Deep N-well CMOS MAPS with in-pixel signal processing and sparsification capabilities for the ILC vertex detector

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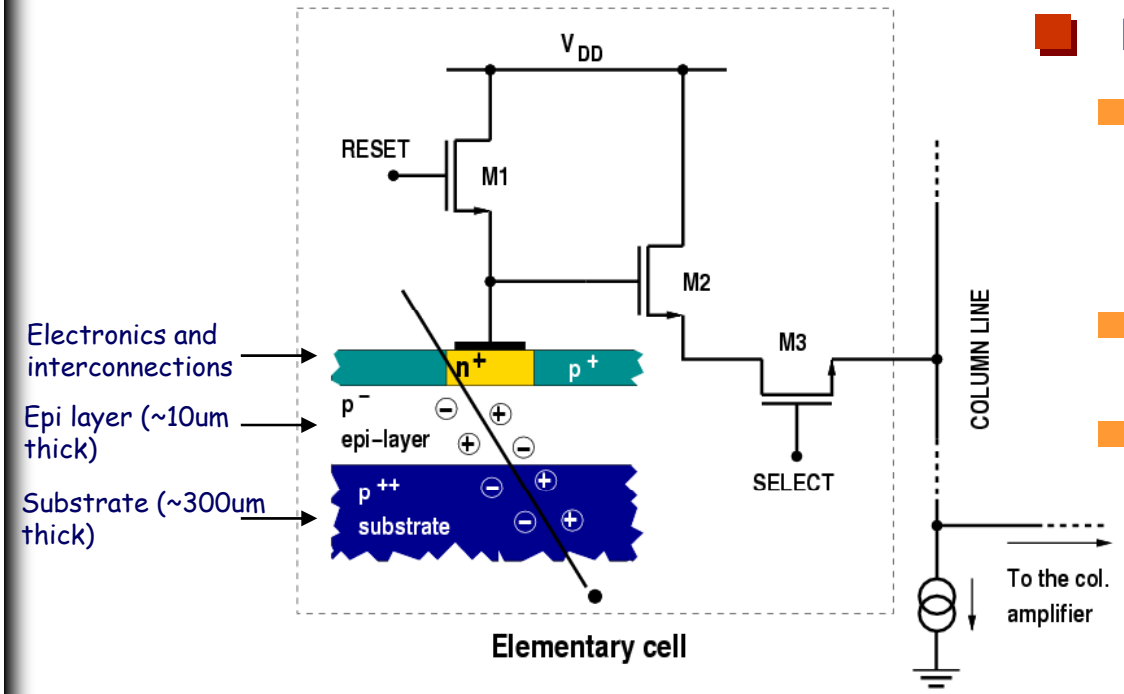
Vertex 2007 – 16th International Workshop on Vertex Detectors

September 23 – 28, 2007 – Lake Placid, NY, USA

Outline

- Introduction: standard CMOS monolithic active pixel sensors
- Deep N-Well pixel sensor
- Description of the sensor level processor
- Digital section and digital readout scheme
- Physical simulations
- Conclusions

Conventional CMOS MAPS

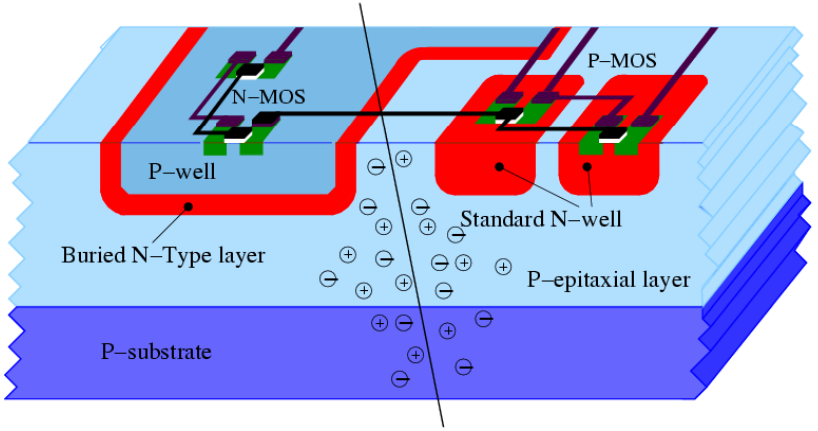


- Principle of operation:
  - Signal generated by a particle is collected by an n-well/p-epitaxial diode, then readout by CMOS electronics integrated in the same substrate
  - Charge generated by the incident particle moves by thermal diffusion
  - Extremely simple in-pixel readout (3-T NMOS, PMOS not allowed)

- Several reasons make CMOS MAPS appealing as tracking devices:
  - Detector and readout on the same substrate
  - Wafer can be thinned down to tens of μm ⇒ minimal amount of material in the detector region (e.g. with respect to hybrid pixel)
  - Deep sub-micron CMOS tecnology ⇒ high functional density and versatility, low power consumption, radiation tolerance and fabrication costs

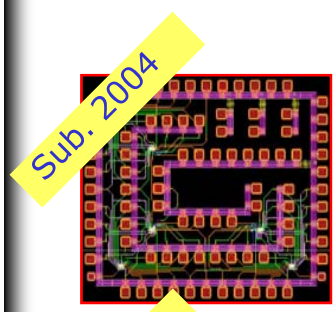
Deep Nwell sensor concept

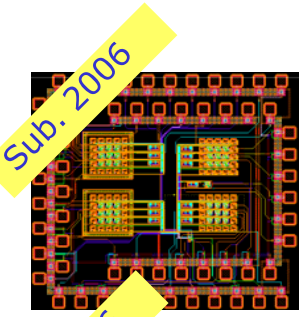
- In triple-well CMOS processes a deep N-well is used to shield N-channel devices from substrate noise in mixed-signal circuits
- DNW MAPS is based on the same working principle as standard MAPS
- A DNW is used to collect the charge released in the epitaxial layer

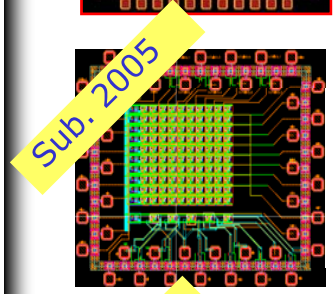


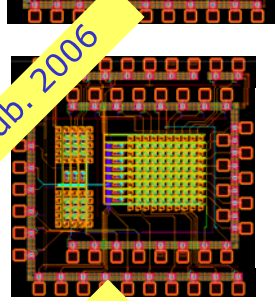
- A charge preamplifier is used for Q-V conversion → gain decoupled from electrode capacitance
- DNW may house NMOS transistors
- Using a large detector area, PMOS devices may be included in the front-end design → charge collection inefficiency depending on the ratio of the DNW area to the area of all the N-wells (deep and standard)

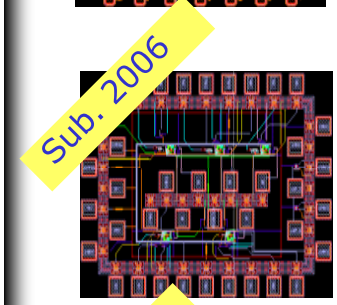
APSEL series chips

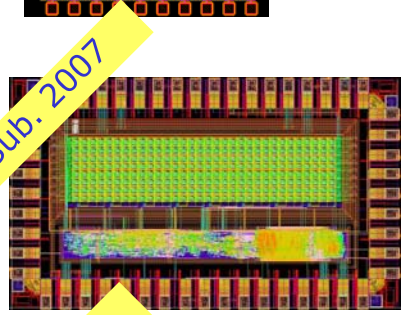


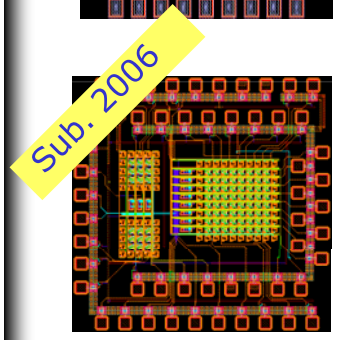


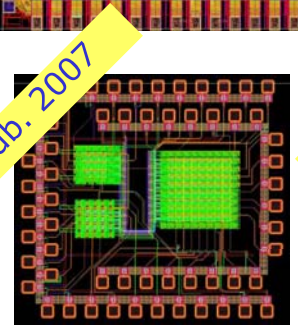


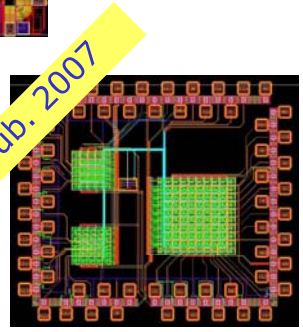








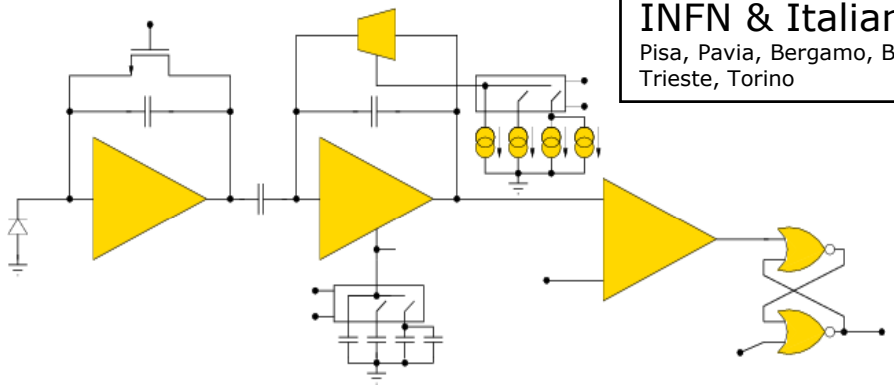




SLIM5 Collaboration:

INFN & Italian Universities

Pisa, Pavia, Bergamo, Bologna, Trento, Trieste, Torino



Full in-pixel signal processing:
PA + shaper + comparator + latch

Prototypes fabricated with the STMicroelectronics 130nm triple-well technology

High sensitivity charge preamplifier with continuous reset + RC-CR shaper with programmable peaking time

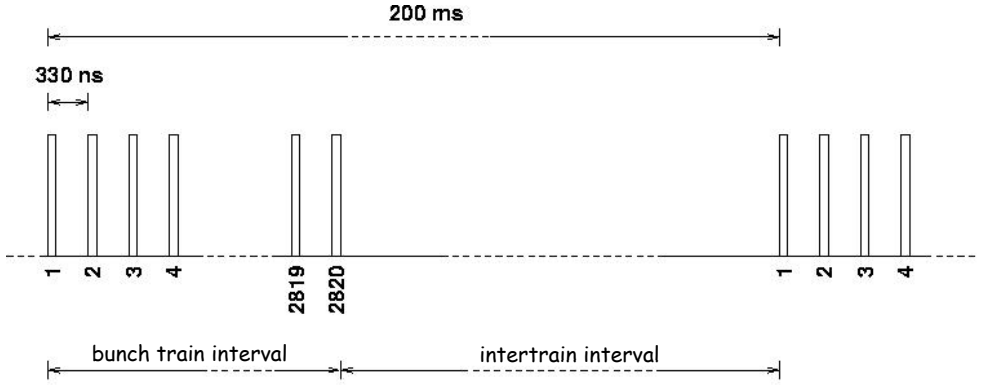
A threshold discriminator is used to drive a NOR latch featuring an external reset

Pixel size about 50μm x 50μm

The first prototypes proved the capability of the sensor to collect charge from the epitaxial layer

Design specifications for the ILC vertex detector

- The beam structure of ILC will feature 2820 crossings in a 1 ms bunch train, with a duty-cycle of 0.5%



  - assuming maximum hit occupancy 0.03 part./Xing/mm^2
  - if 3 pixels fire for every particle hitting → hit rate ≈ 250 hits/train/mm^2
  - if a digital readout is adopted 5μm resolution requires 17.3 μm pixel pitch
  - 15 μm pitch → $O_c \approx 0.056$ hits/train → 0.0016 probability of a pixel being hit at least twice in a bunch train period

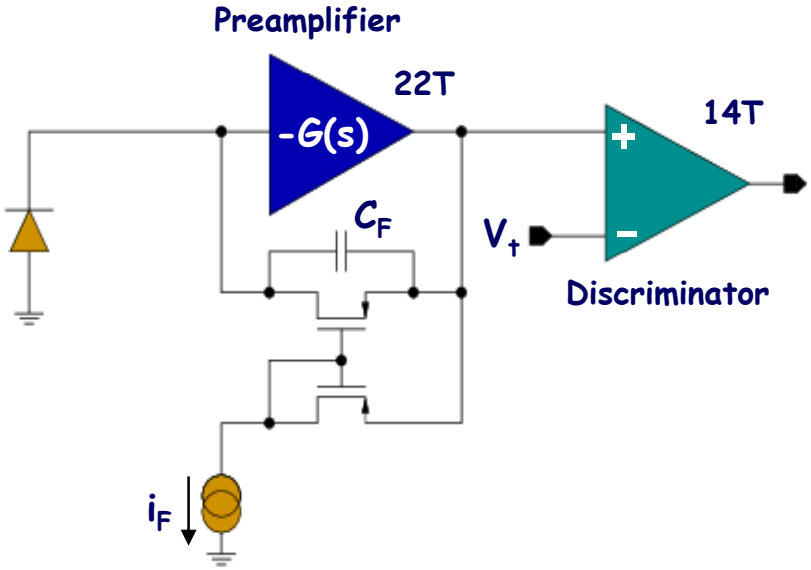
- A pipeline with a depth of one in each cell should be sufficient to record > 99% of events without ambiguity
- Data can be readout in the intertrain interval → system EMI insensitive

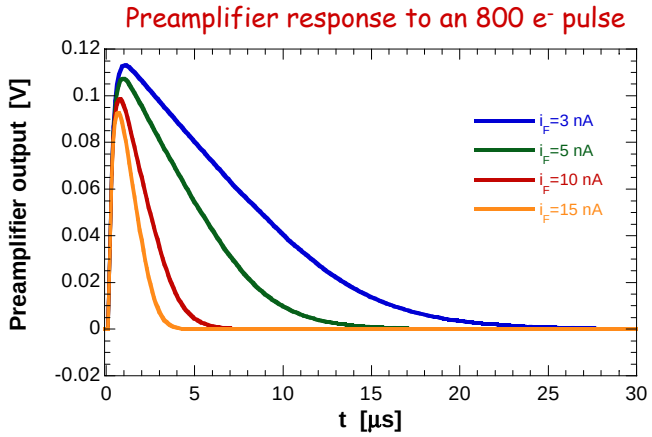
Sparsified readout architecture

- In DNW MAPS sensors for ILC sparsification is based on a token passing readout scheme suggested by R. Yarema (R. Yarema, "Fermilab Initiatives in 3D Integrated Circuits and SOI Design for HEP", *ILC VTX Workshop at Ringberg*, May 2006)

- MAPS sensor operation is tailored on the structure of ILC beam
  - Detection phase (corresponding to the bunch train interval)
  - Readout phase (corresponding to the intertrain interval)

Pixel level processor

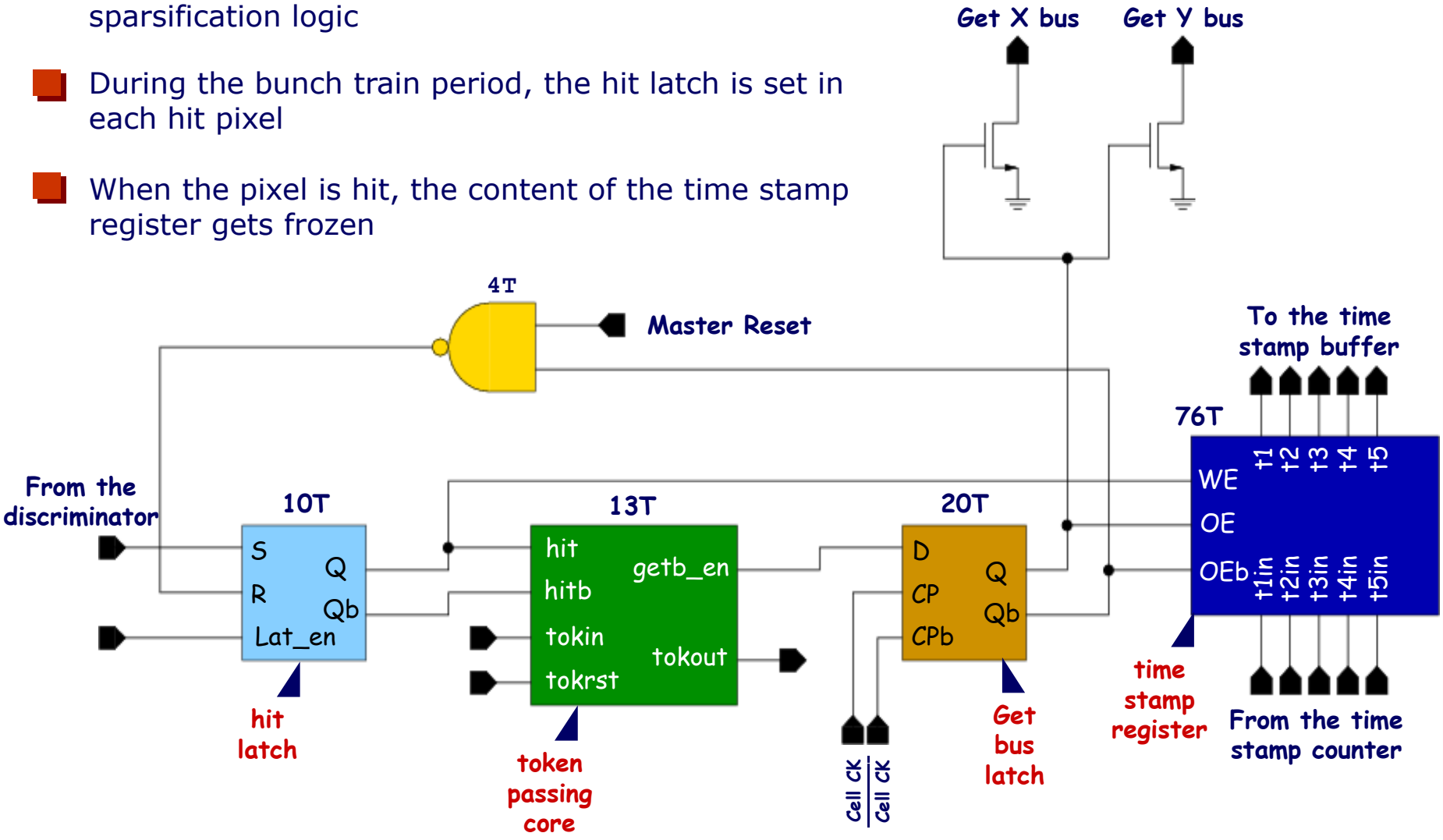




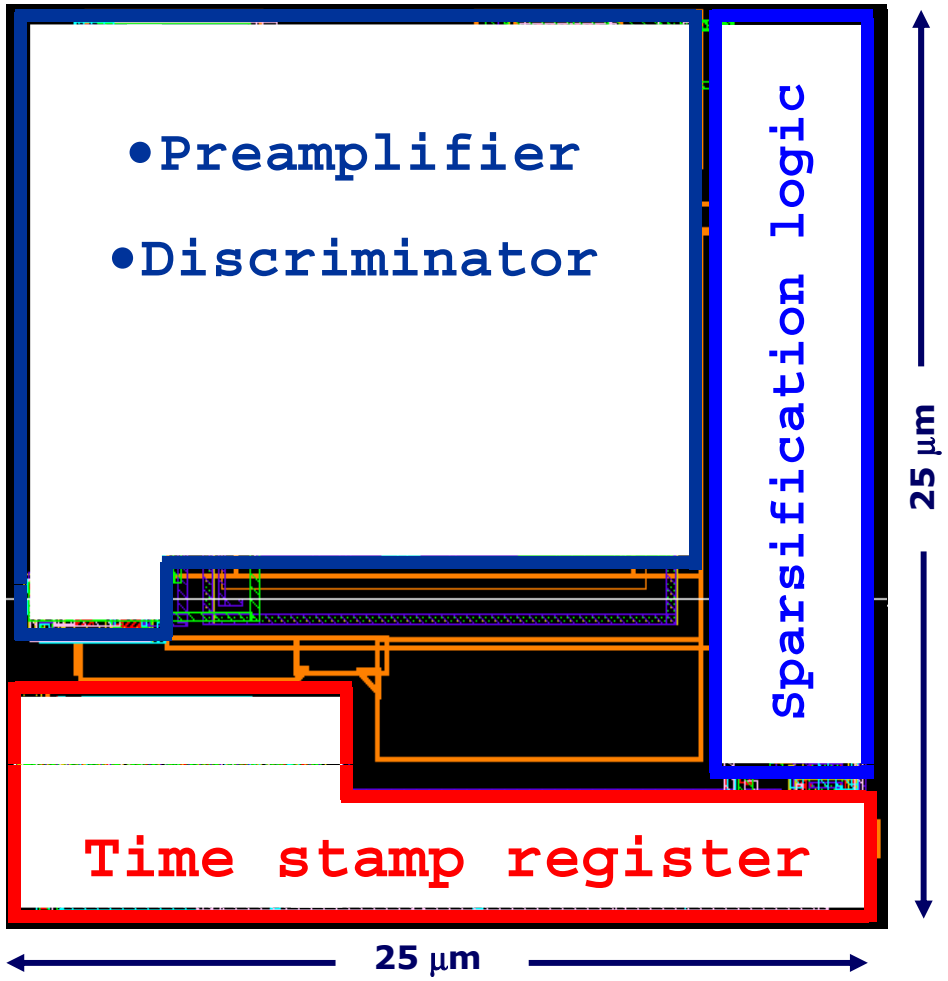
- C_F obtained from the source-drain capacitance
- High frequency noise contribution has been reduced limiting the PA bandwidth
- ENC=**25 e⁻ rms@C_D=100 fF**
- Threshold dispersion ≈ **30 e⁻ rms**
- Power consumption ≈ **5 µW**
- Features power-down capabilities for power saving: the analog section cell can be switched off during the intertrain interval in order to save power (**1% duty-cycle** seems feasible)

Cell digital section

- Includes a 5 bit time stamp register and the data sparsification logic
- During the bunch train period, the hit latch is set in each hit pixel
- When the pixel is hit, the content of the time stamp register gets frozen

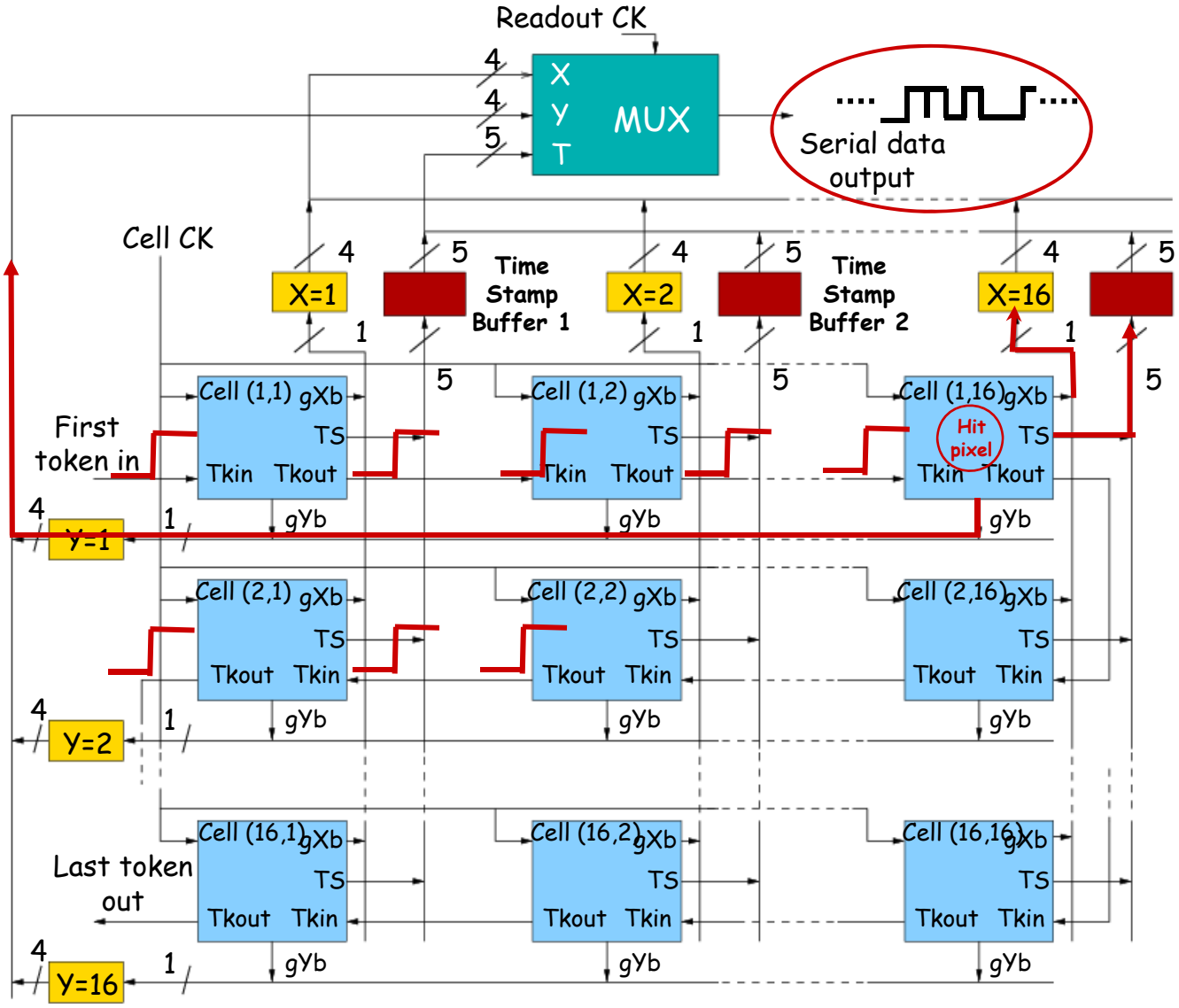


ILC DNW elementary cell



analog front-end
+
digital section
↓
164 transistors

Digital readout scheme



Readout phase:

- token is sent
- token scans the matrix and
- gets caught by the first hit pixel
- the pixel points to the X and Y registers at the periphery and
- sends off the time stamp register content
- data are serialized and token scans ahaed

The number of elements may be increased without changing the pixel logic (just larger X- and Y-registers and serializer will be required)

Power dissipation analysis

- Because low material budget is necessary, there is little room for cooling system ⟶ very low power operation
- Analog power: $P_{an,pix} \approx 5\mu W$/pixel (dissipated in the analog PA)
- Digital power: (power in the periphery neglected since it grows as the square root of the number of matrix cells)
  $P_{DC,pix} \approx 7$ nW/pixel (leakage currents of the digital blocks)
  $P_{dyn,pix} \approx 20$ nW/pixel (to charge the input capacitance of the time stamp register blocks during the detection phase)

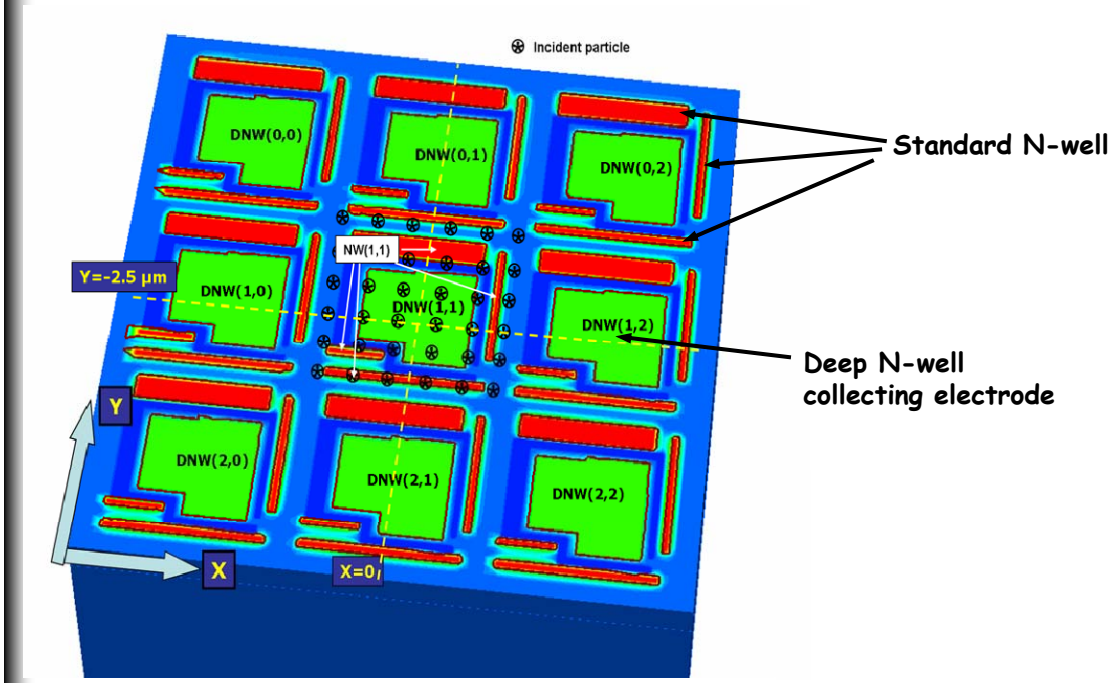
$$P_{tot} = P_{an,pix} \cdot N \cdot M \cdot \delta_P + P_{DC,pix} \cdot N \cdot M + P_{dyn,pix} \cdot N \cdot M \cdot \delta_P$$

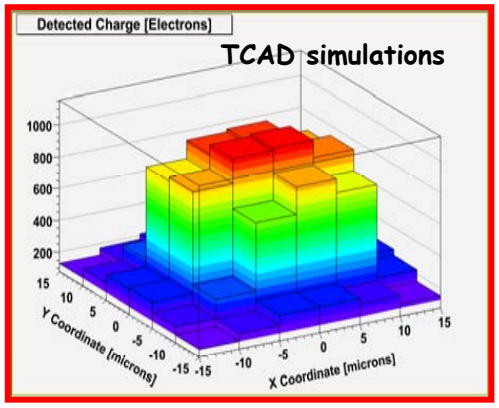
$\approx$ **15.5 W** | **13.6 W** | **1.9 W** | **0.05 W**

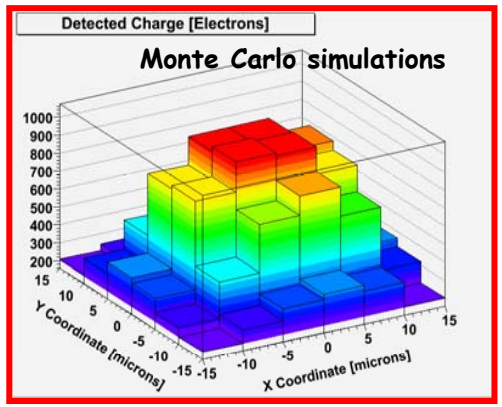
Assuming:
- 170000mm^2 total vertex detector area (pixel pitch of 25 μm);
- 1 Mpixel chips;
- δ_P=0.01 power supply duty cycle

N= number of cell per pixel
M= number of chip composing the detector

3D device simulations







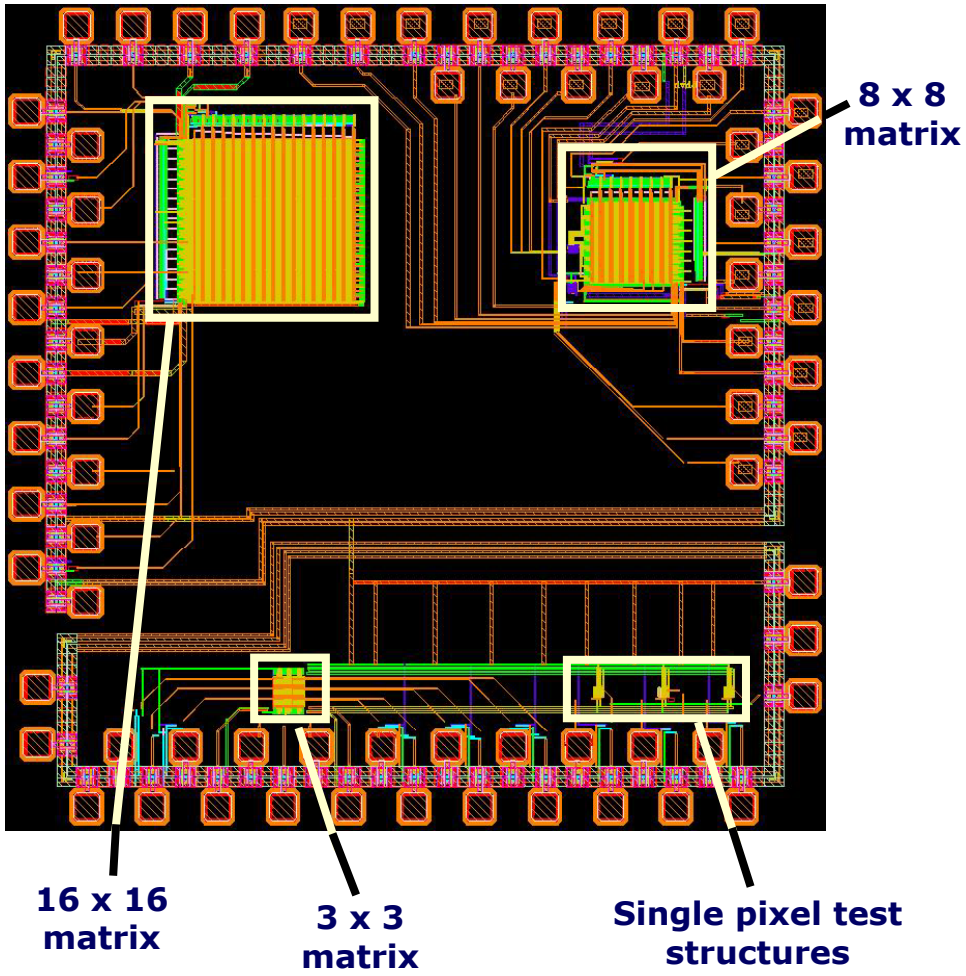
Charge collected by the central pixel in the 3×3 SDR0 matrix

Physical simulation performed by E. Pozzati - University of Pavia (Italy)

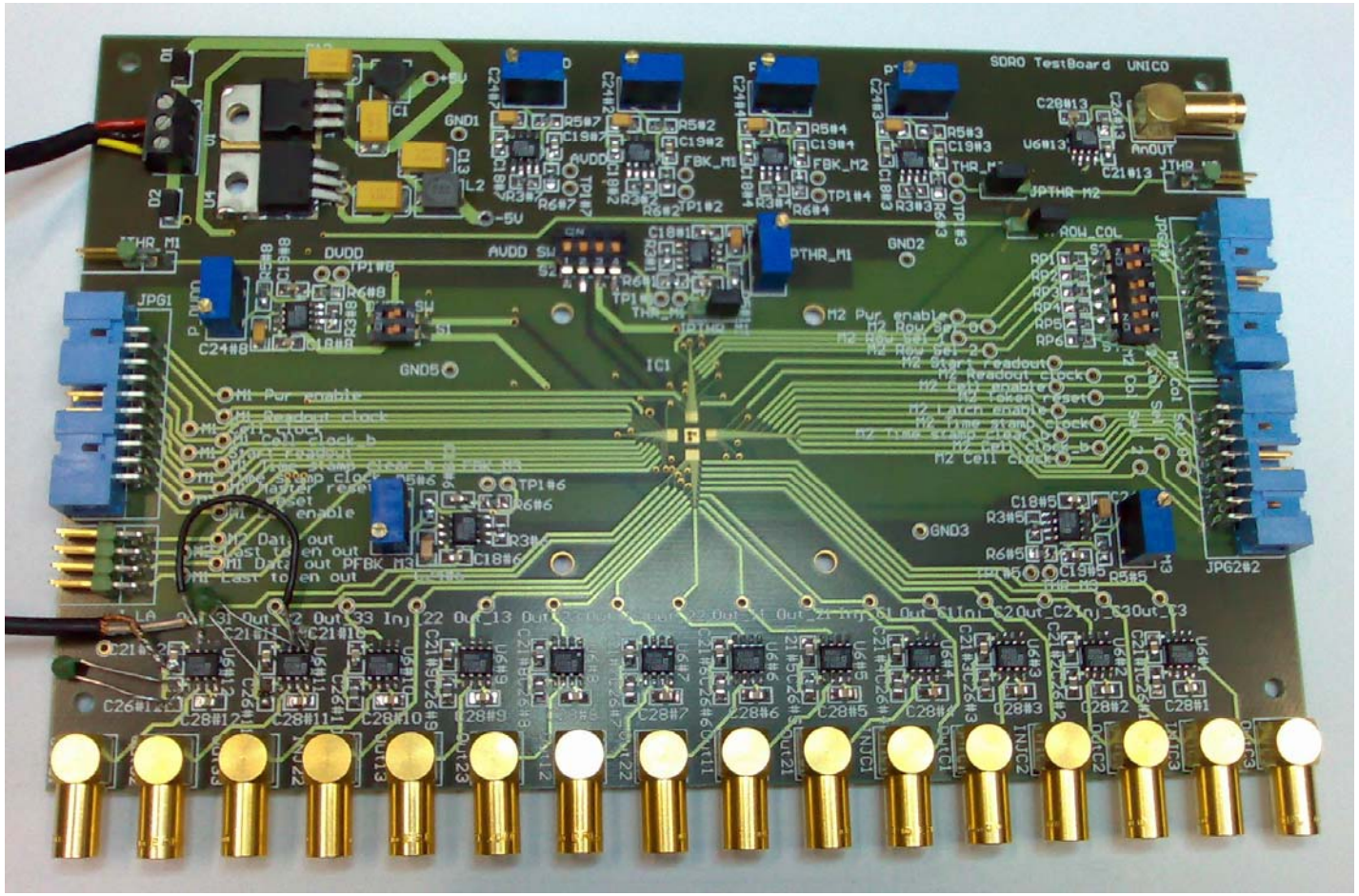
- The simulated structure (with TCAD) required a mesh with 165000 vertices. Because of the really long computation time only 36 simulations, each involving a different MIP collision point, have been performed
- MAPS operation is mainly diffusion driven → computing power required by TCAD may not be needed
- Monte Carlo code based on random walk developed (results of a collaboration with D. Christian – Fermilab)
- Activity presently focused on finely tuning a three-dimensional diffusion model for Monte Carlo simulations of MAPS by comparison with TCAD simulation results
- Advantage: dramatic reduction in computing time
- Next step: take advantage of fast Monte Carlo simulator to maximize detection efficiency through suitable layout choice

The demonstrator chip (SDR0)

- The chip includes:
  - a 16 by 16 MAPS matrix (25 μm pitch) with digital sparsified readout
  - an 8 by 8 MAPS matrix (25 μm pitch) with digital sparsified readout and selectable access to the output of the PA in each cell
  - a 3 by 3 MAPS matrix (25 μm pitch) with all of the PA output accessible at the same time
  - 3 standalone readout channels with different C_D (detector simulating capacitance)
- Delivered end of July 2007



The SDR0 test board



Credit: Fabio Risigo University of Insubria, Como (Italy)

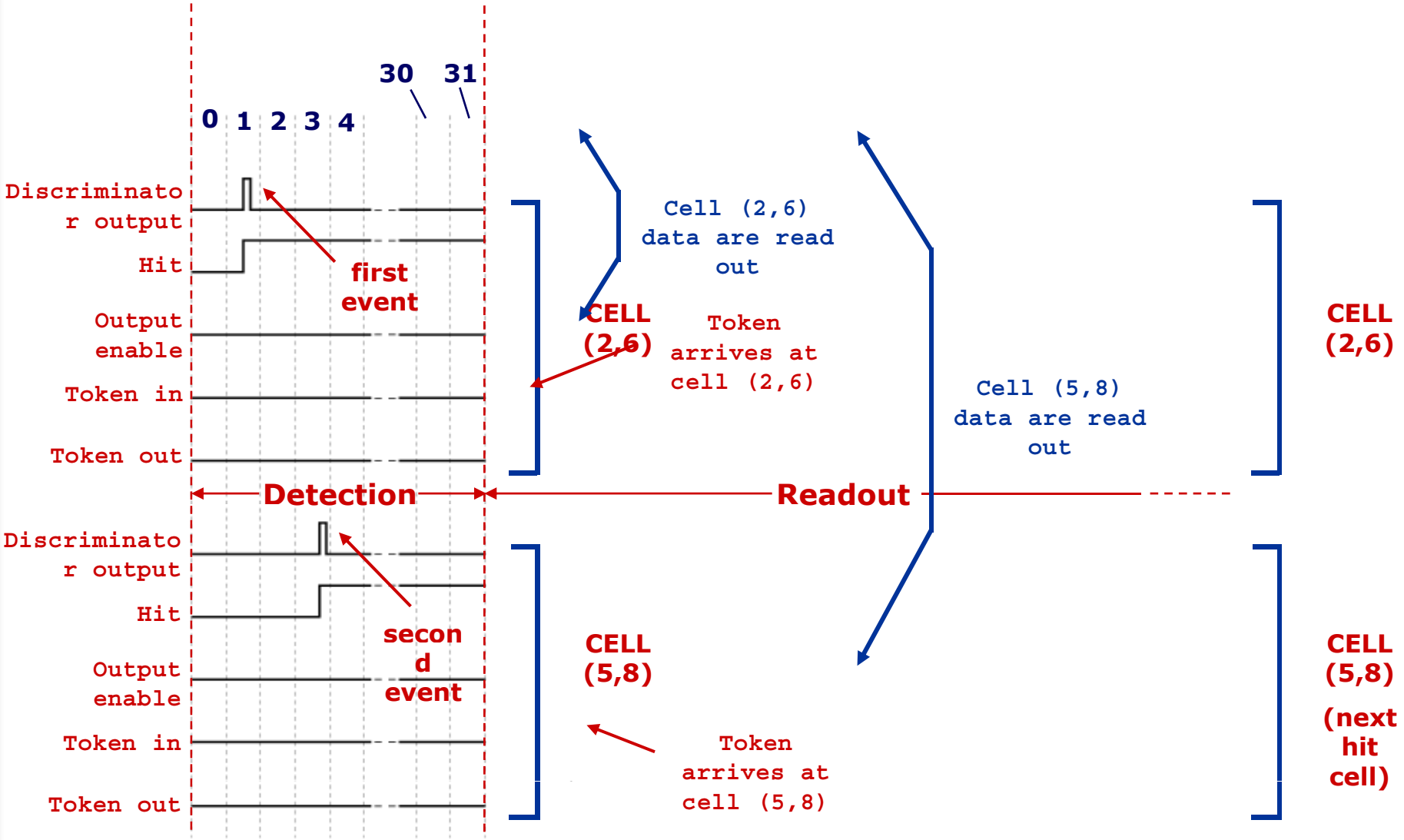
Test board designed by Marcin Jastrzab
University of Science and Technology, Cracow (Poland) and University of Insubria, Como (Italy)

Conclusions

- New DNW MAPS structures with optimized noise and threshold dispersion characteristics have been fabricated in the 130 nm, triple well STM CMOS technology
- Study of the charge collection efficiency and of charge spreading in the epi-layer is underway to assess their suitability for tracking and vertexing applications
  - Monte Carlo method will be used, besides Synopsys TCAD software package, in the design of the next generation prototype chips
- Characterization of a DNW MAPS demonstrator aimed at vertexing applications at the ILC is foregoing
- Plans for the future:
  - design of a 256 x 256 matrix for beam test
  - evaluation of more scaled technologies (90 nm CMOS)

Backup slides

Digital signal diagram



Parameter mismatch

- Identically designed components always show discrepancies in the values of electrical parameters. Fluctuations are induced by microscopic variations in physical quantities (e.g. oxide thickness, doping concentration, device dimensions).
- In CMOS transistors threshold voltage V_{th} and channel transconductance g_m are typically affected; for instance, the threshold voltage variation ΔV_{th} has a normal distribution with zero mean and a variance $\sigma^2(\Delta V_{th})$ inversely proportional to the device gate area:

$$\sigma^2_{\Delta Vth} = \frac{A^2_{vth}}{W \cdot L}$$

A_{vt} is a constant provided by the foundry and included in the device parameter set

- As a design rule, $\sigma_{\Delta Vth}$ can be reduced by acting on the device dimensions
- In the case of a charge processor with binary readout, parameter dispersion affects both the analog an the digital section

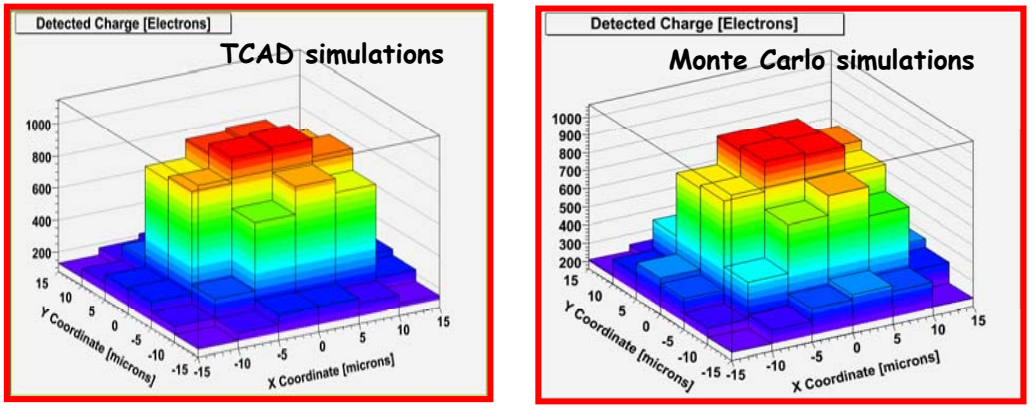
Design specifications for the ILC vertex detector

SDR0 prototype

Hit rate [particles/bco/mm^2]	Detector pitch [μm]					
	5	10	15	20	25	30
0.03	99.99%	99.97%	99.84%	99.52%	98.87%	97.76%
0.06	99.99%	99.87%	99.39%	98.20%	95.91%	92.26%
0.09	99.98%	99.72%	98.69%	96.20%	91.70%	84.93%
0.12	99.97%	99.52%	97.76%	93.68%	86.66%	76.75%
0.15	99.95%	99.26%	96.62%	90.75%	81.13%	68.36%

Detection efficiency for different sensor pitch and hit rate values

3D device simulations



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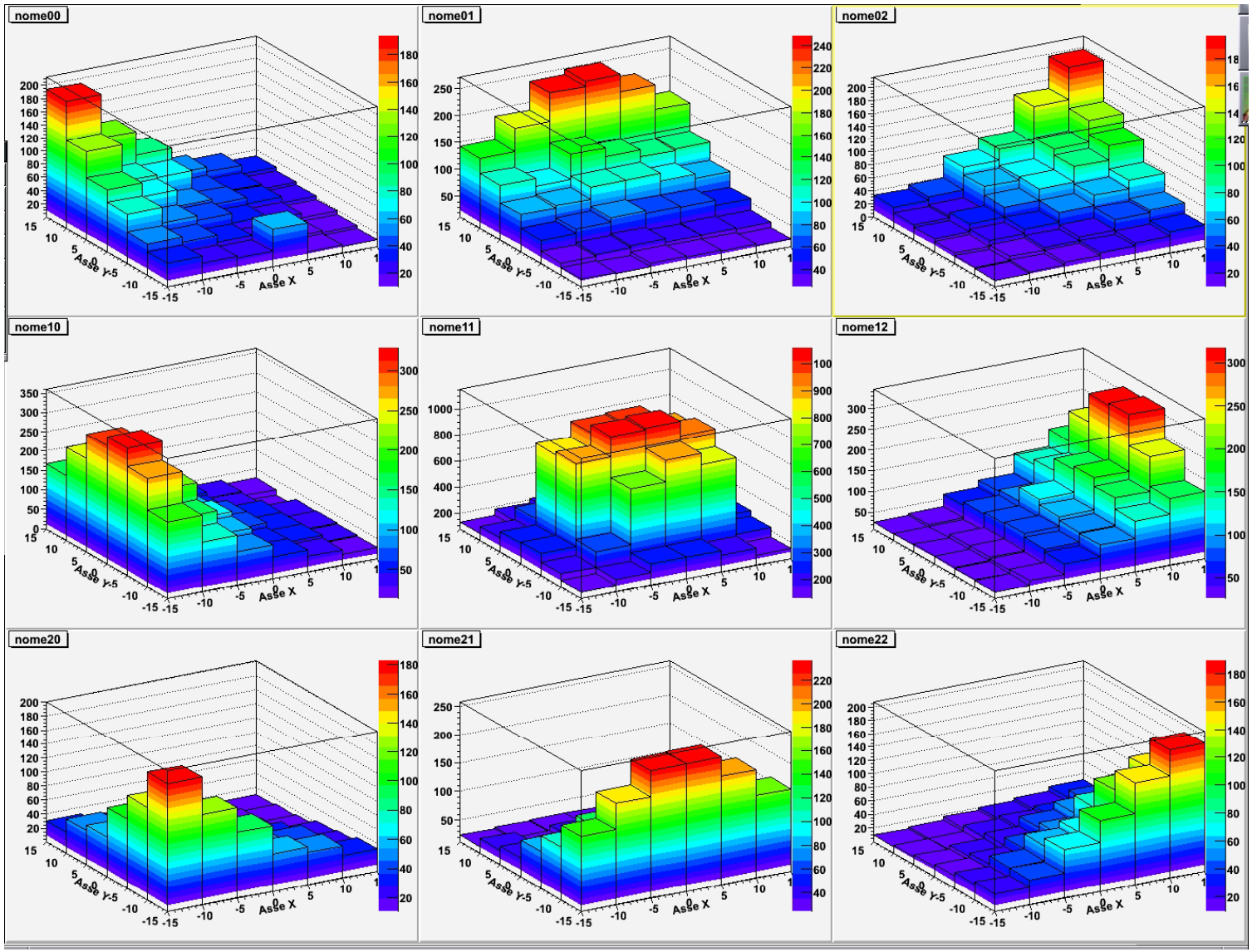
Physical simulation performed by E. Pozzati - University of Pavia (Italy)

▪E. Pozzati, M. Manghisoni, L. Ratti, V. Re, V. Speziali, G. Traversi: "*MAPS in 130nm triple-well CMOS technology for HEP applications*" Topical Workshop on Electronics for Particle Physics, TWEPP 2007, Sept. 3-5, Prague, Czech Republic

Simulations with Monte Carlo code have been performed with the following assumption:

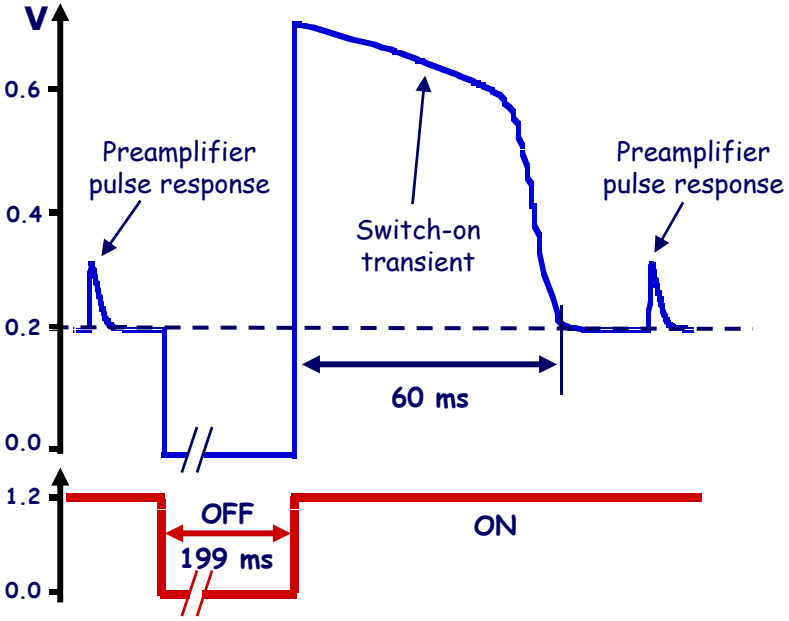
- 80 e-h/μm are generated uniformly along a linear track which is normal to the device surface and feature a gaussian distribution in the plane normal to the track itself (σ=0.5 μm).
- The SDR0 simulation volume is 85x85x80 μm^3.
- Electron lifetime, according to the Scharfetter model is about 9.2 μs at the considered doping levels (10^{15} cm^{-3}) and sets a limit to the random walk duration for each carrier.

3D device simulations



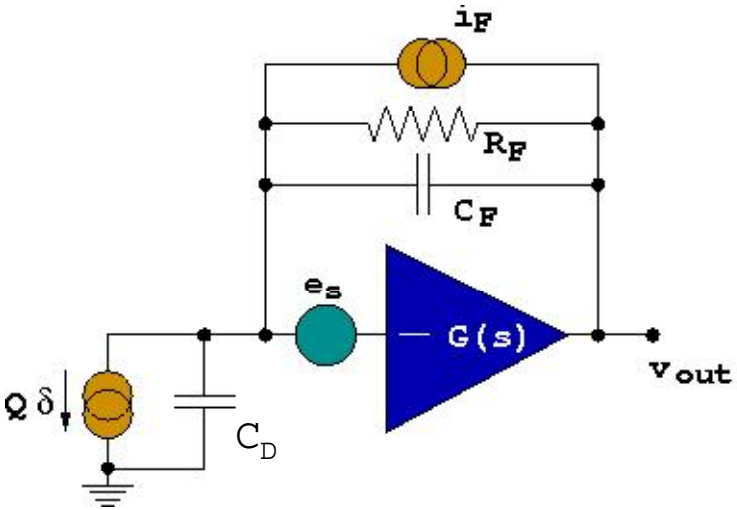
Power cycling simulations

- Power cycling can be used to reduce average dissipated power by switching the chip off when no events are expected
- Example:
  - ✓ILC bunch structure: ~330 ns spacing, ~3000 bunches, 5Hz pulse
- The analog section in the elementary cell can be switched off during the intertrain interval in order to save power (analog power is supposed to be predominant over digital)



- Based on circuit simulations, power cycling with at least **1% duty-cycle** seems feasible

Noise performance analysis



- For the forward stage of the charge preamplifier, a single pole transfer function can be reasonably assumed:

$$G(s) = \frac{G_0}{1 + \frac{s}{\omega_0}}$$

$$\begin{cases} e_s = \sqrt{S_W + \frac{A_F}{f}} \\ i_F = S_P \end{cases}$$

e_s: Input referred series noise of the charge PA

i_F: Parallel noise contribution in the feedback network

- Parallel noise contribution

$$ENC_{i_F} \approx \sqrt{S_P \cdot R_F \cdot C_F}$$

$C_T = C_D + C_{in} + C_F$

C_{in} is the charge PA input capacitance

- Series white noise contribution

$$ENC_{e_s, S_W} \approx \sqrt{S_W \cdot C_T \cdot C_F \frac{GBP}{2}}$$

- Series 1/f noise contribution

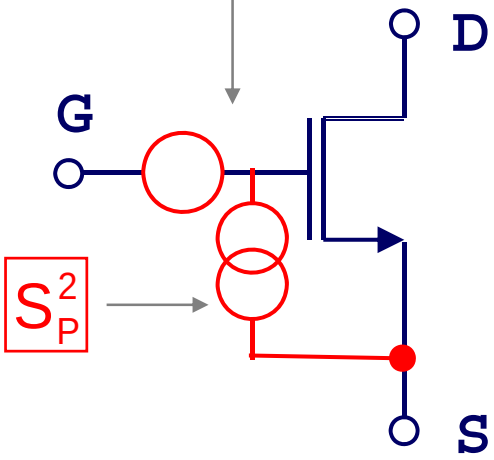
$$ENC_{e_{s,1/f}} \to \infty$$

The mean square value of the noise due to 1/f contribution slowly diverges. Actually, divergence is so slow that this contribution is not supposed to affect significantly the noise properties of the analog front-end (in field operation times).

Noise in CMOS transistors

- Noise in the drain current of a MOSFET can be represented through an equivalent noise voltage source in series with the device gate

$$S_e^2(f) = S_W^2 + S_{1/f}^2(f)$$



S_W - white noise

- channel thermal noise (main contribution in the considered operating conditions)

$$S_{ch}^2 = \frac{4k_B T\Gamma}{g_m}$$

  - k_B Boltzmann's constant
  - T absolute temperature
  - Γ channel thermal noise coefficient

- contributions from parasitic resistances

$S_{1/f}$ - 1/f noise

- technology dependent contribution

$$S_{1/f}^2(f) = \frac{k_f}{C_{OX} W L f^{\alpha_f}}$$

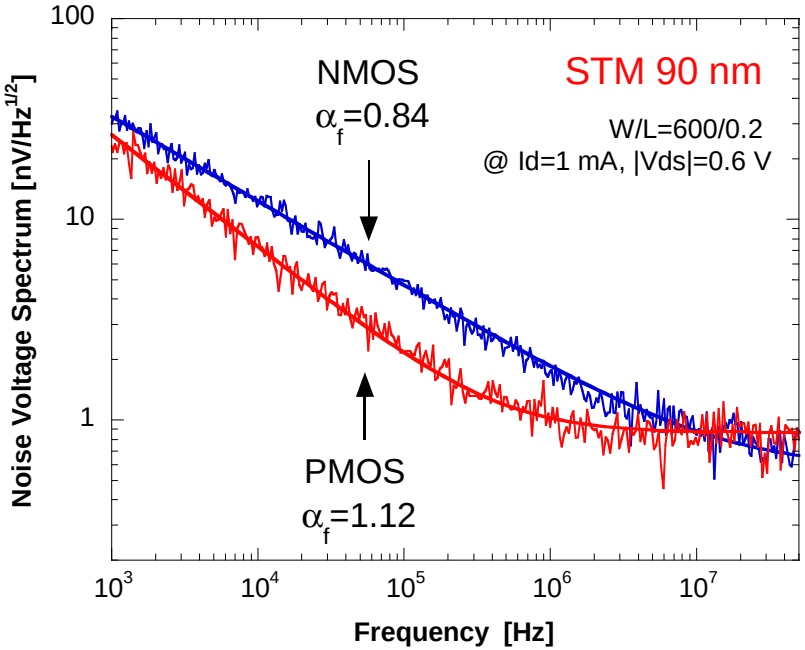
  - k_f 1/f noise parameter
  - α_f 1/f noise slope-related coefficient

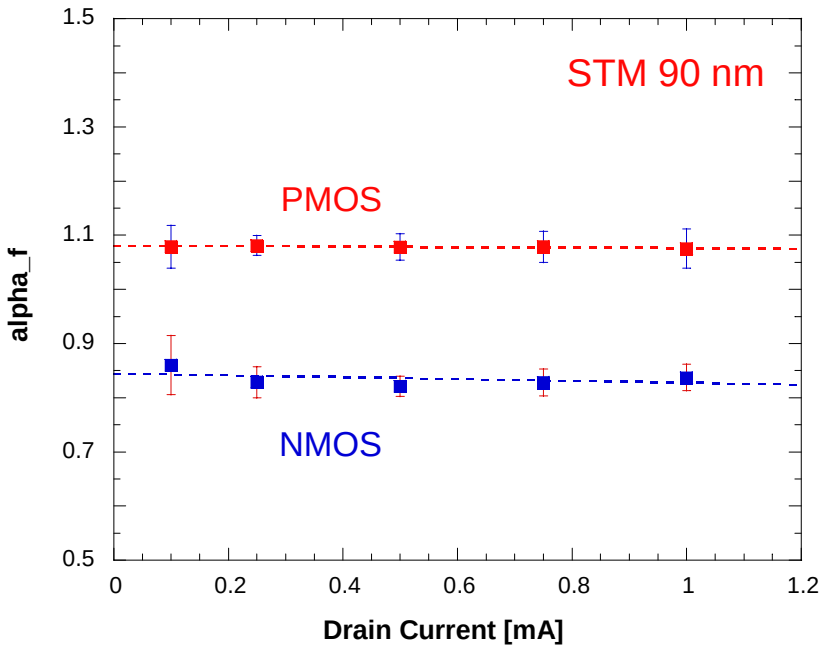
$$S_P^2 = 2qI_G$$

S_P – shot noise in the gate leakage current

$$S_P^2 = 2qI_G$$

Flicker noise – $S_{1/f}(f)$





- Slope α_f of the 1/f noise term is significantly smaller than 1 in NMOS transistors and larger than 1 in PMOS devices
- In the examined operating region, α_f does not exhibit any clear dependence on the drain current or on the channel length
- α_f between 1 and 1.3 for PMOS devices, between 0.8 and 1 for NMOS devices

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[6]Università degli Studi di Bergamo,

[7]INFN Trieste and Università degli Studi di Trieste

[8]INFN Bologna and Università degli Studi di Bologna

[9]INFN Torino and Università degli Studi di Torino

[10]Università degli Studi di Trento and INFN Padova

4 Workpackages:

1 MAPS and Front End Electronics

2 Detectors on high-resistivity Silicon

3 Trigger / DAQ

4 Mechanics/Integration/Test-Beam