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Description of the ERAM signal + some elx noise studies

(simulations using LTSpice + "full" calculation)

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Work made with:

- *Shivam Joshi, Tristan Daret (PhD students)*
- Ahmed Amine Oumarghad, Mohamed Amin Ben Atitallah (M2)
  Soubickchane Ramtchandirin (M1)
  from Gustave Eiffel university (ex. Marne-la-vallée Paris-Est univ.)
- Raphaël Fourquet (M1)
  from CentraleSupélec Paris-Saclay
- Christopher Winterstein (M1)
  from ENSTA Paris, Institut Polytechnique de Paris

+ discussions with colleagues:
Denis Calvet, Pascal Baron, Alain Delbart, David Attié, Paul Colas, etc.

Full simulation/numerisation
Full ERAM prod. analysis,
dE/dx, etc.

LTSpice + some C++/
Python analysis/calculation

Full hand made
simulation/calculation and
analysis (C++/Python)

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Many slides from JFL presentation of
IRFU - MPGD meeting, 05/03/2024

IN2P3-IRFU gaseous det. workshop
Ganil, Caen, 21-22/03/2024

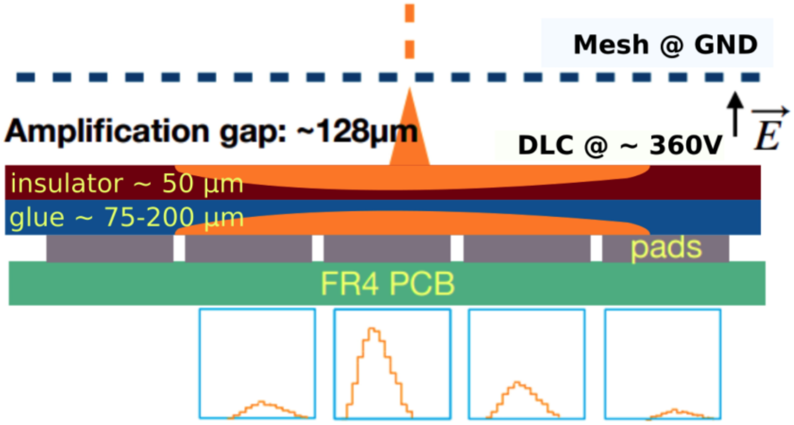
Layout

- Signal formation in resistive (full layer) Micromegas
- Telegraph equation
- Electronique response calculation
- LTSpice modeling (included elx response)
- Space time discretisation
- Elx noise studies

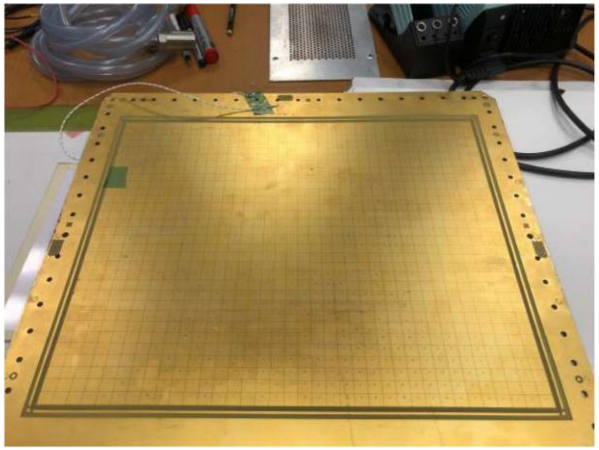
ERAM: ENCAPSULATED ANODE RESISTIVE MICROMEGAS

ERAM are resistive Micromegas, working very well ! (*)

They equip the two High Angle TPCs of the upgrades of the Near Detector ND280 of T2K



Resistive anode (DLC) read by metallic pads
capacitive coupling between resistive layer and pads



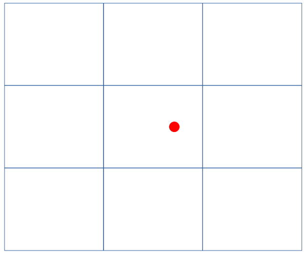
36 x 32 metallic pads
Pad size (mm^2) : 11.28 x 10.19

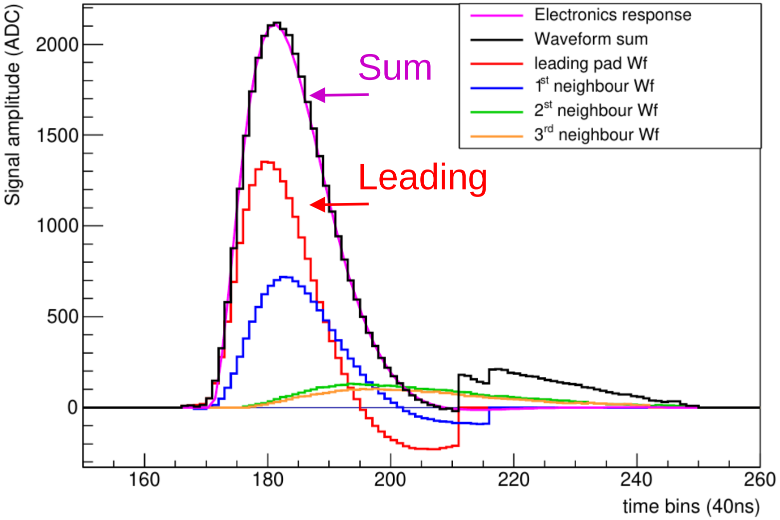
How the signals look ?

(*) nothing to compare with MM for NSW…

SIGNALS: HOW THEY LOOK

Charge deposited punctually on a pad (X ray)





ADC signal : max 4096 counts

Time window of 511 time bins

Time bin (typ.): 40 ns (25 MHz sampling)

Peaking time (typ.) : 412 ns

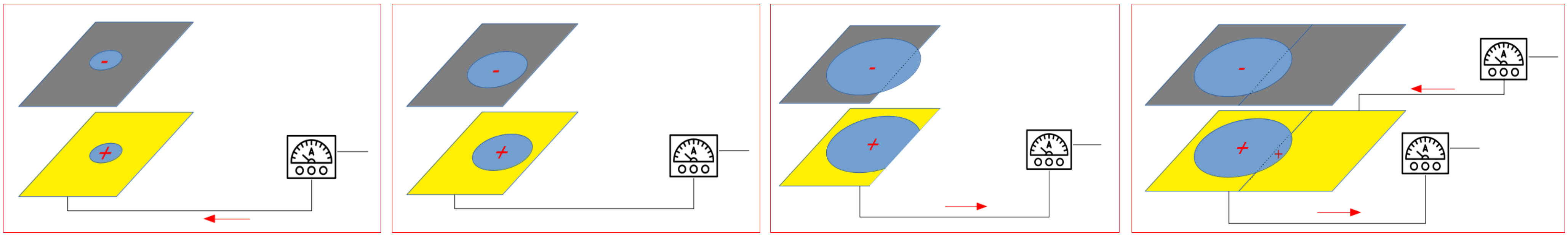
Leading pad : highest and earliest signal ⇒ charge deposited in this pad

Next pads: lower and later signals ⇒ charge has diffused up and through these pads

How the signals look ?

CAPACITIVE COUPLING AND ELECTRONICS SIGNAL

Capacity coupling means
a pad “responds” to the total charge on the resistive layer, lying directly above it

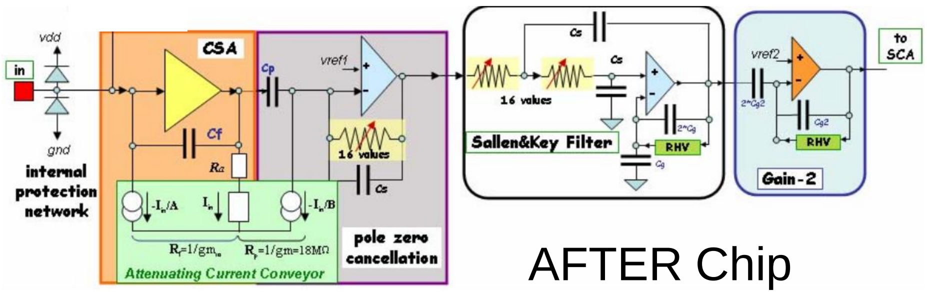


Electronic response : $ADC_{pad}(t) = \frac{dQ_{pad}}{dt} \otimes ADC^{Dirac}$ $(\Rightarrow ADC \neq Q)$

where $ADC^{Dirac}(t)$ is the electronic response to a Dirac pulse of current

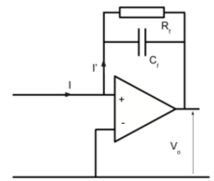
ELECTRONICS PULSE RESPONSE

Pascal B. *et al.*

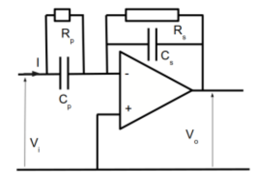


AFTER Chip

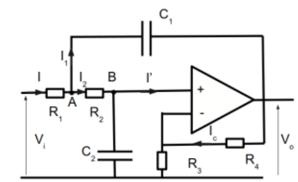
CA



Pole Zero Canc.

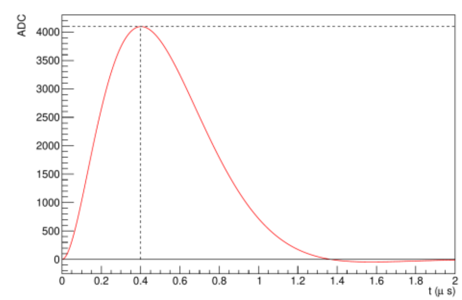


Salen&Key (2nd order)Filter



Laplace transform
⇒ pulse response

JFL



$$ADC^{Dirac}(t) = \frac{4096}{120fC}\,\frac{f(t;w_S,Q)}{f_{max}} \quad \text{where} \quad f(t;w_S,Q)$$

$$= e^{-w_S t} + e^{\frac{-w_S t}{2Q}}\left[\sqrt{\frac{2Q-1}{2Q+1}}\,sin\left(\frac{w_S t}{2}\sqrt{4-\frac{1}{Q^2}}\right) - cos\left(\frac{w_S t}{2}\sqrt{4-\frac{1}{Q^2}}\right)\right]$$

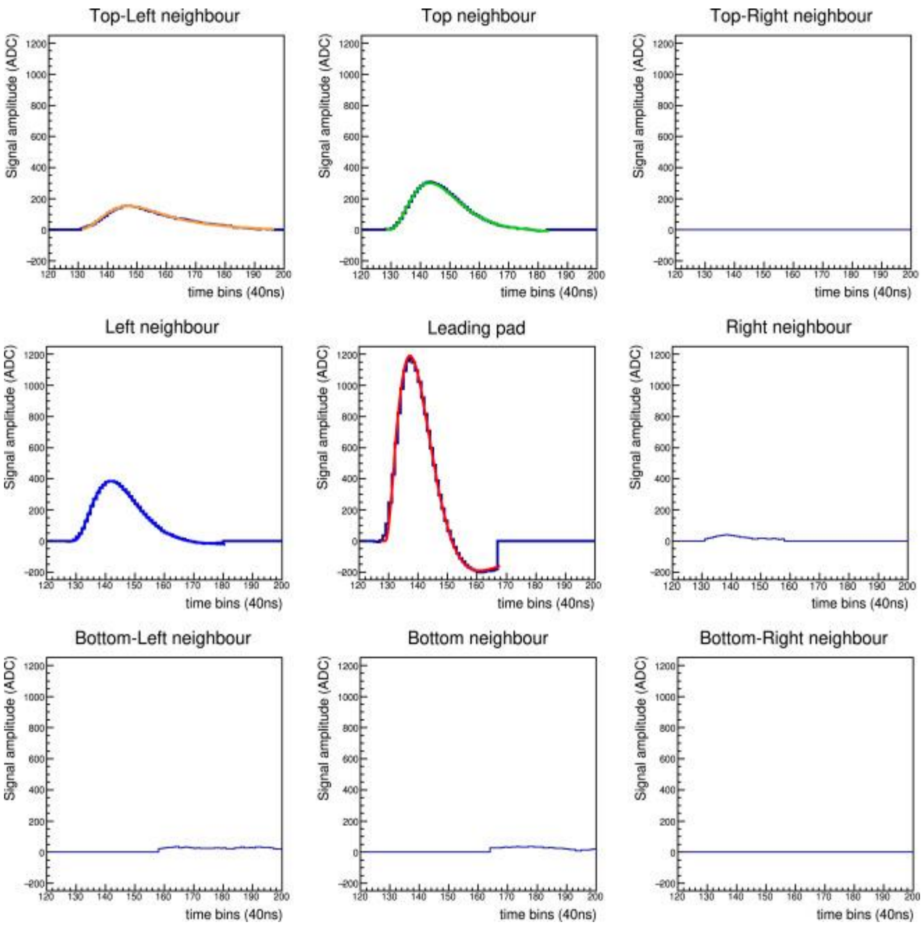
Parametrization of the electronics response with 2 parameters
w_S~1/Peaking time and Q quality factor

The plan: apply everywhere the “simple” model
Telegraph Equation ⊗ Dirac pulse parametrization

FITTING THE WAVES (X RAYS DATA)

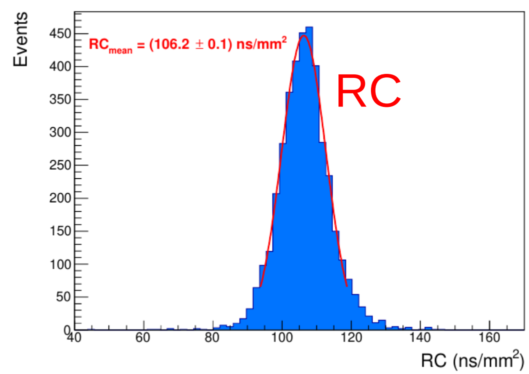
X rays deposited punctually charge on the anode

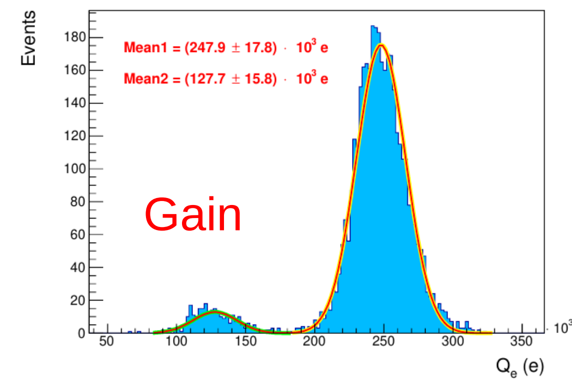
Shivam Joshi's study (PhD)



For a given pad, for each deposit
fit simultaneously the Waveforms of the hottest pads

Extract RC, Gain and deposit position/time

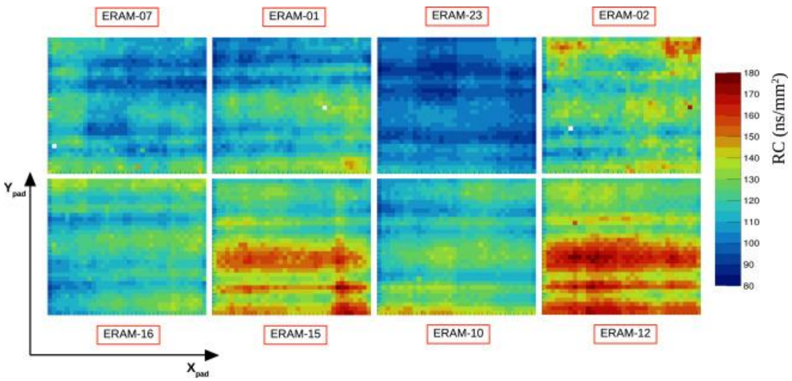




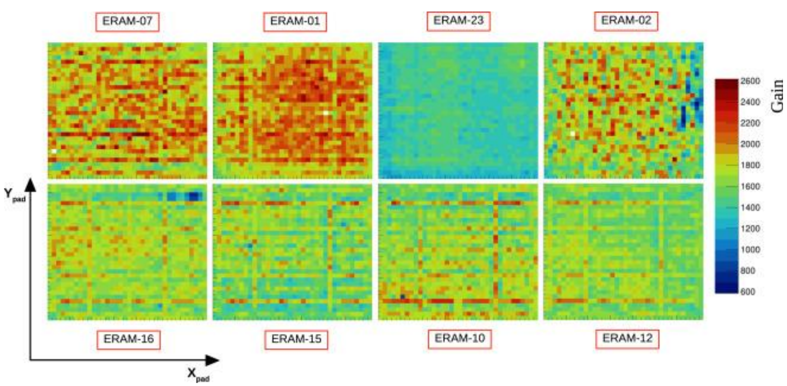
Nucl.Instrum.Meth.A 1056 (2023) 168534

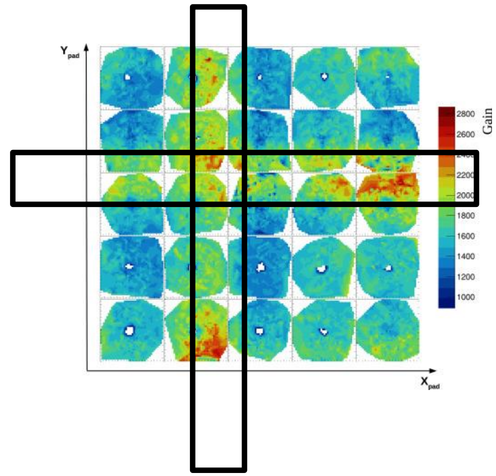
FITTING THE WAVES (X RAYS DATA)

RC maps



Gain maps



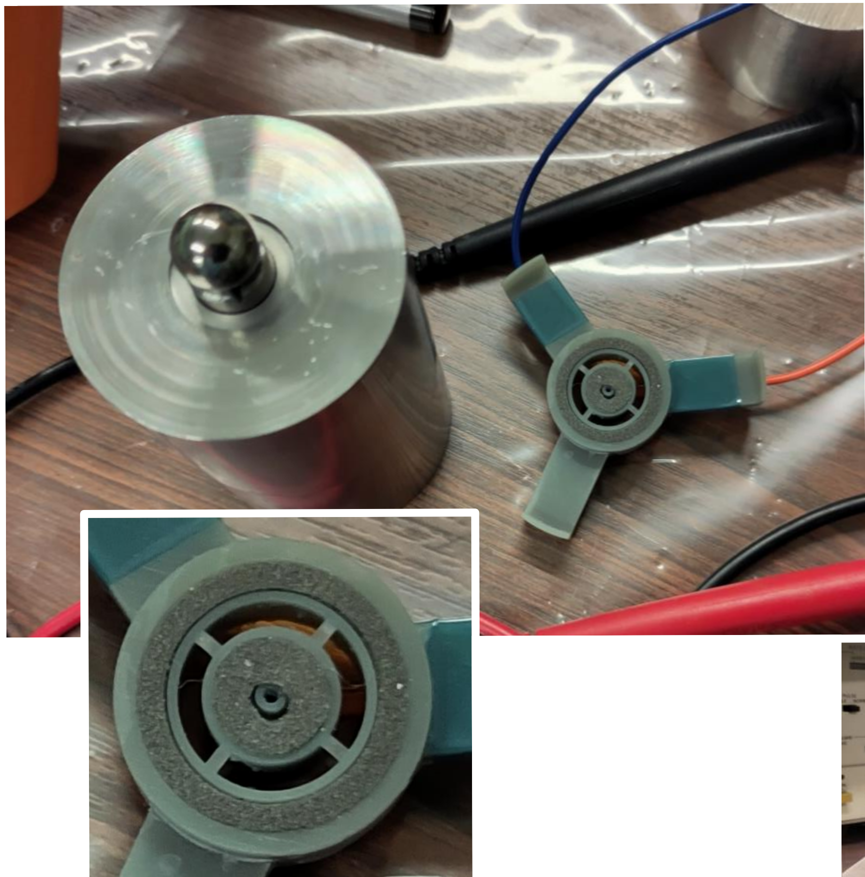


High granularity gain map <= imprint of **mechanical constraints** at assembly

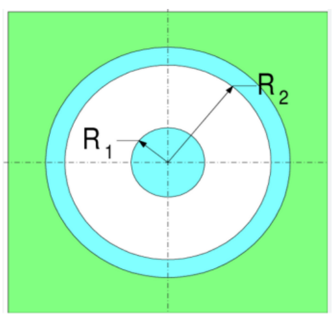
Shivam's work is now one of the cornerstones of the Quality Validation of the ERAMS used in T2K High angle TPCs

Wave in RC?

Measurement of R/sq. of a ERAM PCB # **22** - *given by Rui*



Done with Marc L.
3D printed in resin.



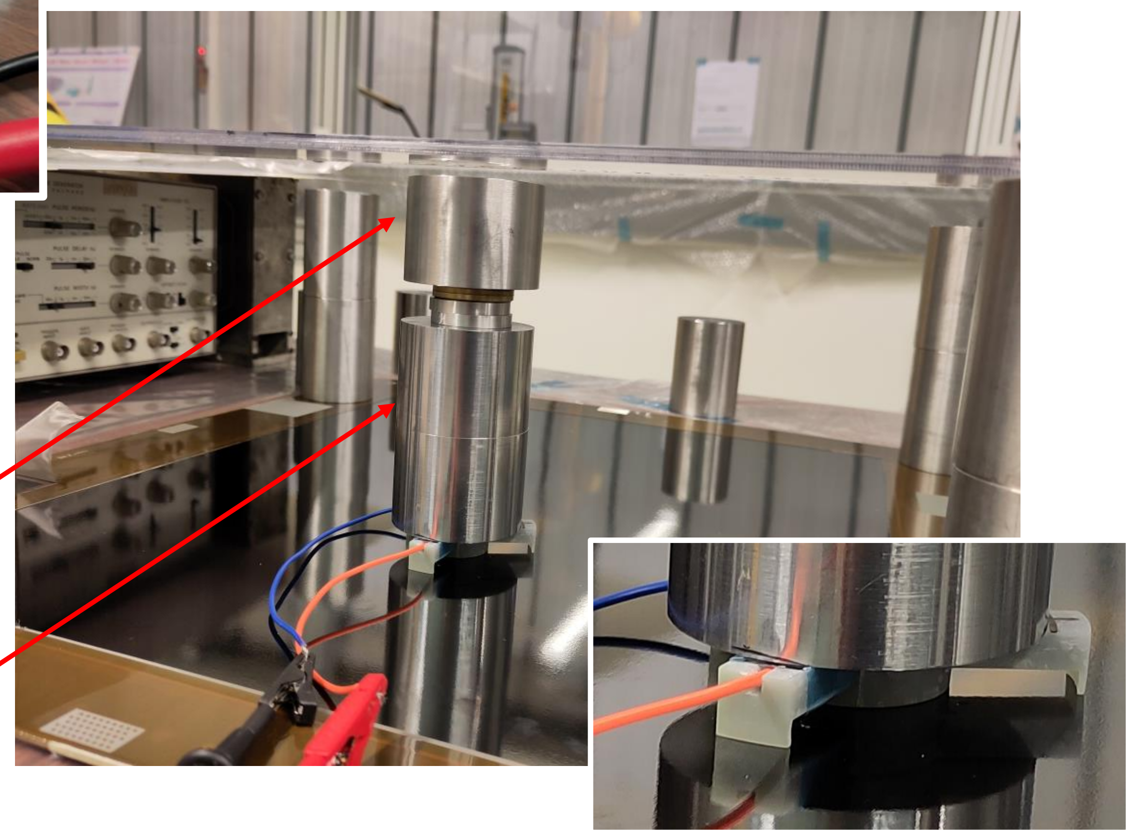
Probe: 2 concentric conductive (polymer) rings

For good/reproducible contact: weights in 2 indep. parts (with identical weights ~ in kg/mm²)

From ohm to R/sq.:

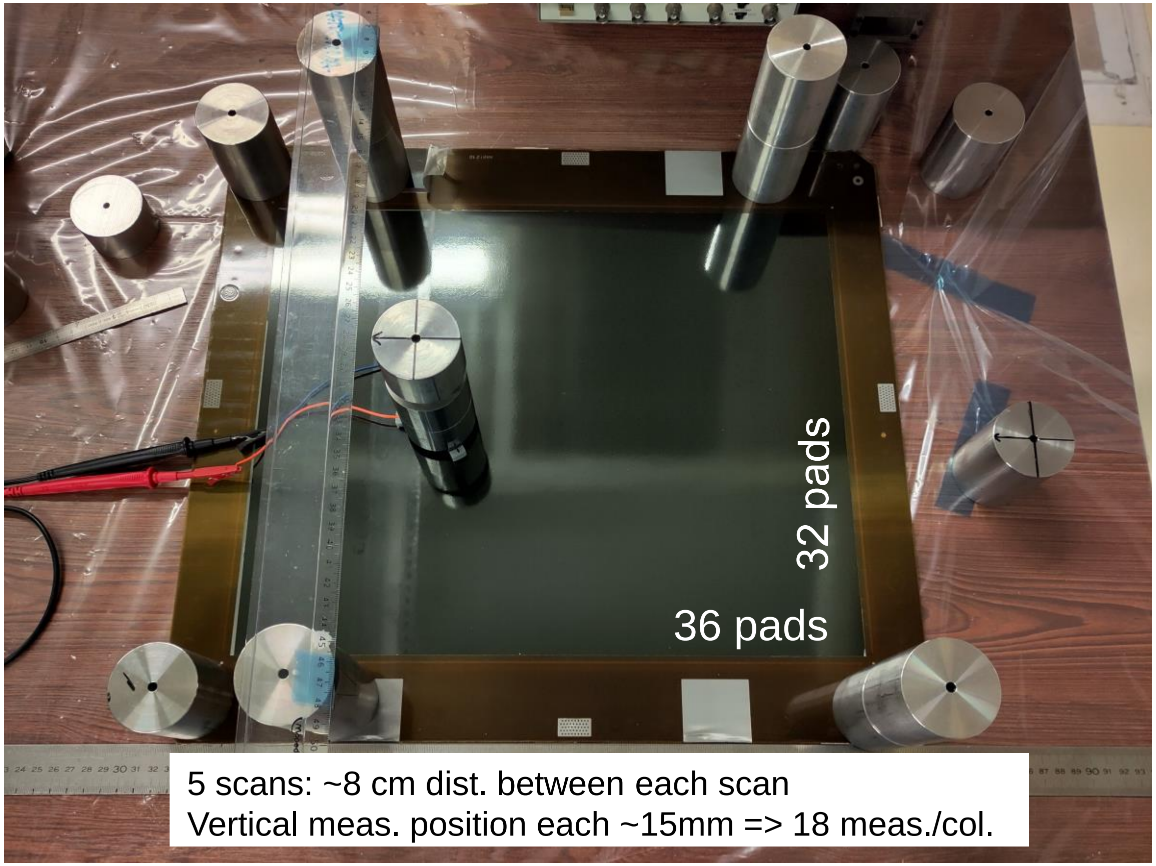
⇒ **correction factor: $K = 2.\pi / \ln(R_{ext}/R_{in})$**

with R_{ext} ~ 8 mm, R_{in} ~ 4,5 mm => K ~ 10,9



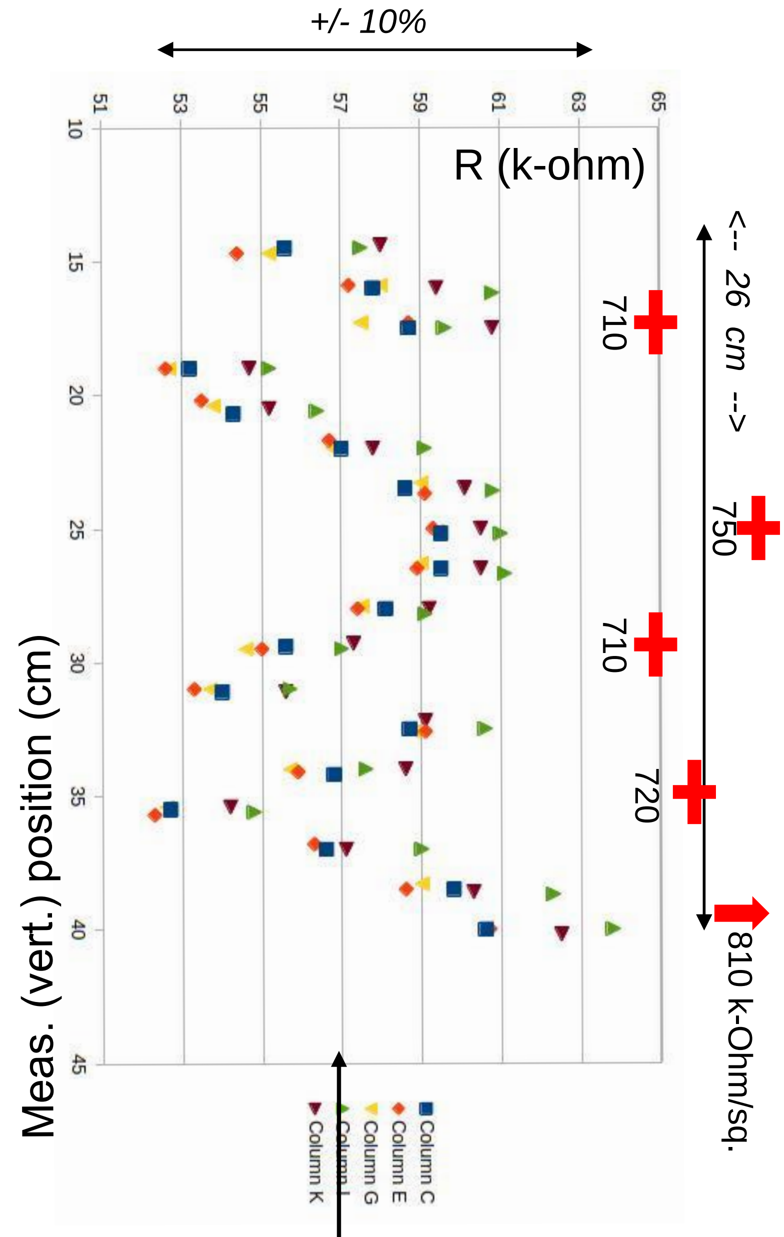
Top weight for the inner cond. ring

Bot. weight for the outer cond. ring



+ 5 measurements ✚ *done, on the Left side of the PCB*

The probe is too large to see the structure of R/sq. of DLC.



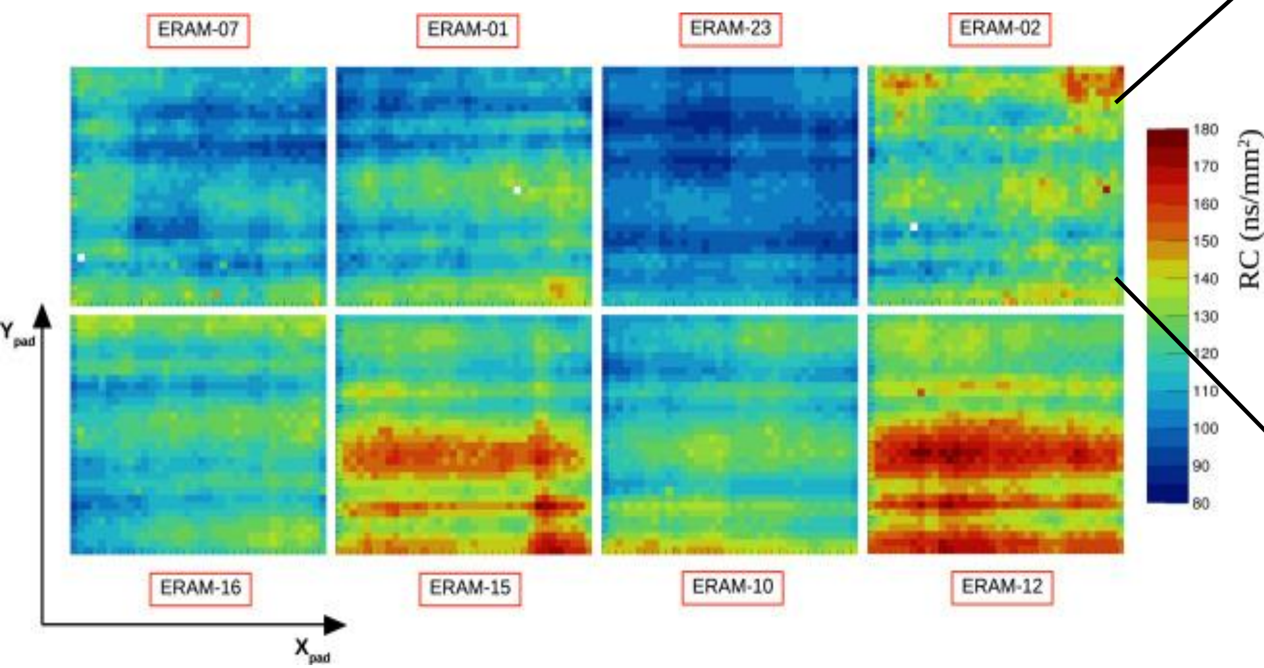
(taking into account K factor)

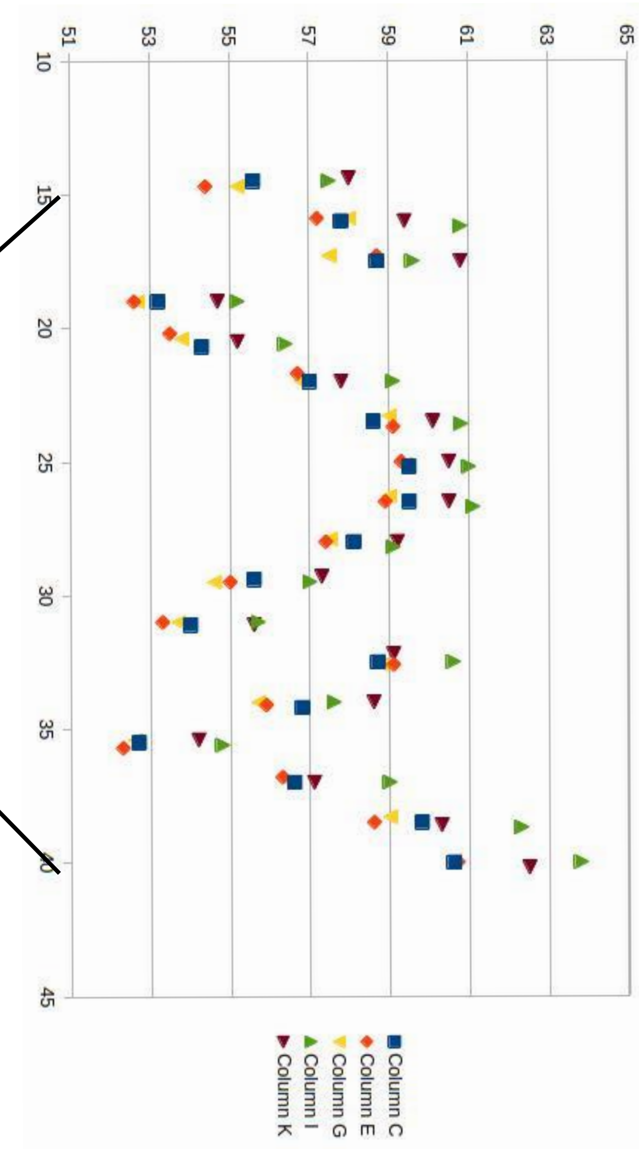
~620 k-Ohm/sq.

FITTING THE WAVES
(X RAYS DATA)

RC maps

(from X-ray runs)





R/sq. variations come from R-sheet production?

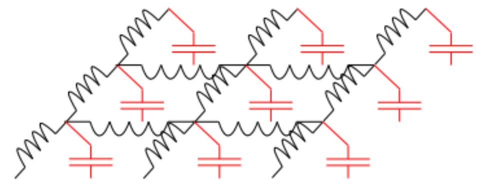
(how to measure C with same pitch, how?)

SPACE DISCRETISATION: LTSPICE

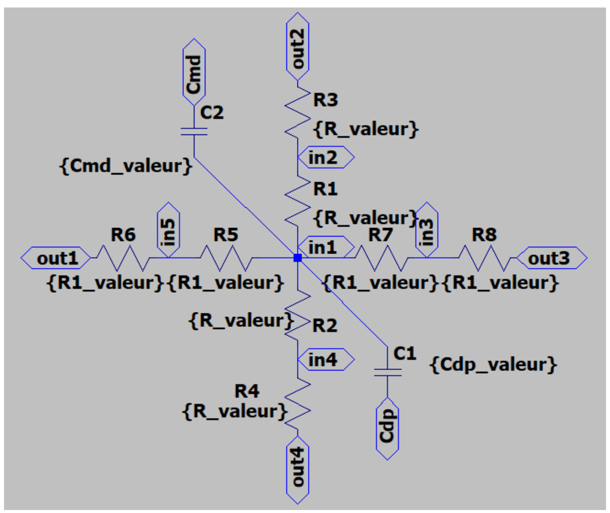
Ben Atitallah Mohamed Amin
Oumarghad Ahmed-amine (M2)

$$\frac{\partial\rho}{\partial t} = \frac{1}{RC}\left(\frac{\partial^2\rho}{\partial^2 x} + \frac{\partial^2\rho}{\partial^2 y}\right) \Rightarrow \frac{dq_{i,j}}{dt} = \frac{V_{i+1,j} - V_{i,j}}{R_x} + \frac{V_{i-1,j} - V_{i,j}}{R_x} + \frac{V_{i,j+1} - V_{i,j+1}}{R_y} + \frac{V_{i,j-1} - V_{i,j-1}}{R_y} \text{ with } R_x = \frac{1}{\sigma}\frac{\Delta_x}{\Delta_y},\ R_y = \frac{1}{\sigma}\frac{\Delta_y}{\Delta_x} \text{ and } V_i = q_i C_s \Delta_x \Delta_y$$

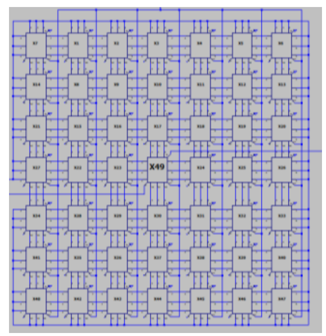
⇔ Layer of resistors connected to ground trough capacitances



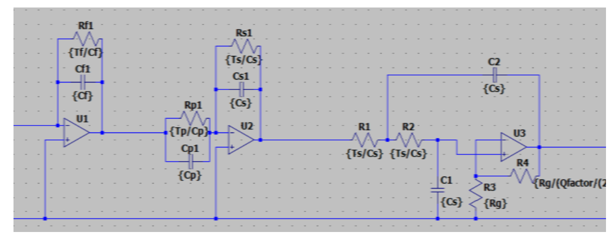
LTspice elements of our framework



<u>Elementary cell</u>:
4 Rs and 2 Cs
(DLC/Mesh, DLC/pad)



An Eram of 8x7 pads
(with a pad=3x3 nodes)



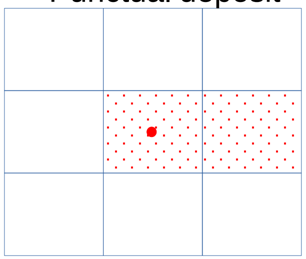
AFTER Chip LTSpice Implementation
(not strictly necessary but fun)

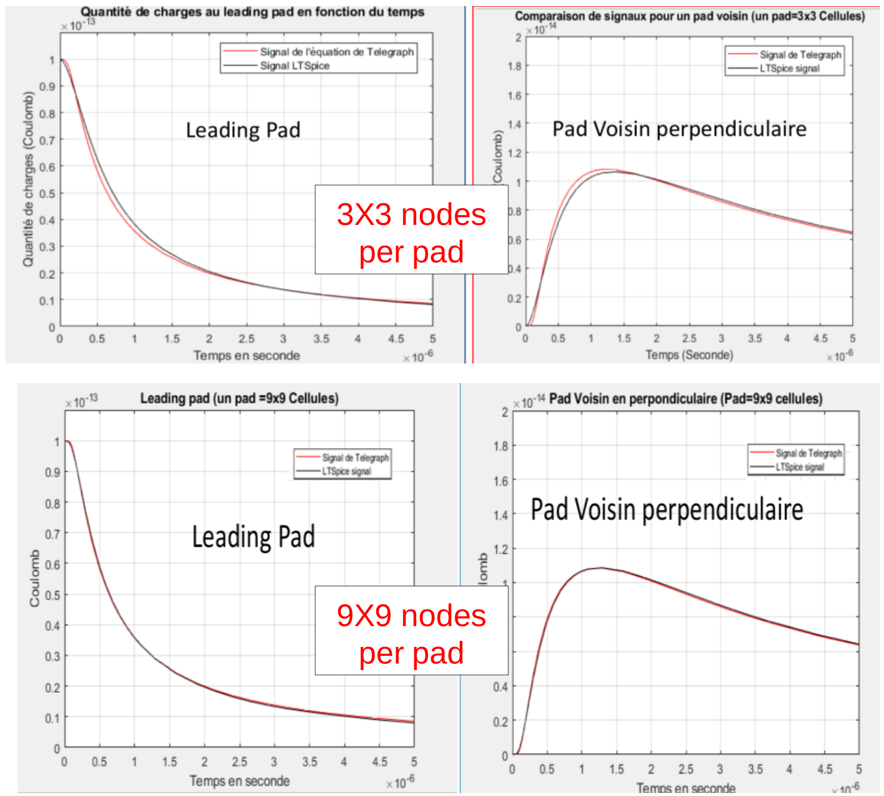
(e-) signal injection at the capa - DLC connexion

SPACE DISCRETISATION: LTSPICE

Charge vs time : Sim. compared to exact Telegraph Eq. solution

Punctual deposit





- How many nodes are needed ?

- Preliminary **X-talk** study : Gerber routing + input ***impedance from P. Baron***

⇒ small effects found but would need more data

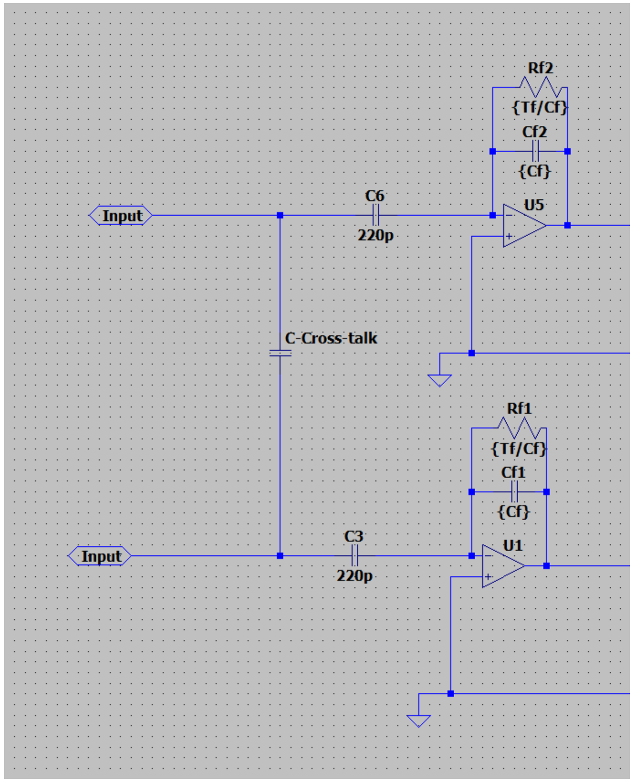
The LTspice framework is now complete

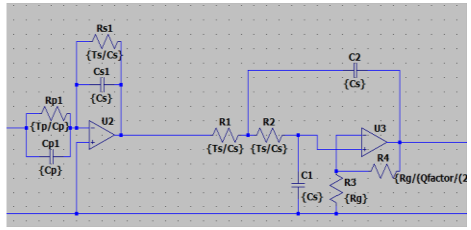
Main issue/showstopper circuits are built graphically nice for debugging for small stuff really problematic for large circuit

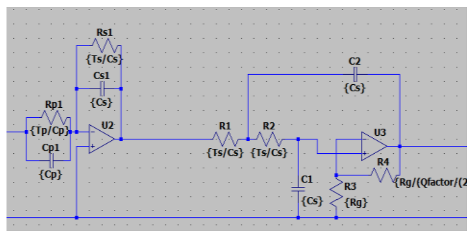
Quickly
humanly not scalable/editable

Possible way out (not explored): ASCII file - *netlist,* description of network (but then no more viewable)

CROSS TALK STUDY: LTSPICE





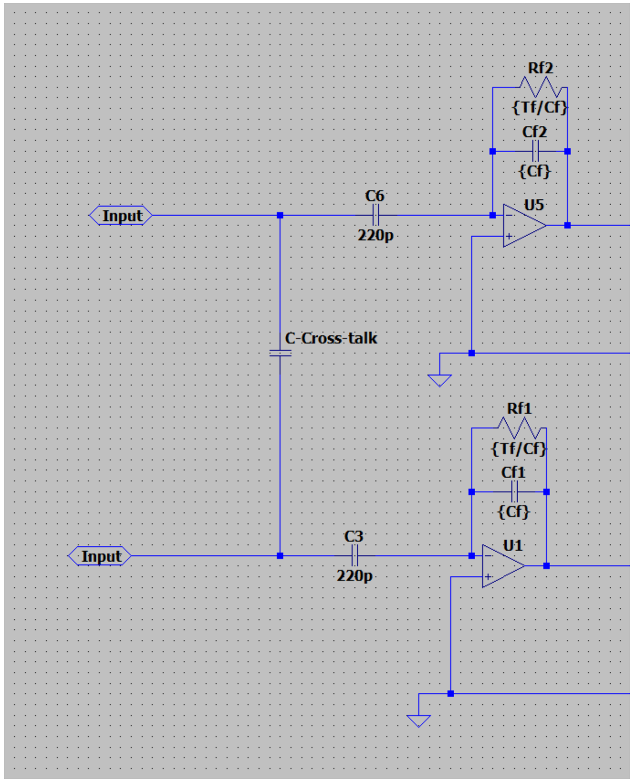


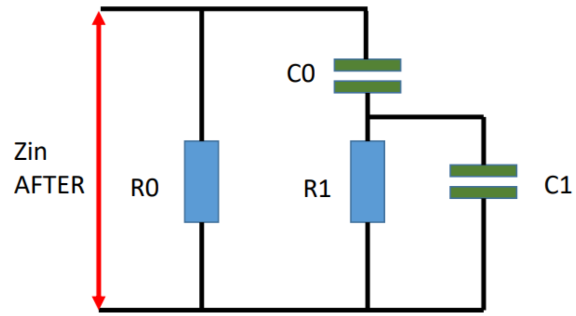
The first chip AFTER simulated uses theoretical elements

$\Rightarrow$ impedance problem…

$\Rightarrow$ Pulse timing problem for the non-leading pads when cross talk

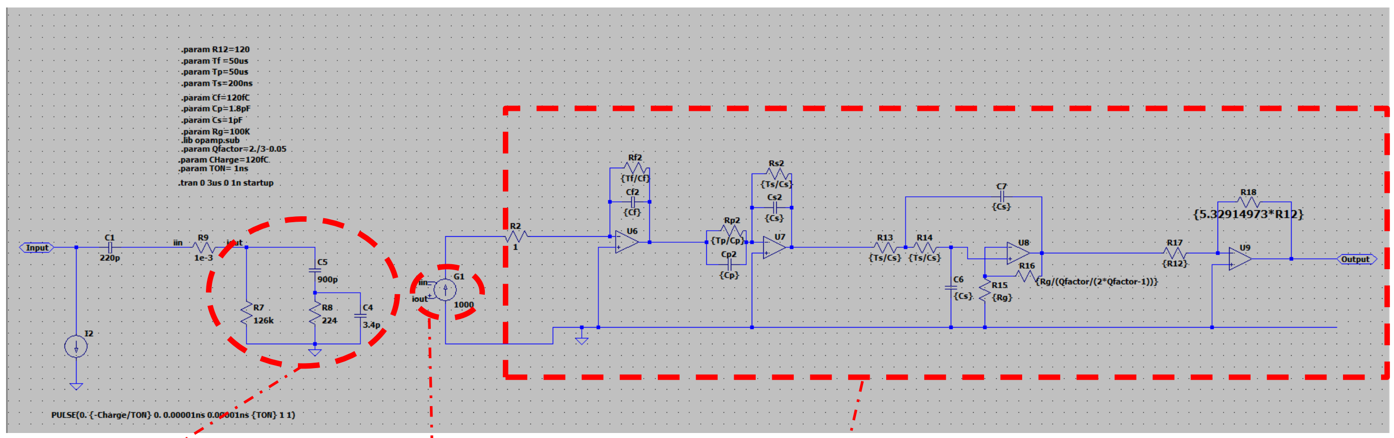
CROSS TALK STUDY: LTSPICE





Gain	R0	R1	C0	C1
120 fC	126 K	224	900 pF	3.4 pF

From Pascal B.



The input Impédance Zin

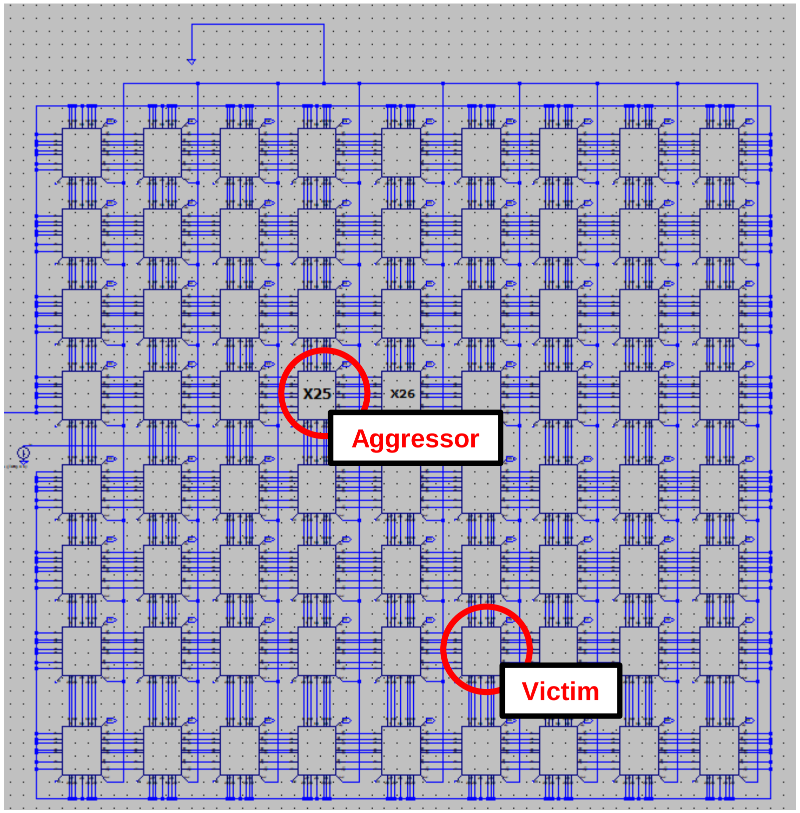
Current mirror

Version 0 AFTER Chip

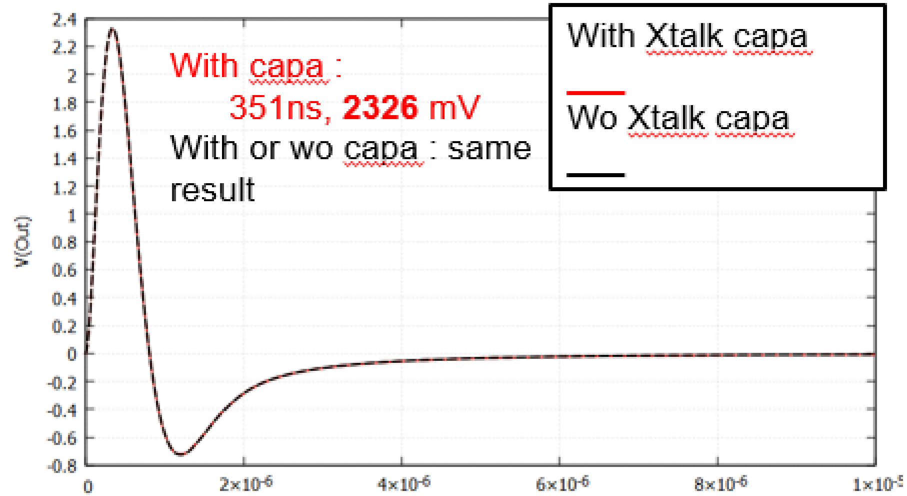
CROSS TALK STUDY: LTSPICE

Oumarghad Ahmed-Amine (M2)

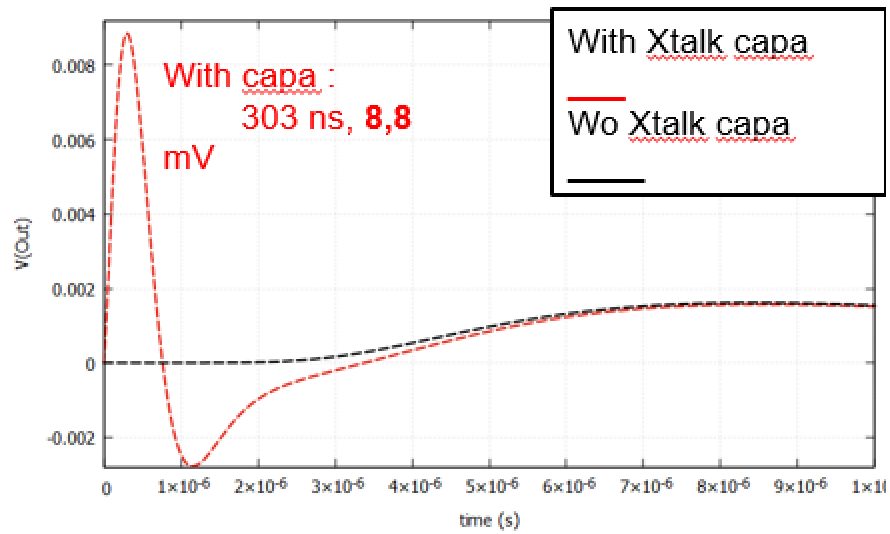
ASIC Circuit : 9x8 Pads



V(Out) : Aggressor



V(out) : Victim



Wrt Aggressor cross talk

- **Cross-Talk ~ 0,4 %**
- ΔT ~ 40 ns (like with real data?)

For a C-cross talk of ~1 pF

What's the real value?

SPACE-TIME DISCRETISATION

SPACE-TIME DISCRETISATION

Christopher Winterstein (M1 Intern)

$$\frac{\partial \rho}{\partial t} = \frac{1}{RC}\left(\frac{\partial^2 \rho}{\partial^2 x} + \frac{\partial^2 \rho}{\partial^2 y}\right) \Rightarrow \frac{q_{i,j}^{t+1} - q_{i,j}^{t}}{\Delta_t} = \frac{q_{i+1,j}^{t} - q_{i,j}^{t}}{C_s \Delta_x \Delta_y R_x} + \frac{q_{i-1,j}^{t} - q_{i,j}^{t}}{C_s \Delta_x \Delta_y R_x} + \frac{q_{i,j+1}^{t} - q_{i,j+1}^{t}}{C_s \Delta_x \Delta_y R_y} + \frac{q_{i,j-1}^{t} - q_{i,j-1}^{t}}{C_s \Delta_x \Delta_y R_y}$$

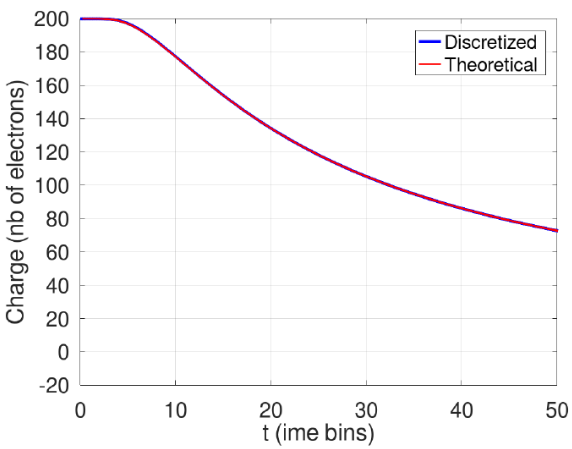
$$\vec{q}^{\,t+1} = (I + \Delta_t S)\ \vec{q}^{\,t}$$

Proofs of

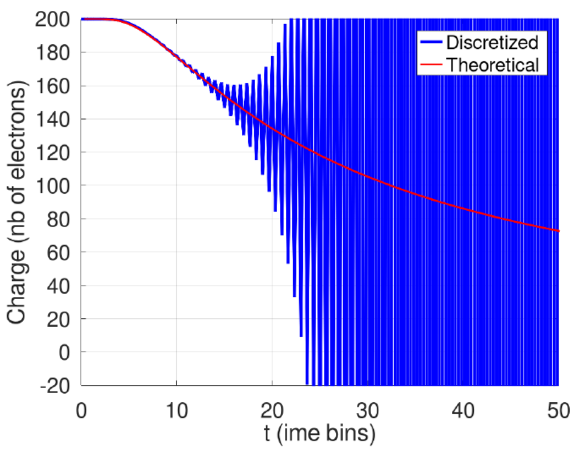
Convergence: numerical solution converges toward continous solution in the limit $\Delta_t, \Delta_{x;y} \to 0$

Stability: space/time discretisation introduces a scale for RC (RC is $Time/Surface$), $\Delta_t/\Delta_{x;y}^2$

The criteria of stability turns out to be: $RC \geqslant 2\left(\frac{\Delta_t}{\Delta_x^2} + \frac{\Delta_t}{\Delta_y^2}\right)$



Δ_t below limit



Δ_t above limit

Actually confortable limit

For $\boldsymbol{\Delta_t} \sim$ **2ns and** $\boldsymbol{\Delta_{x,y}} \sim$ **300µm**

$RC_{min} \sim \mathbf{76\,ns/mm^2}$

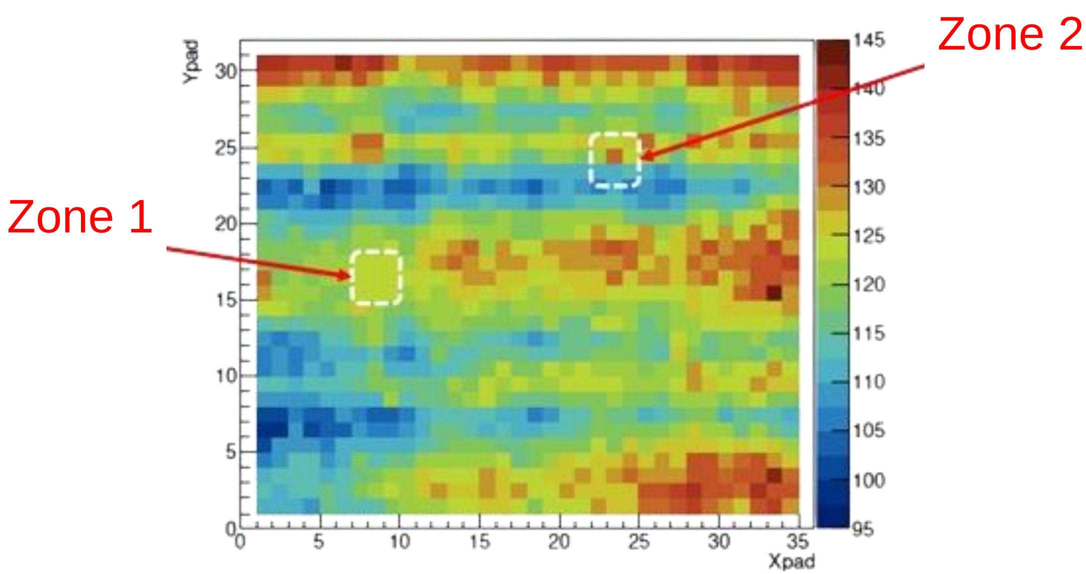
since

Time bin : $40ns$

Pad size: $\sim 1cm$

Our RCs are typically $\geqslant 100\,ns/mm^2$

- Scalability is no more an issue: currently 33 x 33 nodes per pad
- Update of local RCs is easy ⇒ preliminary tests with non uniform RC



From actual Shivam's RC map
of ERAM 16

Zone 1

119.95	121.93	122.85
119.84	121.59	123.52
118.20	123.30	122.03

Calm area

Zone 2

124.62	122.66	125.21
120.82	128.8	121.43
110.31	112.5	113.47

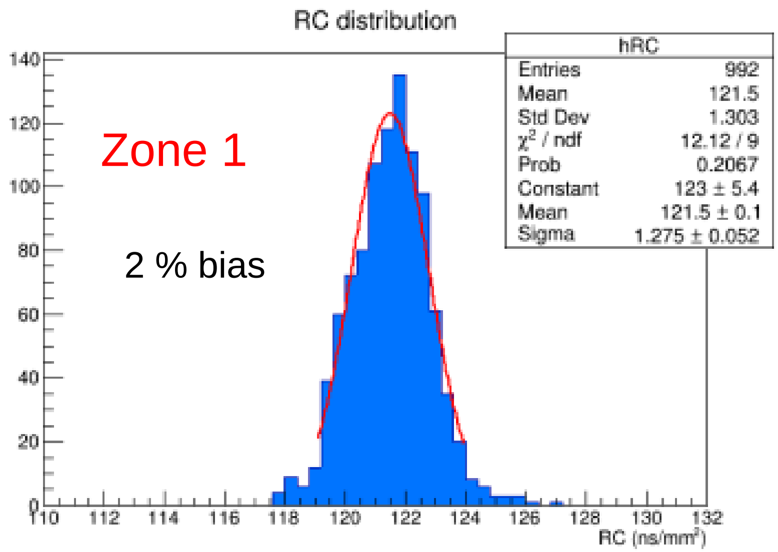
Wild area

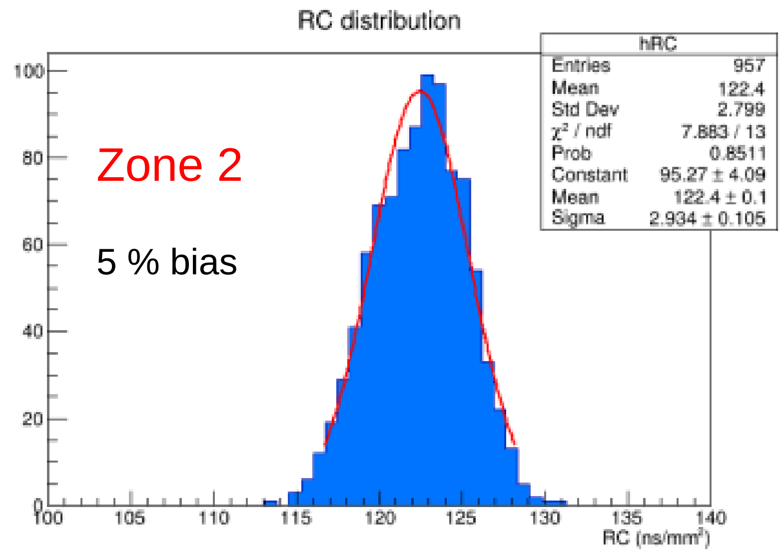
Non uniform RC injected in FDM code
⇒ Toys events to be fitted as X ray
data

Up to now for a given pad, assume all neighbor pads have same RC than leading pad.

SPACE-TIME DISCRETISATION

- Scalability is no more an issue: currently 33 x 33 nodes per pad
- Update of local RCs is easy ⇒ preliminary tests with non uniform RC





Systematics from RC uniformity assumption can be evaluated from simu/FDM code + realist RC maps

Work in progress

UNDERSTANDING THE NOISE

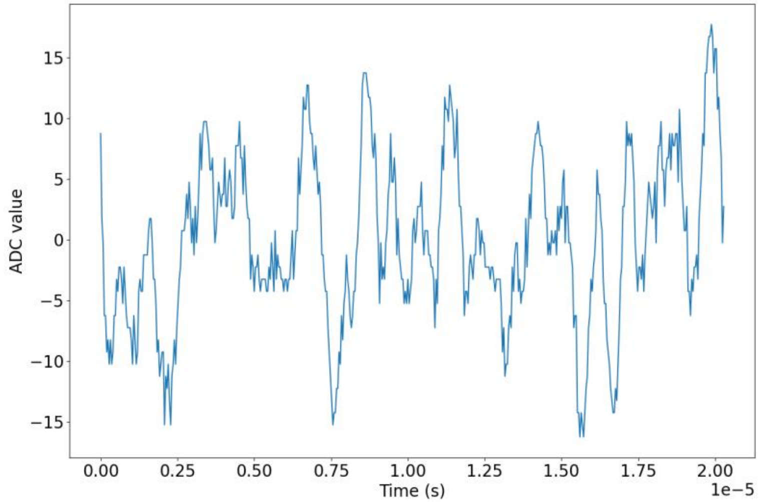
UNDERSTANDING THE NOISE

To understand the signal, one has to understand the noise. So how it looks?

Soubickchane Ramatchandirin + Raphaël Fourquet (M1 interns)

Record of the baseline (no trigger) by D. Calvet

One record
T_p= 412 ns
F_s = 25 MHz



Fluctuations over many time bins

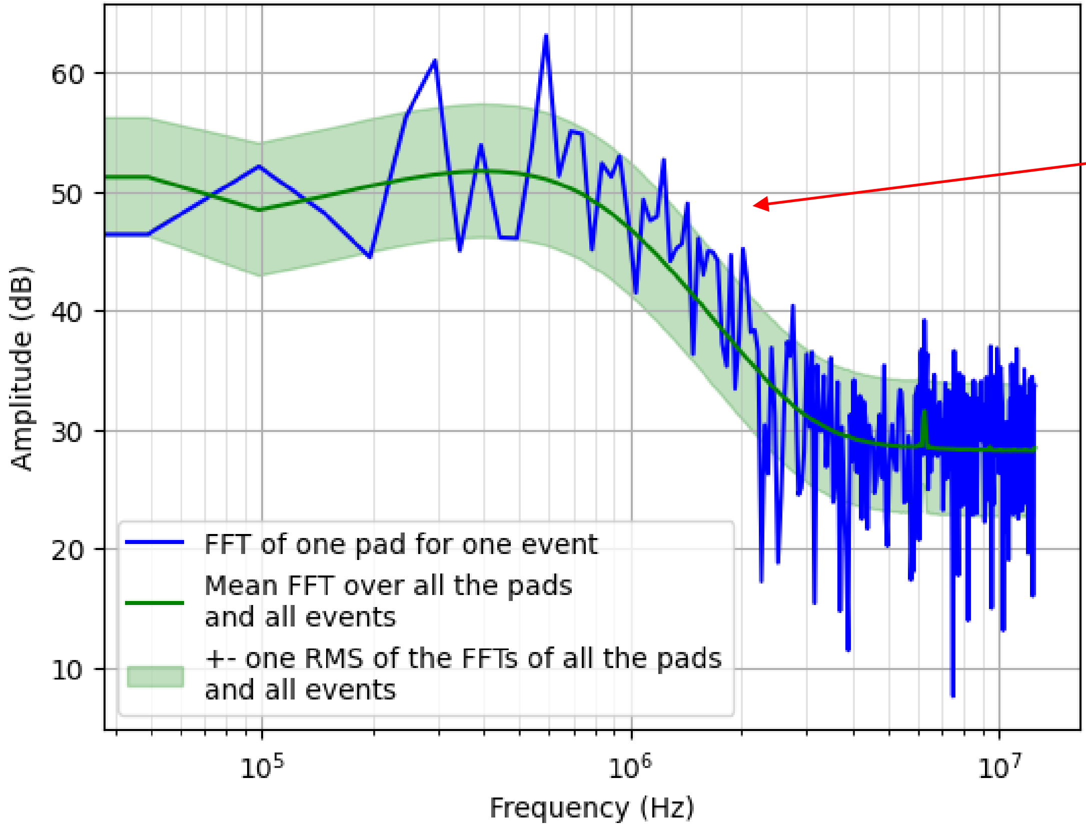
⇒ The frequencies of the bulk of Noise are much lower than 25 MHz (1/time bin = 40ns)

⇒ Low frequency noise,
ie some correlation from time bin to time bin…

Done 10 times for all pads of the **16 Erams now in Japan** (bottom TPC),
for 4 sampling frequencies and 2 peaking times
(~1000 pads / ERAM)

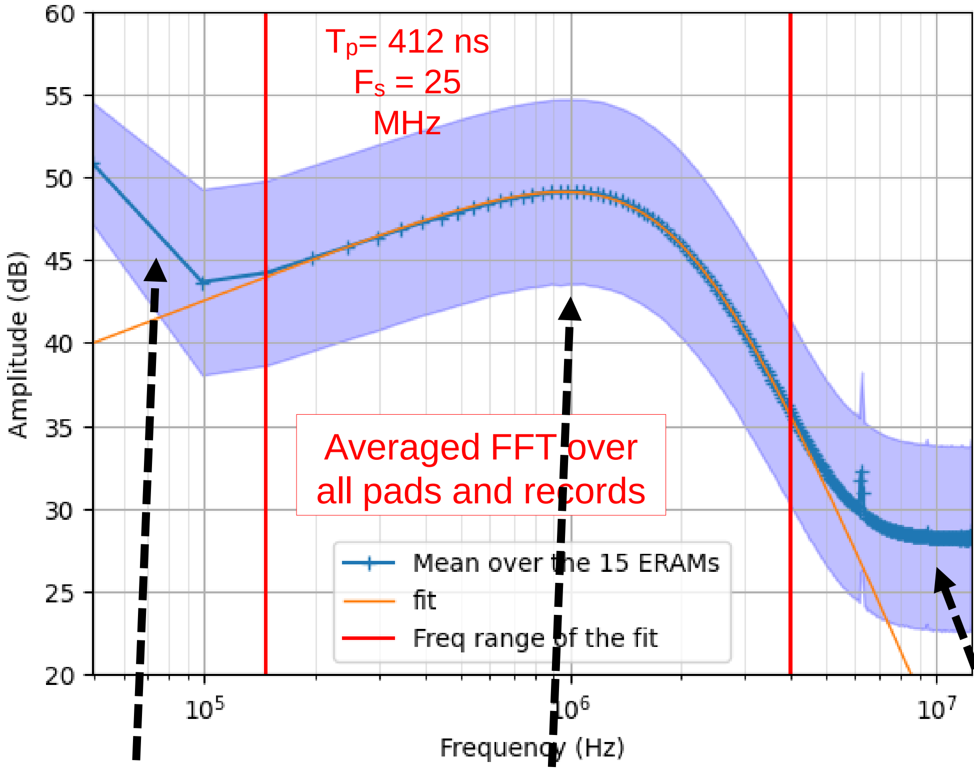
Fast Fourier Transform of the baseline record: one record compared to averaged FFT over all pads and records

T_p= 412 ns
F_s = 25 MHz



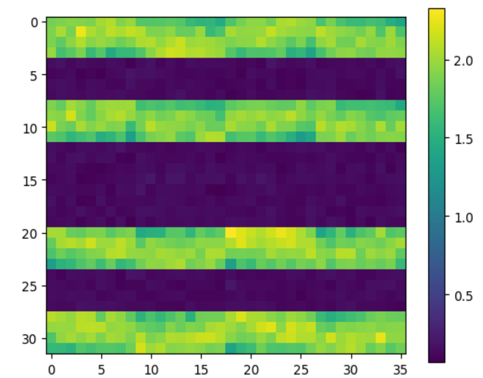
Dominated by frequencies lower than 1 MHz

UNDERSTANDING THE NOISE

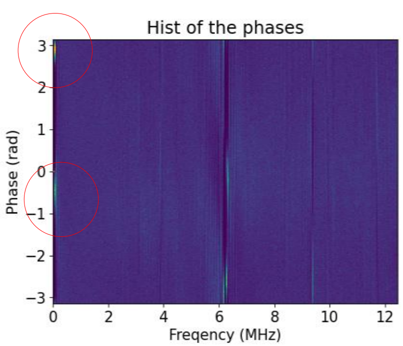


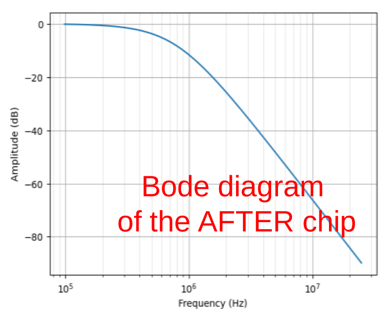
The bulk of the spectrum is understood as the effect of the AFTER chip convoluted with some random current

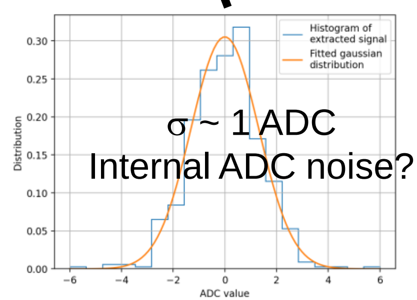
AFTER chip cuts off frequencies above ~1 MHz

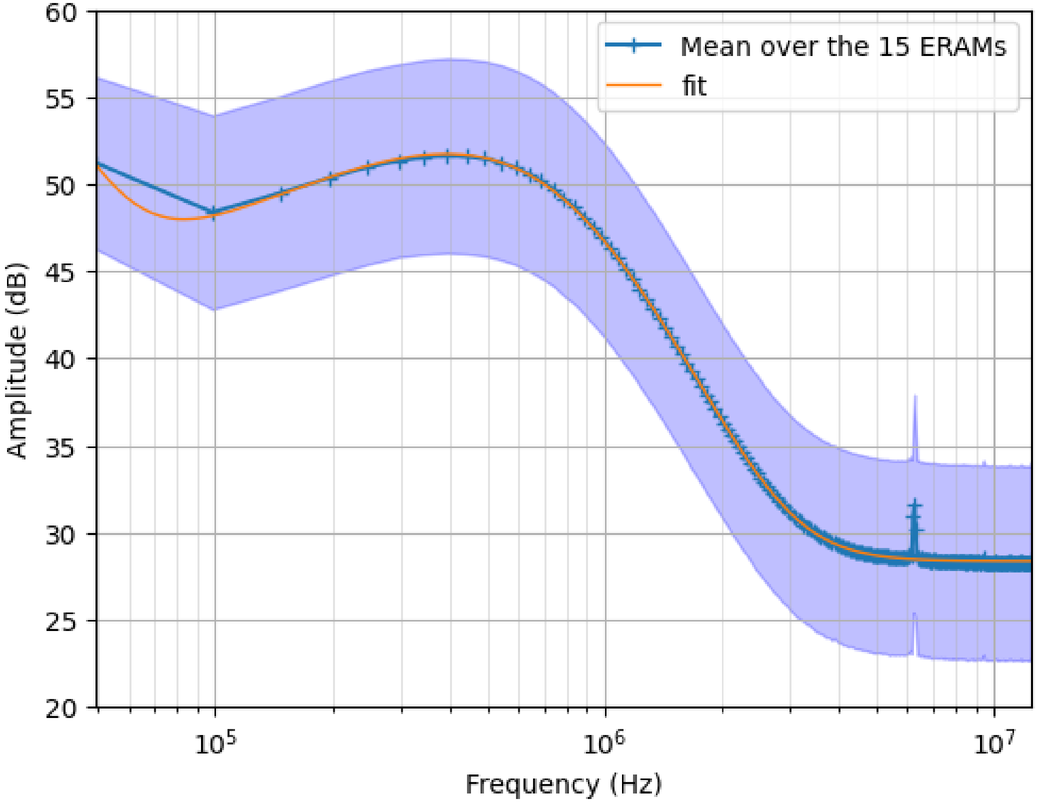


At low f, two populations of pads (2x36), due to pad routing on the ASIC!









The spectrum can be fitted quite decently with a "simple" analytical function

$$\sqrt{\left[\frac{A_0}{f^2}\right]^2 + \left[A_1\sqrt{f}.H_{after}(f)\right]^2 + A_2^2}$$

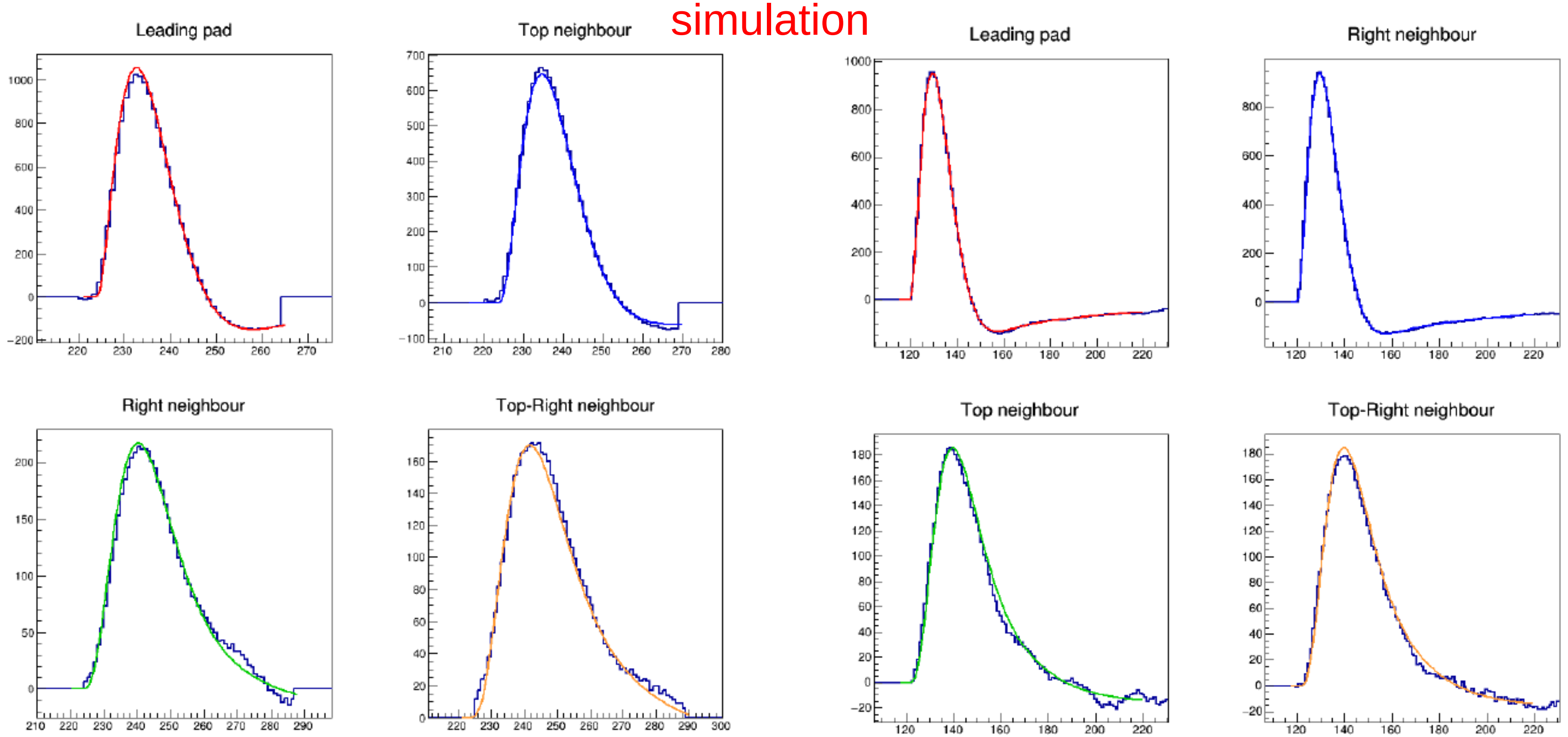
But one wants toys events!

Preliminary tests ; Plots from Shivam

X-ray data waveforms

Very realist simulation

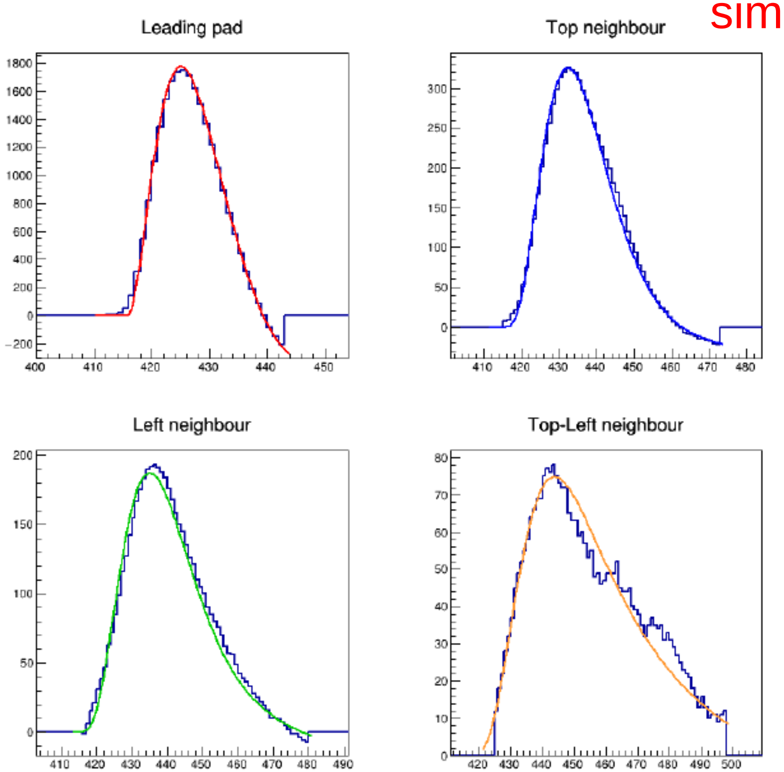
Simulated noisy waveforms



UNDERSTANDING THE NOISE: MAKING NOISE

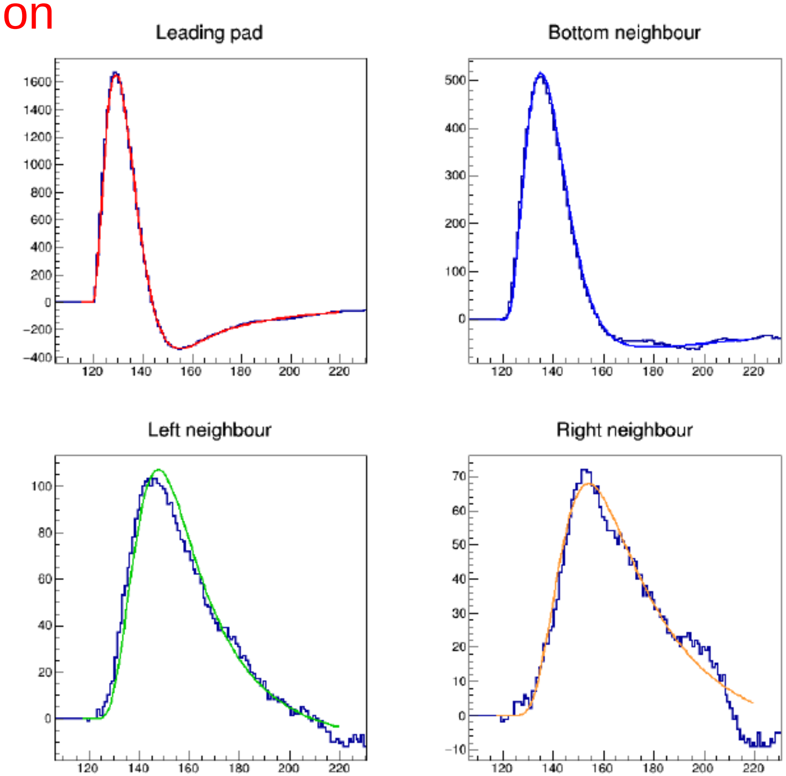
Preliminary tests ; Plots from Shivam

X-ray data waveforms



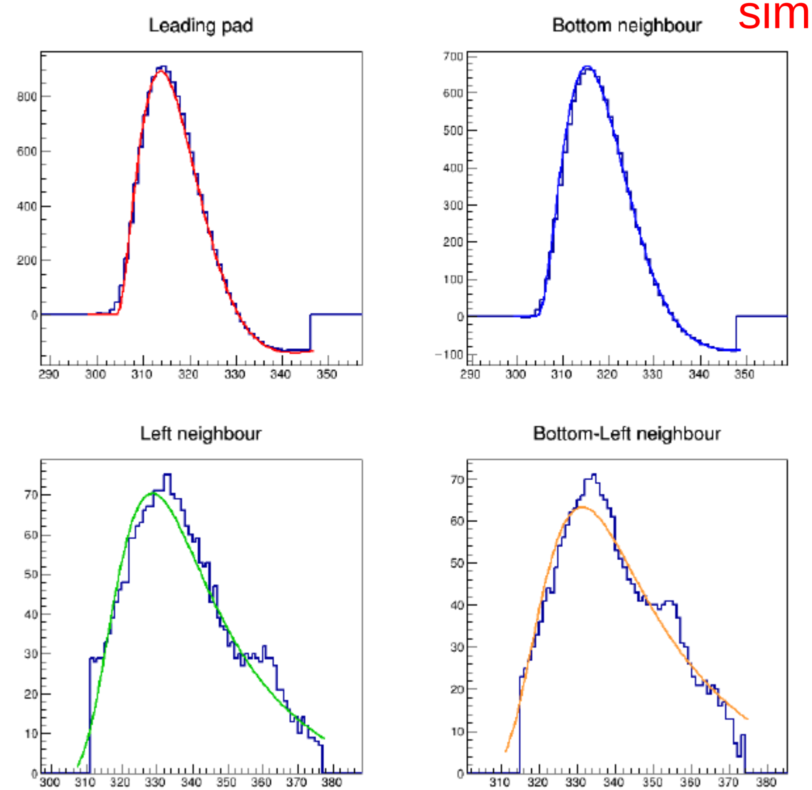
Very realist simulation

Simulated noisy waveforms



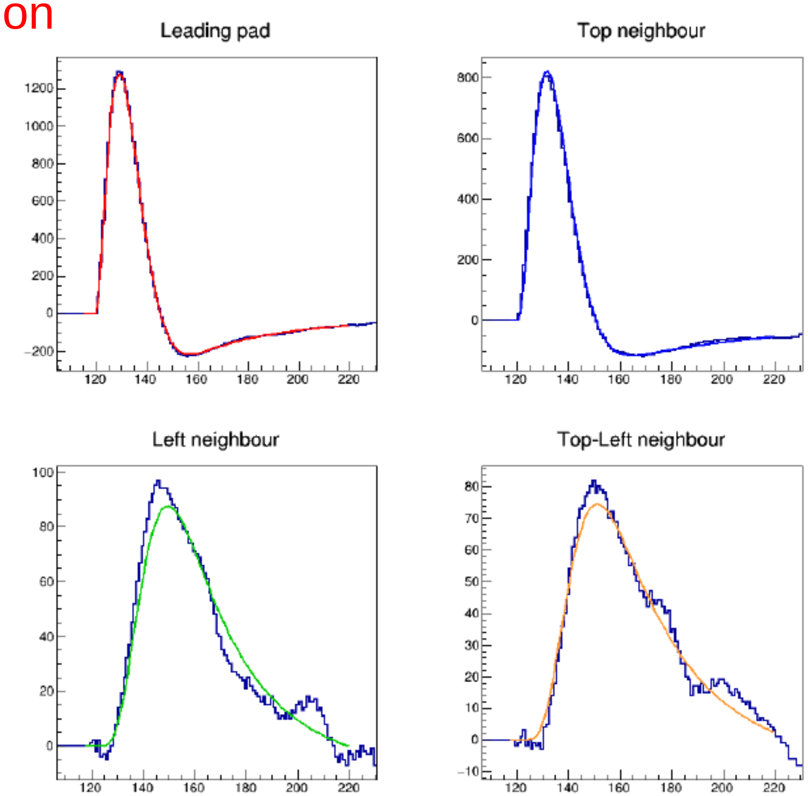
UNDERSTANDING THE NOISE: MAKING NOISE

X-ray data waveforms



Very realist simulation

Simulated noisy waveforms

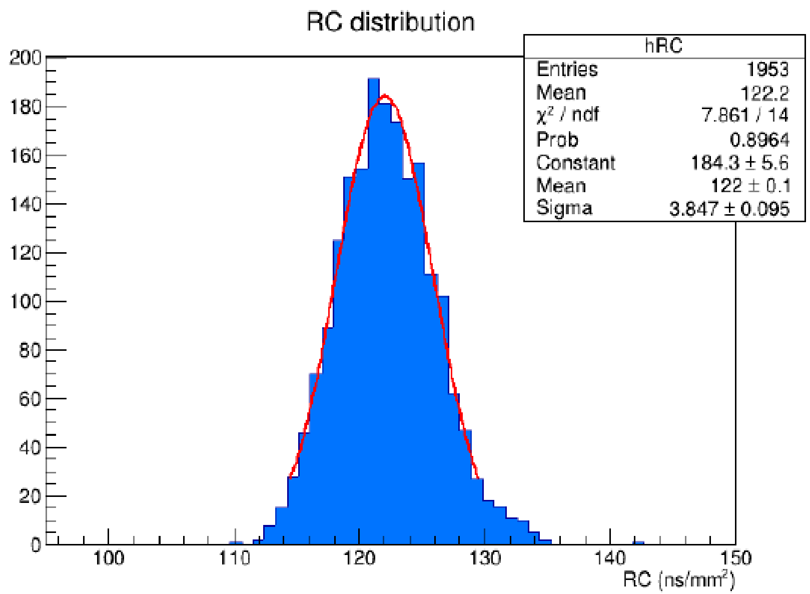


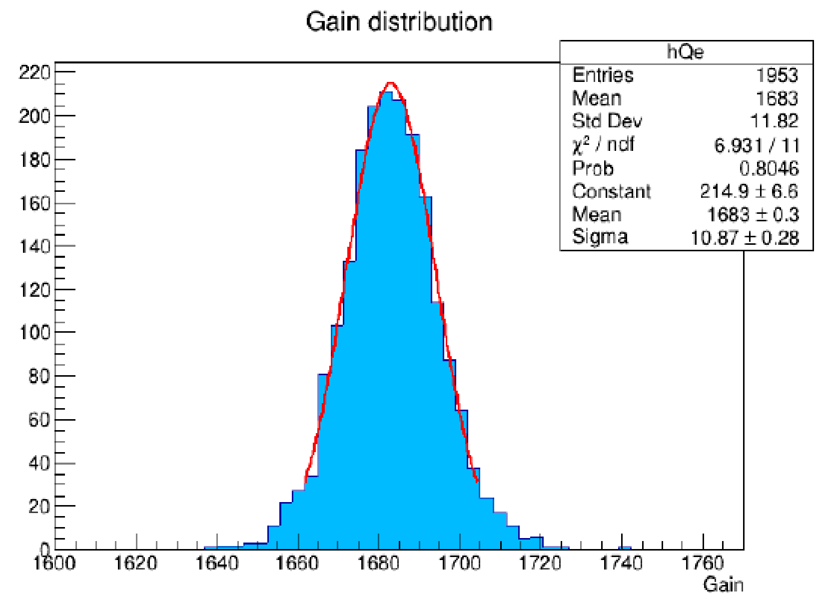
Preliminary tests ; Plots from Shivam

UNDERSTANDING THE NOISE: MAKING NOISE

Simulate noise on some pads + neighbourg

Shivam





- RC_{fit} = 122 ns/mm²
- RC_{input} = 123 ns/mm²
- Diff. = 0.8%

Inputs retrieved at % level

- $Gain_{fit}$ = 1683
- $Gain_{input}$ = 1700
- Diff. = 1%

Work in progress
(to be continued)

Conclusion

- Over the last ~3 years, a consistent workplan was undertaken to test and consolidate the *Telegraph Equation + Dirac pulse parametrization* model of the ERAM signal

- The cornerstone of the validation of the model is provided by the X-rays waveform studies, but the model was found relevant for tracks as well

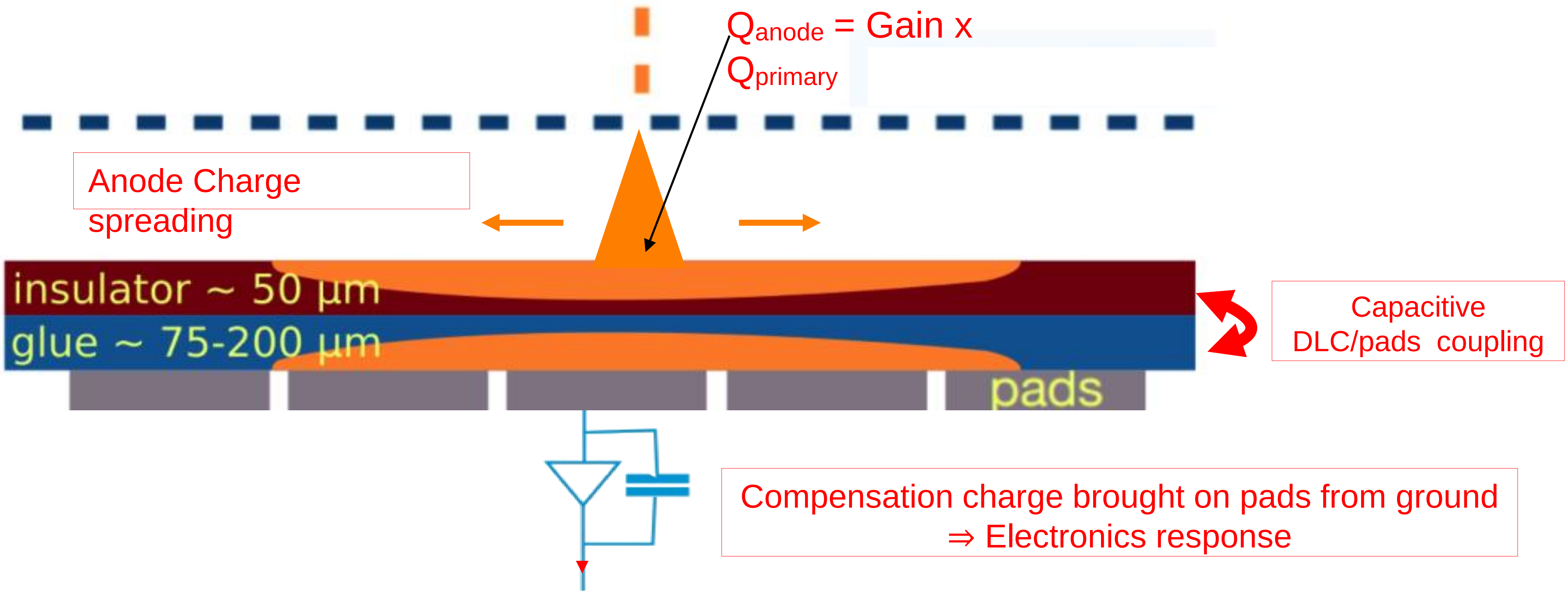
- We have all the needed tools (discretization, noise modeling) to address the systematics due to the RC uniformity and noise assumptions in ERAM signal analyses

(*we didn't take into account gas effects nor particular areas (pillars)*)

- LTSpice is a simple tool to start simulation of r-Micromegas or r-MPGD/gaseous det.
  - (+) need to have the correct **elementary cell**
  - (-) for a full detector, calculation time may be prohibitive… (didn't test "*netlist*" tool)
  - (-/+) one need to **evaluate elementary component** through measurements / specific run
    (or use of other software – COMSOL)

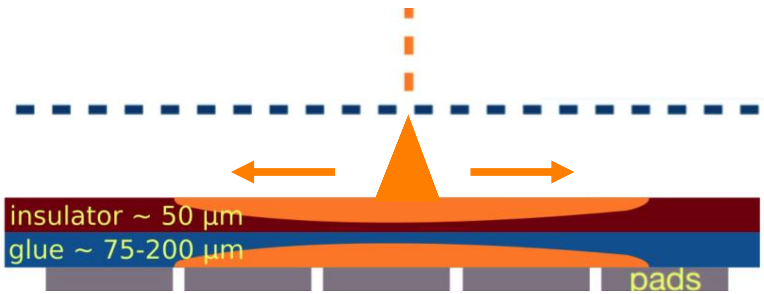
spare

SIGNAL FORMATION



CHARGE SPREADING

Resistance
+
capacitance
⇒ charge diffusion



$$\frac{\partial \rho}{\partial t} = \text{div}\vec{j_S},\ \vec{j_S} = \sigma\vec{E}, \vec{E} = -\nabla V \text{ and } V = \rho/C_S$$

σ surface conductivity , C_S surface capacitance

$$\Rightarrow \frac{\partial \rho}{\partial t} = \frac{1}{RC}\left(\frac{\partial^2 \rho}{\partial^2 x} + \frac{\partial^2 \rho}{\partial^2 y}\right) \text{ with } RC = \frac{C_S}{\sigma} \text{ in } \boldsymbol{s/m^2}$$

2D Telegrapher Equation

Analytical solution for punctual charge deposition (assuming infinite resistive layer and uniform RC)

$$\rho_{punctal}(r,t) = \frac{Q_{anode}}{2\pi\sigma^2(t)} e^{\frac{-r^2}{2\sigma^2(t)}} \text{ where } \sigma(t) = \sqrt{\frac{2t}{RC} + w^2} \text{ and } w \text{ initial width (lateral diffusion)}$$

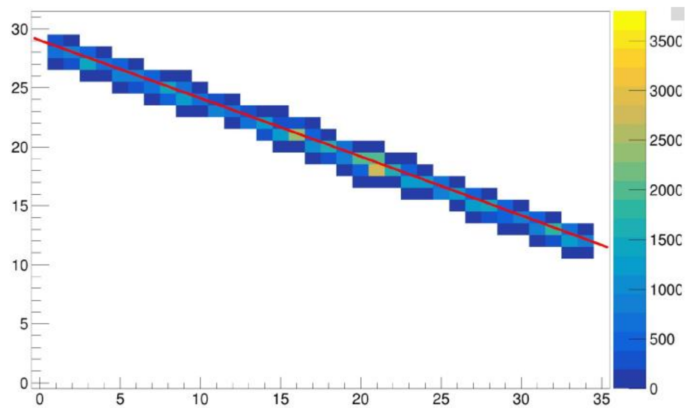
Always work with $Q_{pad}(t) = \iint_{Pad} \rho_{punctal}(r,t)\,dS$ Why? There is no pad on the uniform resistive layer!

IDENTIFY PARTICLES: THE XP METHOD

Signals from a track ⇒ Charge ⇒ Particle Identification by dE/dX

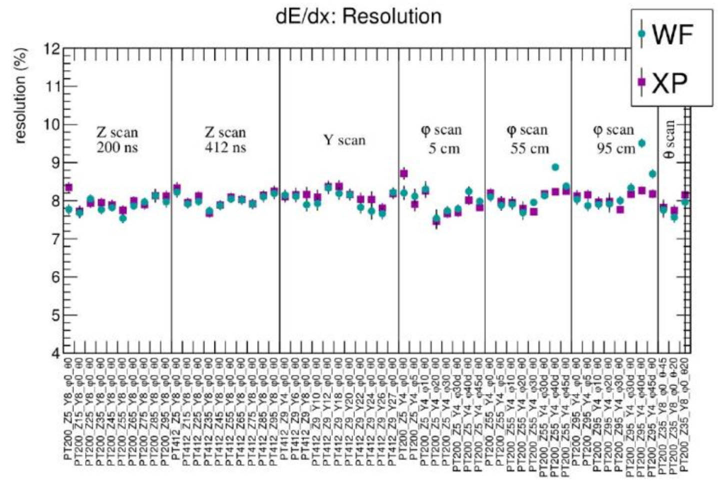
Bold move

use only the pads crossed by the track and *take from the model* the conversion of ADC to Q deposited along the track



Pads display : color = ADC max

And it works pretty well (whatever angle)



Now, one of the 2 PID tools of official T2K reconstruction

Tristan Daret’s study (PhD)

SPACE-TIME DISCRETISATION: FDM CODE

Christopher Winterstein (M1 Intern)

$$\frac{\partial\rho}{\partial t} = \frac{1}{RC}\left(\frac{\partial^2\rho}{\partial^2 x} + \frac{\partial^2\rho}{\partial^2 y}\right) \Rightarrow \frac{q_{i,j}^{t+1} - q_{i,j}^{t}}{\Delta_t} = \frac{q_{i+1,j}^{t} - q_{i,j}^{t}}{C_s\Delta_x\Delta_y R_x} + \frac{q_{i-1,j}^{t} - q_{i,j}^{t}}{C_s\Delta_x\Delta_y R_x} + \frac{q_{i,j+1}^{t} - q_{i,j+1}^{t}}{C_s\Delta_x\Delta_y R_y} + \frac{q_{i,j-1}^{t} - q_{i,j-1}^{t}}{C_s\Delta_x\Delta_y R_y}$$

$$\Rightarrow \quad \vec{q}^{\,t+1} = (I + \Delta_t S)\vec{q}^{\,t}$$

Vector of node charges at t+1

Big rank ~ 10^5

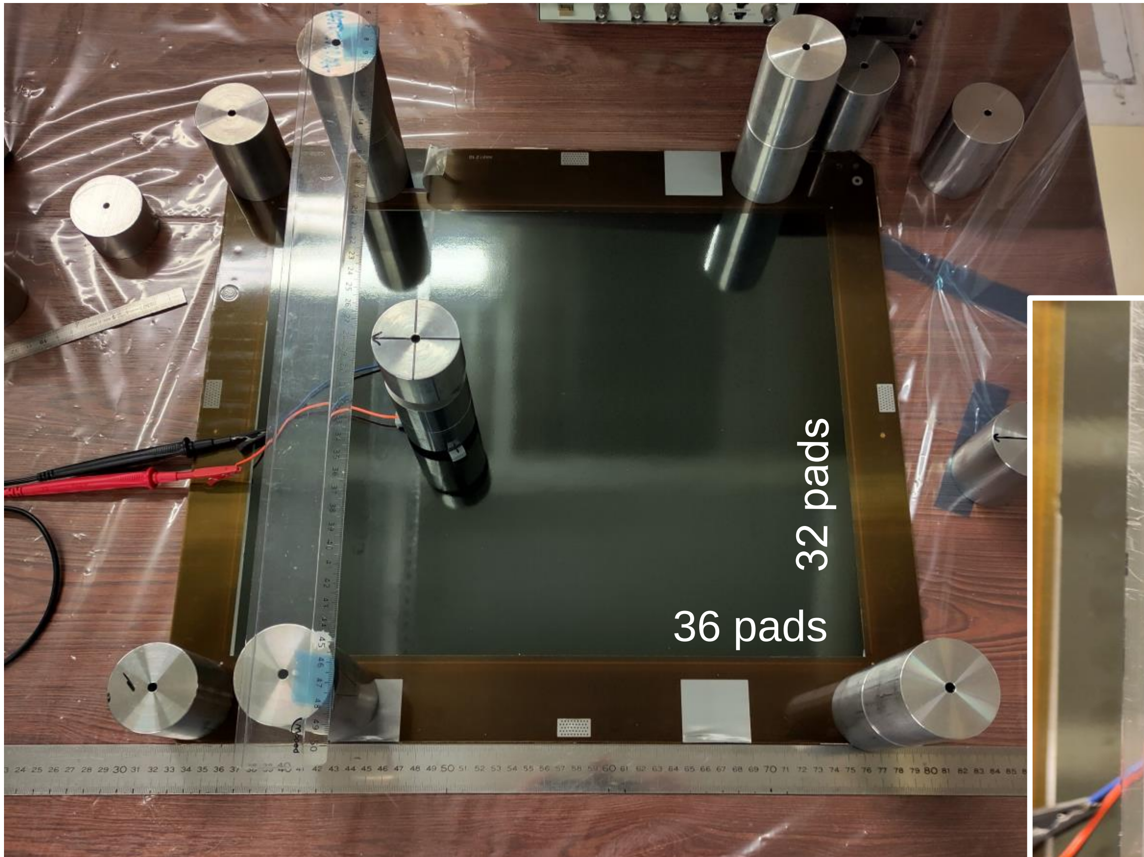
$$\vec{q}^{\,t+1} = (I + \Delta_t S)\,\vec{q}^{\,t}$$

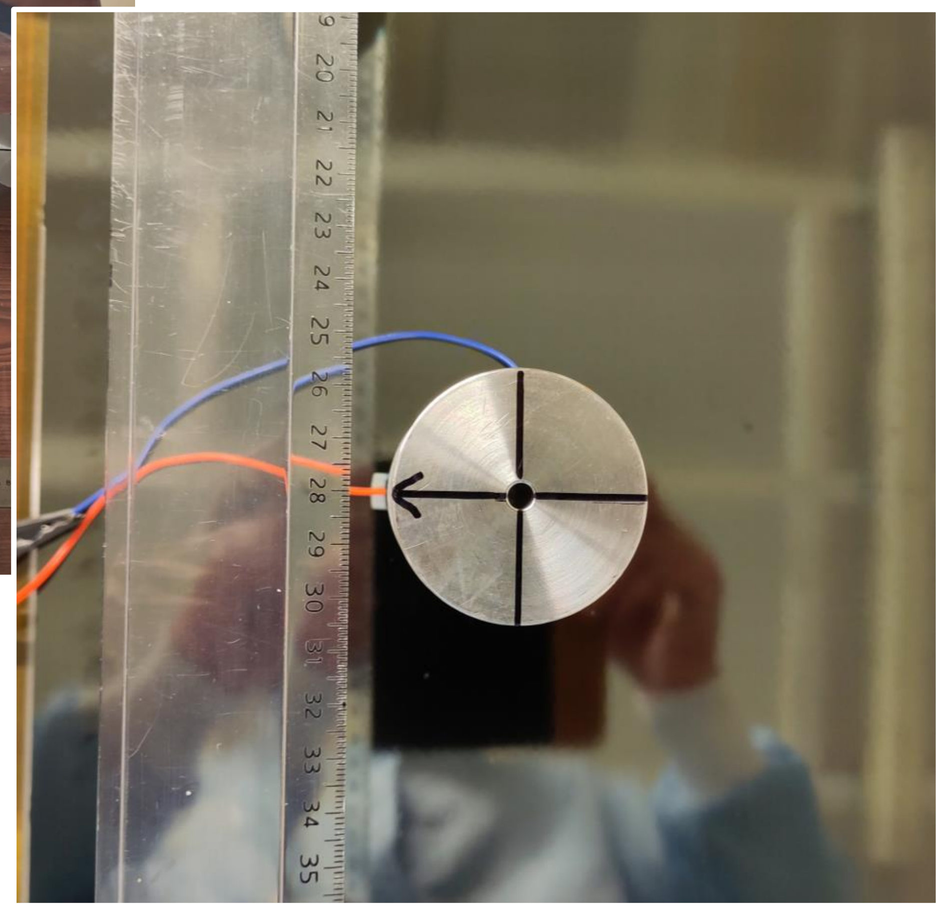
Huge but sparse matrix

Vector of node charges at t

describes node/node connections but actually at most 1 to 4

over the ~10^{10} elements, only ~10^5 not null





Relative positioning error: +/- 2 mm vert. and
+/- 3 mm horiz.

Measurement error: +/- 0.1 k-Ohm - before applying K factor

Absolute precision: ~10 - 15% by calculation (how to check it?)

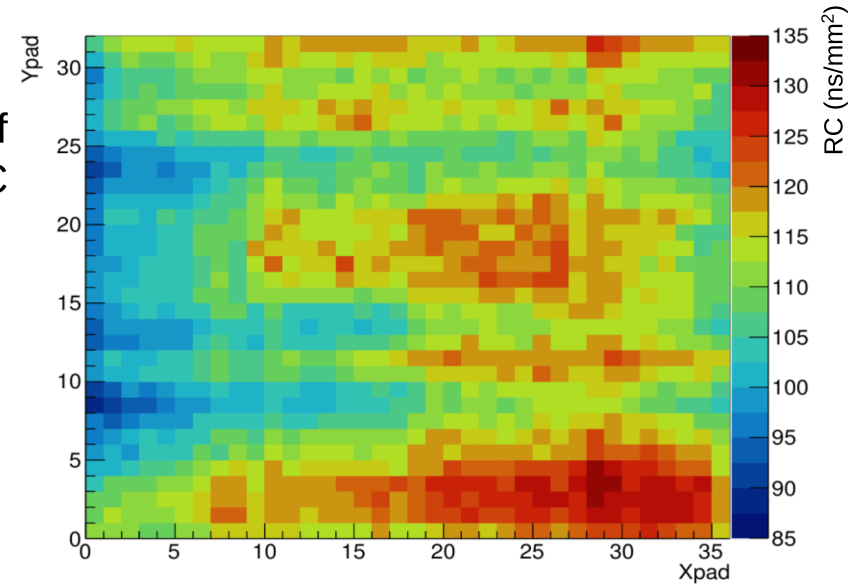
RC NON-UNIFORMITY ISSUE

Previous methods model signal using analytical solution of Telegraph Equation, i.e under the assumption that the RC is uniform

Bur RC is not uniform as demonstrated by Shivam

⇒Systematics; need solution with non uniform RC

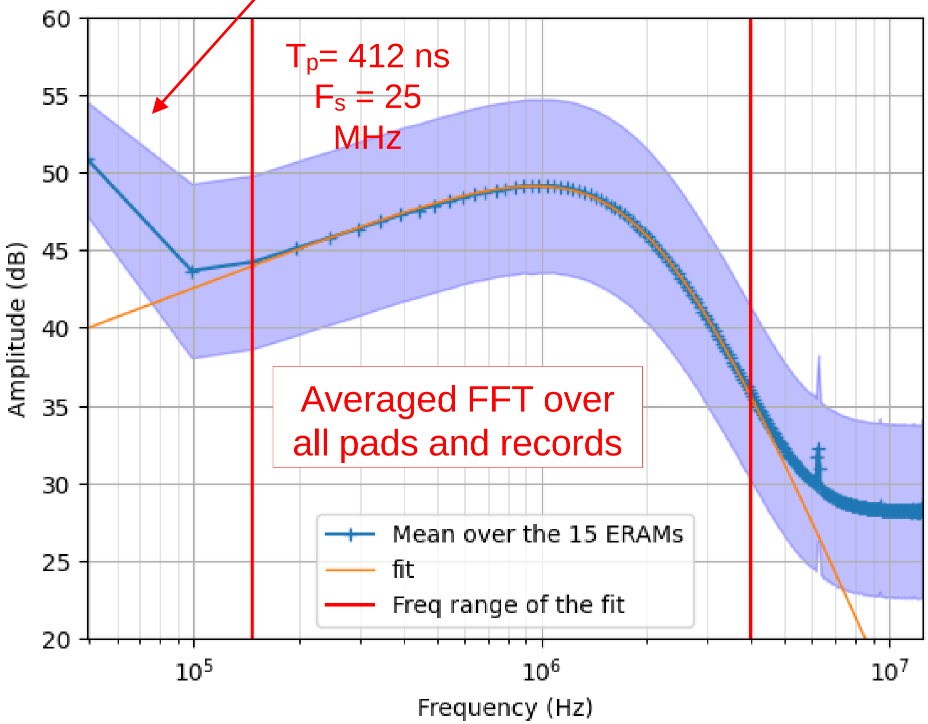
⇒ Discretisation of the Telegraph Equation



A RC map from X ray data

UNDERSTANDING THE NOISE

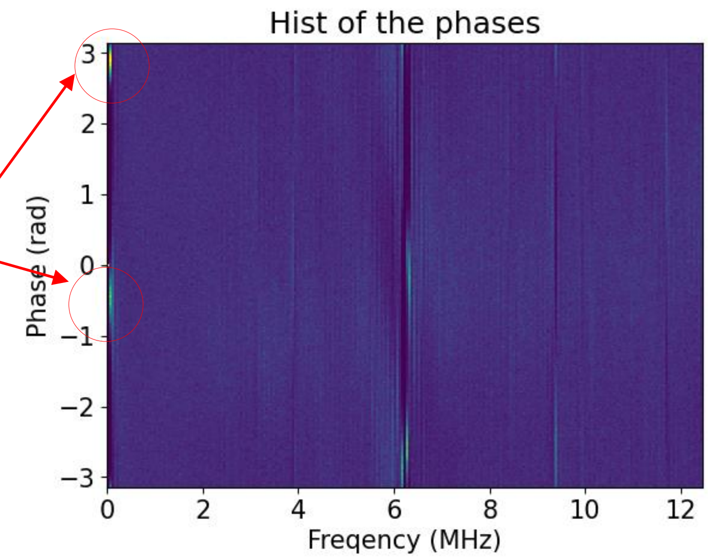
What is this ?



FFT provides also phases : they should be random

At low f, they are not random

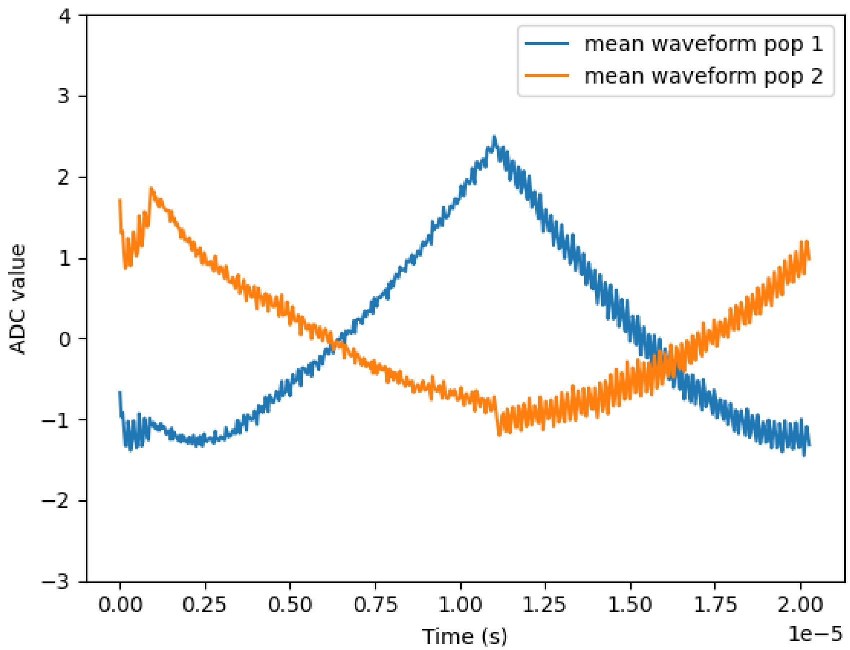
2 populations



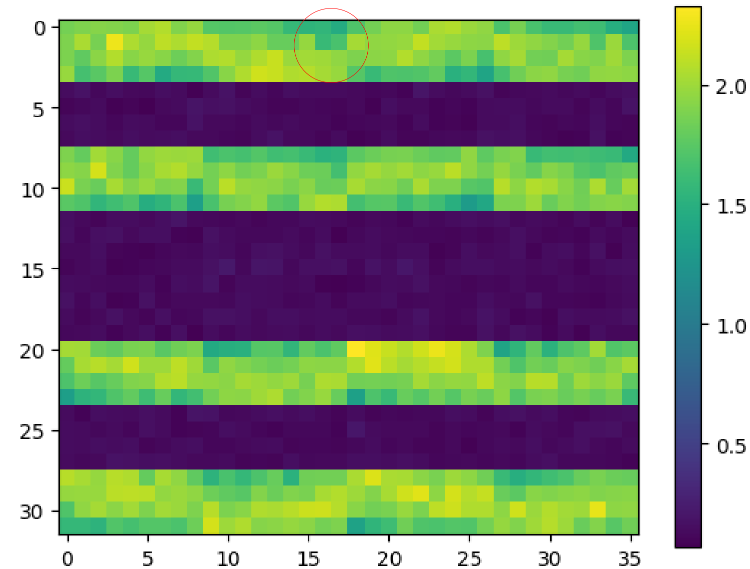
At low f: 2 populations of pads producing regular signals
To catch them : average the waveforms

UNDERSTANDING THE NOISE

Averaged waveform over all Erams and records
very specific (~ |cos(wt)| ?)



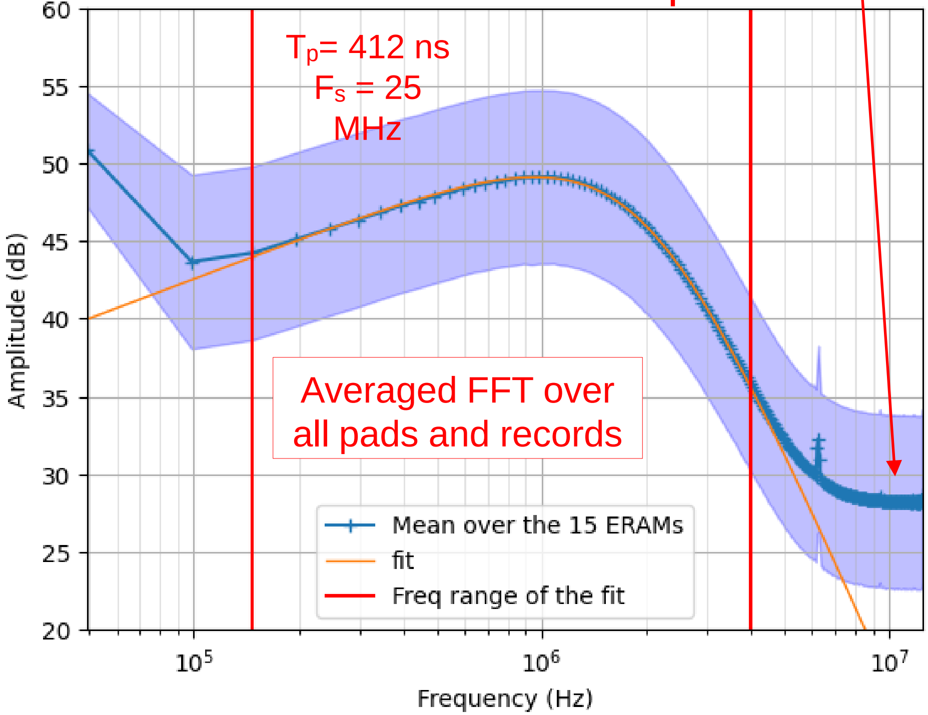
Locations of the 2 populations on the pads board
very specific too



D. Calvet: map the way the channels connect to one or the other of the two sides of the silicon die

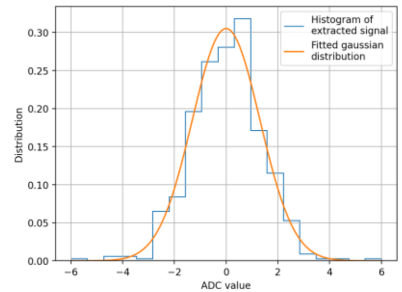
UNDERSTANDING THE NOISE

What is this plateau ?



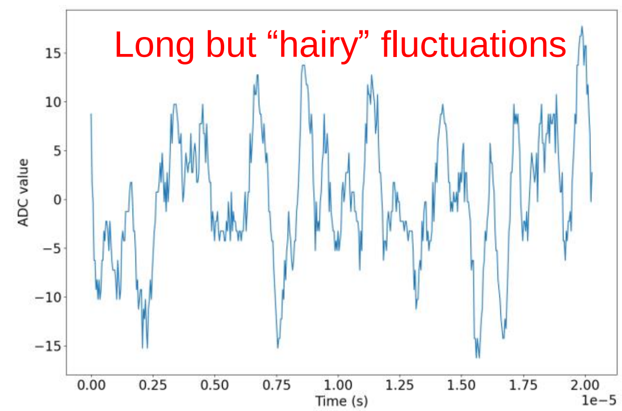
Understood as white noise (flat in frequency) of low amplitude

Filter out low frequency ⇒ return to time domain ⇒ Histogram of the ADC amplitudes

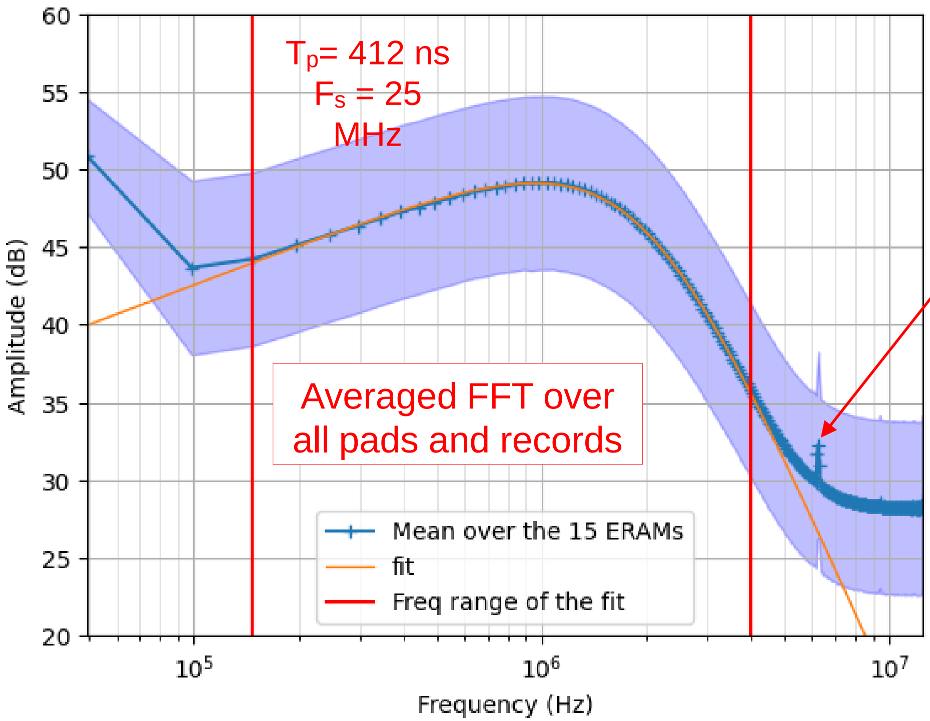


σ ~ 1 ADC

Internal ADC noise?



UNDERSTANDING THE NOISE



And this peak?

No clue (CIA?)

Observed to be

- at ~1/4 of the sampling frequency
- Not random (2 populations)

Ignored in further modeling

UNDERSTANDING THE NOISE

The aim is to produce noise waveforms

Random phases

Schematically:

$$ADC(timebin) = \text{Rounding\&sampling of } \left[\text{Not random signal (t)} + \sum_i A\ \sqrt{f_i} cos(w_i t + \Phi_i) \otimes ADC_{Dirac} \right] + \text{Random Integer}$$

Low f not random noise

The Bulk: $I(f) \times H_{After}(f)$

with $I(f) \propto \sqrt{f}$

High f white random noise