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# CMOS Sensors for High Energy Physics

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**Presented by Renato Turchetta**

**CCLRC - RAL**

# Outline

Introduction. Detectors for Particle Physics

Requirements

Results

- Noise
- Radiation hardness
- CMOS sensors with in-pixel storage:
  Flexible APS (FAPS)

Future experiments

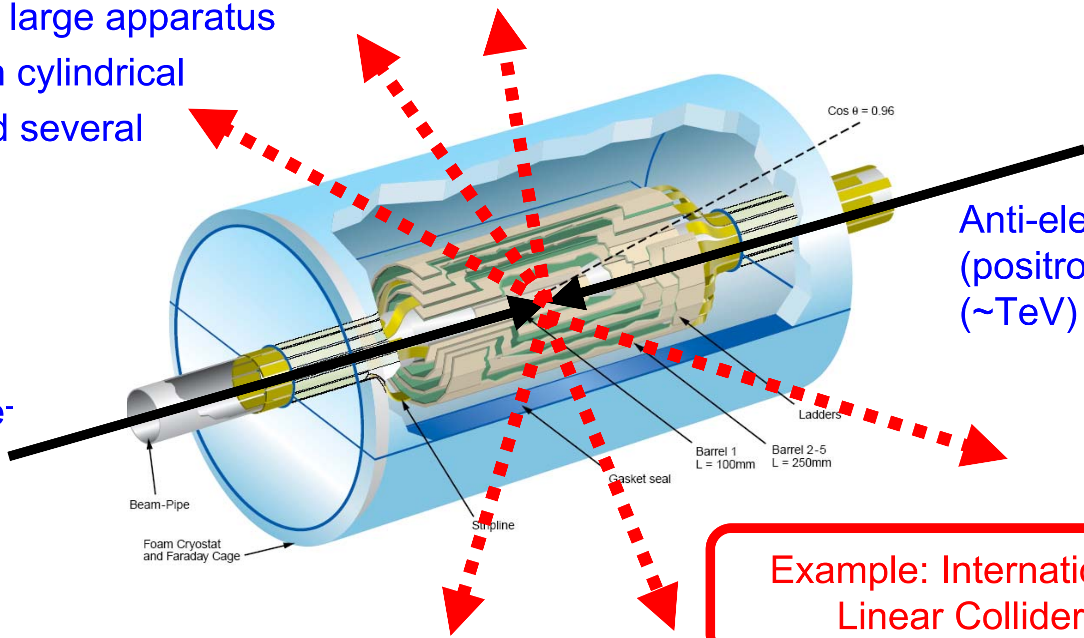
Conclusions

# Particle, or High-Energy, Physics

‘Big science’ projects: large particle accelerators (Ø km), large international (world-wide) collaborations.

High-energy particles (↑ TeV) collide → new particles are created → insight into ultimate structure of matter.

Detectors are large apparatus (size ~m) with cylindrical symmetry and several subdetectors.




Anti-electron (positron) $e^+$ (~TeV)

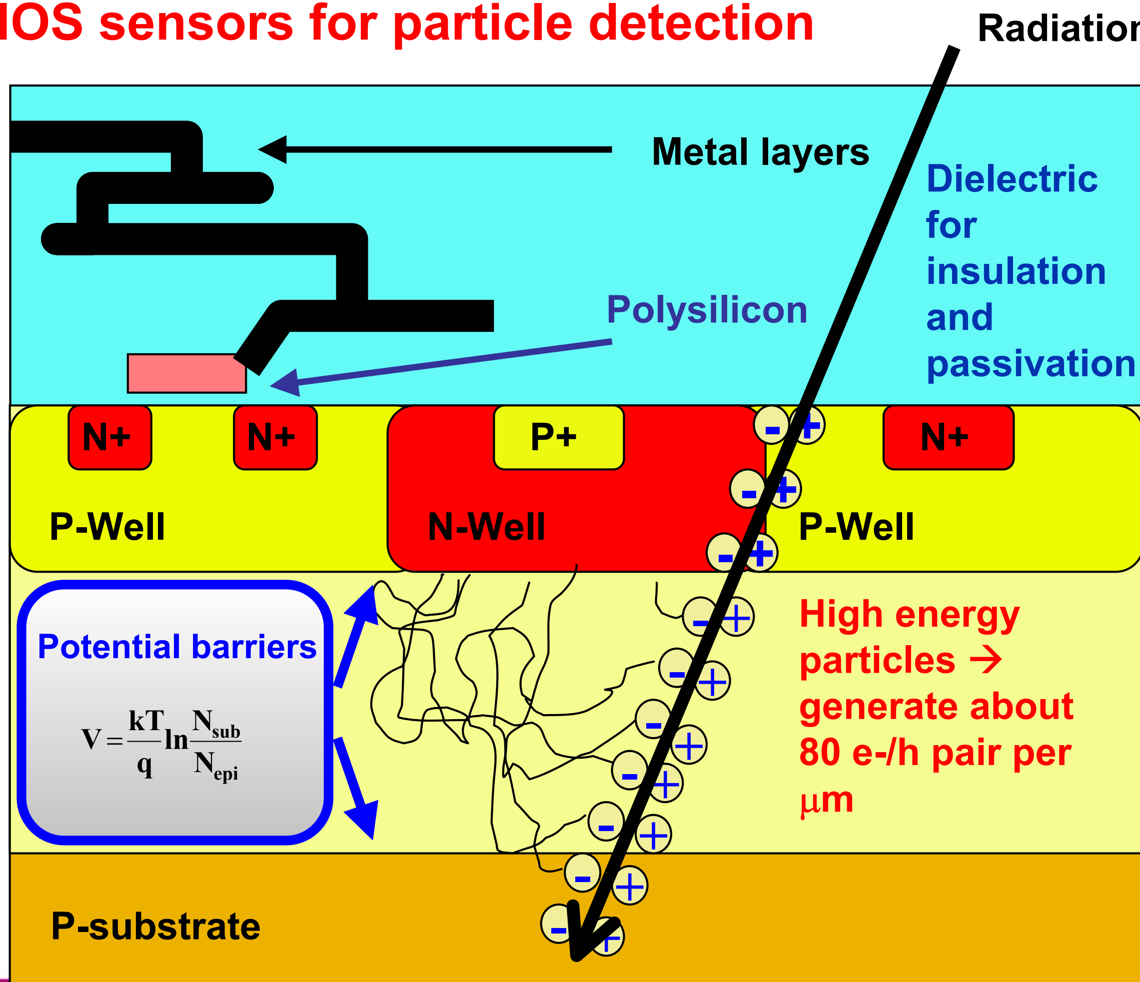
Electron $e^-$ (~TeV)

Example: International Linear Collider

# CMOS sensors for particle detection

**Requirements**

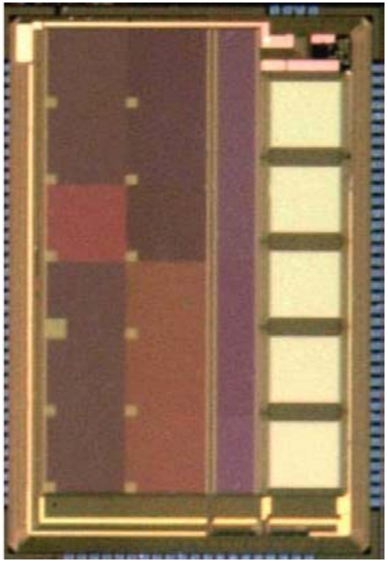
1) Efficiency: 100% or close
2) Noise: signal ~ 100s e-/h pairs
3) Radiation hardness: Mrad and beyond
4) Speed: 'frame rate' > $10^6$/sec
5) Large area: side ~ cm's



# RAL Sensors for Particle Physics

**Parametric test sensor: RAL_HEPAPS family**

RAL_HEPAPS2: 0.25 μm CIS, 8 μm epitaxial layer, 384*224 pixels, 15 μm pitch: 3MOS, 4MOS, ChargePreAmplifier (CPA), Flexible APS (FAPS, 20 μm pitch)

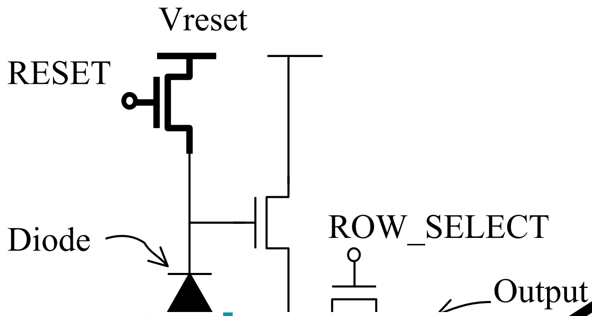


RAL_HEPAPS3: 0.25 μm MM, no epitaxial layer, 192*192 pixels, 15 μm pitch: 3MOS, 4MOS, Deep N-well diodes

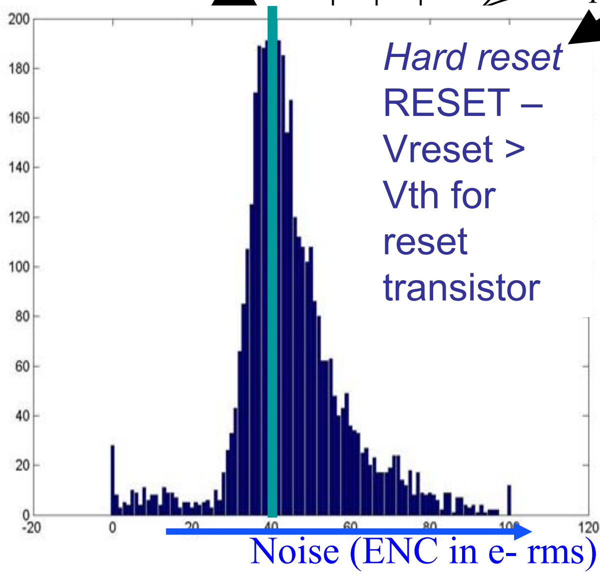
**Test sensors**

RAL_HEPAPS4: 0.35 μm CIS, 20 μm epitaxial layer, 1026*384 pixels, 15 μm pitch. 3 versions: 1, 2 or 4 diodes per pixel. Rad-hard, 5MHz row rate (now in manufacturing)

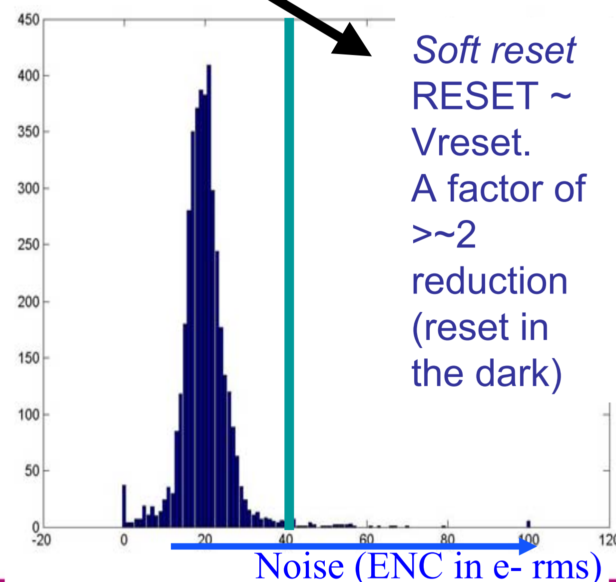
# *Soft* and *hard* reset




Measured noise distributions for a 64x64 pixel test structure.
Not corrected for system noise




*Hard reset*
RESET – Vreset > Vth for reset transistor




*Soft reset*
RESET ~ Vreset.
A factor of >~2 reduction (reset in the dark)

# Radiation hardness

**Transistors.**

Threshold shift: reduces with shrinking feature size

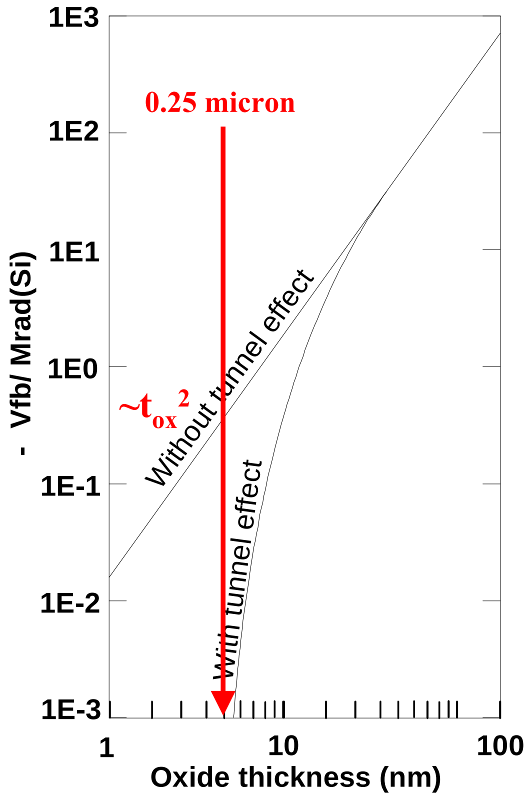
Bird's beak effect: use enclosed geometry transistors

Transistor leakage current: use guard-rings to separate transistors

**Diodes.**

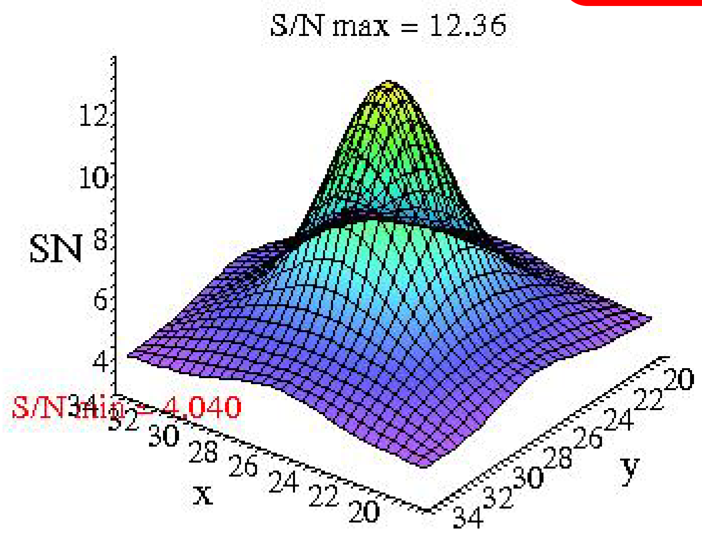
Radiation damage increases leakage current

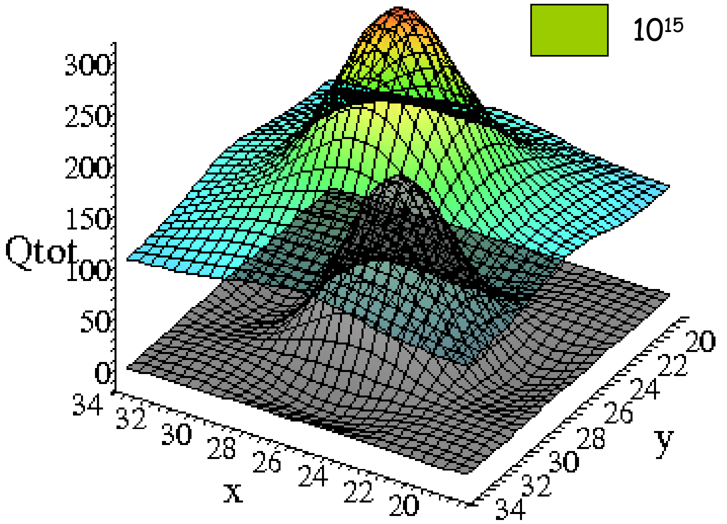
Radiation damage reduces minority carrier lifetime → diffusion distance is reduced



# 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$^2$.

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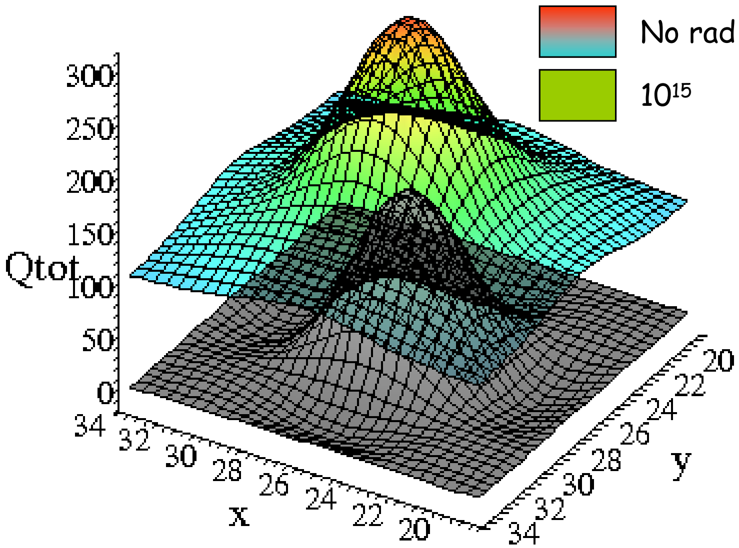
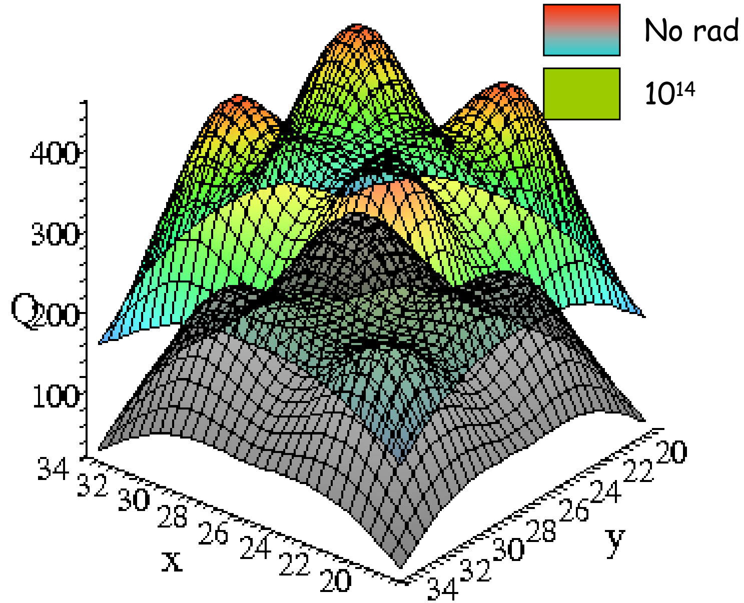
# Single pixel S/N dependence on impact point. 2

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$^2$.

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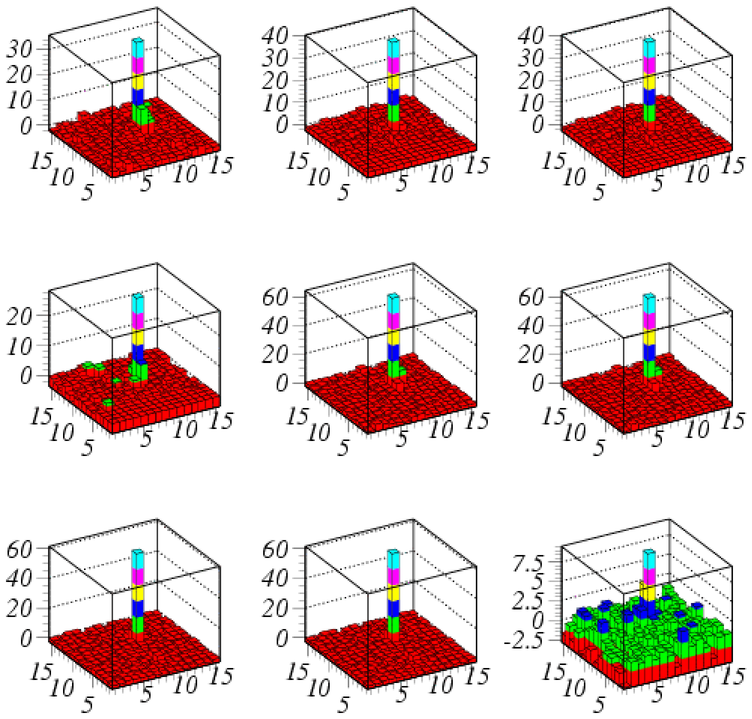
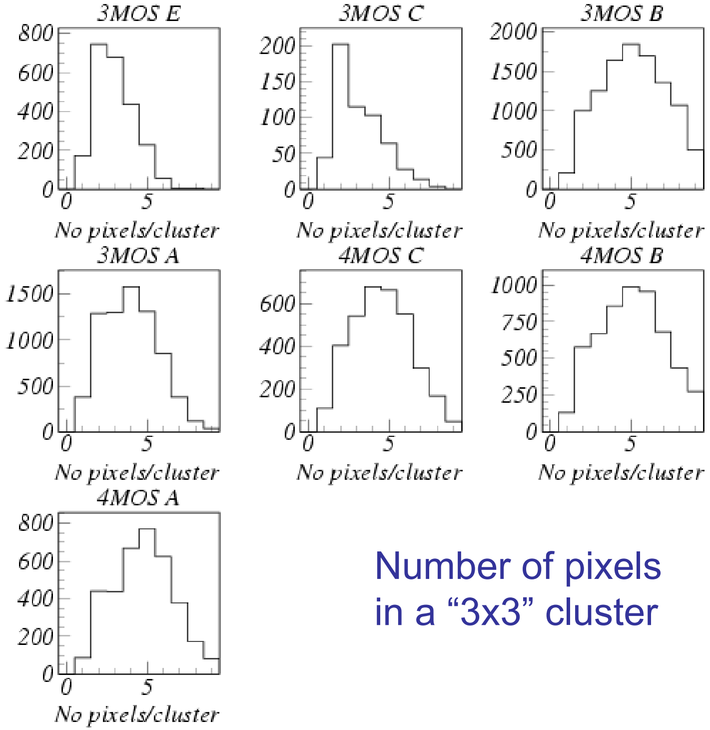
# Signal from individual particles

**Beta source (Ru106) test results. Sensors HEPAPS2.**

## Cluster in S/N



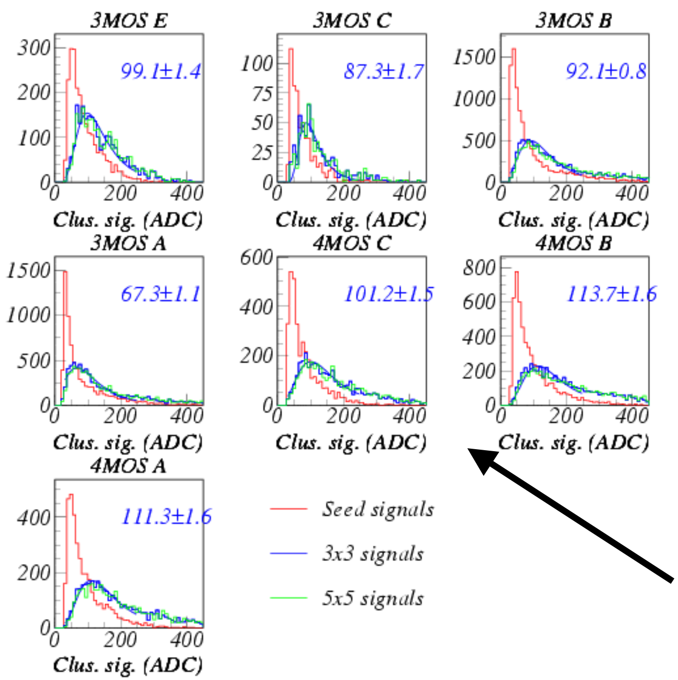
## Signal spread




Number of pixels
in a “3x3” cluster

# Distribution of signals

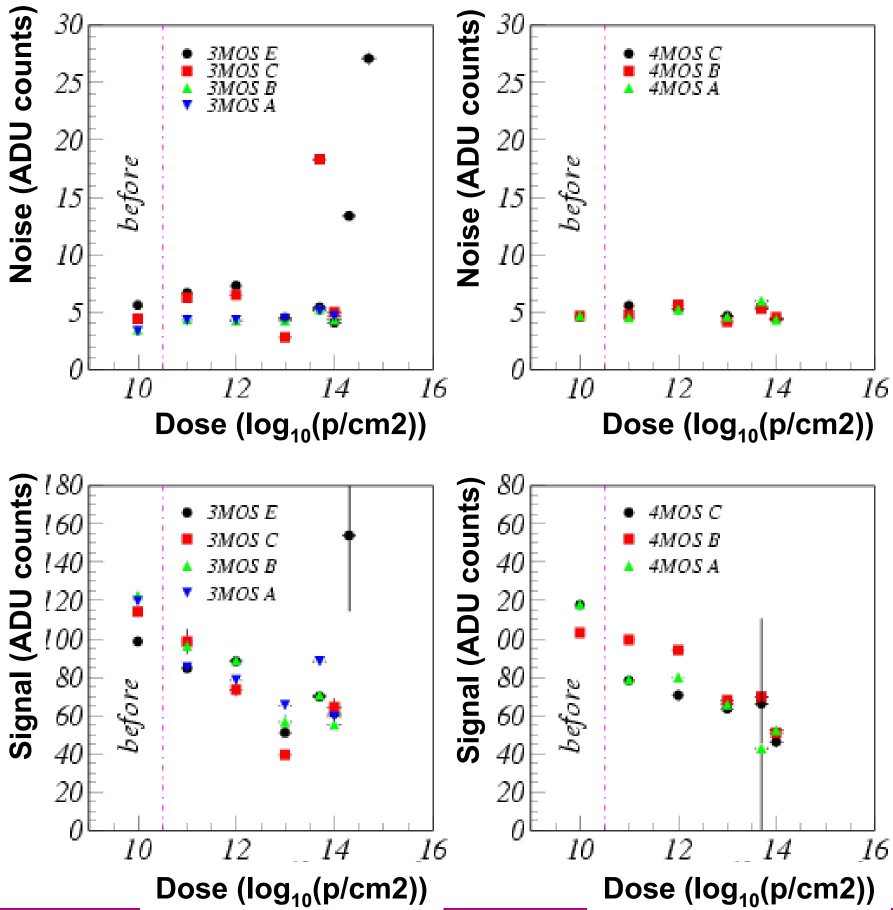
From different types of pixels.
HEPAPS2




| 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

# Radiation test. Source results




- Noise seems to increase slightly with dose.
- Signal decreases with dose.

| | |
|---|---|
| 3MOSA | 3x3 $\mu m^2$ |
| 3MOSB | 1.2x1.2 $\mu m^2$ |
| 3MOSC | GAA |
| 3MOSE | 4 diodes |
| 4MOSA | Reference |
| 4MOSB | Higher $V_T$ |
| 4MOSC | Lower $V_T$ |

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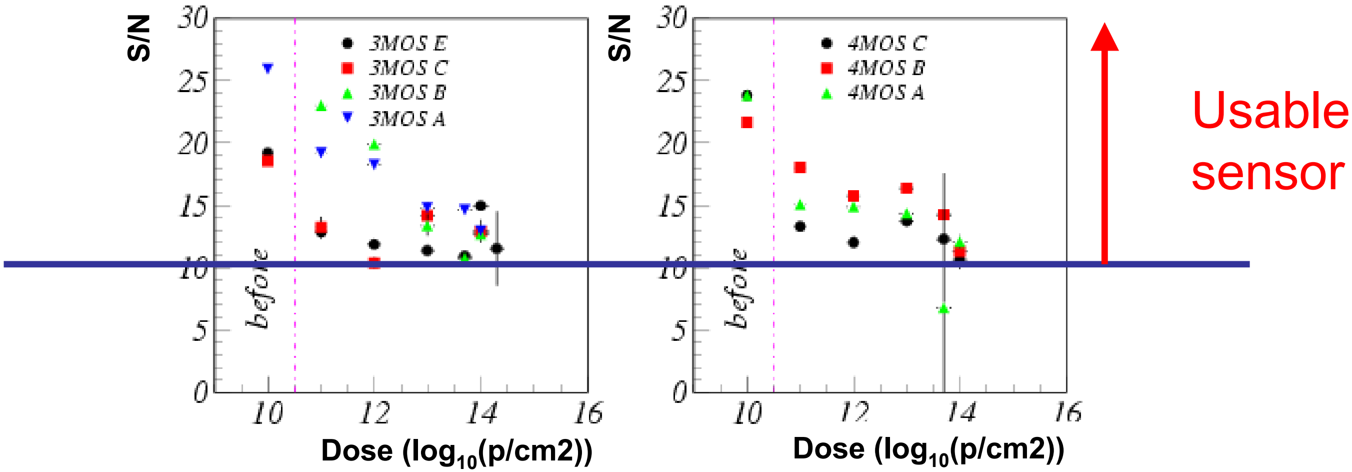
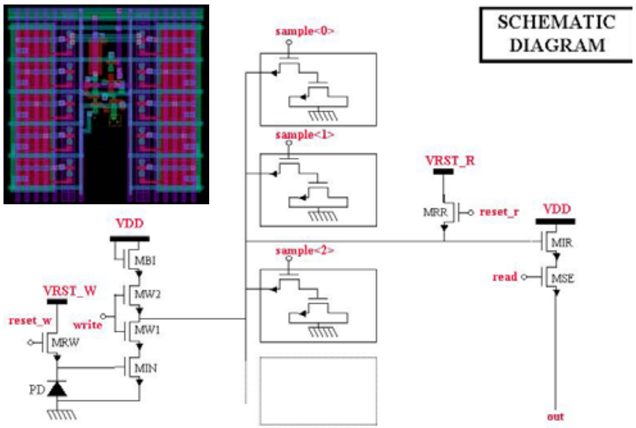
# Radiation test. Summary

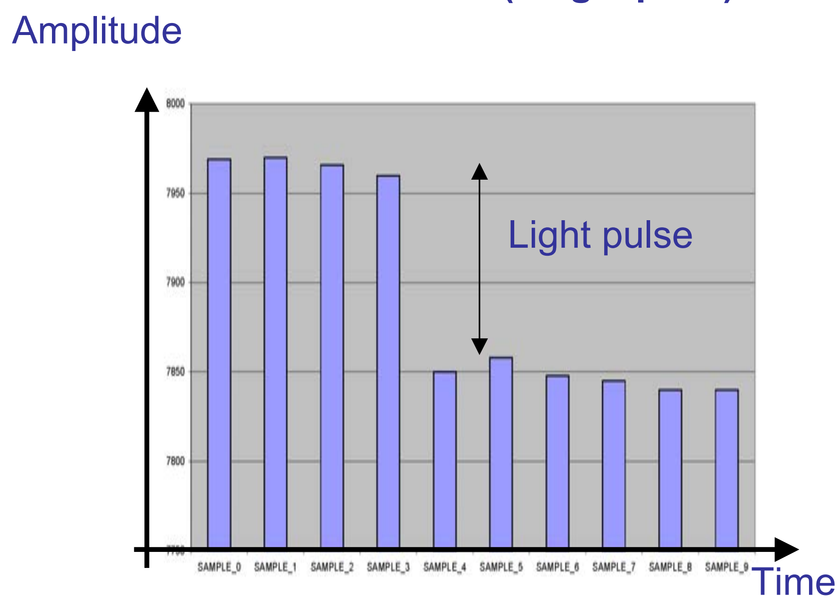



- Sensors yield reasonable S/N up to $10^{14}$ p/cm$^2$
- 0.35 μm technology in the pixel transistors. Enclosed layout in 3MOS_E
- S/N reduction seems to be dominated by charge collection
- Especially 3MOS_E (4 diodes) looks interesting
  - (-) Larger capacitance yields larger noise
  - (+) Four diodes: less dependence of S/N on impact point
  - (+) After irradiation remains a larger “sensitive area”

# Flexible Active Pixel Sensor




## Pulses LED test (single pixel)




10 memory cell per pixel

28 transistors per pixel

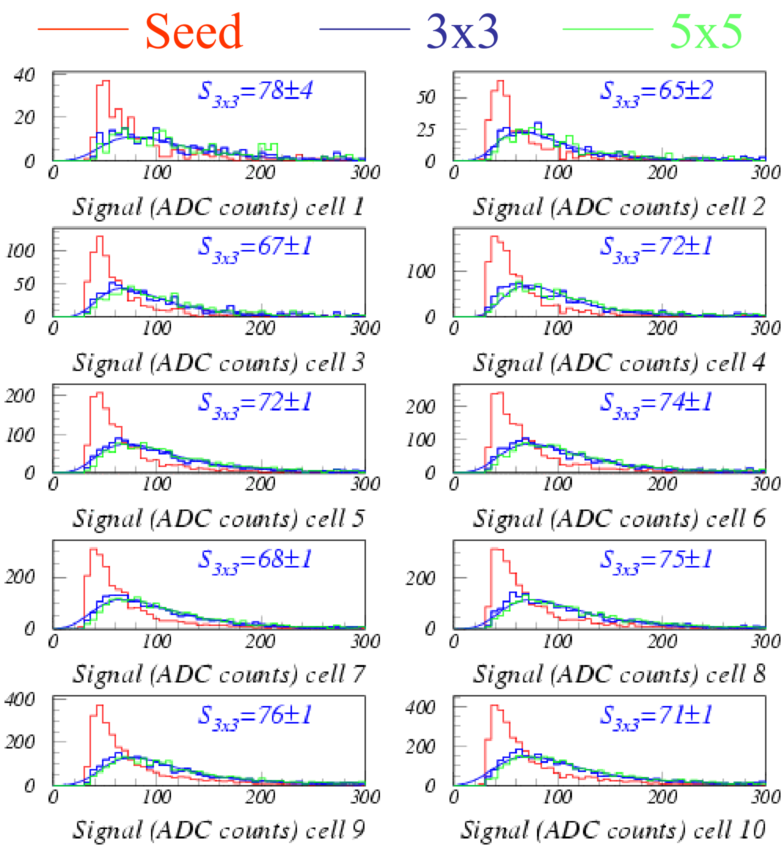
20 µm pitch

40x40 arrays

Design for the Vertex detector at the International Linear Collider

# FAPS. Signal distribution

- Test with source
- Correlated Double Sampling readout (subtract $S_{cell\ 1}$)
- Correct remaining common mode and pedestal
- Calculate random noise
  - Sigma of pedestal and common mode corrected output
- Cluster definition
  - Signal >8σ seed
  - Signal >2σ next
- Note hit in cell *i* also present in cell *i+1*.
- **$S/N_{cell}$ between 14.7±0.4 and 17.0±0.3**

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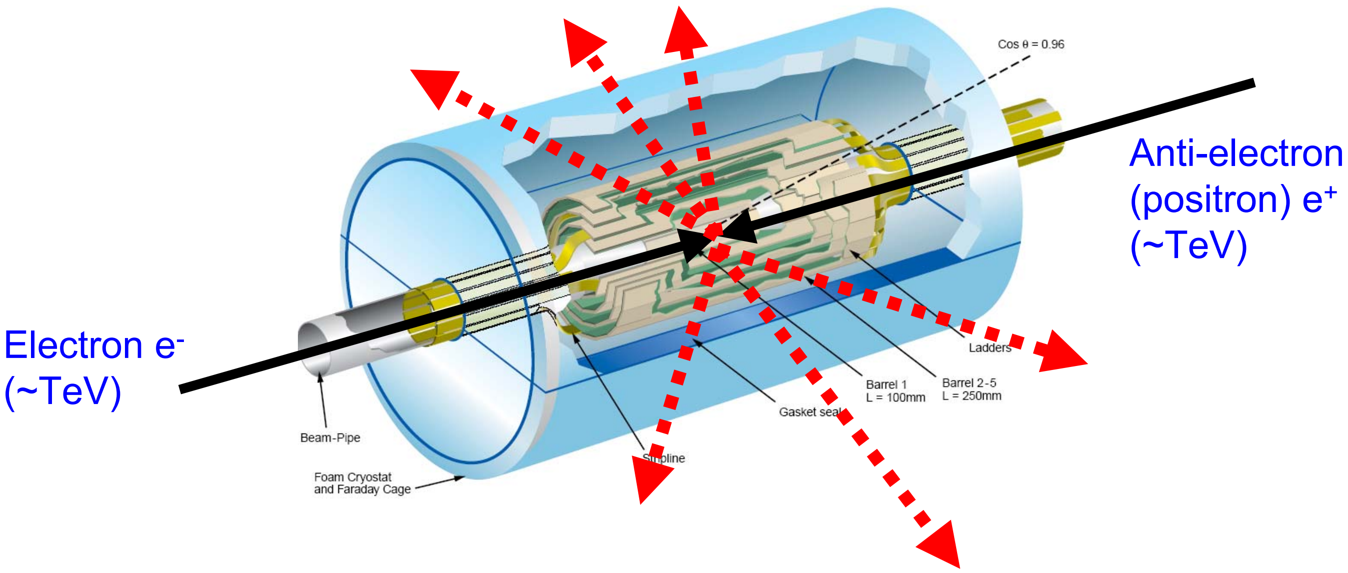
# Future experiments

**International Linear Collider:** CMOS sensors proposed for Vertex and Electromagnetic calorimeter.

Large area (stitched) sensor required in both cases.

Total covered area: **~m²** for Vertex, a few **10⁴ m²** for Electromagnetic calorimeter

Radiation hardness: moderate (~100s kRad, $10^{12}$ n/cm²)



# Conclusions

**Parametric test sensors used to study noise, radiation hardness, new designs.**

**Radiation hardness → $10^{14}$ p/cm$^2$**

**Noise < 20 e- rms (soft reset in dark)**

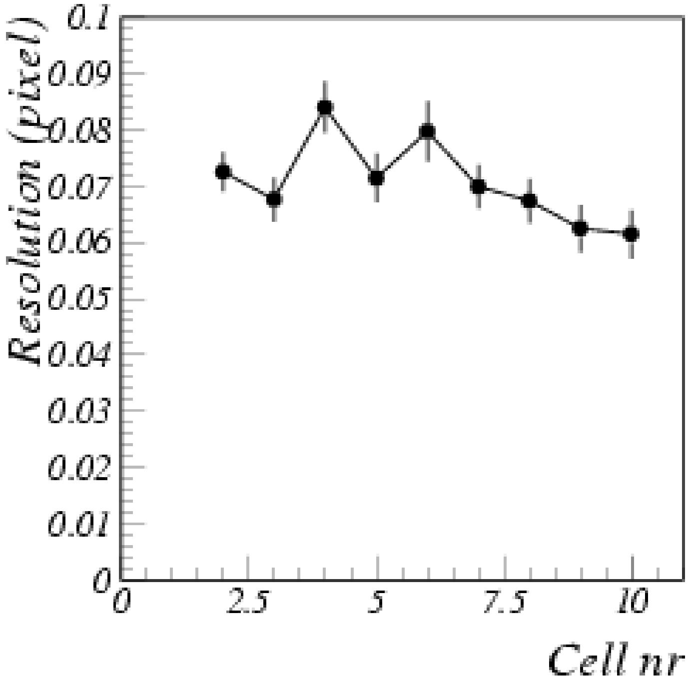
**Three versions for radiation hardness of fast (5MHz/line), rad-hard, large (1024*384) sensor (RAL_HEPAPS4) in manufacturing**

**Future experiments will require stitched sensors. Large area coverage → $10^4$ m$^2$**

**CMOS technology would provide the solution for coverage of large areas with pixel detectors.**

# 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

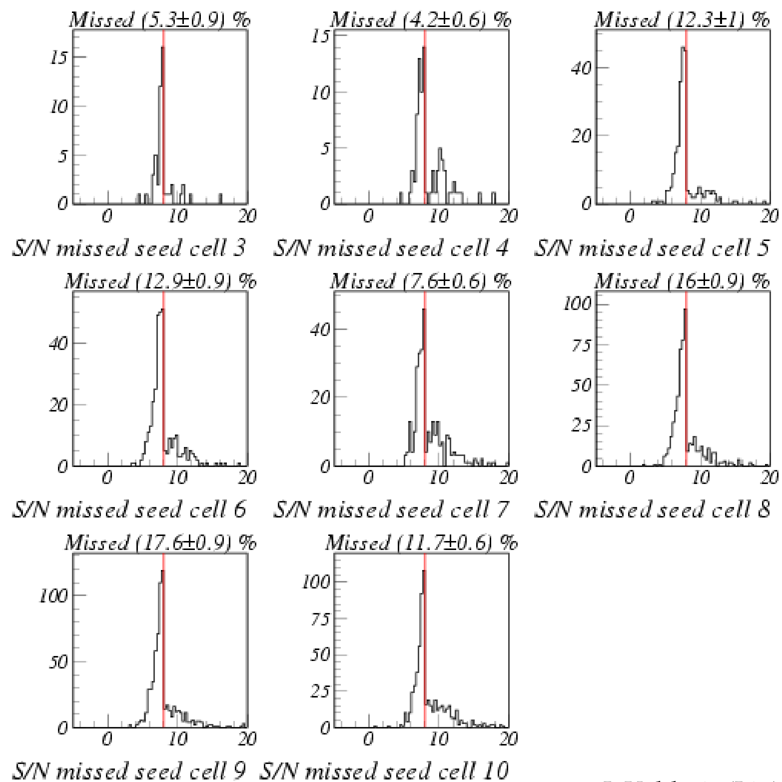


# FAPS efficiency estimate

- 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%

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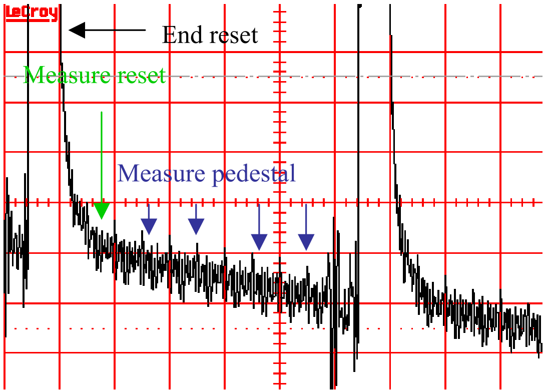
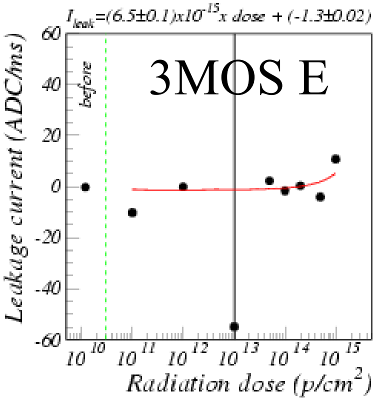
# Radiation test

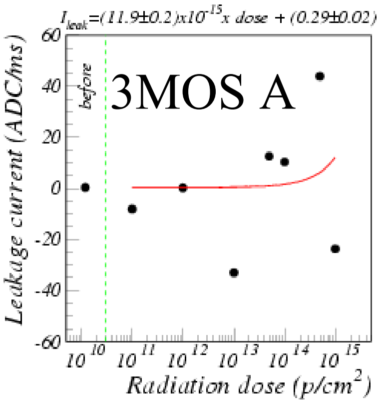
- Irradiated APS2 up to $10^{15}$ p/cm$^2$ at CERN.
  - $10^{12}$ p/cm$^2$ ILC requirement
  - $2\times10^{15}$ p/cm$^2$ 10 years ATLAS pixel layer
- Repeat analysis at each dose with same cuts
  - Seed $>8\sigma$
  - Neighbour $>2\sigma$

| 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




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

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