Timing measurement ASIC for LGAD pixel sensors

ABDERRAHMANE GHIMOUZ

10th Sep. 2024

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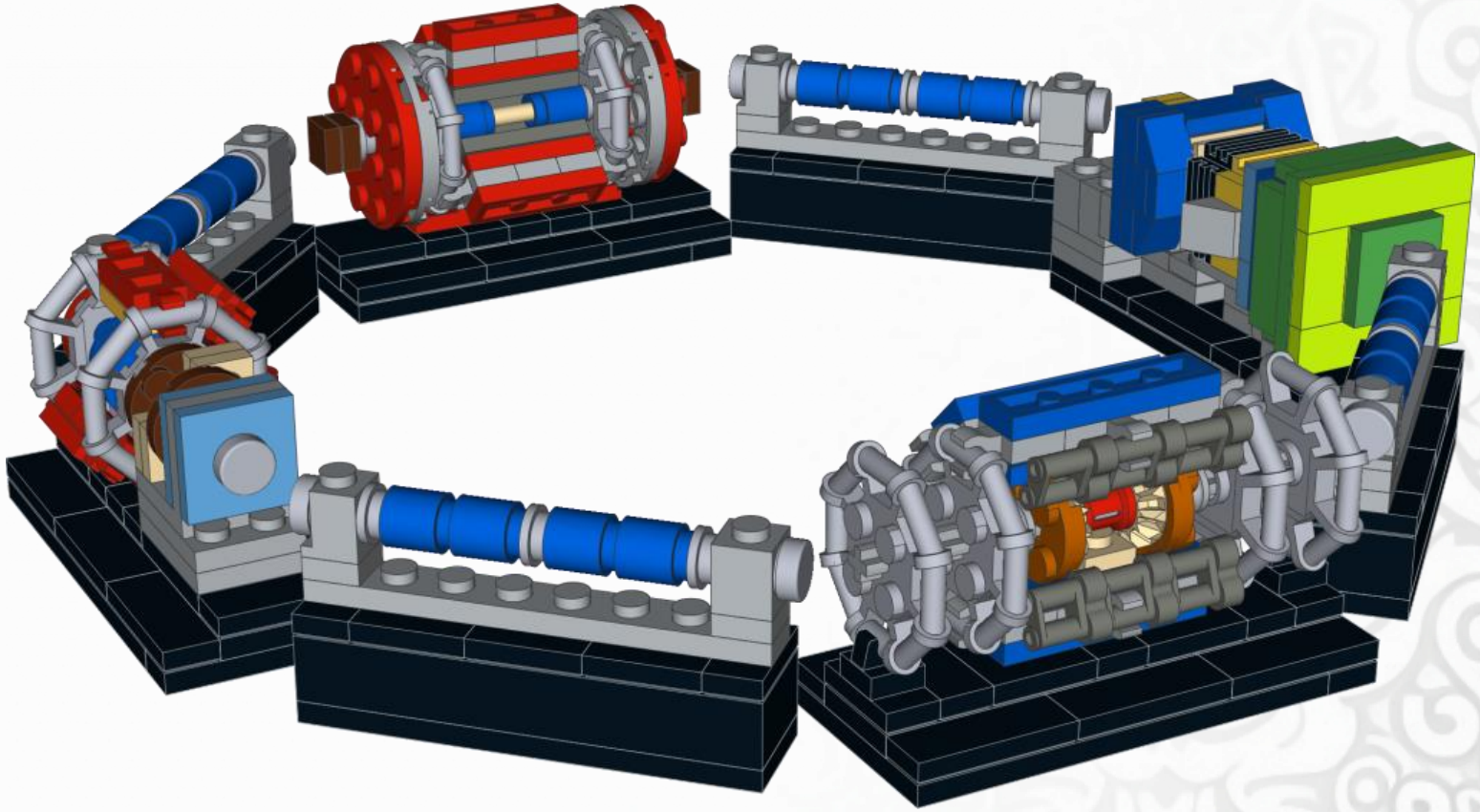
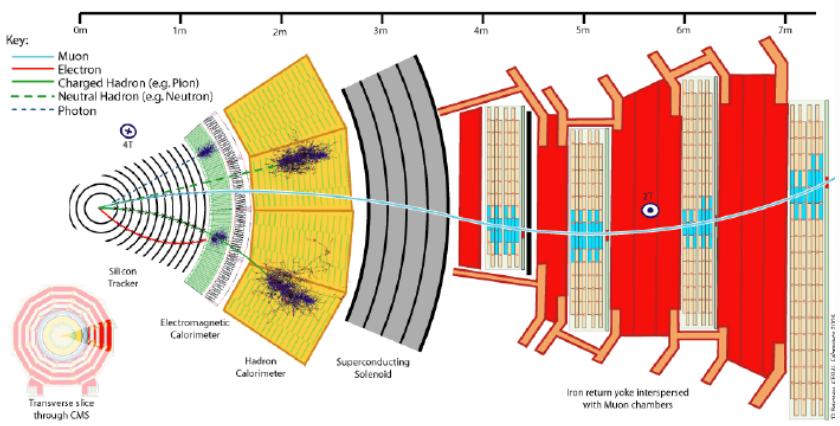
Context of the project (aim)



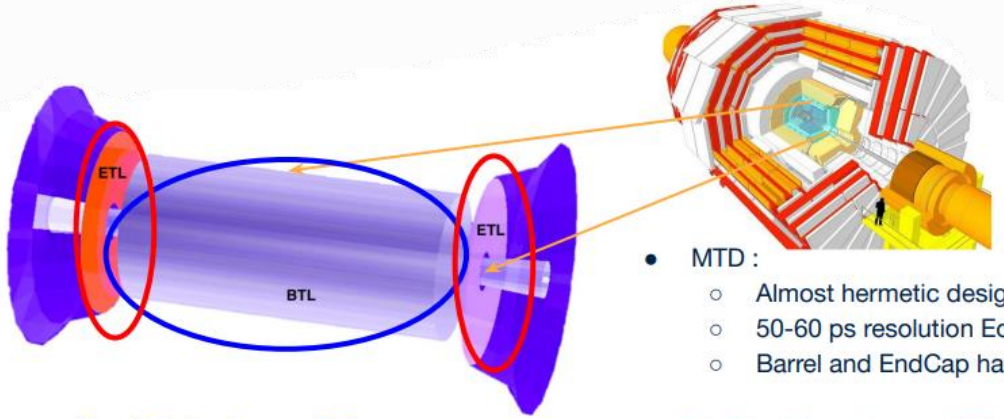
The Phase 2 upgrade of the CMS detector enhances its tracking, calorimetry, and data processing to handle increased luminosity and data rates at the HL-LHC.

Need for timing



The need for timing measurement with the CMS detector for the HL-LHC upgrade:

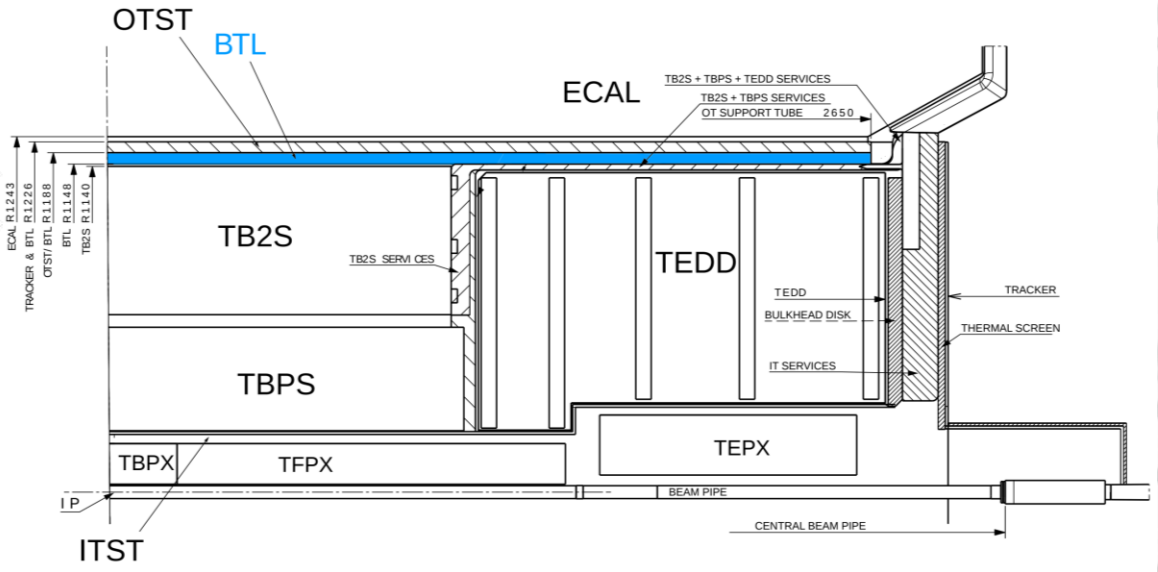
- **Pile-Up Mitigation**: achieves 30-40 picoseconds resolution to separate up to 200 overlapping collisions.
- **Particle Identification**: utilizes precise timing to distinguish particles with speed differences as small as 0.1%.
- **New Physics Sensitivity**: improves detection capability for rare events and particles beyond the standard model.



- MTD :
  - Almost hermetic design, $|\eta| < 3.0$
  - 50-60 ps resolution EoL
  - Barrel and EndCap have different needs

- Barrel Timing Layer - BTL :
  - Sensors: LYSO+SiPM
  - Inner radius: 1148 mm - 40mm thick
  - Length: ± 2.6 m
  - Fluence at 3000 fb^{-1} ~1.7x10^{14} n$_{eq}$/cm^2

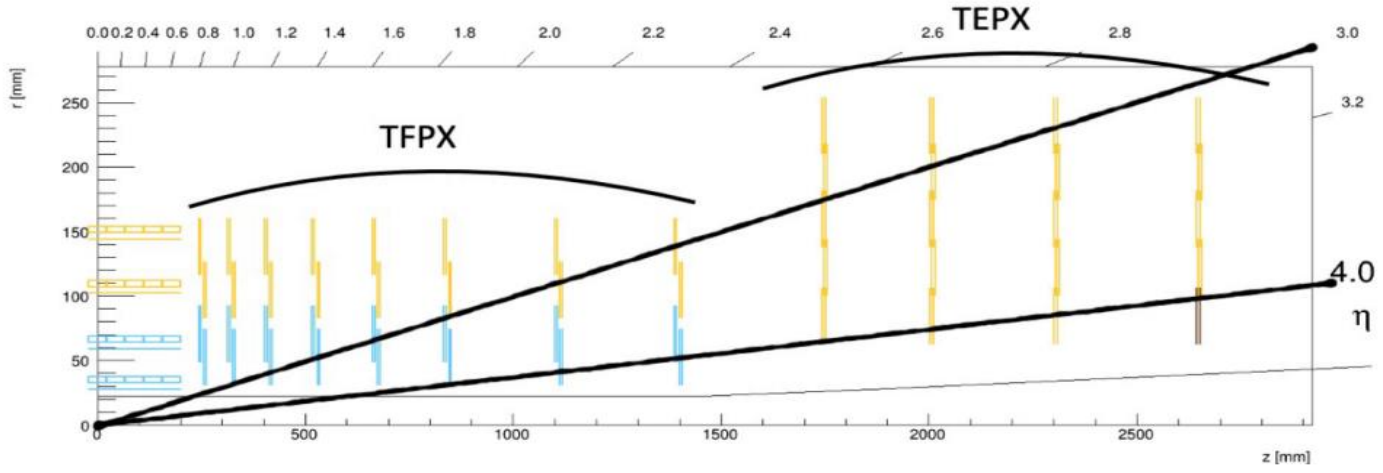
- EndCap Timing Layer - ETL :
  - Sensors: LGAD
  - Radius: 315 mm < r < 1200 mm
  - z-position 3.0 m - 45 mm thick
  - Fluence at 3000 fb^{-1} ~ 1.6x10^{15}n$_{eq}$/cm^2



Credit : CMS CERN Collaboration

Need for timing

How to improve further ?



- CMS 'Phase 2' timing covers region up to $|\eta| = 3$ (BTL: LYSO + SiPM, ETL LGAD pads)
- possible extension to $|\eta| = 4$ in 'Phase 3': replacing 1 or 2 TEPX pixel disks with LGAD pixels

Credit : Dr. Wolfram Erdmann

TEPX (Tracker Endcap Pixel)

- **Disks**: 4 per endcap (8 total)
- **Pixel Size**: 25 x 100 µm
- **Radial Coverage**: 60–300 mm
- **Longitudinal Position**: Up to ~2.7 m from the interaction point
- **Sensor**: Silicon pixel sensors
- **Readout**: RD53 chip, up to 750 Mb/s per module
- **Radiation Tolerance**: Up to 1.5 x 10^{16} neq/cm², 1 Grad

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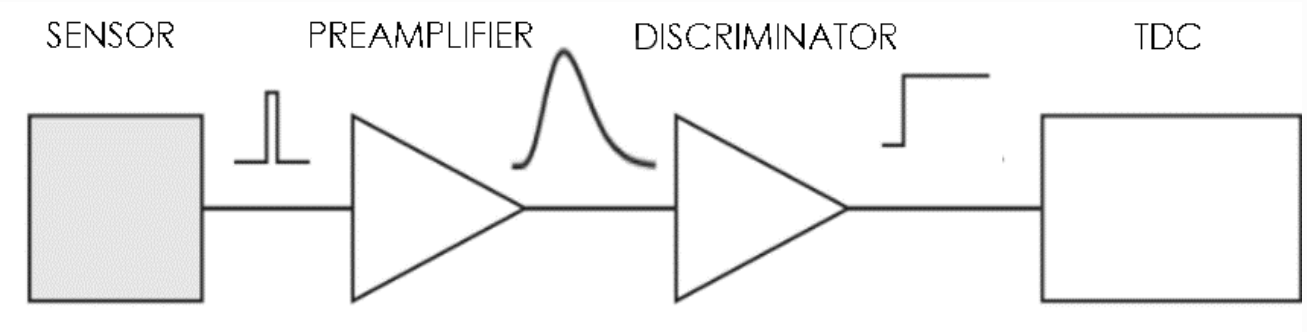
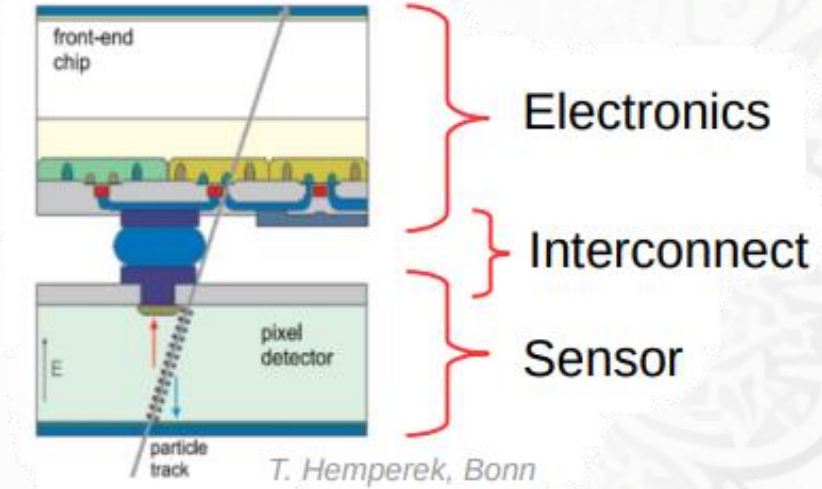
Context of the R&D

To **design** a readout **ASIC** targeting a future **CMS** upgrade. It should be capable of operating with **pixel** detectors based on **LGAD** technology. It is designed in a **28 nm CMOS** technology, for **timing** measurements.

Timing equation





Time resolution of a timing measurement Front End Electronics (FEE)

$$\sigma_t^2 = \underbrace{\sigma^2_{\text{Landau}} + \sigma^2_{\text{Distortion}}}_{\text{To understand (characterization)}} + \underbrace{\sigma^2_{\text{Timewalk}} + \sigma^2_{\text{TDC}} + \sigma^2_{\text{Jitter}}}_{\text{To model and optimize (FEE architecture)}}$$

R&D details

Part 1
LGAD Sensor

- Sensor performance;
- Sensor characterization;
- System requirements.

Part 2
Behavioral modeling

- Model based design using MATLAB® Simulink®;
- Sensor model;
- Architecture of the system;
- Performance of each building block.

Part 3
28nm Technology

- Technology performance;
- Design methodology;
- 28nm CERN Community.

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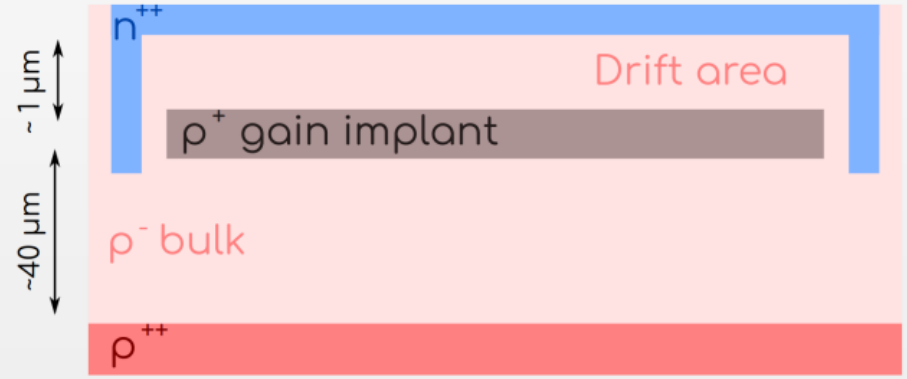
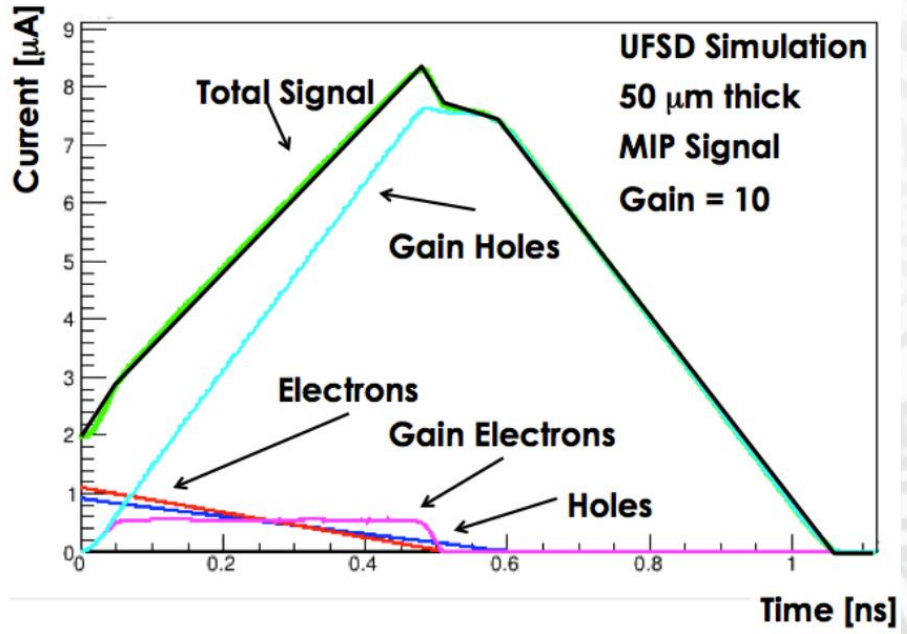
Part 1
LGAD Sensor

Concept of LGAD sensors

- Very thin active thickness ~40 µm.
- Gain layer provides gain ~10.
- Time resolution for 1 MIP ~10-30 ps.



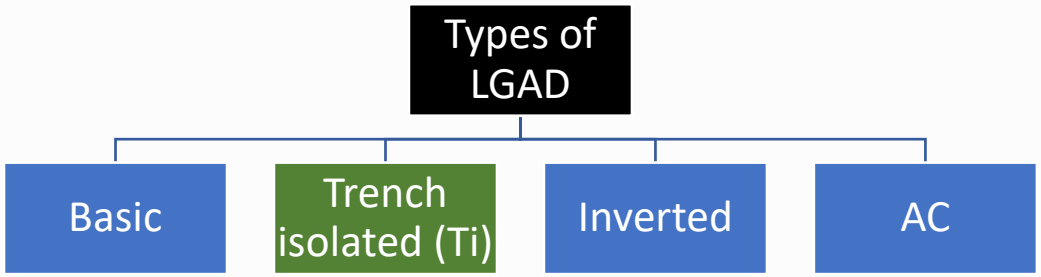


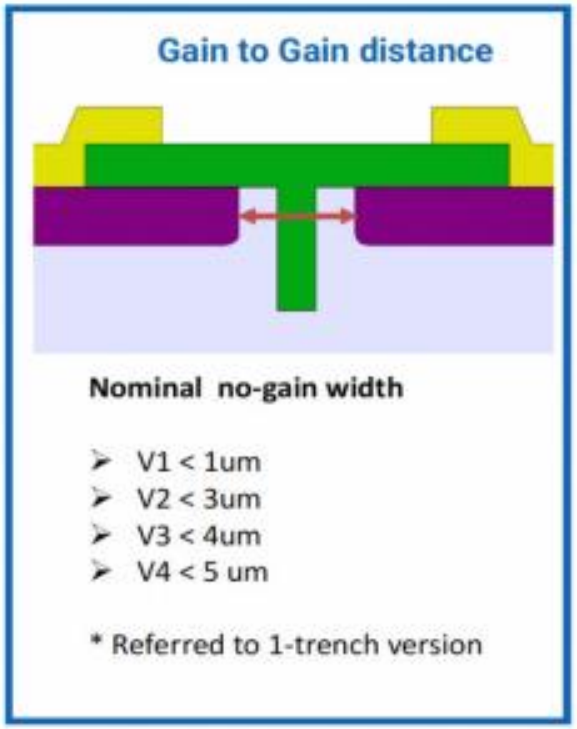
Credit : Matias Senger

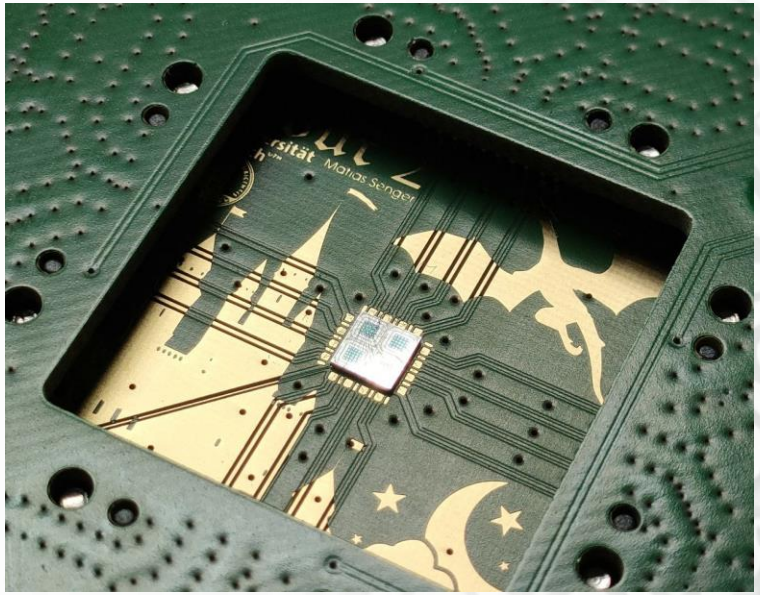
Why use the Low Gain Avalanche Diodes ?

Part 1
LGAD Sensor

Type of LGAD sensors : Ti-LGAD







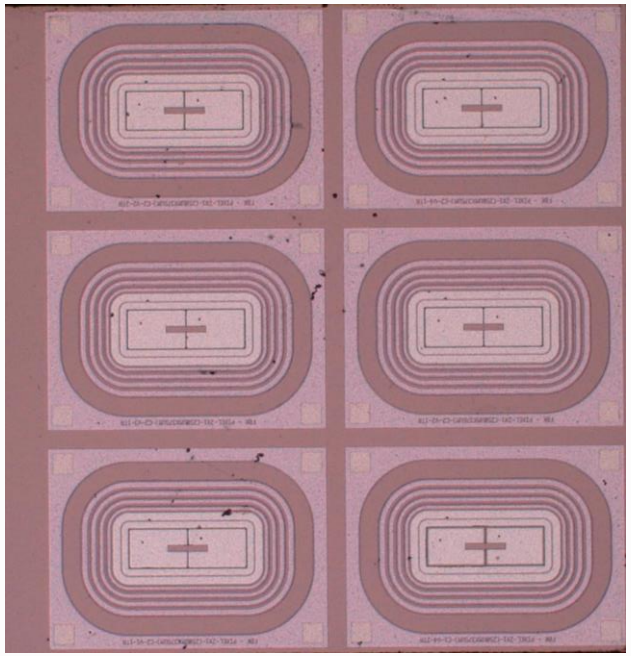
Credit : Matias Senger

Collaboration with the University of Zurich

Part 1
LGAD Sensor

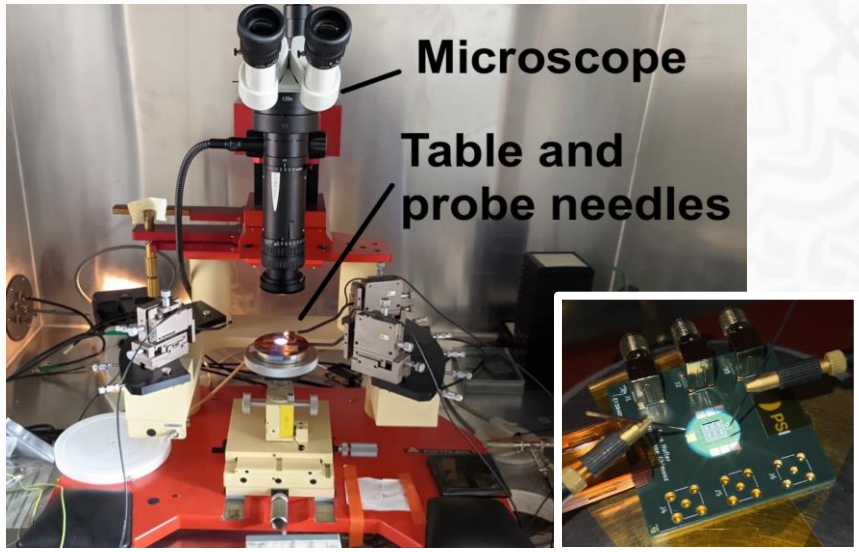
Characterization of Ti-LGAD sensors (setup)

ETHZ Student project (Fynn Hufler)

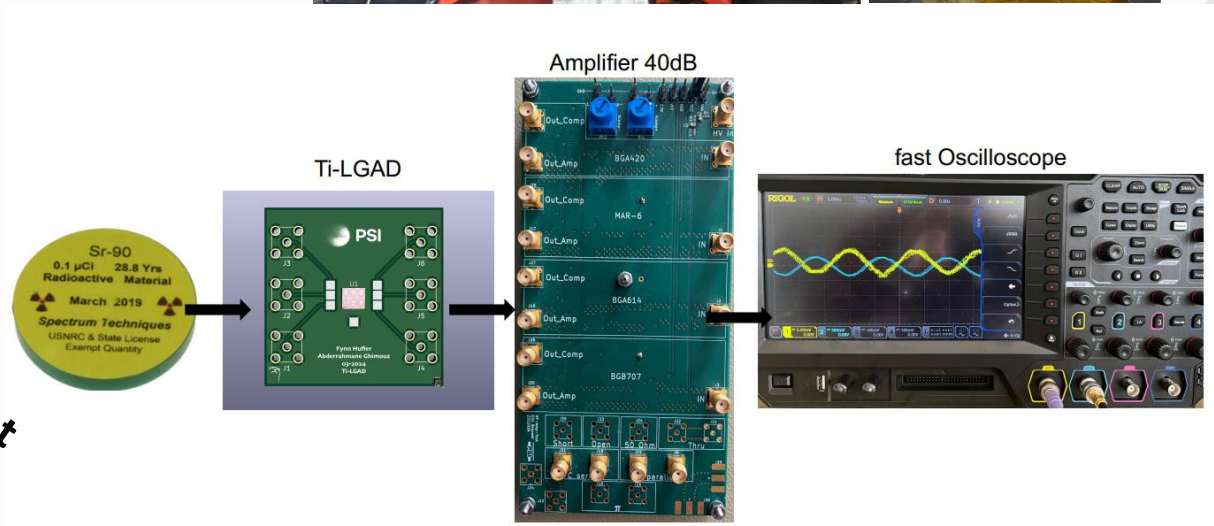


Ti-LGAD sensor sample

Capacitance measurement



Signal measurement



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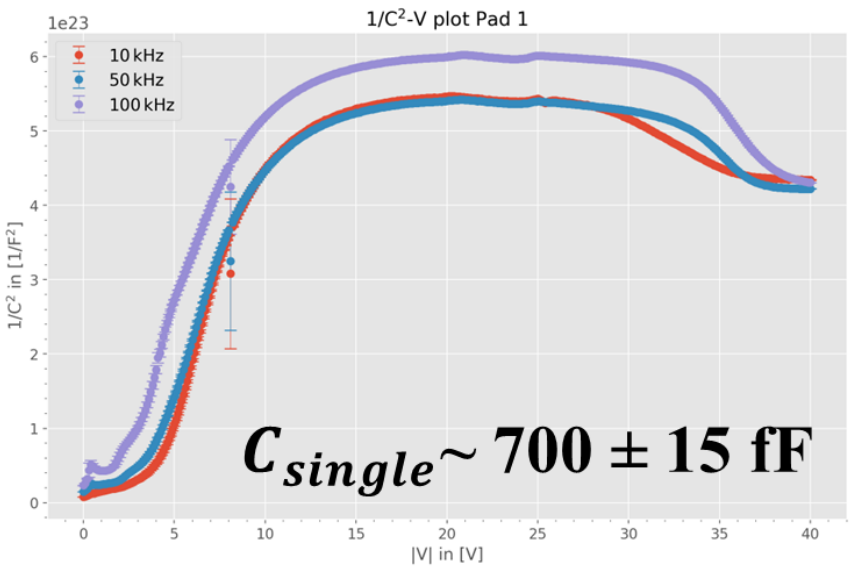
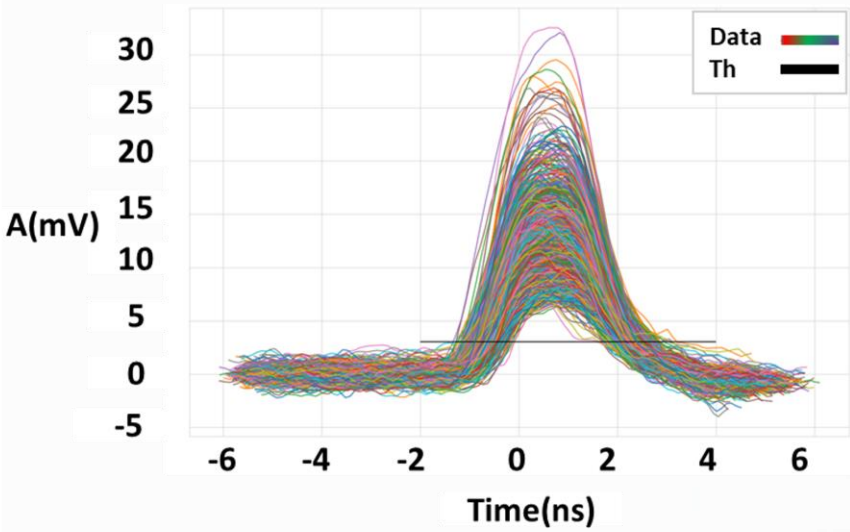
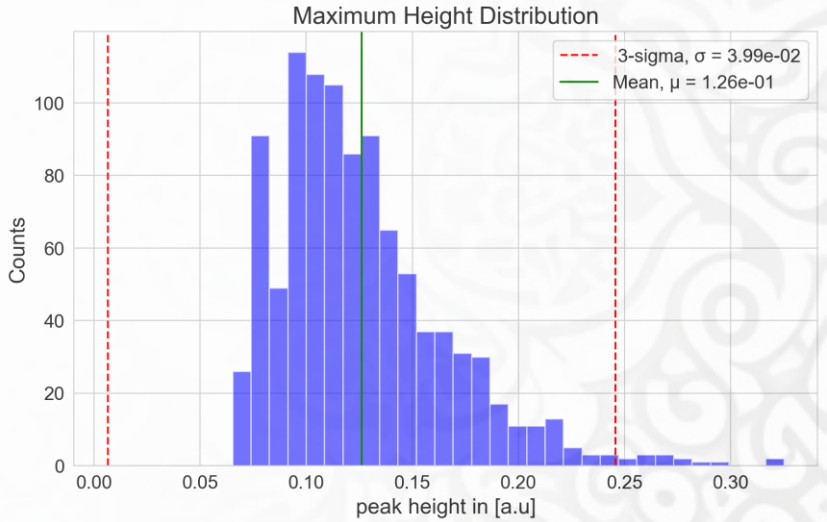
Part 1
LGAD Sensor

Characterization of Ti-LGAD sensors (results)

ETHZ Student project (Fynn Hufler)







- ✓ Capacitance measurements of Ti-LGAD sensors showed **uniform values** with stable performance across **conditions** and mean capacitance for single pixels between **0.63 - 0.70 pF.**
- ✓ The expected **features** of the generated signals were **confirmed**.

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Part 1
LGAD Sensor

System requirement

Property	Value
Pixel size	100 x 100 μm^2 / 200 x 200u μm^2
Input capacitance	~ 1 pF (including parasitic)
Time res RMS	30 ps
Max latency	500 KHz to 1 MHZ per pixel
Max dead time	< 250 ns
Total power density	1 W/cm2
Threshold level	1000 e^-
Dynamic range (Q)	Equivalent 1000 e^- to 100 Ke^-
Pixel rate at hottest pixel	50 KHz

State of the art study to propose different solutions

- Defining the specifications of the preamplifier;
- Defining the technique to measure time;
- Testing the resolution limit of the selected solutions;
- Integrating error corrections;

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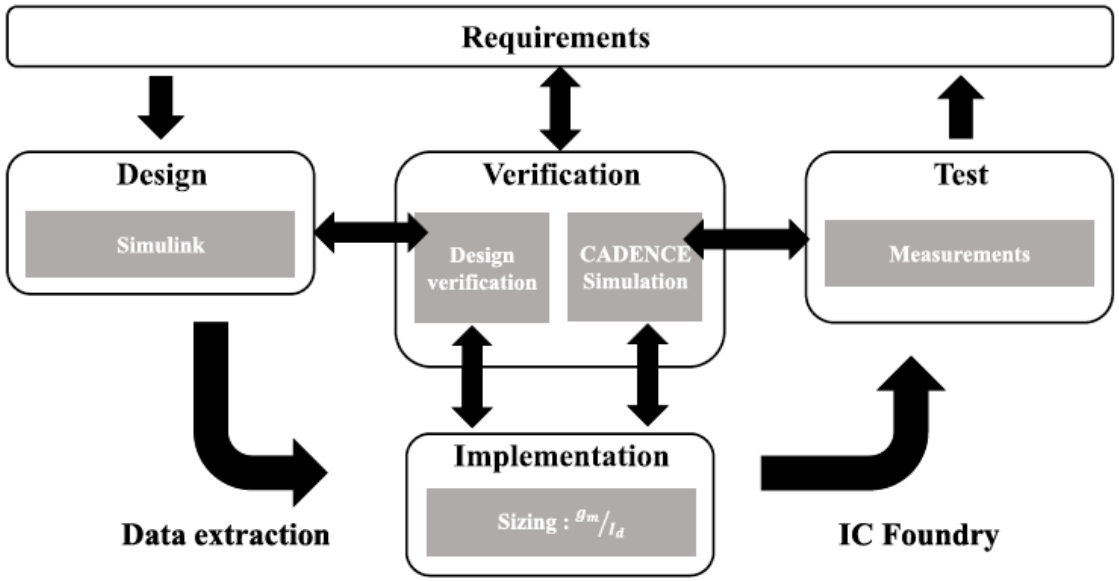
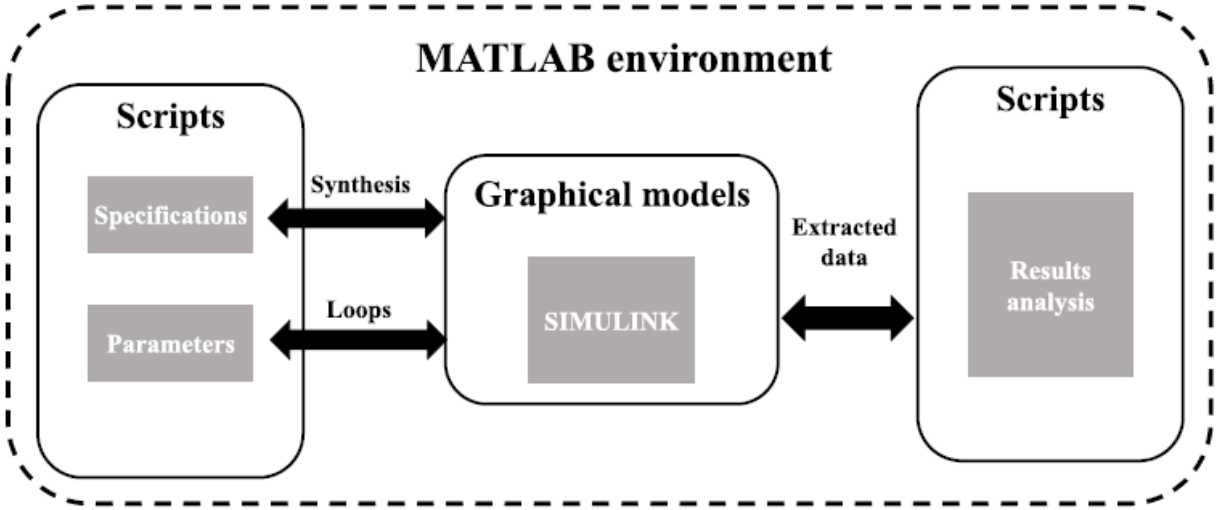
Part 2
Behavioral modeling

Model Base design concept





Defining the best parameters to achieve the desired specifications with efficiency using the model based design approach: implementation in MATLAB® for ASIC design.

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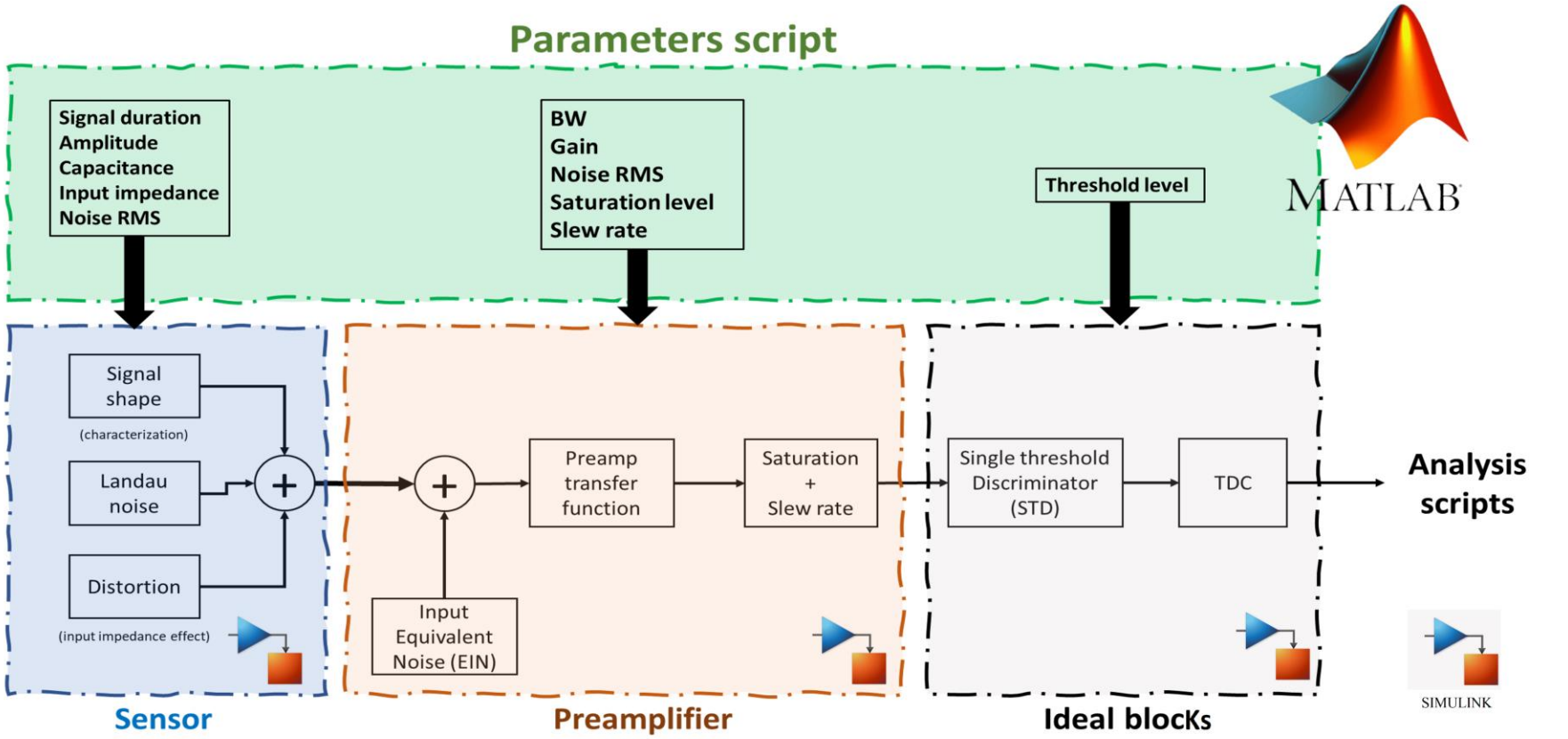
Part 2
Behavioral modeling

Implementation in MATLAB® SIMULINK ®



In this first step, we focus on studying the effect of the key parameters of the preamplifier on the timing resolution (few Ke^-signals) using an ideal Discriminator and TDC. The integration between the sensor and the preamp is modeled as well.

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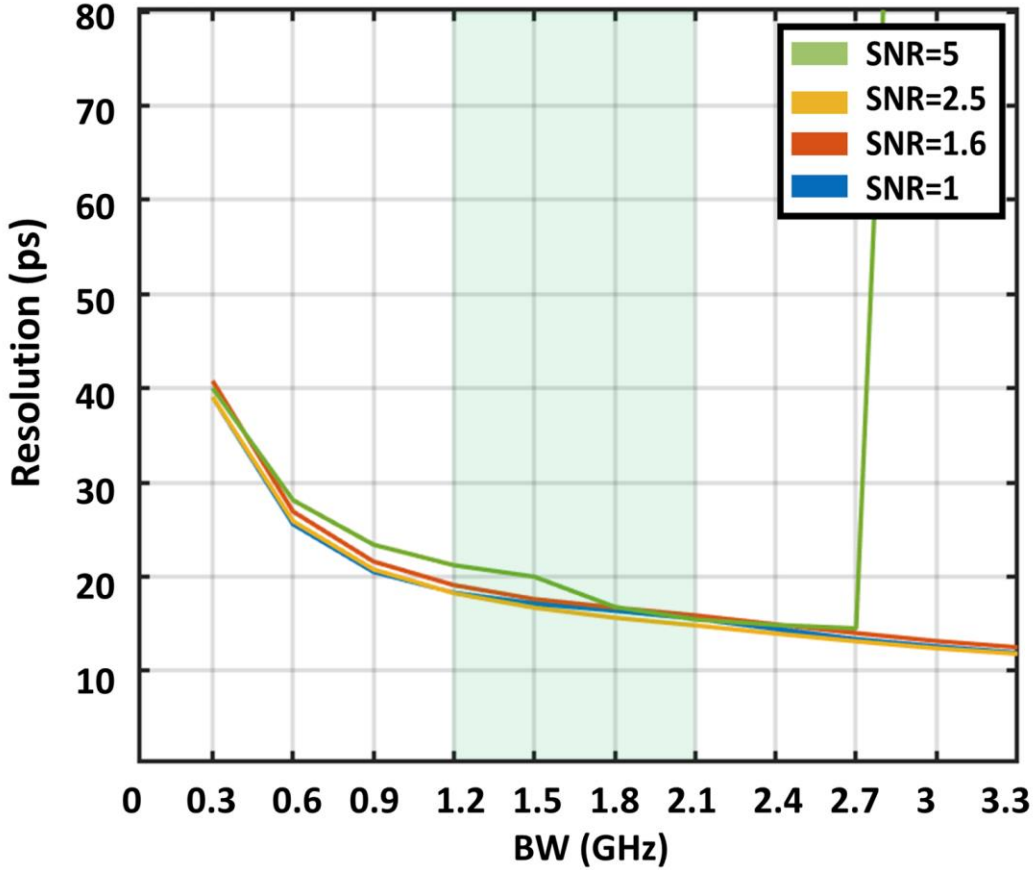
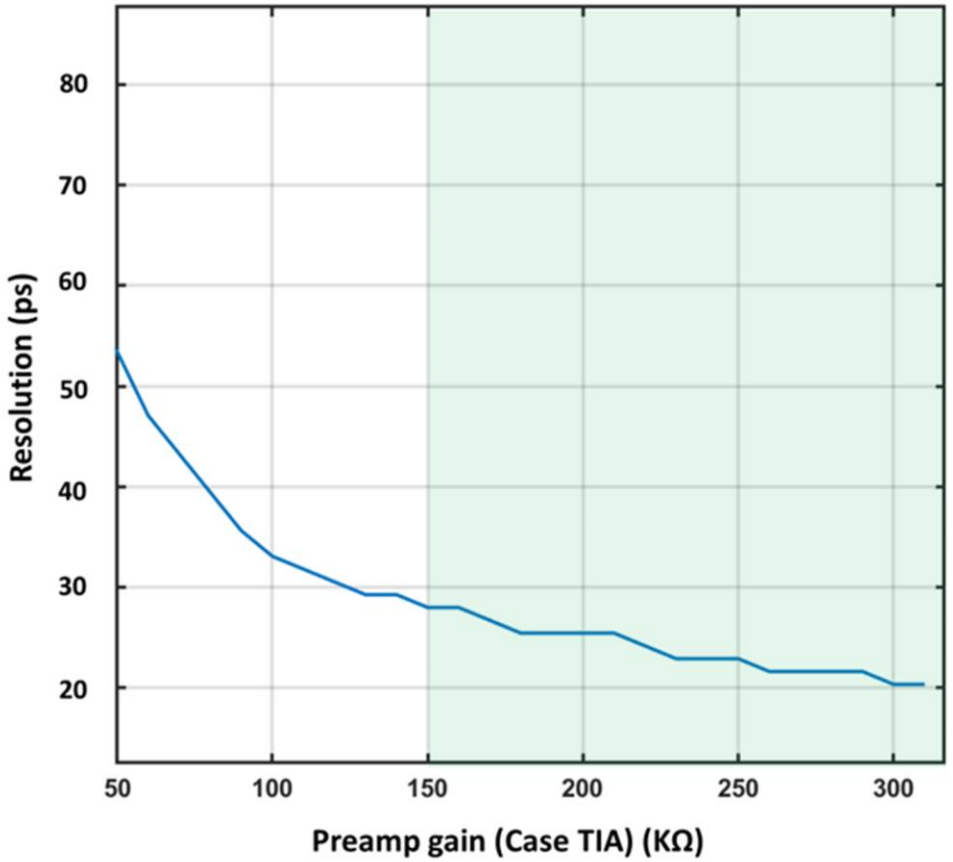
Part 2
Behavioral modeling

Results of the modeling of sensor + preamp stage



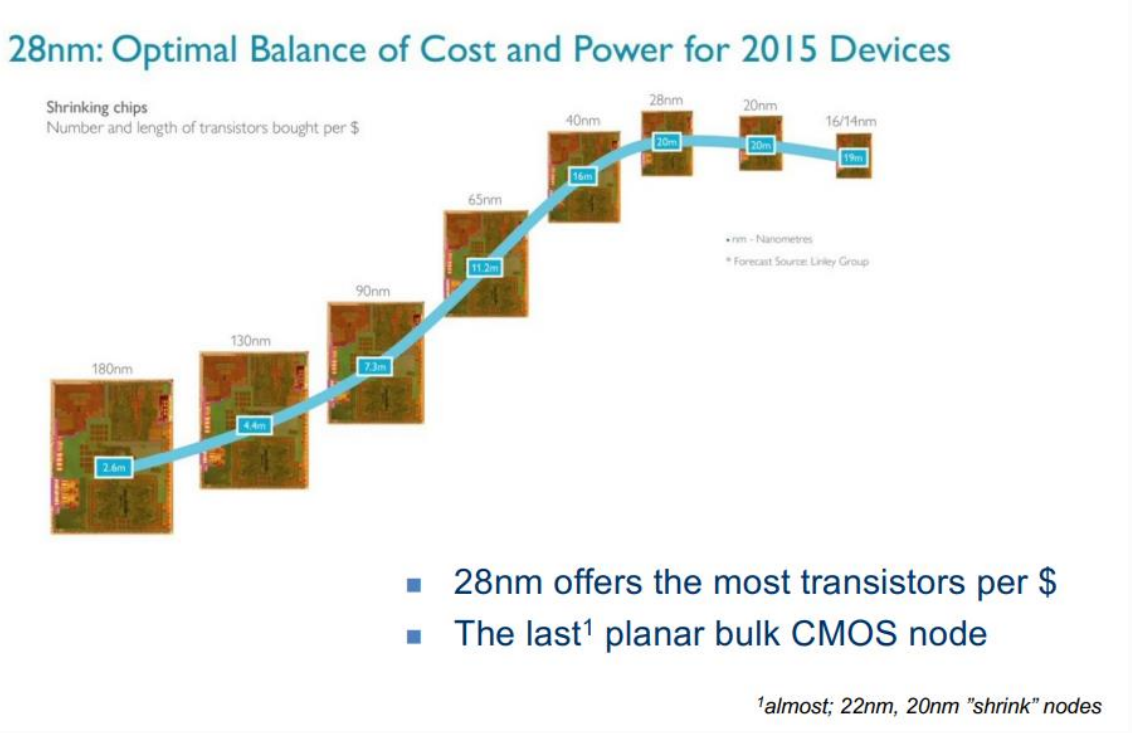


Ghimouz, A. (2024). R&D of a timing measurement ASIC for possible HL-LHC upgrade. *Nuclear Instruments and Methods in Physics Research Section a Accelerators Spectrometers Detectors and Associated Equipment*, 169802. https://doi.org/10.1016/j.nima.2024.169802

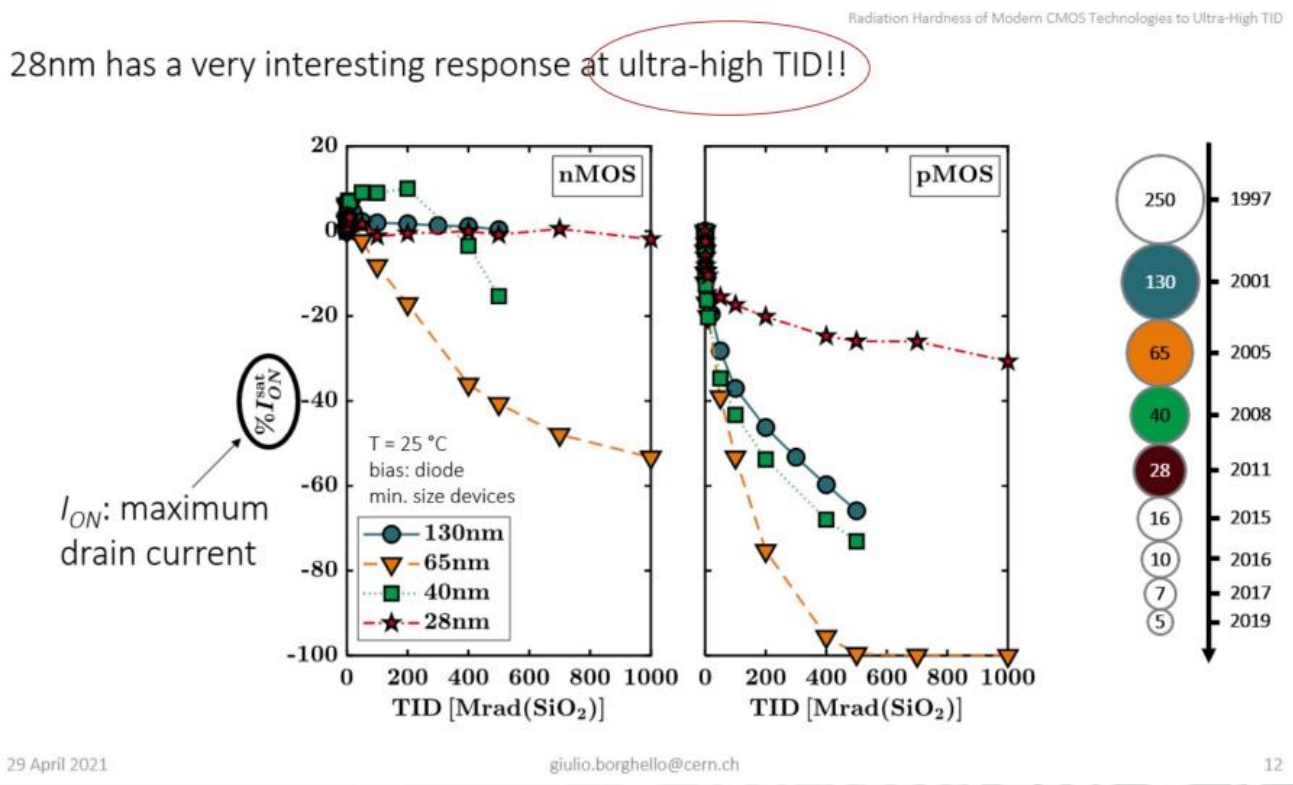
Part 3
28nm Technology

Why 28 nm ? (CERN Community)

From a Moore PoV



From a performance PoV



Credit : CERN 28nm community

Performance compared to 65 nm:

Pros : **x 4-5 gate density increase > x 2 faster**

Cons : **x 50 leakage increase** – can be reduced by exploiting multi-vt and multi-gl designs

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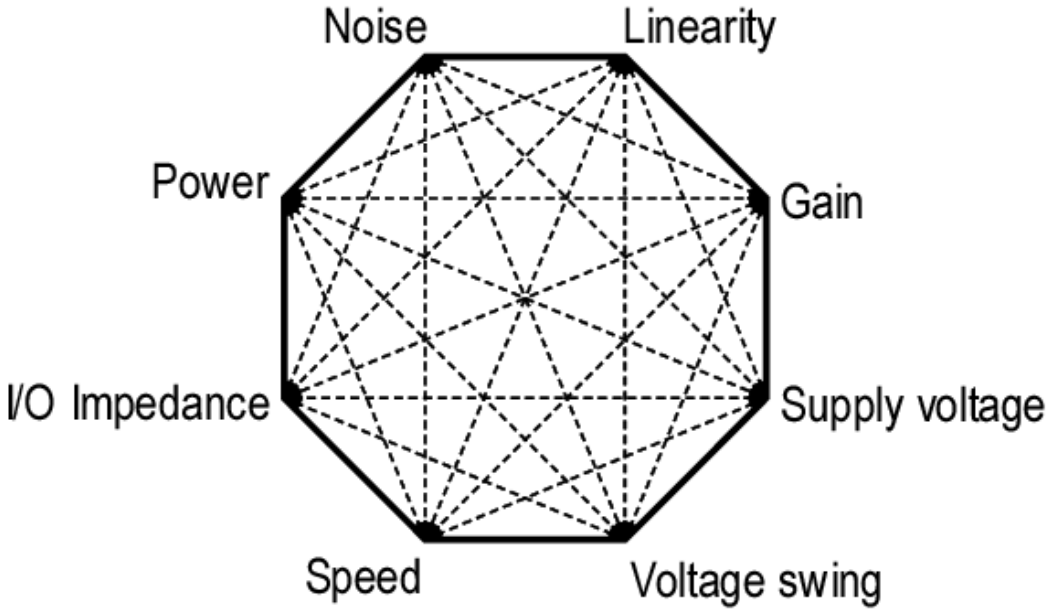
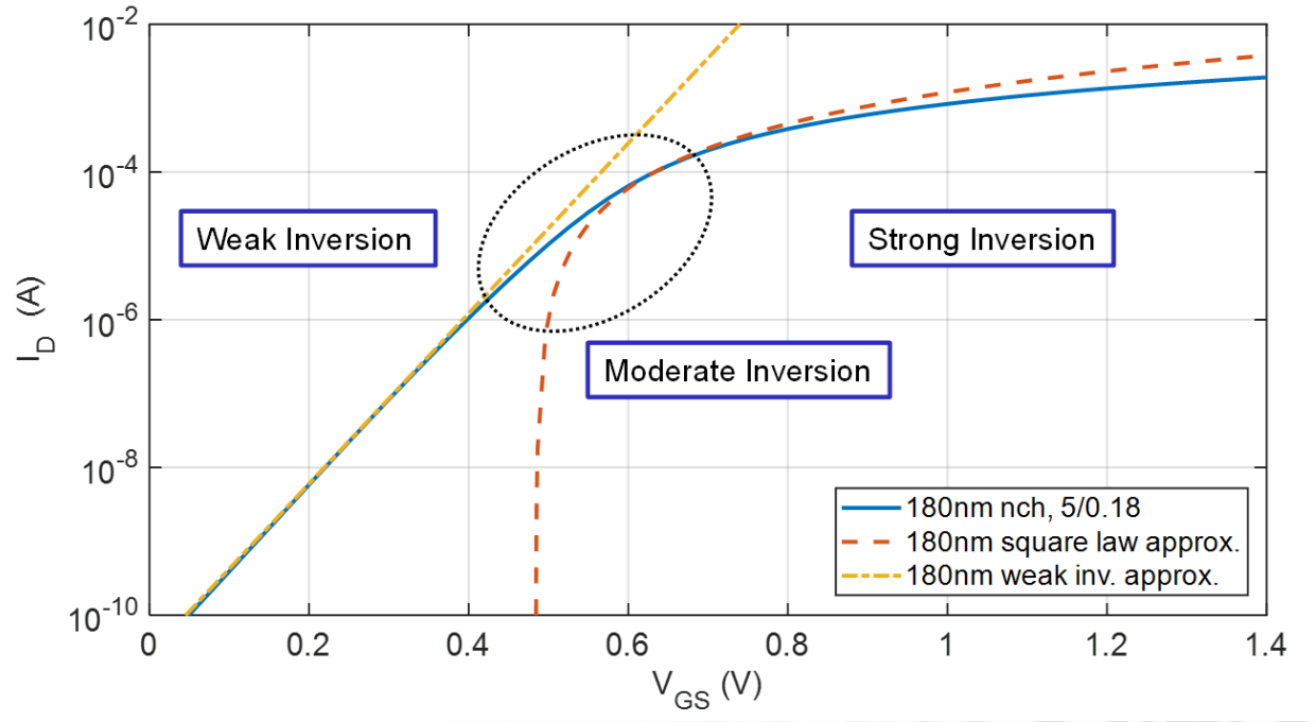
Part 3
28nm Technology

Design methodology : Exploring the $^{g_m}/_{I_D}$





Credit : Boris Murmann

Why analog design is challenging ?

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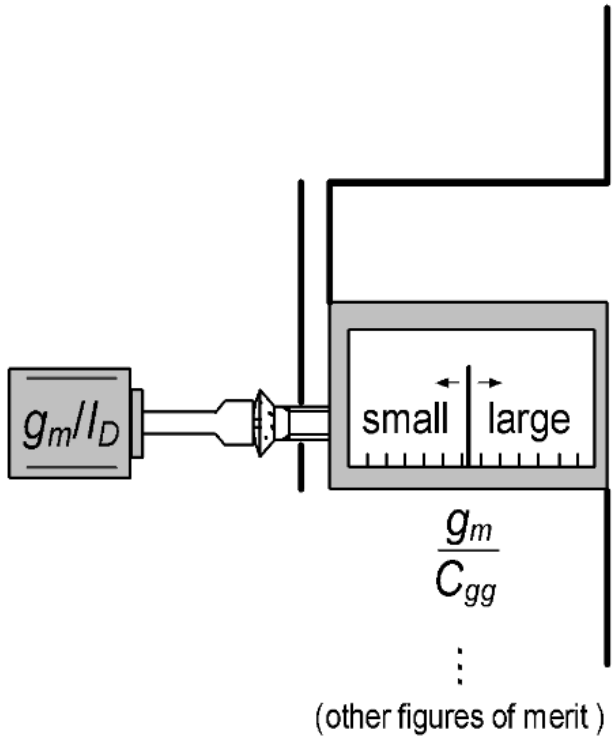
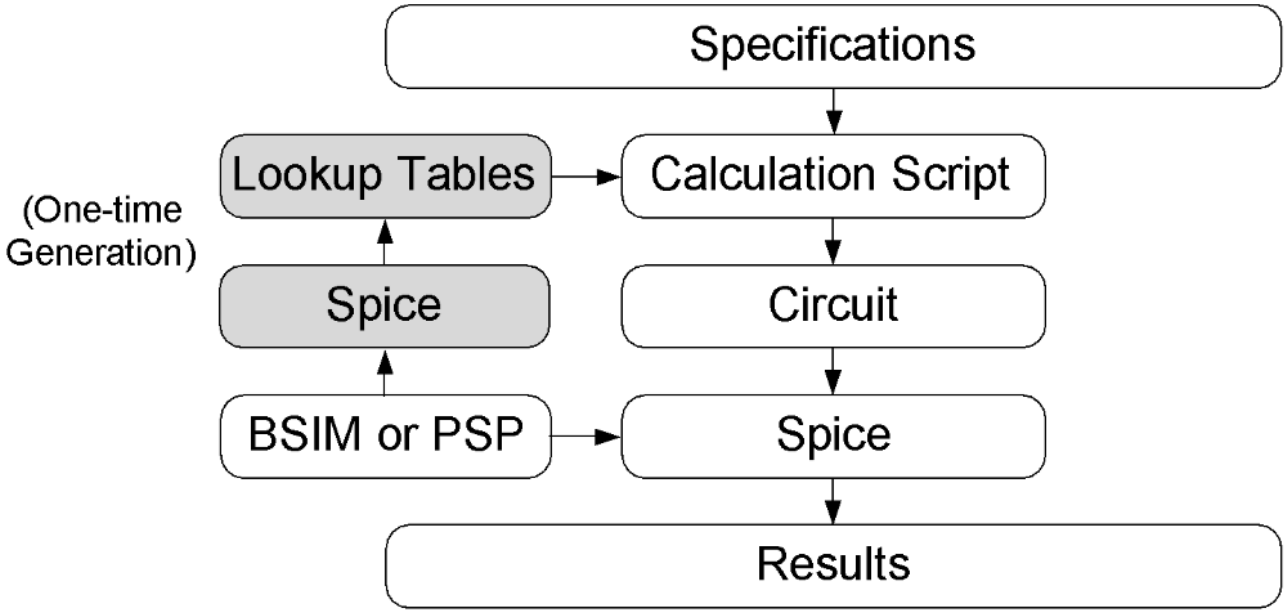
Part 3
28nm Technology

Design methodology : Exploring the $^{g_m}/_{I_D}$





Credit : Boris Murmann

The $^{g_m}/_{I_D}$ methodology uses the ratio of transconductance to drain current to optimize analog circuit design. By generating lookup tables from SPICE simulations, designers can quickly evaluate performance metrics and efficiently achieve desired specifications.

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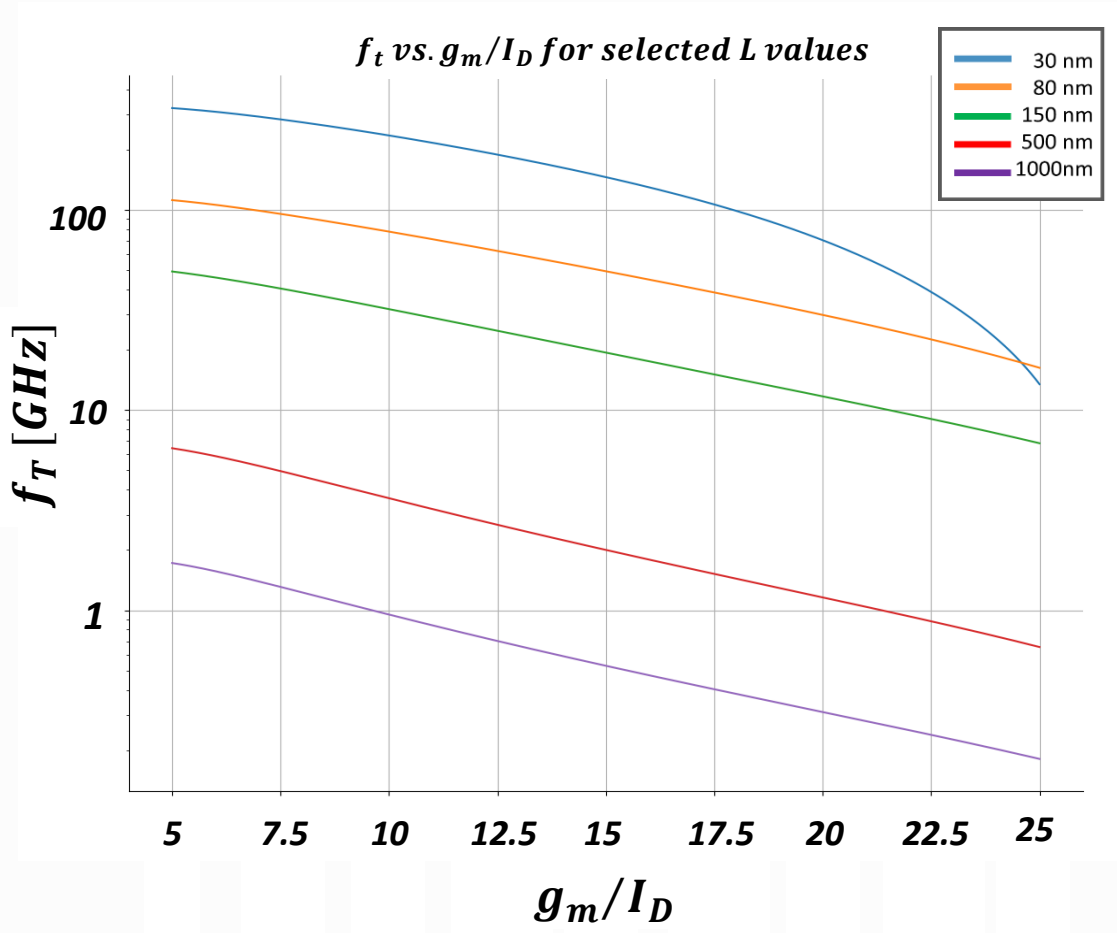
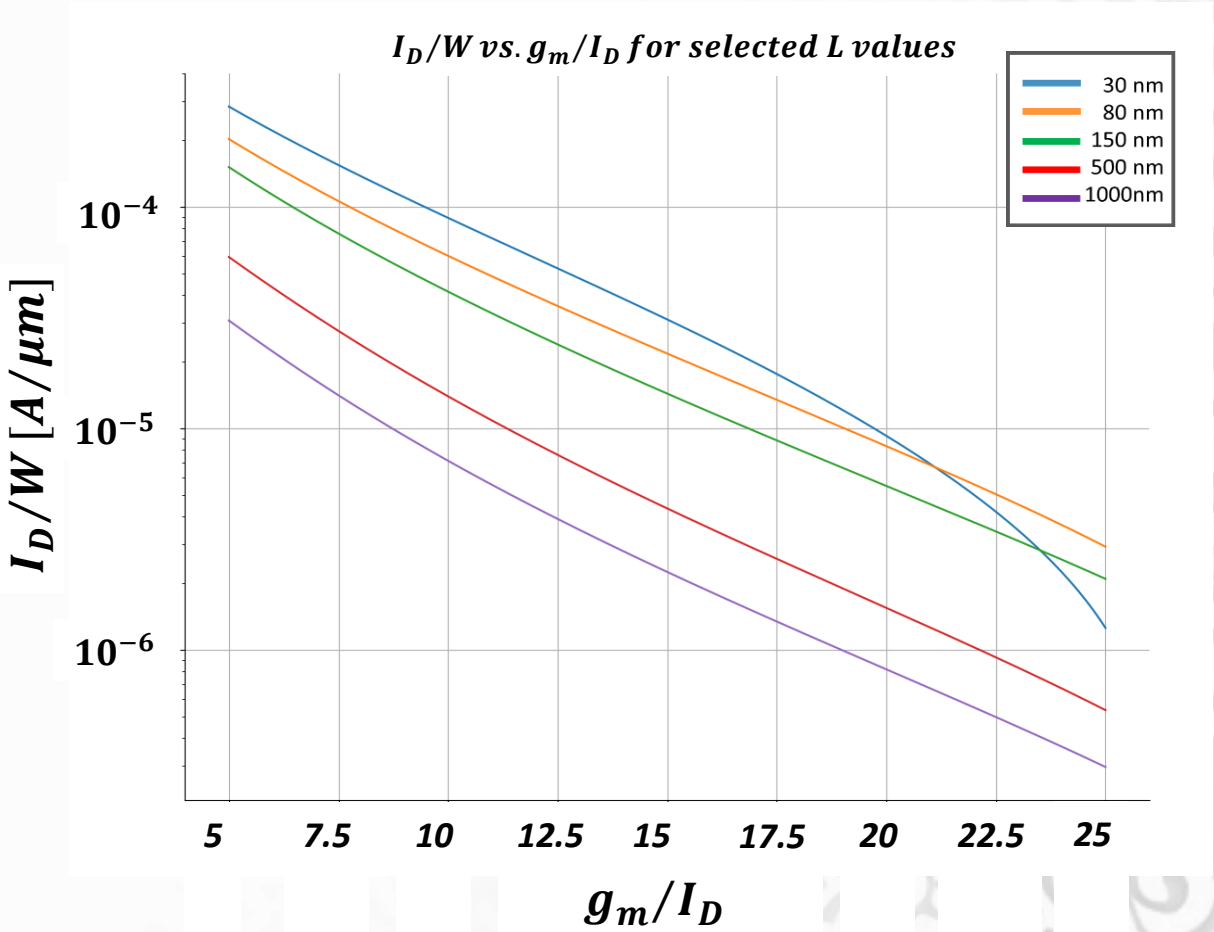
Part 3
28nm Technology

The extraction of the $^{g_m}/_{I_D}$ Lookup tables of the 28nm technology

Speed

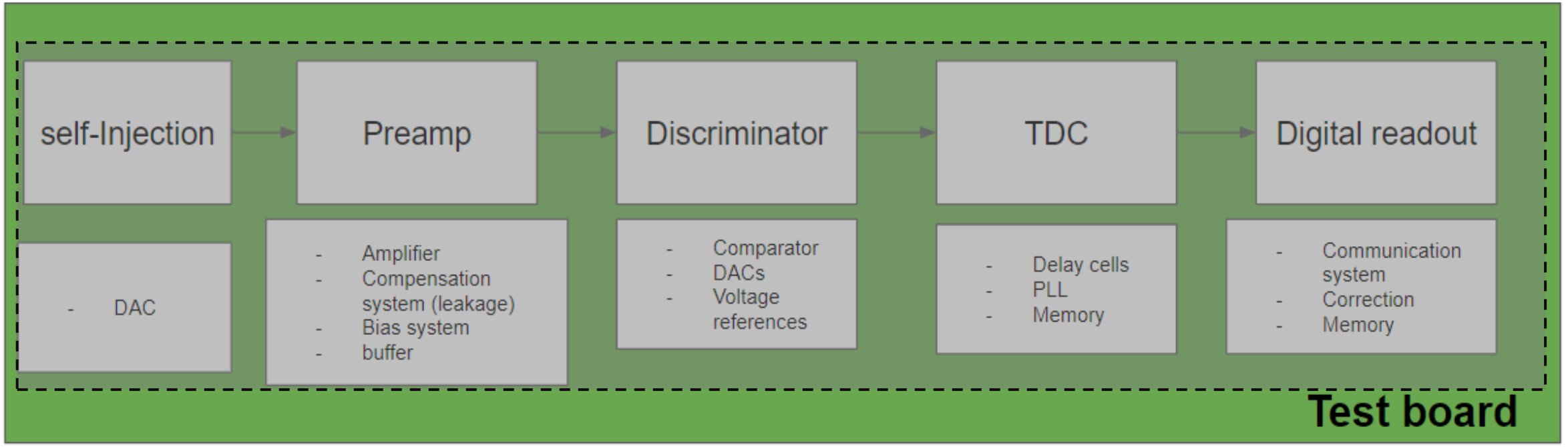


Efficiency



Goal

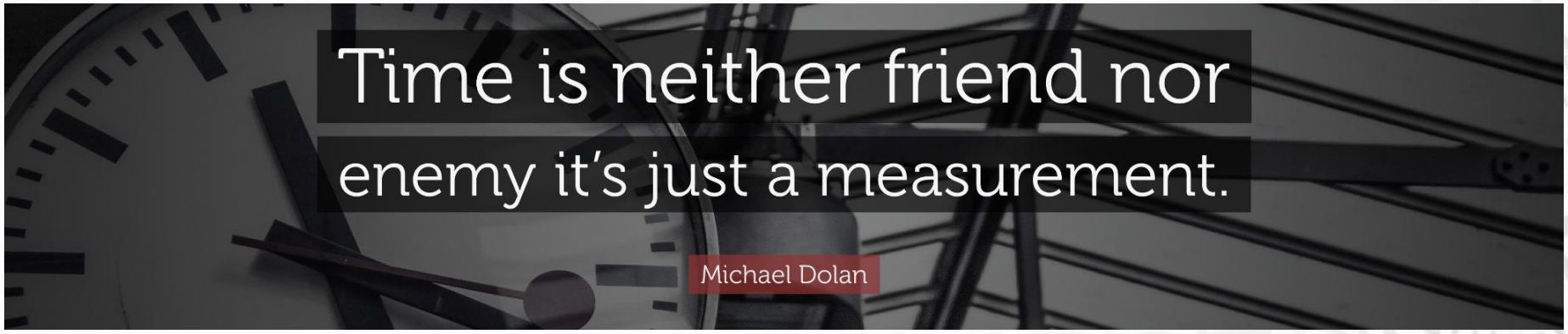
The concept of the targeted ASIC



The *First Gen* of the proposed ASIC is aimed to test different flavors and timing measurement concepts.
It is designed to be integrated with the Ti-LGAD sensors (Hybrid configuration).

Conclusion

- **The Initial system specifications are confirmed** ➔ A multiflavored, multichannel chip is under development.
- **The Behavioral Model is continuously evolving** ➔ Studying multiple solutions to reach the timing requirements ➔ multi-flavors chip
- **Exploring 28nm CMOS technology** ➔ Lookup table extracted, and first design test results are obtained.
- **The project** carried out in collaboration with PSI, UZH, CERN 28nm Community and CERN DRD3/7.



Thank you
Questions are welcome

ABDERRAHMANE GHIMOUZ

10th Sep. 2024

ANNEXE

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Part 3
28nm Technology

Technology performance (test case)