CACTUS: Sub-100ps MIP timing with CMOS DMAPS and X-ray photon detection

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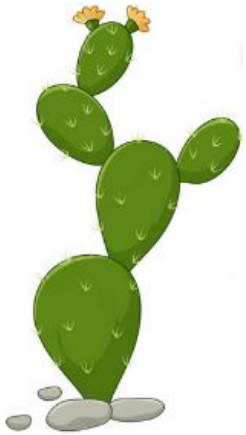
25/04/2023

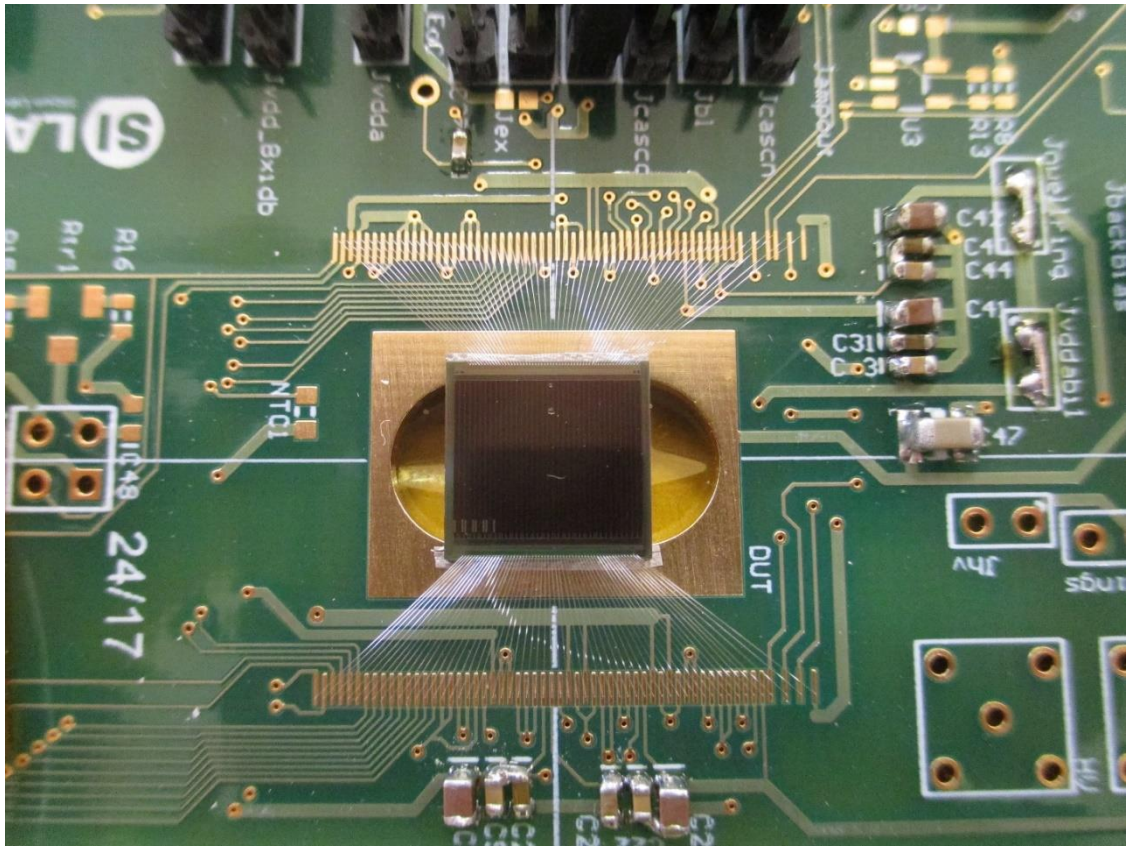


A bit of History

We started around 2017 after being involved into LF-CPIX and MONOPIX strip detector for ATLAS-ITK outer layers (possible backup solution)

At that time, 2 possible applications for sub-100ps timing detectors:

- ATLAS High η muon tagger (upstream forward calorimeter)
- HGTD in front of ATLAS-LAr



First try with CACTUS:

- Yield correct, High break down voltage, homogenous charge collection, deep depletion depth
- Main problem with CACTUS: underestimation of parasitic capacitance → bad S/N

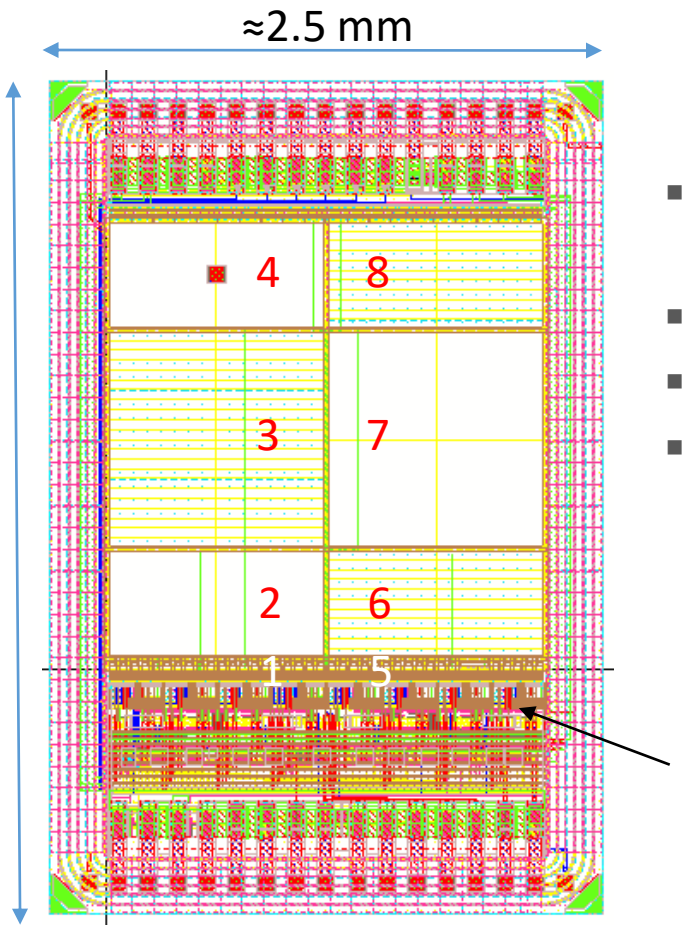
-Also coupling between analogic and digital part → ringing of digital pulse

→ modest timing performance ~500ps

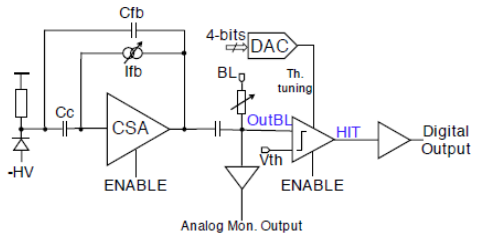
https://arxiv.org/abs/2003.04102

→ Version 2 of CACTUS called Mini-Cactus

MINICACTUS PROTOTYPE CHIP



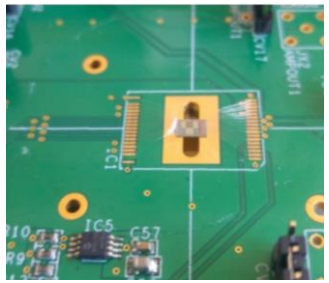
Layout of MiniCACTUS chip



FE (1/pixel)

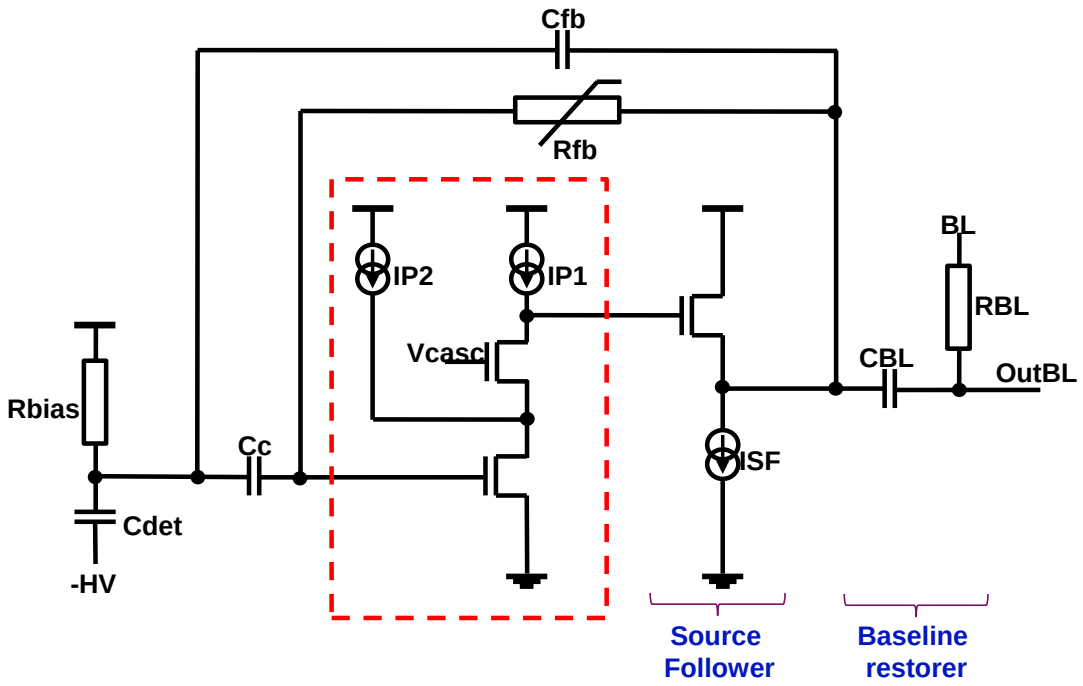
- **MiniCACTUS** is a small detector prototype designed in order to address the *low S/N issue* of the larger size CACTUS
- Main change in MiniCACTUS: FE integrated at column level, pixels mostly passive
- FE parameters programmable through on-chip Slow Control
- 2 digital (LVDS) and 2 analog monitoring (*slower than CSA output*) outputs for 2 columns

Pixel Flavors :
Pixels 3 & 7 : 1 mm x 1 mm baseline pixels
Pixels 2, 4, 6 & 8 : 0.5 mm x 1 mm pixels
Pixel 8 : 0.5 mm x 1 mm pixel with in-pixel AC coupling capacitor (20pF)
Pixels 1 : 50 µm x 50 µm test pixel
Pixels 5 : 50 µm x 150 µm test pixel



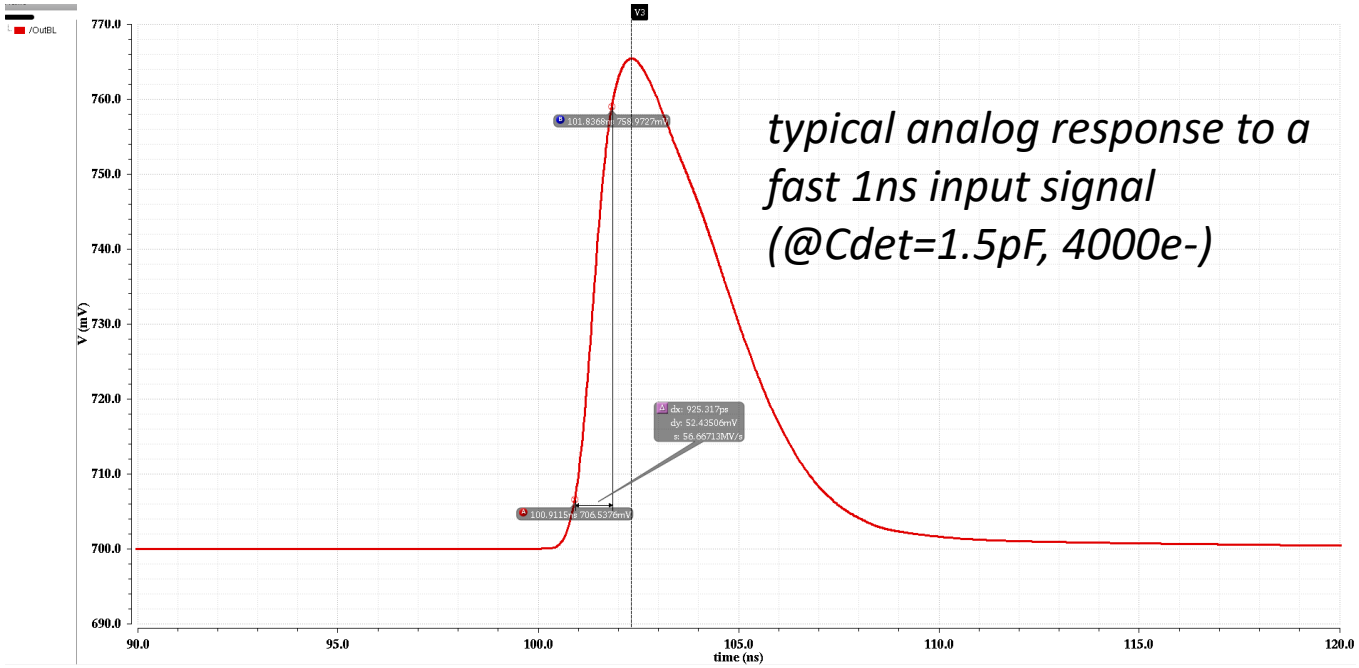
- ❑ **Front-end mostly optimized for 1 mm² pixels** with peaking time of 1-2 ns @ 1-2pF (Ibias_total=800µA → P ≈ 150mW/cm²)
- ❑ Small pixels can be seen as test structures to study charge collection (no power optimized FE available)
- ❑ Some detectors thinned to 100µm/200µm/300µm and than post-processed for backside polarization after fabrication

CACTUS: FRONT-END



CSA architecture plus fast leading edge discriminator. Bias and feedback currents are set from outside by a 6-bit DAC for fine-tuning

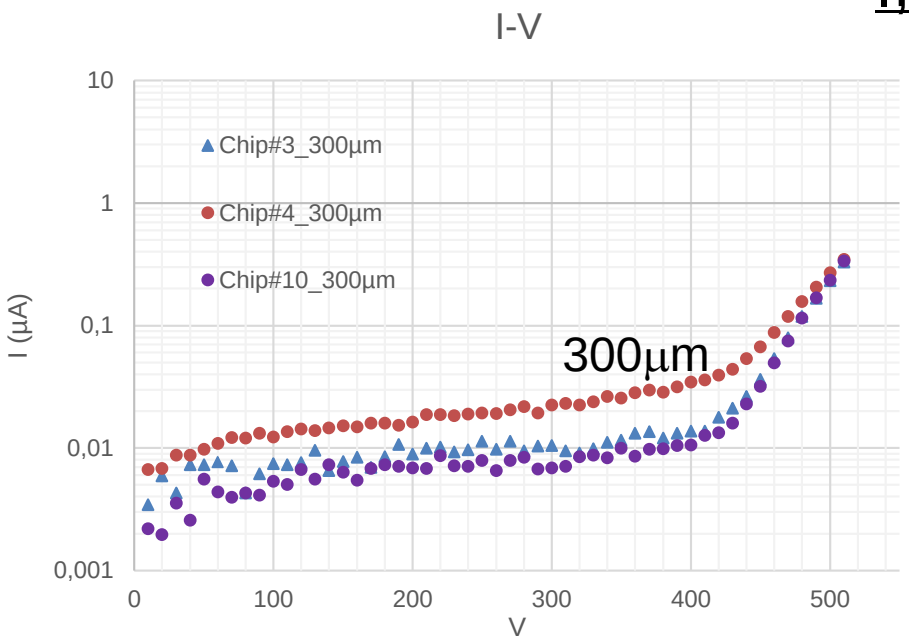
Typical CSA transient simulation result

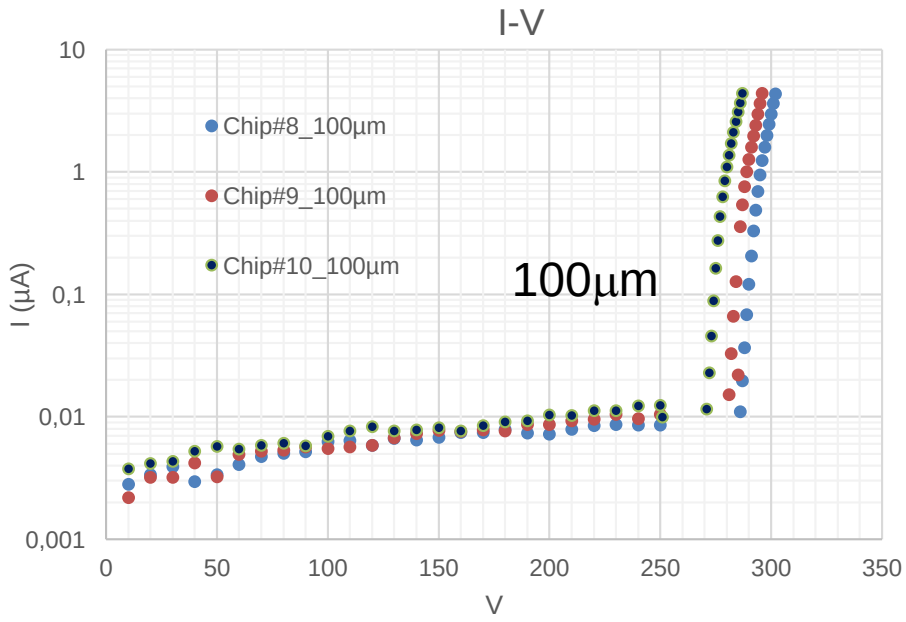


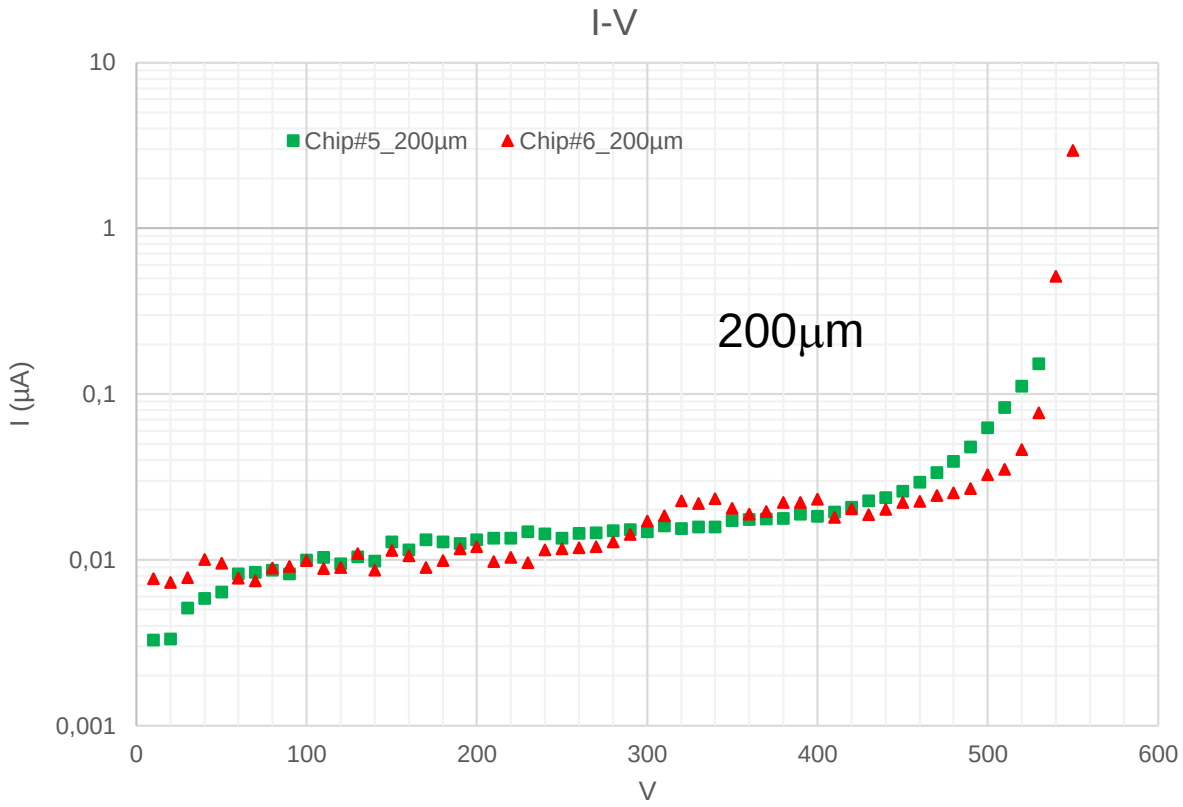
typical analog response to a fast 1ns input signal (@Cdet=1.5pF, 4000e-)

Parameter	1.5 pF	1 pF
Rise Time (from 10% to 90%)	~ 0.9 ns	~ 0.8 ns
Input Referred Noise [estimated from AC simulations]	~ 290 e-	~ 220 e-
Jitter [estimated from $t_r/(S/N)$]	~ 67 ps	~ 44 ps

I,V Curve of MiniCactus





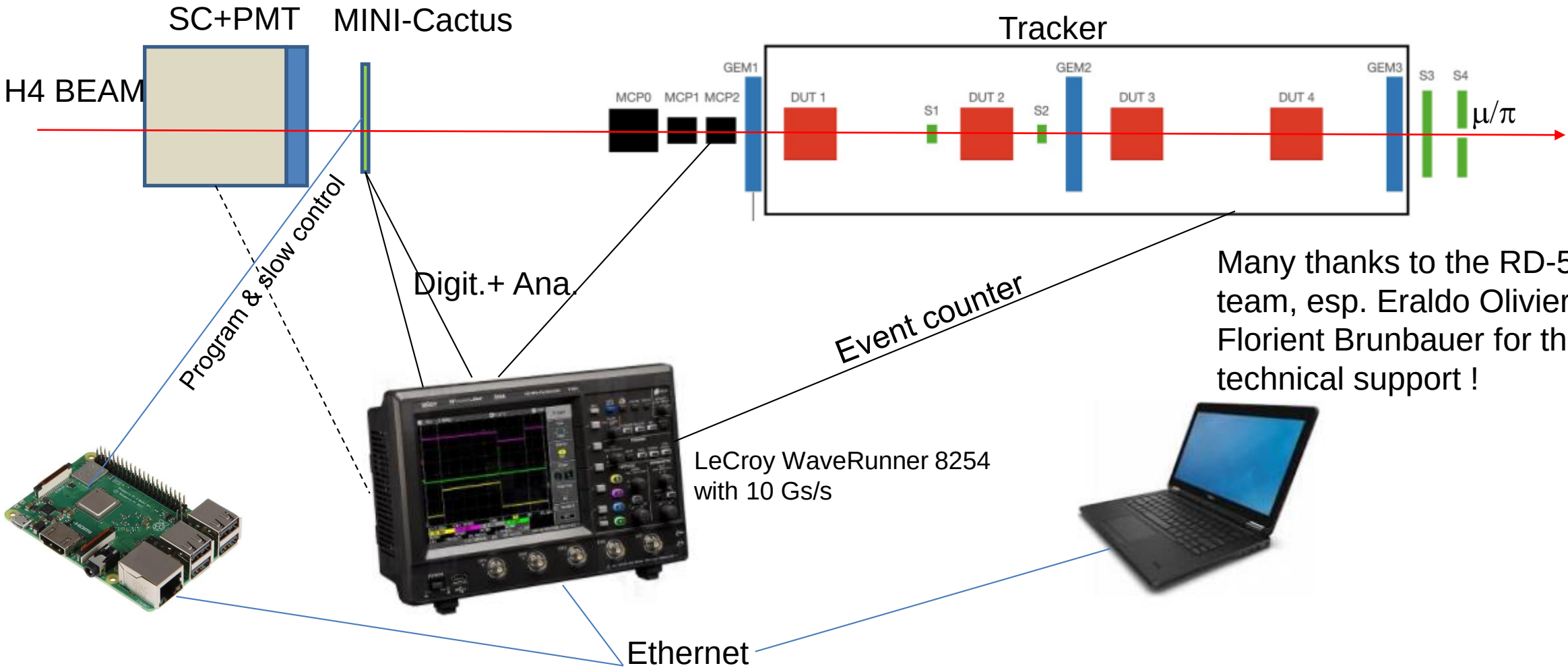


Breakdown voltage from 300 V to 500 V
Variations likely due to posprocessing

Test Beam Setup (parasitic mode RD51):

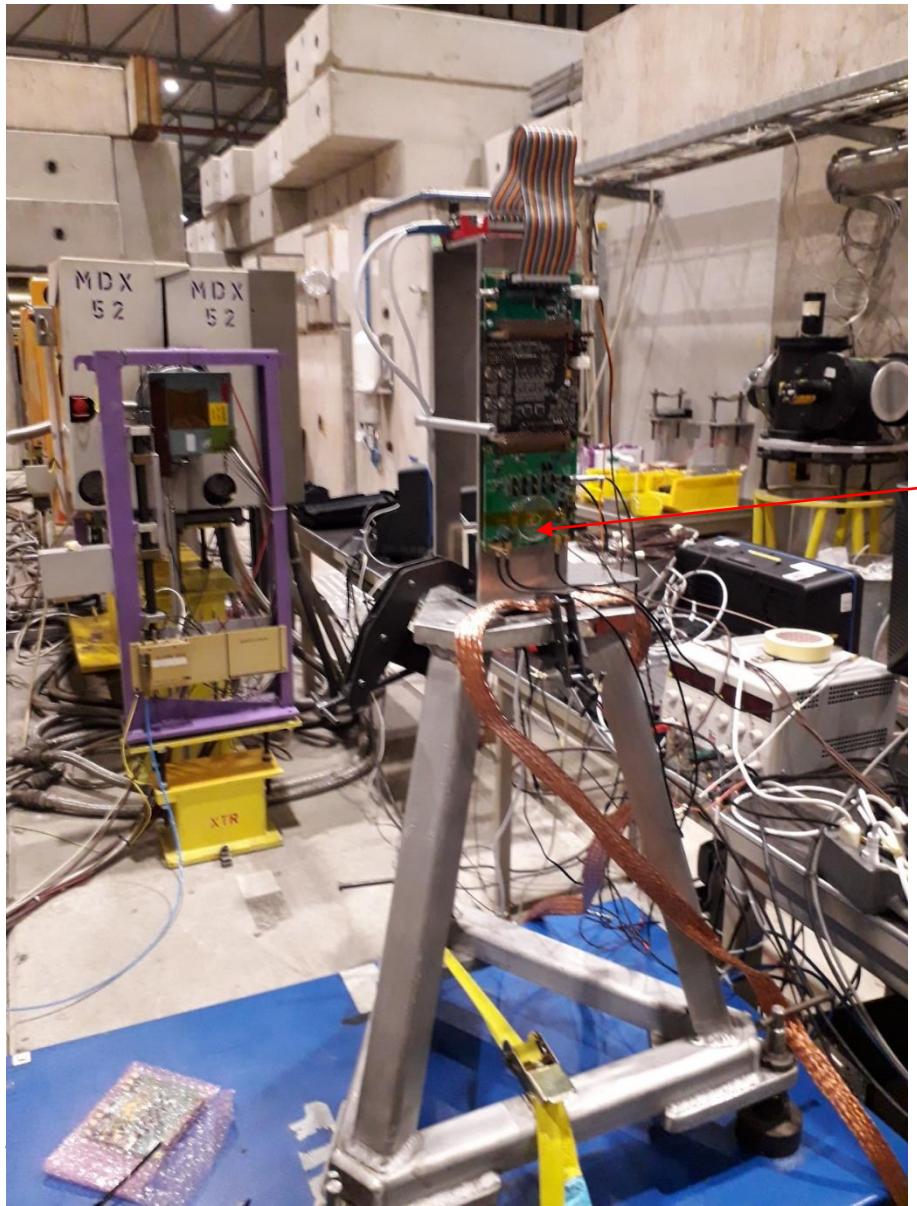
- Period 1: October 21 for ~2 weeks
- Period 2: mid-may 22 for ~3 weeks
- Period 3 : Mid October 22 for ~2 weeks

Muon beam some times Pions at higher intensity which are difficult to use for timing because of pileup



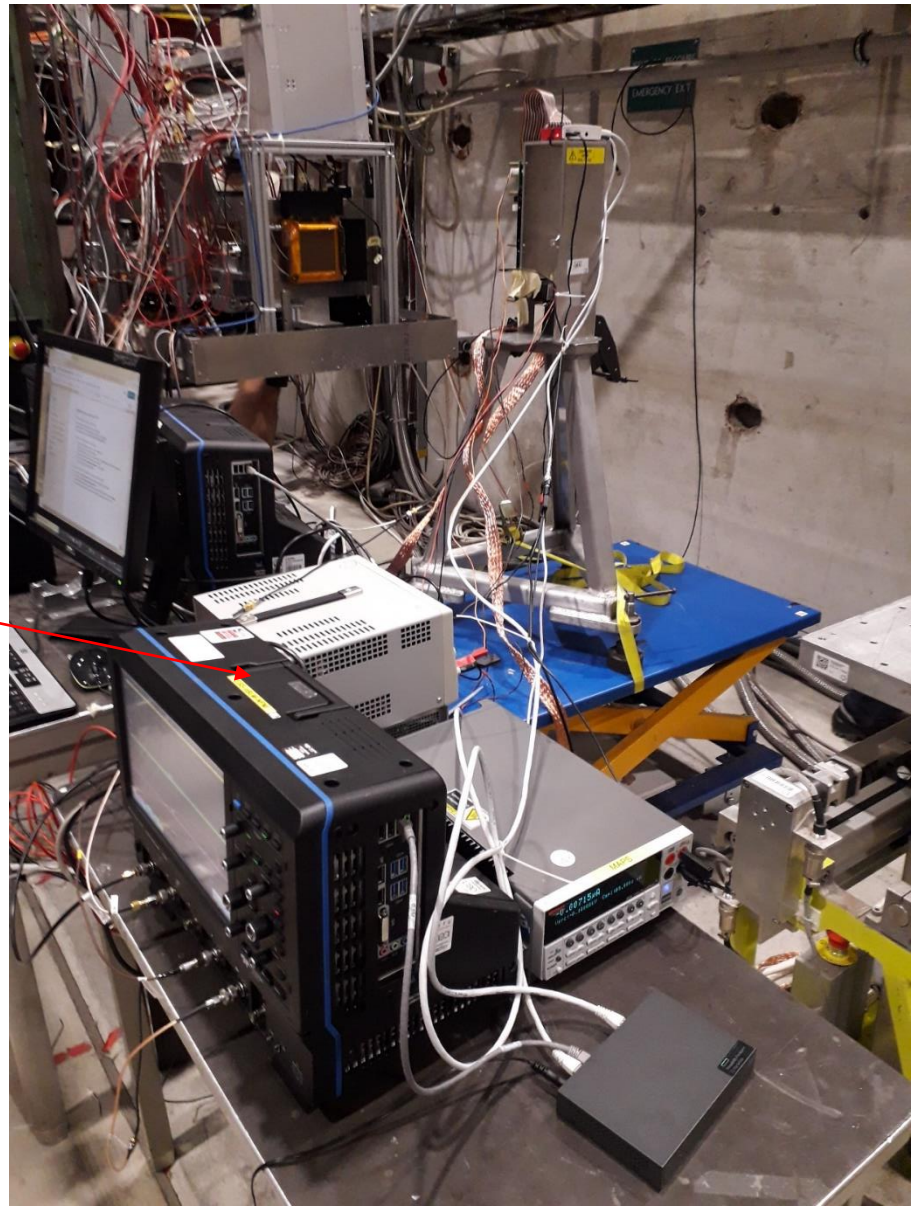
Many thanks to the RD-51 team, esp. Eraldo Olivieri and Florient Brunbauer for the great technical support !

H4 North Area,
RD-51 beamline
at CERN in
parasitic mode

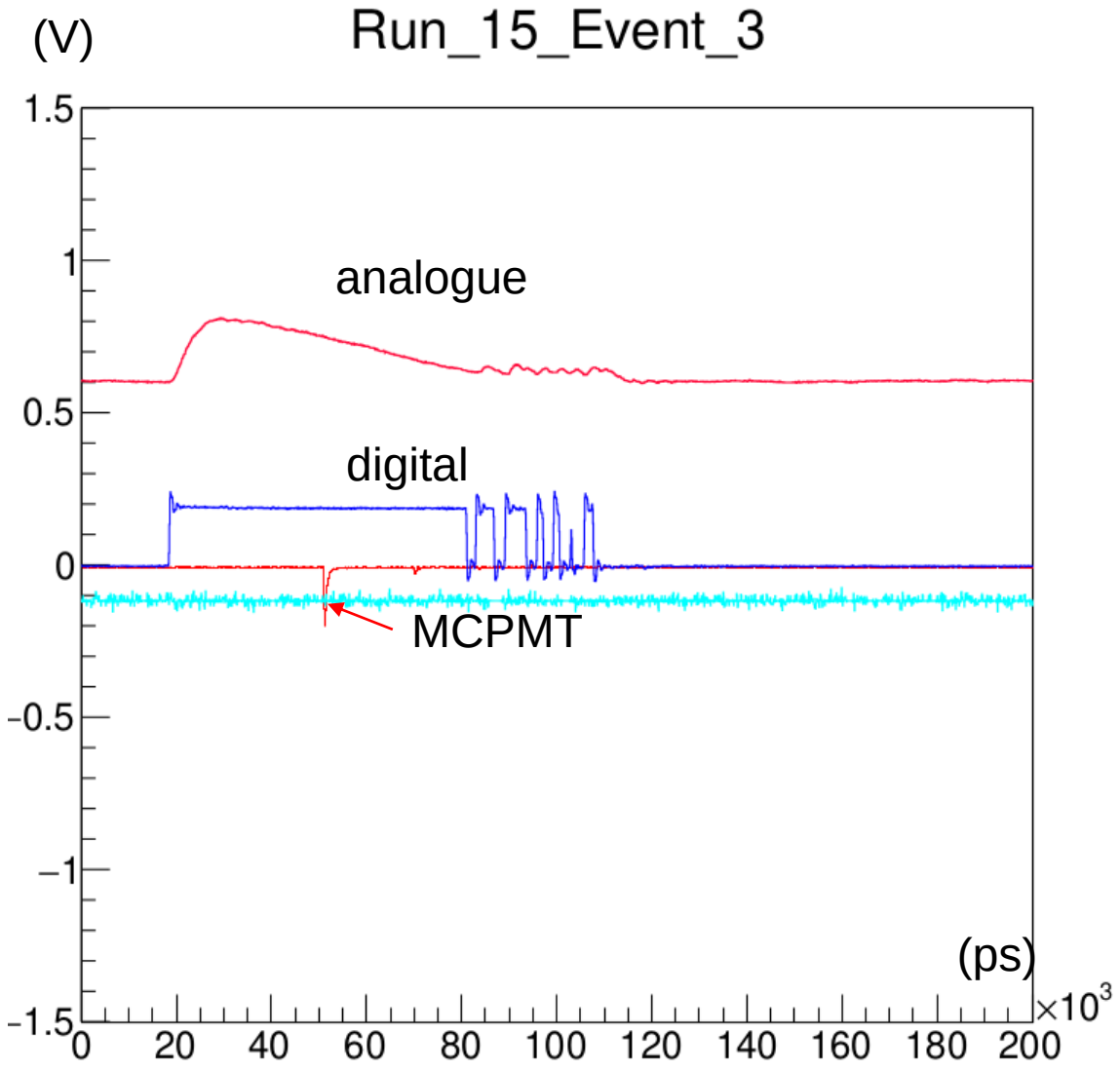


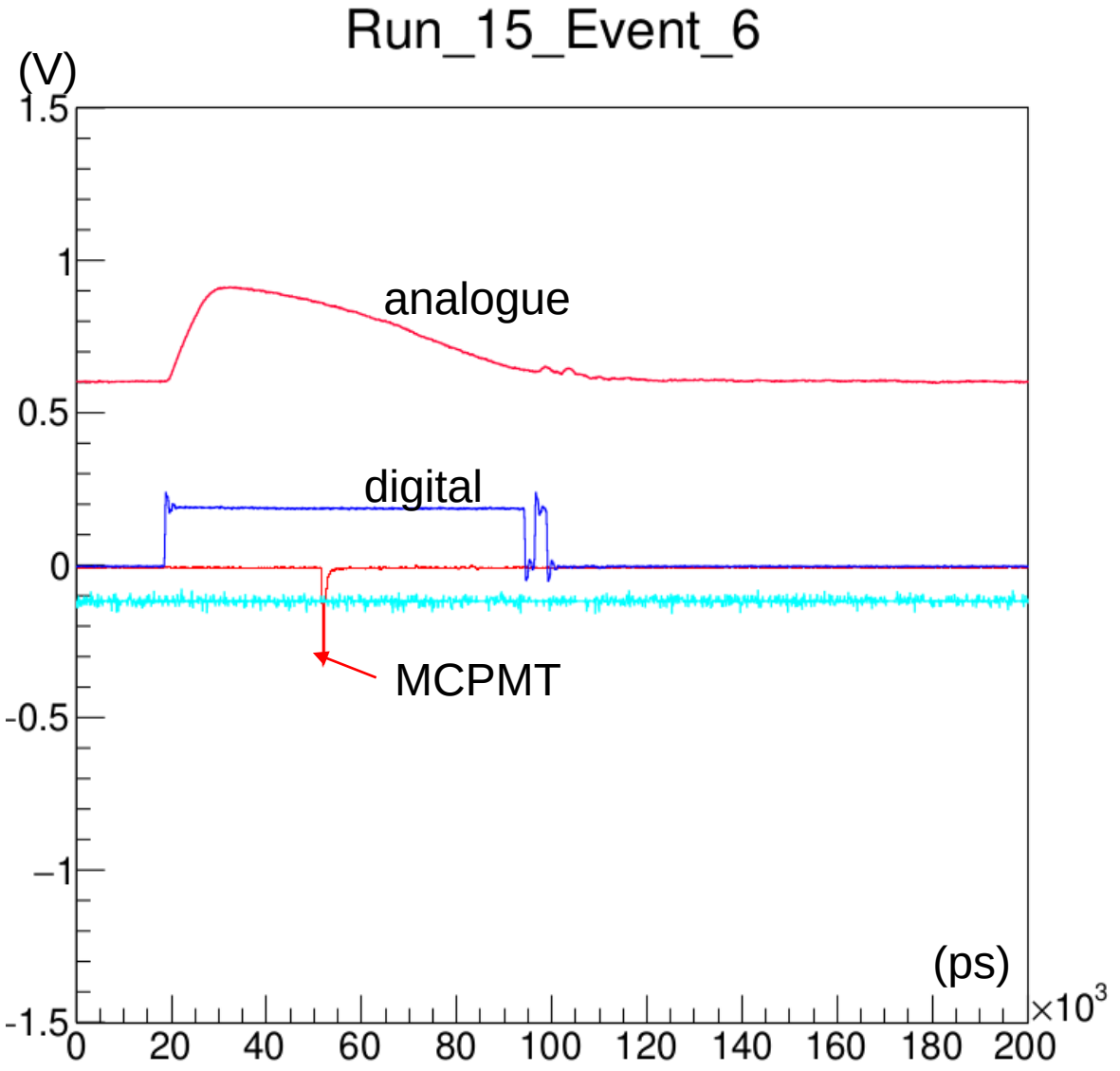
Sensor

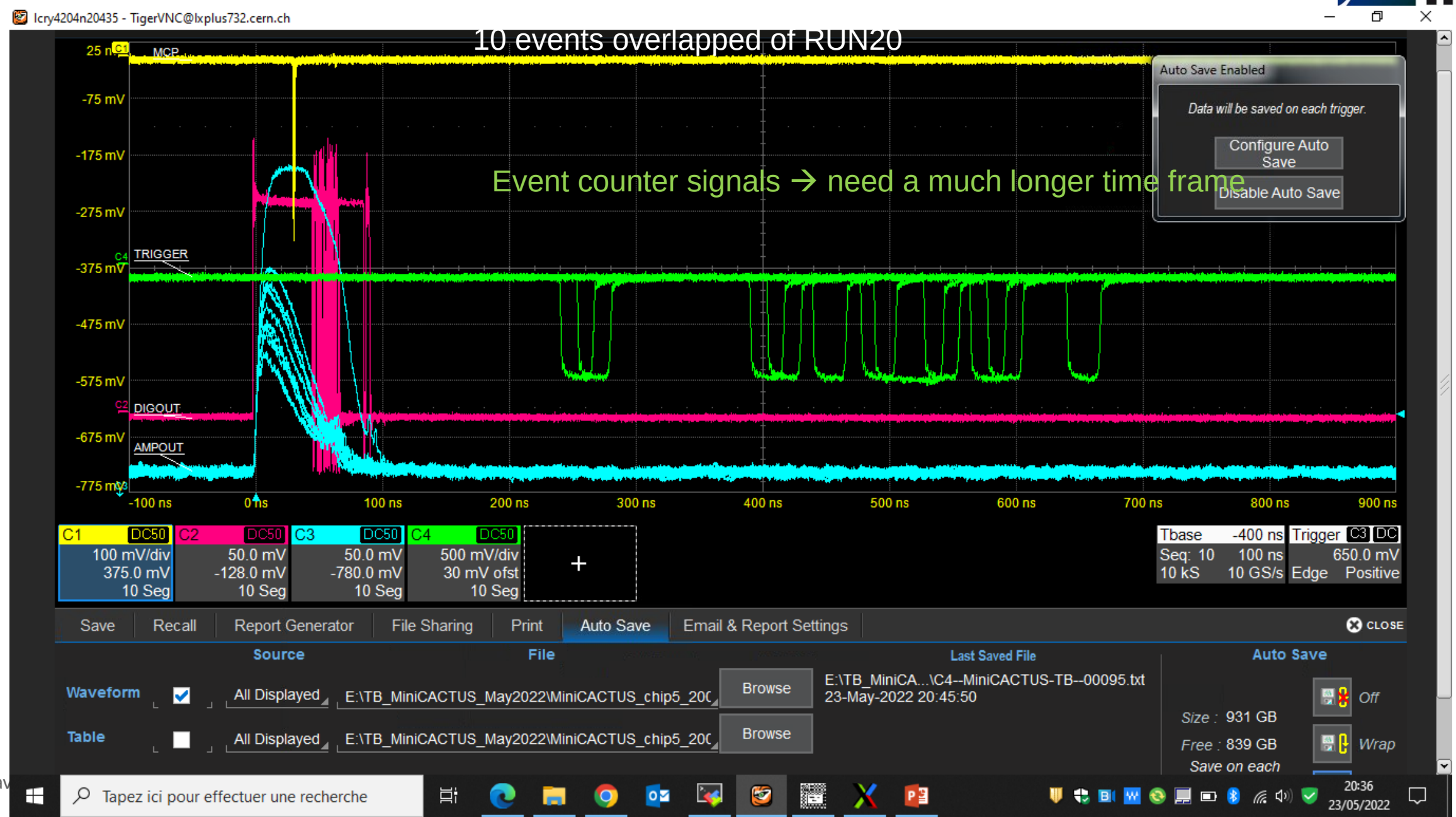
Readout system



Typical testbeam events:

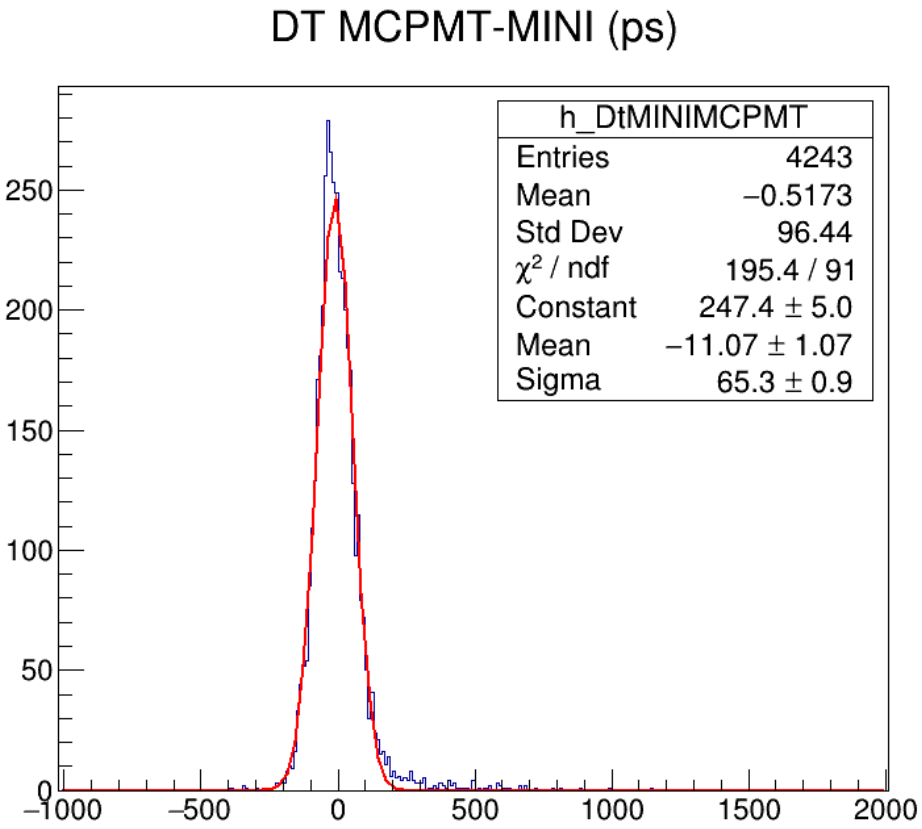





Icry4204n20435 - TigerVNC@lxplus732.cern.ch
10 events overlapped of RUN20
Event counter signals → need a much longer time frame
MCP
TRIGGER
DIGOUT
AMPOUT
-75 mV
-175 mV
-275 mV
-375 mV
-475 mV
-575 mV
-675 mV
-775 mV
-100 ns
0 ns
100 ns
200 ns
300 ns
400 ns
500 ns
600 ns
700 ns
800 ns
900 ns
Auto Save Enabled
Data will be saved on each trigger.
Configure Auto Save
Disable Auto Save
C1 DC50 100 mV/div 375.0 mV 10 Seg
C2 DC50 50.0 mV -128.0 mV 10 Seg
C3 DC50 50.0 mV -780.0 mV 10 Seg
C4 DC50 500 mV/div 30 mV ofst 10 Seg
Tbase -400 ns Seq: 10 100 ns 10 kS 10 GS/s
Trigger C3 DC 650.0 mV Edge Positive
Save
Recall
Report Generator
File Sharing
Print
Auto Save
Email & Report Settings
CLOSE
Source
File
Last Saved File
Auto Save
Waveform
All Displayed
E:\TB_MiniCACTUS_May2022\MiniCACTUS_chip5_20(
Browse
E:\TB_MiniCA...\C4--MiniCACTUS-TB--00095.txt
23-May-2022 20:45:50
Table
All Displayed
E:\TB_MiniCACTUS_May2022\MiniCACTUS_chip5_20(
Browse
Off
Size : 931 GB
Free : 839 GB
Wrap
Save on each
Tapez ici pour effectuer une recherche
20:36
23/05/2022

Result from May 2022 testbeam campaign, RD-51 parasitic data taking (muons)
17 May-7 June 2022

After TW correction

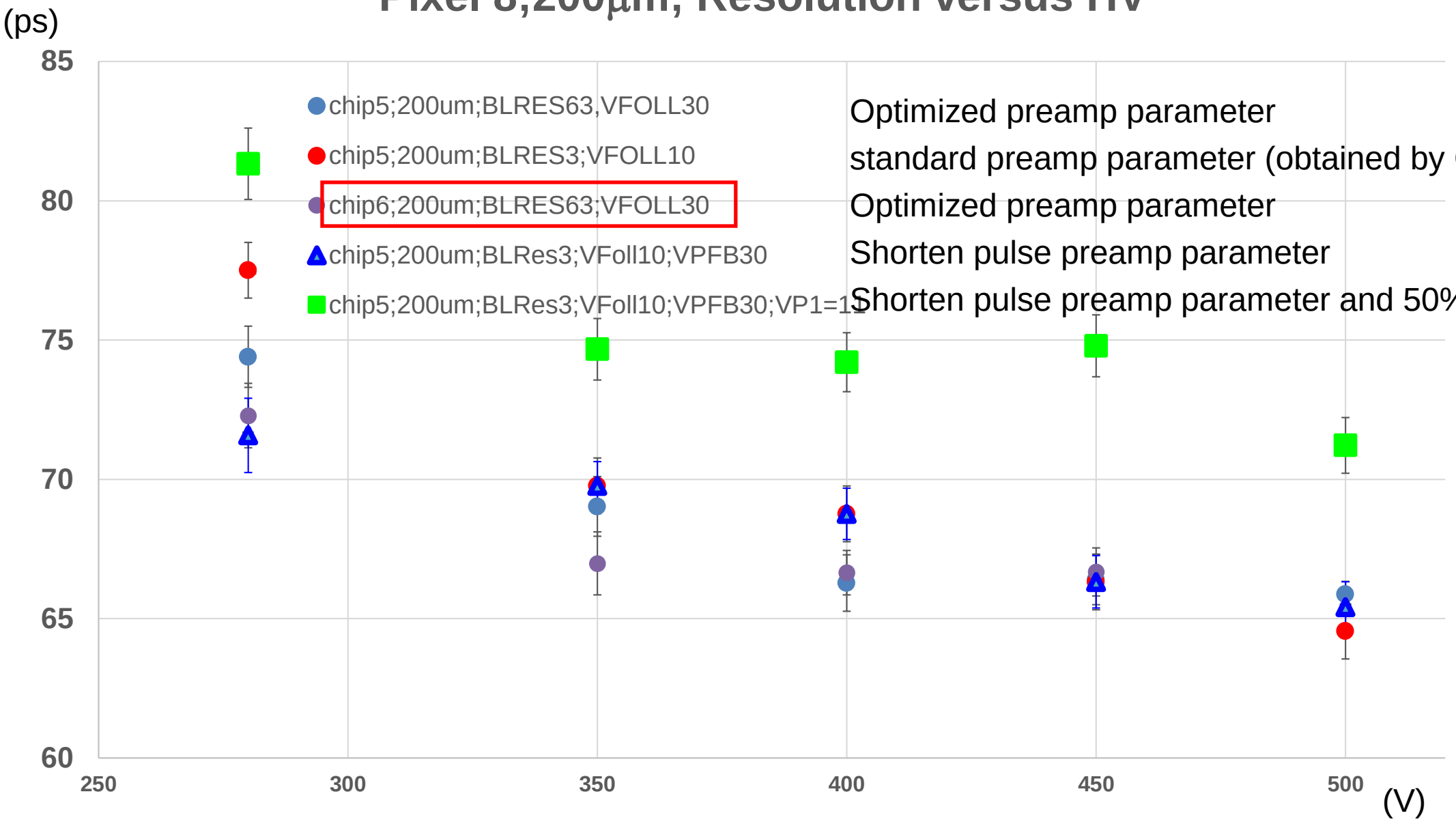


Collected charge is about 8 k electrons (2.5 fC)
Improvements in Front-End settings plus
HV increase give an improvement of 23 ps w.r.t. October 2021 testbeam results

MCP resolution not subtracted, but we have checked it is negligible (runs MCP/PMT/MiniCactus)

65 ps time resolution measured consistently on several runs taken several days apart

Pixel 8;200μm; Resolution versus HV



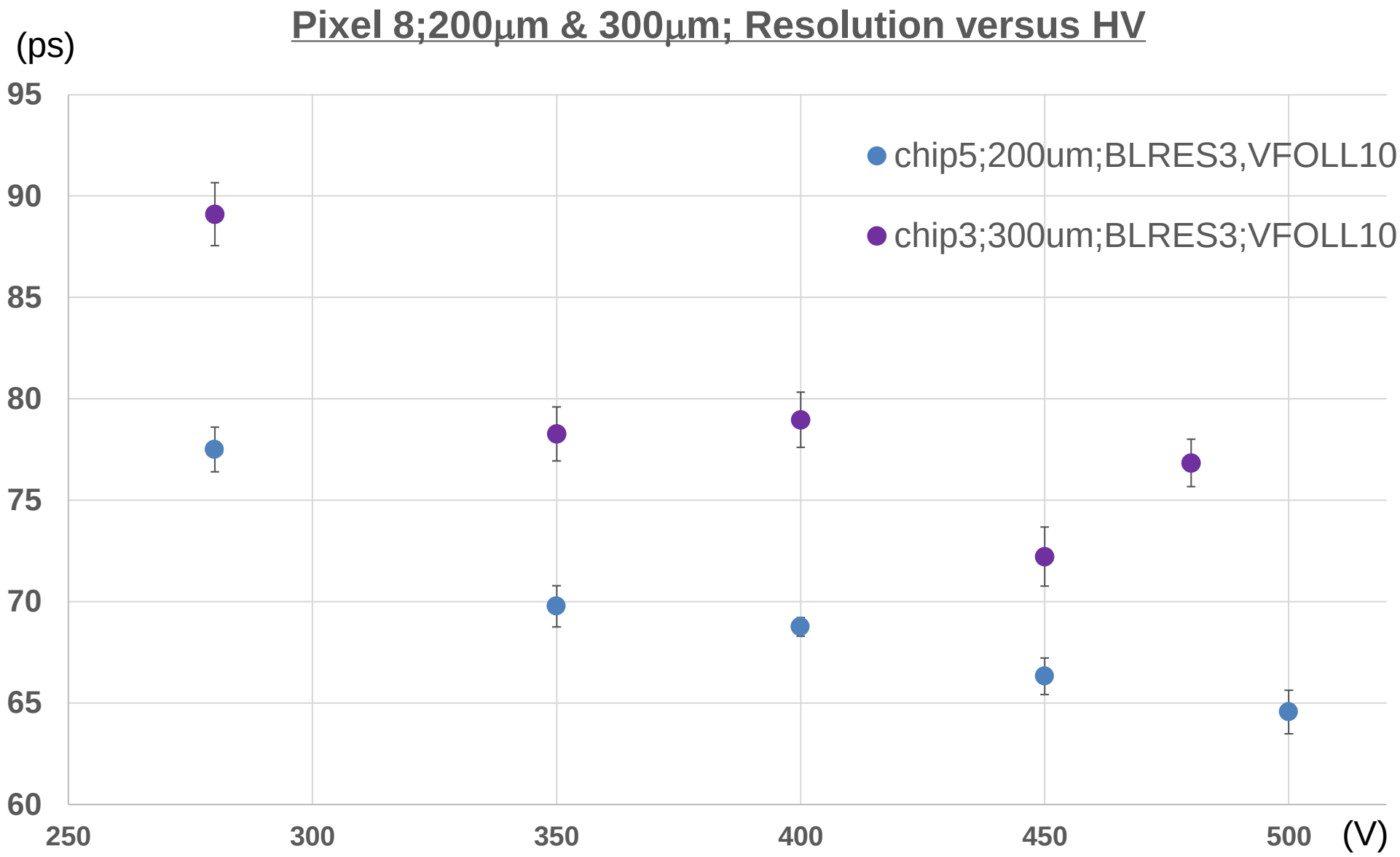
Optimized preamp parameter

standard preamp parameter (obtained by CADENCE)

Optimized preamp parameter

Shorten pulse preamp parameter

Shorten pulse preamp parameter and 50% consumption


Pixel 8;200µm & 300µm; Resolution versus HV
(ps)
95
90
85
80
75
70
65
60
250
300
350
400
450
500
(V)
chip5;200um;BLRES3,VFOLL10
chip3;300um;BLRES3;VFOLL10

Test-beam at Synchrotron Soleil
June and November 2022

Many thanks to Fabienne Orsini and Arkadiusz Dawiec (Synchrotron Soleil)
for the beam time and the technical support !

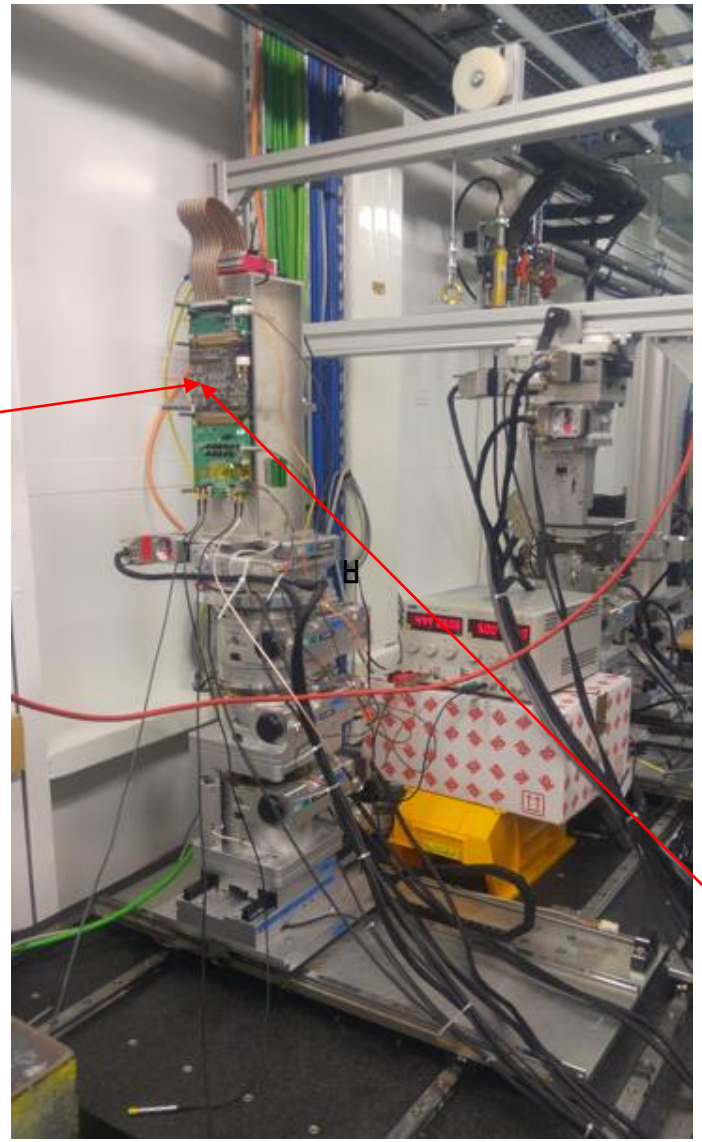
Photon beam is bunched : 90 ps pulse length every 2.6 ns

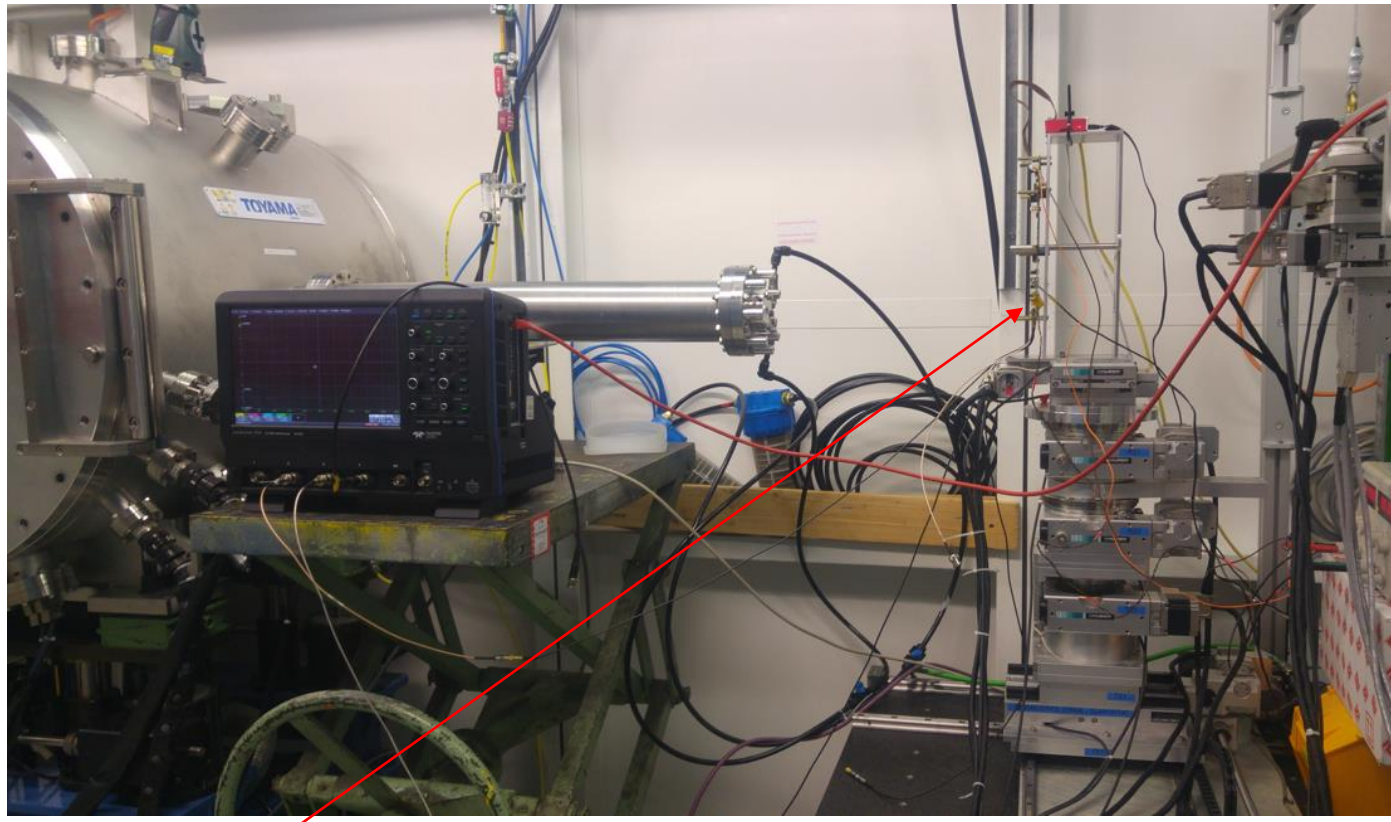
Allows to study energy and time response
Beams of 10 keV, 20 keV, 30 keV, 40 keV available, attenuated to have $\approx$ 1 photon/bunch

With X/γradioactive sources, only energy response can be studied

Setup pictures

Beam direction

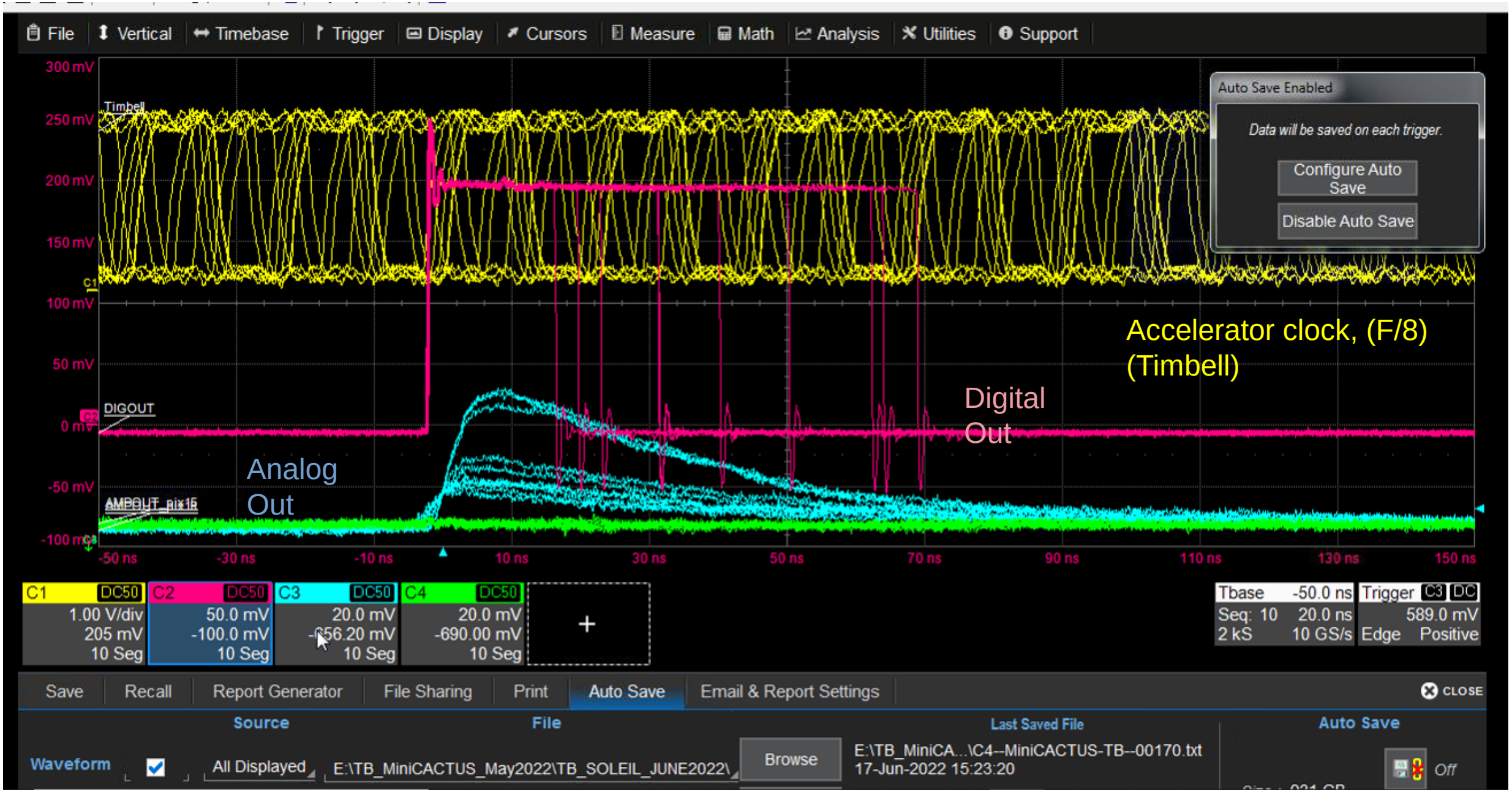




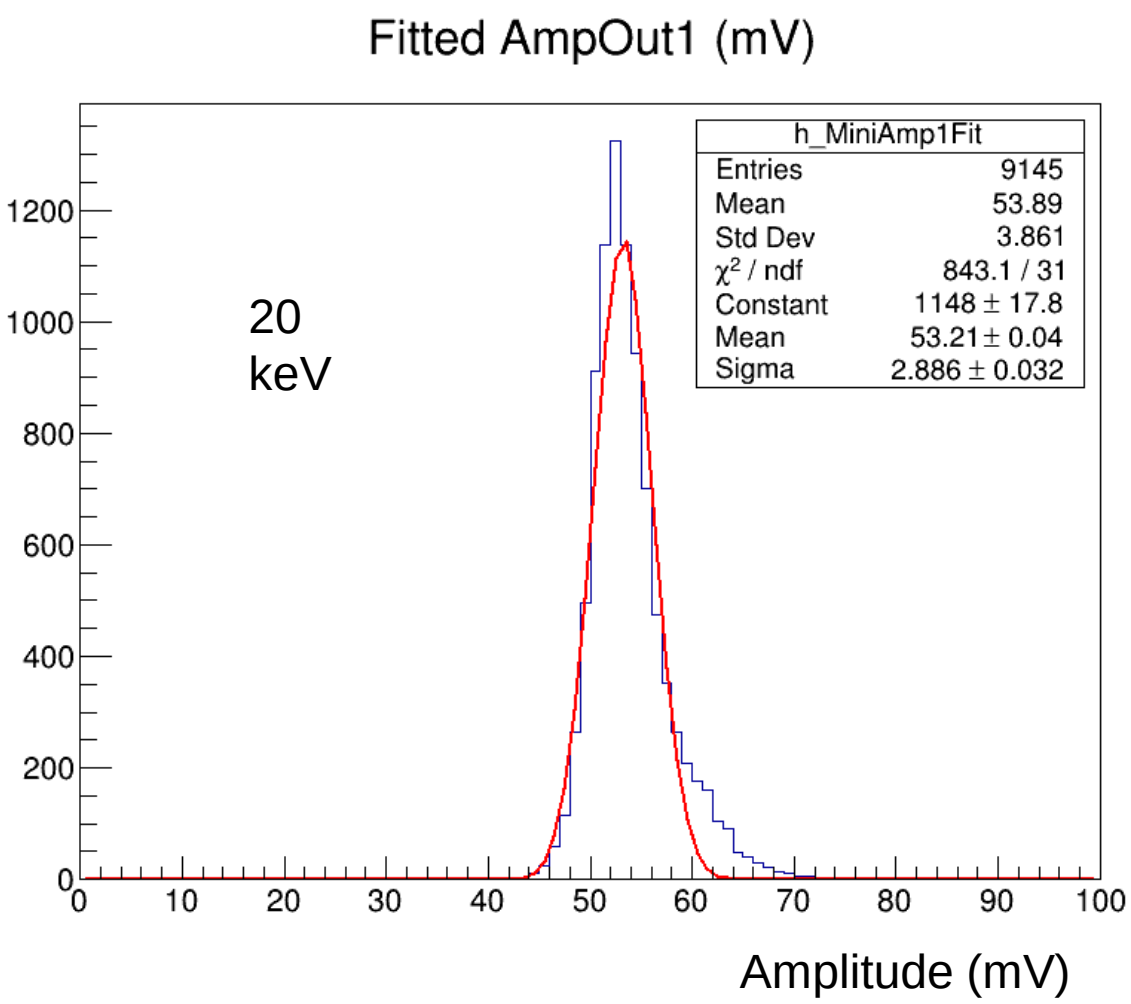
MiniCactus

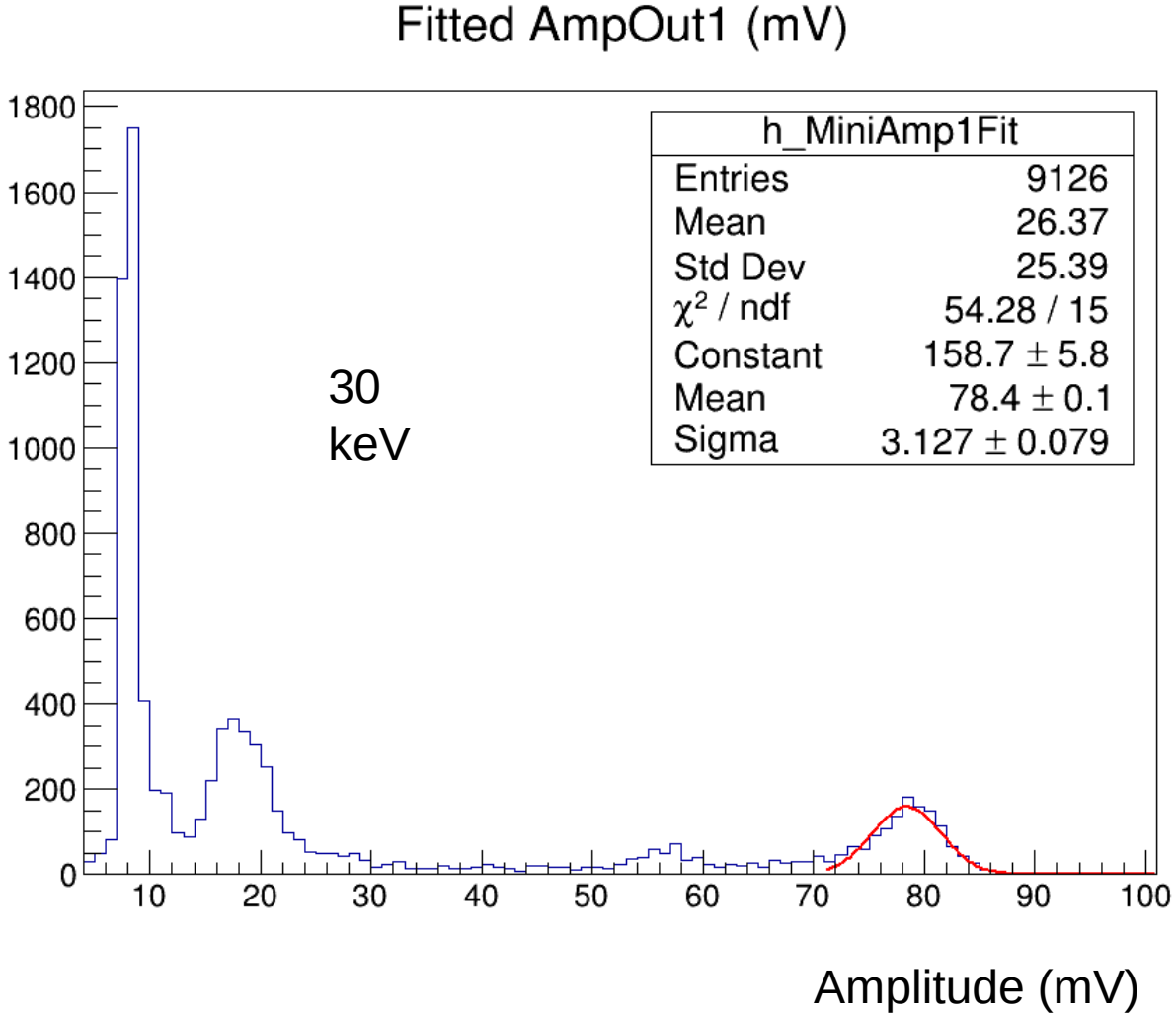
Data acquired with LeCroy oscilloscope,
At 10 GSPS, 8 bits

Typical waveforms



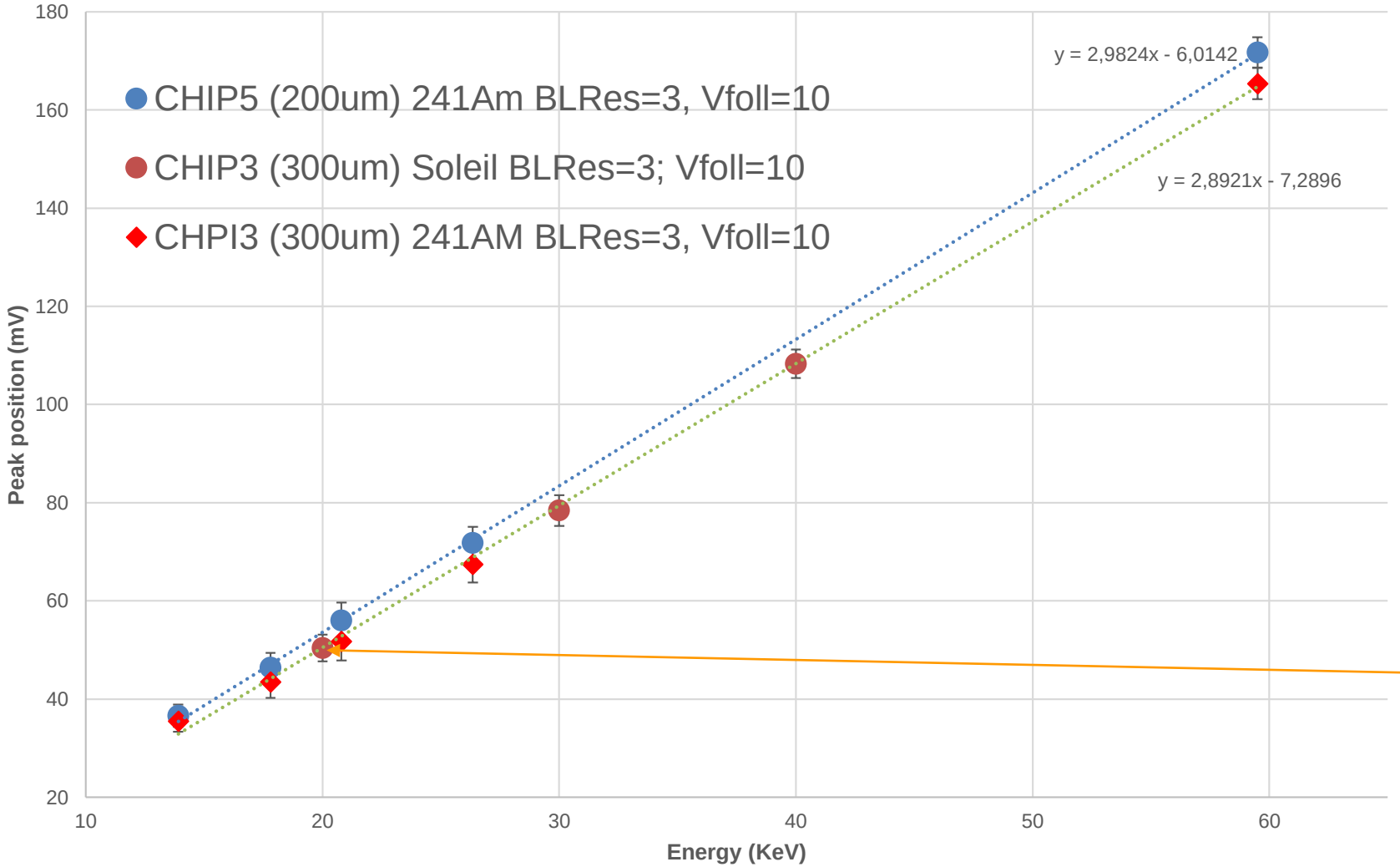
Energy spectra
300 micron chip, pixel 18, 400 V



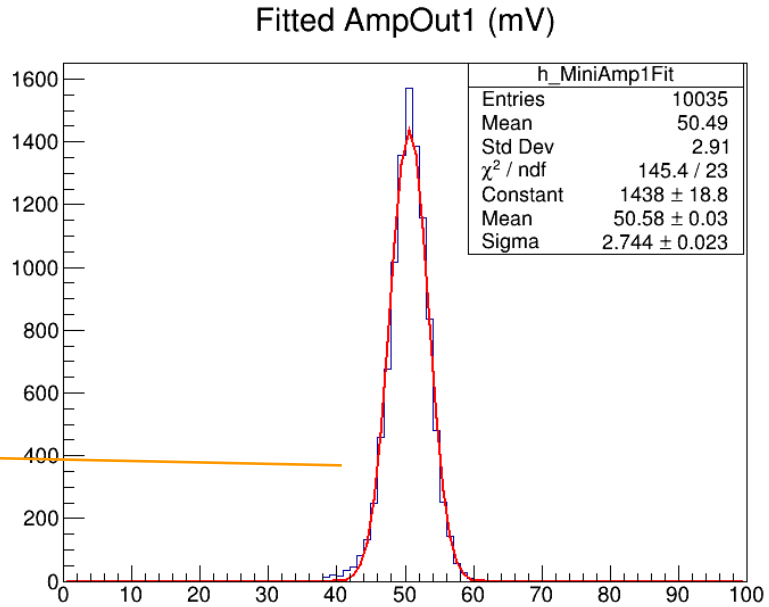


Often get parasitic peaks, due to fluorescence of PCB material

Results from Soleil test beam



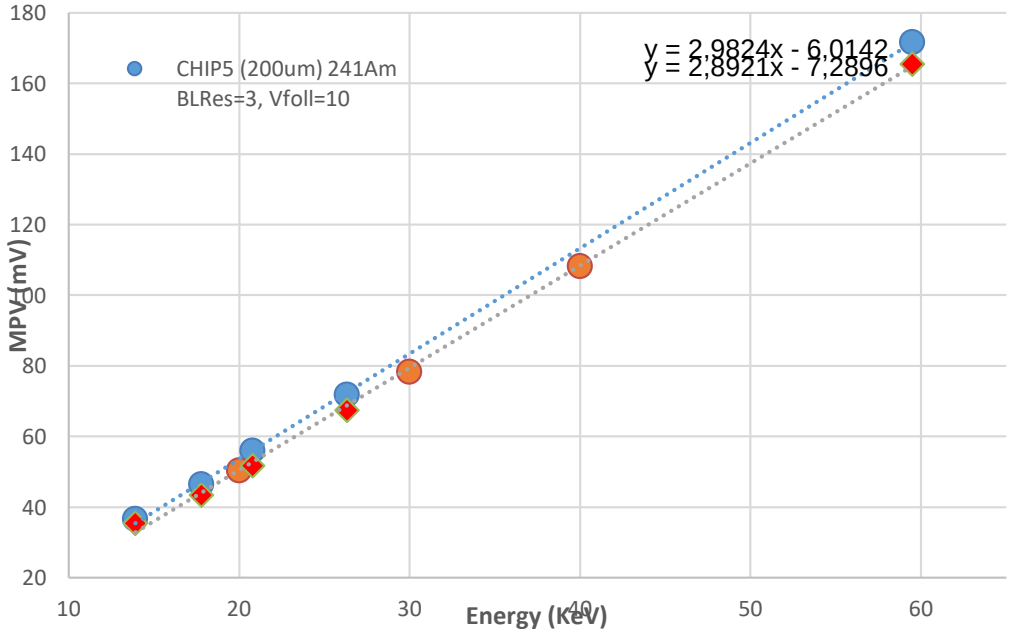
CHIP3: Soleil 20keV

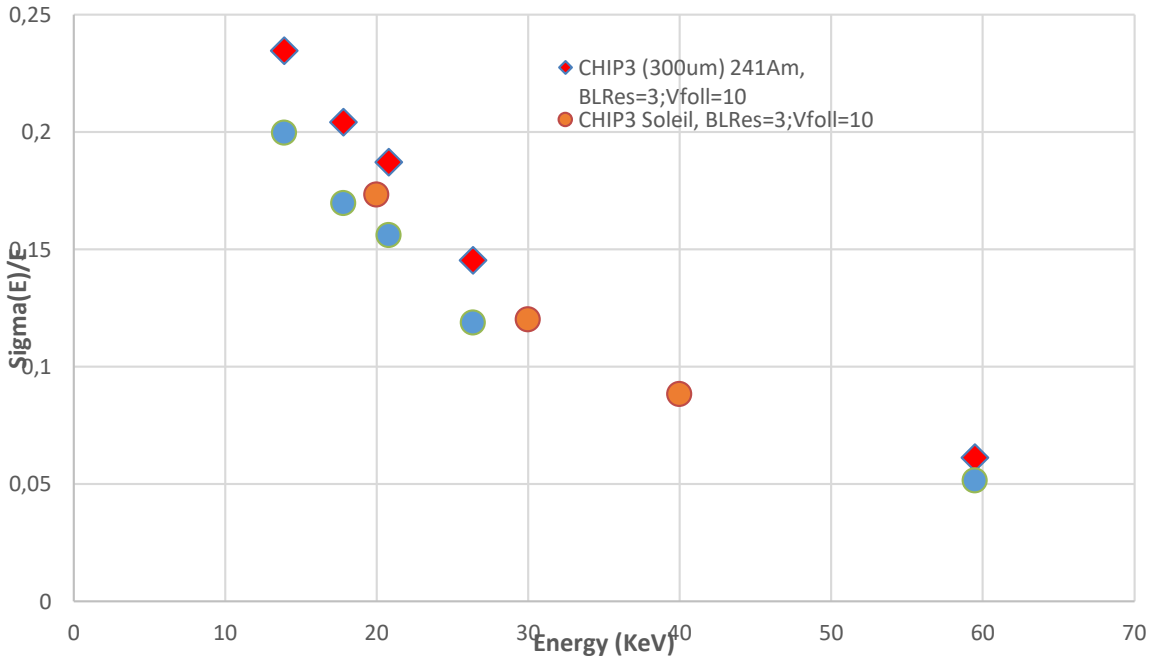


Calibration comparison between Soleil data and 241Am X-ray lines

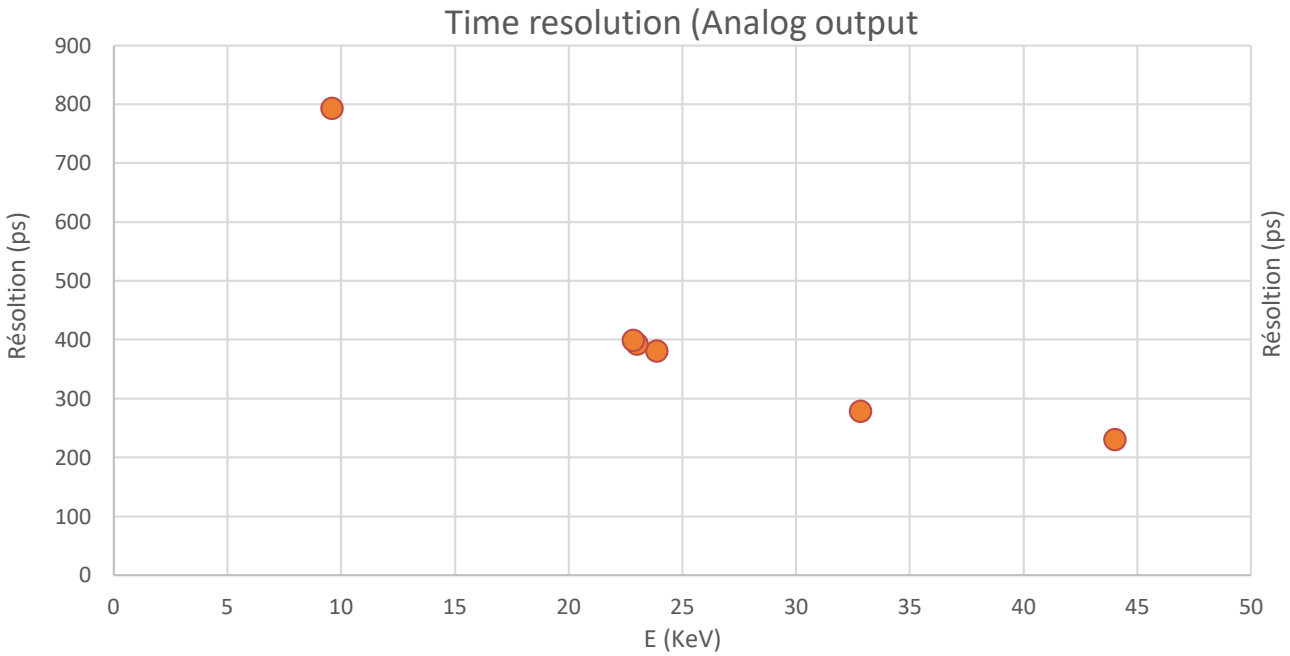
200 μ chip, 241Am data (200 V), px 18

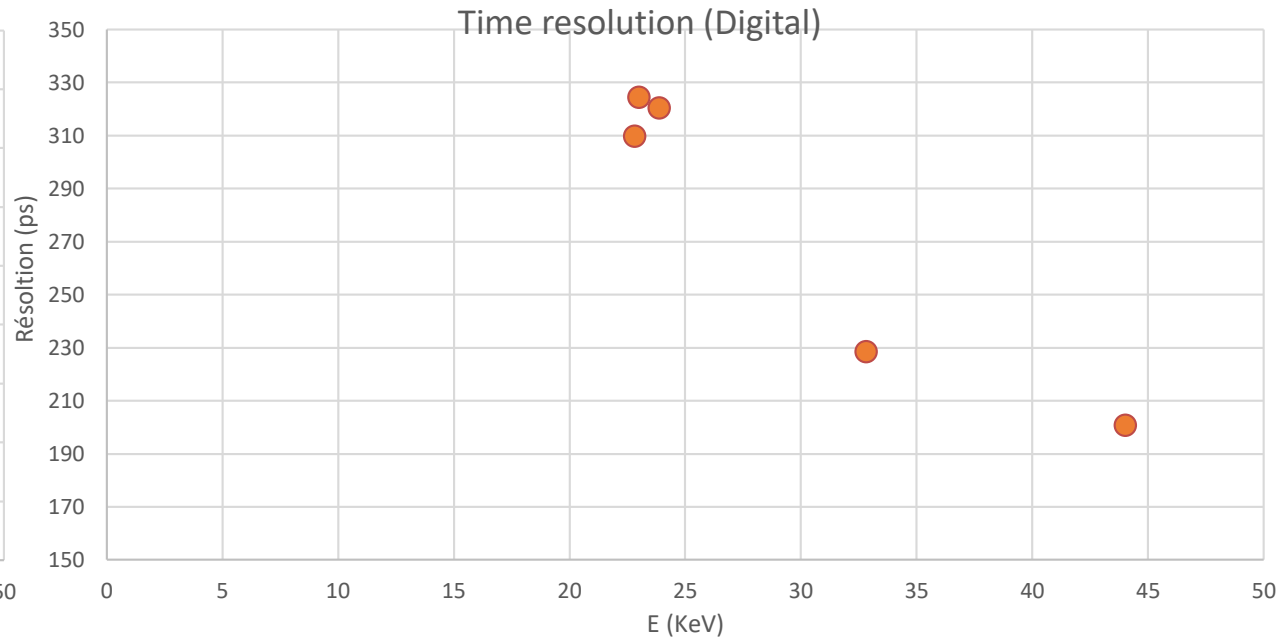
300 μ chip, Soleil data (400 V), px 18





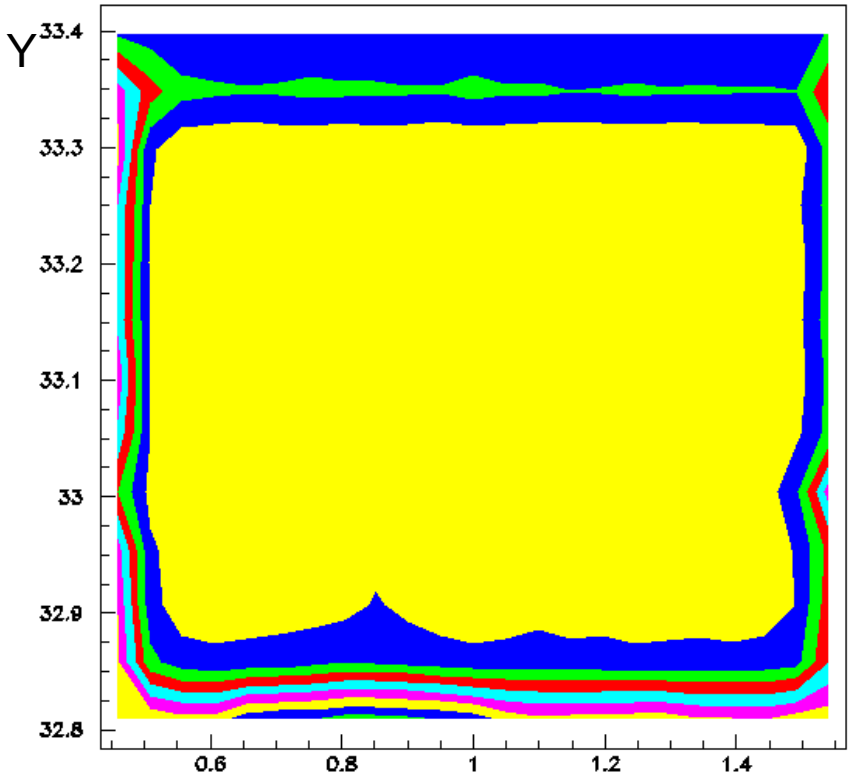
Time resolution with photons

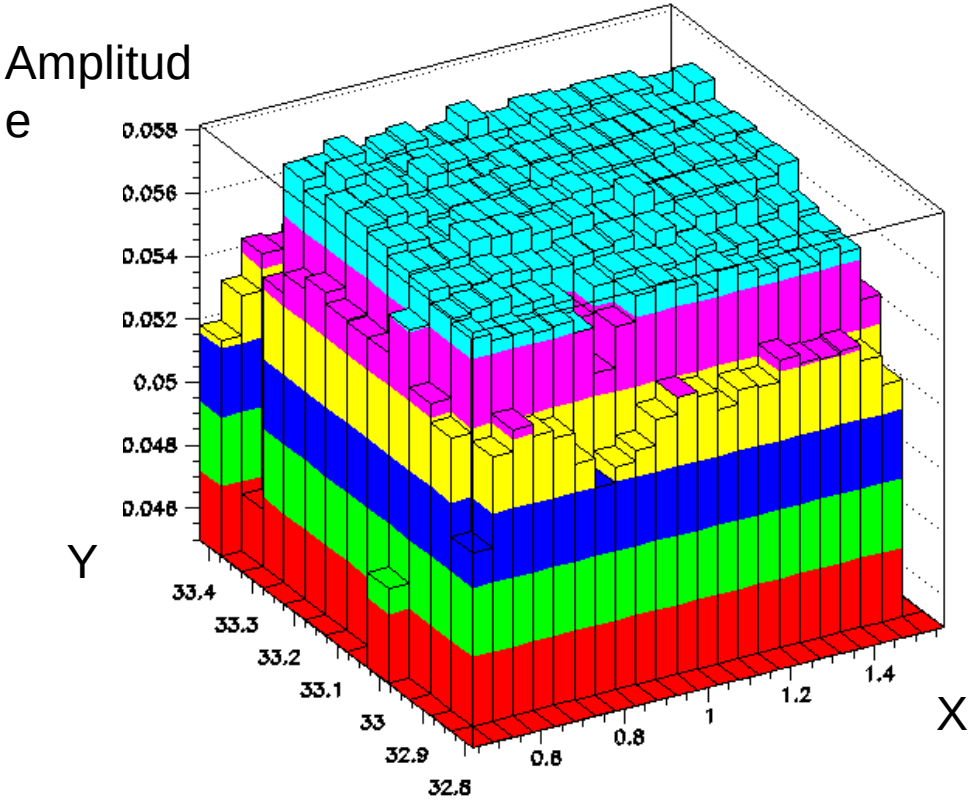




Time resolution worse for photons than for MIPs, at similar S/N

Pixel position scan at 20 keV with photons



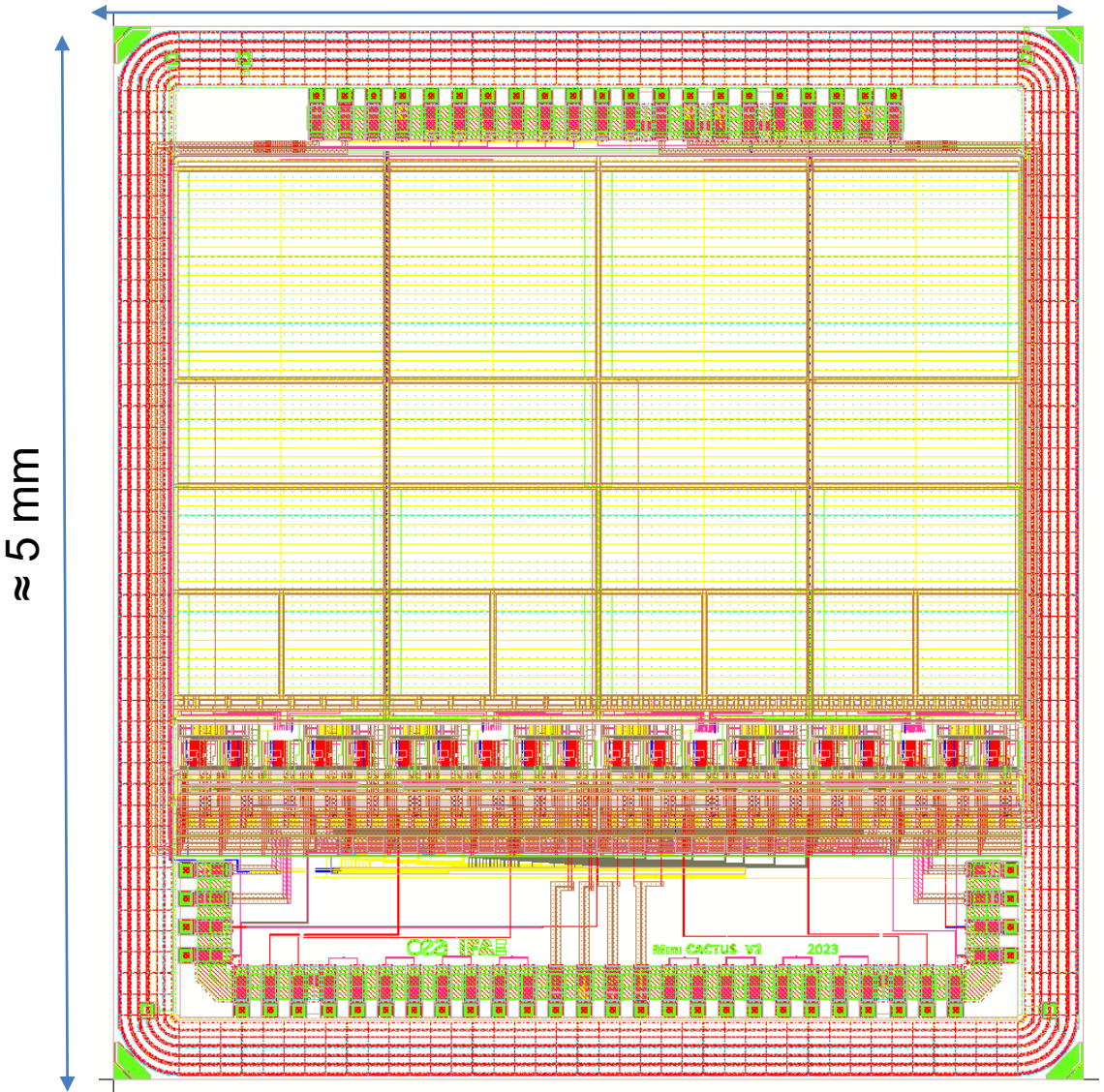


Used a pencil beam (50 microns by 50 microns) to scan pixel surface

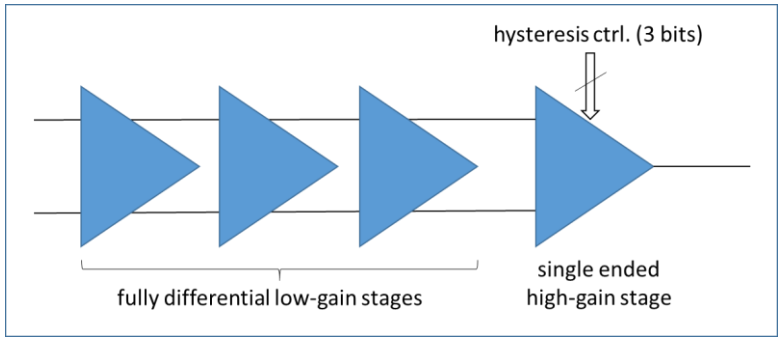
No non-uniformity found

MiniCACTUS_V2 Sensor Chip

Irfu : Yavuz Degerli, Fabrice Guilloux, Jean-Pierre Meyer, Philippe Schwemling
IFAE : Raimon Casanova, Yujin Gan, Sebastian Grinstein



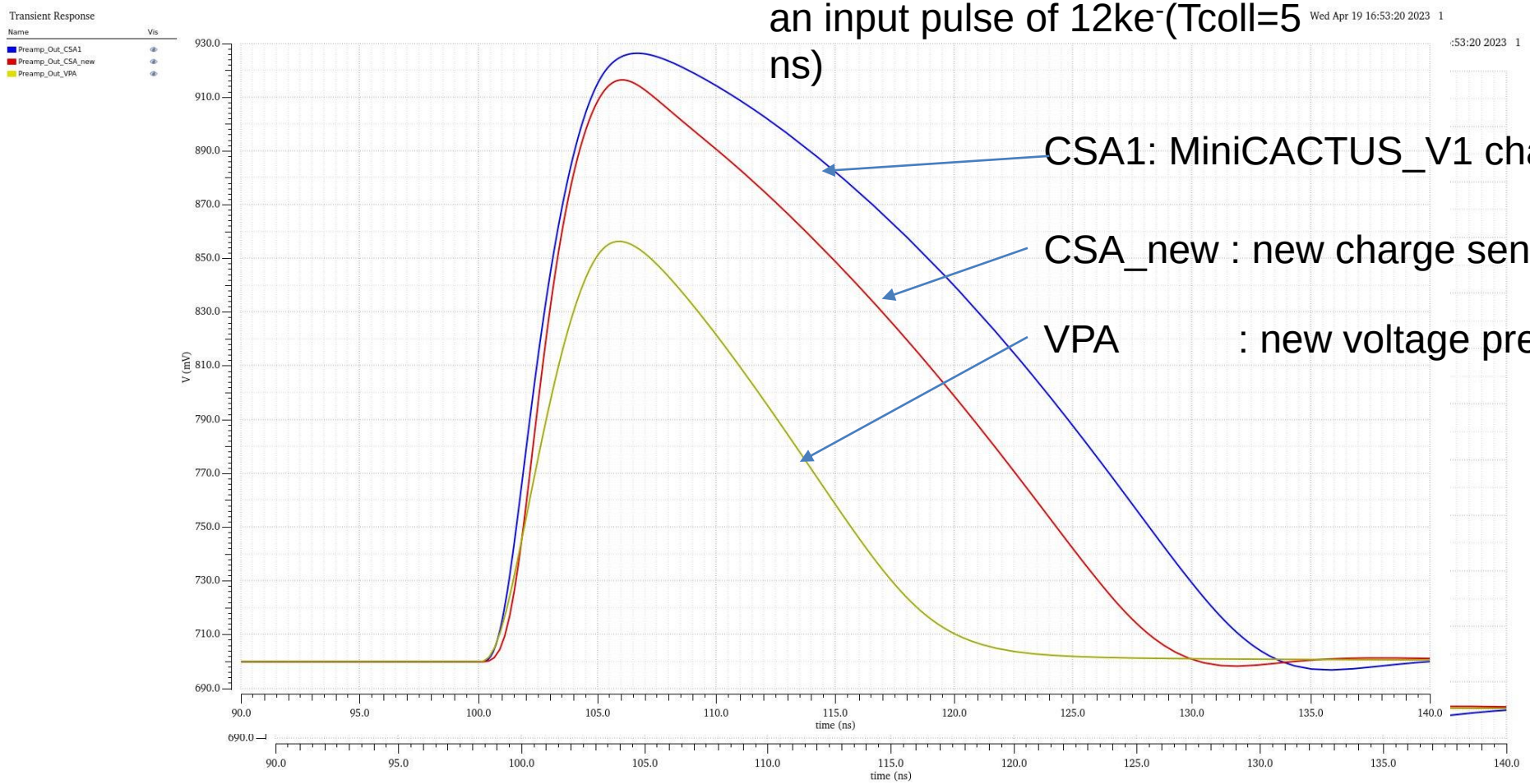
- ~ 2 times larger than MiniCACTUS
- 0.5 mm x 1 mm (baseline), 1 mm x 1 mm and 0.5 mm x 0.5 mm diodes
- 50 µm x 150 µm and 50 µm x 50 µm small test diodes
- 3 different preamps
- New multistage discriminator with **programmable hysteresis**
- Improved layout for better mixed-signal coupling rejection
- **CEA-IRFU** & **IFAE-Barcelona** coll.
- Submission in progress (Lfoundry MPW, 8th May 2023)



MiniCACTUS_V2 Sensor Chip

- 3 different preamps implemented in MiniCACTUS_V2
- 2 new preamps (CSA_new and VPA) designed by **IFAE-Barcelona** for better jitter and reduced ToT

Responses of the 3 preamps to an input pulse of 12ke$^-$(Tcoll=5 ns)



CONCLUSIONS AND NEXT STEPS

- Non amplified HV CMOS MiniCactus v1 sensor reaches 65 ps time resolution on MIPs, power consumption 0.3 W/cm^2
- A new iteration of the MiniCactus is underway, under submission
  - Improved front-end : better discriminator, programmable analog filtering
  - Altiroc-inspired Front-end designed and studied by IFAE, improvements in jitter and shorter signal expected → needed for potential use at LHC
- Irradiated MiniCactus v1 chips (10^{14}, 10^{15}, 10^{16} 1 MeV neq/cm^2) are available, test setup being modified to run at -15°C
- Measurements with X-ray photons from Soleil synchrotron confirms energy calibration obtained in lab with 241Am source, bring complementary information to MIP testbeam measurements
- MiniCactus v1 results presented at VCI 2022, TWEPP 2022 and NSS 2022