PICMIC*: An Ultra Precise 4D Detection Concept

* PICosecond subMICron detection concept

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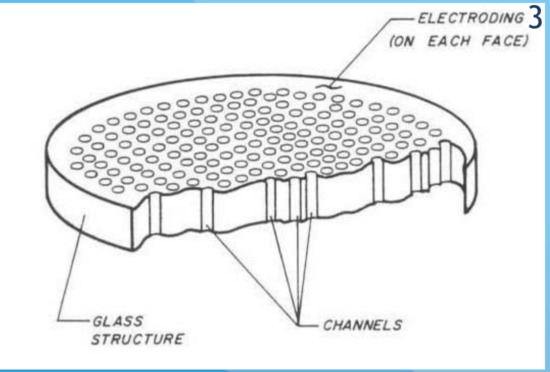
SDU: L. Zhang
Nakai University: Y. Zhao
IHEP: J. Ye, Q. Sen, L. Chen
IMP: A. Serghei, L. Leveque, L. David
INL: J-L. Leclercq, P. Pittet, C. Chevalier, P. Kleimann, B. Rea, N. Terrier
ILM: A. Ayari
XIOPM: P. Chen, X. Zhng

I. Laktineh, PSD14 conference, QM University, London 2026

Outline

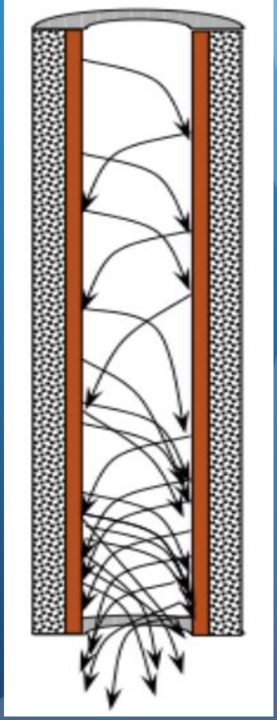
- Introduction
- PICMIC concept
- Time measurement
- Position measurement
- First prototype with MCP and results
- Time and position improvements
- From MCP to NCP

Micro Channel Plate (MCP)



- MCP is considered as the best timing device with a few picoseconds of time resolution.

Few μm diameter

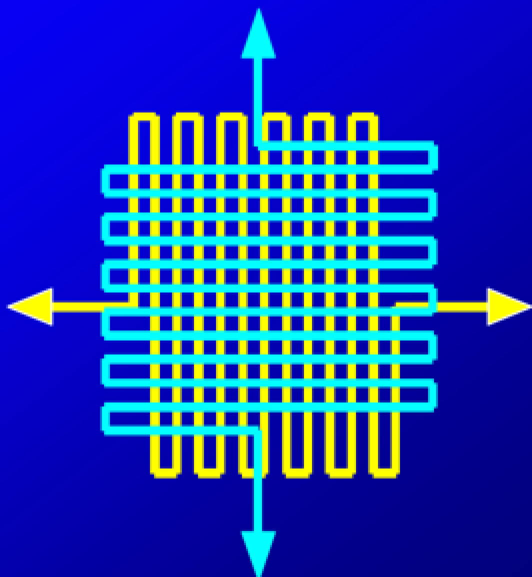


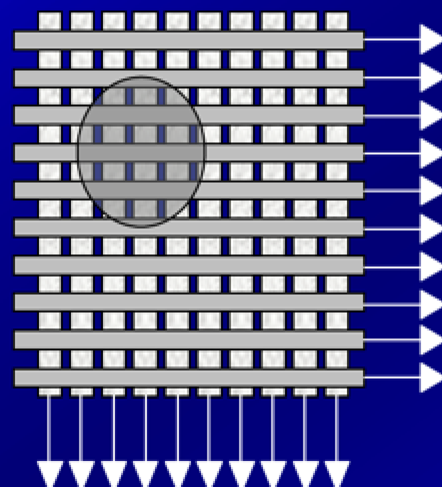
- MCP has an excellent intrinsic spatial resolution since the avalanche produced by the incoming particle is constrained to one of the glass tube whose diameter can be as small as 3 μm

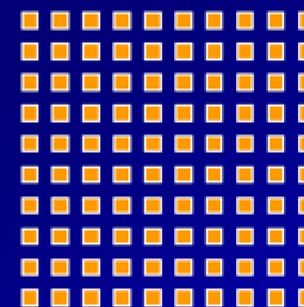
- MCP are often used for their timing (reaching few to tens ps) while their spatial resolution is not appropriately exploited.

Readout Anode Types (partial list)

Courtesy J.Vallegra







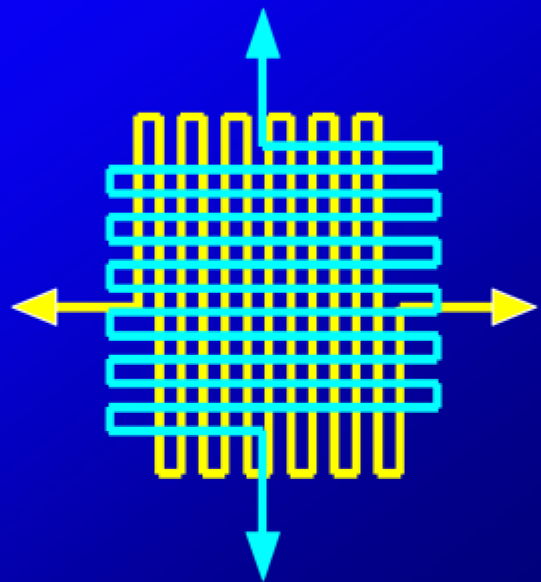
Cross Delayline (XDL)	Cross Strip (XS)	Medipix ASIC Intensified CCD
4 amps	2 x N amps	N x N amps
Gain ~ 10^7	Gain ~ 10^6	Gain ~ 10^4
Rate ~ 200kHz	Rate ~ 2MHz	Rate ~ 200MHz
Δt ~ 100ps	Δt ~ 100ps	Δt ~ 1 ms

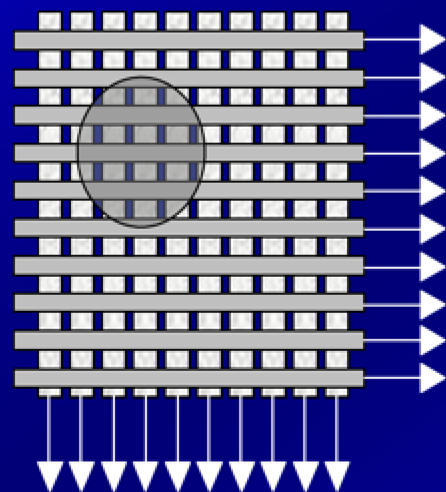
Few mm

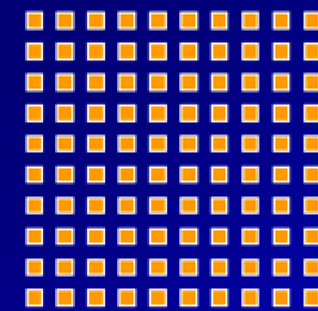
100 µm

Readout Anode Types (partial list)

Courtesy J.Vallegra







Cross Delayline (XDL)

Few mm

4 amps
Gain ~ 10^7
Rate ~ 200kHz
Δt ~ 100ps

Cross Strip (XS)

2 x N amps
Gain ~ 10^6
Rate ~ 2MHz
Δt ~ 100ps

Medipix ASIC Intensified CCD

100 µm

N x N amps
Gain ~ 10^4
Rate ~ 200MHz

Timpix4: 193 ps lsb

MCP intrinsic spatial resolution is not well exploited as its temporal one

We propose the following scheme :

- **A transparent grid placed downstream the MCPs and read out by sensors with excellent time resolution. Followed by:**
- **A detection matrix with micrometric pixels to measure with great precision the position of the avalanche while requiring limited number of electronics channels.**

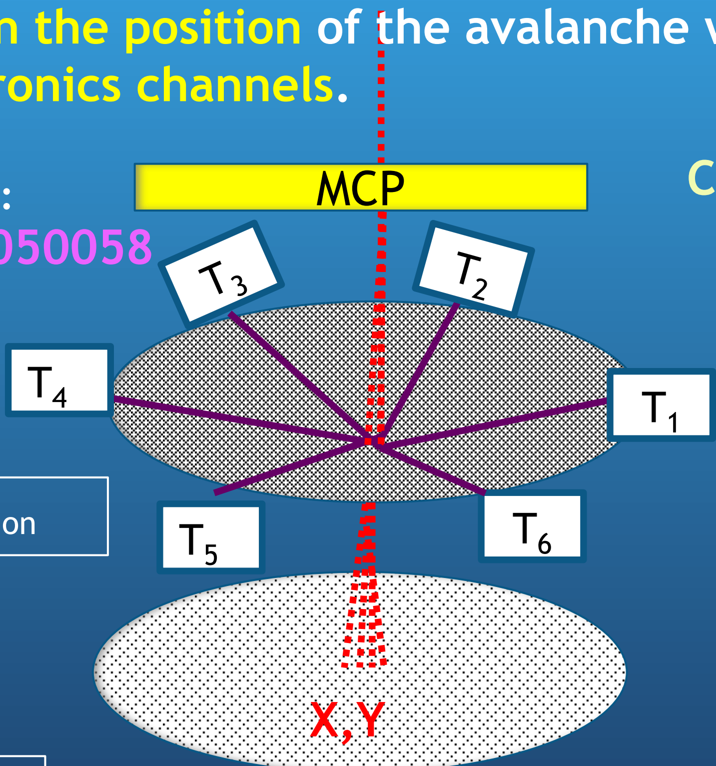
Patented concept:
PCT/EP2020/050058

Metallic Grid

Time + position

Pixels

Position+ time



Concept description

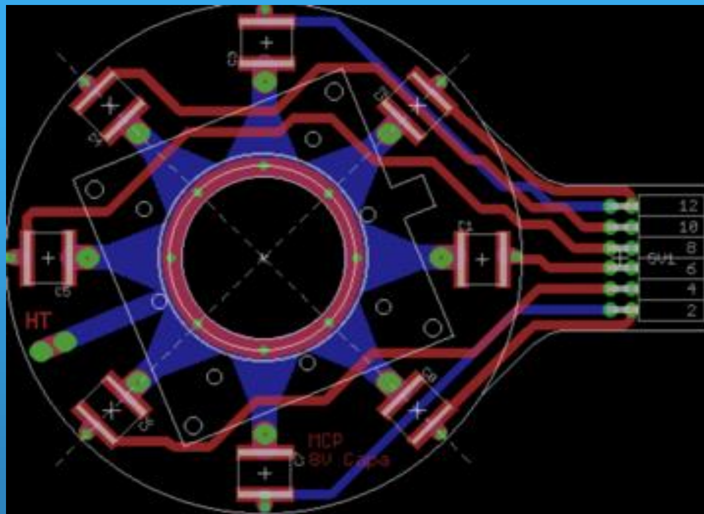
- **Delay plane concept**

  The grid can be the metallic anode of the MCP

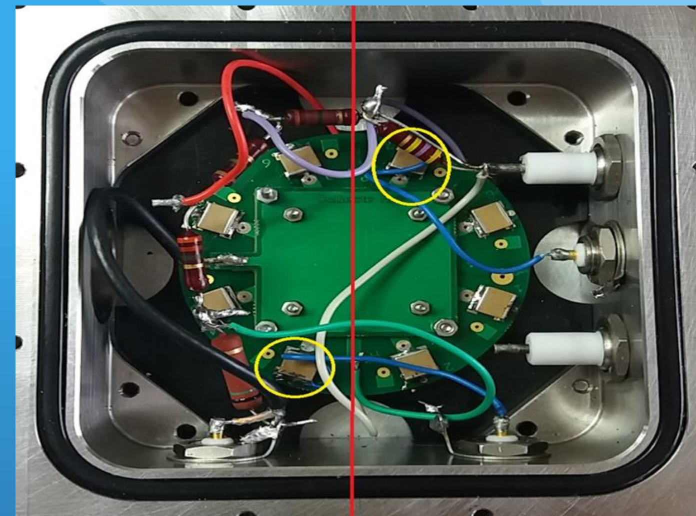
- **Woven strips→ 3d interconnected pixels concept**

Use (x,y) to subtract the time propagation on the grid and then improve on time measurement : $T_{abs} = \frac{\sum_0^N T_i - T_{i-propag}}{N}$

Time measurement

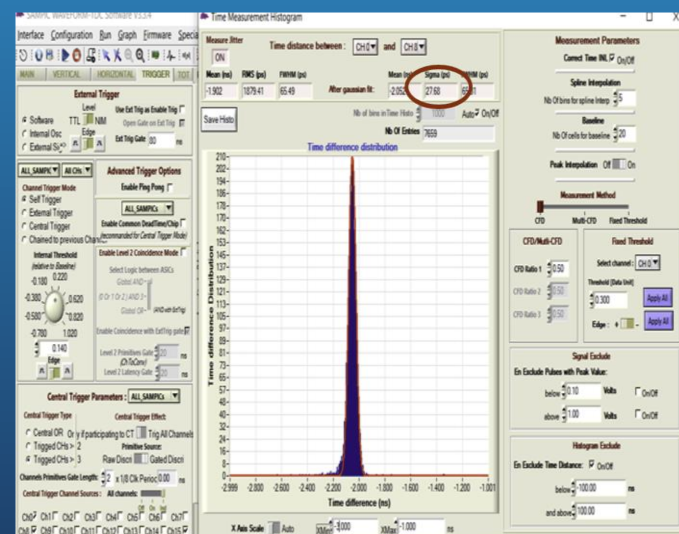


Delay-plane readout



First setup with two MCP of 2.5 cm diameter to validate the delay plane principle

SAMPIC: a waveform digitizer (3ps)



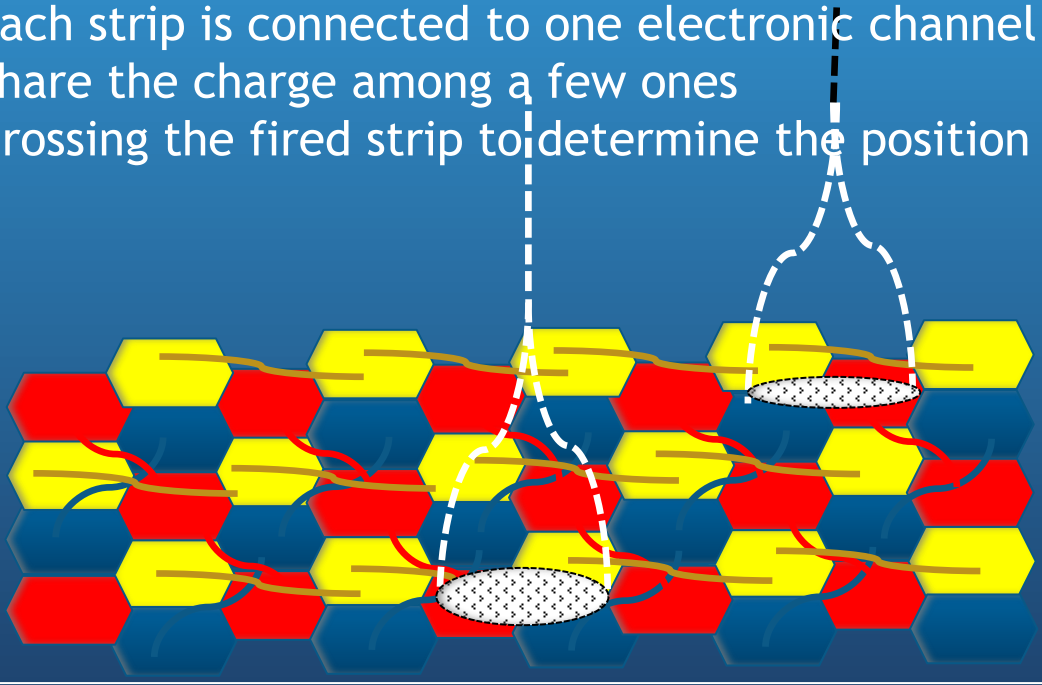
σ_{Ti-Tj}=30 ps $\rightarrow$ σ_T = 8 ps

Position measurement

PCT/EP2018/053561

To reach few microns resolution with a limited number of electronic channels, a new concept was developed and successfully **tested** (Tricot)

- ❑ Connect the pixels in woven strips in three or more orientations
- ❑ Two neighboring pixels are connected to two different strips of different orientations
- ❑ Each strip is connected to one electronic channel
- ❑ Share the charge among a few ones
- ❑ Crossing the fired strip to determine the position

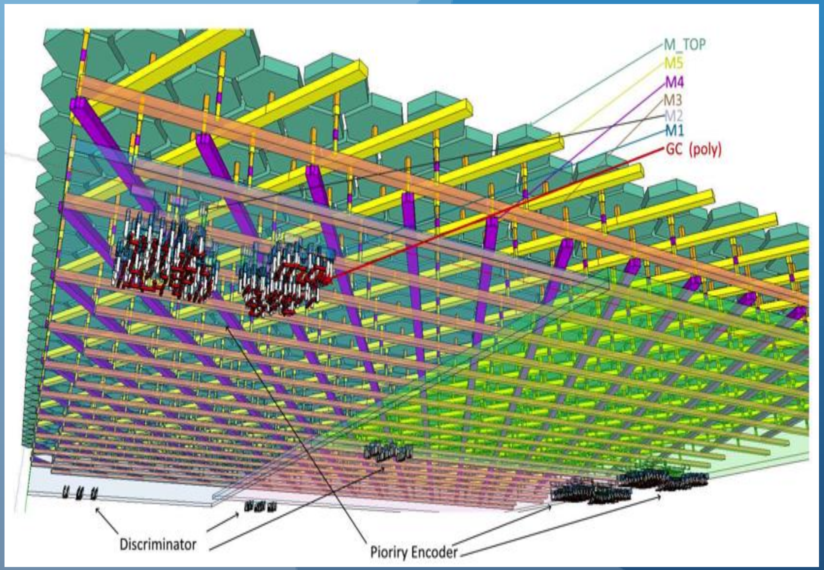


Ambiguity is eliminated thanks to the 3D interconnection

NXN → 3N : Reduction of electronic channels, power consumption and occupancy

Pixel sensor & electronics

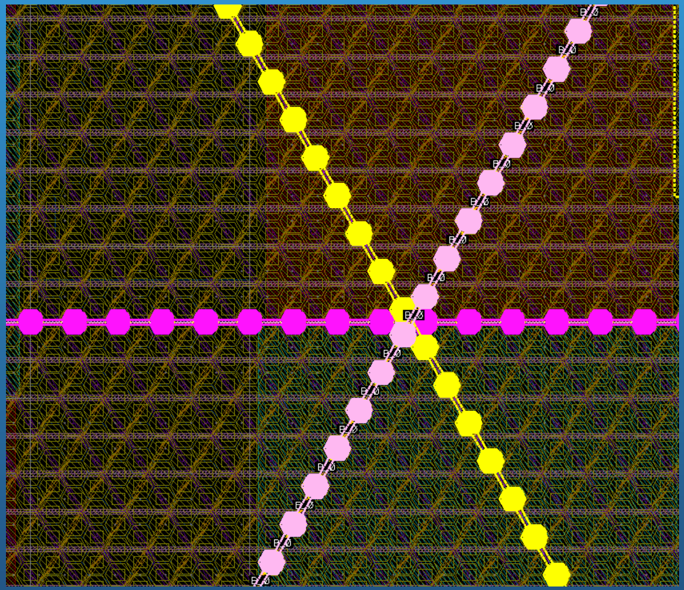
- Pixels of a few microns are needed to exploit the spatial resolution
- Only wafer-based technique can offer such a structure
- TJ 180 nm, 6 metallic layer wafer
- Current conveyer preamplifier
- Priority encoder

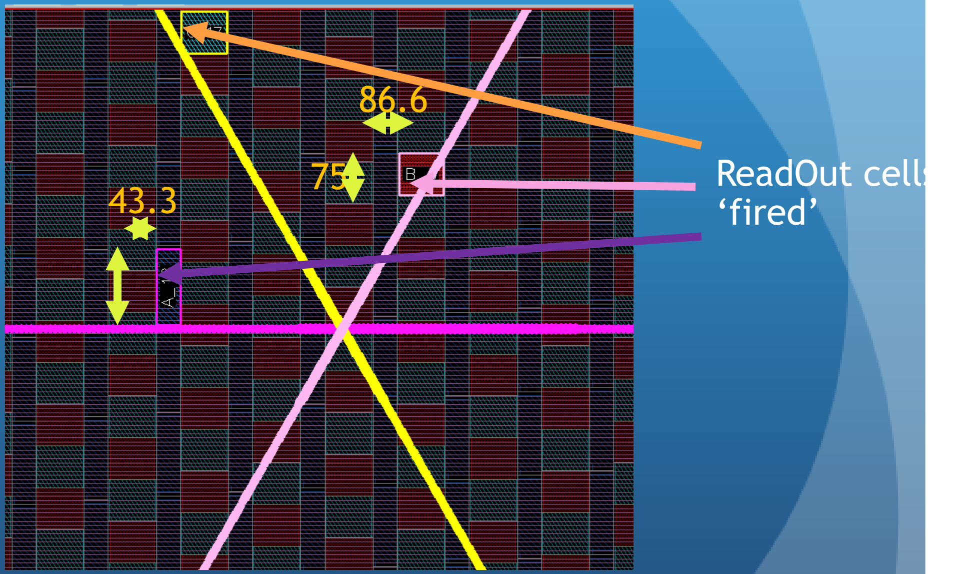


Parameters	Value
Design Flow	Cadence DoT flow
Technology	TJ CIS 180nm
Power supplies	1.8V
Power density	>172mW/cm² (only analog static current)
Die dimension	~7.5x7.5 mm² (**6.5x7.5mm²**)
Anode dimension	~22μ²(5μm hexagonal pitch)
Readout pixel dimension	50μmx140μm
Readout matrix	128x54 cells (**only 2556 active**)
Input clock	40MHz
Read-out port	13-bit parallel
I/O Pad	CMOS
Slow control	I2C
Max data rate (1Mhz hit rate)	390Mbps

The 2556 RO cells allow reading out the **2 216 000 pixels of 5 μm pitch**

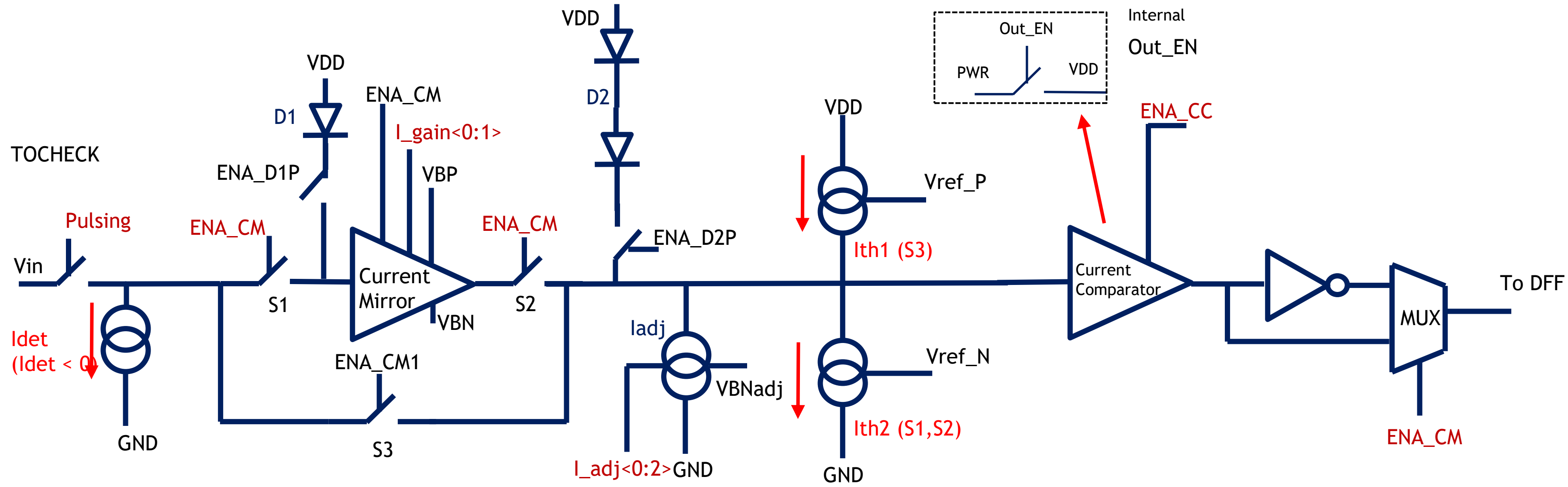
The signal is transmitted from the fired pixels to their associated readout cells





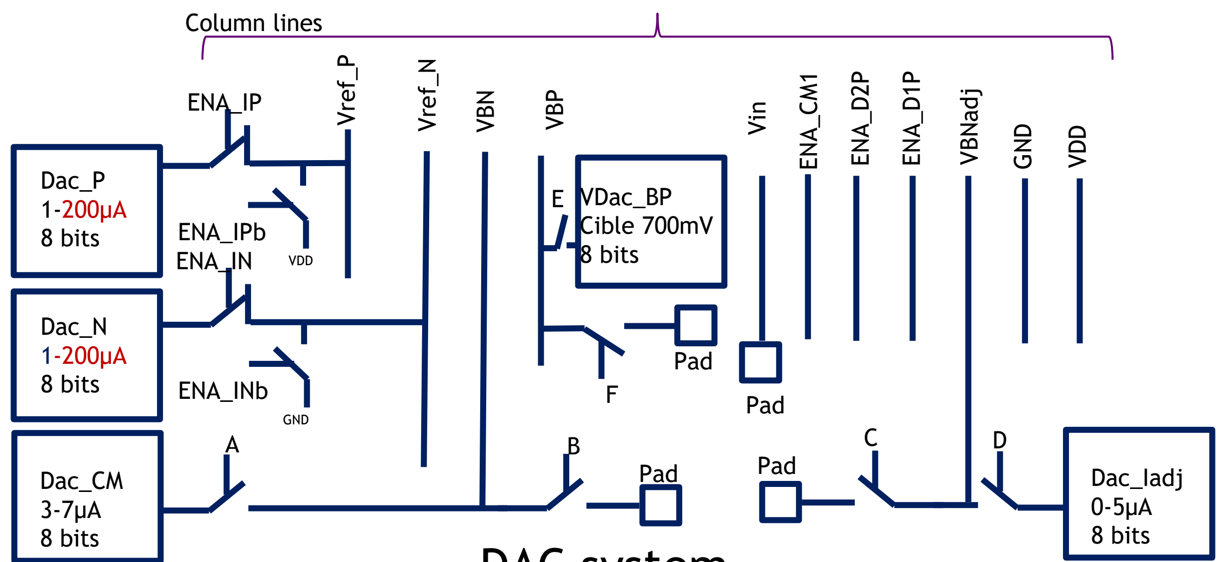
Crossing the lines associated to the fired channels provides the position

Front End lock



Current conveyer preamplifier

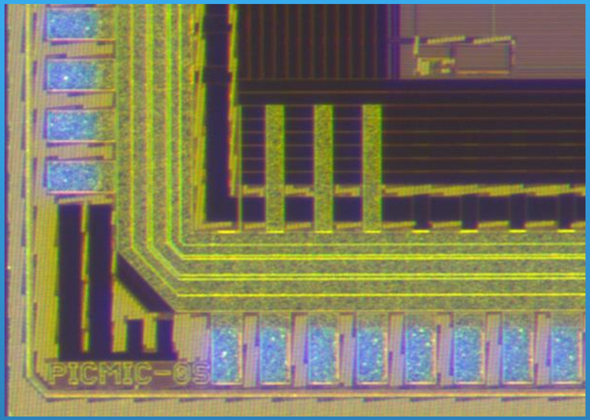
Dynamic range:
> 10 fC

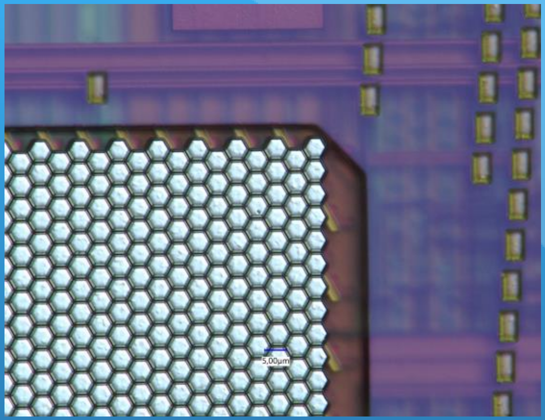


DAC system

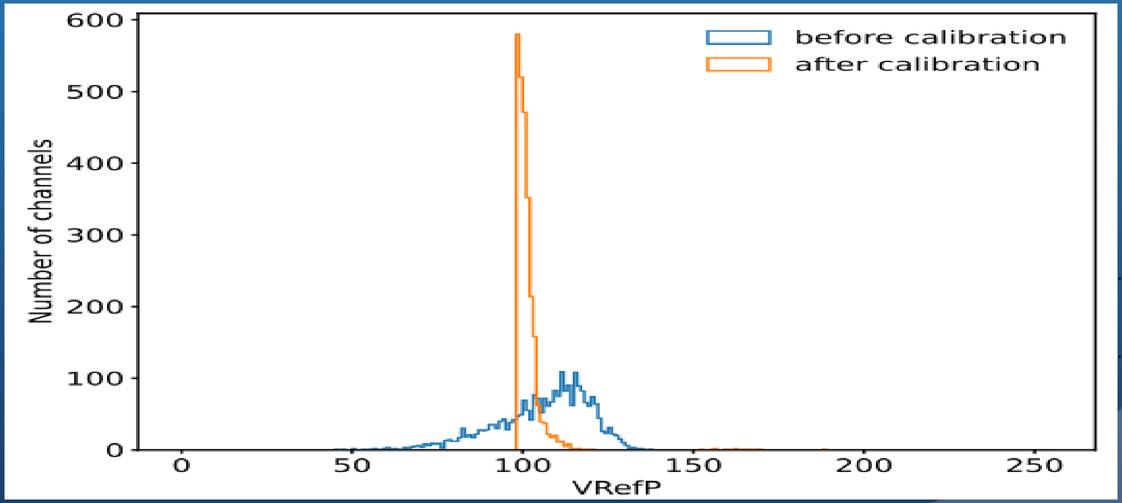
The chip was submitted in November 2021and received on July 2022

TowerJazz 180 nm



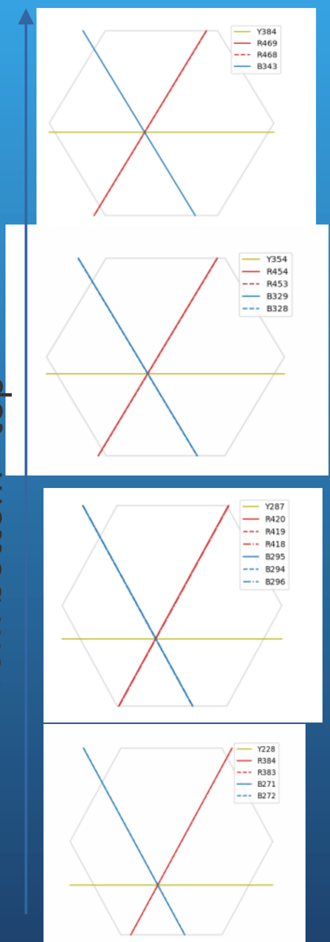


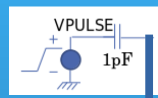
A calibration system was developed to reduce the S-Curve dispersion of the 2556 channels. 3-bit local DAC is used to reduce the dispersion.

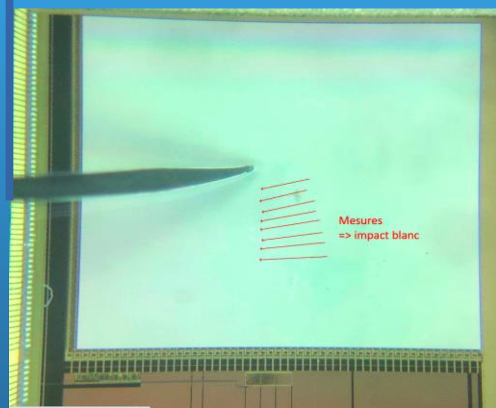


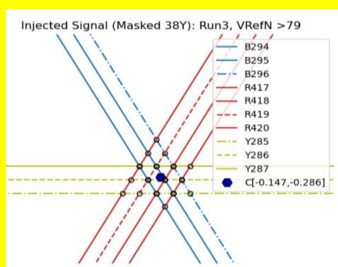
Tests with direct injection using probes

Probe scan from bottom - top



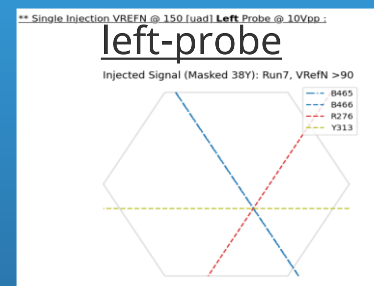


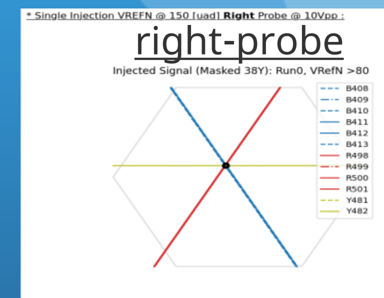


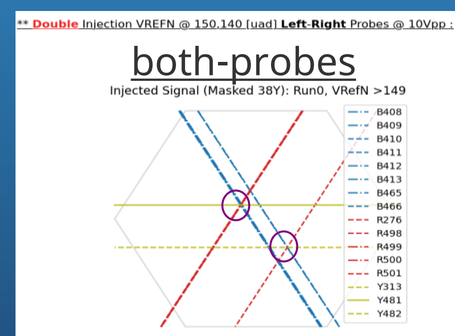


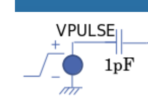
Clustering and centroid estimation

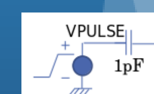
Two probes injection

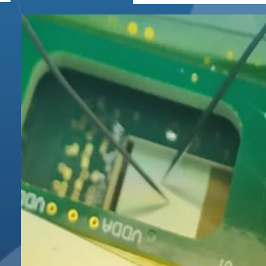












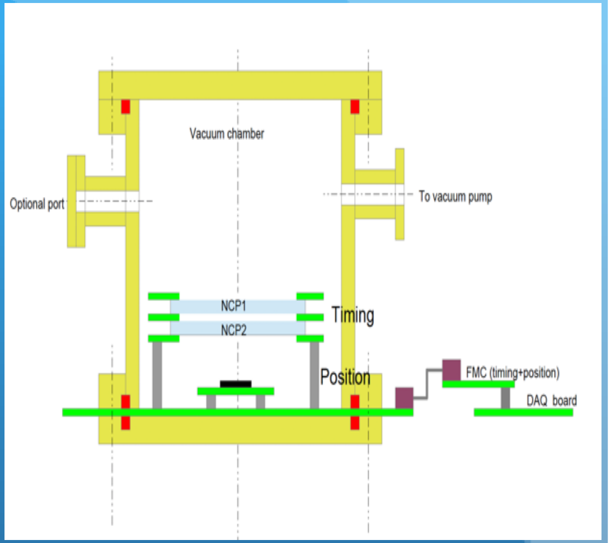
The first PICMIC demonstrator

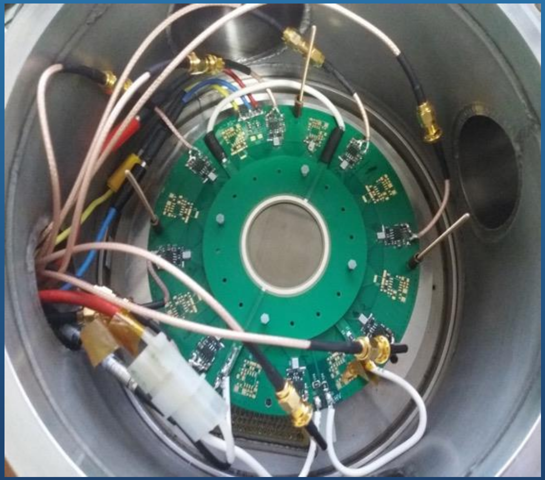
The first prototype including:

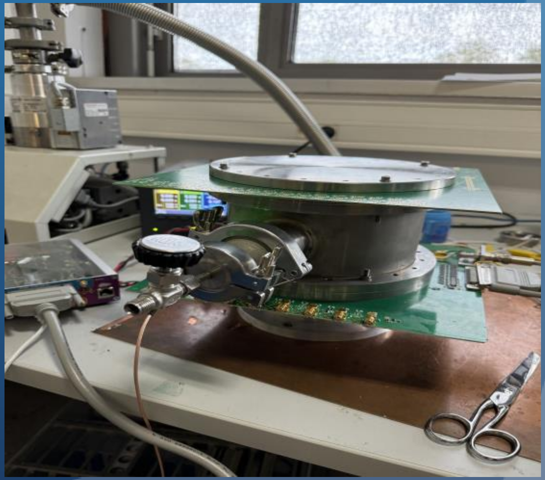
- Two 5-cm diameter MCP (Hamamatsu, Photonis, CBMA)
- A board hosting 16 timing sensors (only 8 were cabled)
- A mezzanine hosting the pixel sensors
- A Master board

All are placed within a vacuum system (<10e-5 mB)

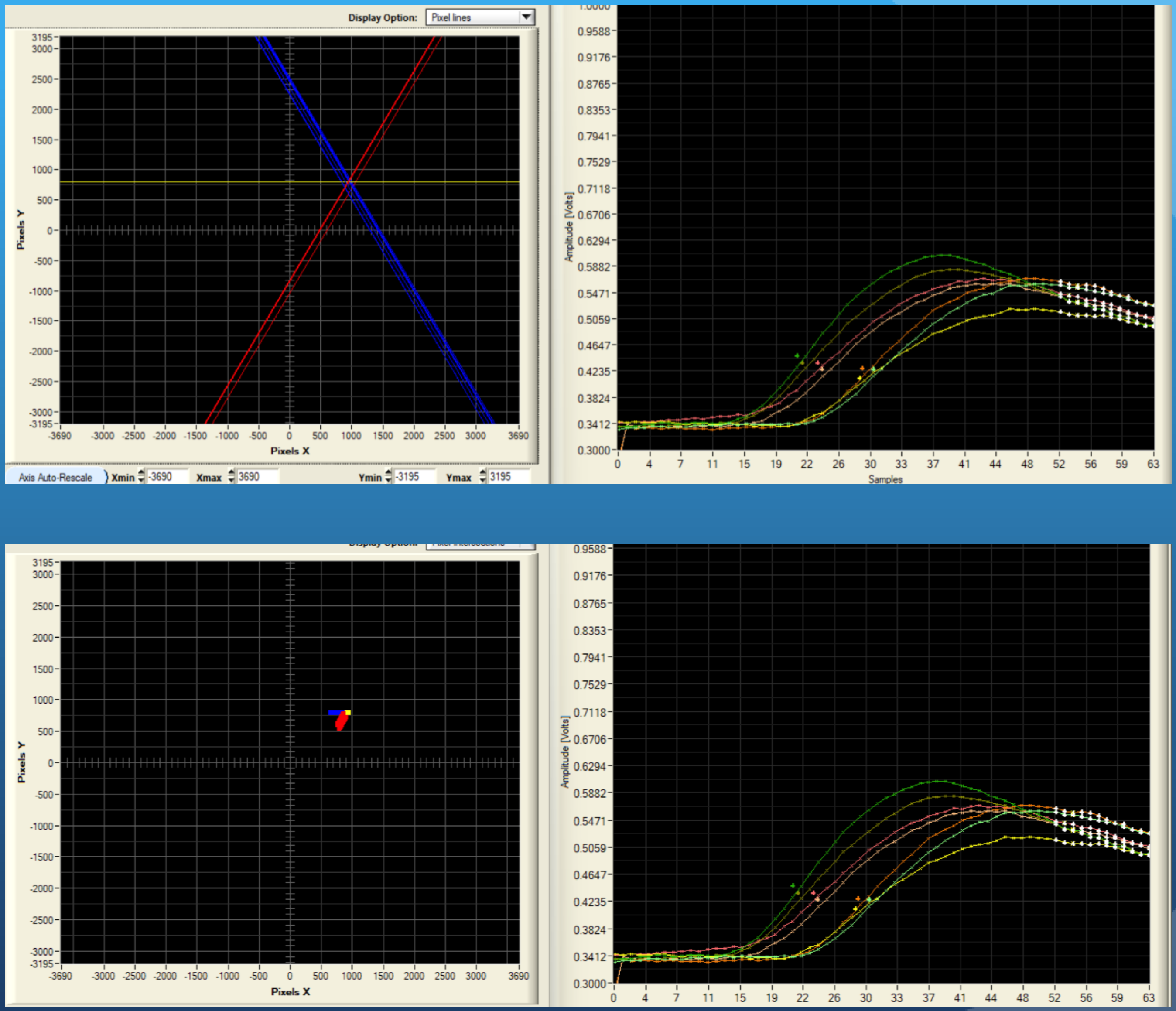
A DAQ board allowing the synchronization between the time and the position measurement (40 MHz clock).





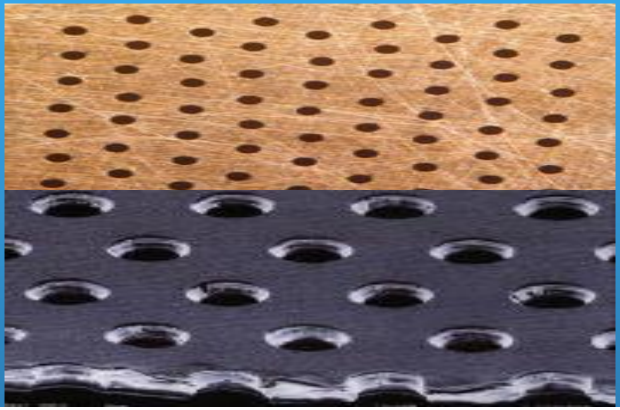


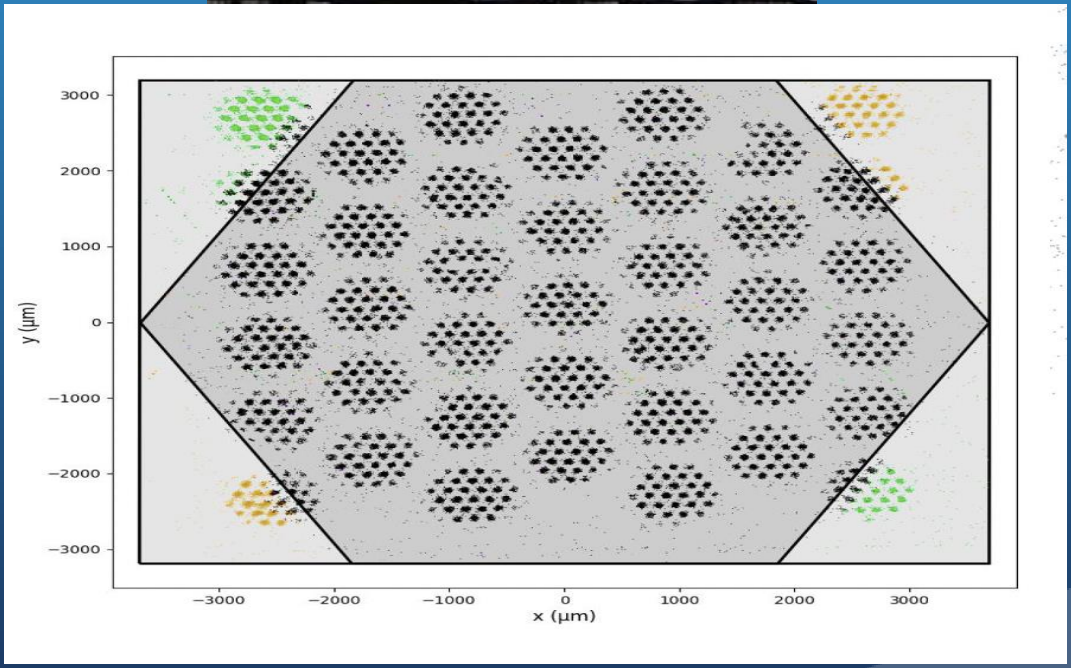
The whole system was tested by using collimated α and γ sources



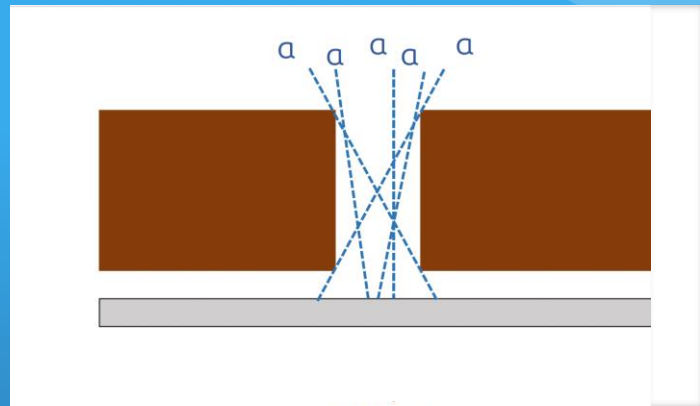
Spatial resolution

α source seen through a holes of 0.3 mm diameter and 0.8 mm pitch placed on a GEM foil with 50µm diameter and 140µm pitch



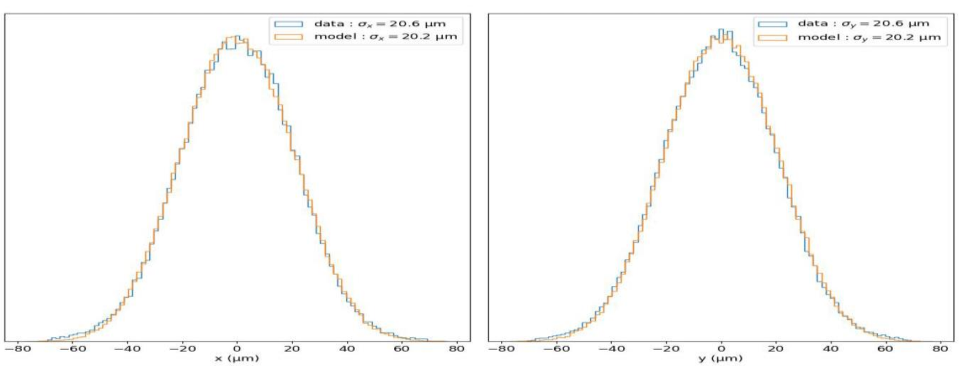


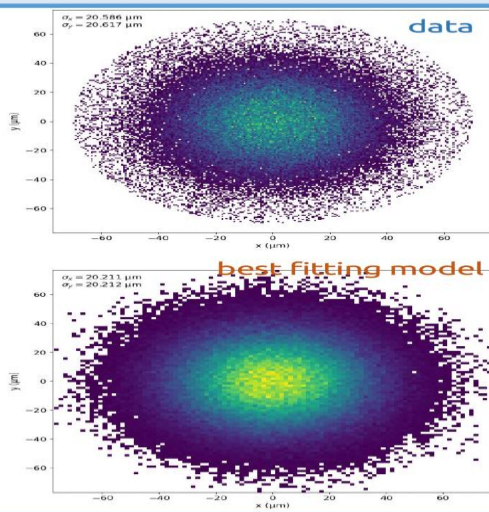
Spatial resolution



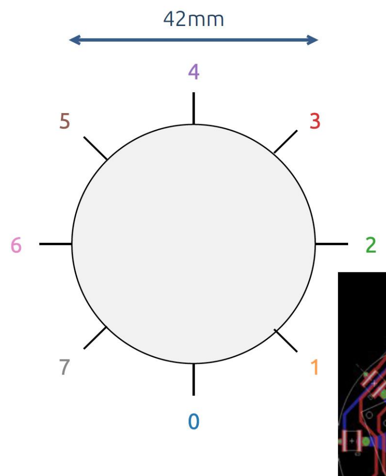
To estimate the spatial resolution, we developed a simulation tool to describe the alpha trajectories and their impact on the MCP. We then convolute the impact with a 2D gaussian distribution. The best data-simulation fit provides the spatial resolution of our detector

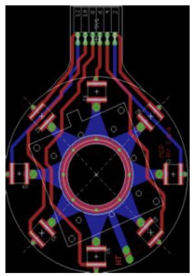
Best fit→ σ_x , σ_y of **14.5 μm**



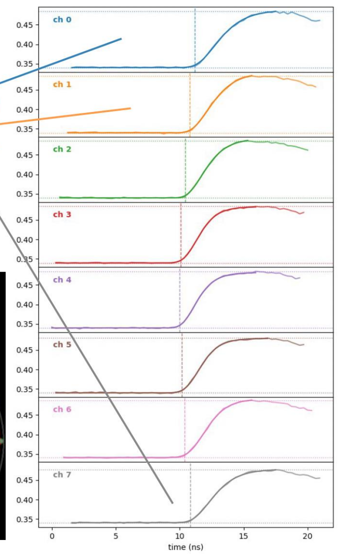


Timing detector





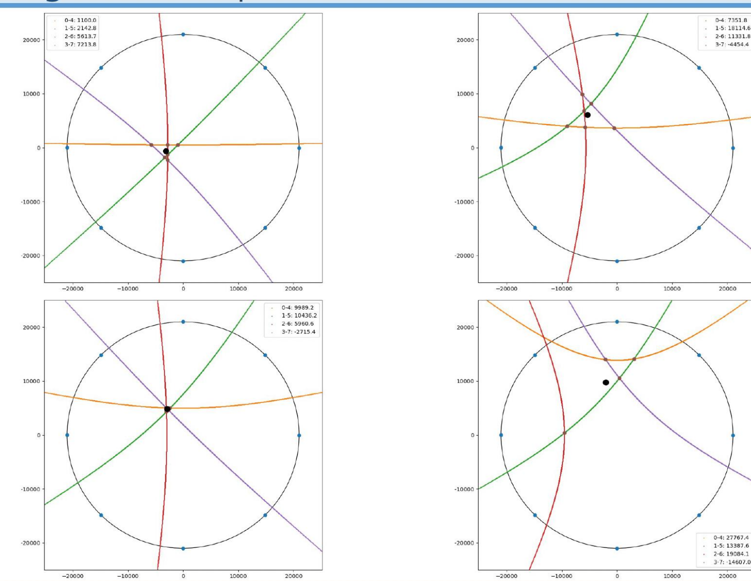
slower rising times for ch0, 1, 7 due to longer lines



fitting function :

$$f = C + a\cdot(1 - \nu\cdot e^{-f(x-\mu)})^{-1/\nu}$$

Timing detector – position reconstruction



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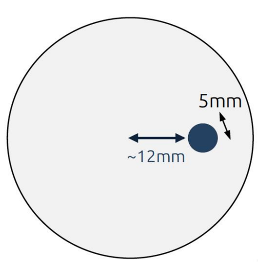
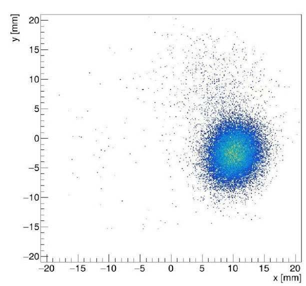
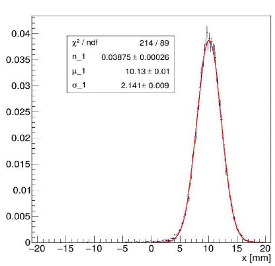


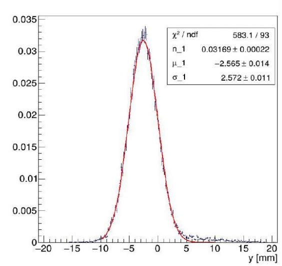


1000 V/MCP

σ_x_fit = 2.1 mm
σ_y_fit = 2.6 mm

substracting the hole width
=> **σ_x = 1.7 mm**
=> **σ_y = 2.3 mm**





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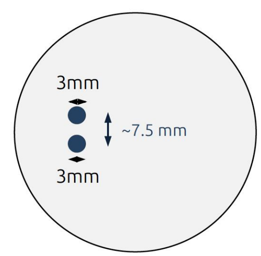
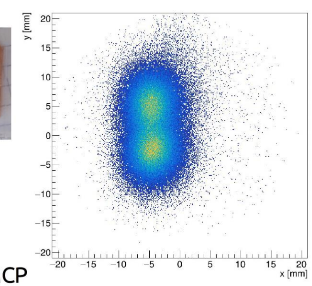
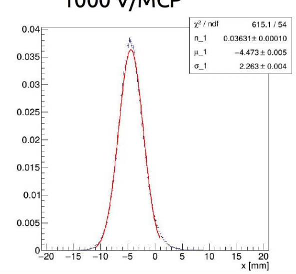


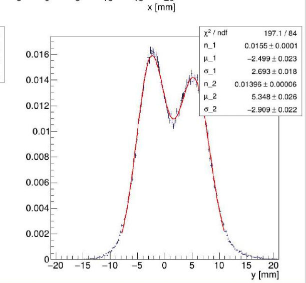


1000 V/MCP

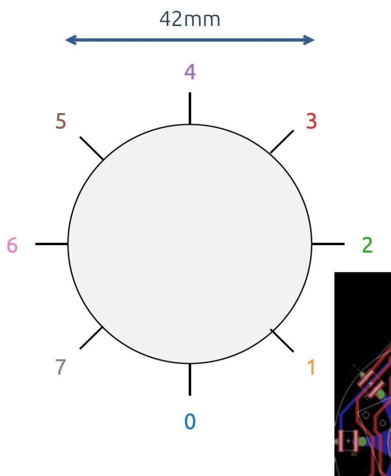
σ_x_fit = 2.3 mm
σ_y_fit ~ 2.8 mm

substracting the hole width
=> **σ_x = 2.2 mm**
=> **σ_y = 2.7 mm**





Timing detector



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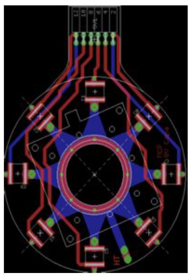

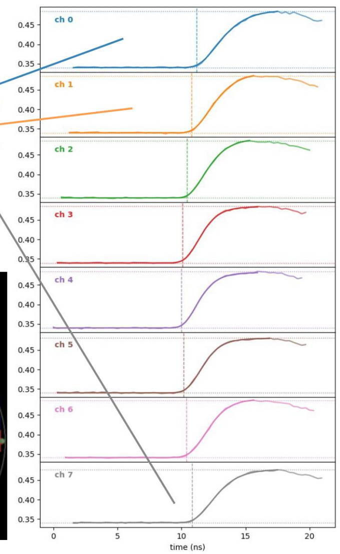

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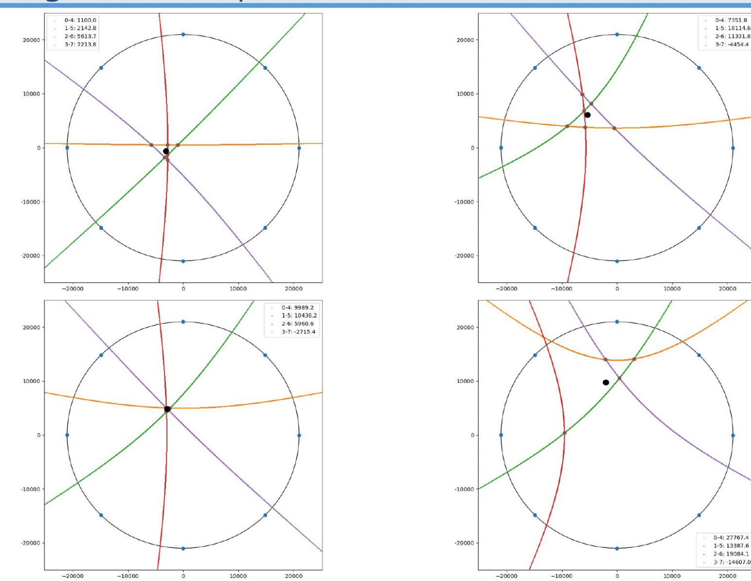
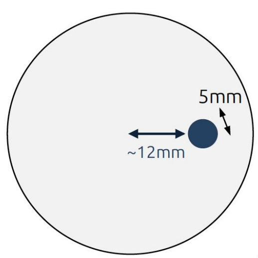
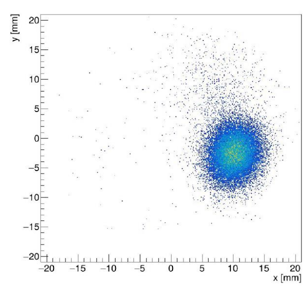


Timing detector – position resolution





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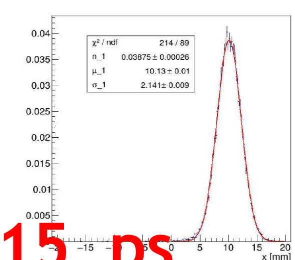
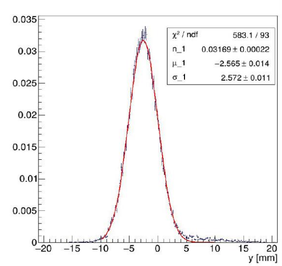
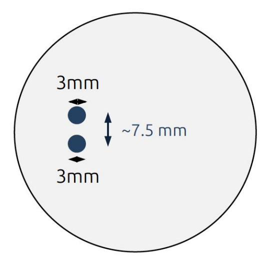
=> σ_x = 1.7 mm
=> σ_y = 2.3 mm

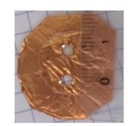


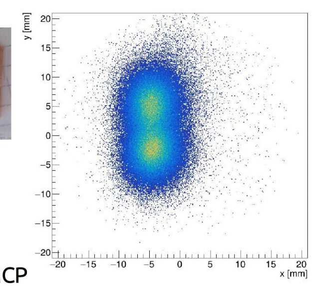


15 ps

Timing detector – position resolution



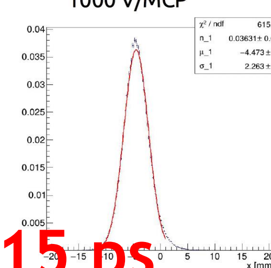


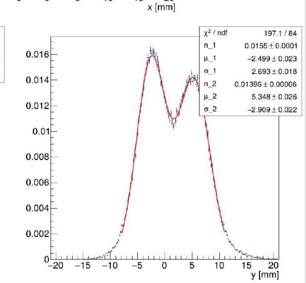


1000 V/MCP

σ_x_fit = 2.3 mm
σ_y_fit ~ 2.8 mm

substracting the hole width
=> σ_x = 2.2 mm
=> σ_y = 2.7 mm

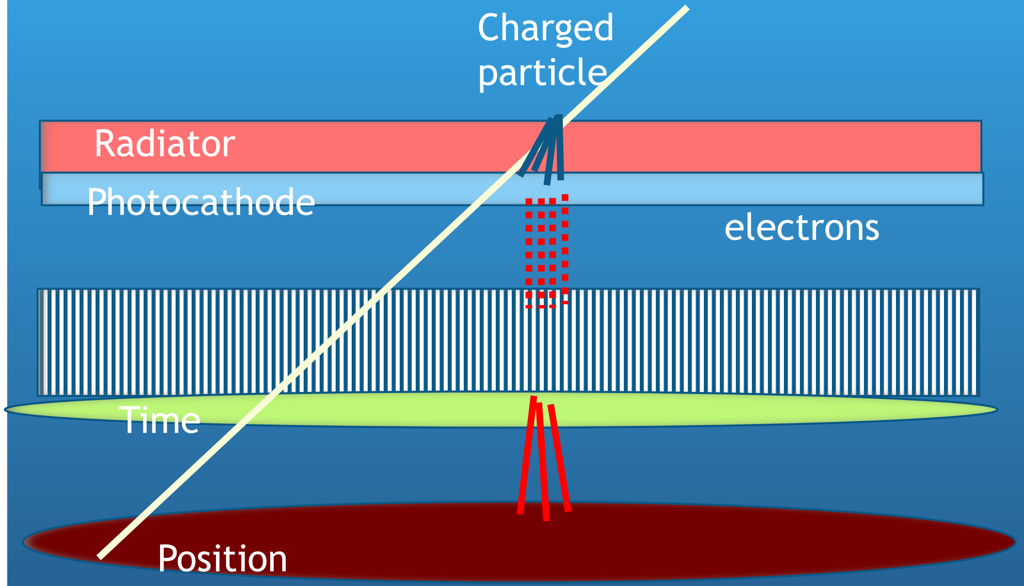


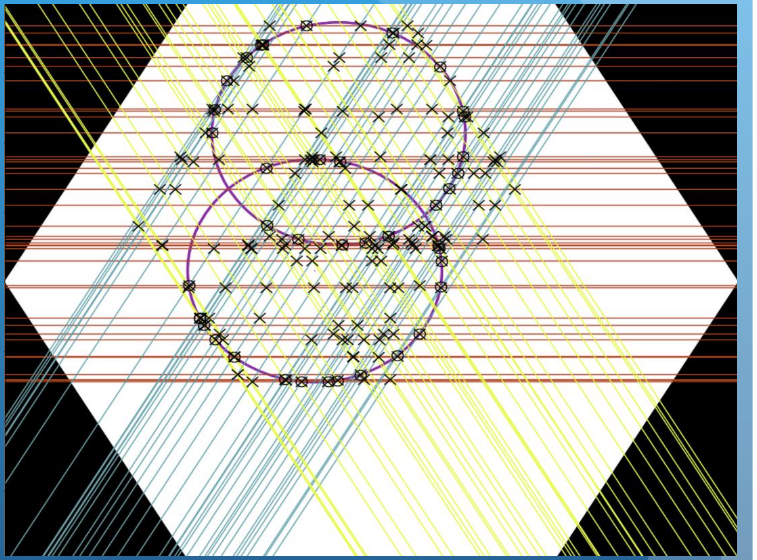


15 ps

Next step

Can we use PICMIC for tracking





Radiator should fulfil two constraints:

1) Enough Cerenkov photons are produced
2) Small budget material

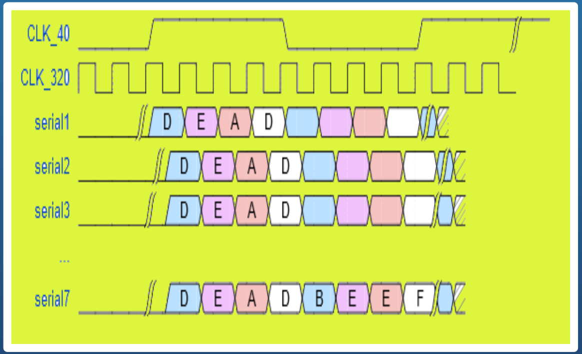
Cherenkov rings construction using Hough Transform

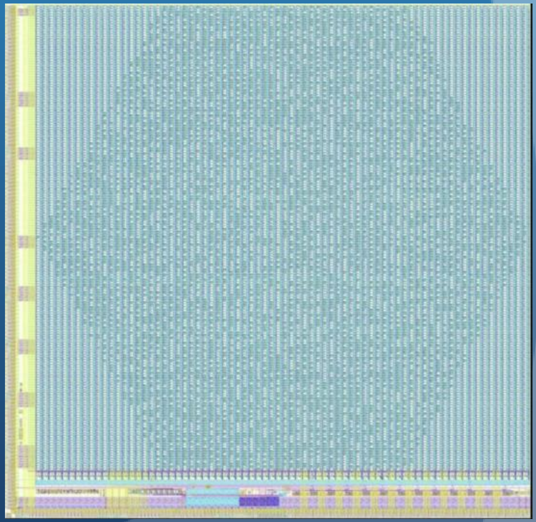
MgF2 crystal of 3 mm thickness was coated with DLC @ CERN and will soon be tested on the PICMIC setup

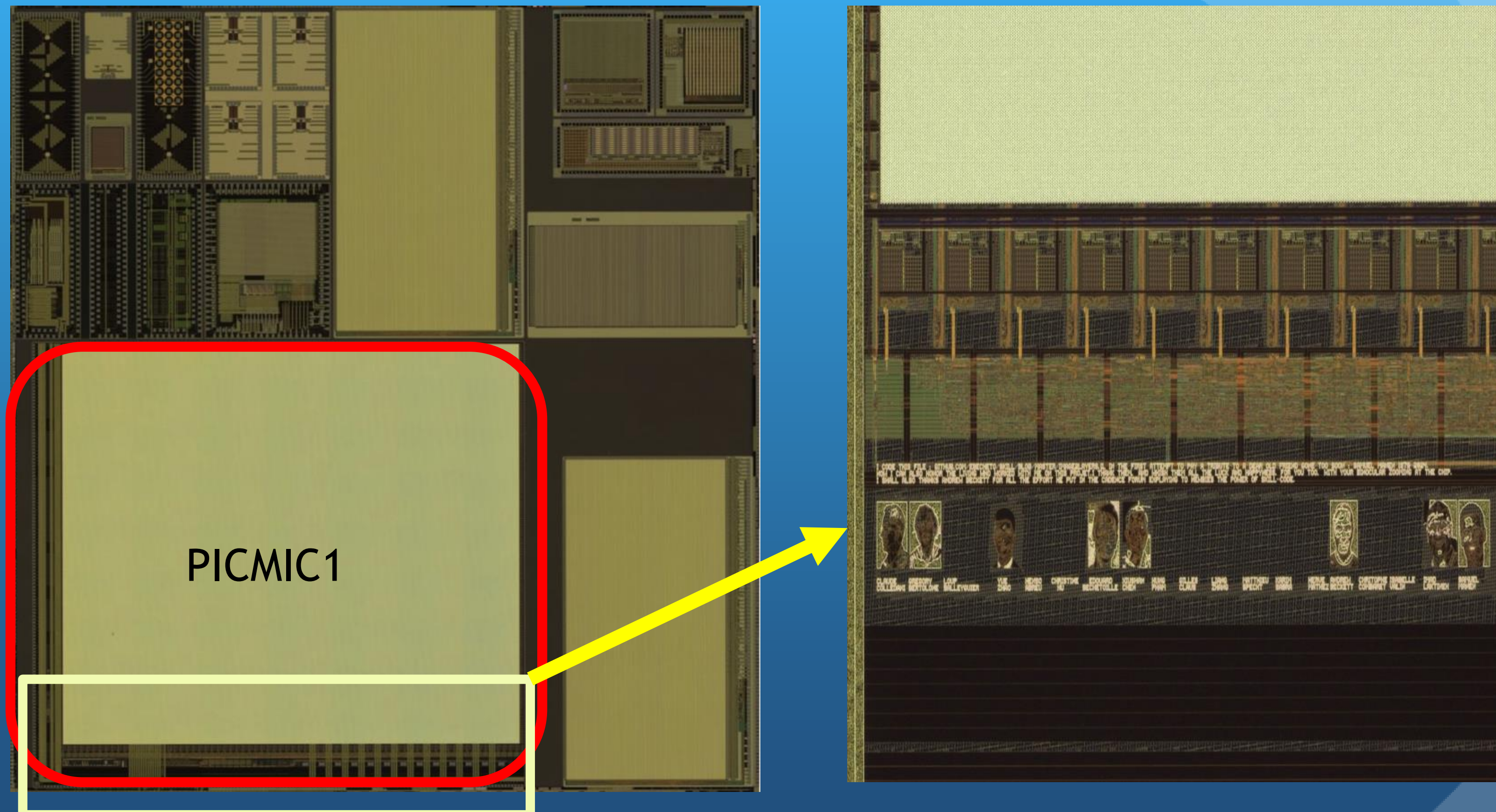
Next step: Spatial Measurement

The PICMIC0 chip was the first attempt to demonstrate the concept. We need to improve on several features:

- Better calibration possibilities (**8 bits DAC**) to get better uniformity
- Higher acquisition rate (**1 Mhz → 10-30 MHz**)
  By reading out each column separately
- By increasing the surface of the sensor by a factor of 4 (**1.2 cm x 1.4 cm**)
- Adding a **charge preamplifier** to avoid current smearing problems for long tracks.
- Few channels outputs are directly accessible to test external TDC






PICMIC1

Next step: Time Measurement

SAMPIC is an excellent toot but has a dead time of about **1.25 µs**.
Another timing measurement having a TDC with negligible dead time is needed to use PICMIC in higher rate modes.

A board integrating a low-jitter timing preamplifier and discriminator (**LIROC-OMEGA**) as well as a precise TDC (**picoTDC-CERN**) was conceived.
The board will use the GBTX developed by the CERN to communicate with the DAQ system.

The board is ready: 10 ps is obtained measured with charge injection of 1 pC

Next step: Acquisition

IDROGEN board that was developed within the DAQGEN of the IN2P3 will be used.

To be able to exploit the IDROGEN board we need:

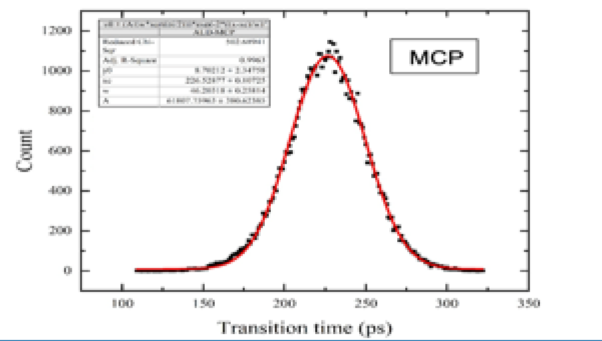
- **develop appropriate interface/mezzanine boards** between the IDROGEN and the timing and position boards.
- develop **an appropriate firmware to synchronize the data**

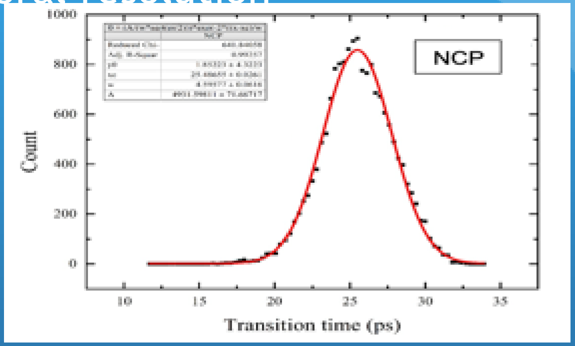
This work is now in an advanced stage. First tests with the board is foreseen before end of 2026

Going beyond the MCP→ NCP

NCP

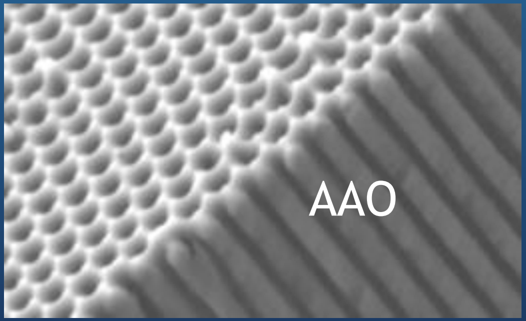
A new kind of MCP that we call NanoChanel Plate (NCP) is being developed.
It aims at producing structures with nanoholes that could be coated with emissive and resistive materials.
→ At least ten ttimes better spatial and temporal resolution

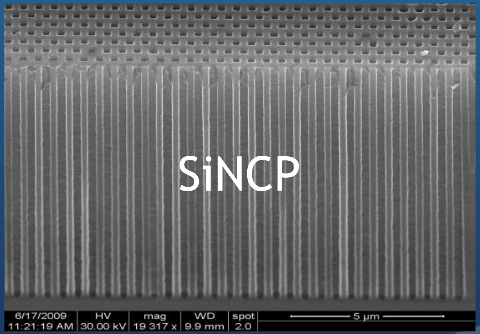


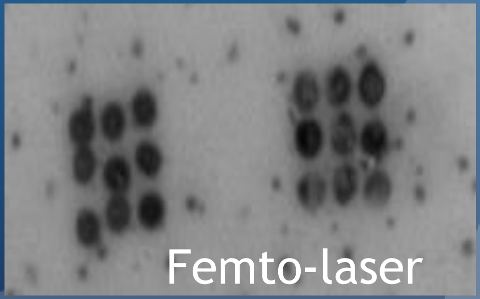


Three technologies are followed:

- Anodized Aluminium Oxide AAO (with IMP→ ANR NanoPolyPad)
- Silicon electrochemical etching (with INL →ANR NCP)
- Femto-laser digging (with LHC→ ANE LAMP?)





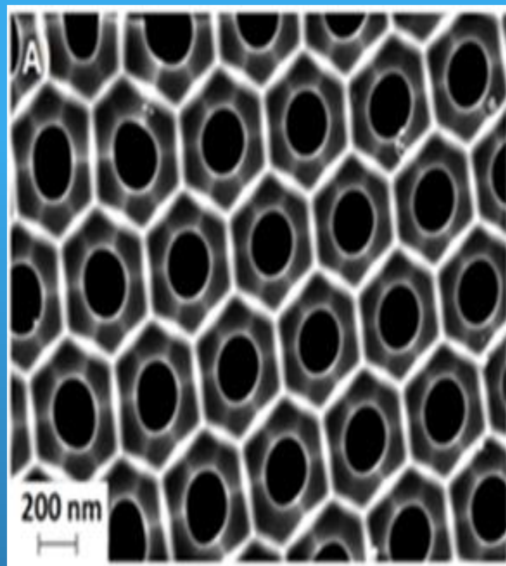


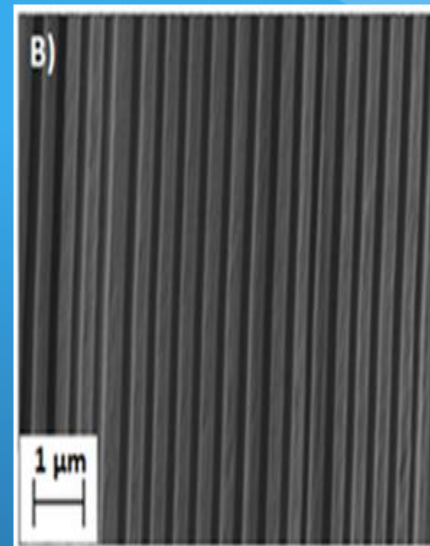
Summary

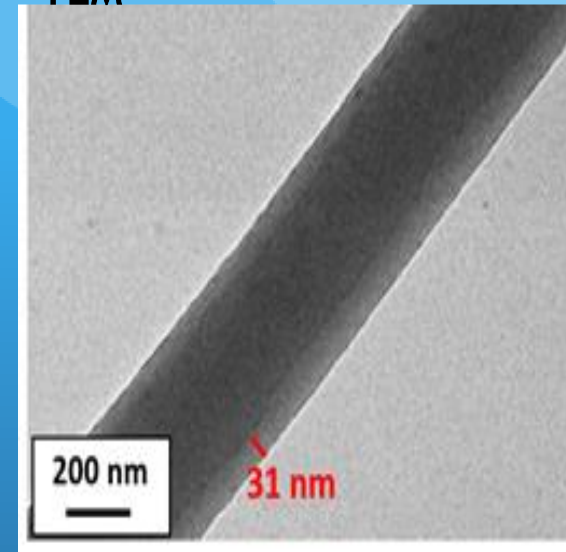
- The PICMIC concept proposed to to simultaneously exploit the time and position intrinsic resolutions of MCP is validated
- Time resolution of 15 ps has been achieved
- Spatial resolution of 15 μm has been achieved
- New version of PICMIC will allow to exploit the intrinsic resolutions of MCP.
- the system can be used as timing tracker as well as a precise 4D camera.
- A new generation of MCP called NCP with the aim to reach 1 ps and sub-micrometer resolutions are being developed

NCP-AAO

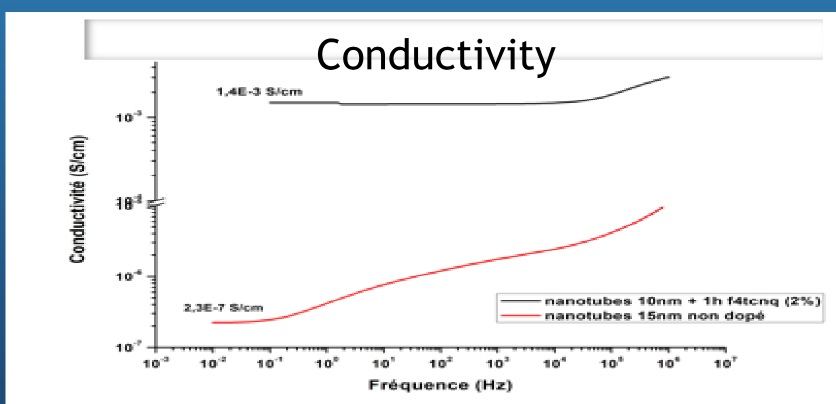
TEM

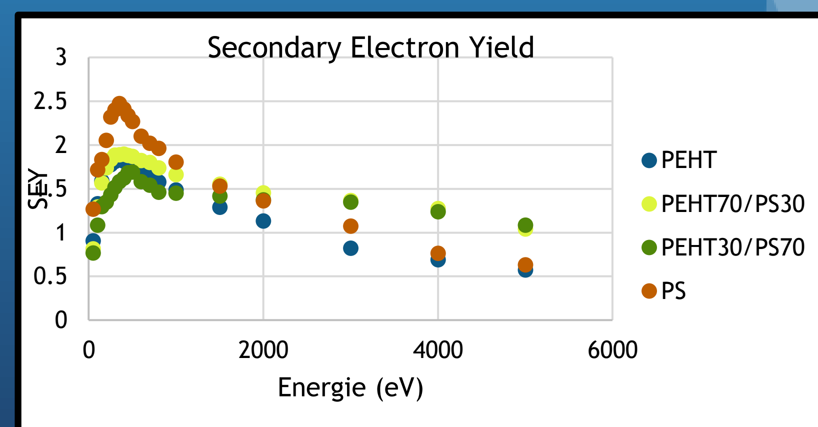






Coating





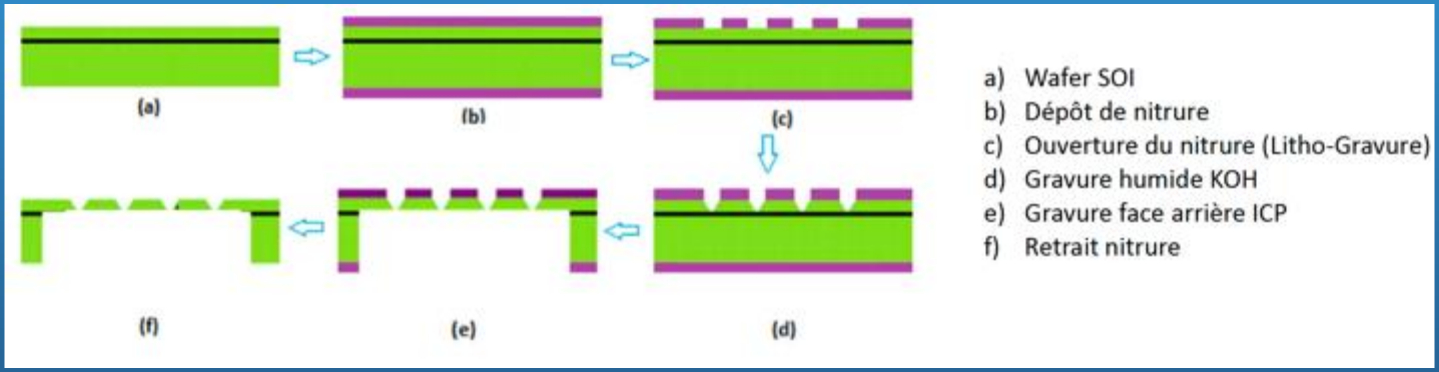
We are developing a new coating using ALD techniques to reach higher SEY

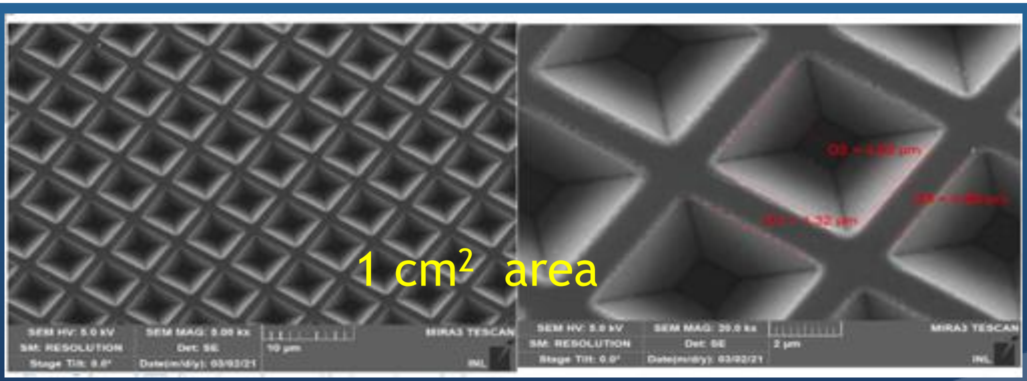
PICMIC for photodetection

We are developing a highly granular reflective photocathode.
Photocathode is made of holes with conic shape.

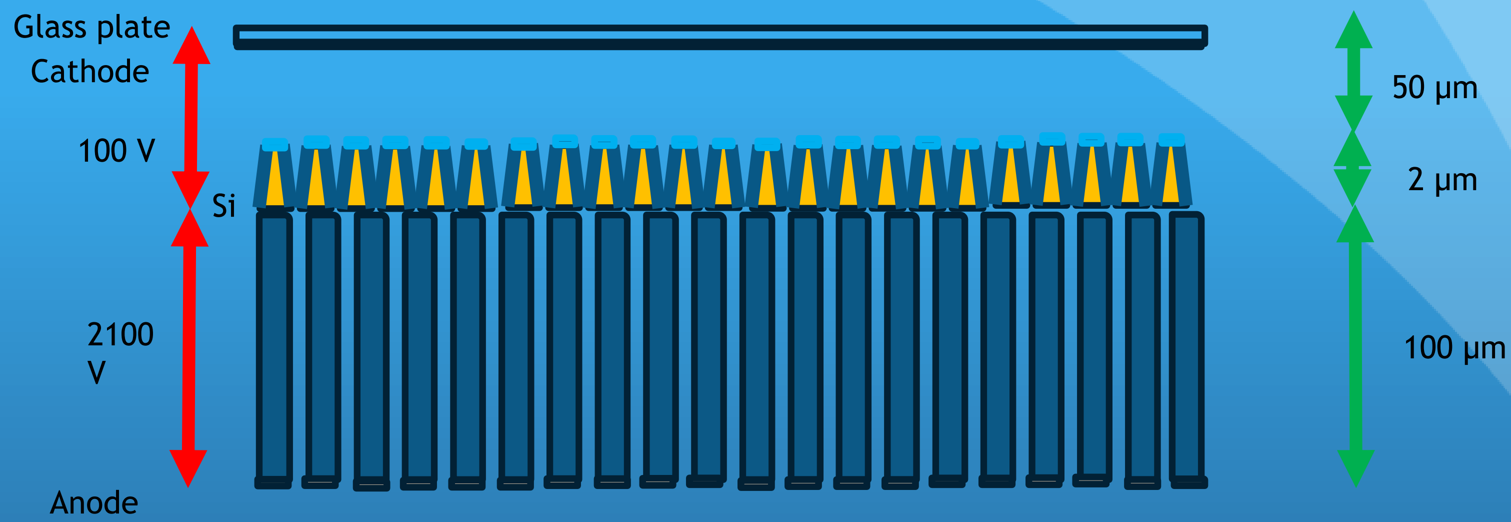
- Exploit the high spatial resolution the MCP offers
- Increase the quantum efficiency

The structure is produced on a silicon wafer will be coated with different kinds of photocathode materials (DLC,B_4C) and then cast on MCP to test PICMIC as a photodetector concept.

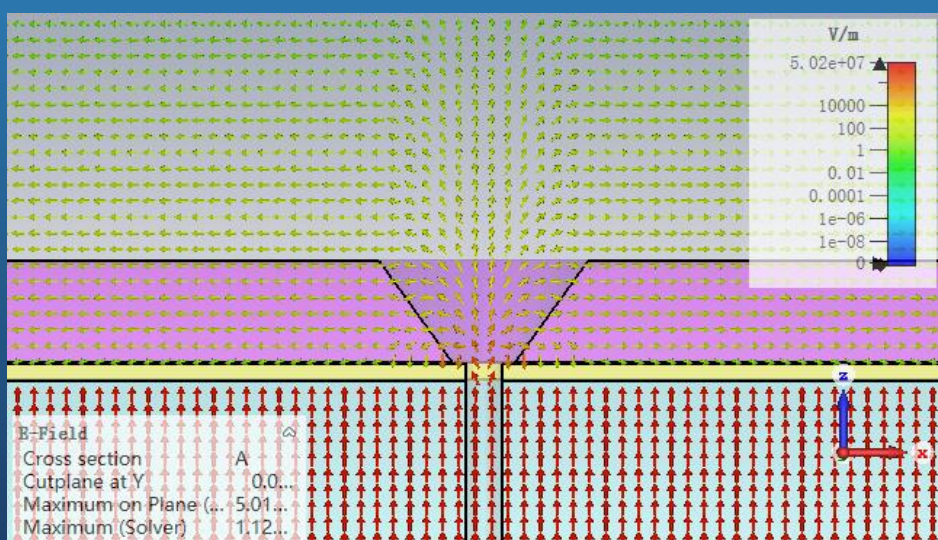


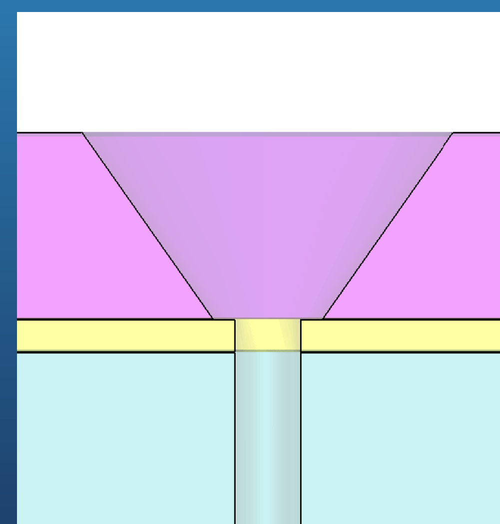


PICMIC for photodetection



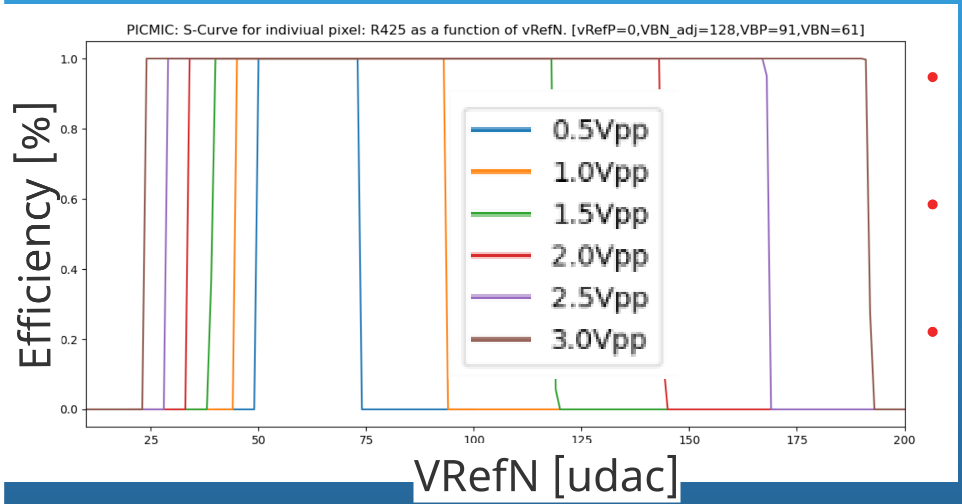
Simulation with CST



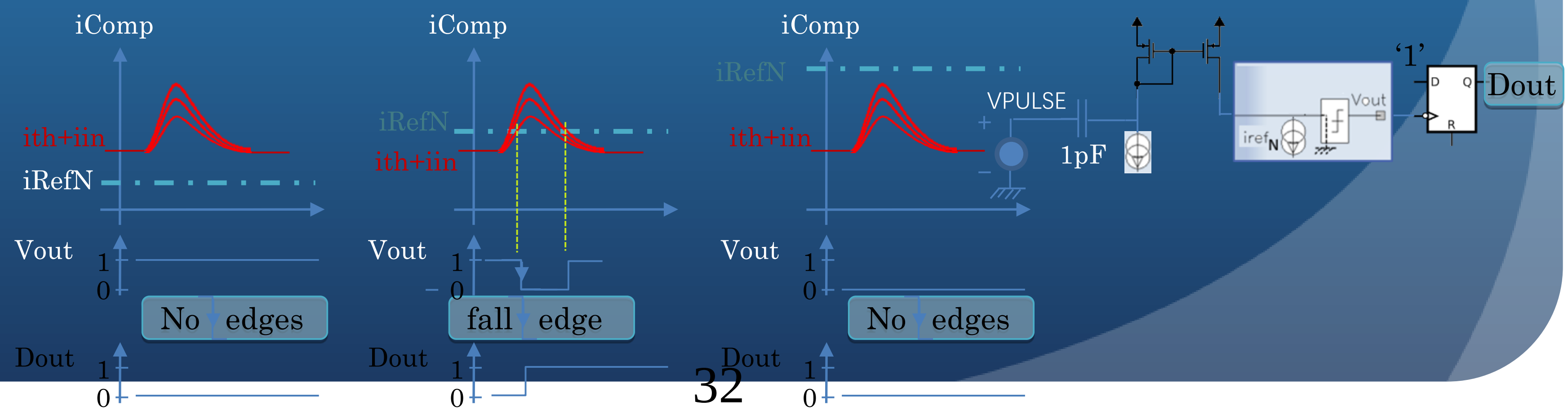


Injections Studies (1/2)

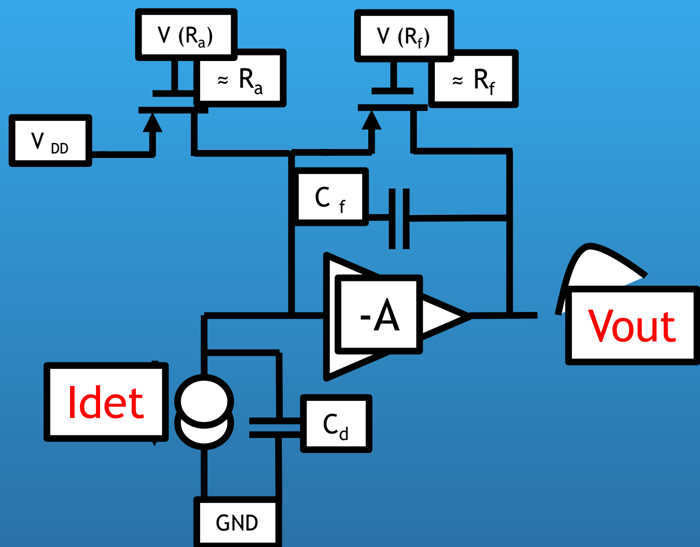
PICMIC allows external signal injection trough the (PAD):
- **R424**[R68,C28],**R425**[R103,C35] and **R426**[R6,C15].
- * it also allows to excite whole columns in the channel matrix (no shown in above layouts).

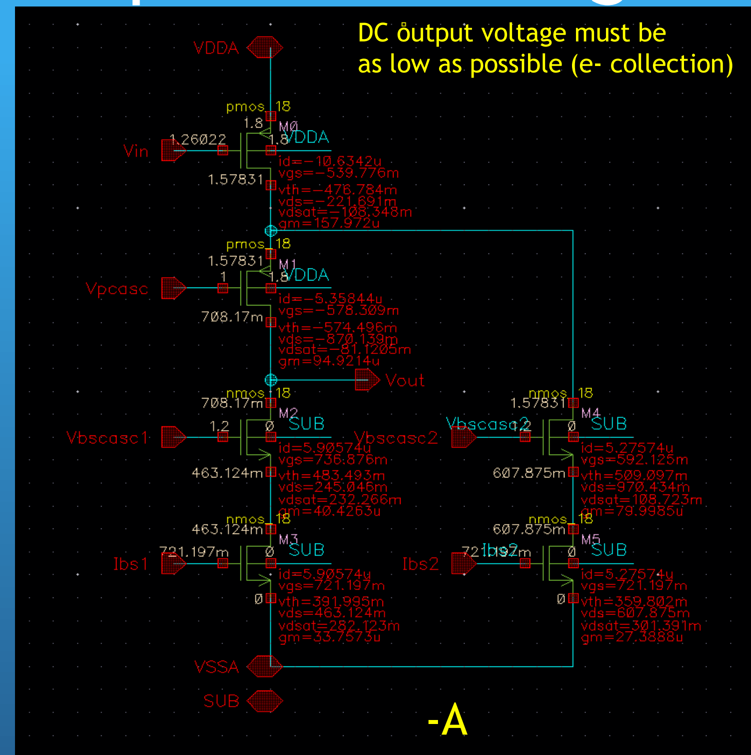


- Voltage injection through external 1pF, then scan of the threshold of Current Comparator.
- Below the current threshold, the falling edge sensitive does not trig.
- The signal is recorded on falling edge, so above a certain value of iRefN added to threshold current, the comparator does not trig anymore → chapeau!



CSA Architecture from previous design





- R_a and R_f are made of 2 PMOS transistor polarized in triode region
- $V(R_a)$ and $V(R_f)$ could be use to modify the DC output voltage (e^- or h^+ collection

$$V_{DC\_Out} = V_{DC\_In}\left(1+\frac{R_f}{R_a}\right) - \frac{R_f}{R_a}V_{DD}$$

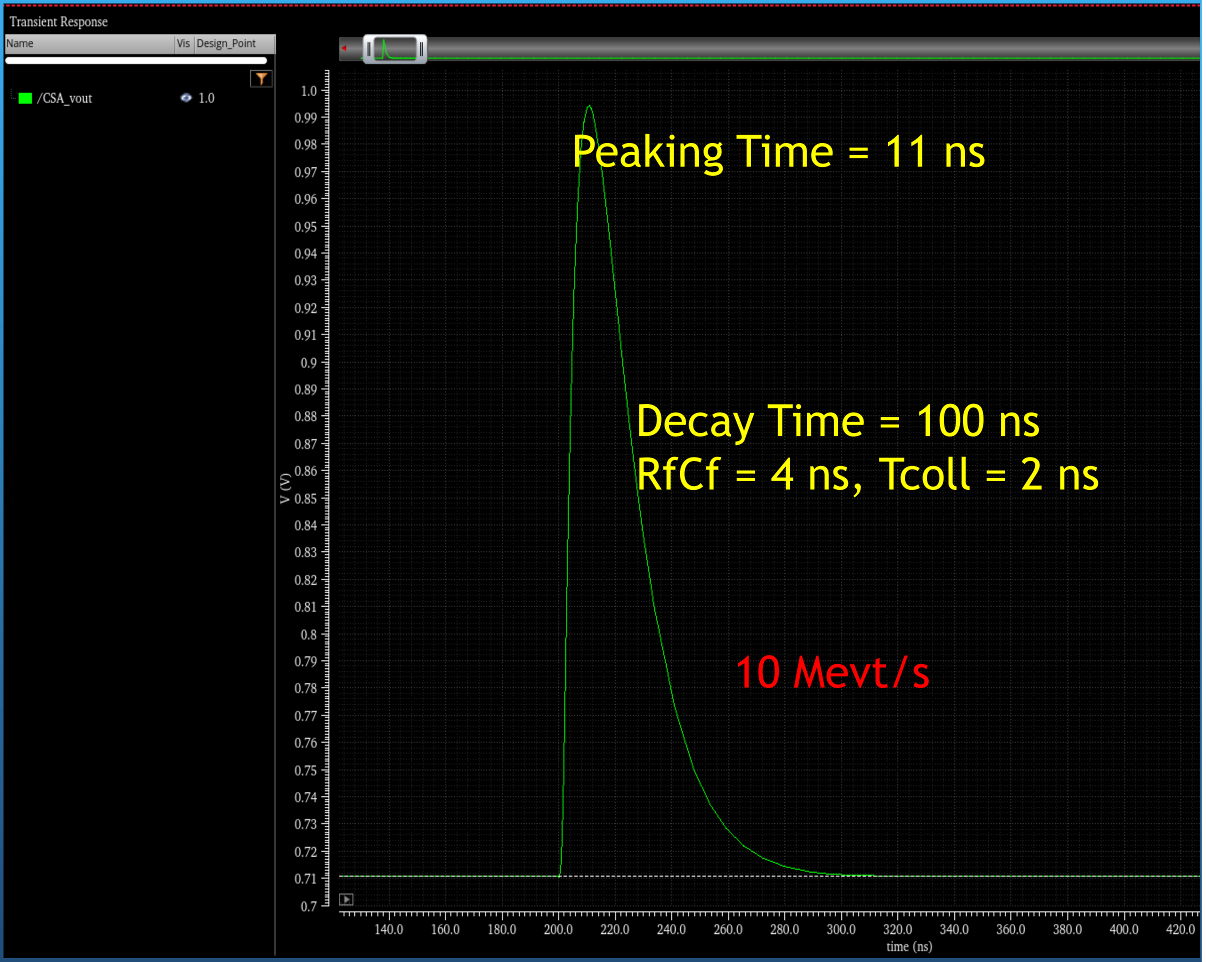
Input signal characteristics

Estimated from Picmic_0

- Input current : 2 µA to 20 µA
- Charge collection time : (1 ns)
- Input charge : (10^5 e^- to 10^6 e^-) (16 fC to 160 fC)
- Simulation with (8 fC to 80 fC) (factor 2)
- Counting rate : 10 Mevt/s minimum value)
- Detector capacitance
  - C_d = (7,66 fF/50 µm) * 15 mm = 2,2 pF (CSA simulations with 5 pF) (C_{d-max} = 5 pF)
  - 2 pF < Cd < 5 pF, C_{d-sim} = 3 pF
- ENC < 0,4 fC (2500 e-)
- CSA output signal :
  - Rise time ≈ (10 ns)
  - Decay time ≈ (100 ns)
  - Output Voltage : qq 100 mV
- Feedback network :
  - C_f ≈ (20 fF)
  - $R_f \approx R_a$ (200 kΩ) made with PMOS and could be modified to adjust DC level output

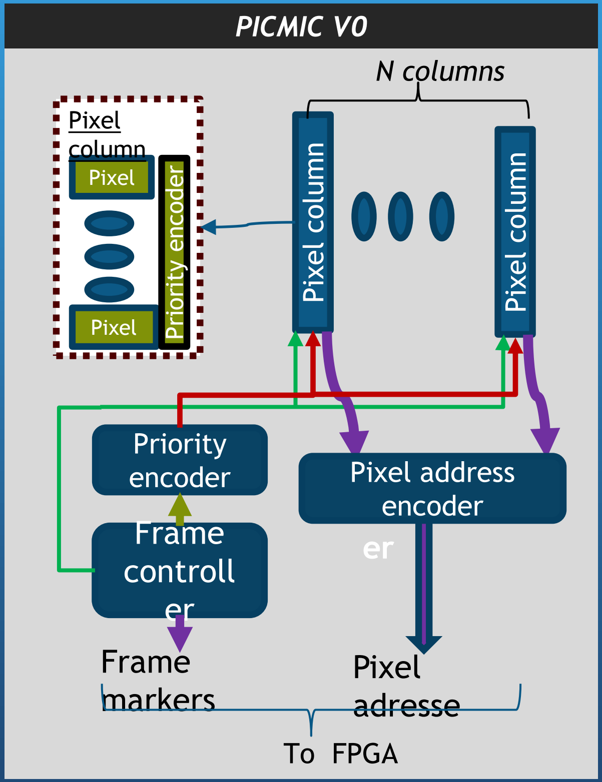
CSA Sim Results

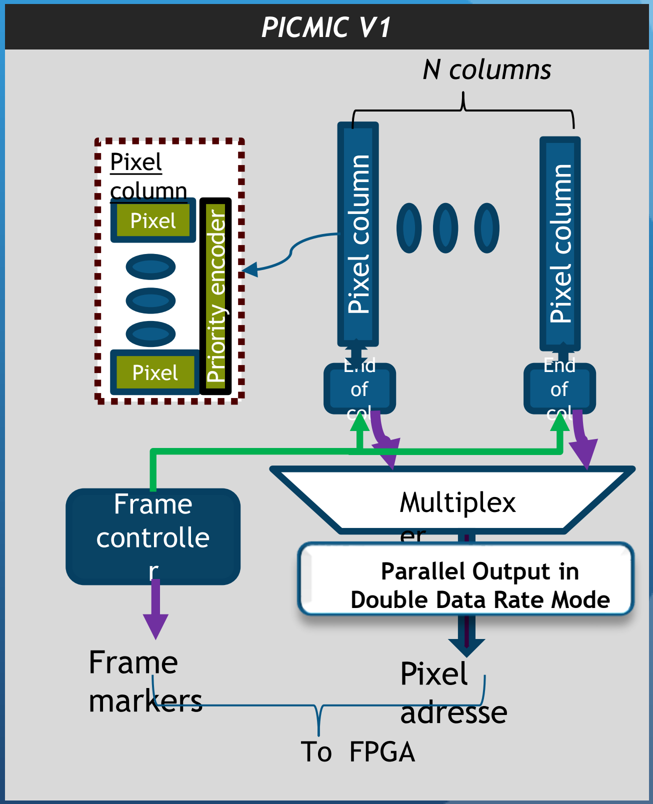
- Feedback network :
  - Cf ≈ 20 fF
  - R_f and R_a = 200 kΩ
  - C_d = 3 pF
- Q_{in} = 42 fC
- Vdc_Out = 0,715 V
- Vdc_In = 1,26 V
- CSA bias current (input Transistor) : 15 µA
- Output voltage = 310 mV (42 fC/20 fF = 2 V !) due to amplifier GBW

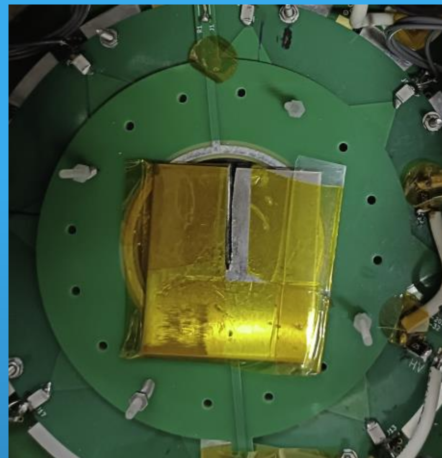


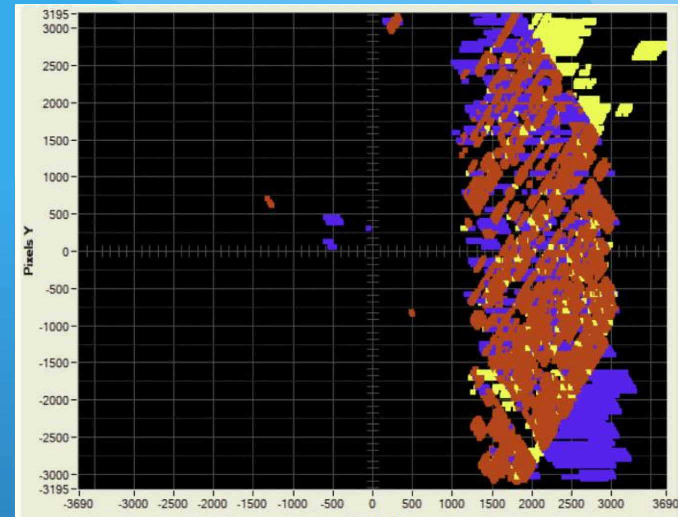
DAQ system : PICMIC V0 vs PICMIC V1

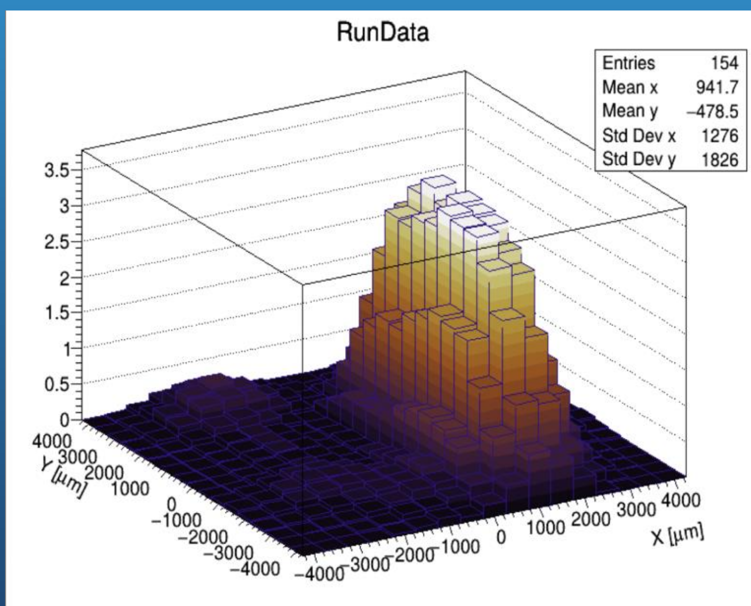
Both ASICs employ a *frame-based mechanism* to periodically transmit the addresses of stimuli pixels, but with different readout column modes. The stimulated pixels record information in their in-pixel logic and send it out in the next frame.

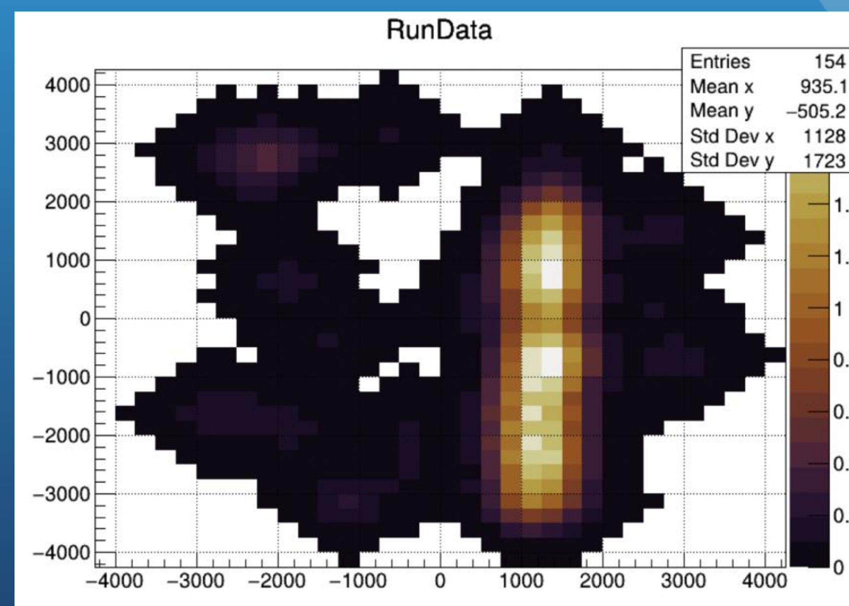







Pixels Y
3195
3000
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
-3195
-3690 -3000 -2500 -2000 -1500 -1000 -500 0 500 1000 1500 2000 2500 3000 3690

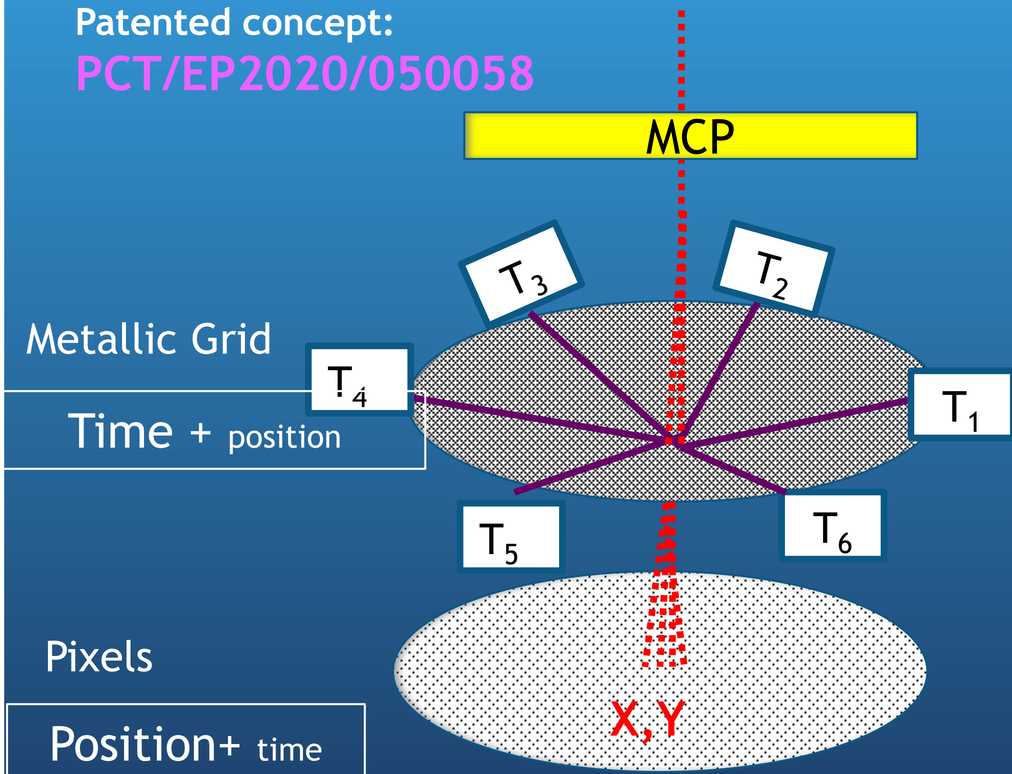

RunData
Entries 154
Mean x 941.7
Mean y −478.5
Std Dev x 1276
Std Dev y 1826
Y [μm]
X [μm]


RunData
Entries 154
Mean x 935.1
Mean y −505.2
Std Dev x 1128
Std Dev y 1723

To fully exploit MCP we propose the following scheme:

- ❑ A transparent grid placed downstream the MCPs and read out by sensors with excellent time resolution. Followed by:
- ❑ A detection matrix with micrometric pixels to measure with great precision the position of the avalanche while requiring limited number of electronics channels.

Patented concept:
PCT/EP2020/050058



Concept description

- ❑ The avalanche crosses a transparent grid connected on its periphery to a few timing sensors
- ❑ The avalanche is then collected by pixels

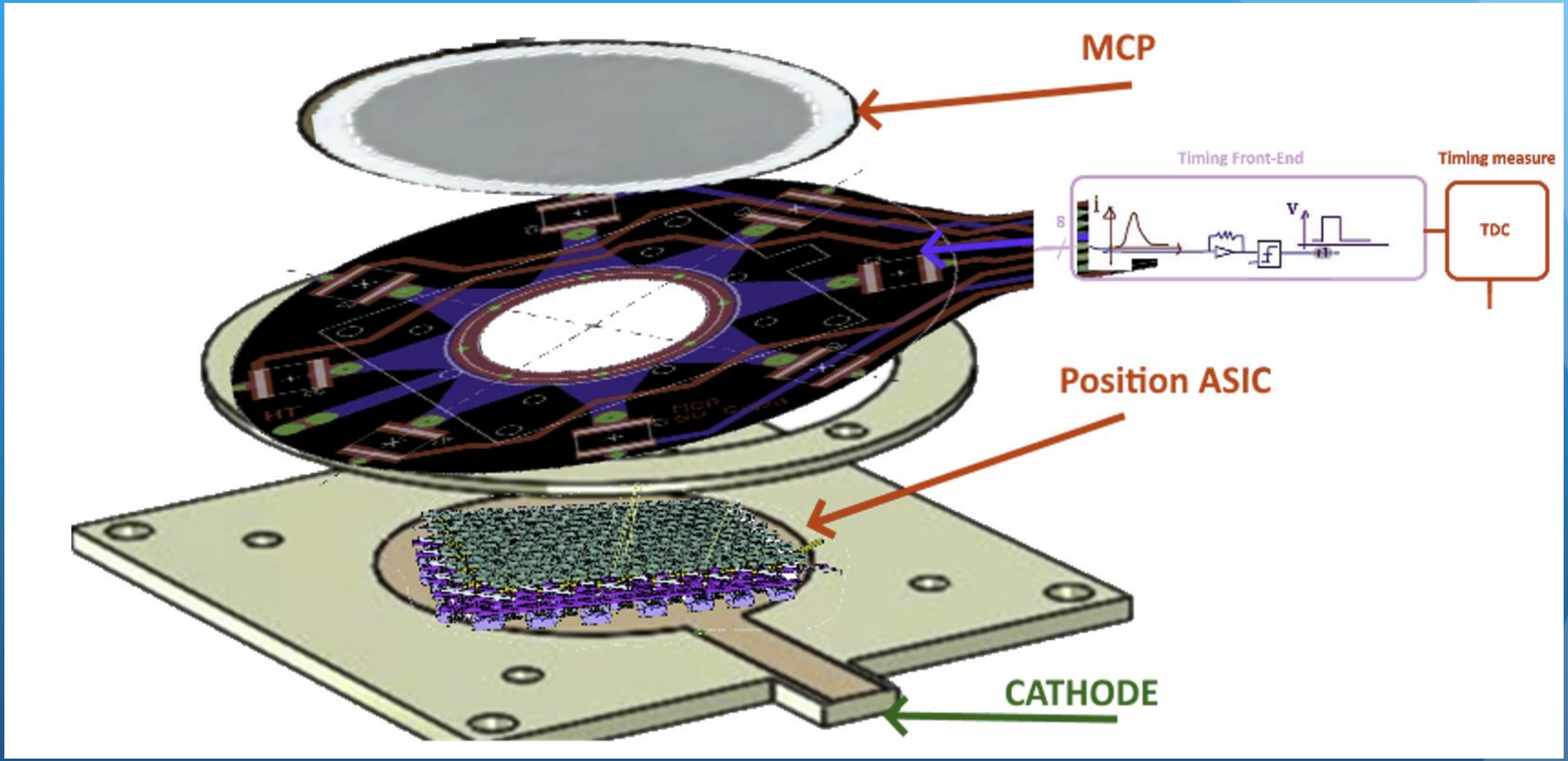
1- Measure X,Y, from the fired woven strips b crossing them geometrically

2- Measure T_i (from time sensors)

3-Substract time propagation using speed propagation and X-Y)
4- average on the (T_i-T_i(propag))

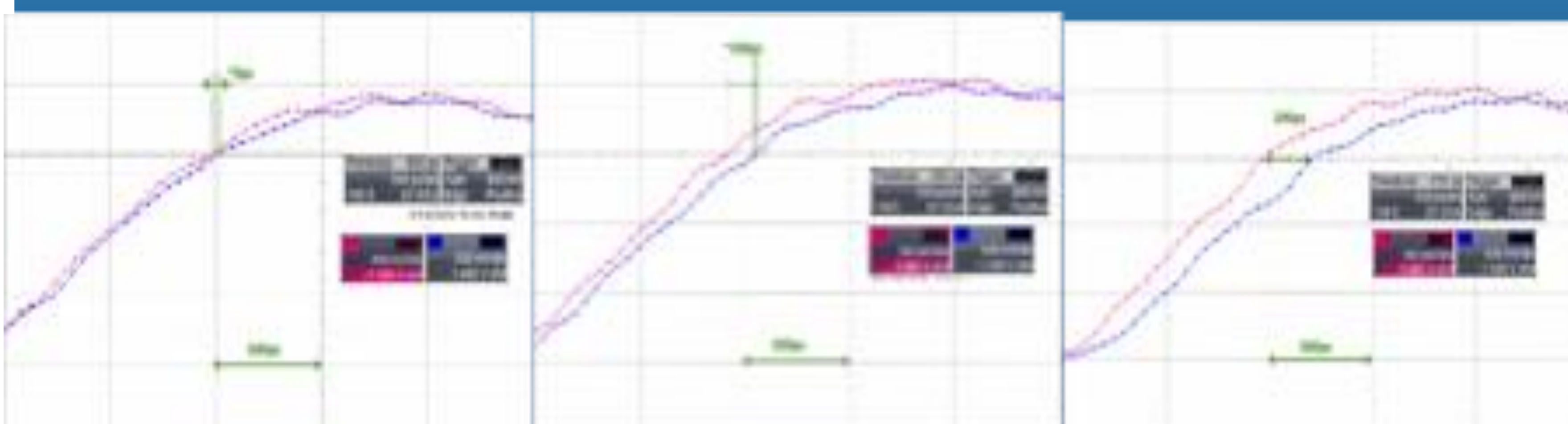
$$T_{abs} = \frac{\sum_0^N T_i - T_{i-propag}}{N}$$

PICMIC: Proof of Concept



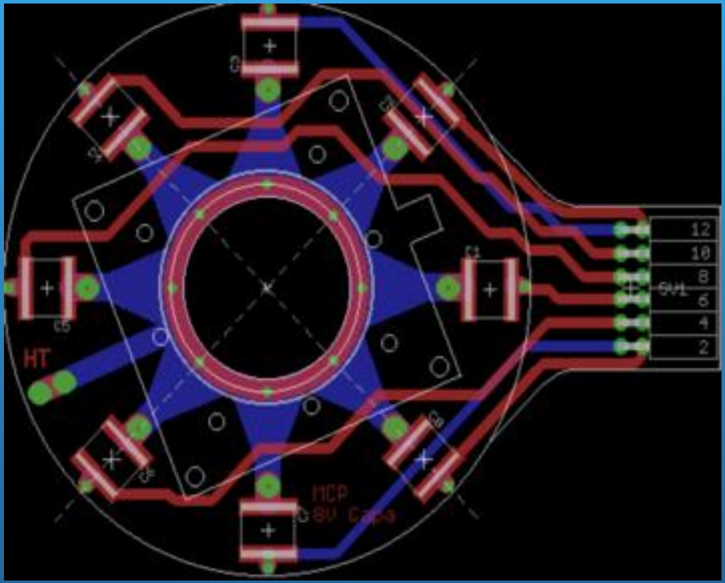
Metallic grid is replaced by the 100% transparent MCP grid (metallic anode)

First step: Delay plane concept ?



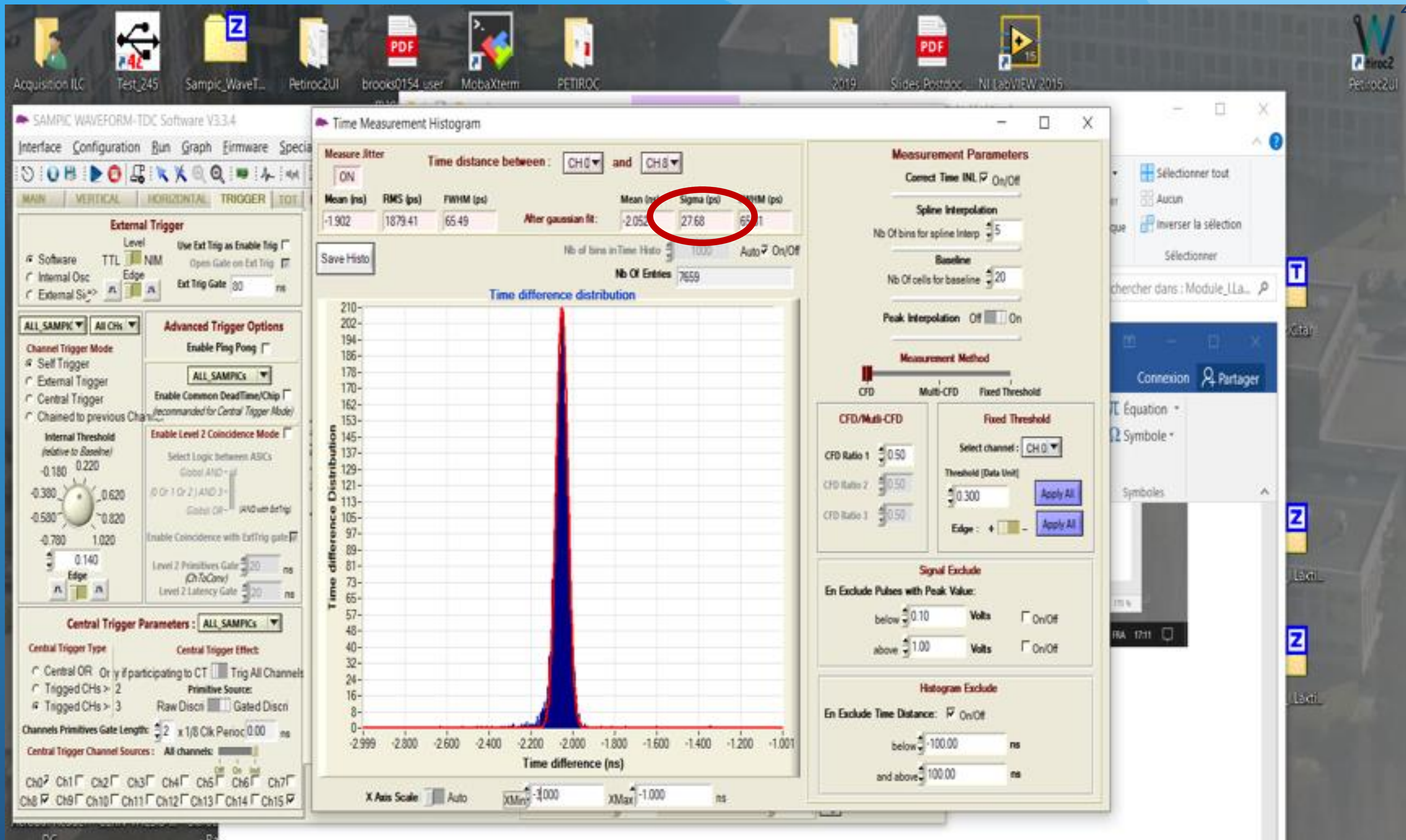
Second step :
Setup with timing sensors+1 large pad (collect) for the position

Time Measurement



8-point PCB for the time measurement.
PCB to be in contact with the grid

SAMPIC: TDC ASIC allowing to reach 3 ps time resolution

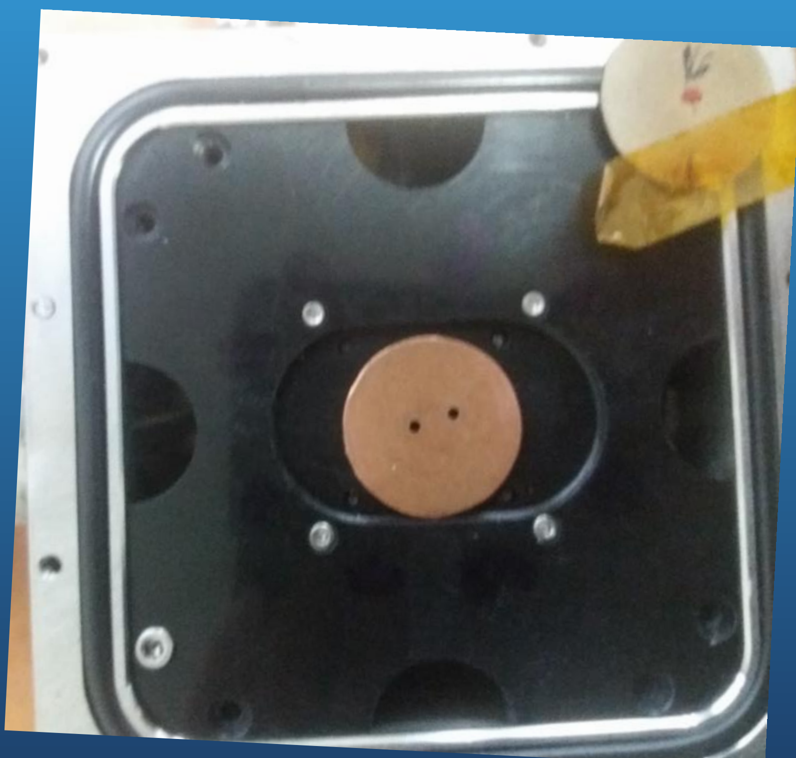


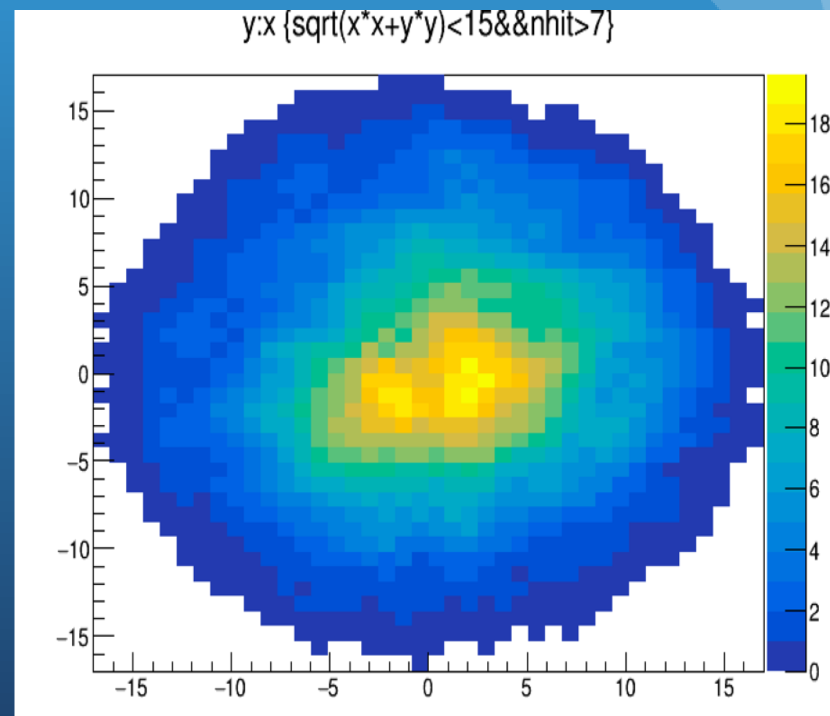
ΔT (ps)

Time difference between two channels

Time measurement → position measurement

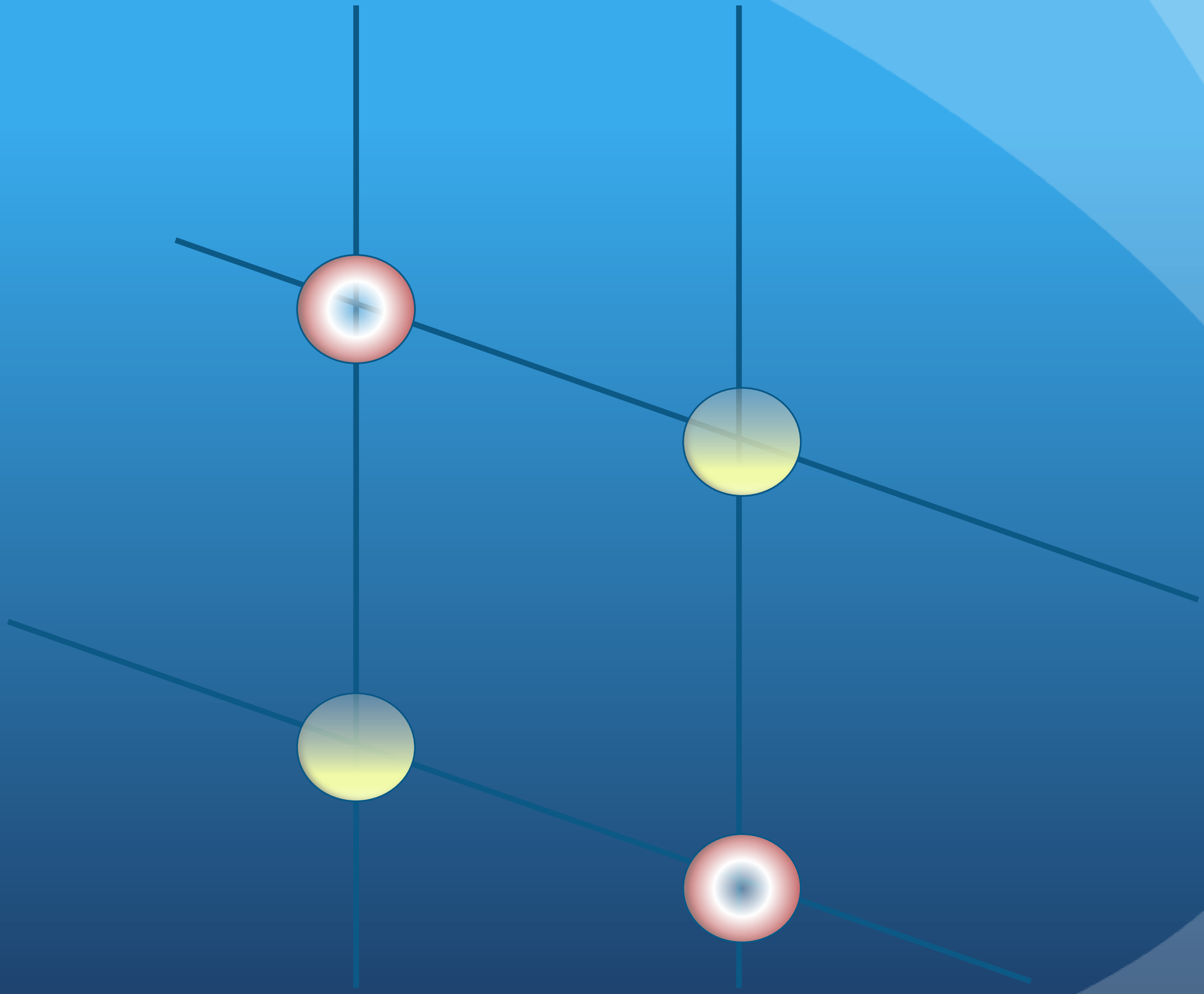
Waiting to have the pixel matrix to measure the position, two algorithms using the difference of time of arrival among the different channels were developed to obtain the position of the hitting particle.

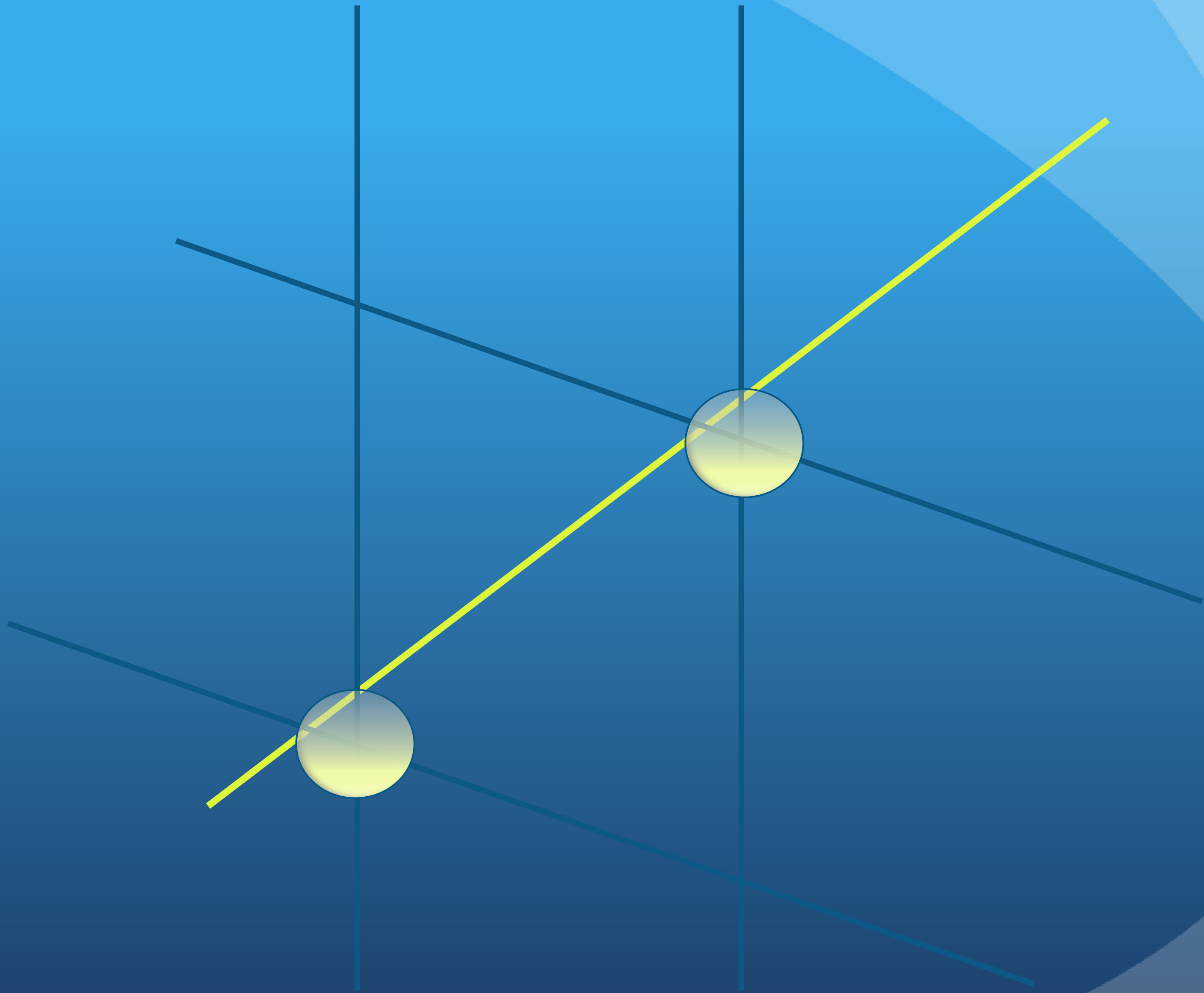




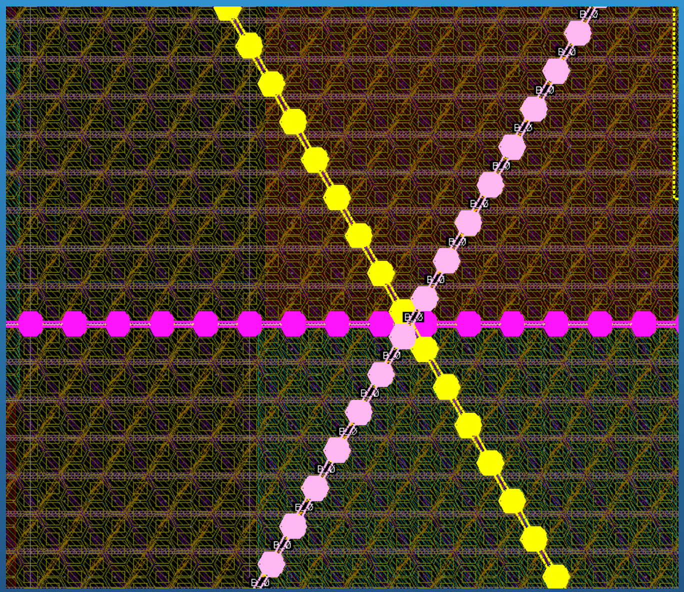
Where is it useful?

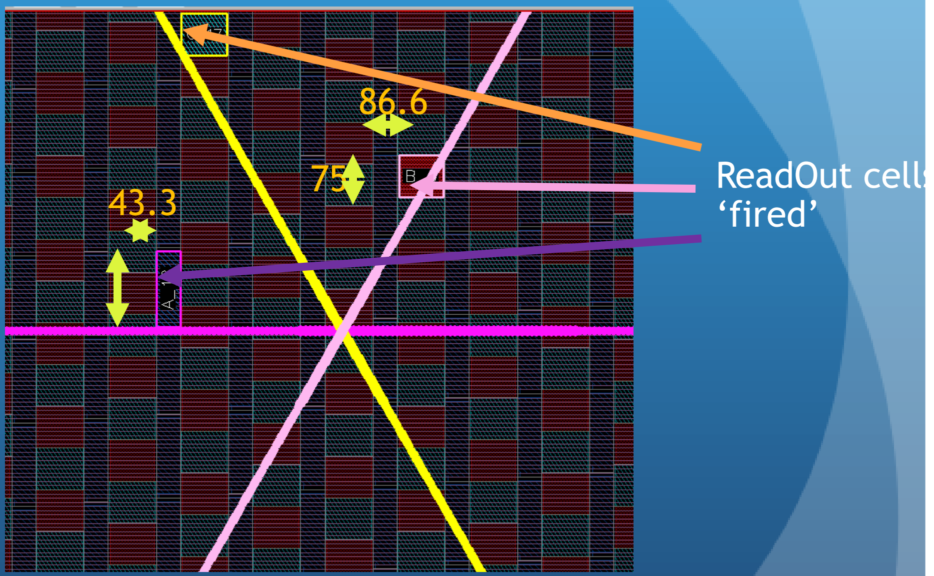
- **High Energy Physics,**
  - **Cerenkov detectors, trackers, etc.. For FCChh /SPPC**
- **Nuclear Physics**
  - **Mass Spectrometry (ToF)**
- **Accelerator**
  - **Beam monitoring, Streak Camera**
- **Free Electron laser**
  - **Analysis of the structures of materials, in particular biological objects (XFEL, LCLS2, Shine)**
- **Spectrophotometry : FLIM fluorescence lifetime microscopy, Raman spectroscopy, Time-resolved near IR spectroscopy**
- **Medical equipment : PET Scan, CT-Scan, In-Vitro Assay, Gamma Cameras**
- **Biotechnology : Flow cytometry, confocal laser microscopy, DNA sequencers, Mass spectrometry**
- **Environmental measurement : Dust counters, LIDAR (ToF 3D imaging)**



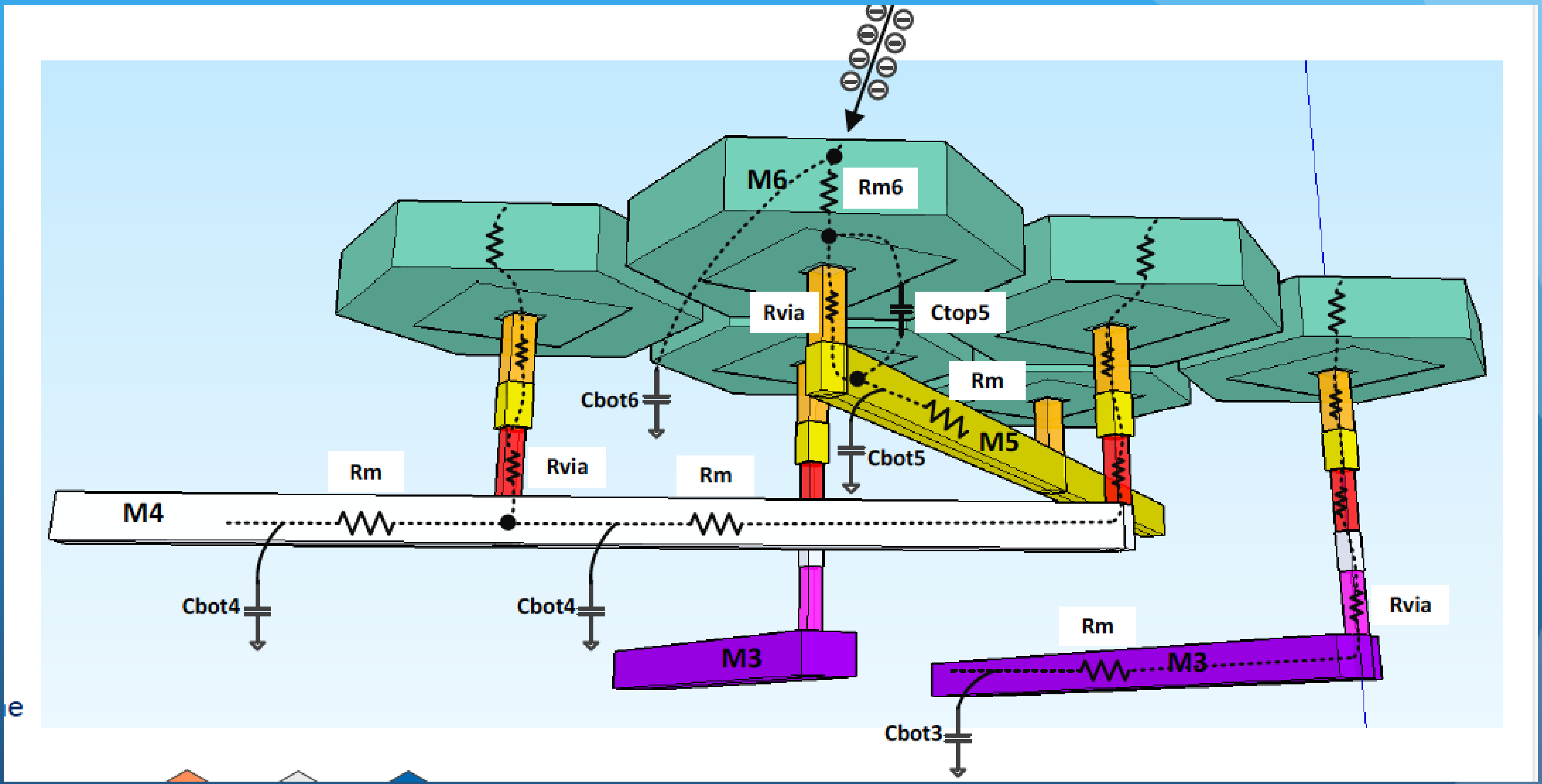


The signal is transmitted from the fired pixels to their associated readout cells

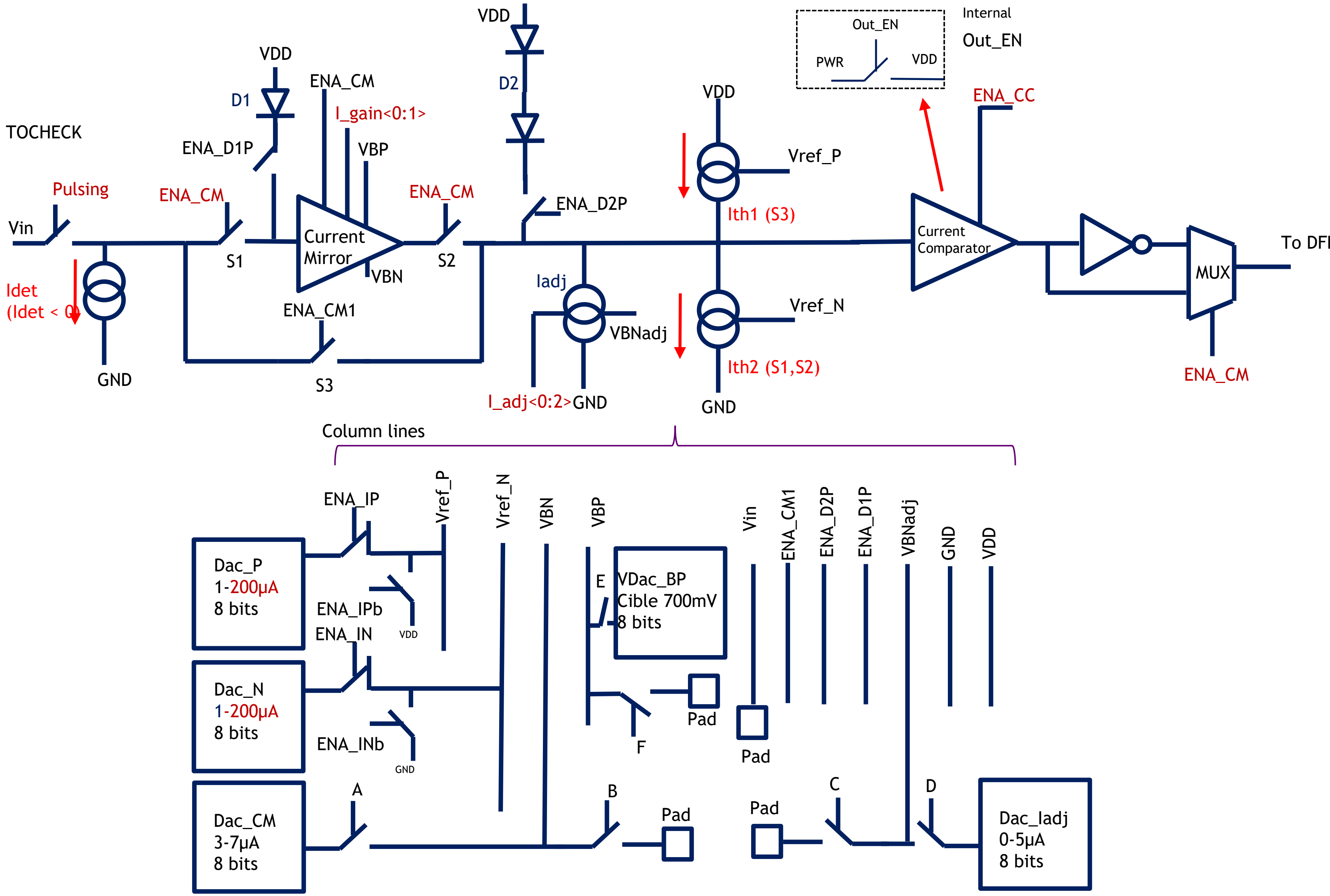




Cross-talk was carefully studied and showed less than 10%.



Front End lock



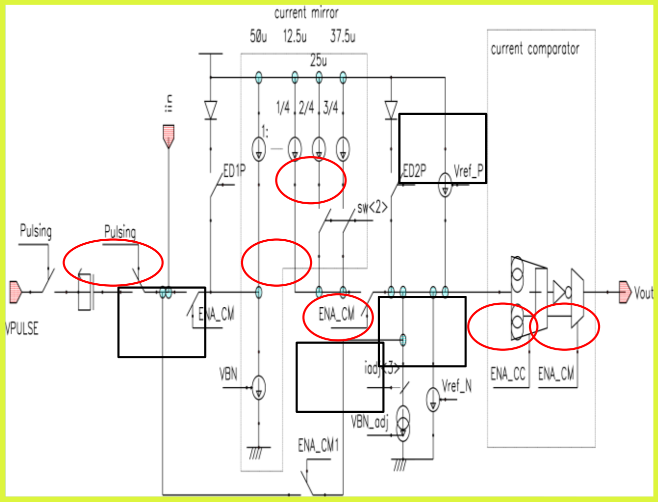
Pedestal threshold calibrations

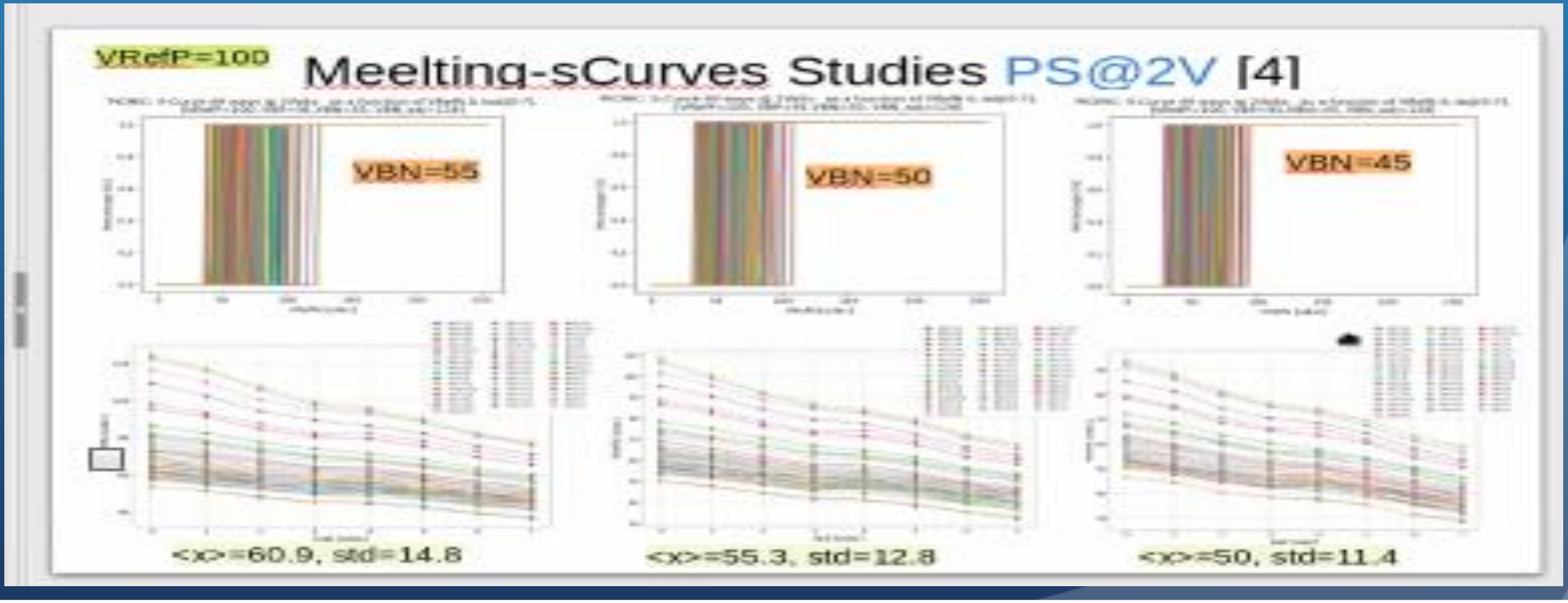
1) Freeze a set of **DAC**(Global) values driven by :
   - small dispersion between s-Curves
   - bigger number of sCurves in a given space of phase vs VRefN(quite sensitive)

2) Then, additional scan in **local** values are performed:
   - iadj<3bits>, sw<2bits>, EN_CM, EN_CC.

3) To determine value @50% inflection point.

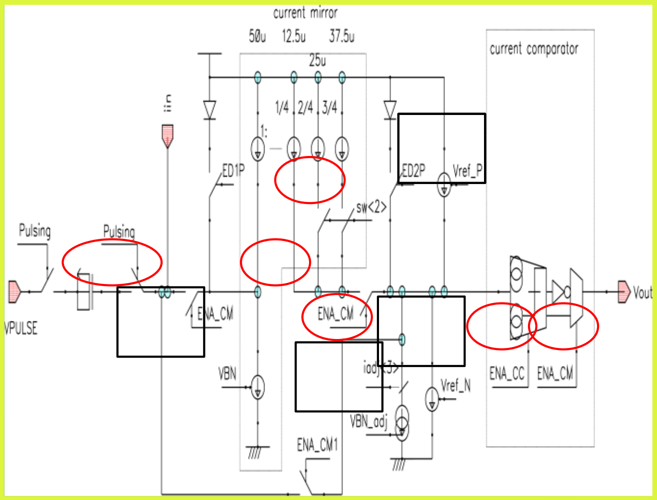
4) To select the closest sCurves@50% in VRefN



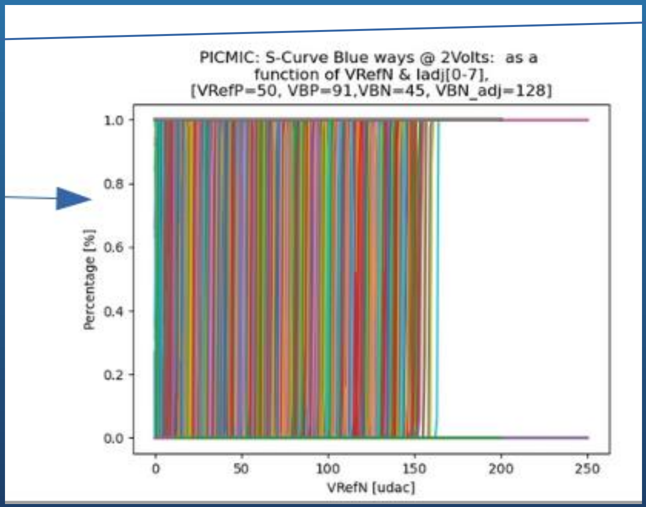


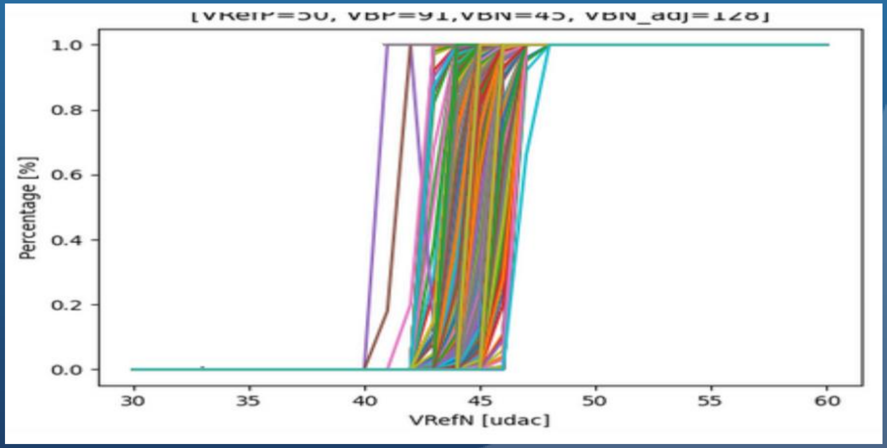
Pedestal threshold calibrations

1) Freeze a set of **DAC**(Global) values driven by :
 - small dispersion between s-Curves
 - bigger number of sCurves in a given space of phase vs VRefN(quite sensitive)
2) Then, additional scan in **local** values are performed:
 - iadj<3bits>, sw<2bits>, EN_CM, EN_CC.
3) To determine value @50% inflection point.
4) To select the closest sCurves@50% in VRefN

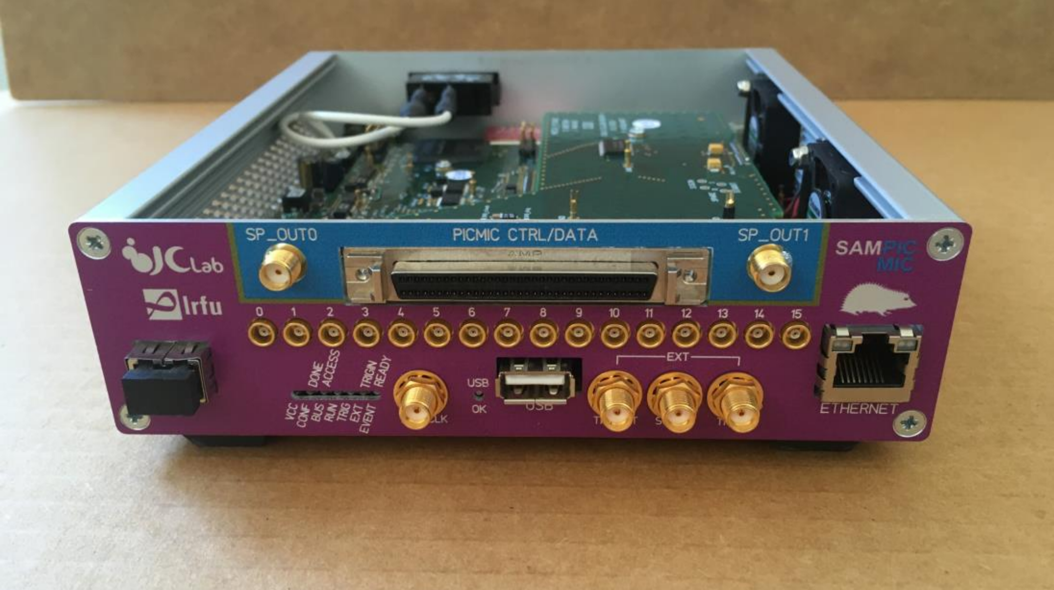


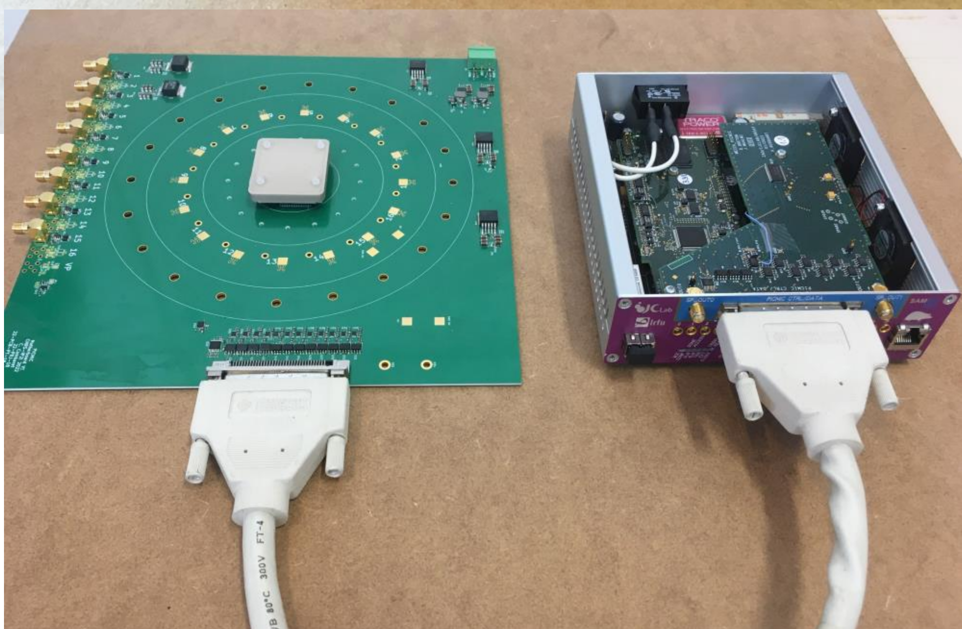
full matched sCurves(VRefN)

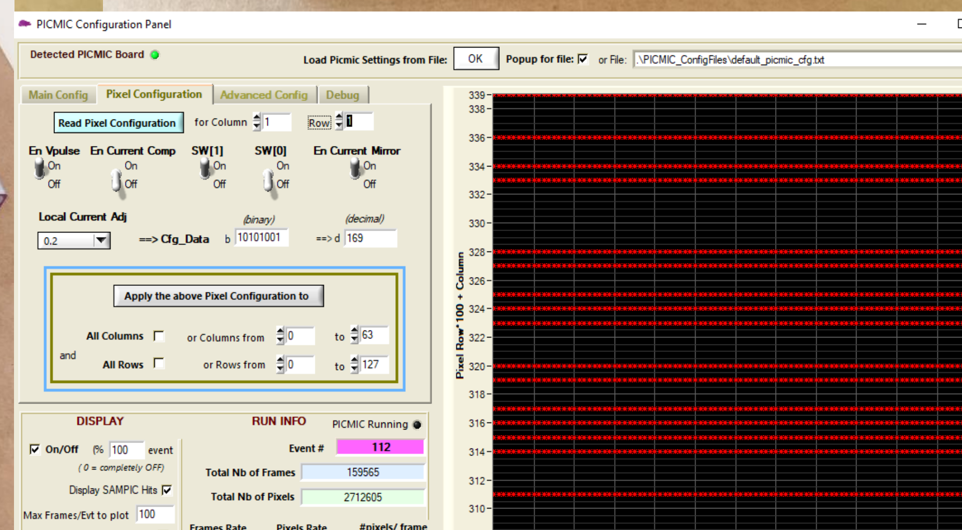




DAQ to read both time (SAMPIC) and PIXEL sensor

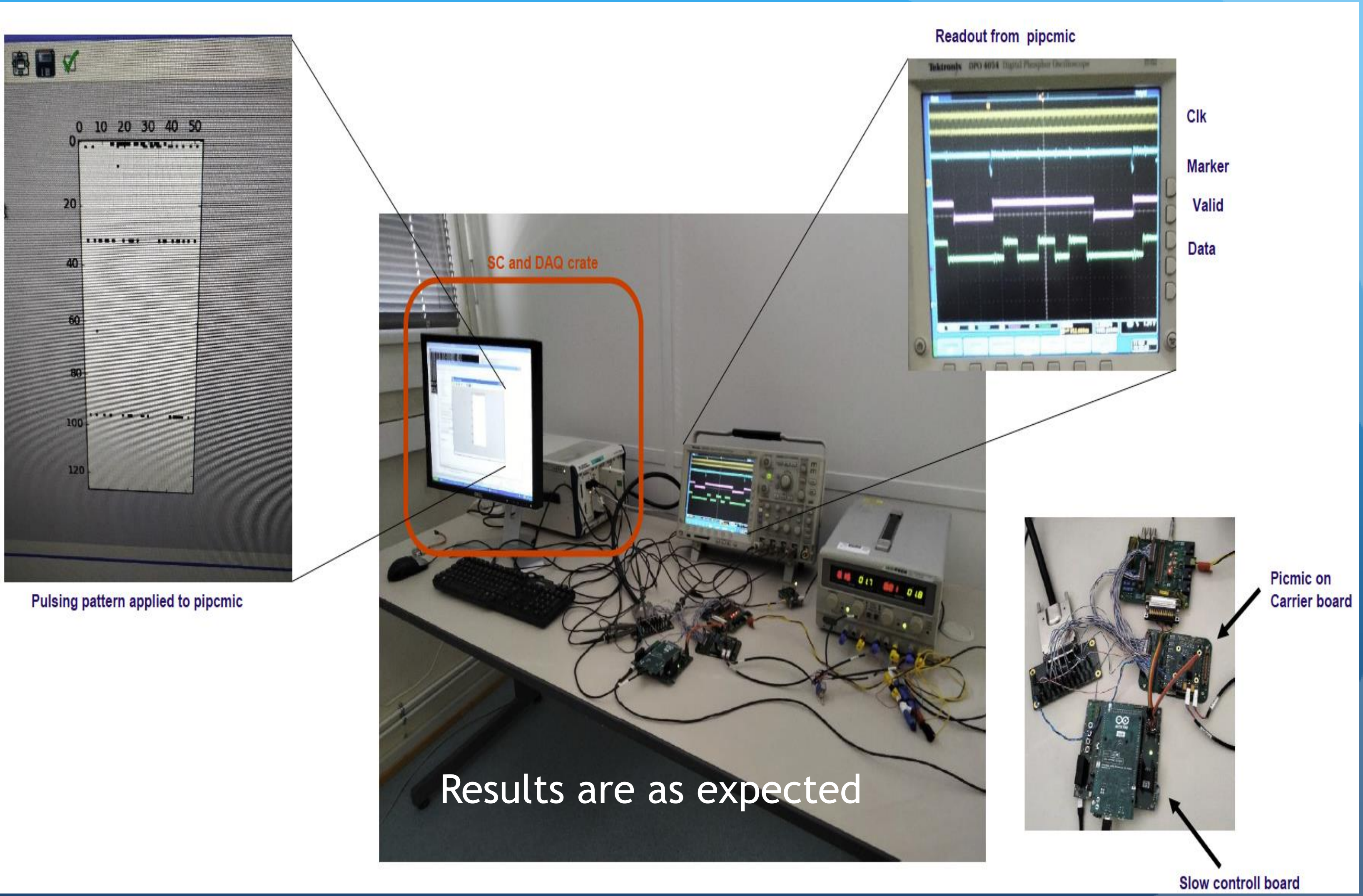






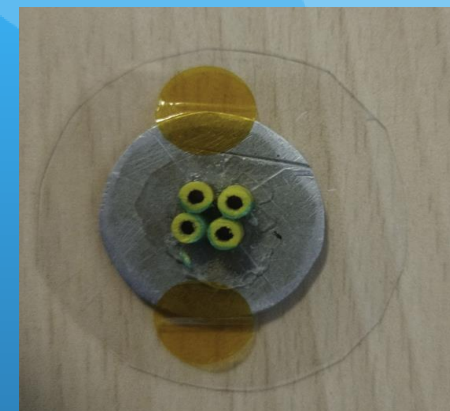
- 40 MHz clock is generated and distributed to the two devices (time, pixels)
- Data are collected by both sorted out with the same counter

Digital test bench



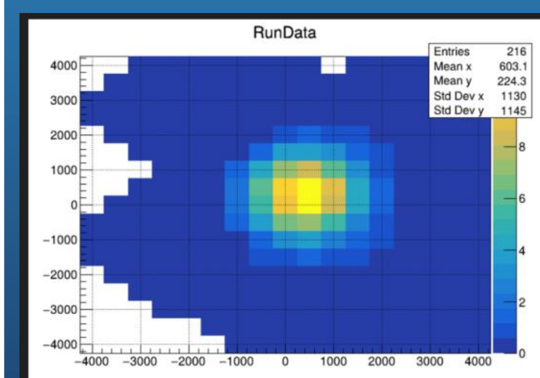
The whole system was tested by using alpha and gamma sources

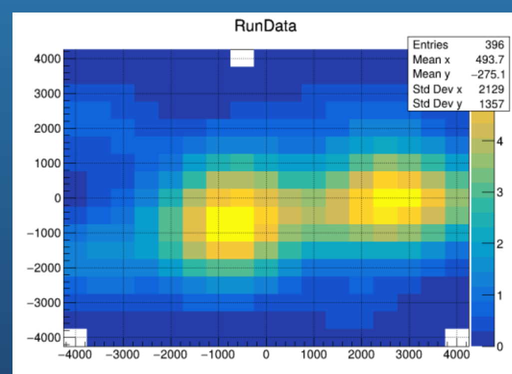


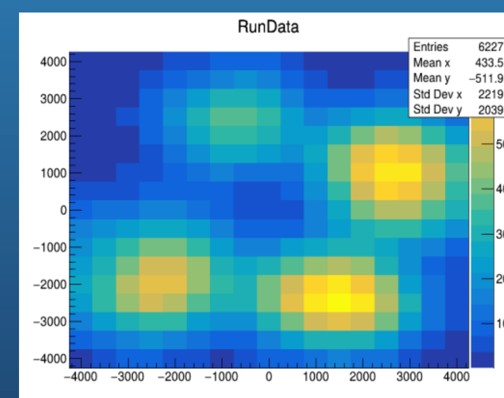


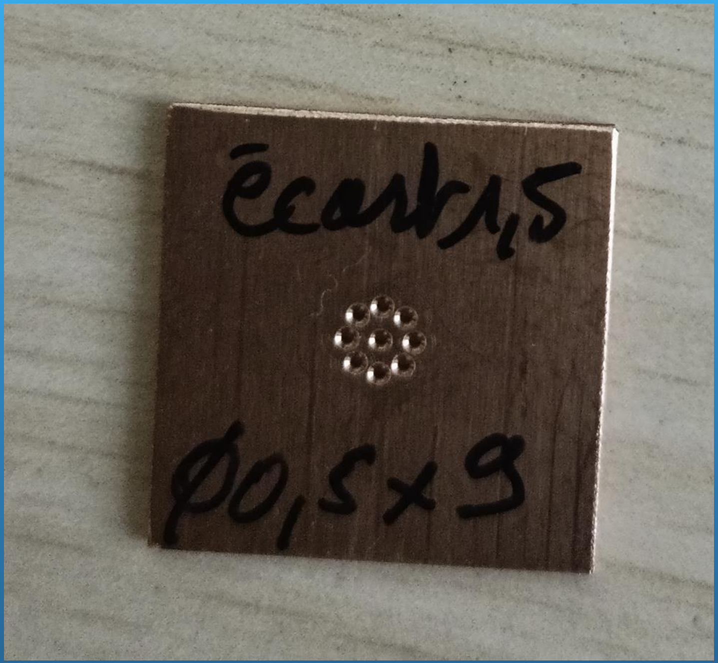
1 mm holes

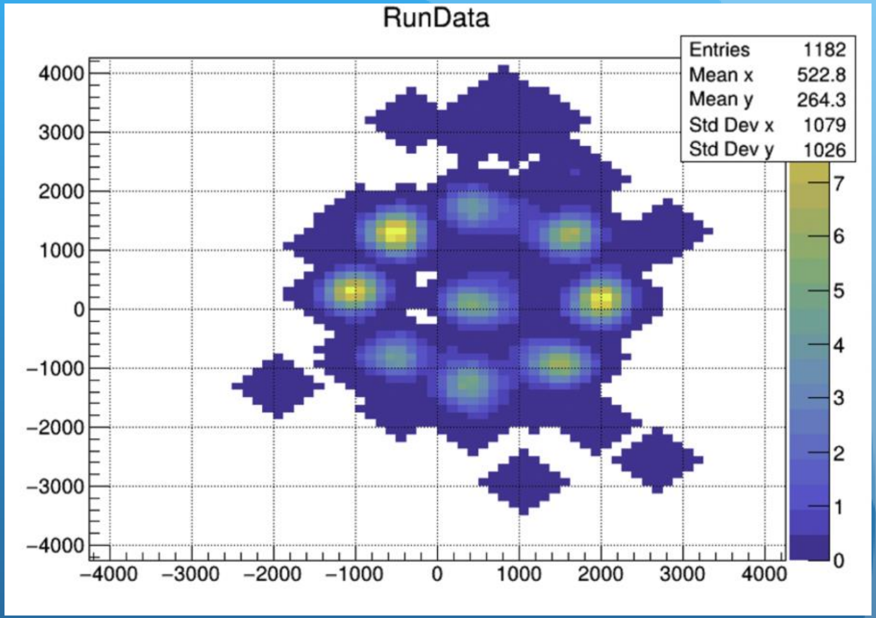
2 mm holes



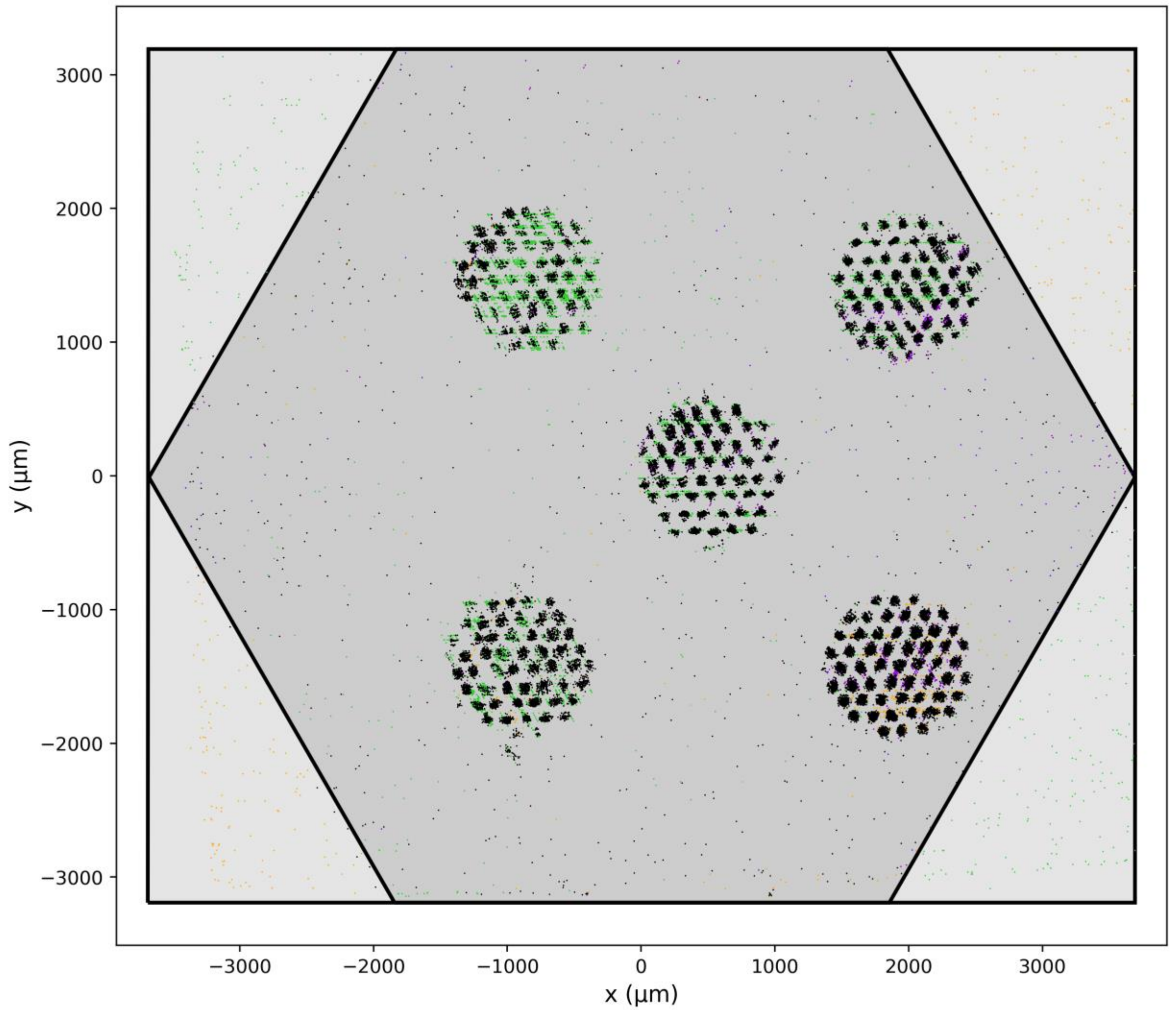





écart 1,5
φ0,5×9


RunData
Entries 1182
Mean x 522.8
Mean y 264.3
Std Dev x 1079
Std Dev y 1026
4000
3000
2000
1000
0
−1000
−2000
−3000
−4000
−4000 −3000 −2000 −1000 0 1000 2000 3000 4000
7
6
5
4
3
2
1
0

0.5 mm holes

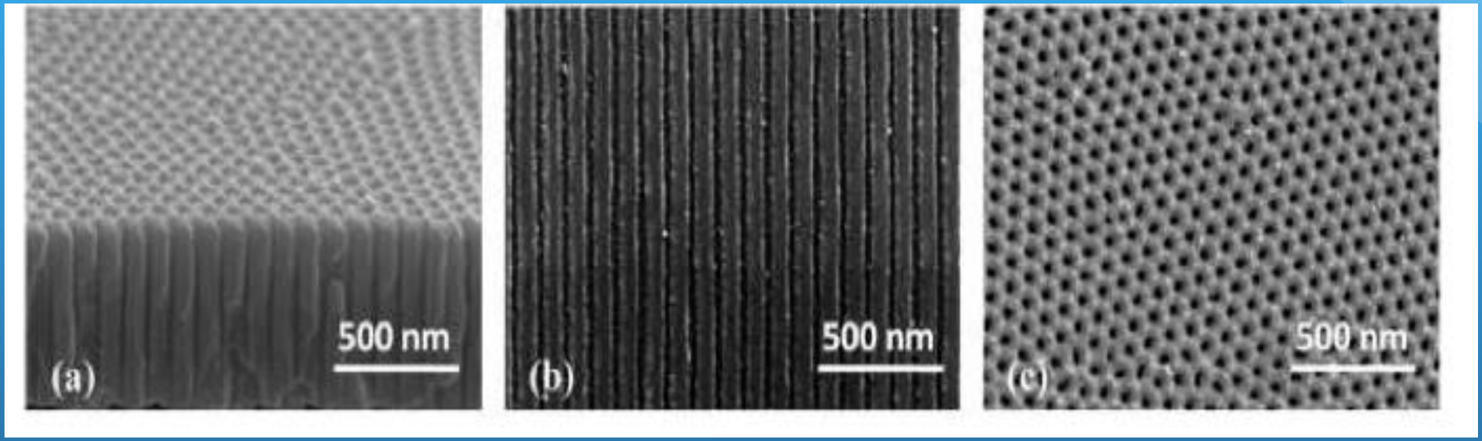


GEM foil+ cooper plate with 3holes of 1 mm diameter eachwith

PICMIC will be soon tested with a channeltron producing single electrons of energy up to 30 keV in a MEB to have independent time and resolution measurement

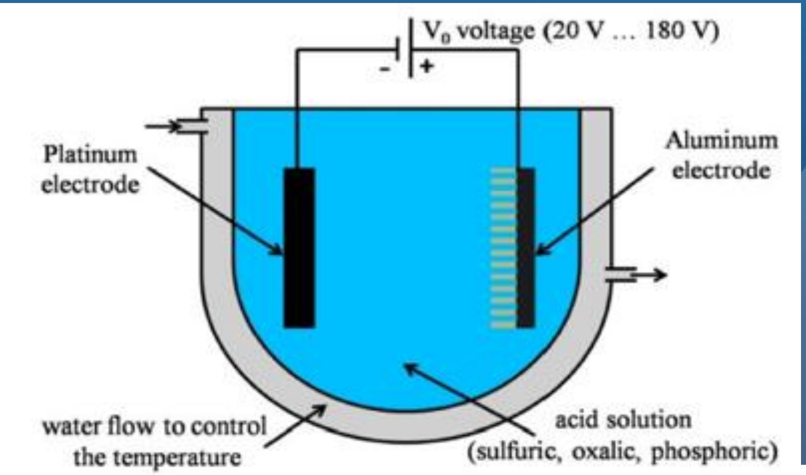
AAO NCP

Nano Channel alumina structure made by electrolyse was invented twenty years ago: **H. Masuda, K. Fukuda, Science 268, 1466 (1995)**



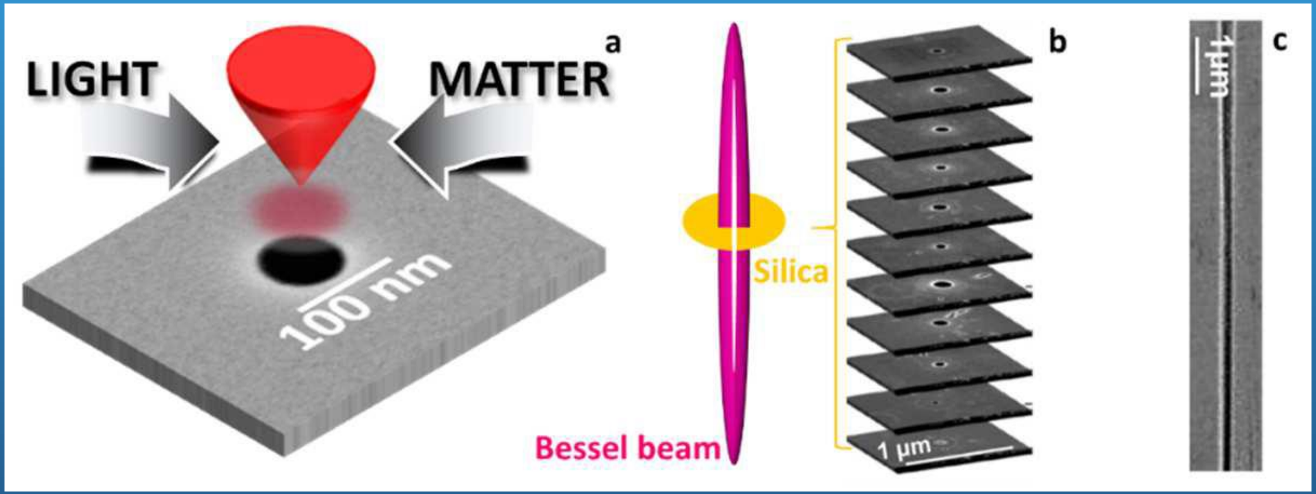
L/d = 200-300, L is the plate thickness and d the tube diameter
In principle we should have better timing than that of the MCP (less dispersion (TTS))

Nanopores are obtained with simple electrolysis process.

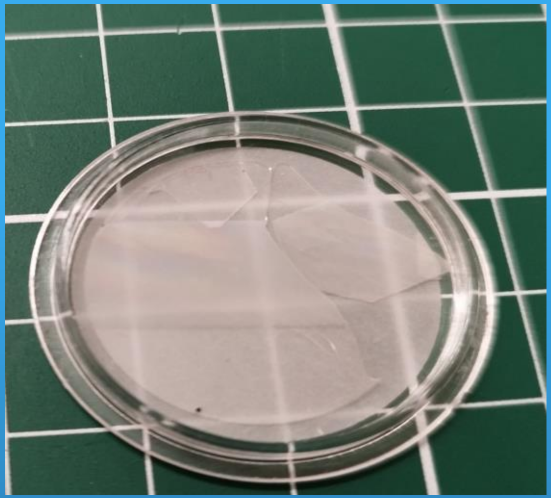


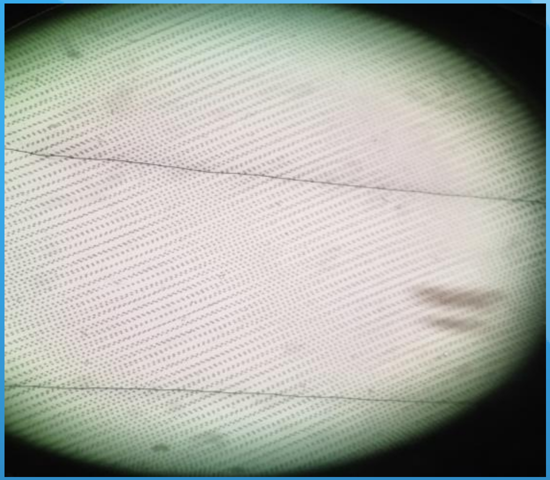
Femto-Laser NCP

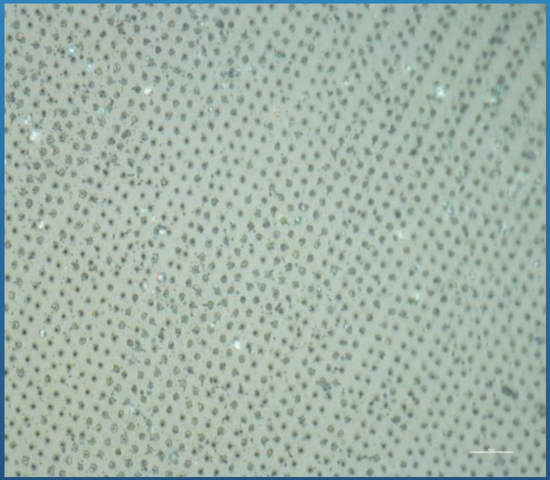
The concept is to produce micro/nano-pore using the Femto-Laser techniques
Bessel beam allows digging deep in transparent material producing regular pores

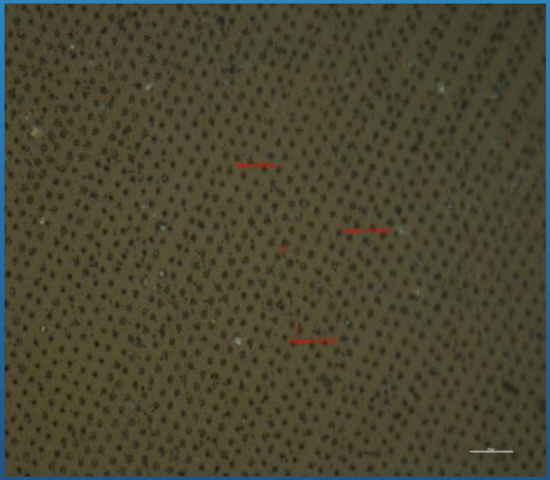


By using lead-glass plates and obtaining high density of pores, one can not only produce NCP but also reduce the tedious chemical process used in MCP fabrication



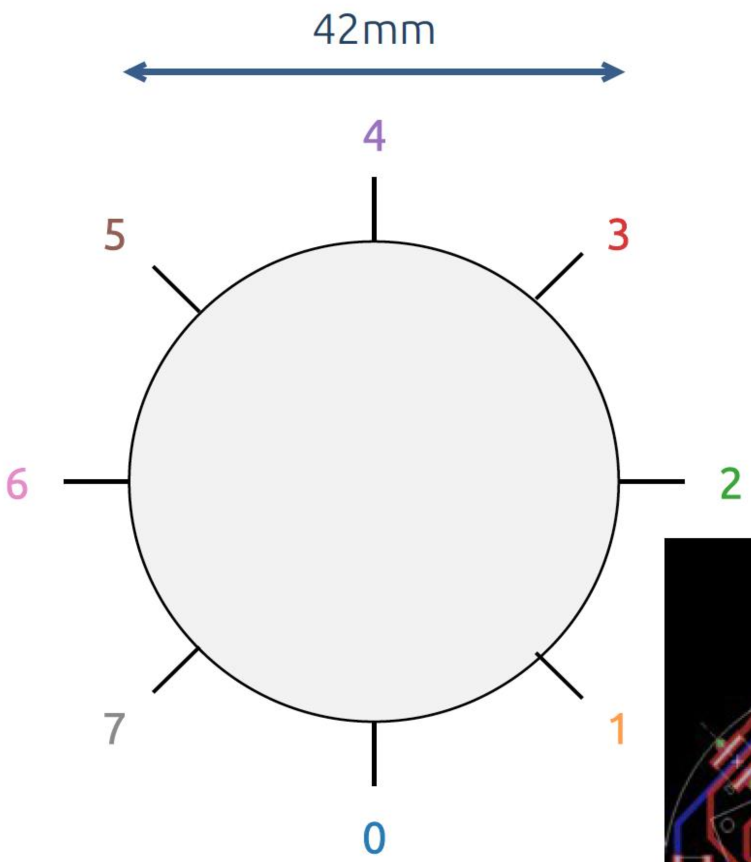


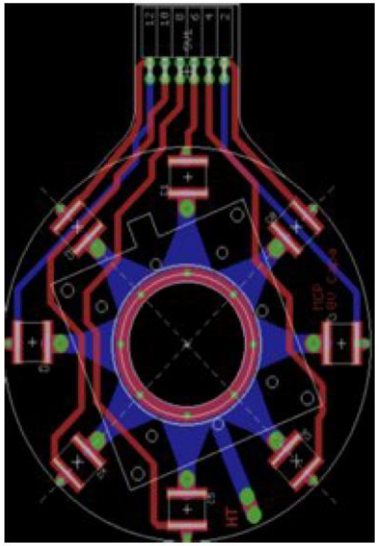




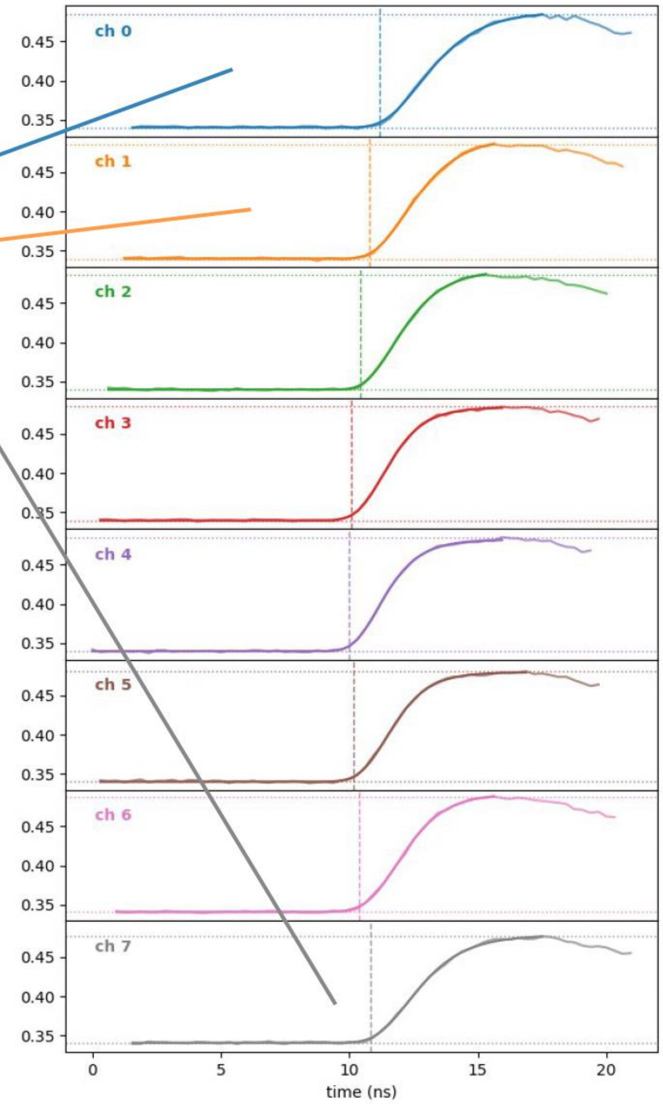
0.4 μm diameter and 2.5 μm pitch

Timing detector





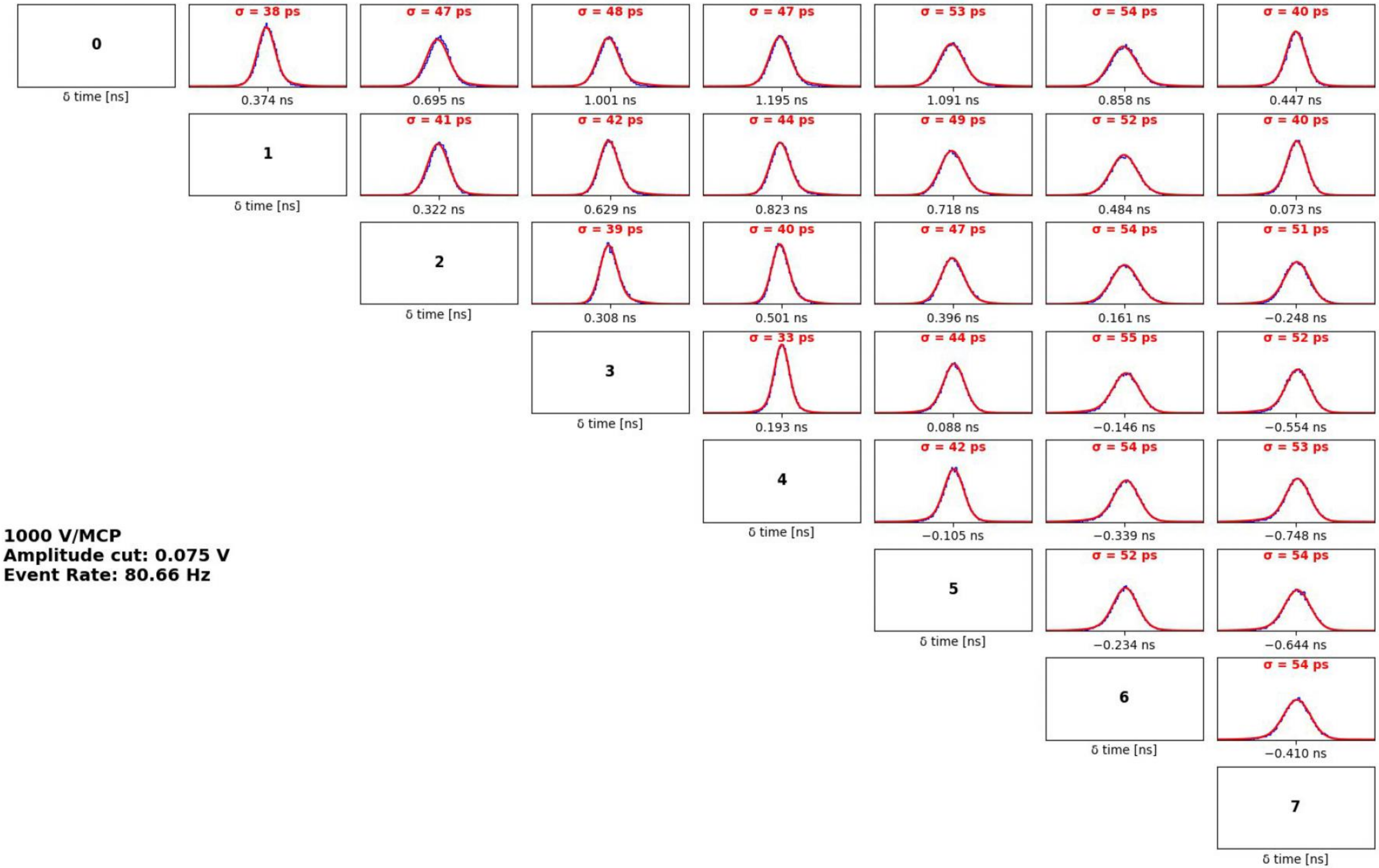
slower rising times for ch0, 1, 7 due to longer lines



fitting function :

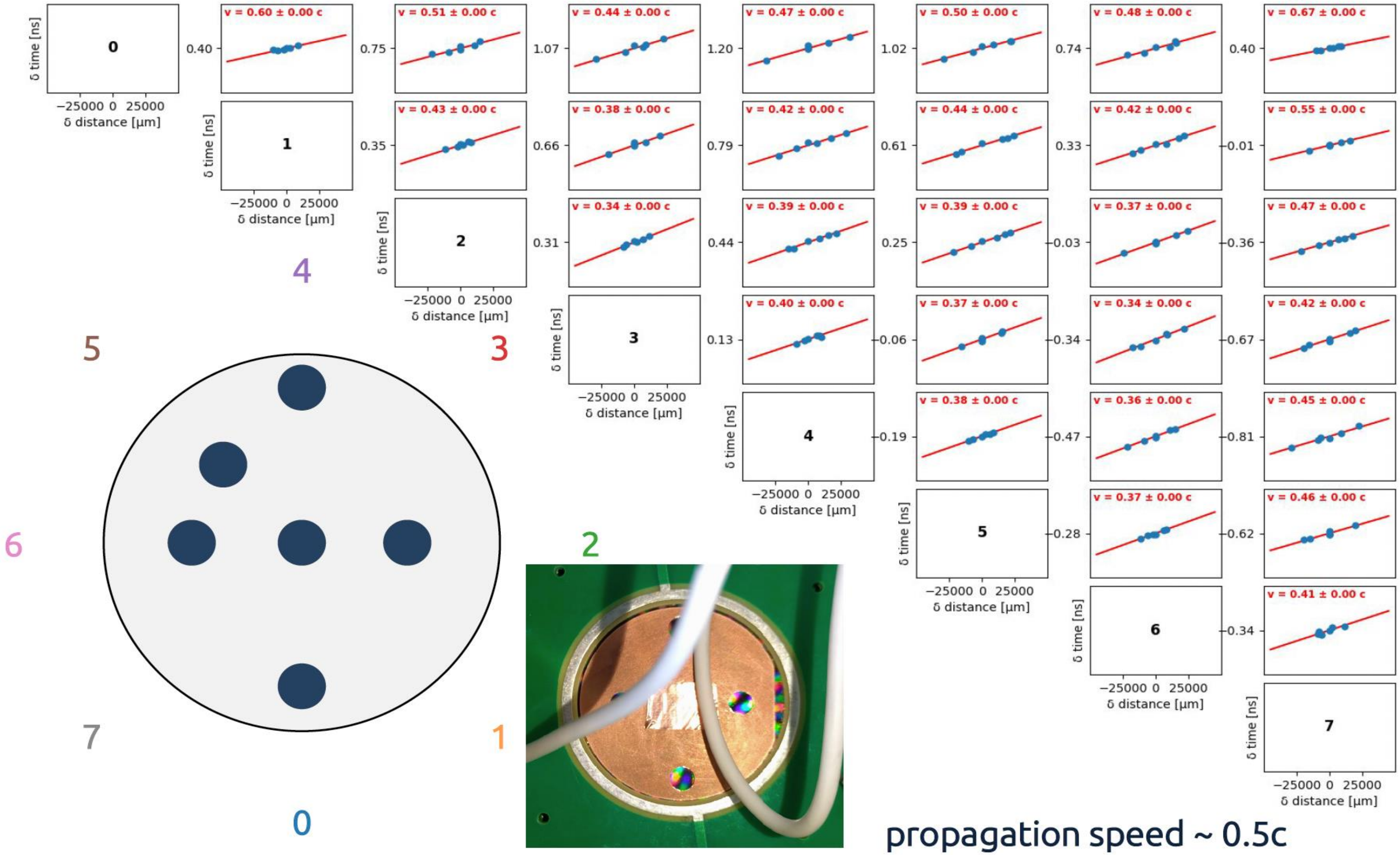
$$f = C + a\cdot(1 - \nu\cdot e^{-f(x-\mu)})^{-1/\nu}$$

Timing detector – time resolution



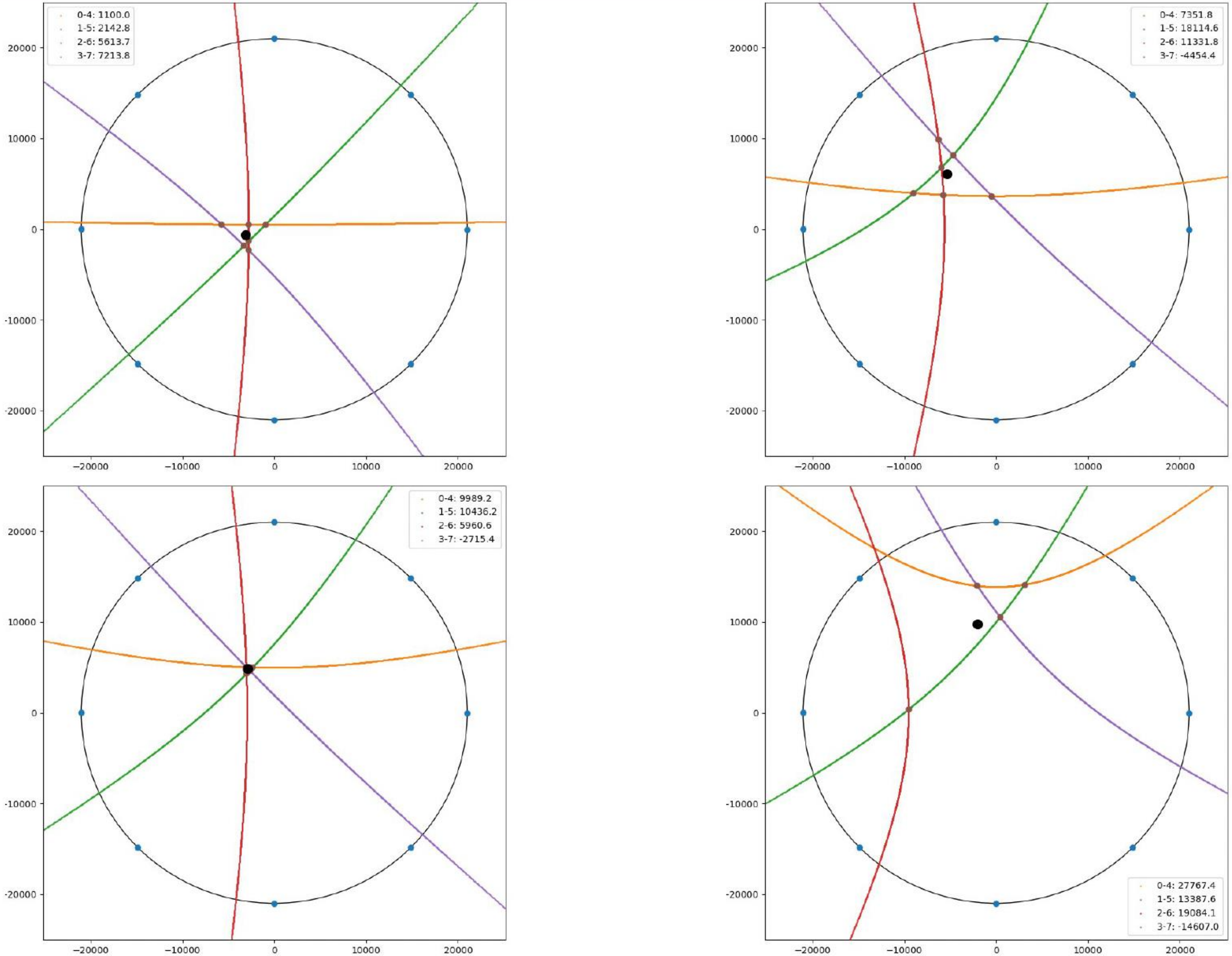
1000 V/MCP
Amplitude cut: 0.075 V
Event Rate: 80.66 Hz

Timing detector – delta times vs delta distances

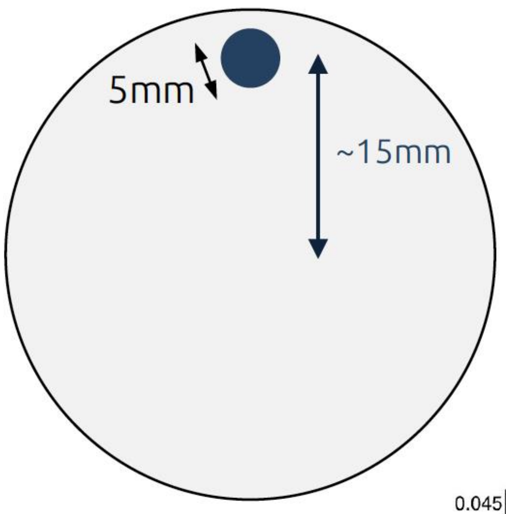


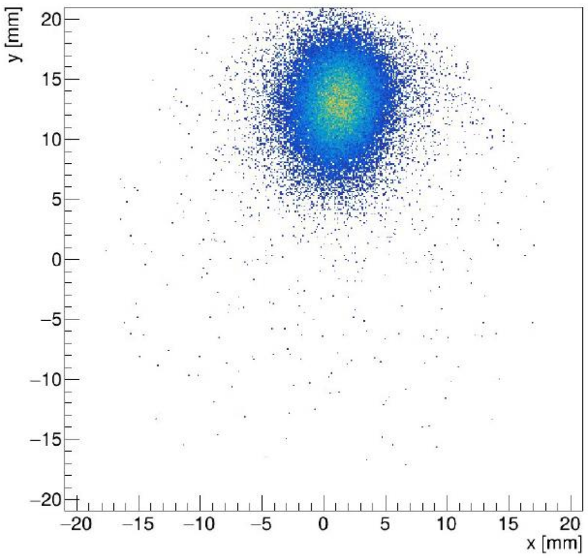
propagation speed ~ 0.5c

Timing detector – position reconstruction



Timing detector – position resolution

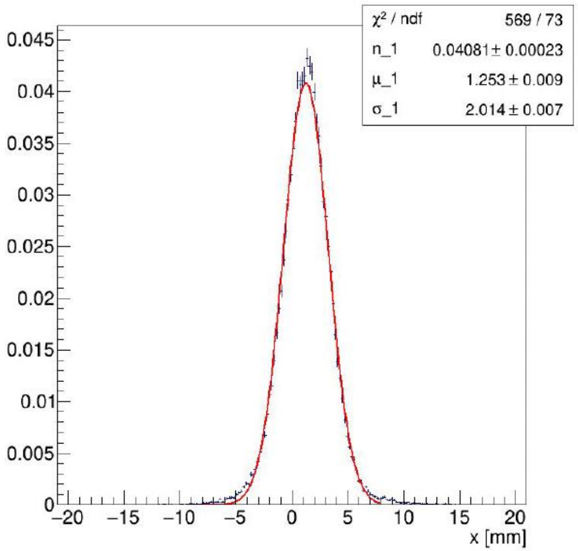


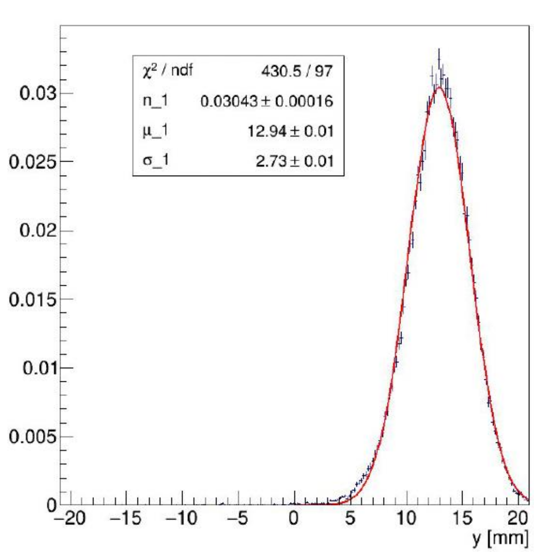


1000 V/MCP

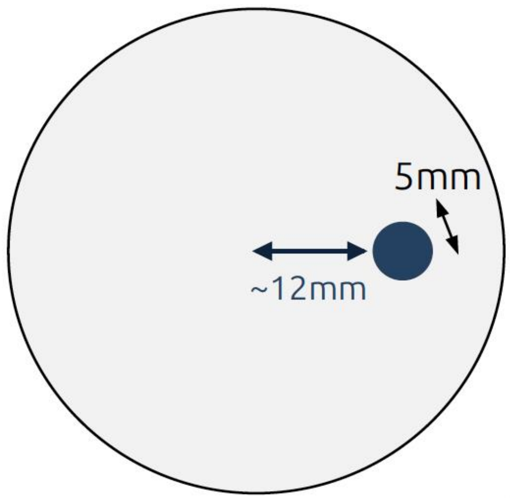
σ_x_fit = 2 mm
σ_y_fit = 2.7 mm

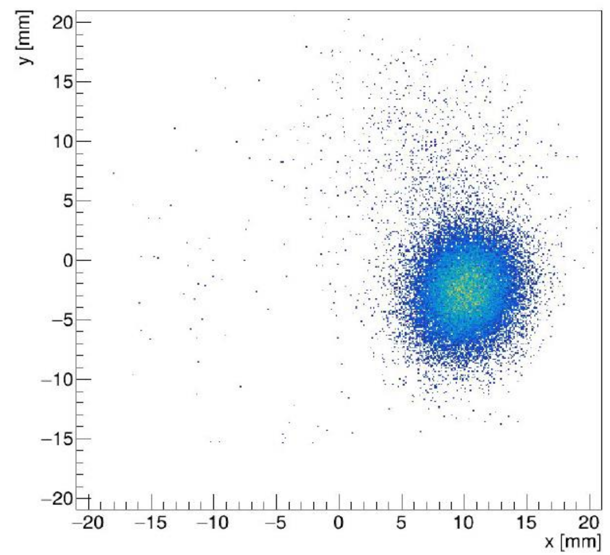
substracting the hole width
=> **σ_x = 1.6 mm**
=> **σ_y = 2.4 mm**





Timing detector – position resolution

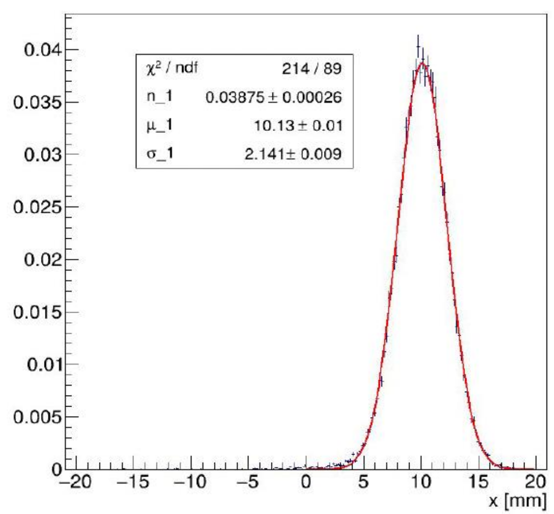


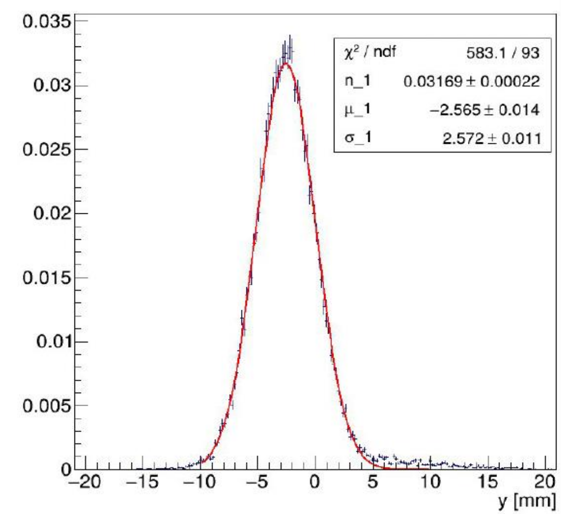


1000 V/MCP

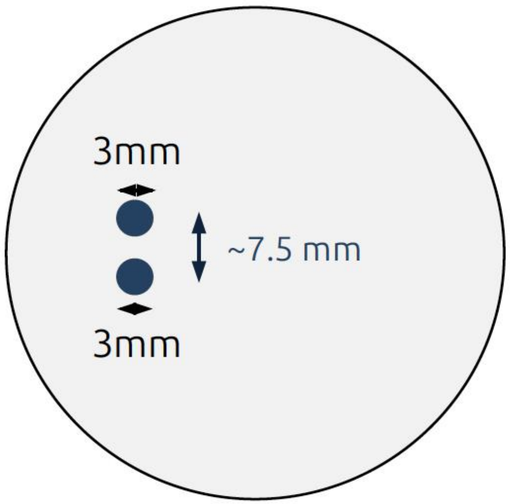
σ_x_fit = 2.1 mm
σ_y_fit = 2.6 mm

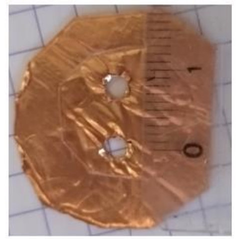
substracting the hole width
=> **σ_x = 1.7 mm**
=> **σ_y = 2.3 mm**

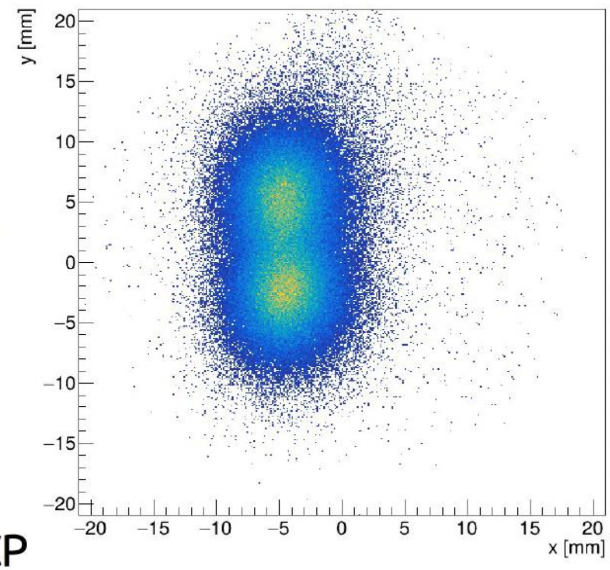




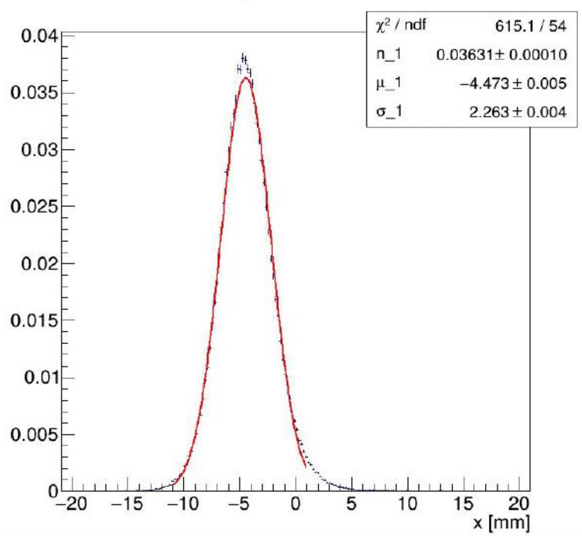
Timing detector – position resolution

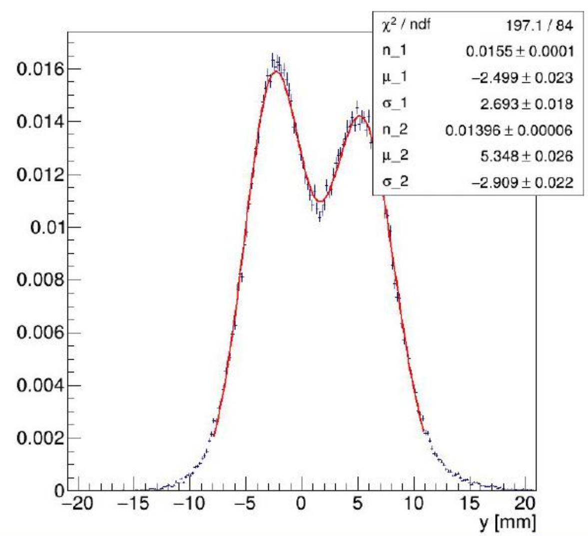






1000 V/MCP



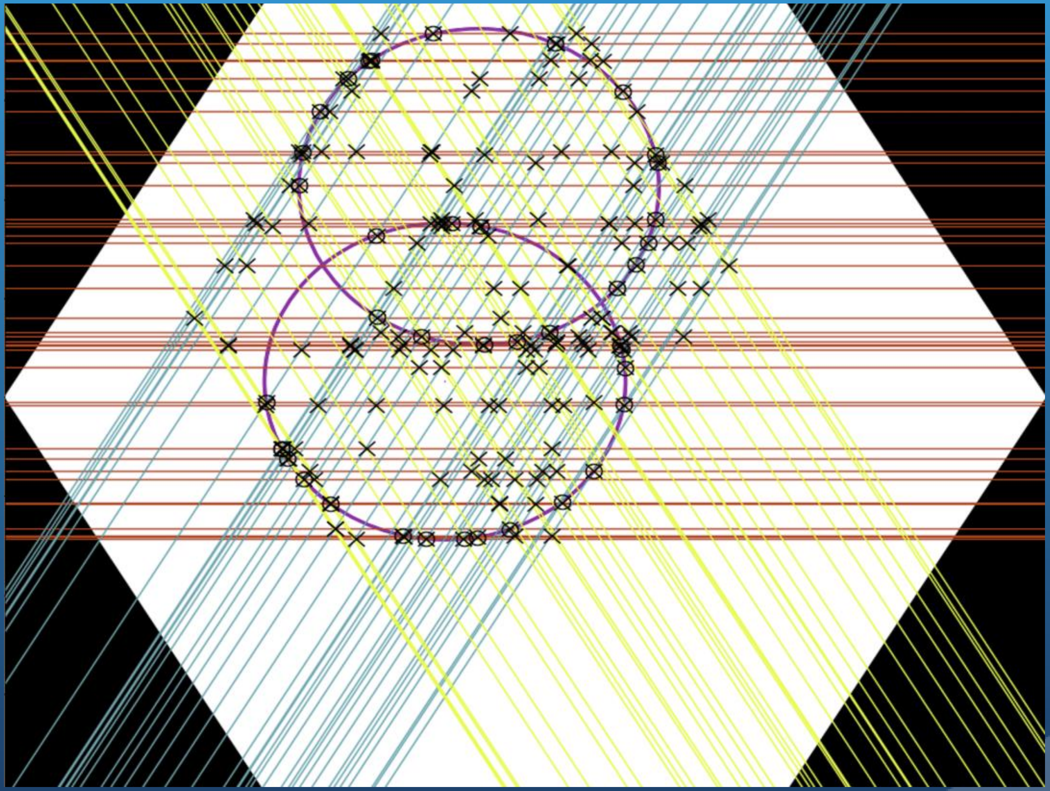


σ_x_fit = 2.3 mm
σ_y_fit ~ 2.8 mm

substracting the hole width
=> **σ_x = 2.2 mm**
=> **σ_y = 2.7 mm**

Can we use PICMIC for Cherenkov?

We are studying the performance of PICMIC to be used in a Cerenkov detector when associated to a photocathode and a radiator.
Using Hough Transform we are able to determine the contour of a Cerenkov ring of a few mm.



P. Roger