Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Study of a time-based readout architecture for the cryogenic ASIC

Meeting Annuale della Collaborazione Nazionale DUNE-Italia

Speaker: Sofia Blua (INFN – sezione Torino)

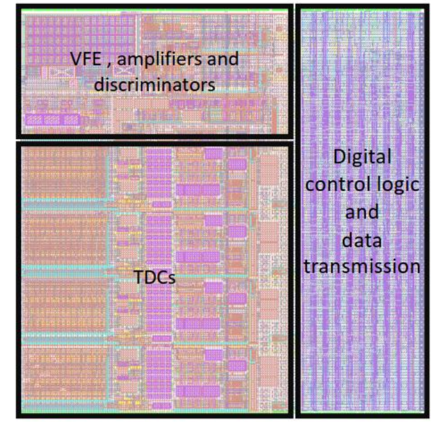
06/11/2023

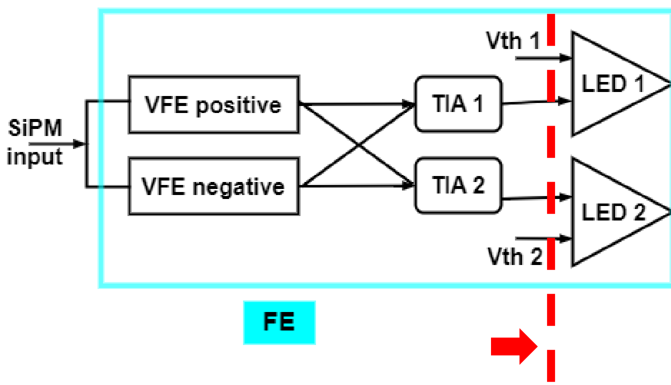
OUTLINE

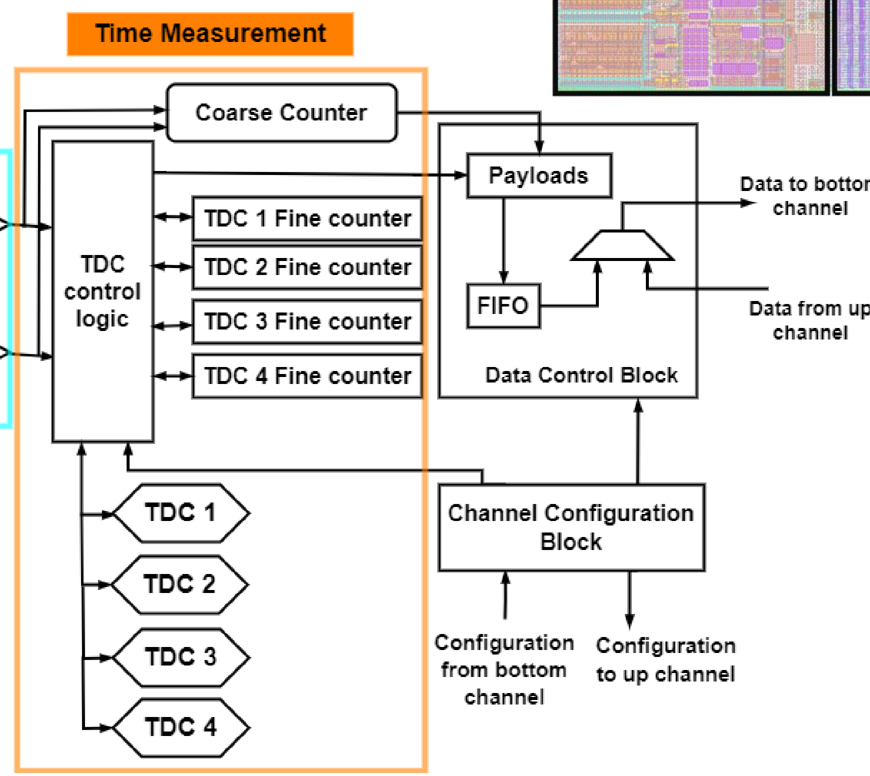
- Simulation testbench for a time-based readout architecture
- SiPM model and single P.E. response at low temperature
- Signal pile-up and time-over-threshold studies for GRAIN

ALCOR: CHANNEL ARCHITECTURE

- ALCOR: test vehicle for a time-based readout architecture at cryogenic temperatures
- **Readout chain** (either anode or cathode SiPM signals):
  1. Dual-polarity low-impedance (10-20 Ω) VFE based on RCG (Regulated Common Gate)
  2. 2 indipendent gain branches (TIA) + **LED (Leading-Edge Discriminator)** ➡ **trigger**







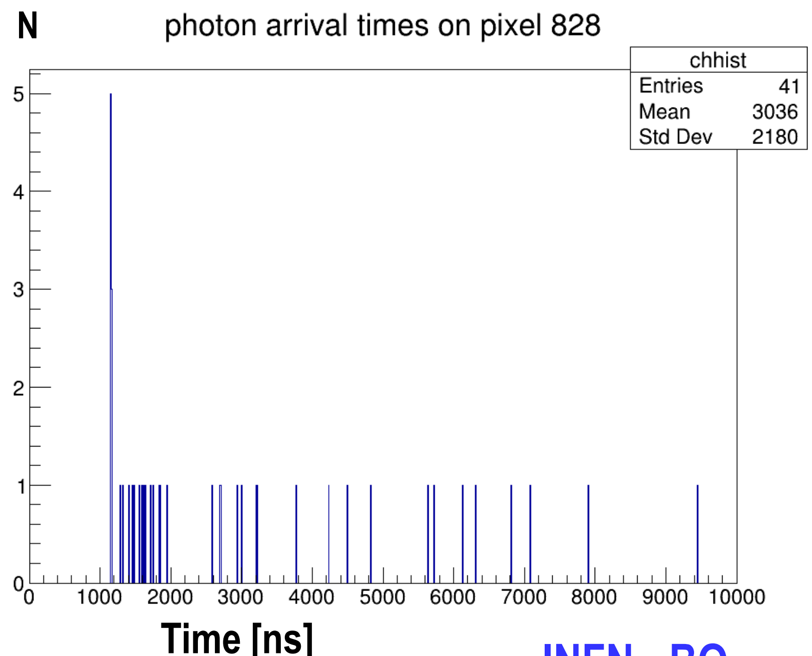
  3. Timing measurements:
     - Course timestamp ➡ 15-bit counter
     - Fine timestamp ➡ **4 dual ramp TDCs**

SIMULATION TEST BENCH

STARTING POINT: Monte Carlo simulations of charged tracks and photons in the optical system of GRAIN (BO)

```
I1000 (anode Vbias_p) SiPM_spad ts=6310.252509n
I1001 (anode Vbias_p) SiPM_spad ts=7909.722309n
I1002 (anode Vbias_p) SiPM_spad ts=5633.745519n
I1003 (anode Vbias_p) SiPM_spad ts=1619.669377n
I1004 (anode Vbias_p) SiPM_spad ts=1752.208531n
I1005 (anode Vbias_p) SiPM_spad ts=1483.203236n
I1006 (anode Vbias_p) SiPM_spad ts=7080.727761n
I1007 (anode Vbias_p) SiPM_spad ts=4496.877135n
I1008 (anode Vbias_p) SiPM_spad ts=3771.991602n
I1009 (anode Vbias_p) SiPM_spad ts=5728.355110n
I1010 (anode Vbias_p) SiPM_spad ts=1325.340684n
I1011 (anode Vbias_p) SiPM_spad ts=1159.202383n
I1012 (anode Vbias_p) SiPM_spad ts=1162.981585n
I1013 (anode Vbias_p) SiPM_spad ts=6817.967855n
I1014 (anode Vbias_p) SiPM_spad ts=2941.143995n
I1015 (anode Vbias_p) SiPM_spad ts=1157.357231n
I1016 (anode Vbias_p) SiPM_spad ts=1286.134020n
I1017 (anode Vbias_p) SiPM_spad ts=1647.831395n
I1018 (anode Vbias_p) SiPM_spad ts=6120.674058n
I1019 (anode Vbias_p) SiPM_spad ts=3224.847052n
I1020 (anode Vbias_p) SiPM_spad ts=2698.451500n
I1021 (anode Vbias_p) SiPM_spad ts=1855.419581n
I1022 (anode Vbias_p) SiPM_spad ts=1458.424114n
I1023 (anode Vbias_p) SiPM_spad ts=1158.711752n
I1024 (anode Vbias_p) SiPM_spad ts=1555.016123n
I1025 (anode Vbias_p) SiPM_spad ts=1159.146577n
I1026 (anode Vbias_p) SiPM_spad ts=3201.496401n
I1027 (anode Vbias_p) SiPM_spad ts=2706.592441n
I1028 (anode Vbias_p) SiPM_spad ts=1162.430133n
I1029 (anode Vbias_p) SiPM_spad ts=2585.714538n
I1030 (anode Vbias_p) SiPM_spad ts=4237.280447n
I1031 (anode Vbias_p) SiPM_spad ts=1156.791763n
I1032 (anode Vbias_p) SiPM_spad ts=1161.219772n
I1033 (anode Vbias_p) SiPM_spad ts=1402.366011n
I1034 (anode Vbias_p) SiPM_spad ts=1717.951852n
I1035 (anode Vbias_p) SiPM_spad ts=4829.198521n
I1036 (anode Vbias_p) SiPM_spad ts=9440.488181n
I1037 (anode Vbias_p) SiPM_spad ts=1836.853481n
I1038 (anode Vbias_p) SiPM_spad ts=3000.626679n
I1039 (anode Vbias_p) SiPM_spad ts=1591.942222n
I1040 (anode Vbias_p) SiPM_spad ts=1947.029911n
I5000 (anode Vbias_p) SiPM_spad_off
I5001 (anode Vbias_p) SiPM_spad_off
```

Generation of **ToA** netlists for **ELECTRONIC SIMULATIONS** using **Cadence tools** (virtuoso-schematic, ADE+Spectre)

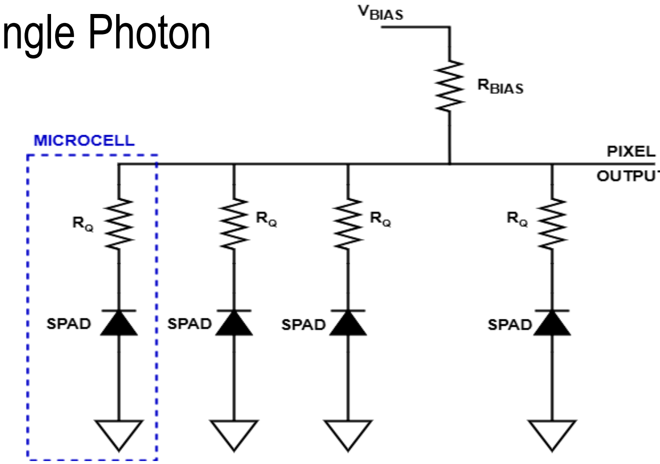


INFN - BO

Simulation of a **single SiPM response** through the electrical model implemented

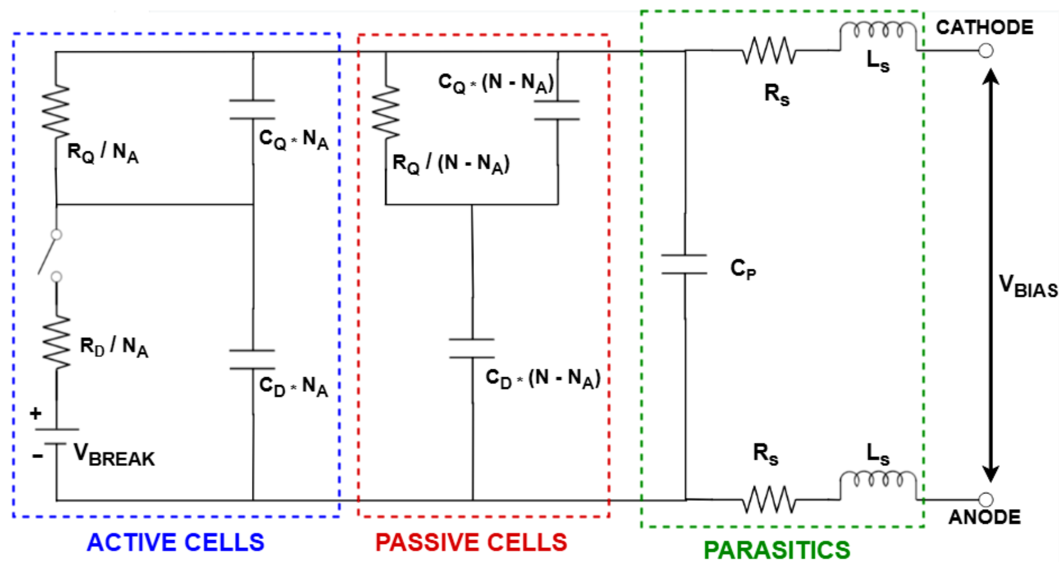
SiPM MODEL

- Array of **N microcells** composed by a Geiger mode SPAD (Single Photon Avalanche Diode) in series with a quenching resistor
- Output signal = sum of every microcell signal

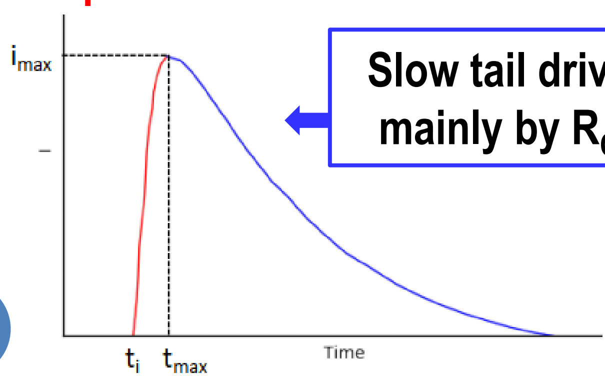


SiPM ELECTRICAL MODEL:

- In an event if N_A is the number of **active cells**, there will be **($N - N_A$) inactive cells**!
- **Both** active and inactive cells give a **contribution to FE input capacitance**
- **Circuit implemented in virtuoso schematic:**



Shape of output signal:
sharp rise + slow tail



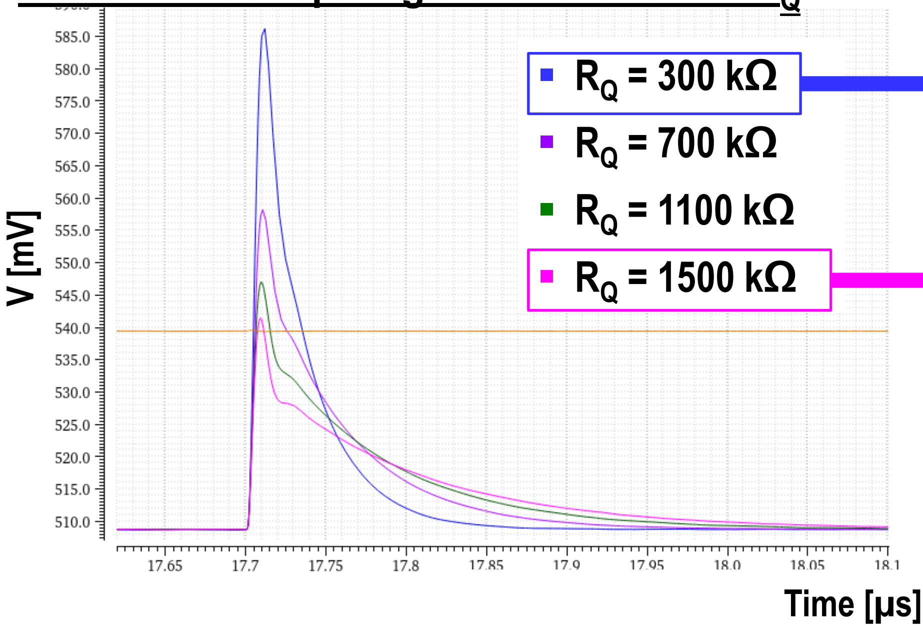
Slow tail driven mainly by R_Q !

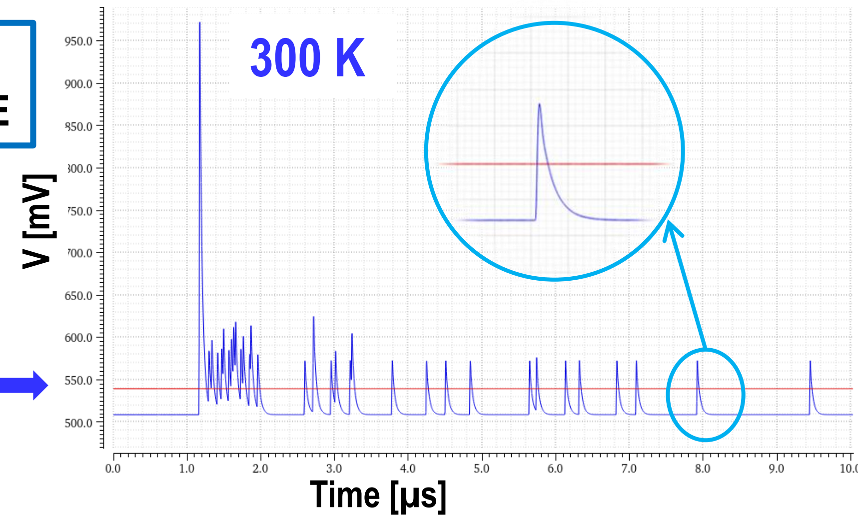
SIMULATION SETTINGS

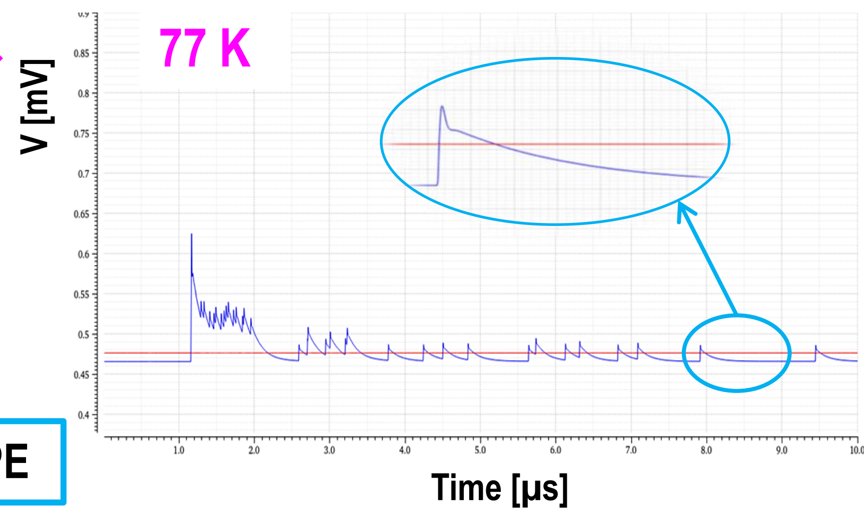
SIMULATION FOR NPE COUNTING: Evaluate if the counting of the number of photoelectrons signals (NPE) **from the ToT measure** is possible considering the different pile up at 300 K and 77 K

At cryogenic temperatures: R_Q **INCREASE** → ❑ **Lower Amplitude** ❑ **Longer Tail** → **PILE UP INCREASE**

Simulation of 1 pe signal with different R_Q



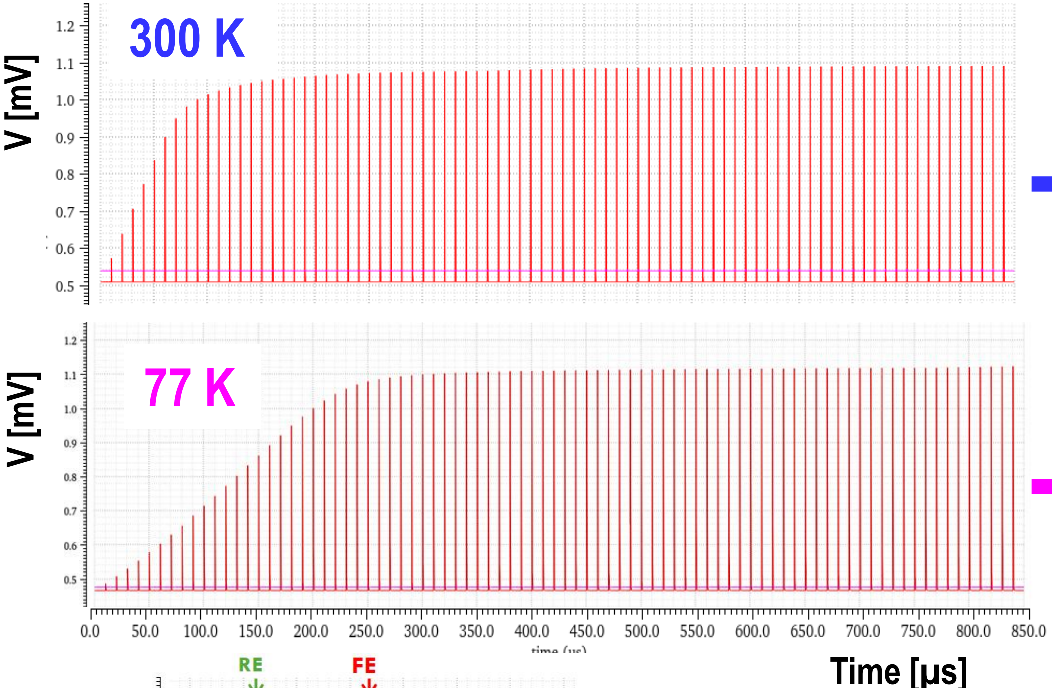




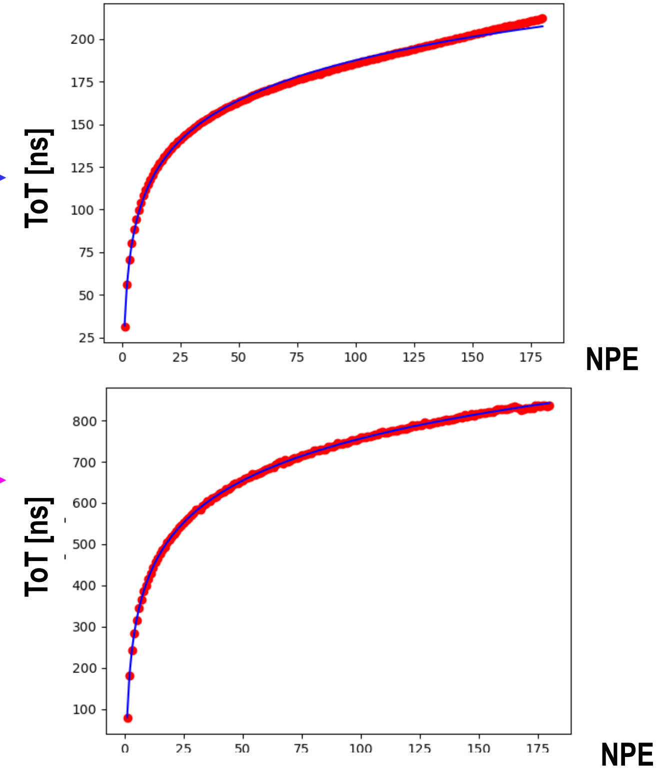
Discriminator **threshold** set in the **middle of 1 PE**

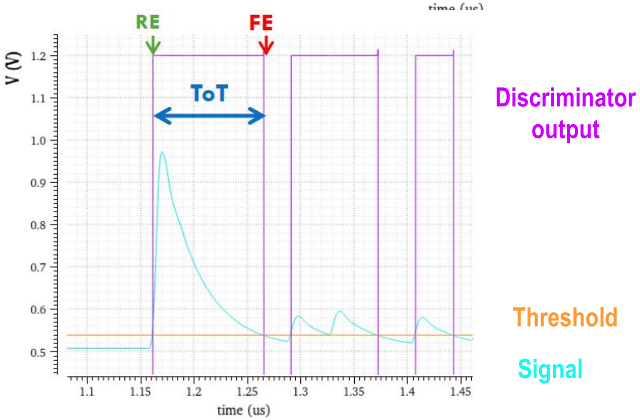
CALIBRATION PROCEDURE AND RESULTS

Simulation of "perfect pile up" from 1 to 180 NPE



$$ToT = A\, log_{10}(NPE) + B$$





ToT = FE - RE → **NPE**

NEXT STEP: test this method with "real pile up" data (higher variability)

DATA SIMULATION

Purpose: collect ToT [ns], NPE and NPE calculated from Calibration Function in Dataframes for both cases of 300 K and 77 K (**same Setting of Calibration Procedure)**

DATAFRAME GENERATION METHOD:

A. **ToT** from the difference between rising and falling edge

B. **NPE from calibration** curves through the inverted expression and ToT measure:

$$NPE = 10^{\left(\frac{1}{A}ToT - \frac{B}{A}\right)}$$

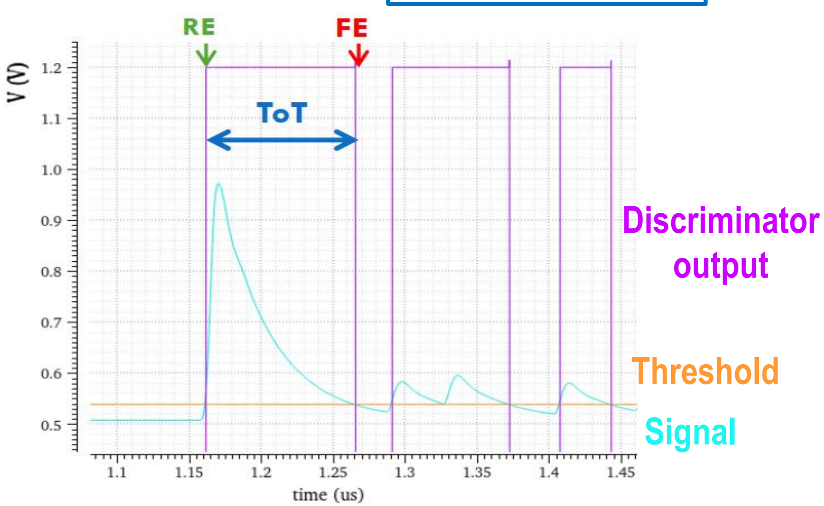
C. **NPE** from the counting of ToA timestamps (ts) associated with a ToT measure

1) Find the lowest **ts** that triggers the discriminator **RE**

RE = 1161.28 ns

2) Find **ts < FE**

FE = 1265.22 ns



ts=6310.252509n	ts=2941.143995n	ts=1162.430133n
ts=7909.722309n	ts=1157.357231n	ts=2585.714538n
ts=5633.745519n	ts=1286.134020n	ts=4237.280447n
ts=1619.669377n	ts=1647.831395n	ts=1156.791763n
ts=1752.208531n	ts=6120.674058n	ts=1161.219772n
ts=1483.203236n	ts=3224.847052n	ts=1402.366011n
ts=7080.727761n	ts=2698.451500n	ts=1717.951852n
ts=4496.877135n	ts=1855.419581n	ts=4829.198521n
ts=3771.991602n	ts=1458.424114n	ts=9440.488181n
ts=5728.355110n	ts=1158.711752n	ts=1836.853481n
ts=1325.340684n	ts=1555.016123n	ts=3000.626679n
ts=1159.202383n	ts=1159.146577n	ts=1591.942222n
ts=1162.981585n	ts=3201.496401n	ts=1947.029911n
ts=6817.967855n	ts=2706.592441n	

NPE = 8

DATA SIMULATION

DATAFRAME EXAMPLE:

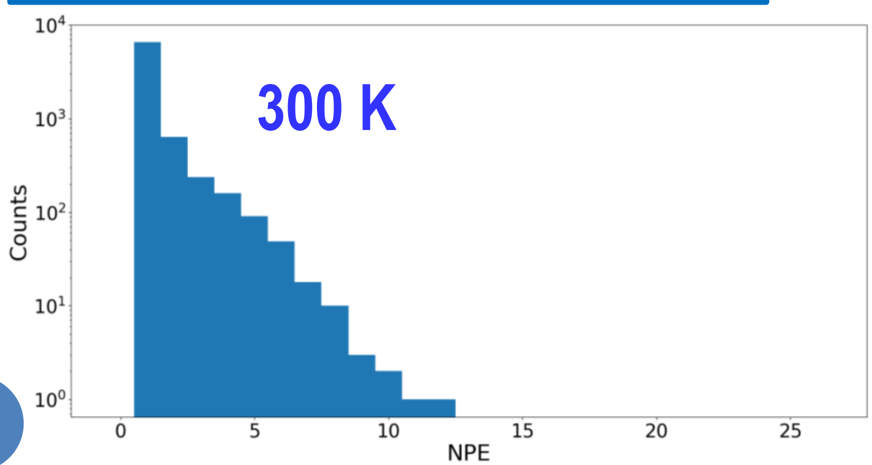
300 K

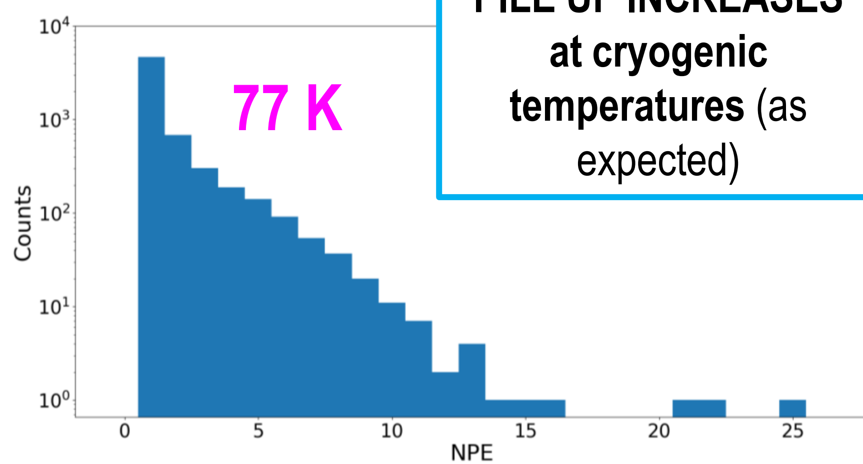
RE [ns]	ts [ns]	NPE	FE [ns]	ToT [ns]	NPE Calib
1161.28	[1156.79, 1157.36, 1158.71, 1159.15, 1159.2, 1161.22, 1162.43, 1162.98]	8	1265.22	103.94	8.41
1290.76	[1286.13, 1325.34]	2	1372.29	81.53	4.33
1407.38	[1402.37]	1	1443.03	35.65	1.11
1462.79	[1458.42, 1483.2]	2	1535.08	72.29	3.29
1559.64	[1555.02, 1591.94, 1619.67, 1647.83]	4	1702.16	142.52	26.39
1722.35	[1717.95, 1752.21]	2	1800.82	78.47	3.96
1842.07	[1836.85, 1855.42]	2	1908.56	66.49	2.77
1952.32	[1947.03]	1	1986.75	34.43	1.07
2591.9	[2585.71]	1	2621.7	29.8	0.94
2704.34	[2698.45, 270[illegible]	[illegible]	[illegible]762.97	58.63	2.2
2947.29	[2941.14[illegible]	[illegible]	[illegible]977.26	29.97	0.94
3005.39	[3000.63[illegible]	[illegible]	[illegible]042.24	36.85	1.15
3207.64	[3201.5, 322[illegible]	[illegible]	[illegible]274.83	67.19	2.83
3778.15	[3771.99[illegible]	[illegible]	[illegible]808.02	29.87	0.94
4243.35	[4237.28]	1	4273.28	29.93	0.94
4503.04	[4496.88]	1	4532.94	29.9	0.94
4835.37	[4829.2]	1	4865.2	29.83	0.94
5639.91	[5633.75]	1	5669.75	29.84	0.94
5734.03	[5728.36]	1	5766.55	32.52	1.01
6126.83	[6120.67]	1	6156.72	29.89	0.94
6316.4	[6310.25]	1	6346.41	30.01	0.94
6824.12	[6817.97]	1	6854.01	29.89	0.94
7086.89	[7080.73]	1	7116.77	29.88	0.94
7915.87	[7909.72]	1	7945.79	29.92	0.94
9446.66	[9440.49]	1	9476.49	29.83	0.94

77 K

RE [ns]	ts [ns]	NPE	FE [ns]	ToT [ns]	NPE Calib
1159.8	[1156.79, 1157.36, 1158.71, 1159.15, 1159.2, 1161.22, 1162.43, 1162.98, 1286.13, 1325.34, 1402.37, 1458.42, 1483.2, 1555.02, 1591.94, 1619.67, 1647.83, 1717.95, 1752.21, 1836.85, 1855.42, 1947.03]	22	2181.0	1021.2	606.03
2589.22	[2585.71]	1	2660.37	71.15	0.95
2700.81	[2698.45, 2706.59]	2	2903.07	202.26	2.31
2943.49	[2941.14, 3000.63]	2	3170.31	226.82	2.73
3203.75	[3201.5, 322[illegible]	[illegible]	3417.87	214.12	2.5
3775.43	[3771.9[illegible]	[illegible]	3848.32	72.89	0.96
4240.79	[4237.2[illegible]	[illegible]	4311.57	70.78	0.94
4500.0	[4496.8[illegible]	[illegible]	4591.71	91.71	1.09
4832.49	[4829.2]	1	4915.02	82.53	1.02
5637.35	[5633.75]	1	5703.08	65.73	0.91
5730.52	[5728.36]	1	5858.6	128.08	1.39
6124.02	[6120.67]	1	6202.92	78.9	1.0
6313.11	[6310.25]	1	6419.38	106.27	1.2
6821.49	[6817.97]	1	6892.28	70.79	0.94
7083.91	[7080.73]	1	7171.76	87.85	1.06
7913.36	[7909.72]	1	7978.68	65.32	0.91
9444.12	[9440.49]	1	9508.62	64.5	0.9

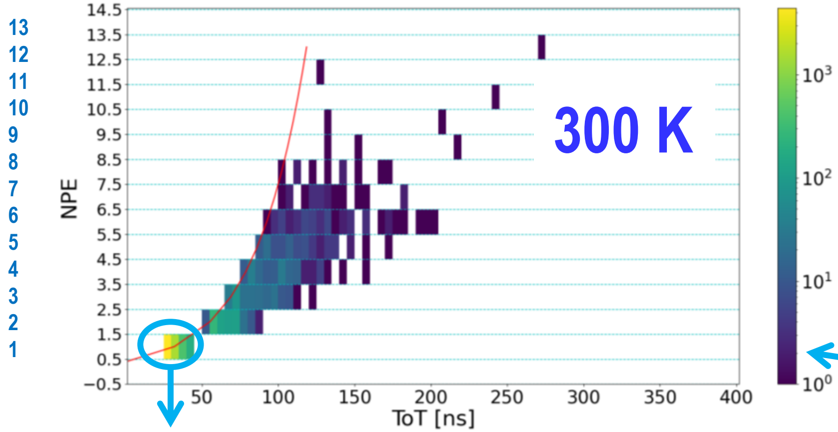
Histogram of NPE from all Dataframes





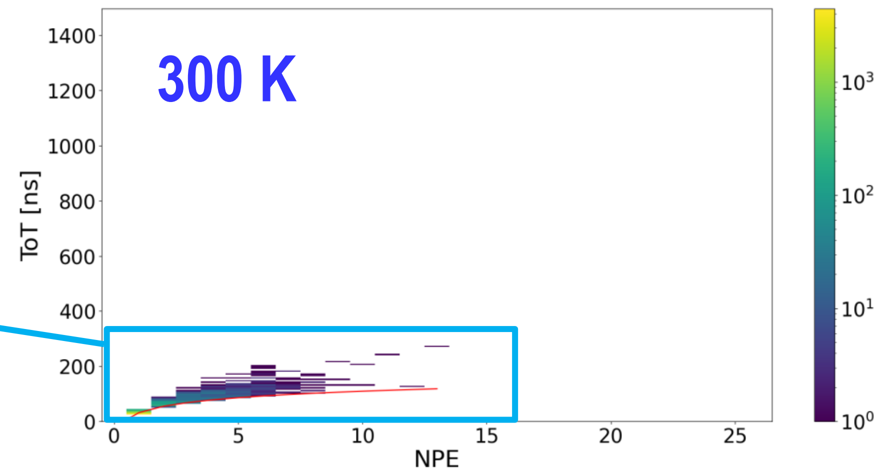
PILE UP INCREASES at cryogenic temperatures (as expected)

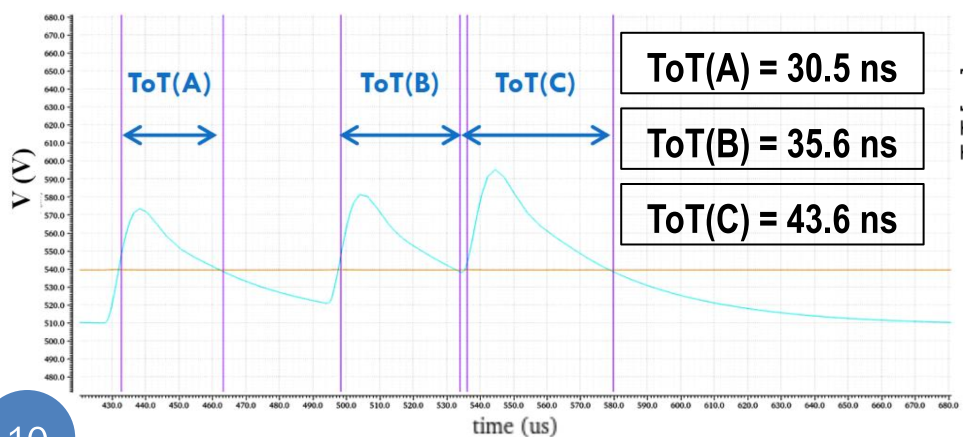
ANALYSIS RESULTS



There is a distribution of ToT with a peak for 1 PE

This **variability in 1 PE ToT** is caused by the **overlap with the tail** of previous signal (higher baseline)

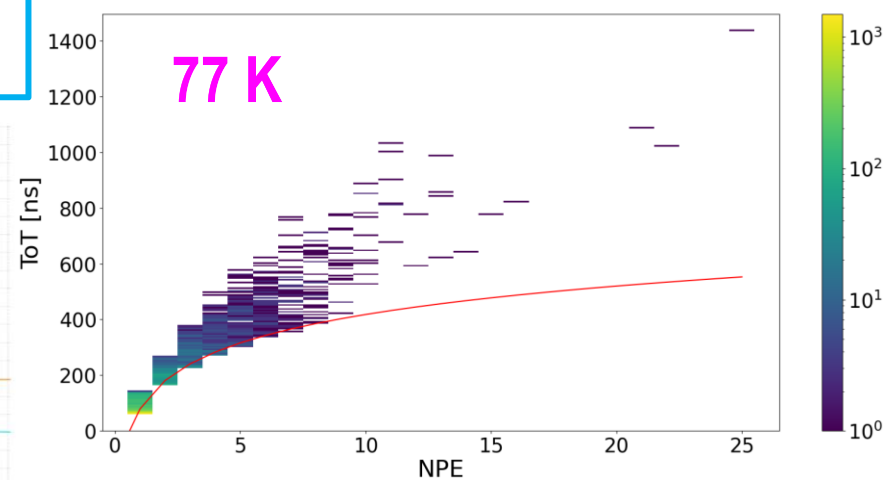




ToT(A) = 30.5 ns

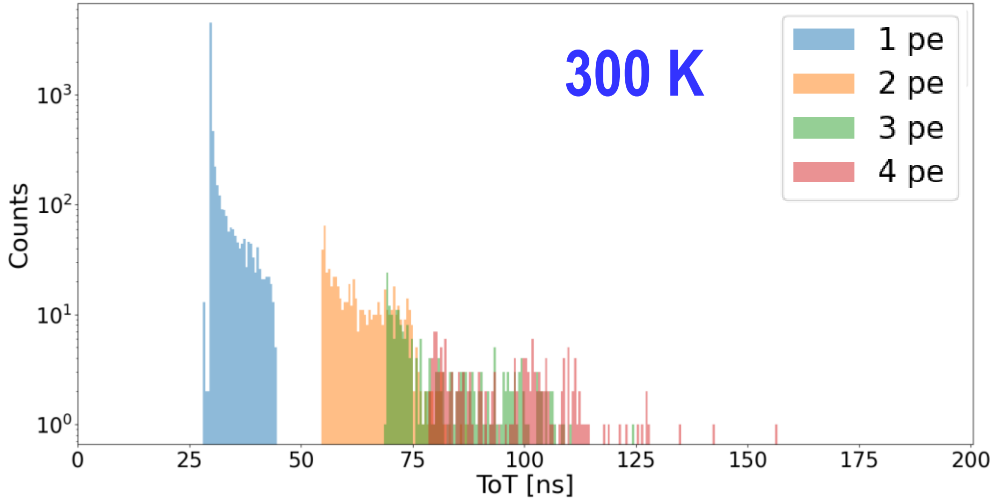
ToT(B) = 35.6 ns

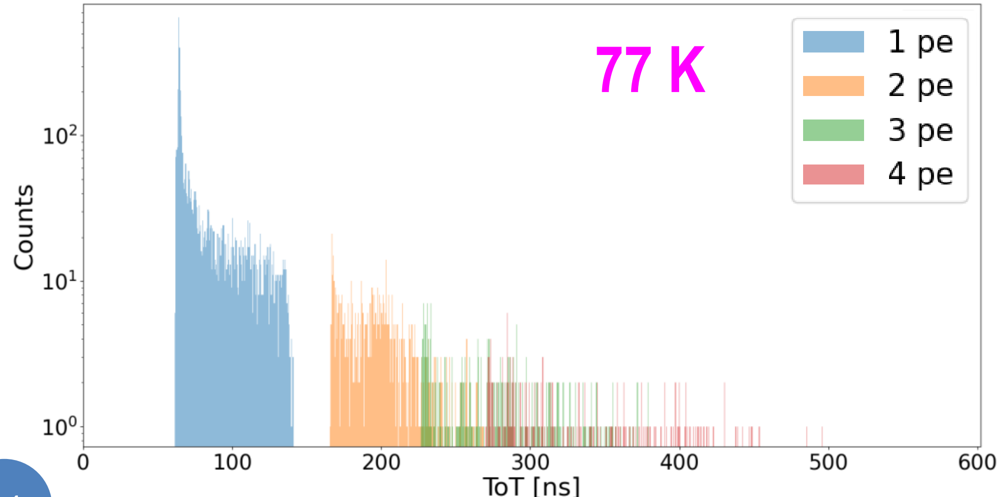
ToT(C) = 43.6 ns



ANALYSIS RESULTS

Histograms of ToT for each NPE until 4

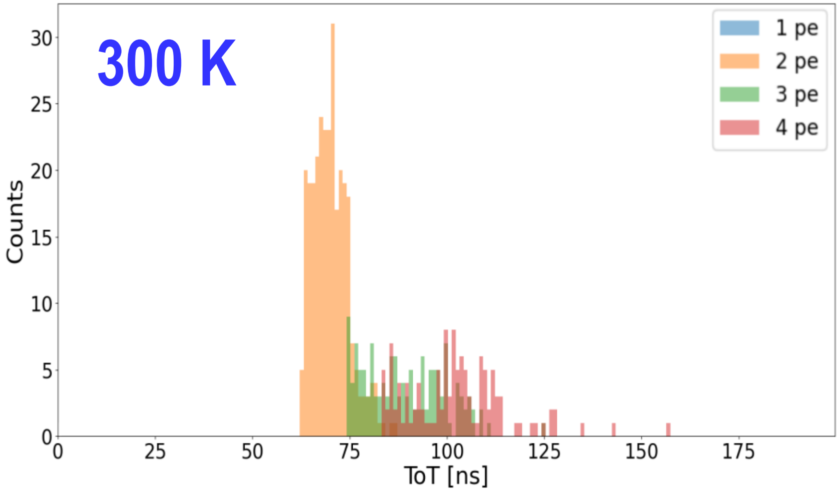


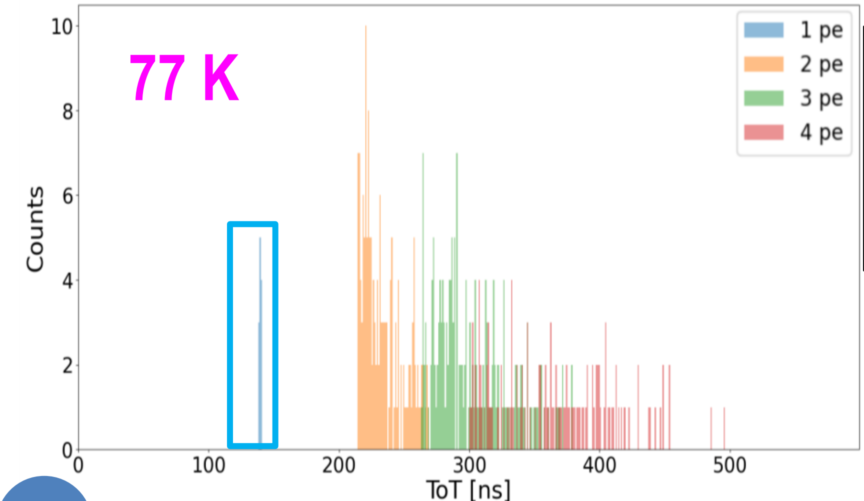


- Higher ToT at 77 K
- Larger distribution at 77 K because of the slower tail at 77 K
- No noise considered

ANALYSIS RESULTS

Histograms of ToT that the Calibration Function fails to associate at the right NPE





300 K:

NPE	Entries of ToT	Counts of wrong NPE	% Wrong NPE
1	6559	0	0.0
2	647	292	45.1
3	241	136	56.4
4	159	120	75.5

77 K:

NPE	Entries of ToT	Counts of wrong NPE	% Wrong NPE
1	4685	12	0.3
2	682	157	23.0
3	303	184	60.7
4	189	120	63.5

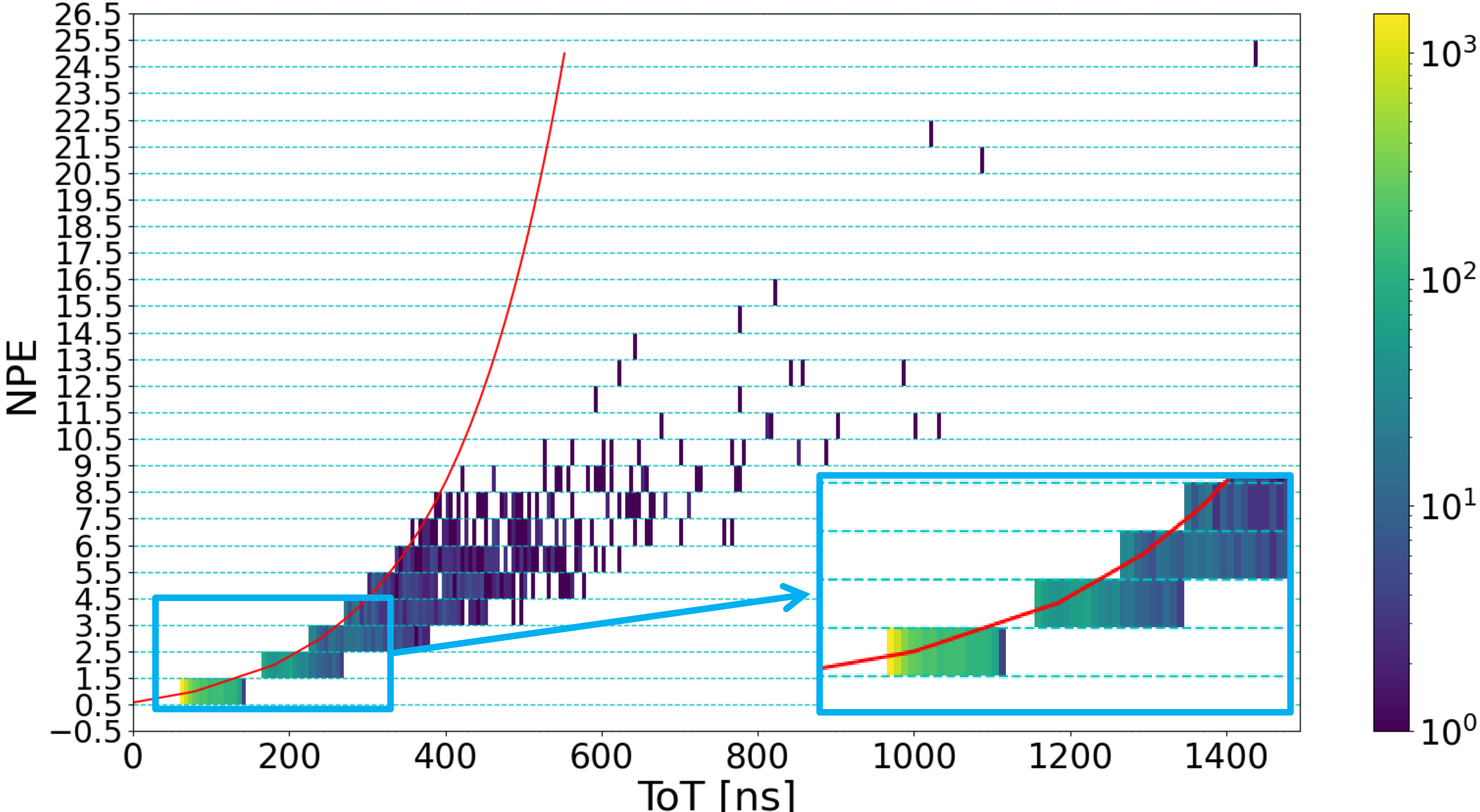
CONSIDERATIONS

- This simulation and analysis framework has been implemented for the evaluation of the feasibility of a time-based readout architecture, this is the first step for the future implementation of the mixed-signal ASIC: it can allow the evaluation of options in term of signal shaping and type of measure for photon counting
- Preliminary results with GRAIN Monte-Carlo data seems to indicate possible limitations on the use of a time-based readout architecture
- Next step: optimisation of the front-end (gain, shaping), study of a tail suppression and AC coupling topologies

THANK YOU FOR YOUR ATTENTION!

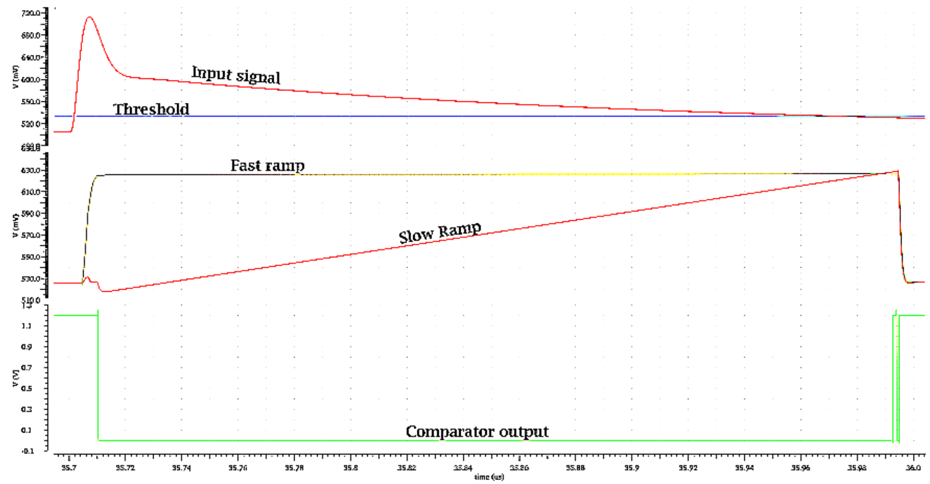
BACKUP SLIDES

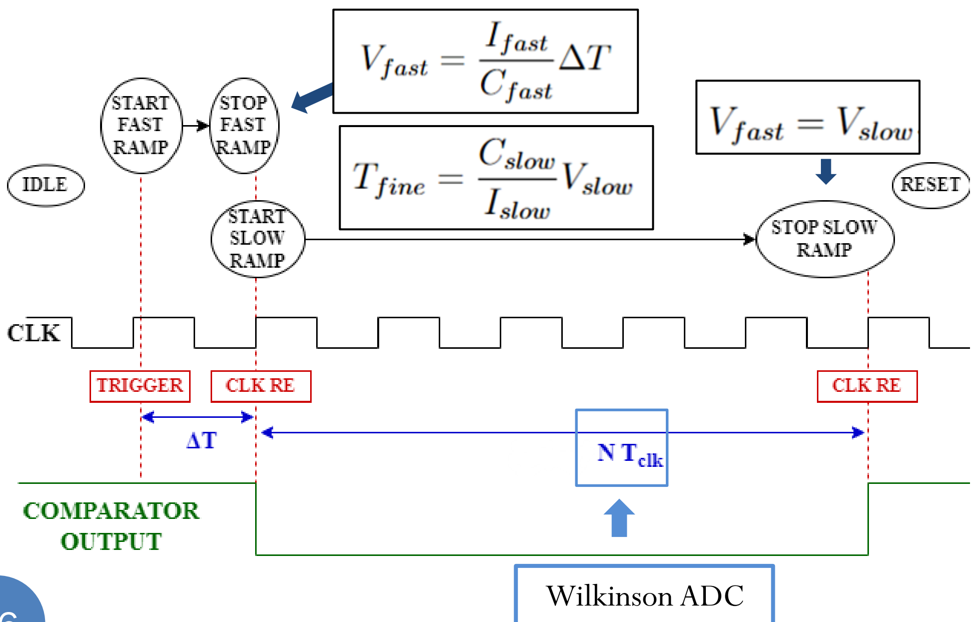
2D HISTOGRAM 77 K



ALCOR: TDCs ARCHITECTURE

- **TDC (Time to Digital Converter)**: supplies a digital representation of a time measure with a resolution up to **25-50 ps for 160-320 MHz**
- 4 TDCs for each pixel
  ➡ higher count rate capability
- **Low Power Analog based dual ramp**: based on charging of 2 equal capacitors with $\mathbf{I_{fast} >> I_{slow}}$, enabled by switches





$$V_{fast} = \frac{I_{fast}}{C_{fast}} \Delta T$$

$$T_{fine} = \frac{C_{slow}}{I_{slow}} V_{slow}$$

$$V_{fast} = V_{slow}$$

Interpolation Factor (IF) defines time binning:

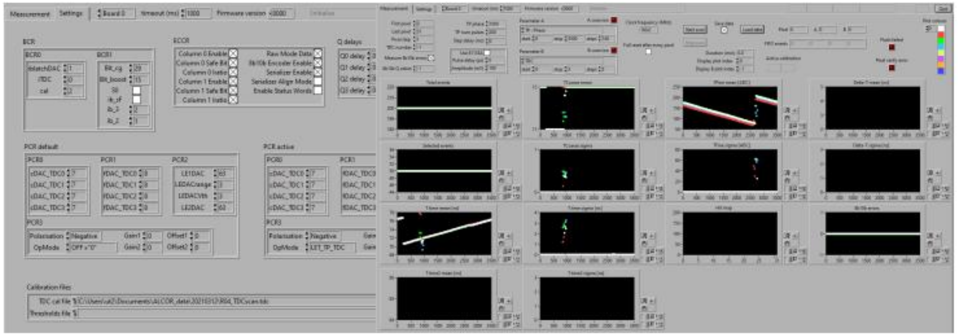
$$IF = \frac{T_{fine}}{\Delta T} = \frac{C_{slow}}{I_{slow}} V_{slow} \frac{I_{fast}}{C_{fast} V_{fast}} = \frac{I_{fast}}{I_{slow}}$$

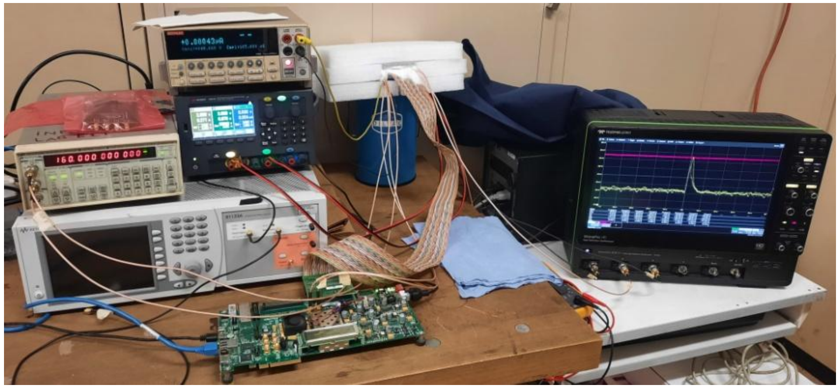
$$\mathrm{LSB} = \frac{T_{clk}}{IF}$$

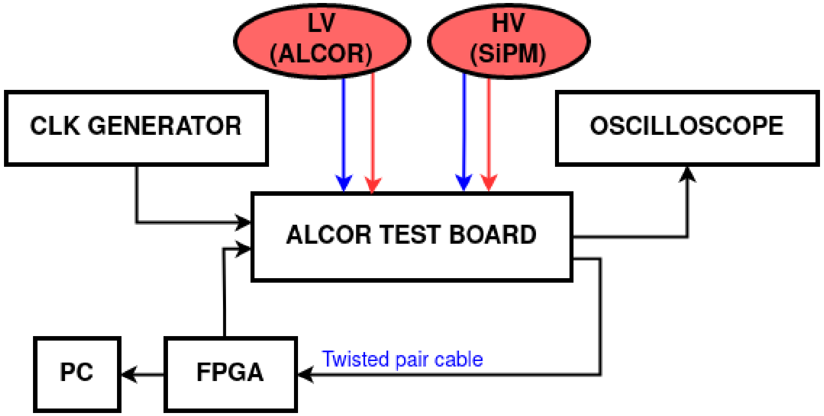
$f_{clk,Max} = 320$ MHz

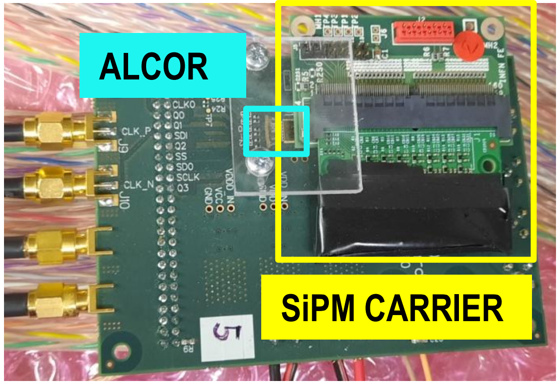
ALCOR CHARACTERISATION WITH SiPMs

- **ALCOR Test Board** ➡ chip wire bonded
- **LabVIEW:** configuration and DAQ program
- **DAQ system:**
  - LN container
  - FPGA: provides ASIC configuration, reads and sends output to PC
  - Clock Generator: f_{clk} = 160 MHz
  - **SiPMs** : HAMAMATSU S13360 series with pixel pitch of 25 μm and 50 μm (3 x 3 mm^2)





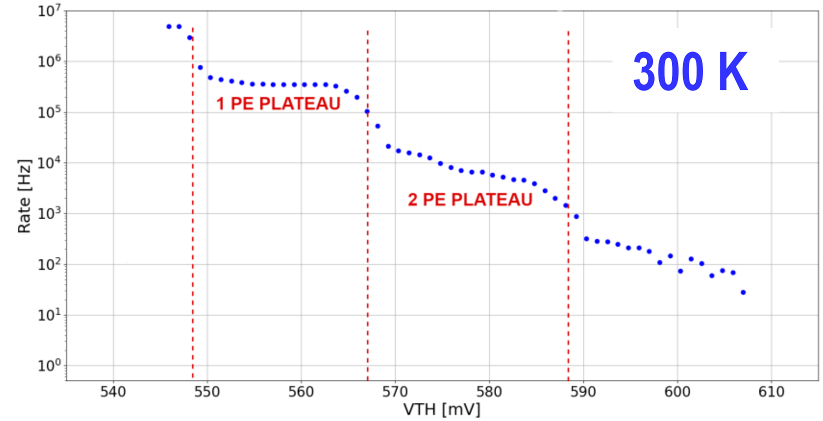




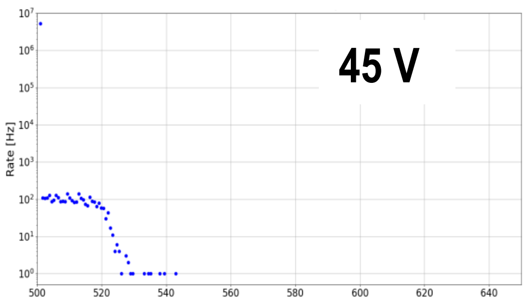
FE THRESHOLD SCAN

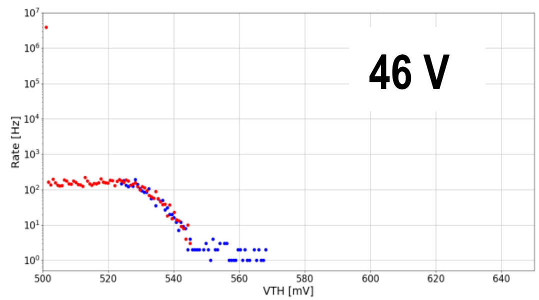
TEST OF FE RESPONSE:

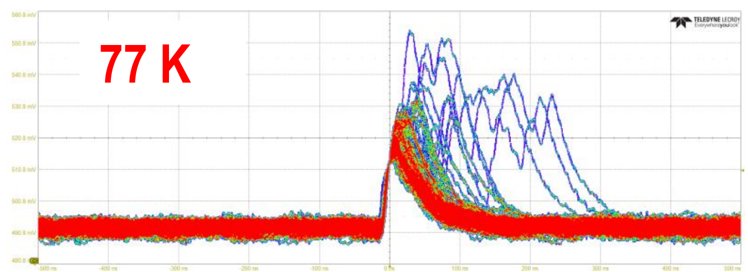
- **Threshold Scan:** SiPM input signal supplied to FE and threshold value changed step by step from maximum to minimum
- **Fit of** resulting **S-curve** provides signal amplitude values

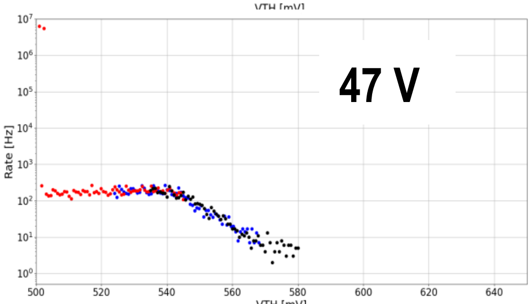


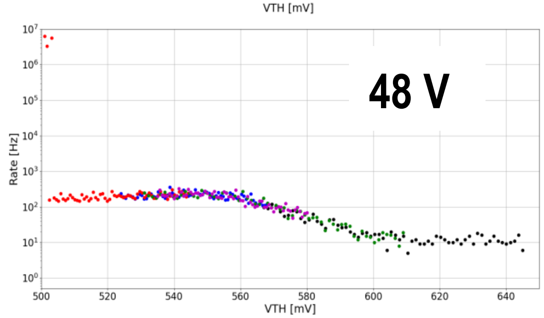
Signal amplitude study at 77 K:









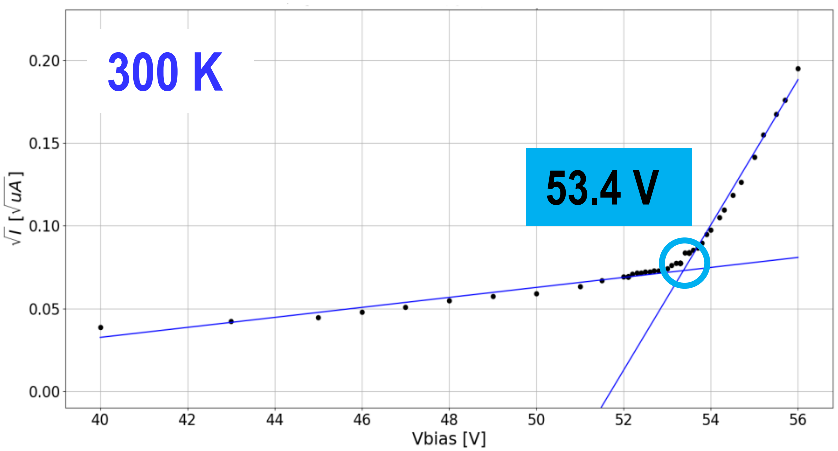


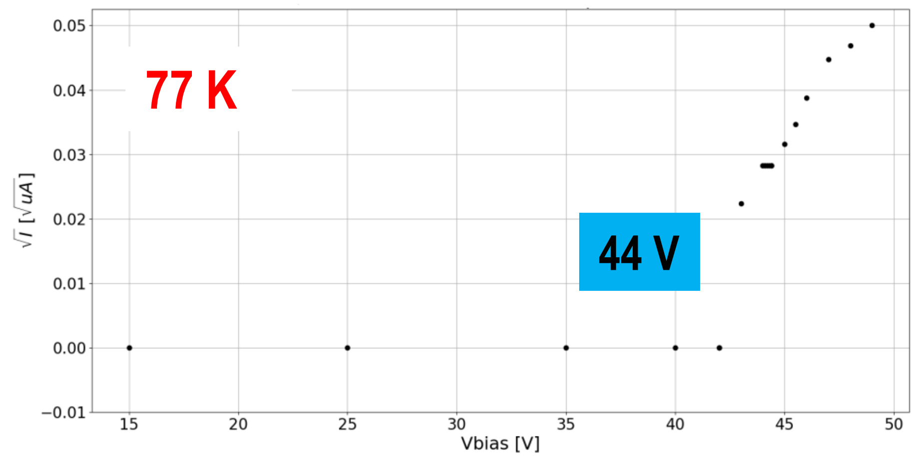
$$y = \frac{norm}{2} \cdot erfc\left(\frac{x-\mu}{\sqrt{2}\sigma}\right) + A$$

$$erfc(z) = 1 - erf(z) = 1 - \frac{2}{\sqrt{\pi}} \cdot \int_0^z e^{-t^2}\, dt$$

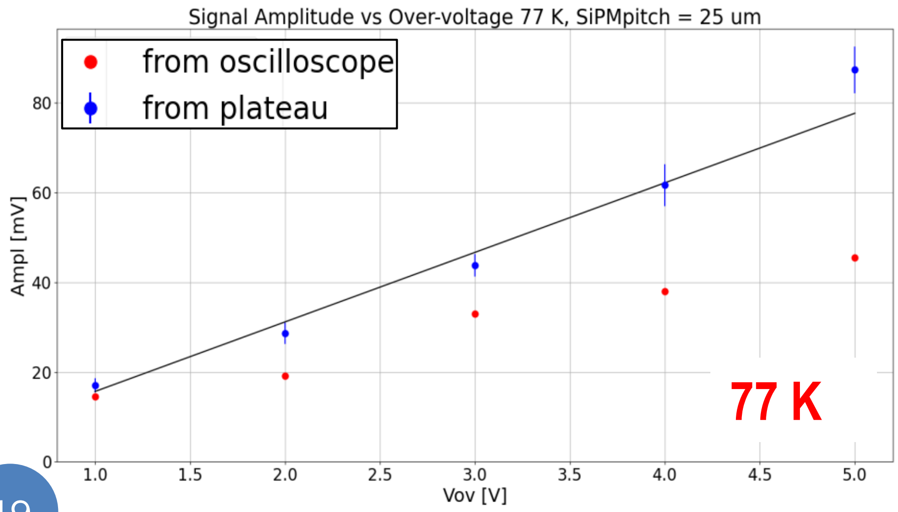
THRESHOLD SCAN RESULTS

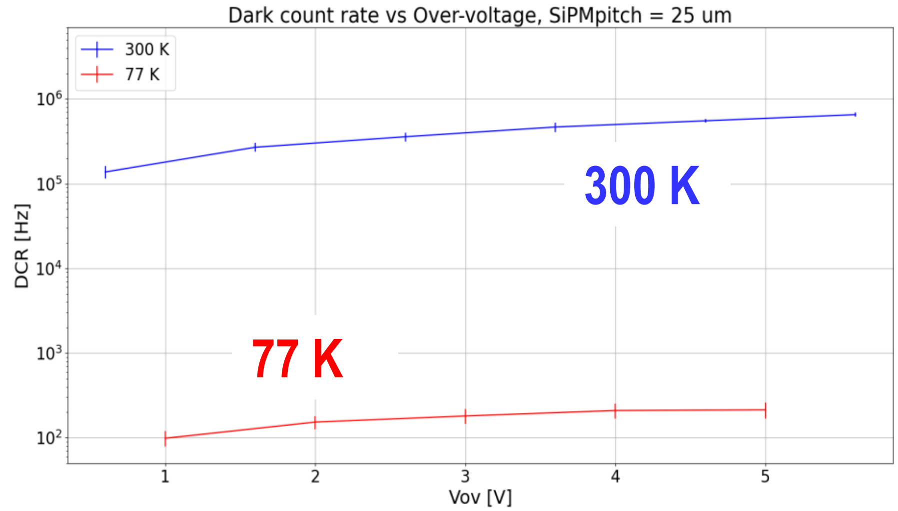
V_{BD} extraction through I-V characteristics:





SIGNAL or DCR vs OVER_VOLTAGE:





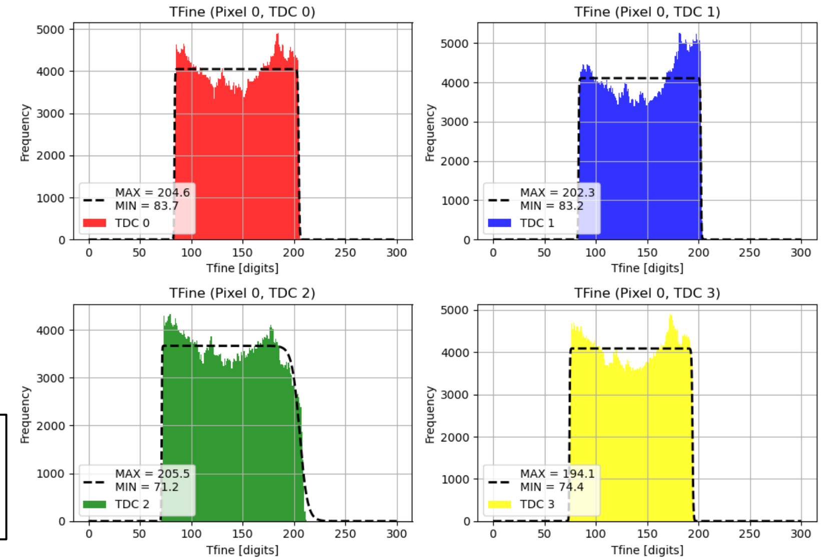
TDCs CHARACTERISATION

TDCs CALIBRATION AT 77 K:

T_{fine} histograms with randomly distributed signals to evaluate LSB

- **MIN** and **MAX** evaluated as μ of **double Fermi-Dirac curve** fit of histograms' extremes:

$$LSB = \frac{T_{clk}}{MAX - MIN}$$

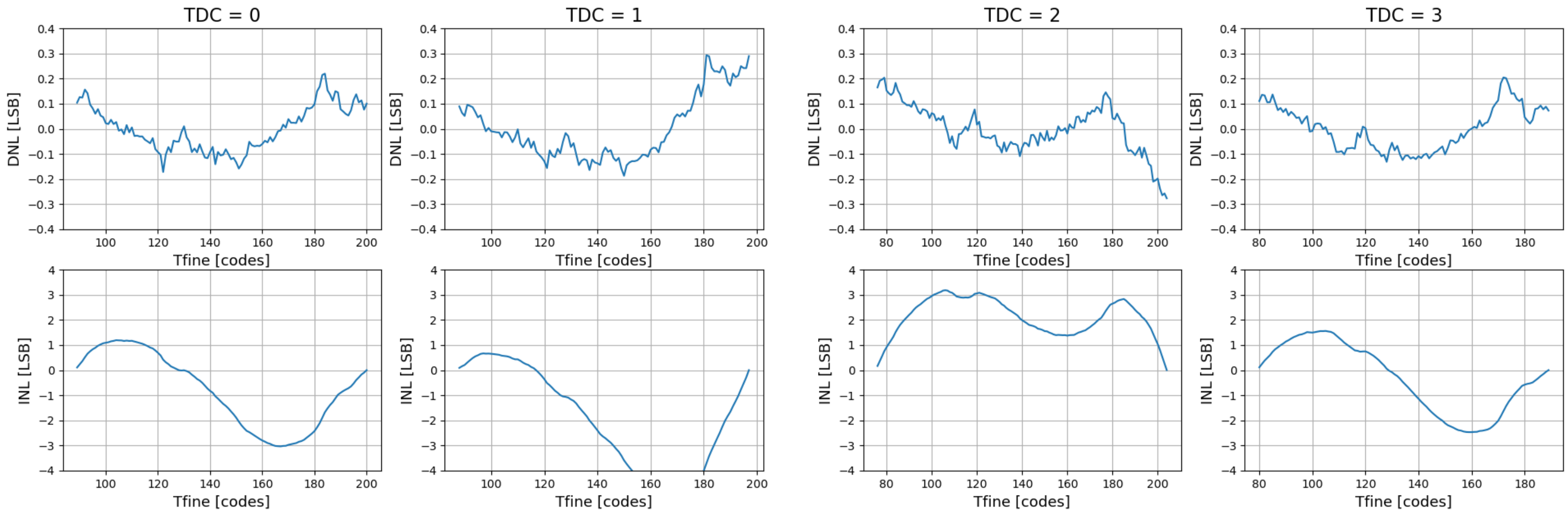


Tfine plateau isn't exactly flat

$$DNL(i) = \frac{N_i - N_{mean}}{N_{mean}}$$

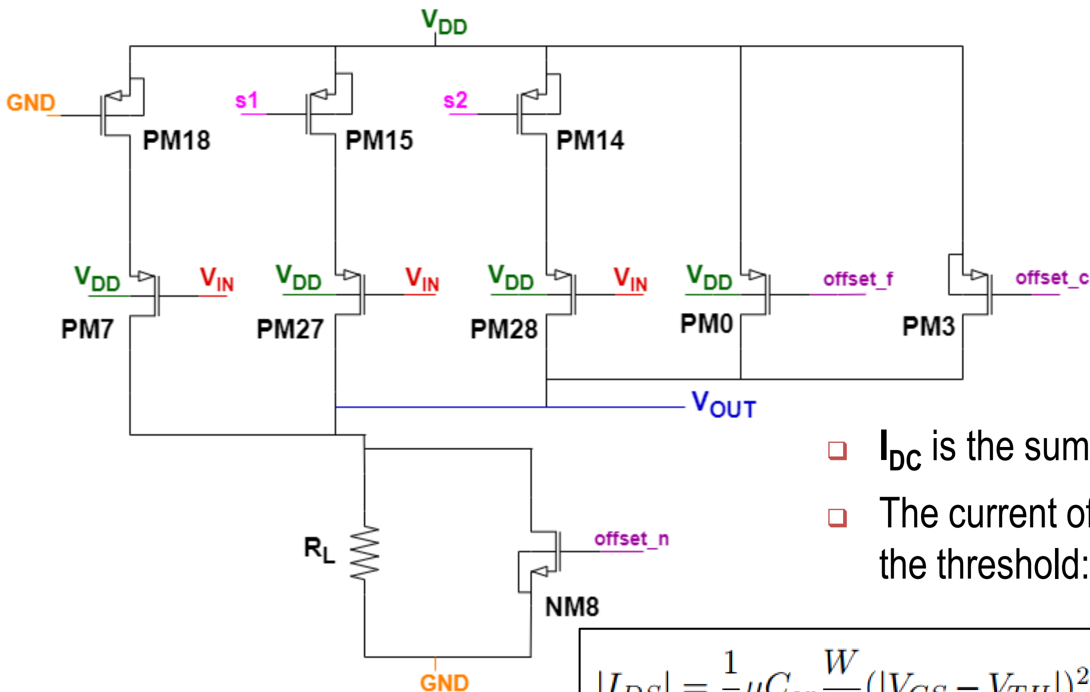
$$INL(i) = \sum_{k=0}^{i} DNL_i$$

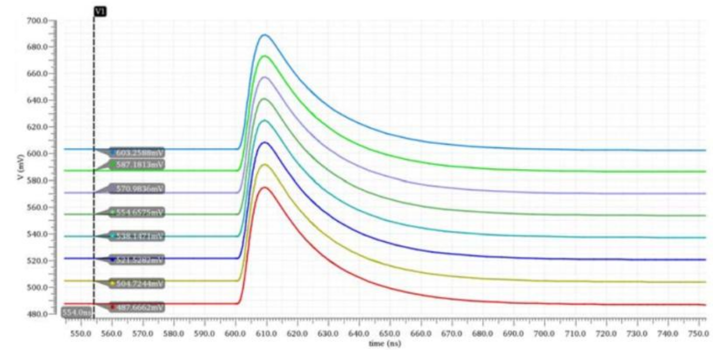
DNL (Differential Non-Linearity) and INL (Integral Non-Linearity) of Pixel 0:



STUDY OF DC OPERATING POINTS

FE output stage: TIA (TransImpedence Amplifier)





$$V_{OUT} = I_{DC} \cdot R_L$$

- I_{DC} is the sum of each branch currents
- The current of each branch has a direct dependence on the threshold:

$$|I_{DS}| = \frac{1}{2}\mu C_{ox}\frac{W}{L}(|V_{GS} - V_{TH}|)^2 \cdot (1 + \lambda|V_{DS}|)$$

Saturation region:

$$|V_{DS}| \geq |V_{GS}| - |V_{TH}|$$

Configuration	V_{DD} [V]	V_{ref} [mV]	Offset1
1	1.2	600	1
2	1.3	700	7

Shift of ≈ + 200 mV

T [K]	I_{DC} [μA]	V_{OUT} [mV]
300	189.8	508.4
77	89.7	240.2