



Baseline (minimum) design.

Low noise detection of MIPs first demonstrated in 2001.

Since then, with a number of technologies/epi thickness:

AMS 0.6/14, 0.35/∞, 0.35/14, 0.35/20, AMIS (former MIETEC) 0.35/4, IBM 0.25/2, TSMC 0.35/10, 0.25/8, 0.25/∞, UMC 0.18/∞

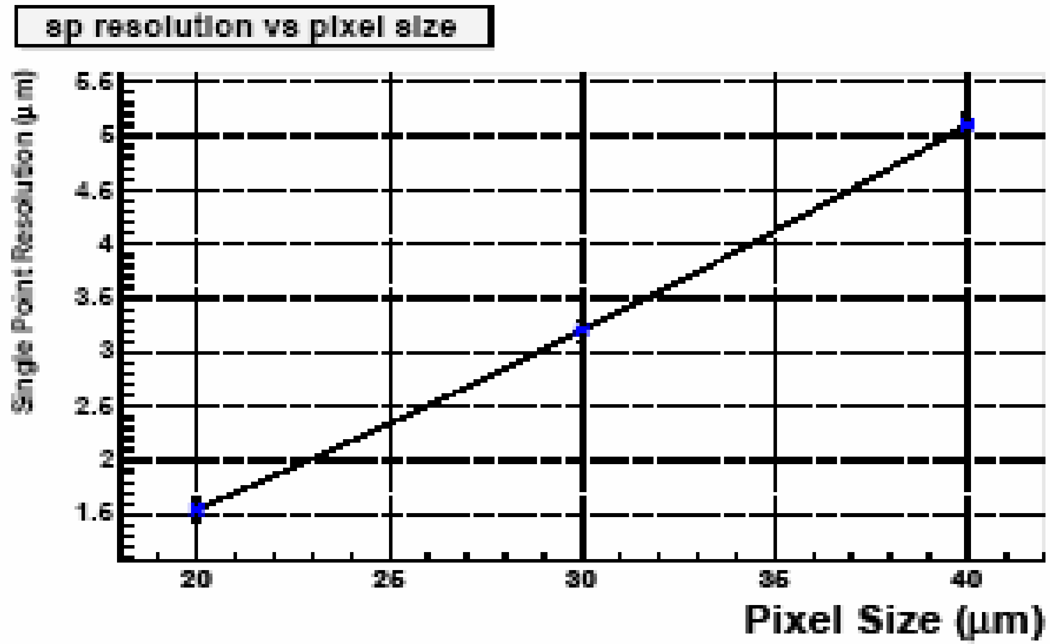
Noise <~ 10 e- rms

Spatial resolution 1.5 μm @ 20 μm pitch, with full analogue readout

Good radiation hardness

Low power

Speed: rolling shutter can be a limit



Radiation hardness

Transistors.

Threshold shift: reduces with shrinking feature size

Bird's beak effect: use enclosed geometry transistors

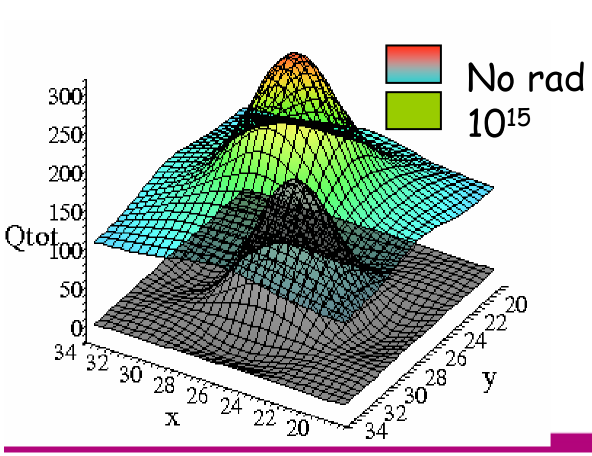
Transistor leakage current: use guard-rings to separate transistors

Diodes.

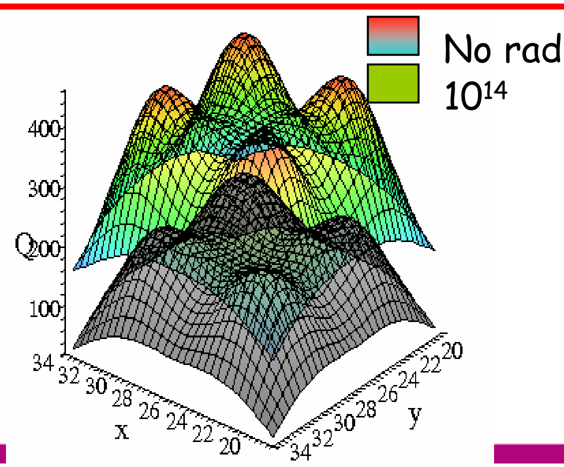
Radiation damage increases leakage current

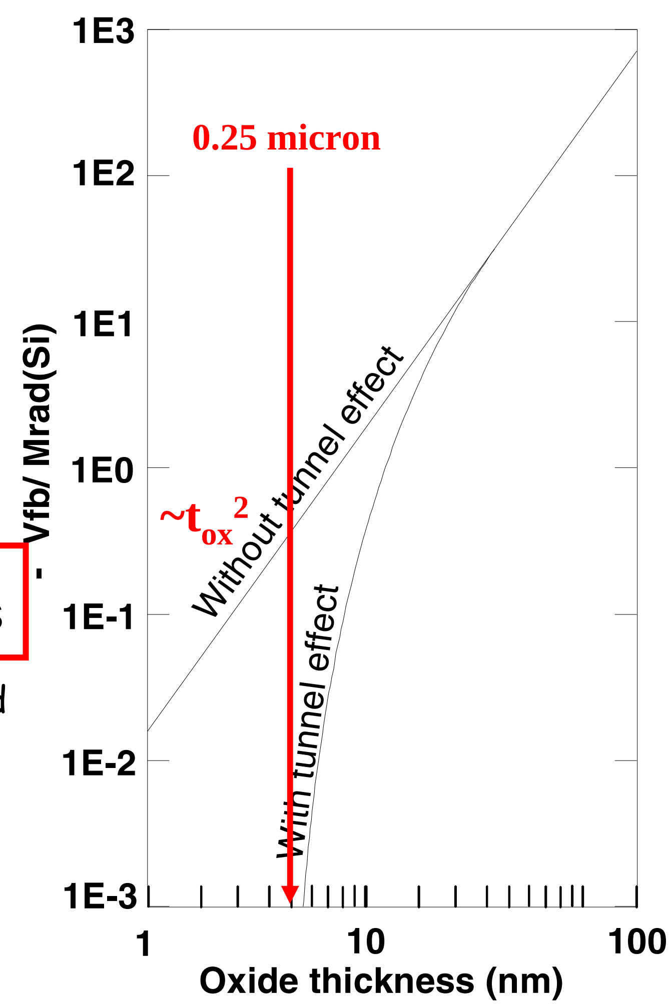
Radiation damage reduces minority carrier lifetime → diffusion distance is reduced

15-μm pixel with 1 diode

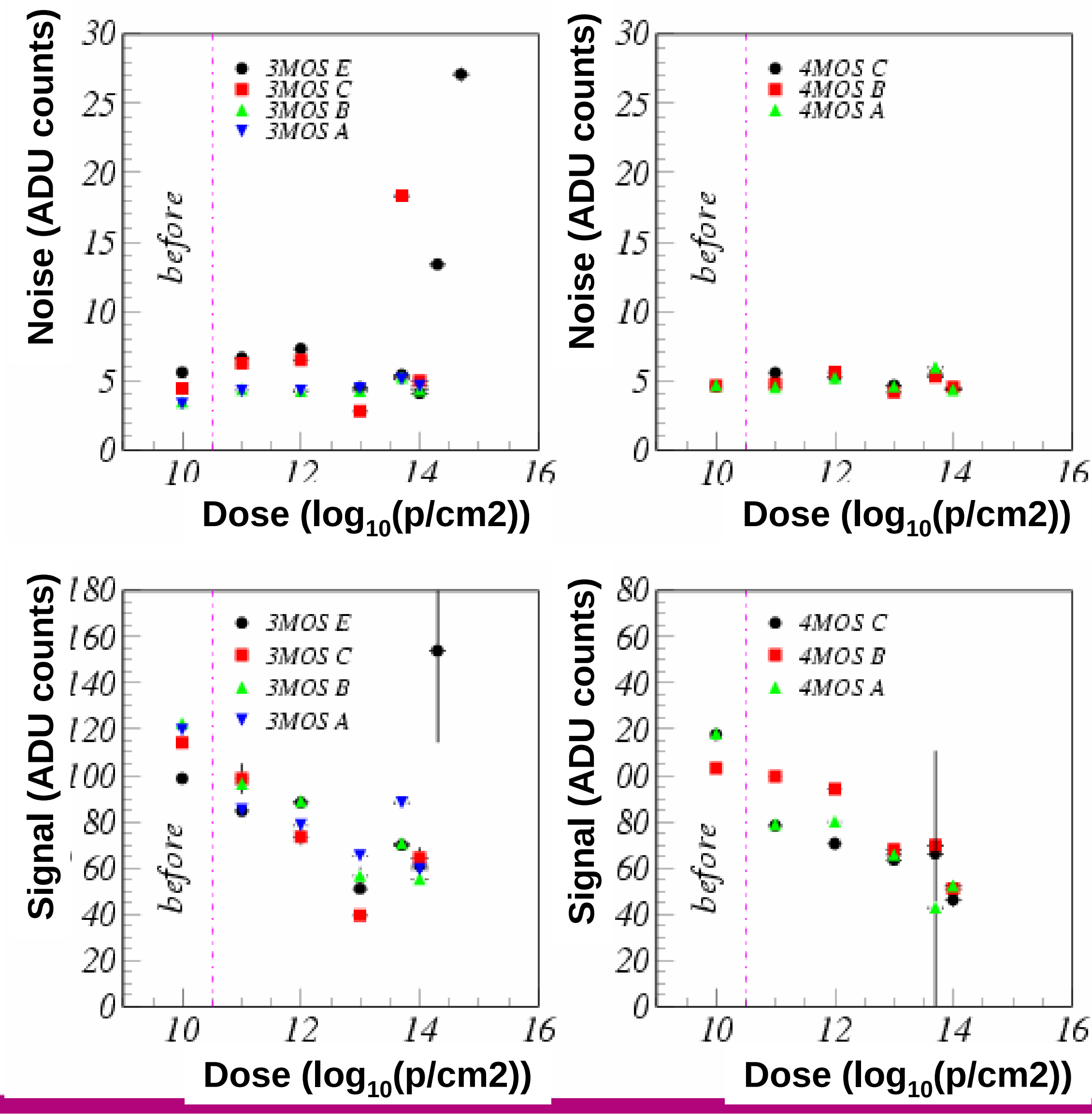


15-μm pixel with 4 diodes

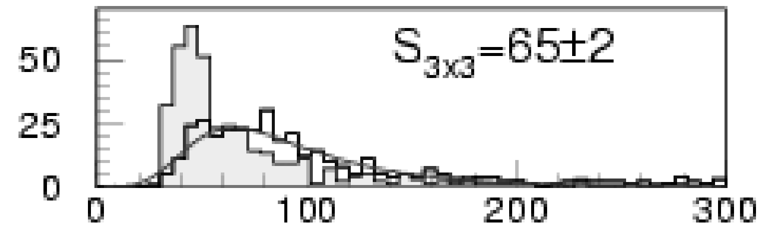




Radiation test. Source results

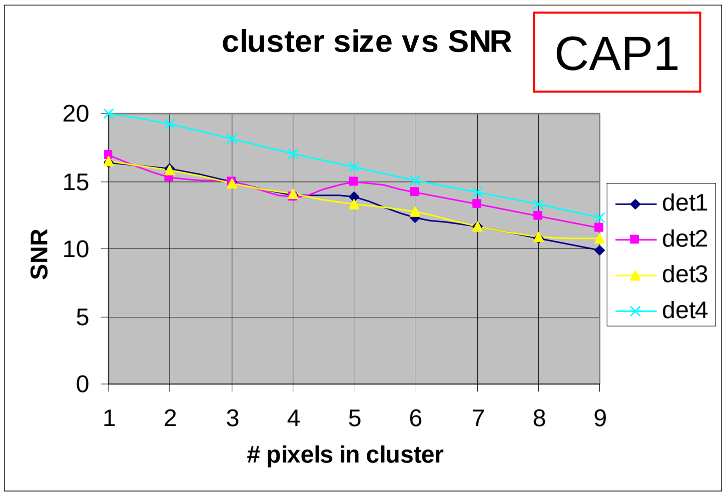


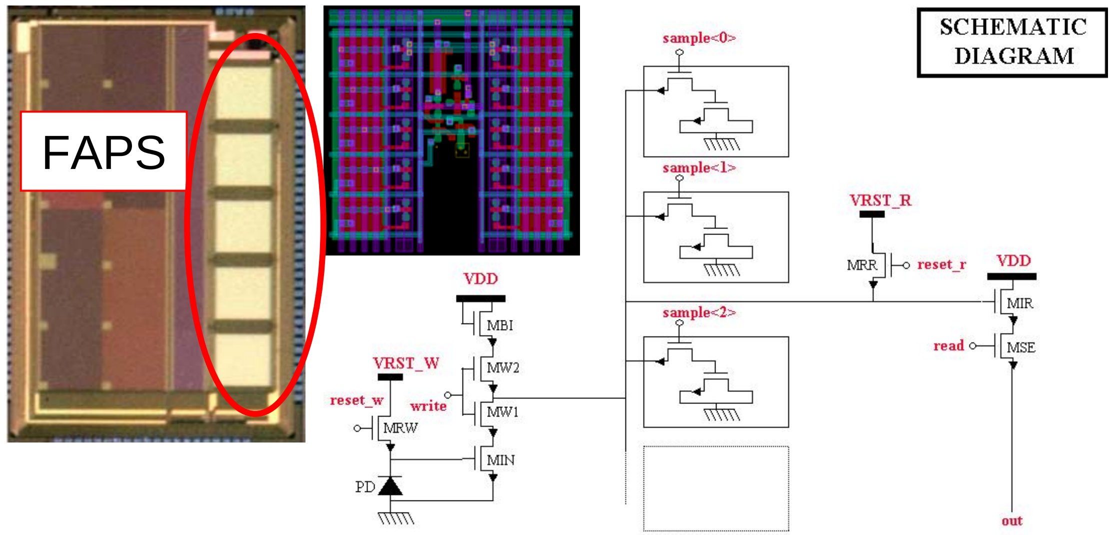
- Test with parametric test sensor RAL_HEPAPS2. Designed in TSMC 0.25/8, in-pixel transistors with 0.35-equivalent oxide thickness
- Several types of pixels
- Noise seems to increase slightly with dose.
- Signal decreases with dose.
- Leakage current increase only noticeable beyond 10^{14} p/cm^2



Pipeline pixels

Flexible Active Pixel Sensor (FAPS, RAL): TSMC 0.25/8, 10 memory cell per pixel; 28 transistors per pixel; 3 sub-arrays of 40x40 pixels @ 20 μm pitch, sampling rate up to 10 MHz. Noise ~ 40 e- rms, single-ended readout





Continuous Acquisition Pixel (CAP, Hawaii): three versions (CAP1/2/3) in TSMC 0.35/8 and 0.25/8, 5 pairs cell/pixel in CAP3 40-50 e- rms single ended → 20-25 differential

MIMOSA12 (Strasbourg) in AMS 0.35/14: 4 pairs/pixel

Digital readout

- Several imagers designed by RAL with column-parallel ADC: single-slope (10-bit) and successive approximation (up to 14-bit)

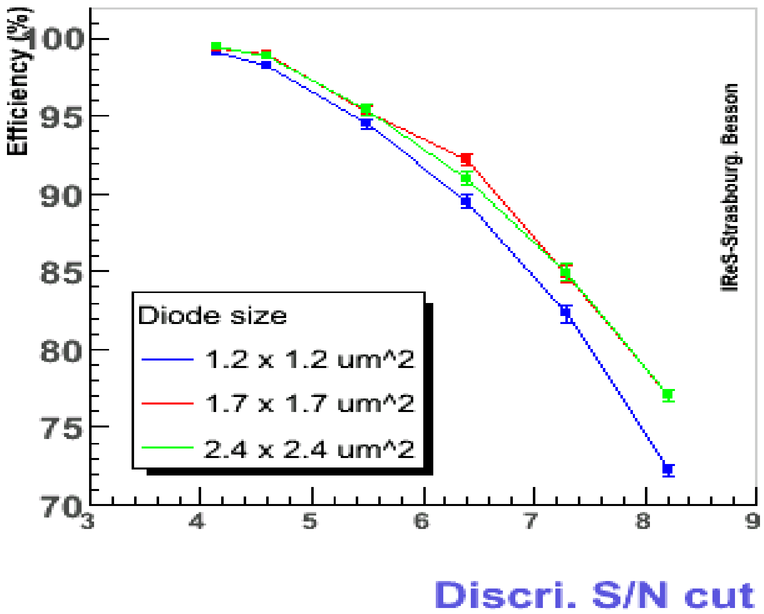
- Mimosa 8 (Saclay)

- Test in lab: ^{55}Fe results
  - Pixel noise ~ 15 e-
  - CDS ending each column
  - ⇨ Pixel-to-pixel dispersion ~ 8 e-
- Test beam results (DESY, 5GeV e-)
  - S/N (MPV) ~ 8.5 - 9.5
  - Efficiency > 98%

- TSMC 0.25 µm fab. process with ~ 8 µm epitaxial layer
- Pixel pitch: 25 µm
- 3 sub matrices with 3 diode size: 1.2 x 1.2 μm^2, 1.7 x 1.7 μm^2, 2.4 x 2.4 μm^2
- 24 // columns of 128 pixels with 1 discriminator per column
- 8 analog outputs

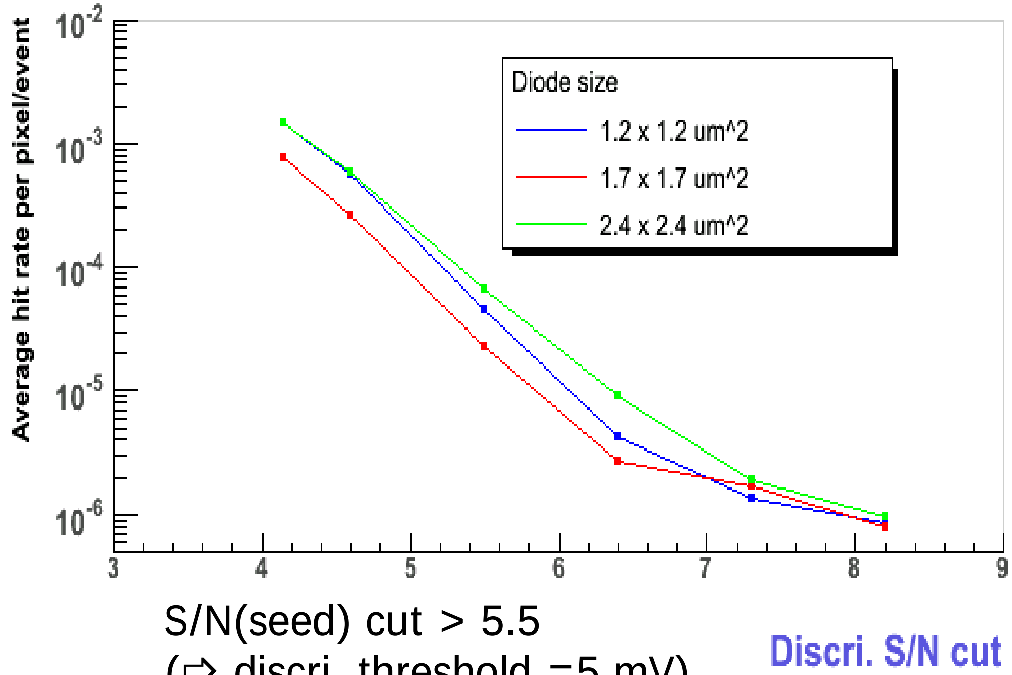
Column comparator

Efficiency (%)



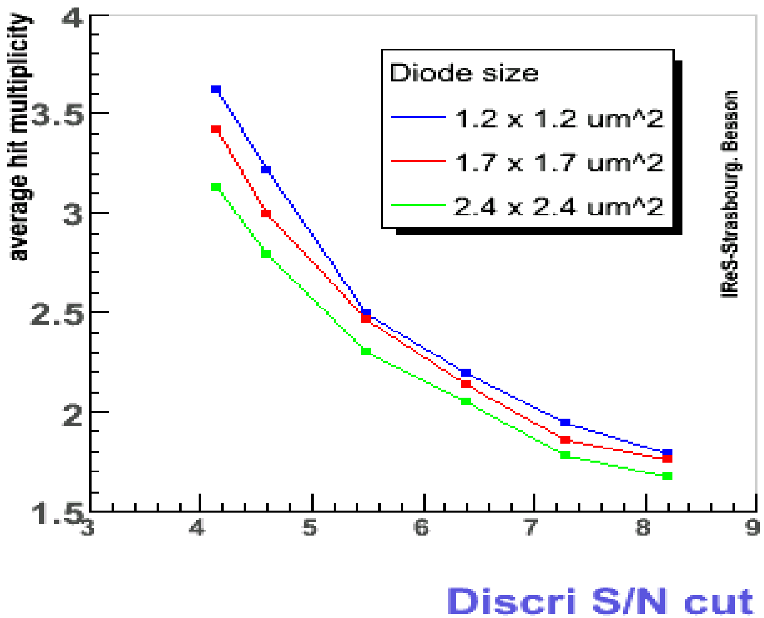
Temp. = 20ºC; r.o. = 40 MHz

Fake Hit rate / pixel / event



Average hit multiplicity

(num of pixels in cluster)



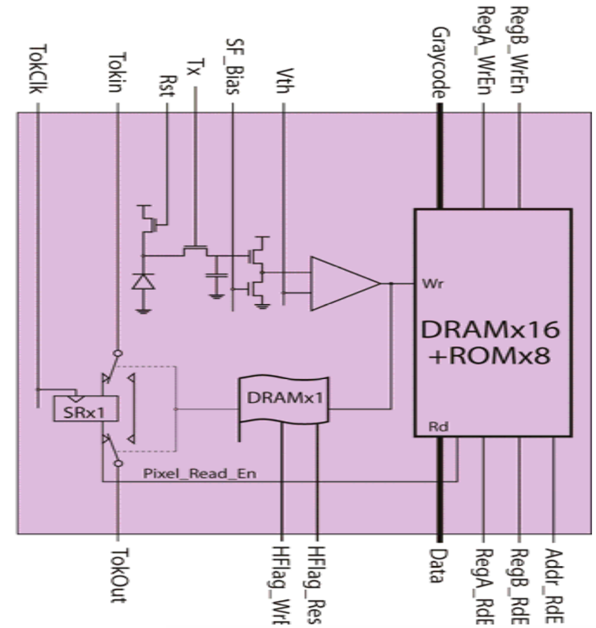
S/N(seed) cut > 5.5

(⇨ discri. threshold =5 mV)

Contamination ~< 5 x 10^{-5}

In-pixel digitisation

- OPIC (On-Pixel Intelligent CMOS Sensor). Designed by RAL within UK MI3 consortium
- In-pixel ADC (single-slope 8-bit)
- In-pixel TDC
- Data sparsification



Test structure. 3 arrays of 64x72 pixels @ 30 μm pitch
Fabricated in TSMC 0.25/8
PMOS in pixel → sub-100% efficiency
Starting point for R&D on ILC-ECAL Calice

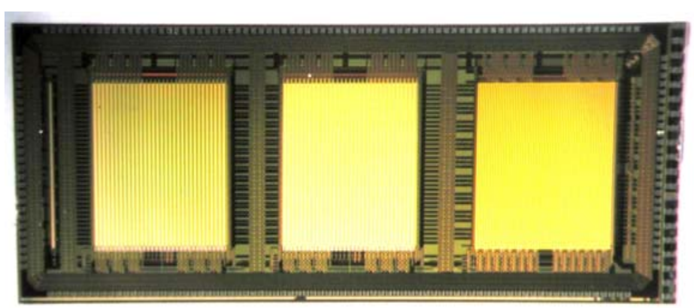
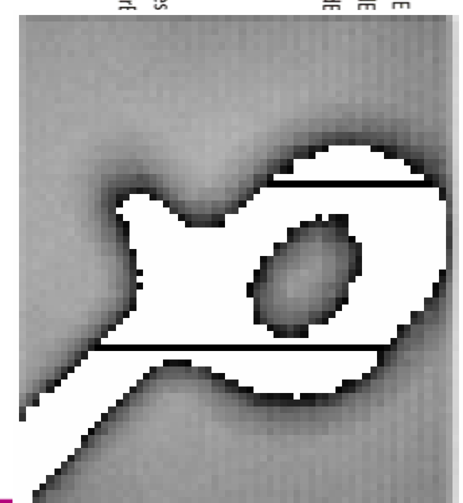
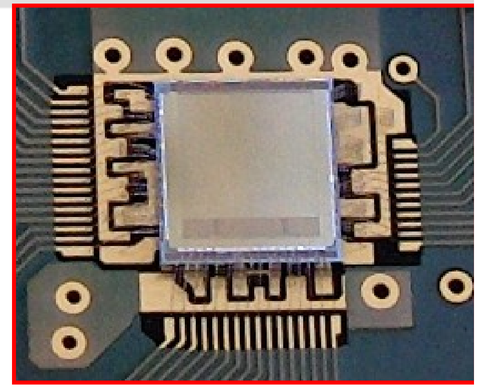


Image obtained with the sensor working in TDC mode with sparse data scan. White pixels are those which didn't cross threshold



MAPS for STAR



MimoSTAR-2 (France)

- AMS 0.35 µm OPTO. 30 µm pitch
- 2 matrices 64 x 128, JTAG architecture
- Rad. hard structure (based on Mimosa 11)

To be installed in STAR (2006)

⇨ Ionising radiation tolerant pixel validated at temperature up to + 40 °C

⇨ No active cooling needed at int. time ~< O(1 ms)

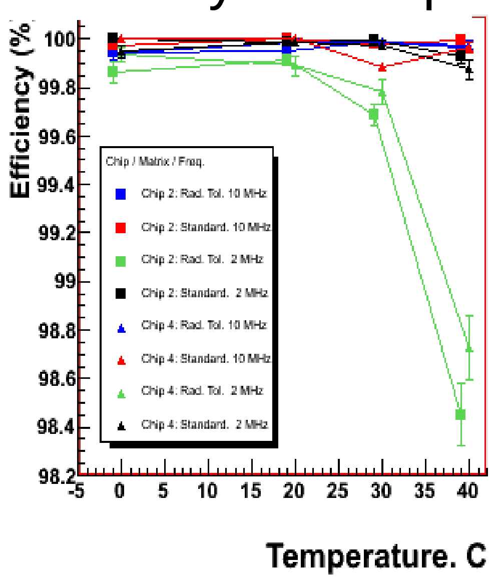
MimoSTAR-3L in design in AMS 0.35: 200 kpixels, $t_{r.o.}$ = 2 ms, 2 cm^2

⇨Test-beam results (DESY, 5 GeV e-)

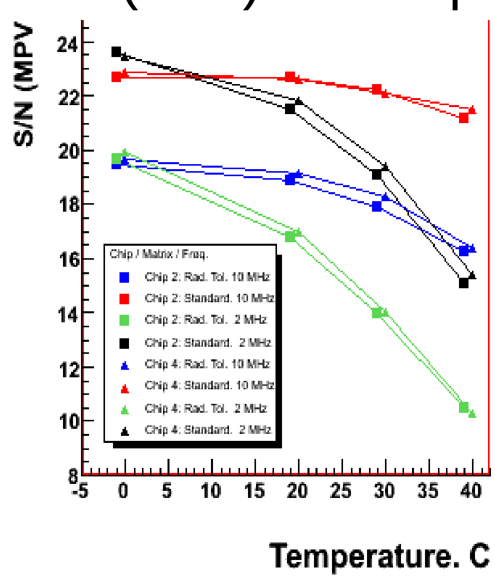
✓ 2 r.o. time (2 and 10 MHz)

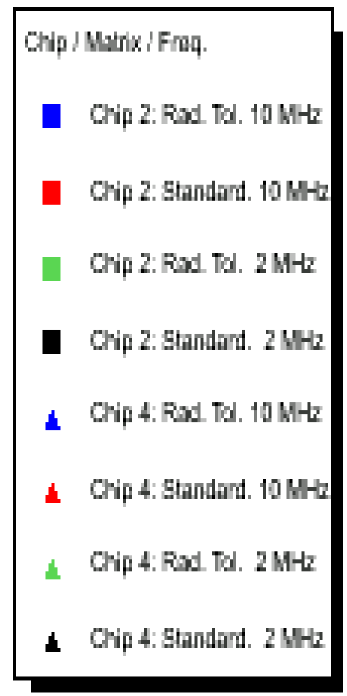
⇨ 800 µs and 4 ms

Efficiency vs Temp



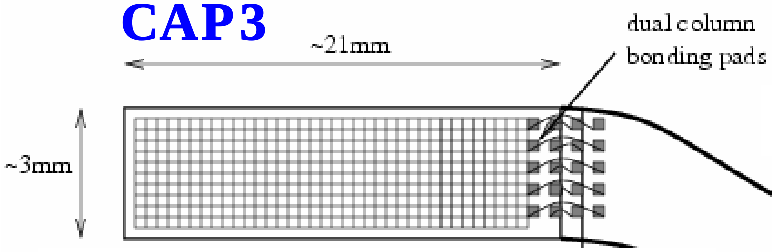
S/N (MPV) vs Temp



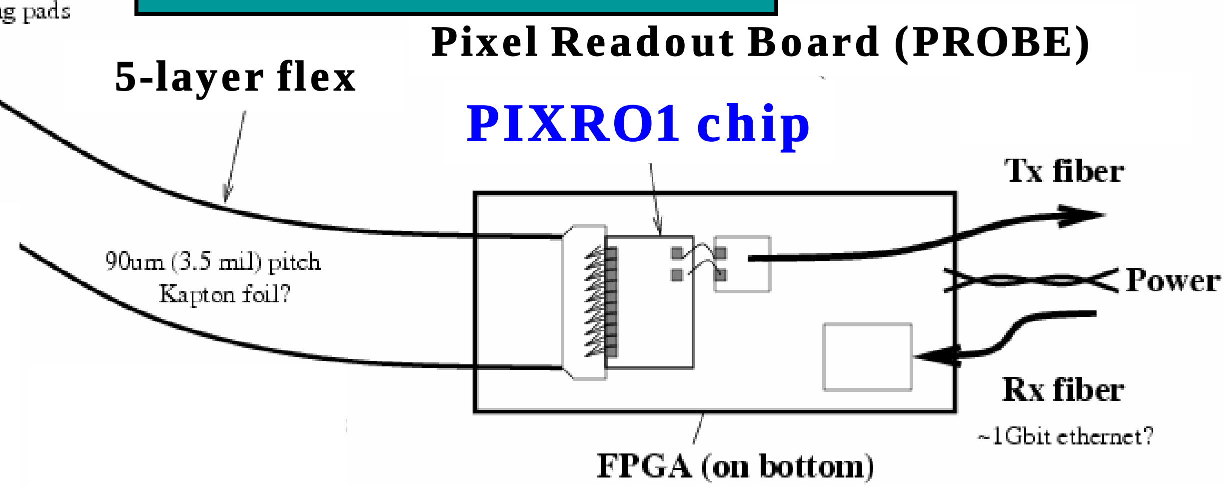


MAPS for Belle

CAP3



Half ladder scheme



128 x 928 pixels, 22.5μm²

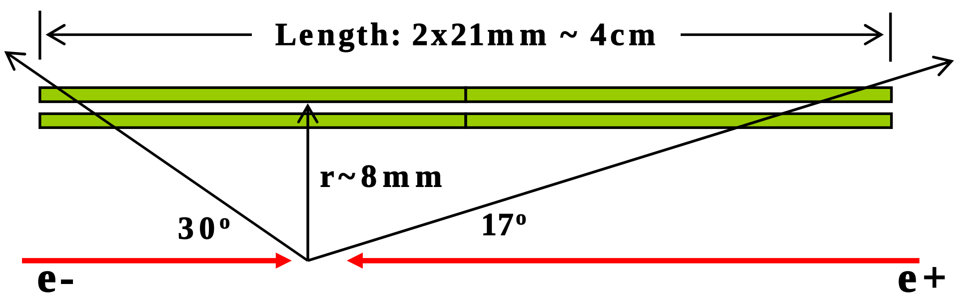
~120 Kpixels / CAP3

0.25 μm process

5 pipeline cell pairs per pixel

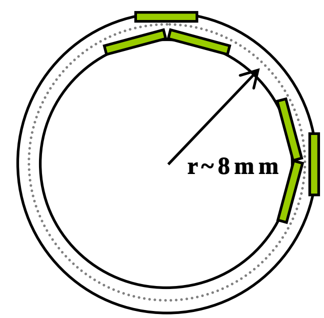
CAP4 also in design

Side view



End view

Double layer, offset structure



# of Detector / layer ~ 32

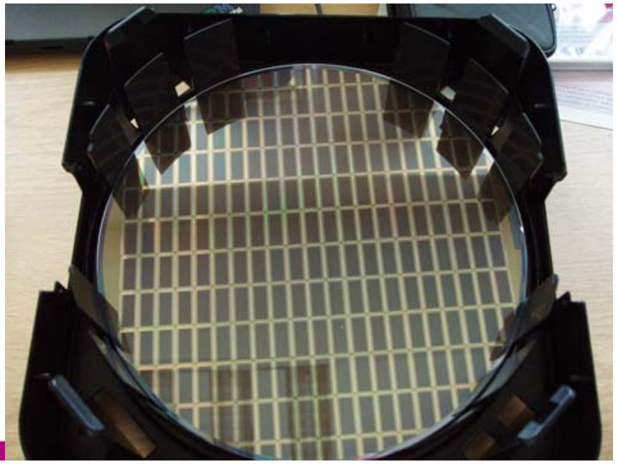
MAPS for ILC

Vertex: R&D in France (MIMOSA family) and UK (RAL_HEPAPS family)

MIMOSA family: latest is n. 15. Several prototypes with different technologies and pixel architectures: 3T, column-parallel comparator, pipeline pixel. Good S/N, radiation hardness, spatial resolution, detection efficiency, … demonstrated

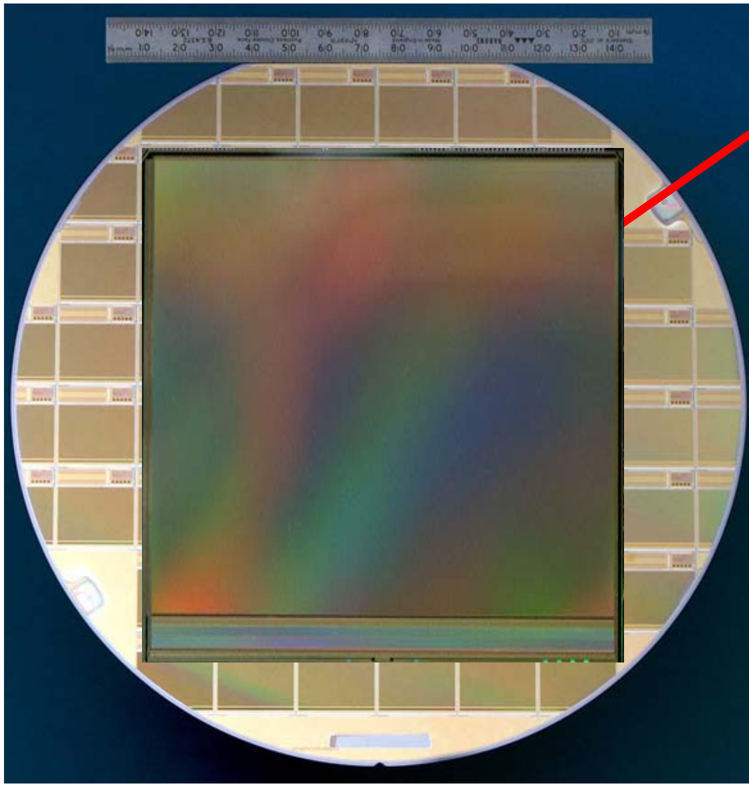
RAL_HEPAPS family: latest is n.4. First demonstrator (FAPS) of pipeline architecture. Fast, column-parallel ADC demonstrated within LCFI- CPCCD

RAL_HEPAPS 4: large format. 3 versions, each with 1026x384 pixels (0.4M pixel), 15 μm pitch, 3T pixel. D1: single diode, enclosed geometry transistors. D2: double-diode. D4: four-diode
ENC <~ 15 e- rms (reset-less)
5 MHz line rate
Rad-hard: > Mrad



ECAL (Calice): R&D just starting in the UK for large area, digital MAPS

Large area sensors



Reticle. Size limited to ~ 2 cm. Reticle is stepped-and repeated → gaps between reticles

CCD foundry. Sometimes large chips are required → different programming of stepping to have no gap ⇔ *'stitching'*

CMOS sensor market

Driven by design of CMOS sensors as replacement of 35 mm film. At a few foundries, it is now possible to design stitched (seamless) sensors → 'wafer-scale'

Foundry choice rapidly widening

Stitched sensors likely to be needed for ILC: Vertex and ECAL (Calice)

Conclusions

CMOS MAPS first proposed as detectors for particle physics in 1999

100% efficiency detection demonstrated in 2000

Since then, good performance in terms of S/N, detection efficiency, radiation hardness, spatial resolution demonstrated with 3T

New sensors architecture developed: pipeline pixels, digital sensors, digital pixels

R&D for MAPS at Belle and STAR well underway. They could be the first experiments to have a MAPS-based vertex detector

Development at ILC in progress for both Vertex and ECAL. They are likely to need stitched sensors

Acknowledgements

M. Barbero and G. Verner, Haiwaii, for CAP and Belle
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T. Anaxagoras
R. Halsall
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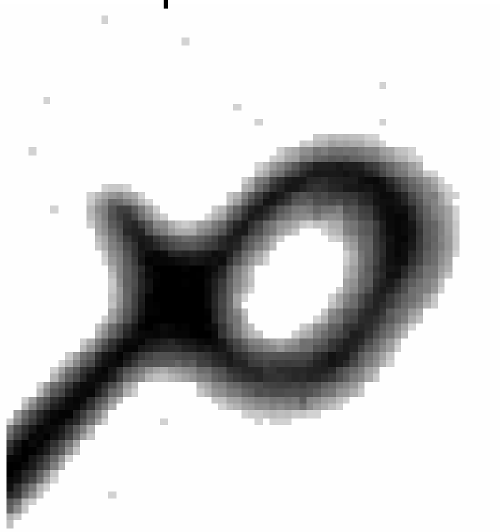
S. Martin
M. French
M. Prydderch

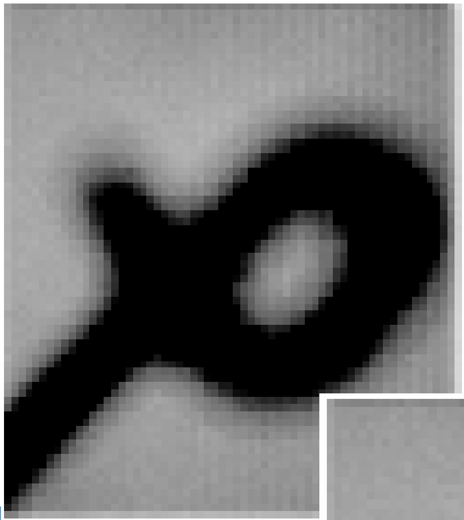
G. Villani
M. Tyndel
P. Allport
G. Casse
A. Evans
D. Prior
J. Velthuis
P. Dauncey
N. Watson
+ ... all the others I forgot to mention!

Experimental results

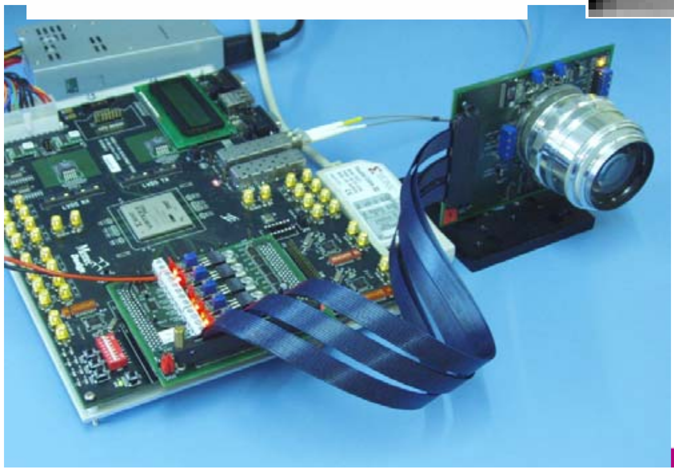
In-pixel ADC

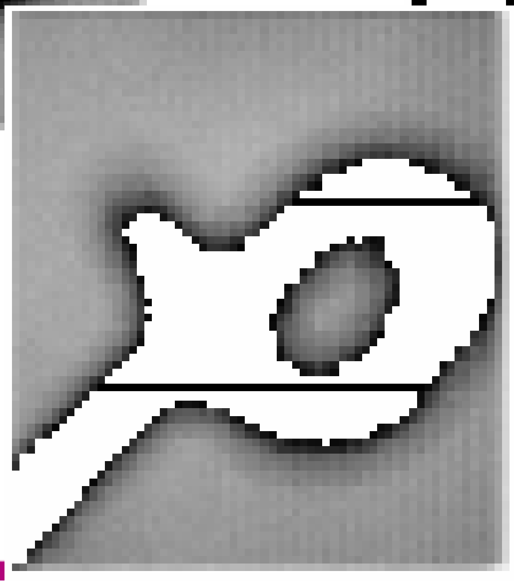


Timing mode capture



In-pixel thresholding

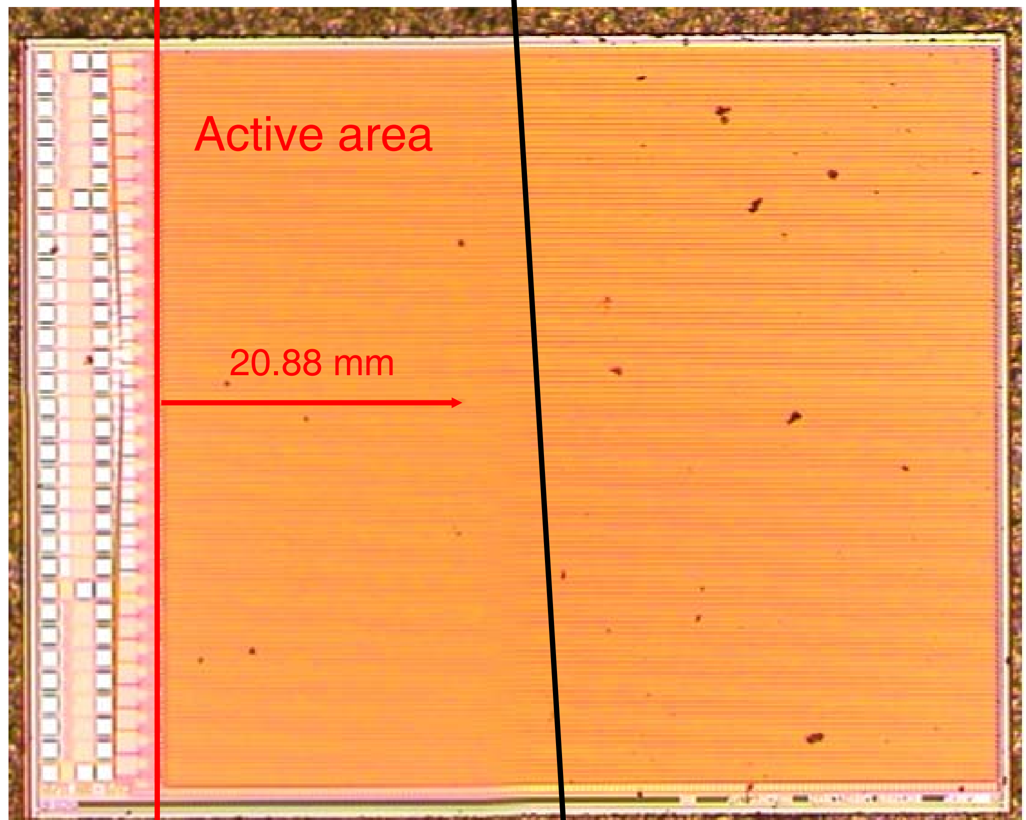




Sparse data
(timing mode)

CAP3 – full-sized!

21 mm



928 x 128 pixels = 118,784

~4.3M transistors

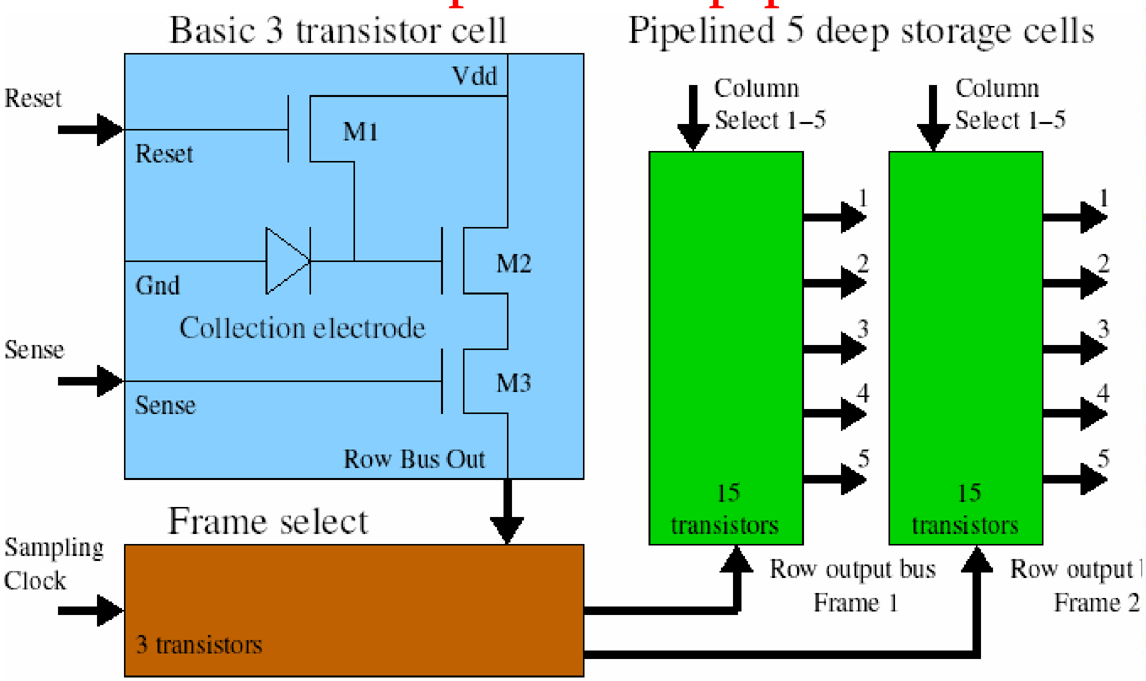
>93% active without active edge processing

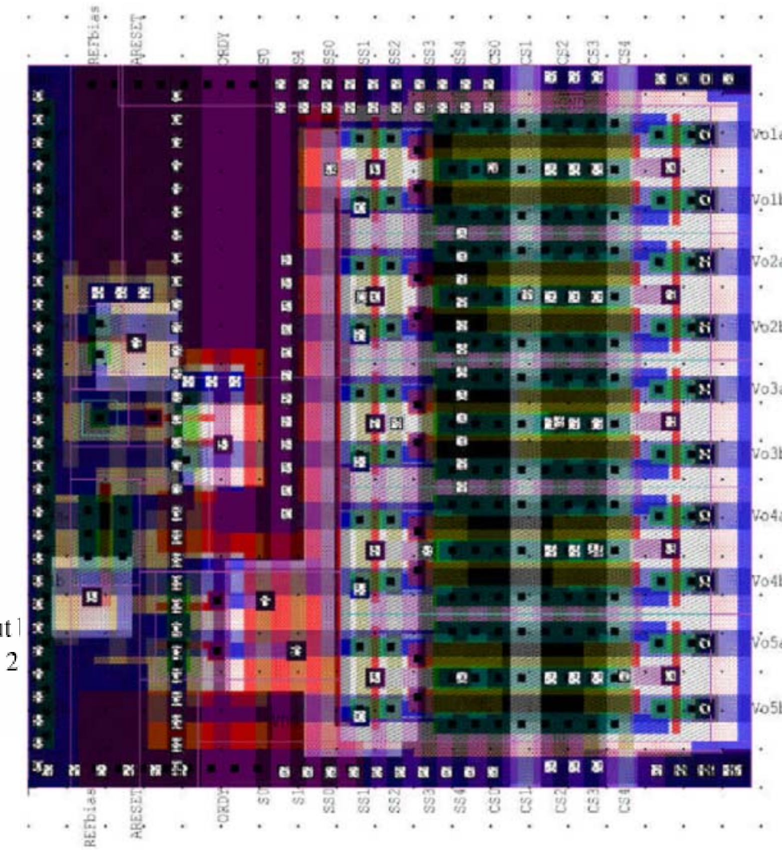
CAP3

~120Kpixel sensor (128x928 pix)

TSMC 0.25μm Process

5-deep double pipeline





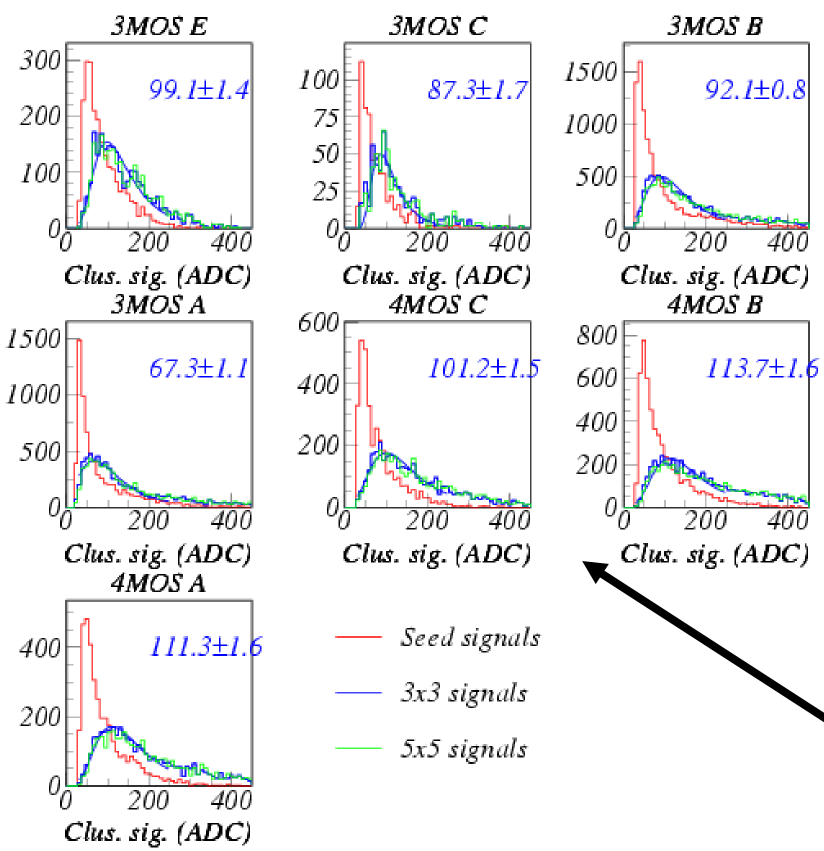
36 transistors/pixel

5 sets CDS pairs

5 metal layers

Distribution of signals

From different types of pixels.
HEPAPS2

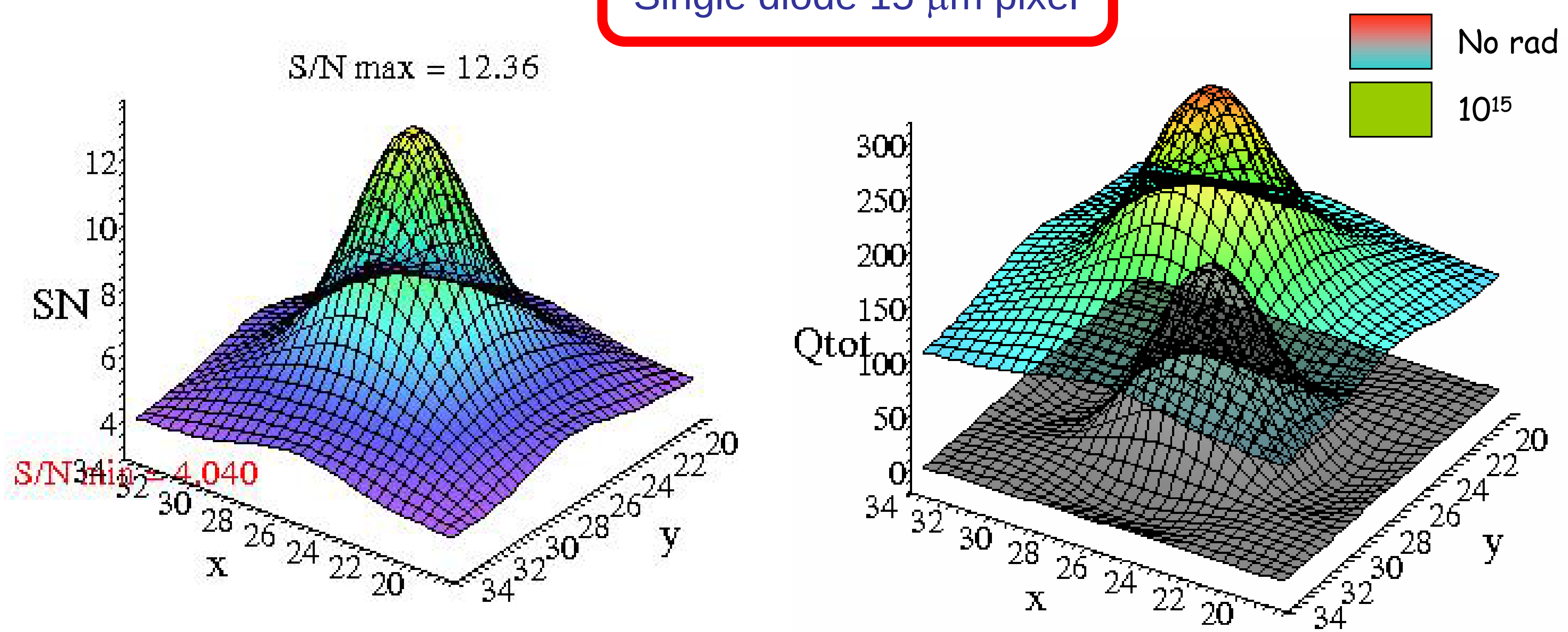


Type	Specs	S	N	S/N
3MOS E	4 diodes	99	4.94	20.1
3MOS C	GAA	87	4.85	18.0
3MOS B	Diode 1.2x1.2	92	3.87	23.8
3MOS A	Diode 3x3	67	3.31	20.3
4MOS C	Lower V_T	101	4.14	24.4
4MOS B	Higher V_T	114	4.70	24.2
4MOS A	Reference	111	4.45	25.0

Typical ‘Landau distribution

Single pixel S/N dependence on impact point. 1

Device simulation.
Single diode 15 μm pixel



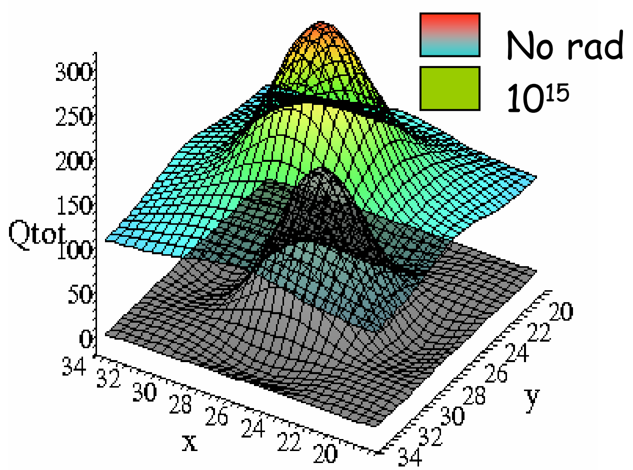
- S/N varies over pixel between 12 and 4 before irradiation.
- S drops to zero at edges after 10^{14} p/cm^2.

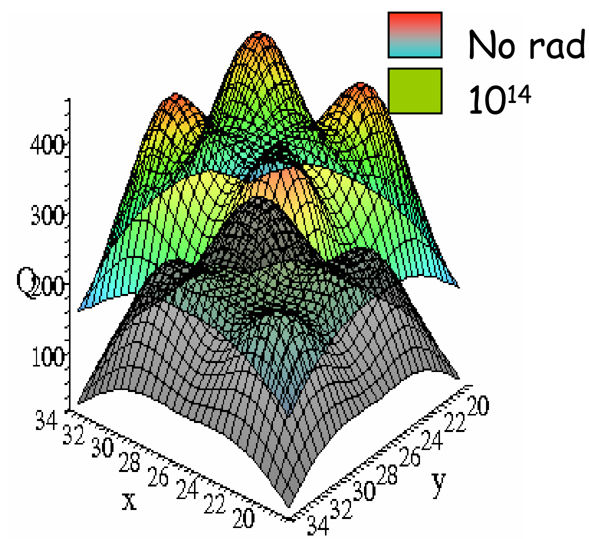
G. Villani (RAL)

Single pixel S/N dependence on impact point. 2

Device simulation.
Single diode 15 μm pixel

Device simulation.
4-diode 15 μm pixel





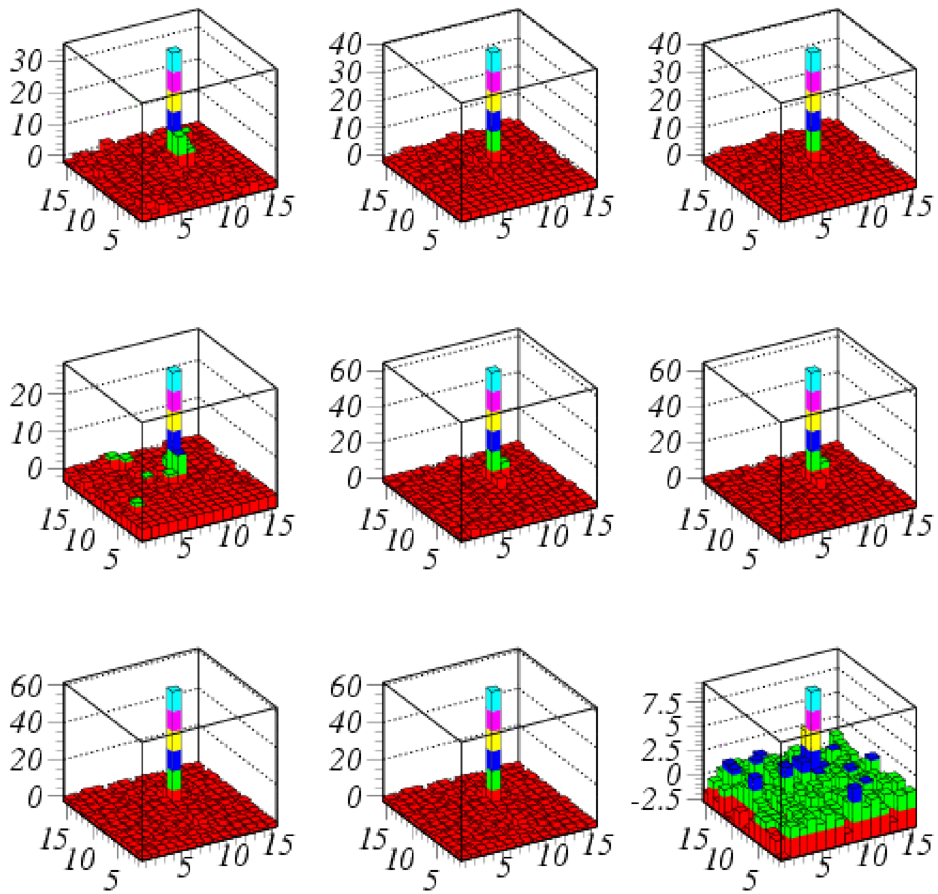
- Less variation in S/N varies over pixel before and after irradiation.
- S at edges still usable after 10^{15} p/cm^2.

G. Villani (RAL)

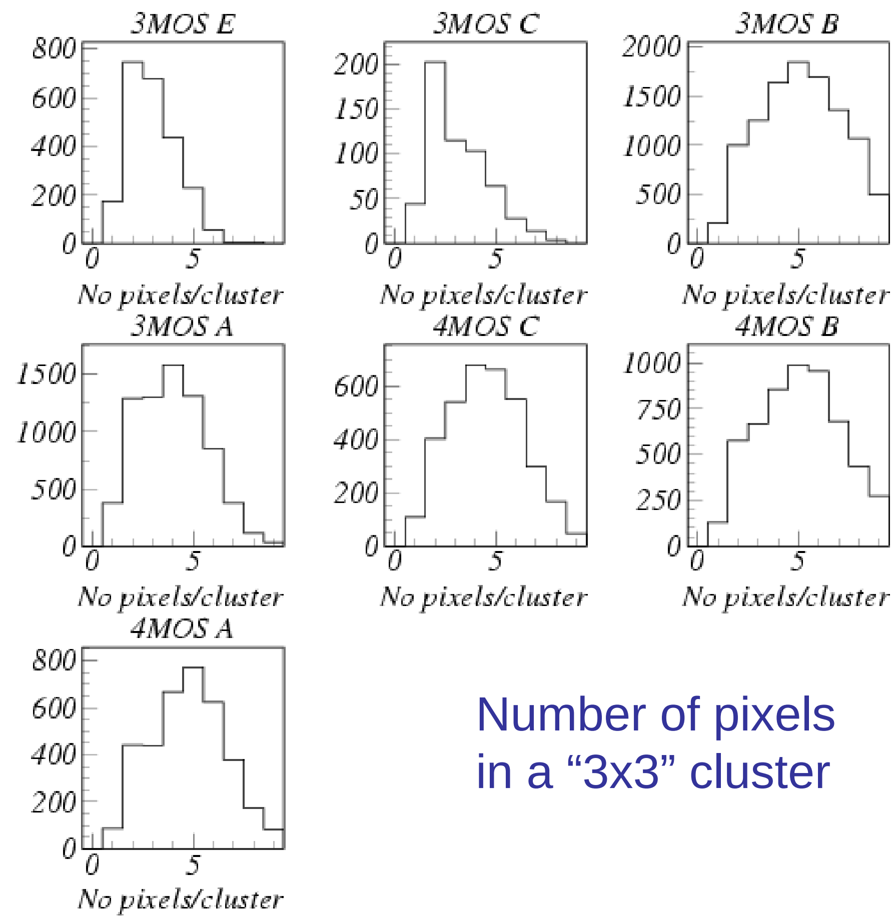
Signal from individual particles

Beta source (Ru106) test results. Sensors HEPAPS2.

Cluster in S/N



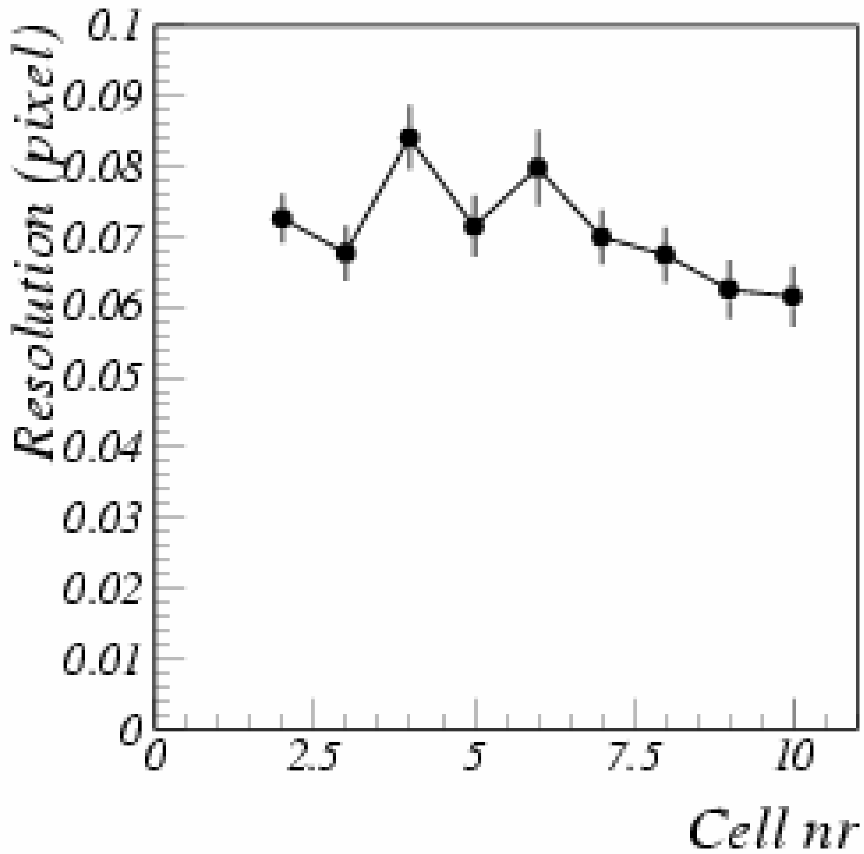
Signal spread



Number of pixels in a “3x3” cluster

FAPS Hit resolution

- Hit Resolution≠spatial resolution!!!
- Take hits found in cell 2
- Reconstruct x and y each cell using Centre-of-Gravity
- Calculate average hit position
- Determine residual position for each memory cell
- Hit resolution approximately 1.3 μm

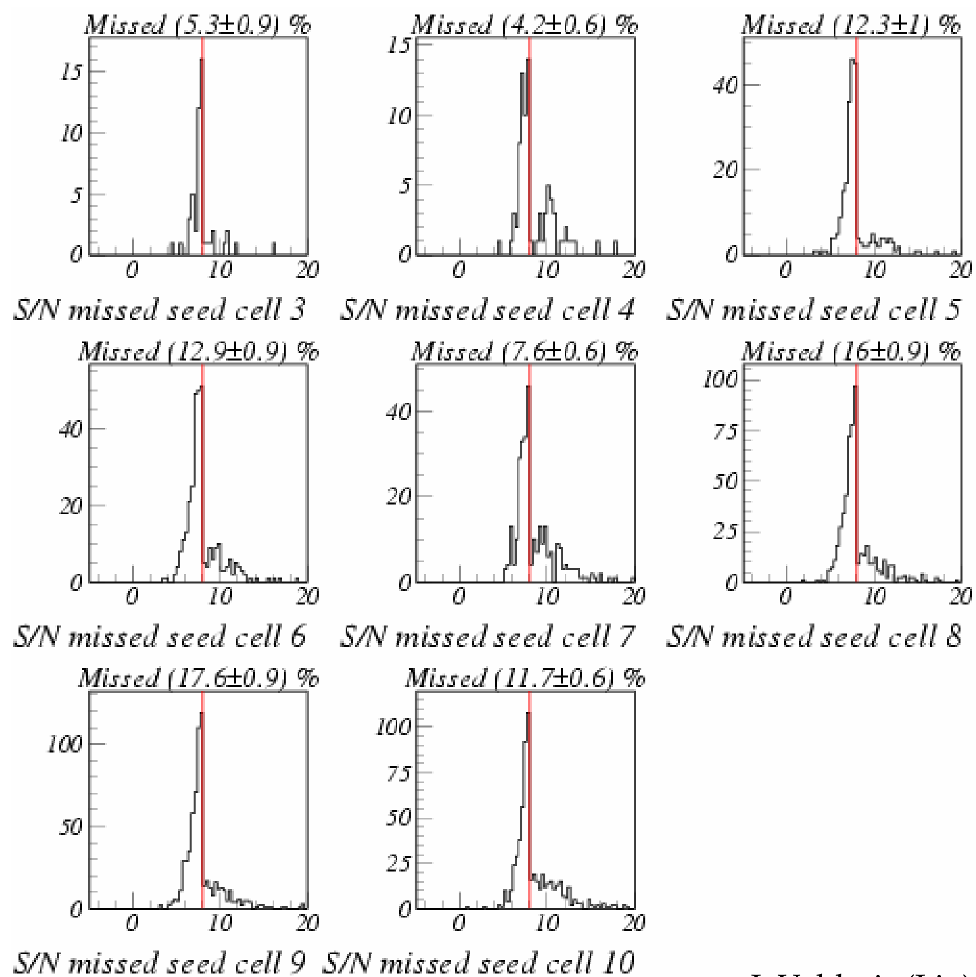


FAPS efficiency estimate

- Find hits in all cells
- Plot max S/N_{pixel} in 3x3 area around expected hit position if hit not found
- Define:

$$Missed = \frac{\#\, missed\ seed\ cut}{\#\, seeds\ cell\ (i-1)}$$

- Clearly, strongly dependent on seed cut. Lowering seed cut to 5σ yields inefficiency ranging between 0.08±0.08% and 0.5±0.1%



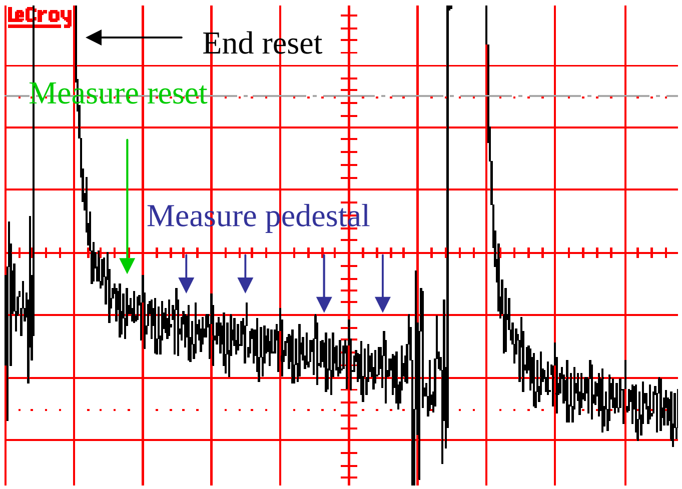
J. Velthuis (Liv)

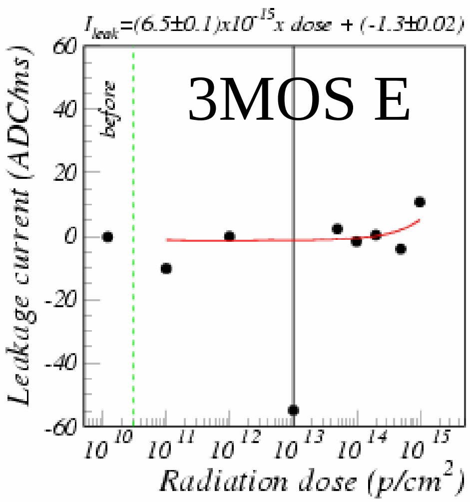
Radiation test

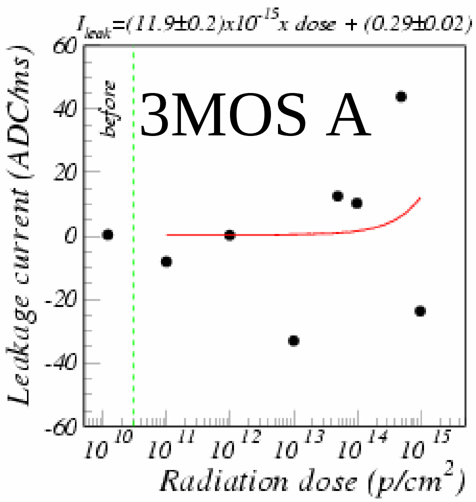
- Irradiated APS2 up to 10^{15} p/cm^2 at CERN.
  - 10^{12} p/cm^2 ILC requirement
  - 2×10^{15} p/cm^2 10 years ATLAS pixel layer
- Repeat analysis at each dose with same cuts
  - Seed $>8\sigma$
  - Neighbour $>2\sigma$

Dose (p/cm^2)	#APS2
0	3
1e11	4
1e12	4
1e13	4
5e13	4
1e14	2
2e14	2
5e14	2
1e15	2

Radiation test. Leakage current measurements







J. Velthuis (Liv)

- Slope is due to leakage current
  - Measure pedestal-reset(time)
  - Fit straight line
  - Plot average slope versus dose
- No significant increase in leakage current.