Primary particles tracking integrated with secondary radiation detectors for next generation of ion beam delivery system

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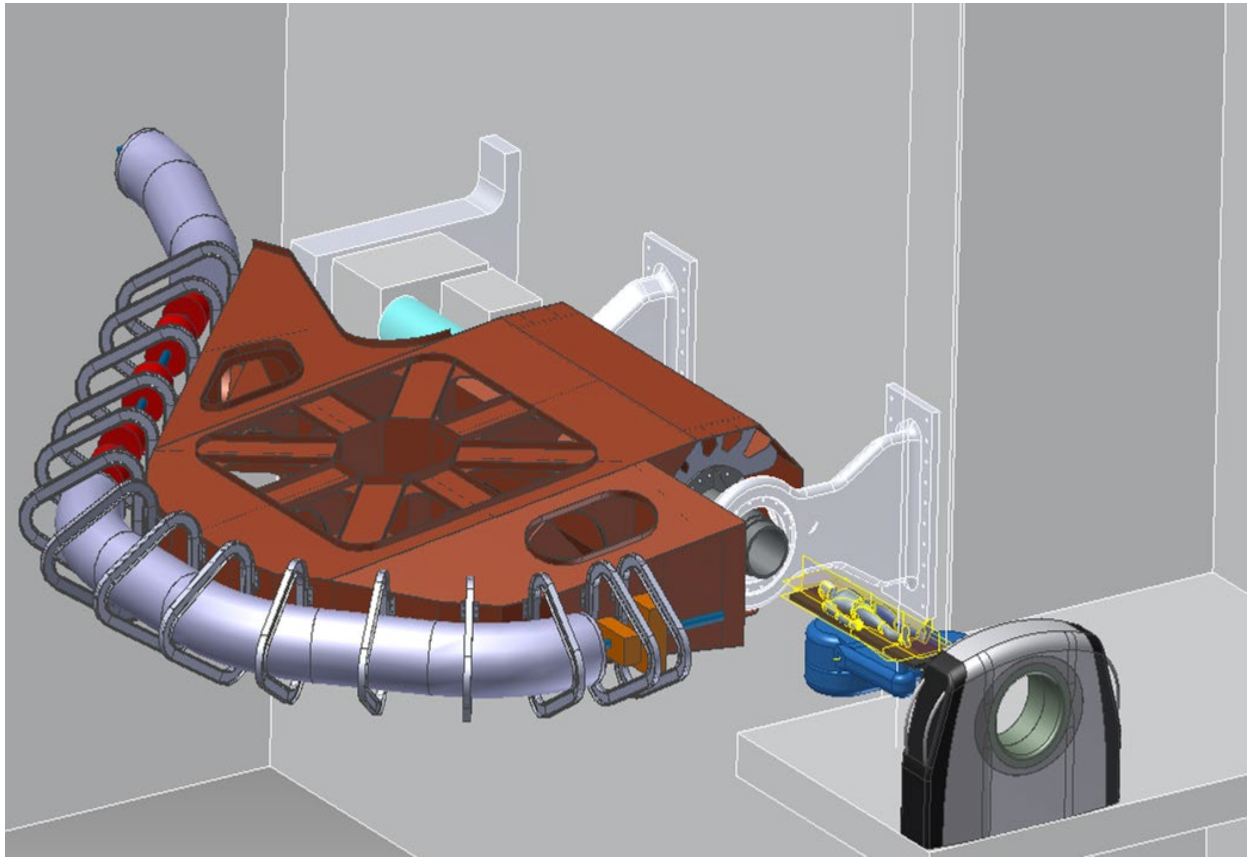
SUMMARY

- MOTIVATION
- LGADS FOR BEAM MONITORING
- RANGE VERIFICATION SYSTEM BASED ON PGT
- PARTICLE TRACKING INTEGRATION WITH THE RANGE VERIFICATION SYSTEMS
    - PICOTDC INTEGRATION FOR PRIMARIES
    - LABORATORY TEST FOR PRIMARIES
    - PICOTDC INTEGRATION FOR SECONDARIES
    - LABORATORY TEST FOR SECONDARIES
- BEAM TEST WITH PRIMARIES ONLY
- BEAM TEST WITH PRIMARIES AND SECONDARIES
- CONCLUSIONS

MOTIVATION

Developing a novel beam monitoring system for single particle 4D tracking (position and time) integrating a range verification system based on Prompt Gamma Timing (PGT)



INFN GRV Call involving INFN-MI, INFN-GE, CERN, CNAO

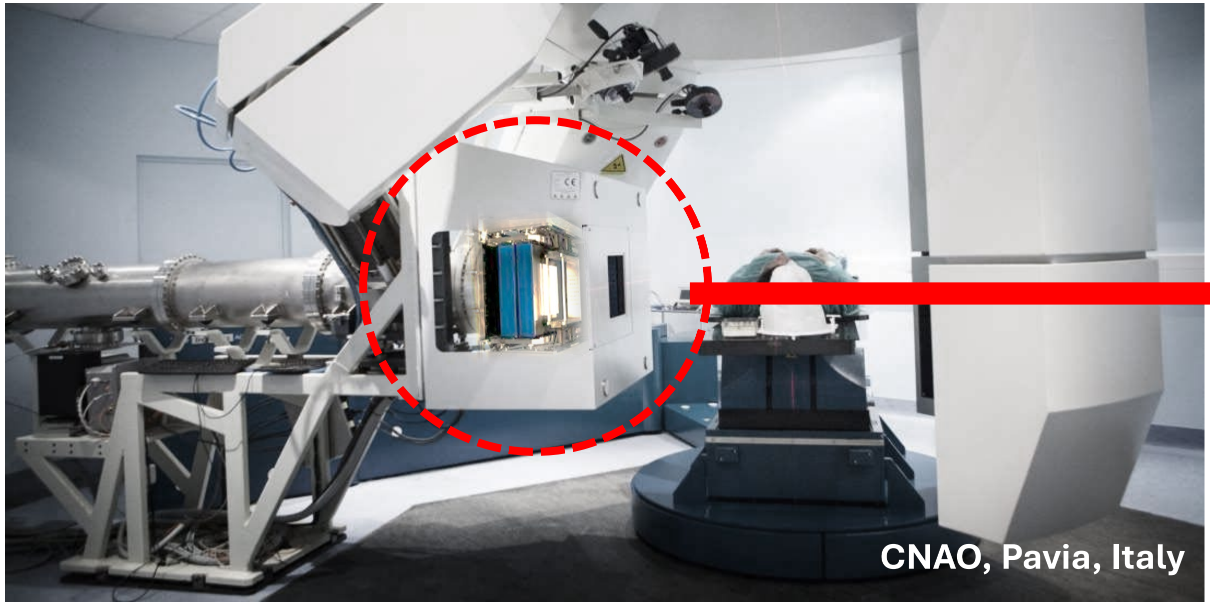
Superconducting Ion Gantry

- Particles up to a rigidity of 6.6 Tm (430 MeV/u **carbon ions**)
- 14 m long, ~50 tons weight
- 4 T curved superconducting dipoles
- Superconducting spool piece quadrupoles
- Downstream scanning magnet system
- **Dose Delivery and Range Verification Systems for adaptive cancer treatments**

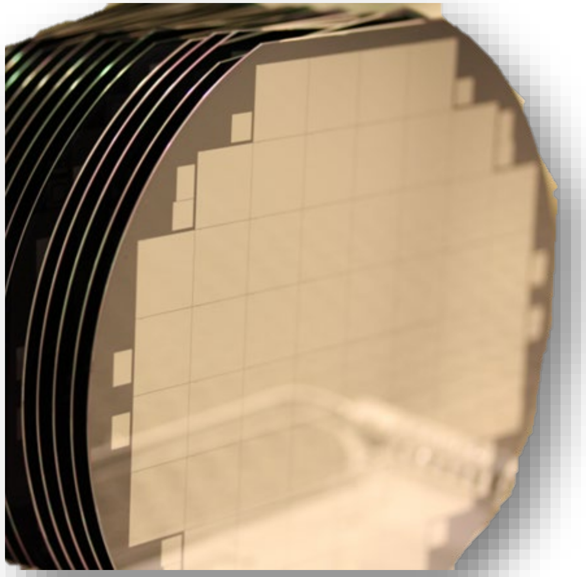
MOTIVATION

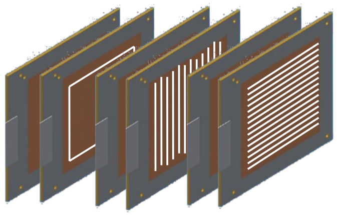
Monitoring: from Integrated Charge with Gas Ionization Chambers to Number of Particles with Thin Silicon Detectors

Gas detector



Thin Silicon Detectors



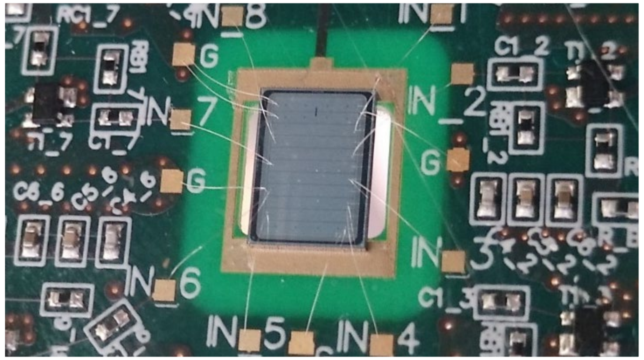


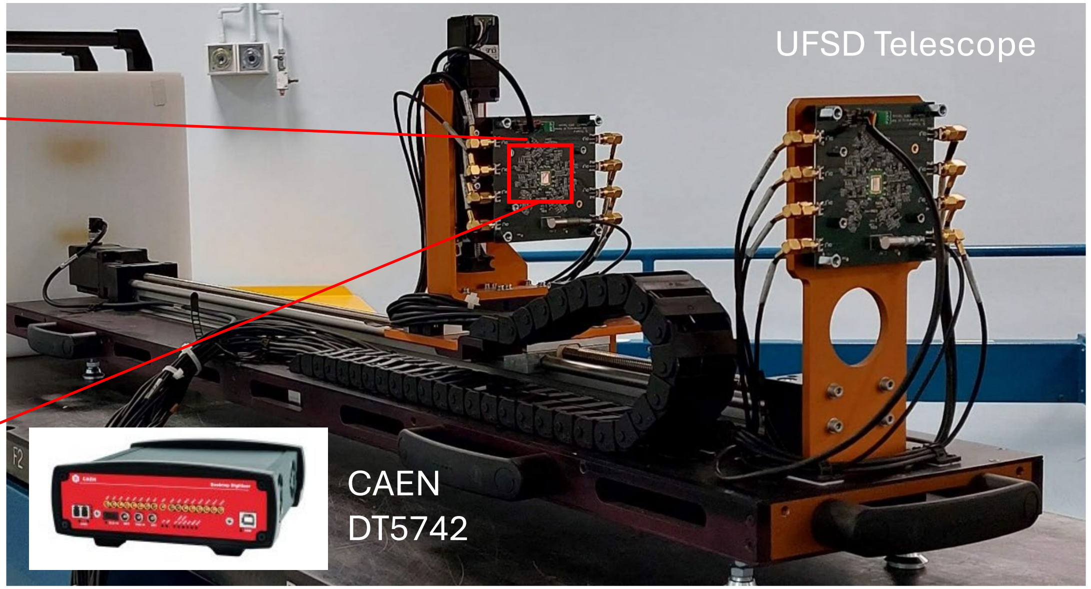
- Sensitivity : 10^4 protons → single particle
- Collection times: ~ 100 µs → ~ ns
- Time resolution: poor → ~ 50 ns
- Not suitable for fast scanning modalities → Direct counting at clinical fluence (10^8 cm^{-2} s^{-1})

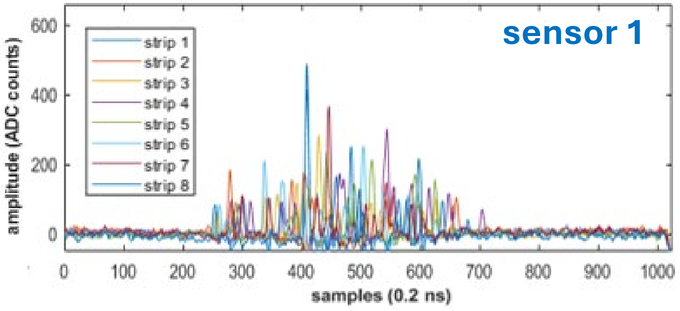
Fast readout electronics needed

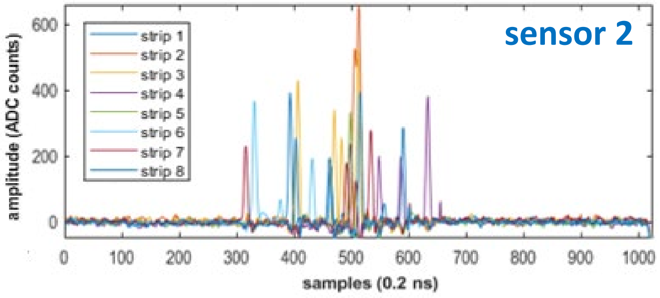
LGADS FOR BEAM MONITORING. ENERGY MEASSUREMENT.

UFSD:
- 11 strips of 2.2 mm^2 (4000 µm x 550 µm)
- strips distance 51 um
- with gain (protons) without gain (carbon ions)
- 50 µm active thickness

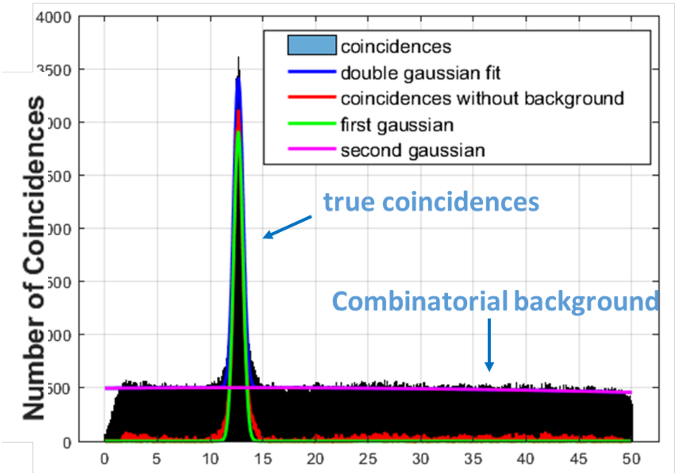




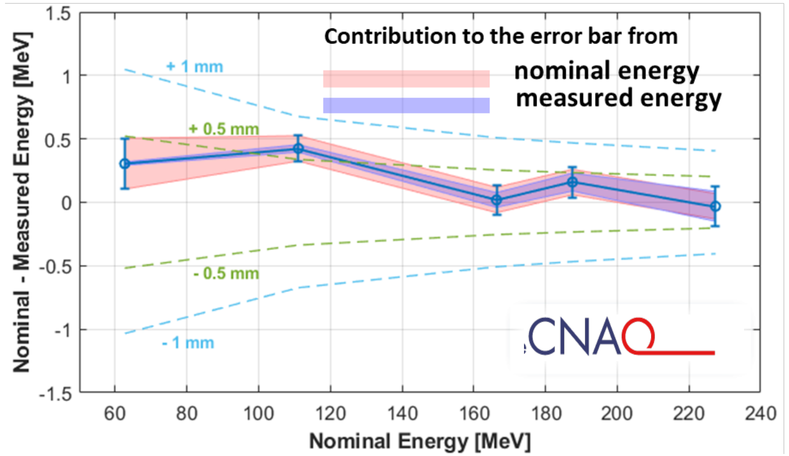




Example: E=182.8 MeV, d= 400.328 mm



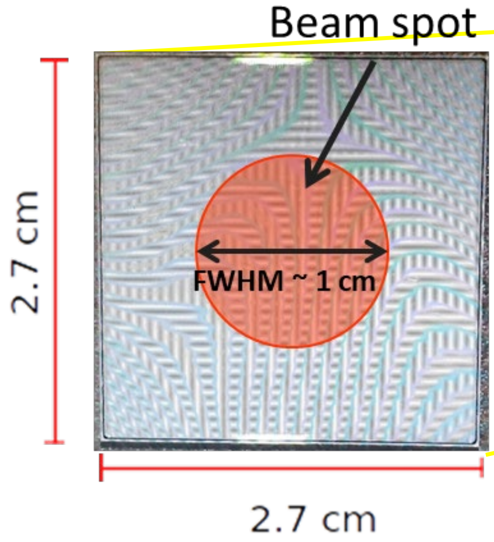
d = 95 cm (lowest error and best stability)

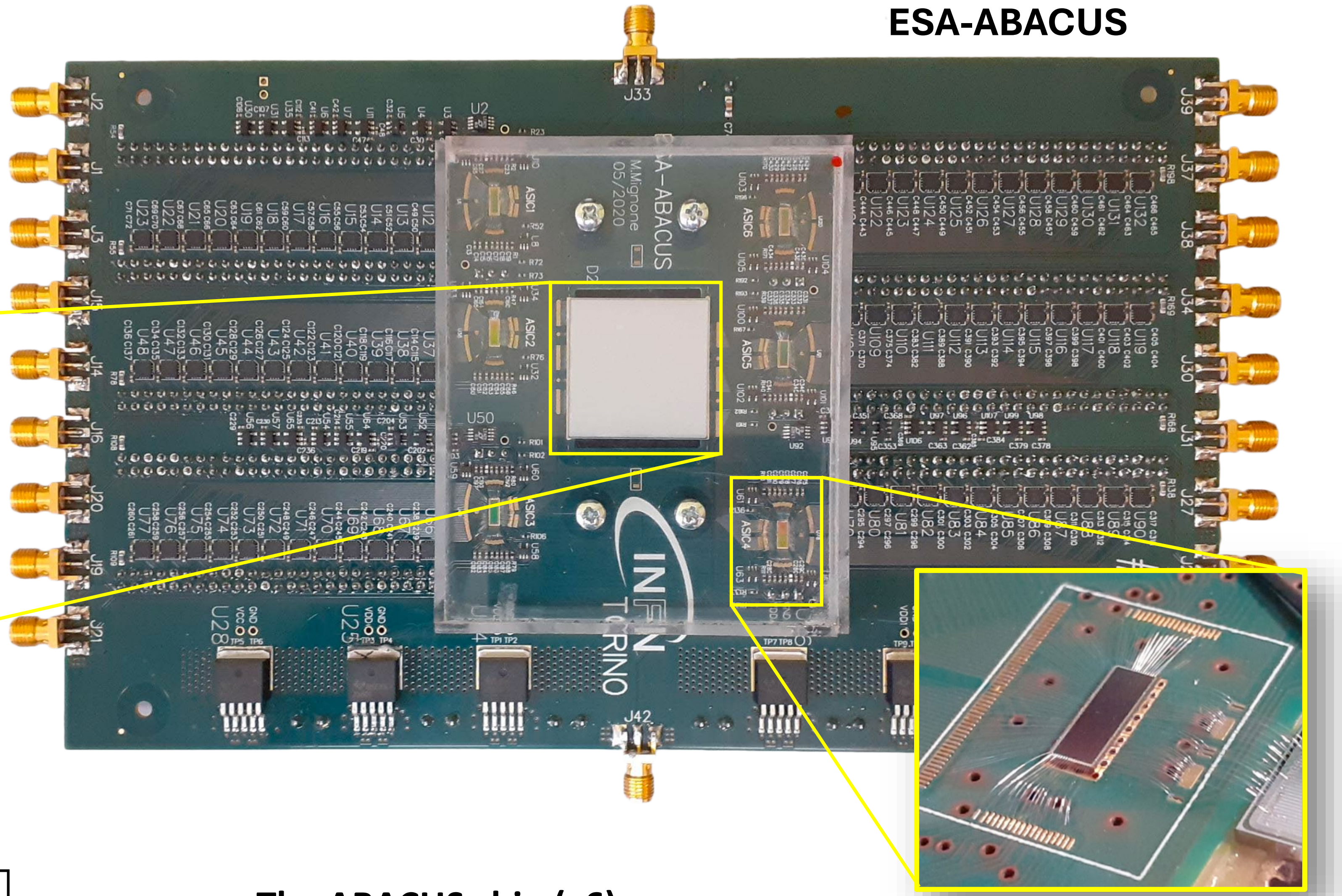


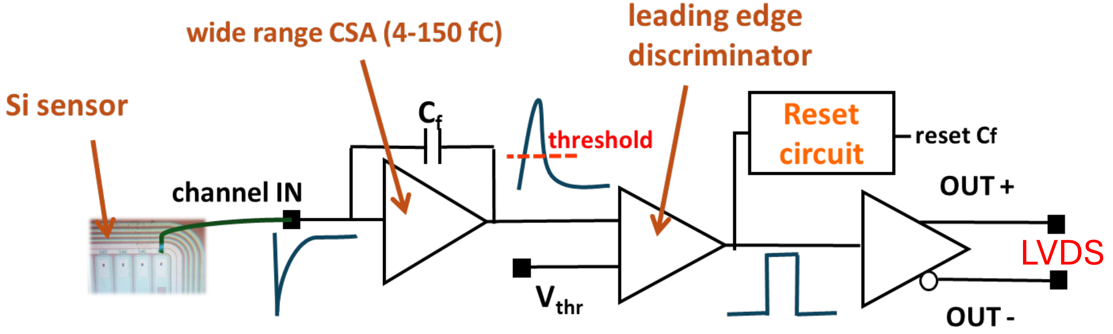
Tested at CNAO and TIFPA

LGADS FOR BEAM MONITORING. PARTICLE COUNTING.

- Strips width: 114 μm
- Pitch: 180 μm
- Inter strip distance 80 μm
- Active thickness: ~50 μm
- Capacitance: ~7 pF





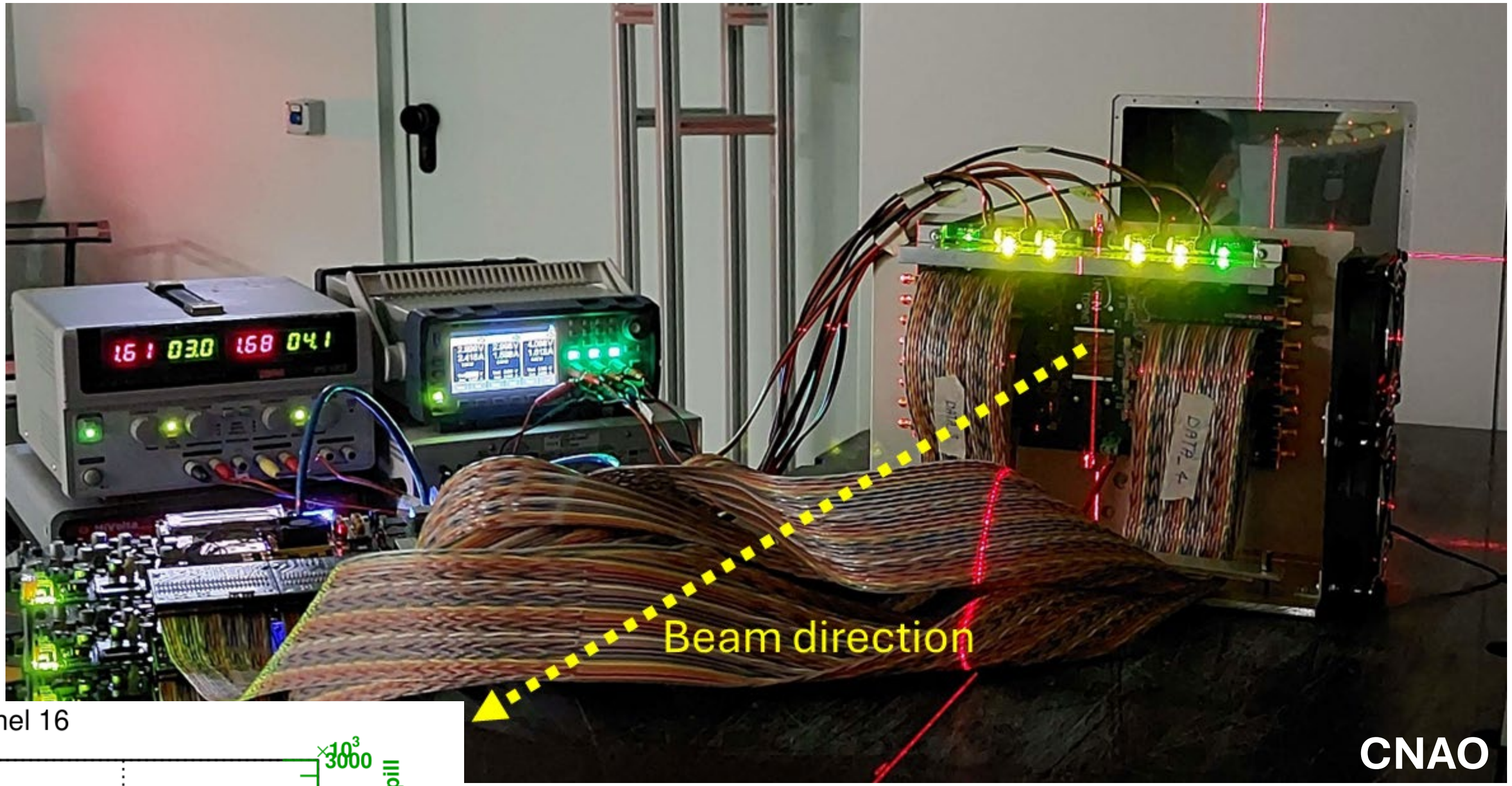


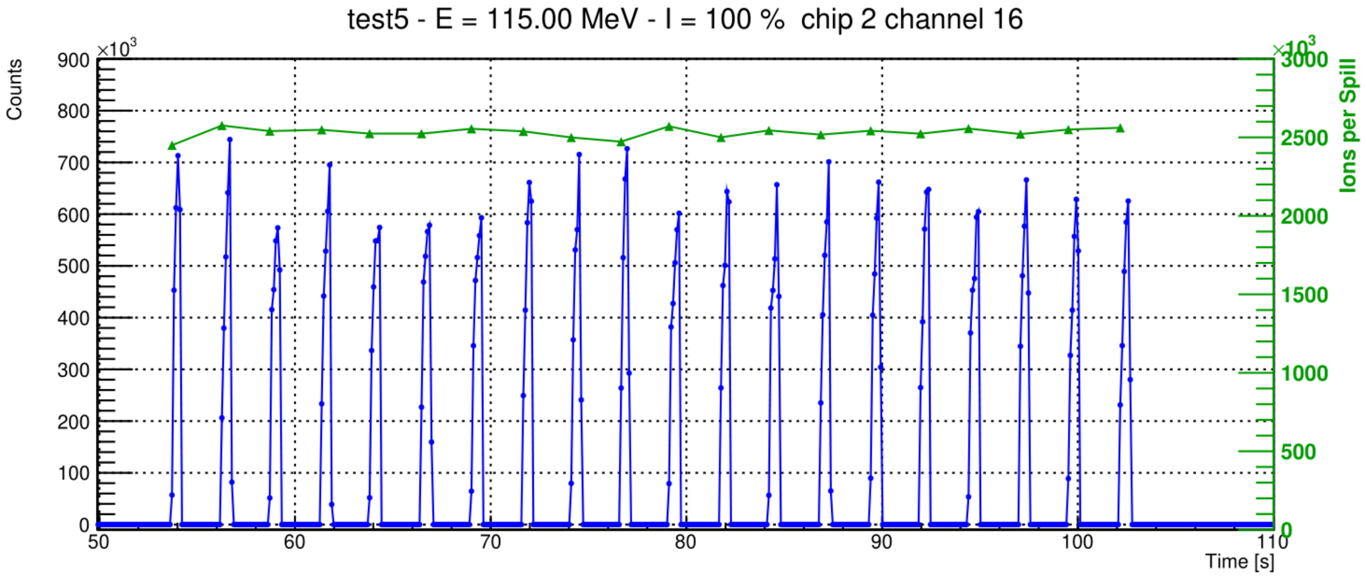
The ABACUS chip (x6)

110 nm CMOS technology, chip area = 2 × 5 mm^2, 24 channels, 144 in total. CSA dynamic range: 4 fC – 150 fC. Dead time : ~ 10 ns.

LGADS FOR BEAM MONITORING. PARTICLE COUNTING.

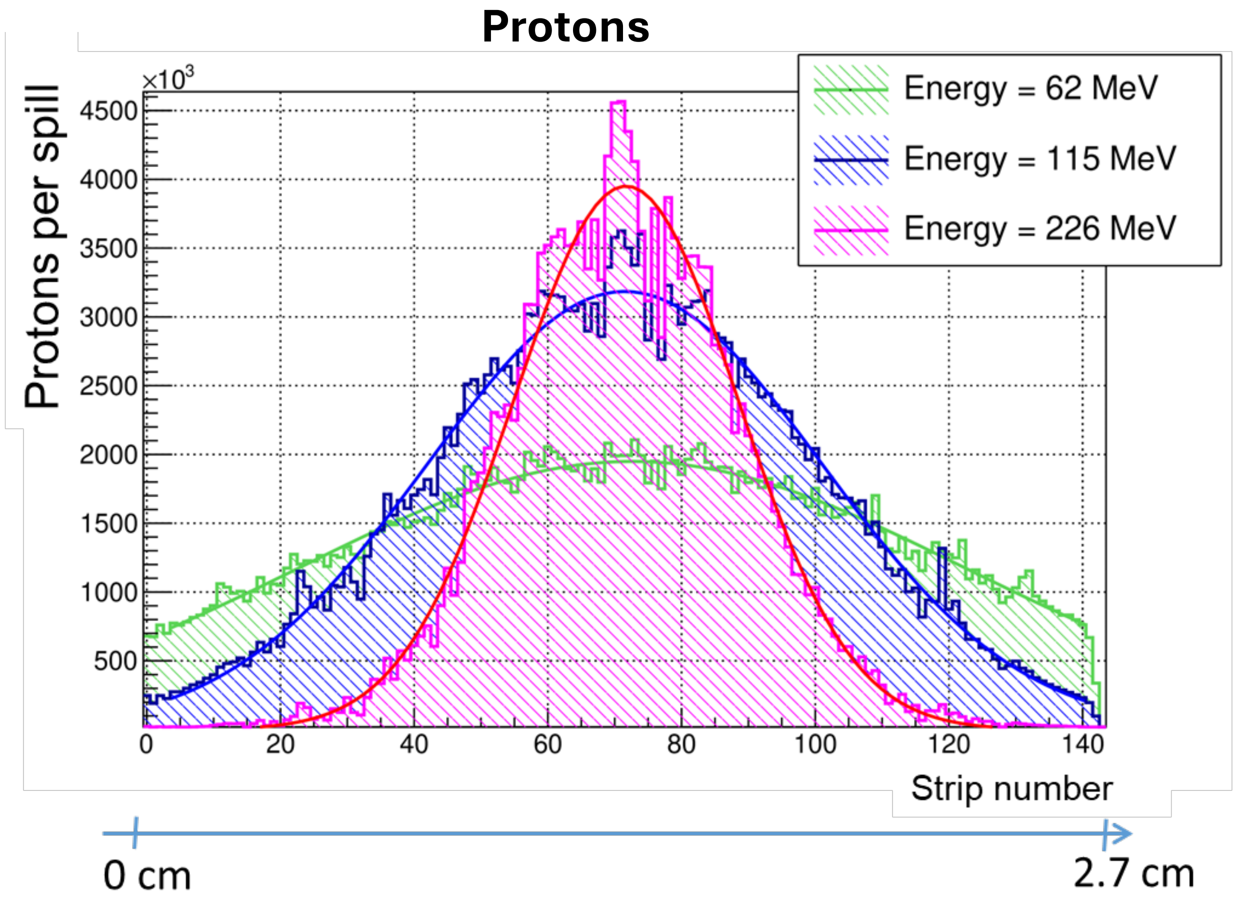
- Tested at CNAO
- ESA-ABACUS-1 (protons)
- ESA-ABACUS-2 (carbon ions)
- Energies: 60 - 230 MeV (protons) and 115 - 400 MeV/u (carbon ions)
- Beam rates: 20, 50, 100 % of the maximum fluence

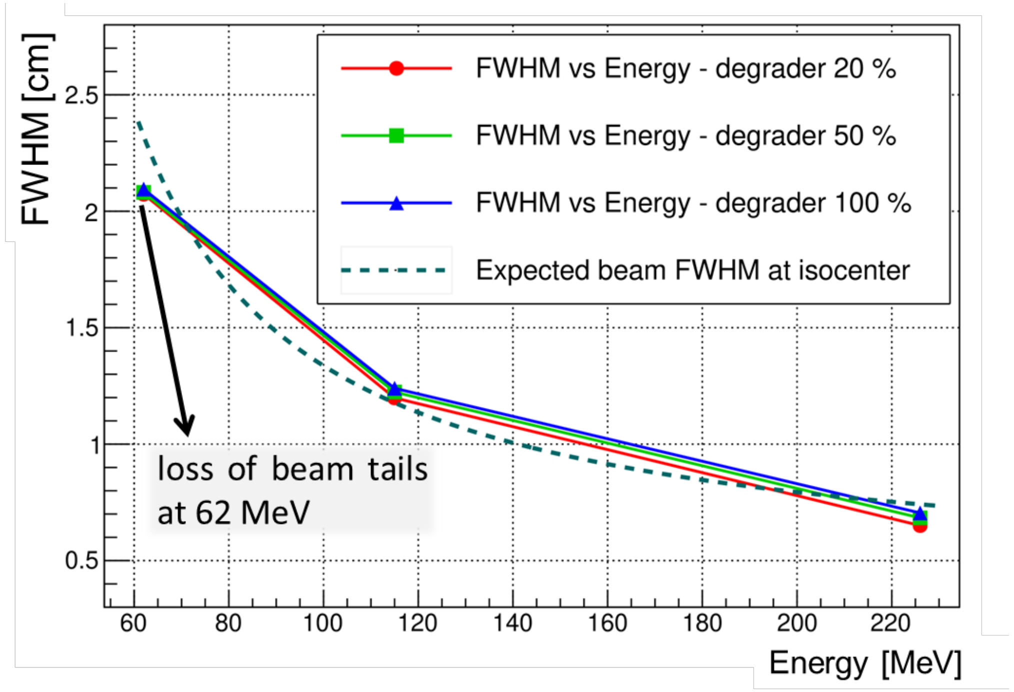


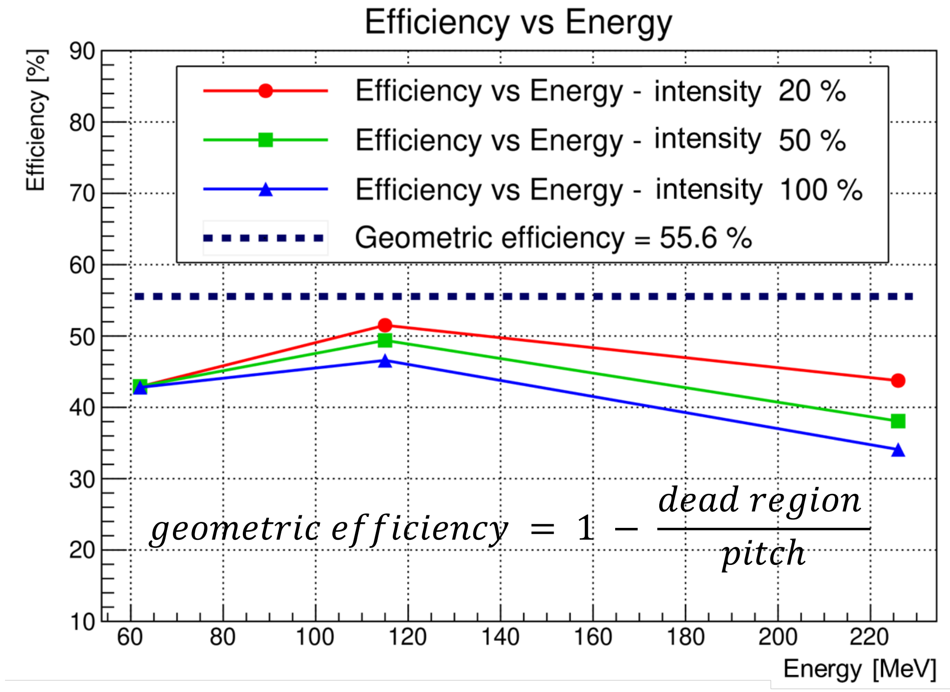


- Detected protons in one strip
- Total particles per spill
- Spill structure well observable

LGADS FOR BEAM MONITORING. PARTICLE COUNTING.

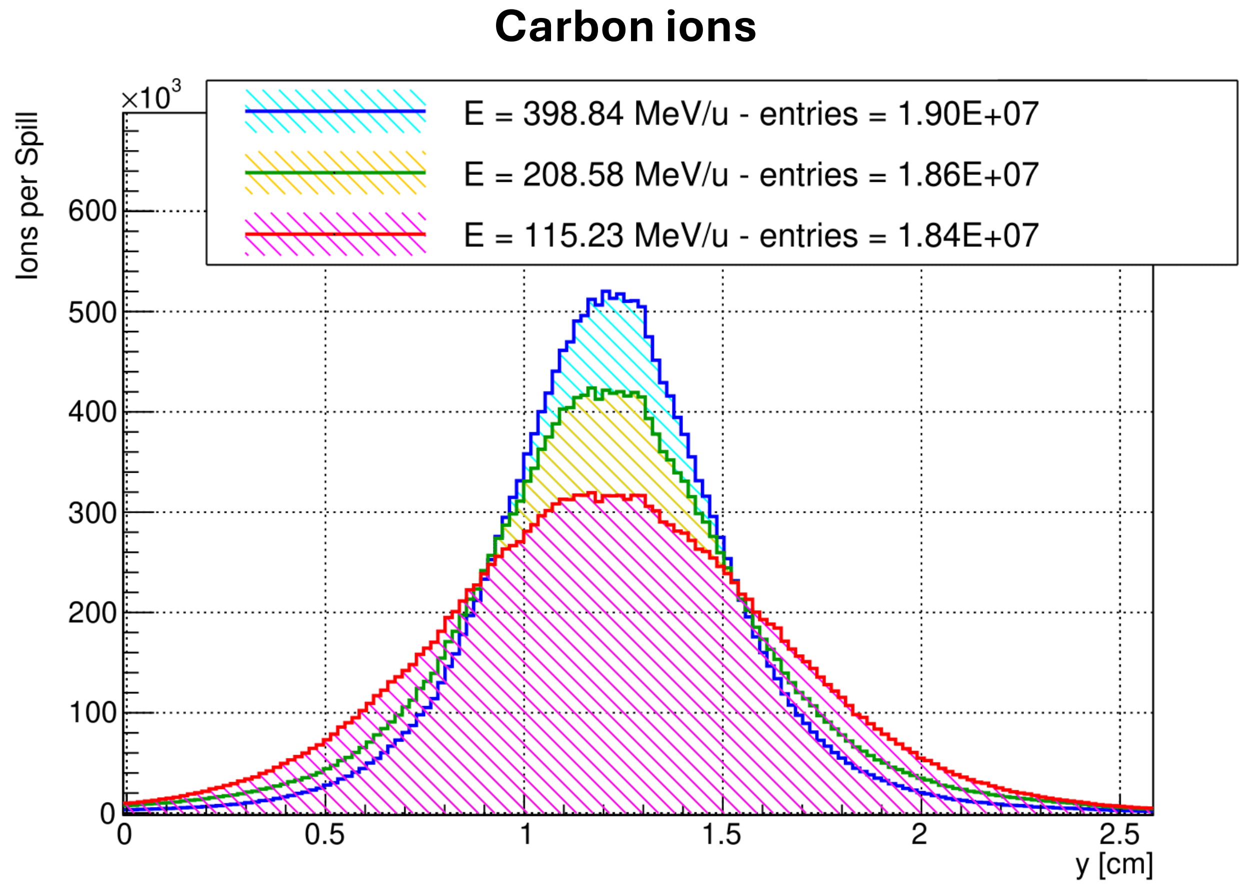


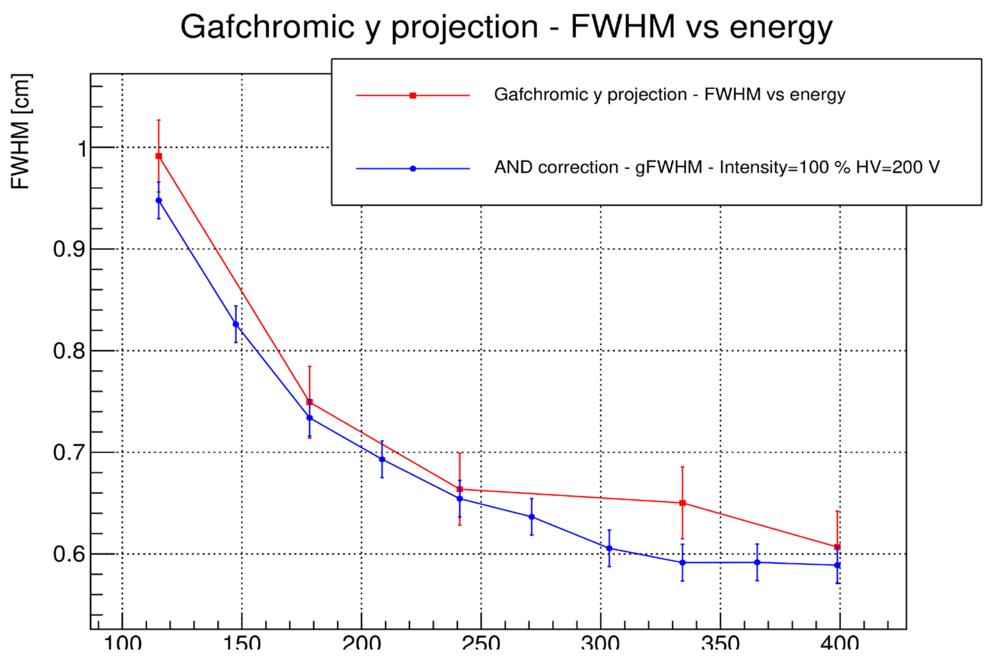


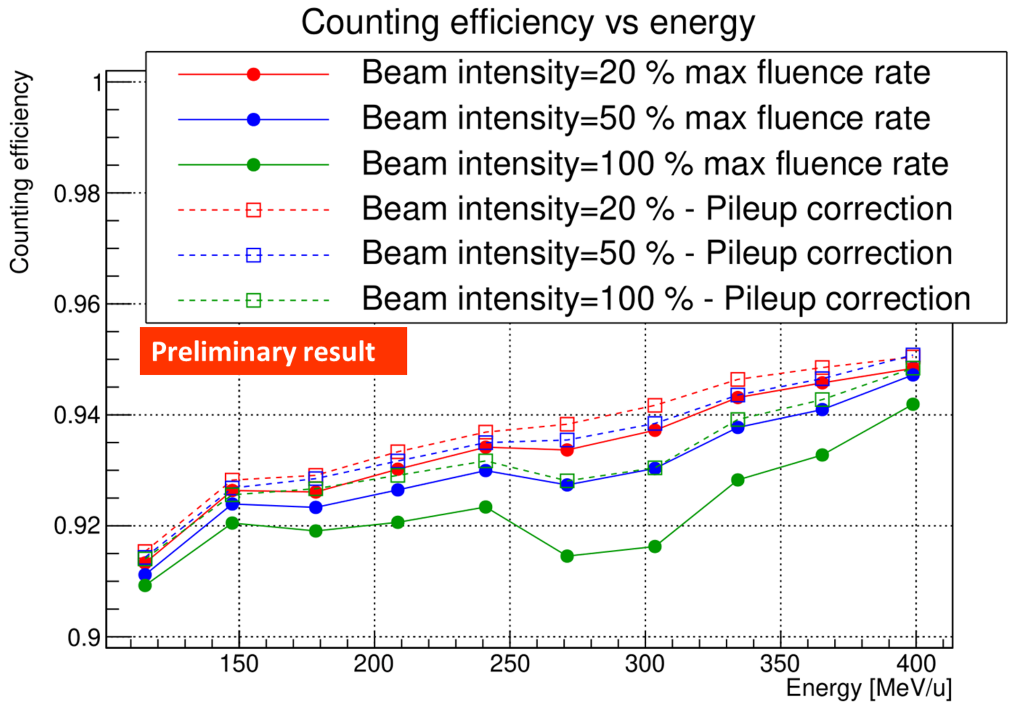


- Loss of protons in the tails for lower energies
- Signal superposition with noise for high energies
- Efficiency decreases because of pile-up in the beam center or high fluence.
- Correction for pile-up is necessary (10.1016/j.nima.2022.167195)

LGADS FOR BEAM MONITORING. PARTICLE COUNTING.



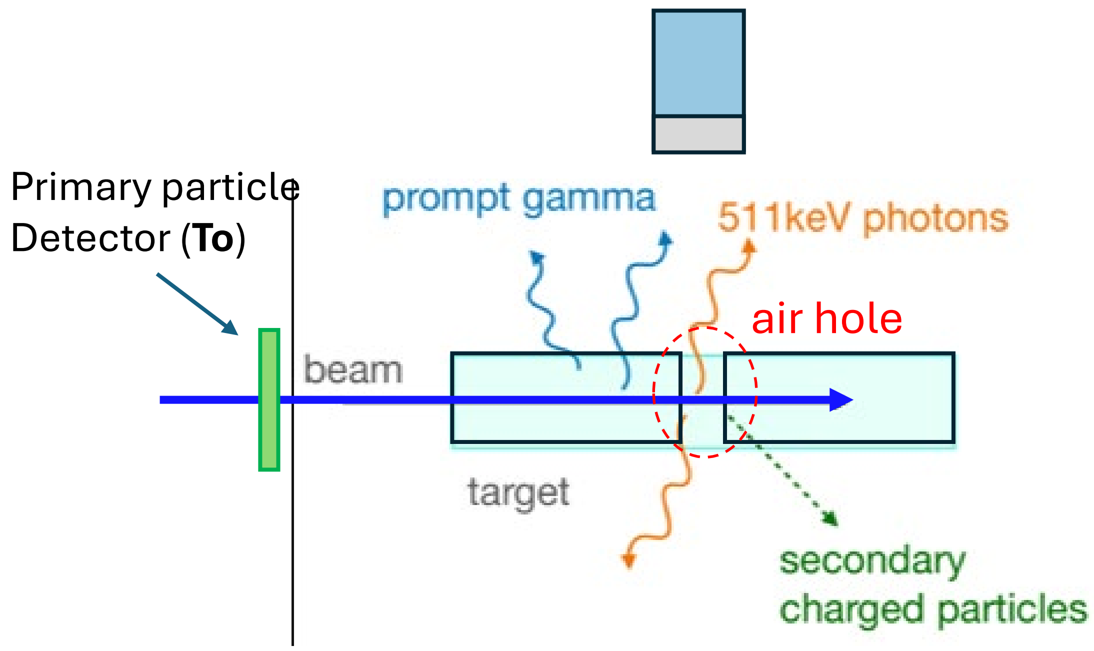




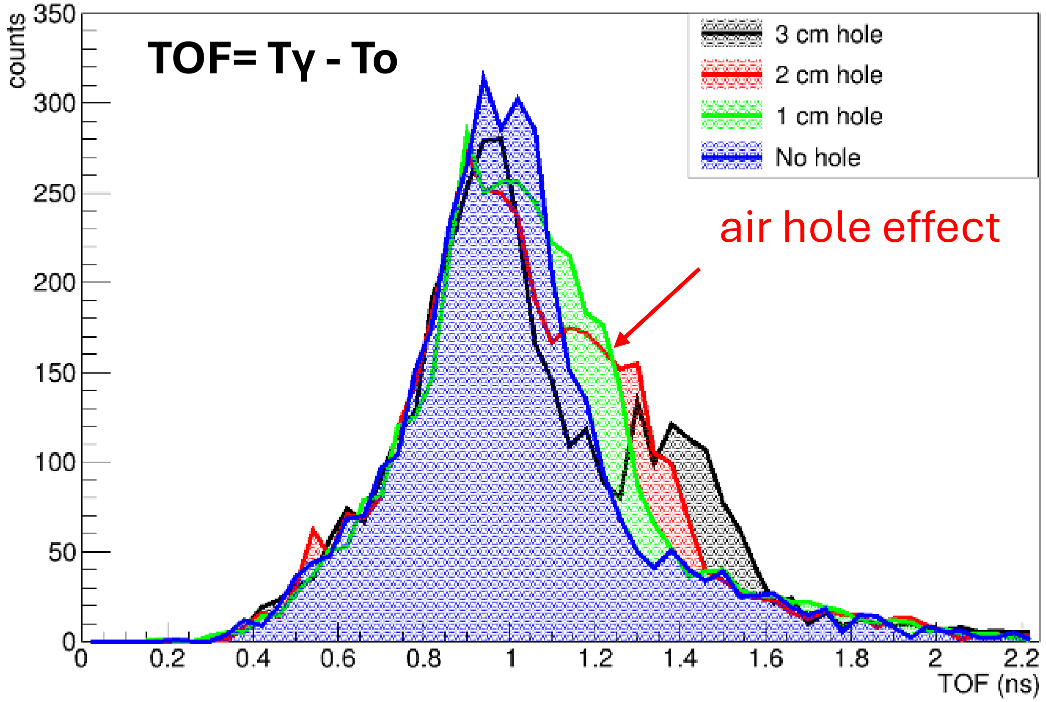
- Efficiency larger than 90 %
- No dead region between strips
- Charge sharing between strips under study
- Pile-up correction algorithm (10.1016/j.nima.2022.167195) based on the time duration of digital pulses, AND combinations between adjacent strips

RANGE VERIFICATION SYSTEM BASED ON PGT

- Used for the in vivo control of Hadrontherapy.
- Uses the correlation between primary charged particles and the emission of Prompt- gamma



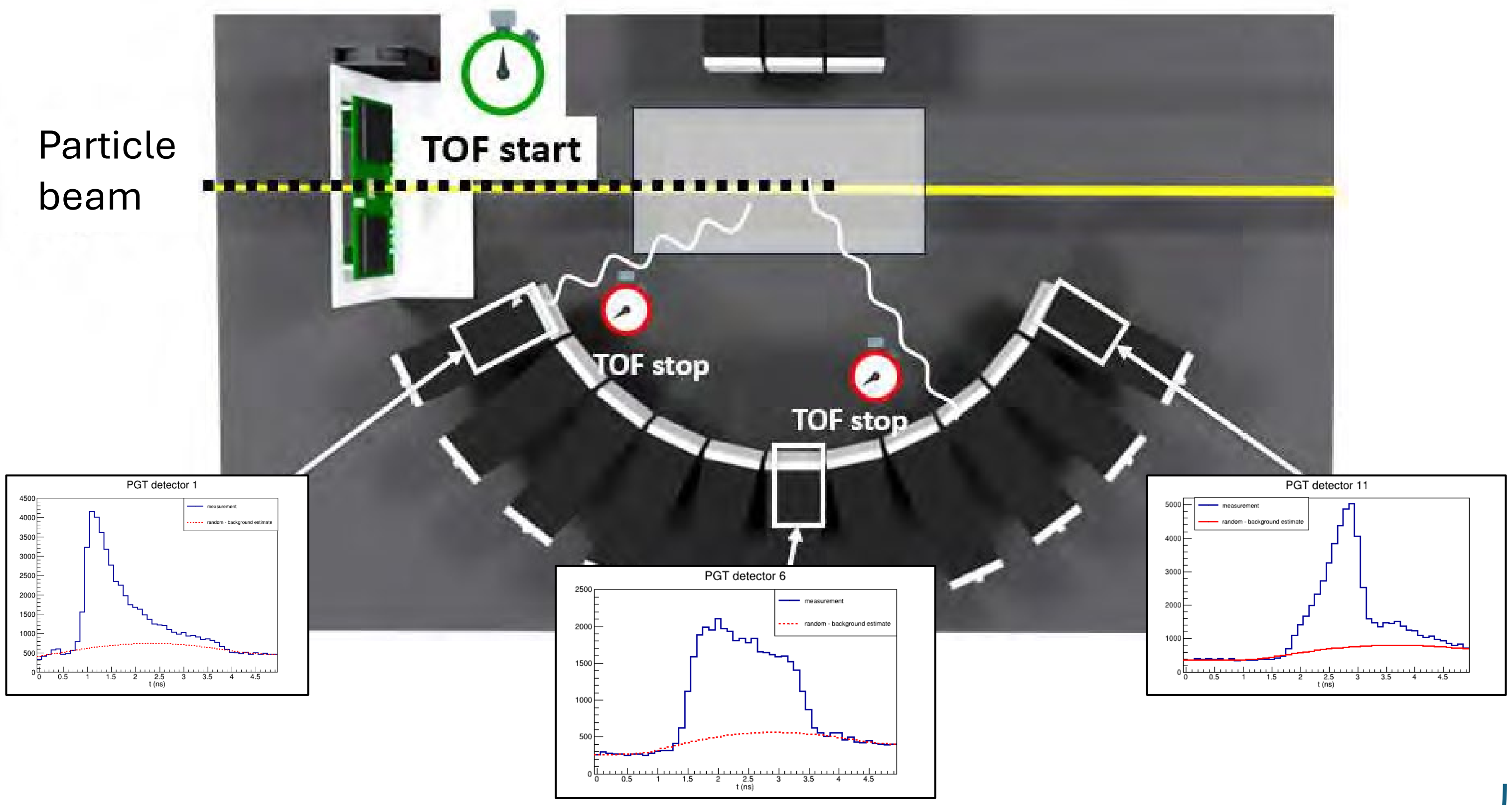
Fluka simulation of prompt gamma TOF



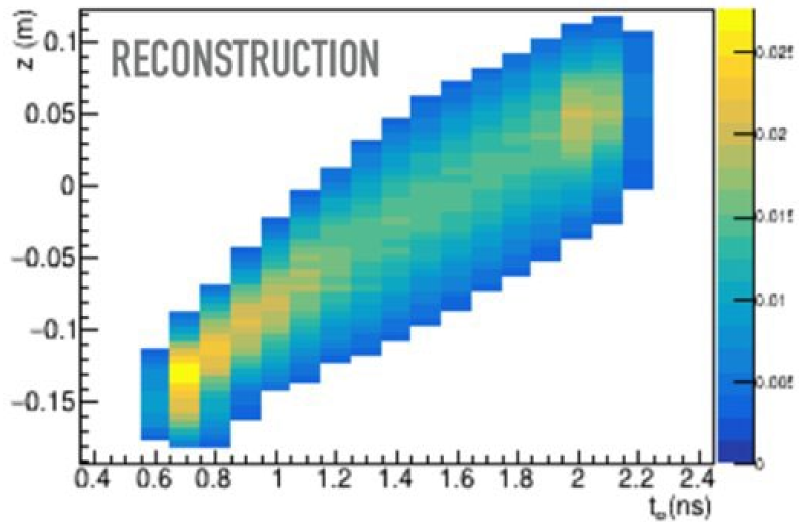
Courtesy of V. Ferrero

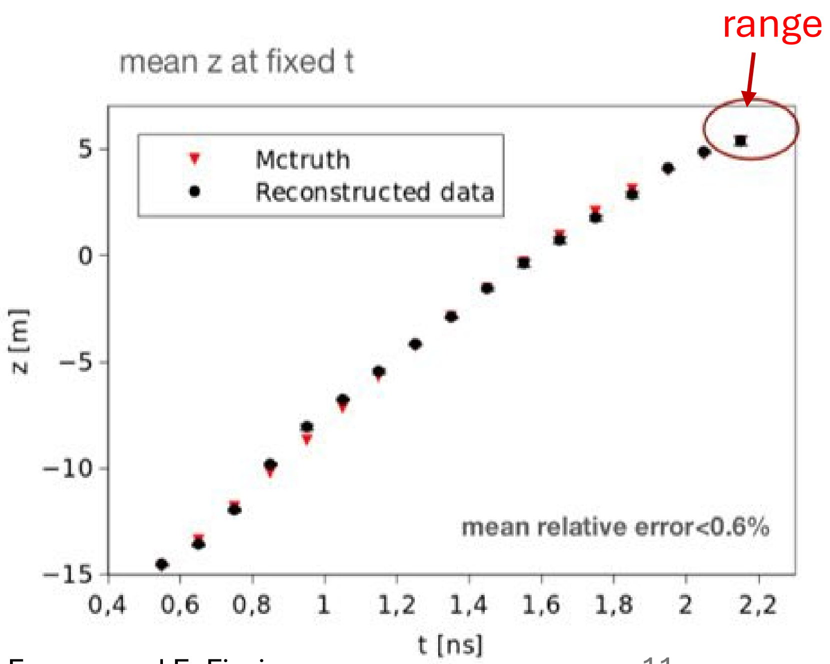
- PG emitted on sub-nanosecond timescale (allows in-beam and spill range verification)
- TOF spectrum depends on the particle beam path
- No collimator needed
- A secondary detector optimization for prompt gamma signals is mandatory (remove 511KeV signals)

RANGE VERIFICATION SYSTEM BASED ON PGT



Spatiotemporal Emission Reconstruction MLEM-based solution



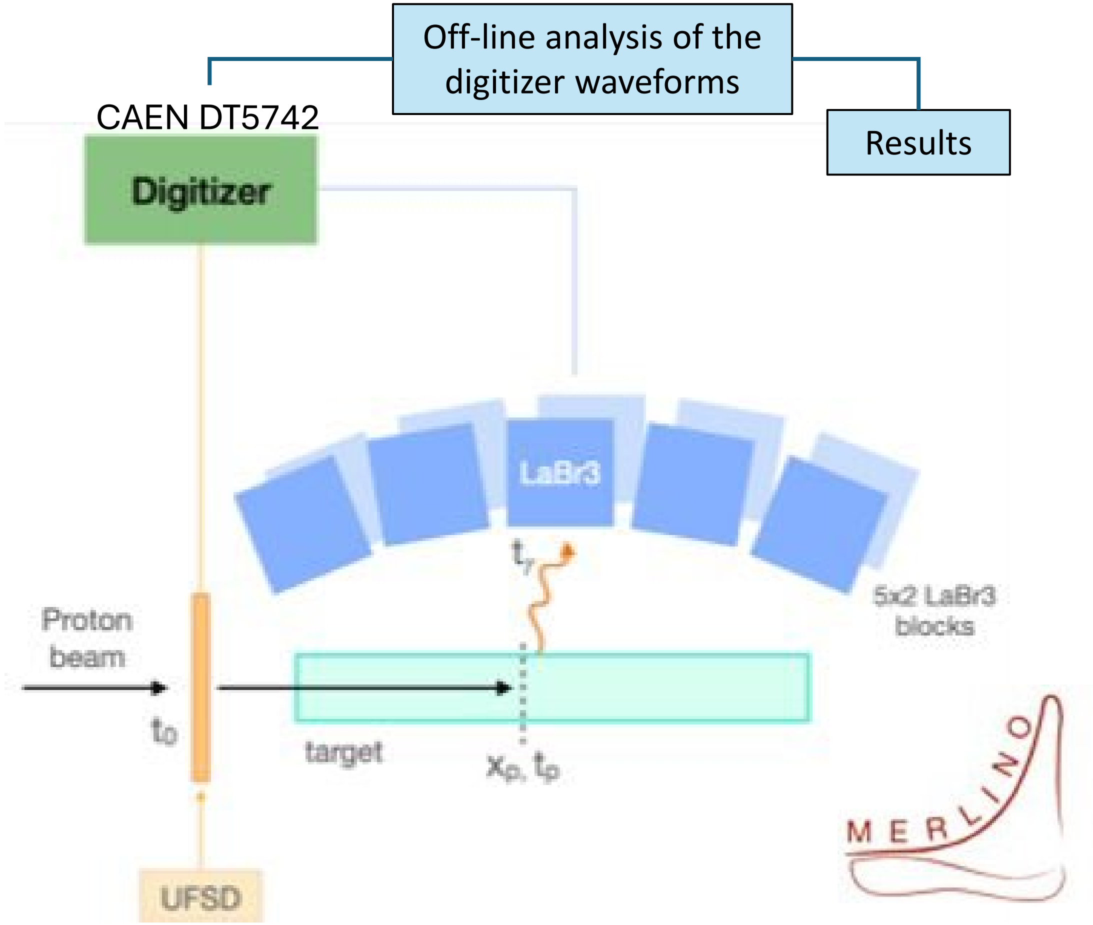


Pennazio, F, et al. "Proton therapy monitoring: Spatiotemporal emission reconstruction with prompt gamma timing and implementation with PET detectors." *PMB* 67.6 (2022): 065005.

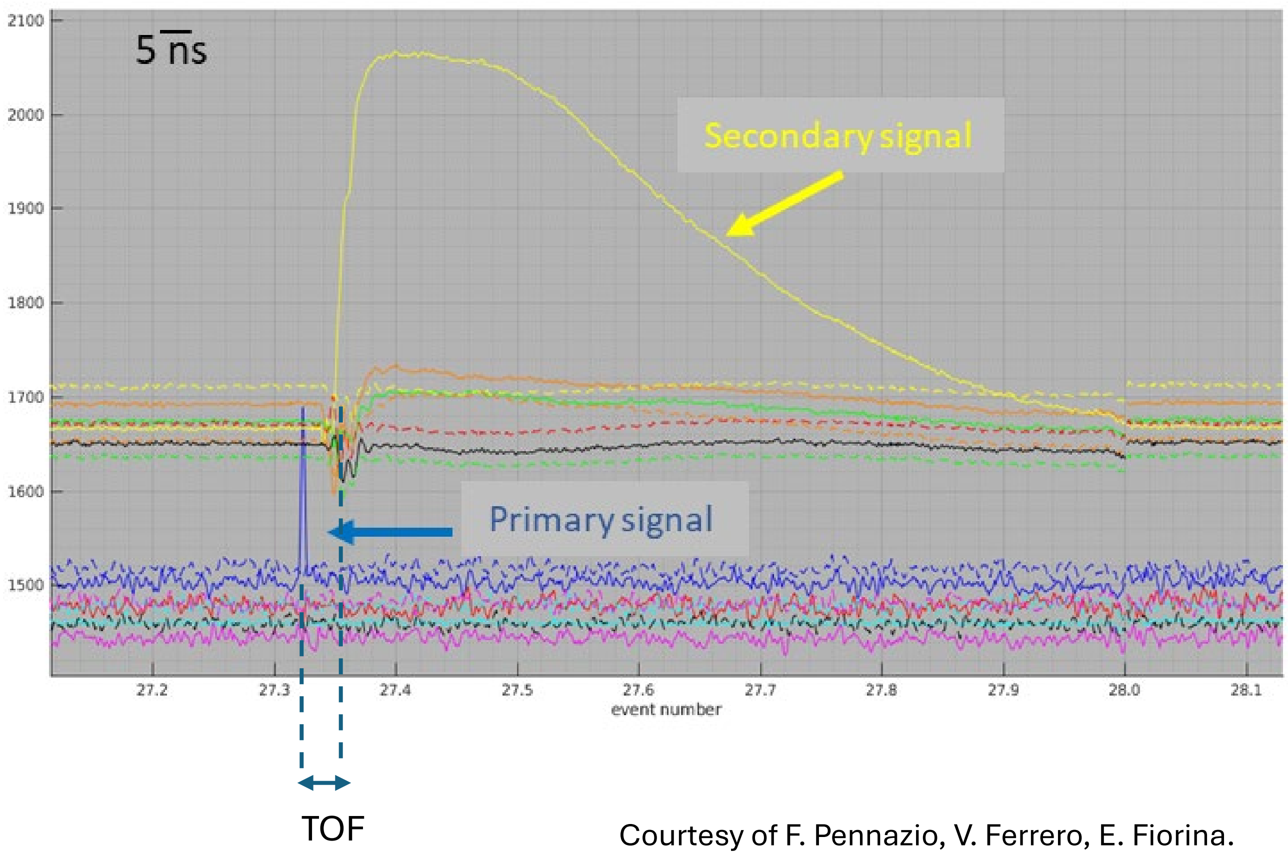
Courtesy of F. Pennazio, V. Ferrero and E. Fiorina.

RANGE VERIFICATION SYSTEM BASED ON PGT

- Proof of concept: MERLINO - Measurement of the EneRgy Loss for IN-vivo Optimization in proton therapy.



Example of digitizer waveforms

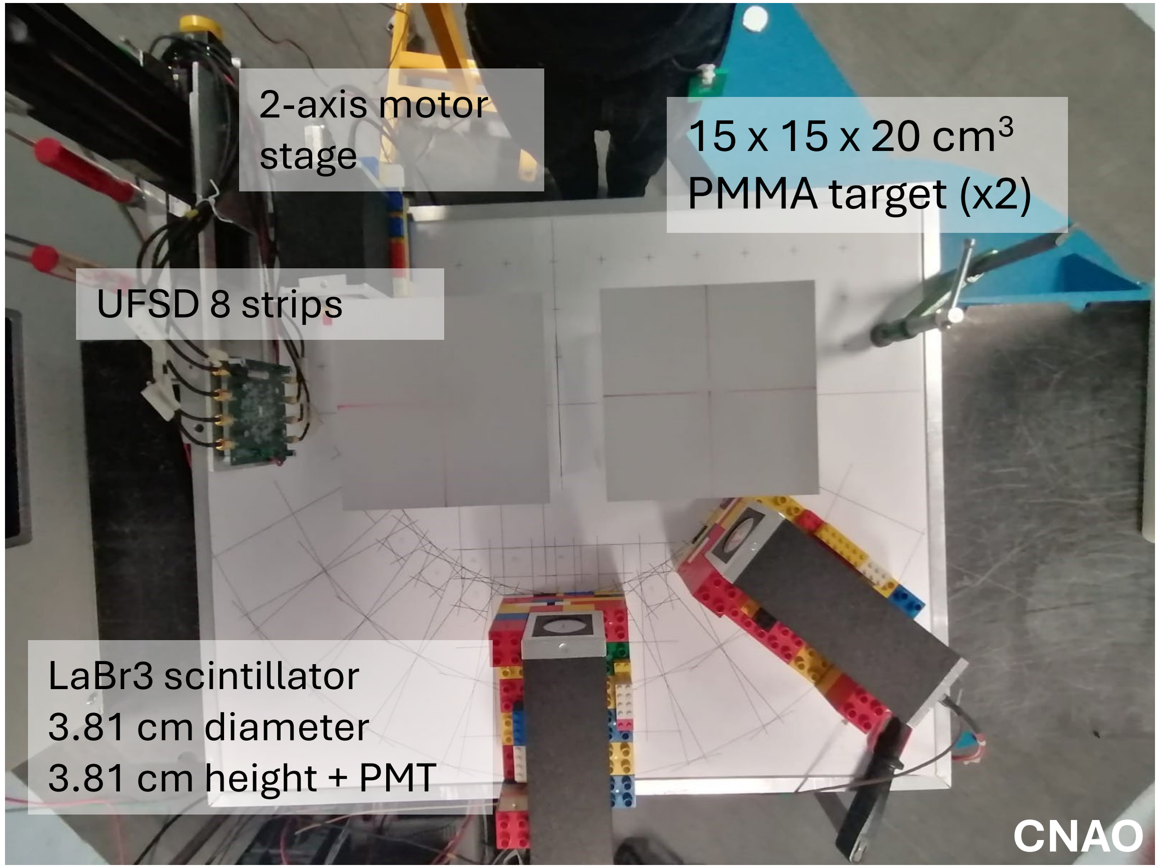


Courtesy of F. Pennazio, V. Ferrero, E. Fiorina.

RANGE VERIFICATION SYSTEM BASED ON PGT

- Proof of concept: MERLINO - Measurement of the EneRgy Loss for IN-vivo Optimization in proton therapy.

Experimental setup

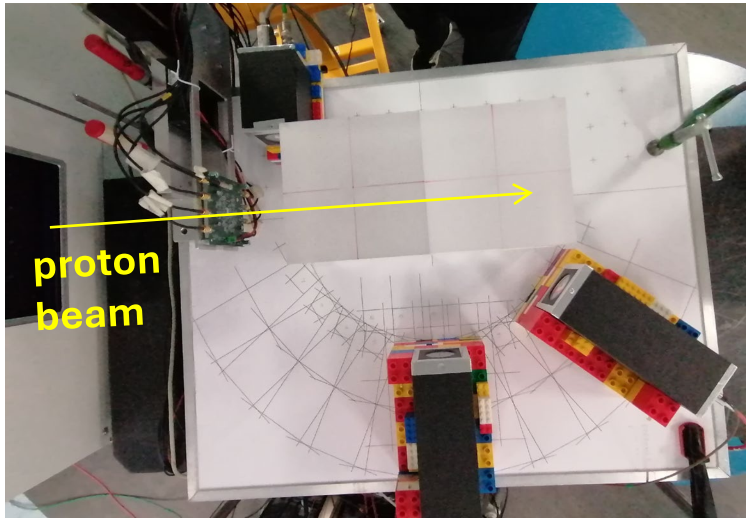


Courtesy of F. Pennazio, V. Ferrero, E. Fiorina.

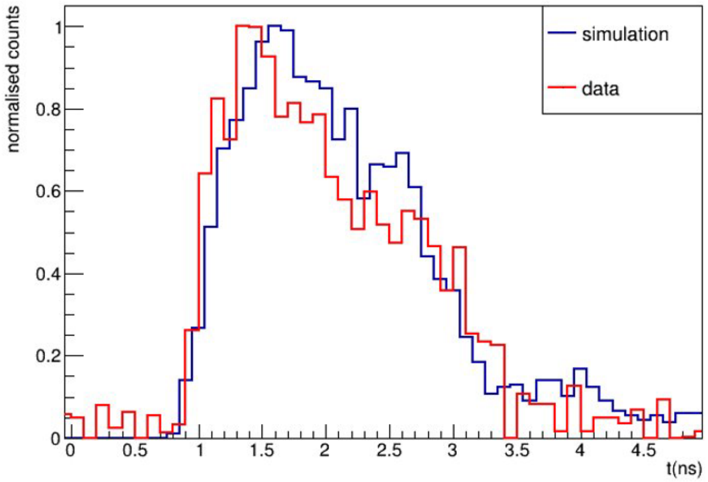
- UFSD 8 strips + digitizer 2.5GHz
- 227MeV proton beam in the sub-clinical range (average rate 10^7 pps)
- Comparison of measurements from two setups:
    - Homogenous PMMA
    - 4cm air cavity

RANGE VERIFICATION SYSTEM BASED ON PGT

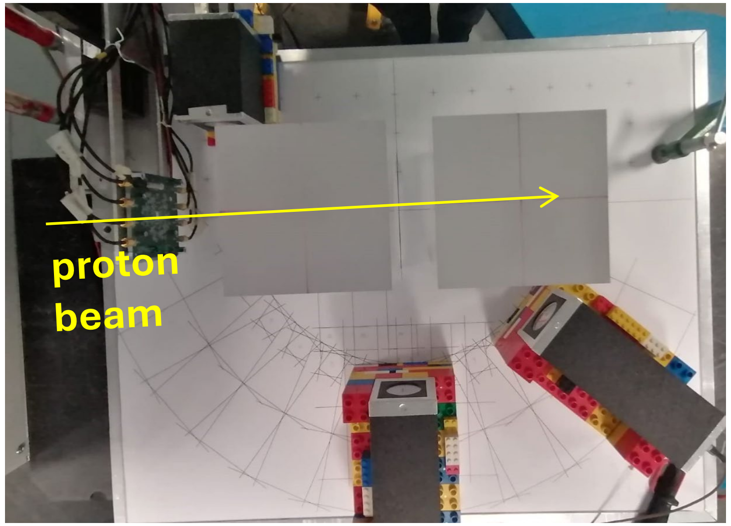
Homogeneous PMMA



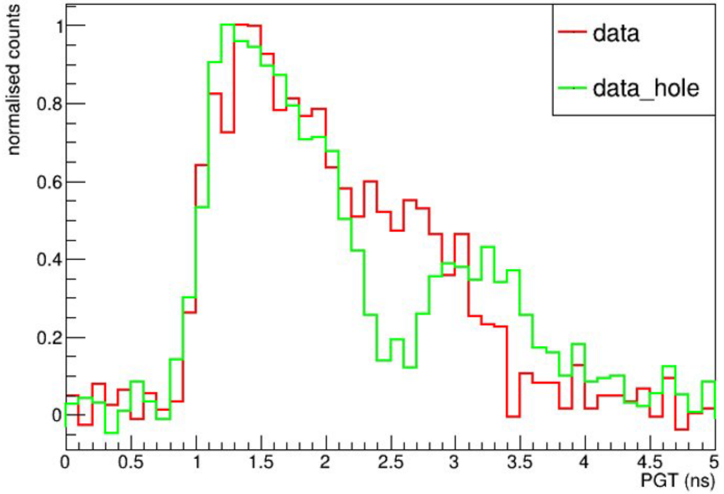
PGT TOF distribution



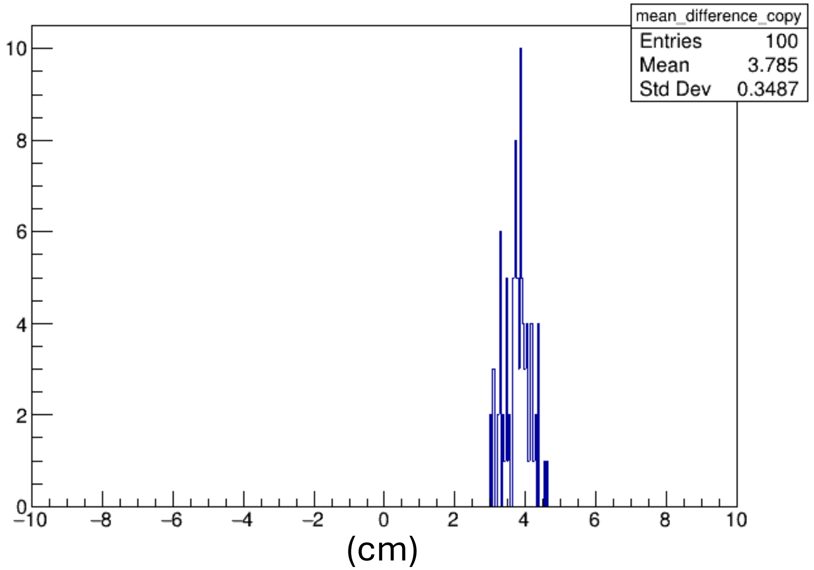
Target with a 4 cm air cavity



PGT TOF distribution



Proton range difference



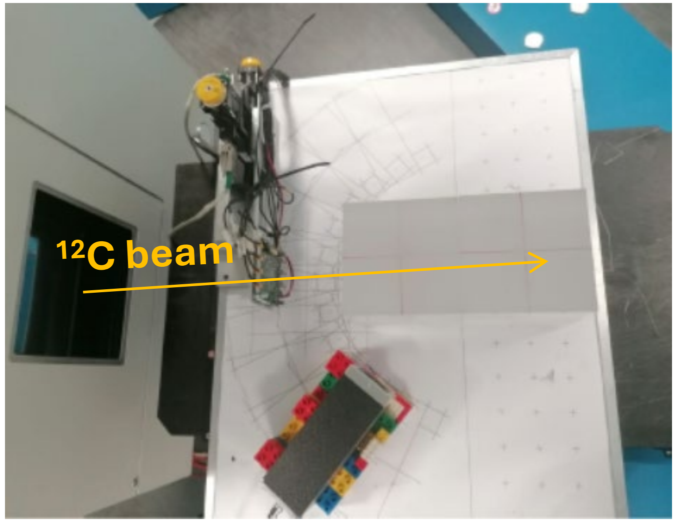
Result: 3.8 ± 0.3 cm, no outliers
Expected value: 4.0 cm

Courtesy of F. Pennazio, V. Ferrero, E. Fiorina.

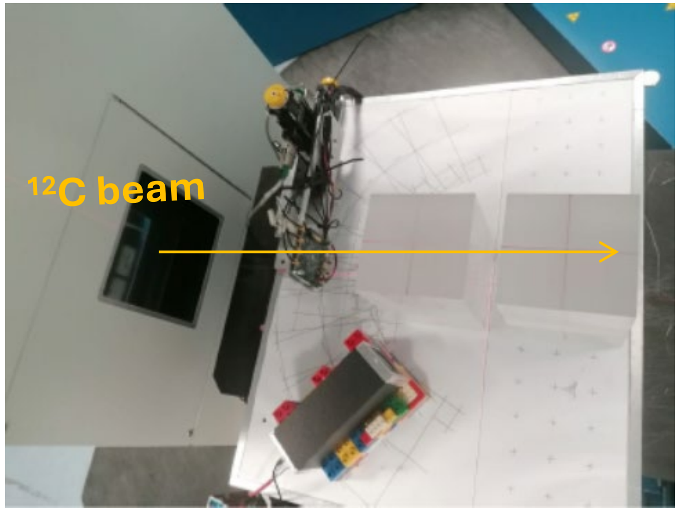
RANGE VERIFICATION SYSTEM BASED ON PGT

- Measurement with Carbon ion beams 398 MeV/u, sub-clinical rate

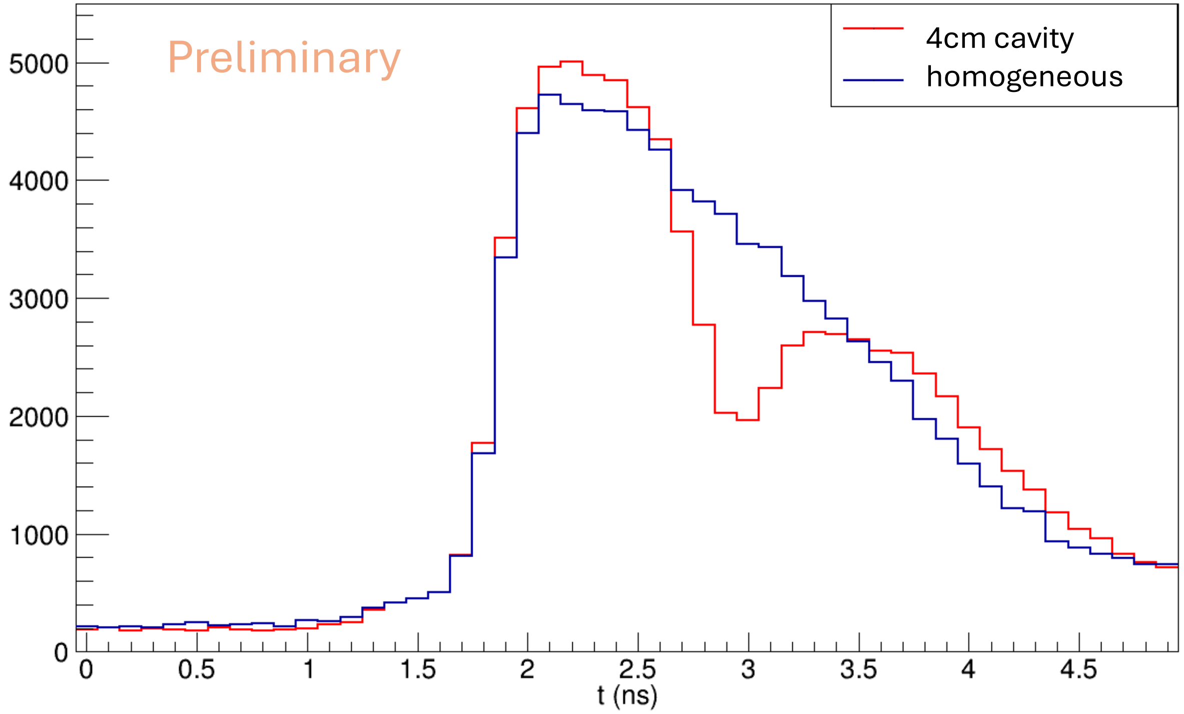
Homogeneous PMMA



Target with a 4 cm air cavity

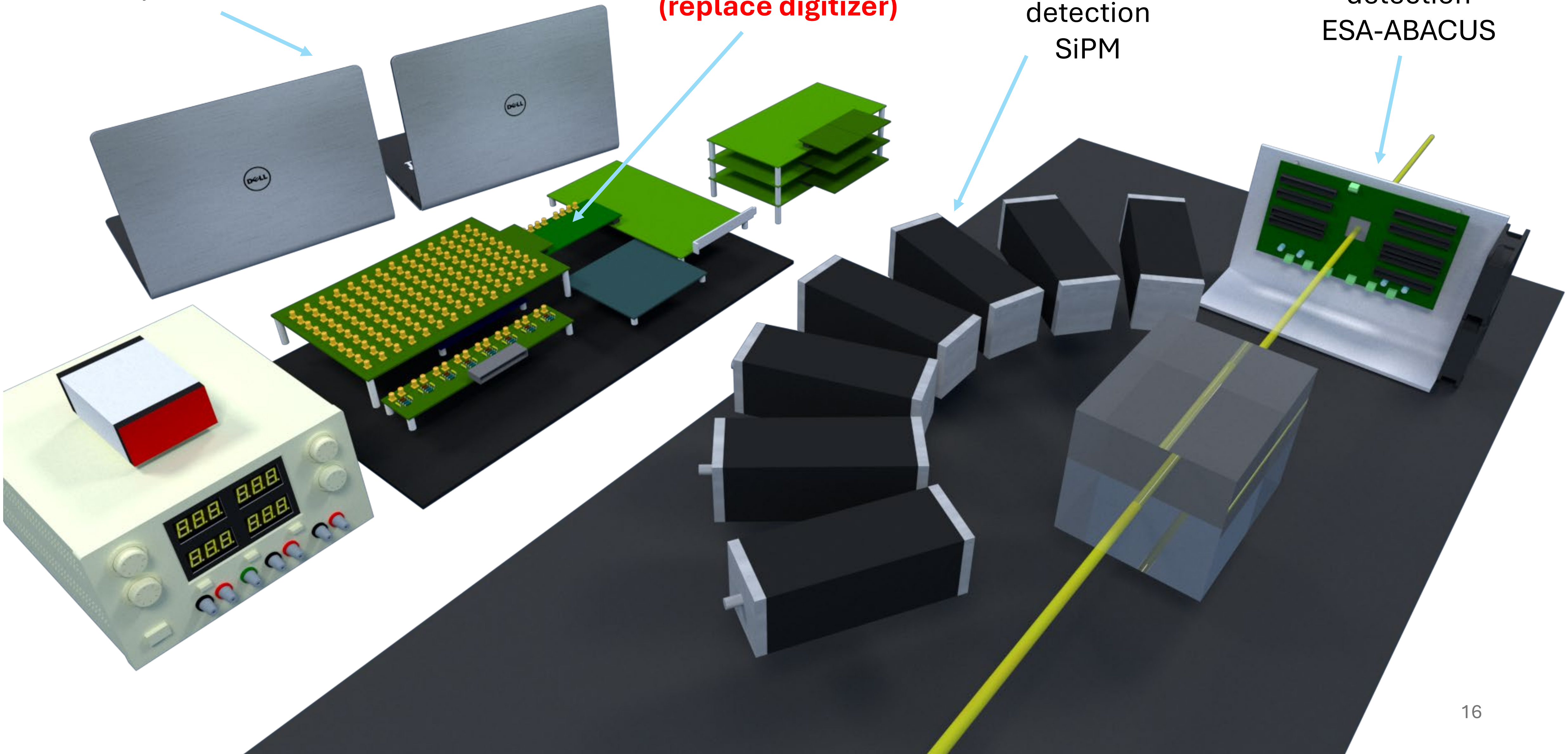


PGT TOF distribution



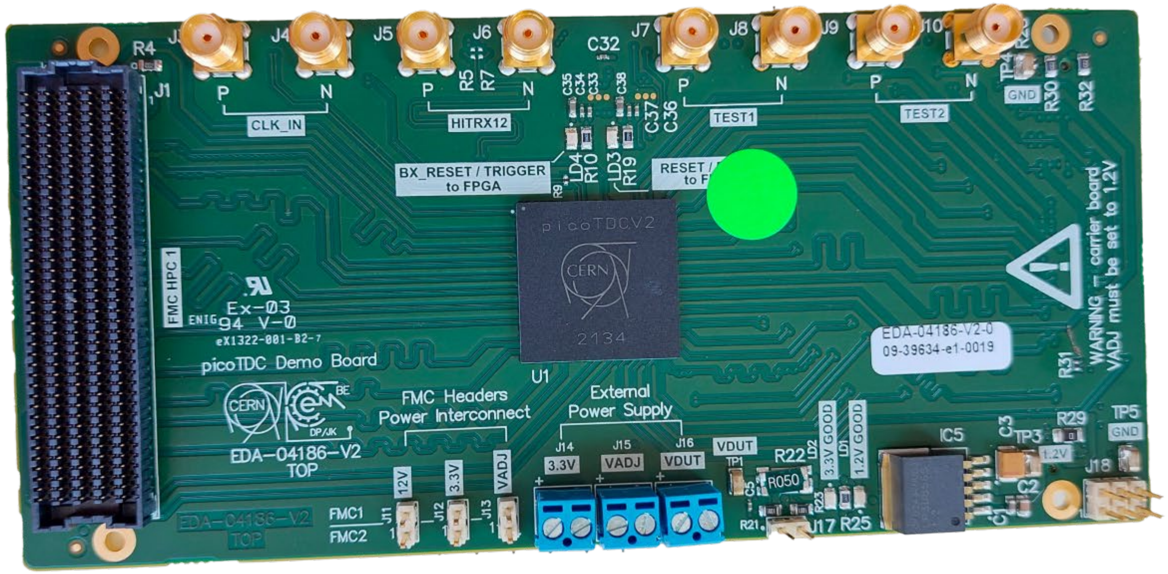
Courtesy of F. Pennazio, V. Ferrero, E. Fiorina.

PARTICLE TRACKING INTEGRATION WITH THE RANGE VERIFICATION SYSTEMS



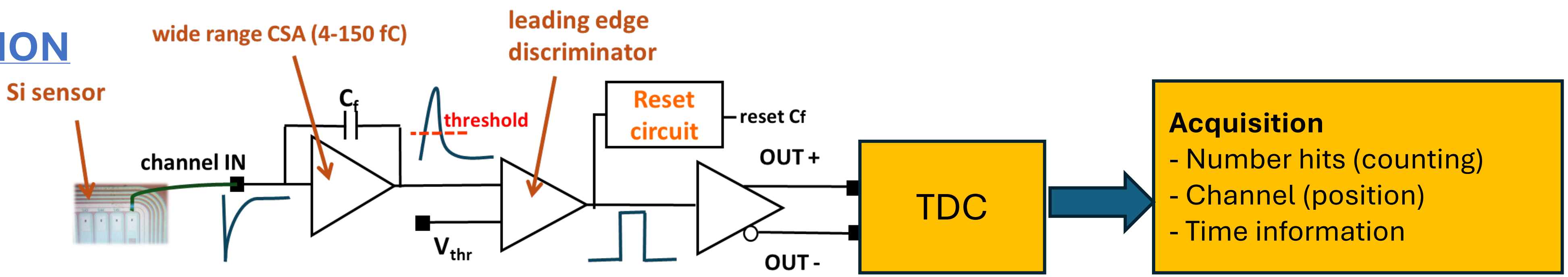
PICOTDC INTEGRATION FOR PRIMARIES

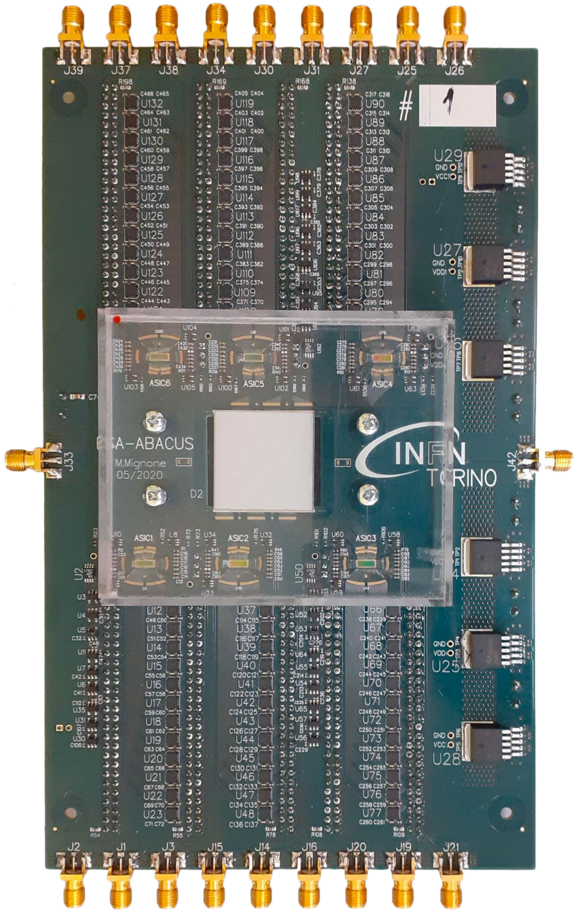
PicoTDC Demo board developed at CERN:



- Time of arrival and Time over Threshold (TOT)
- based on Delay Locked Loop with 64 delay elements
- Bin size = 3.05 ps (40.0 MHz clock)
- Dynamic range = 205 µs
- 64 channels
- LVDS18 input signals
- Acquisitions mode
  - Streaming
  - Triggered

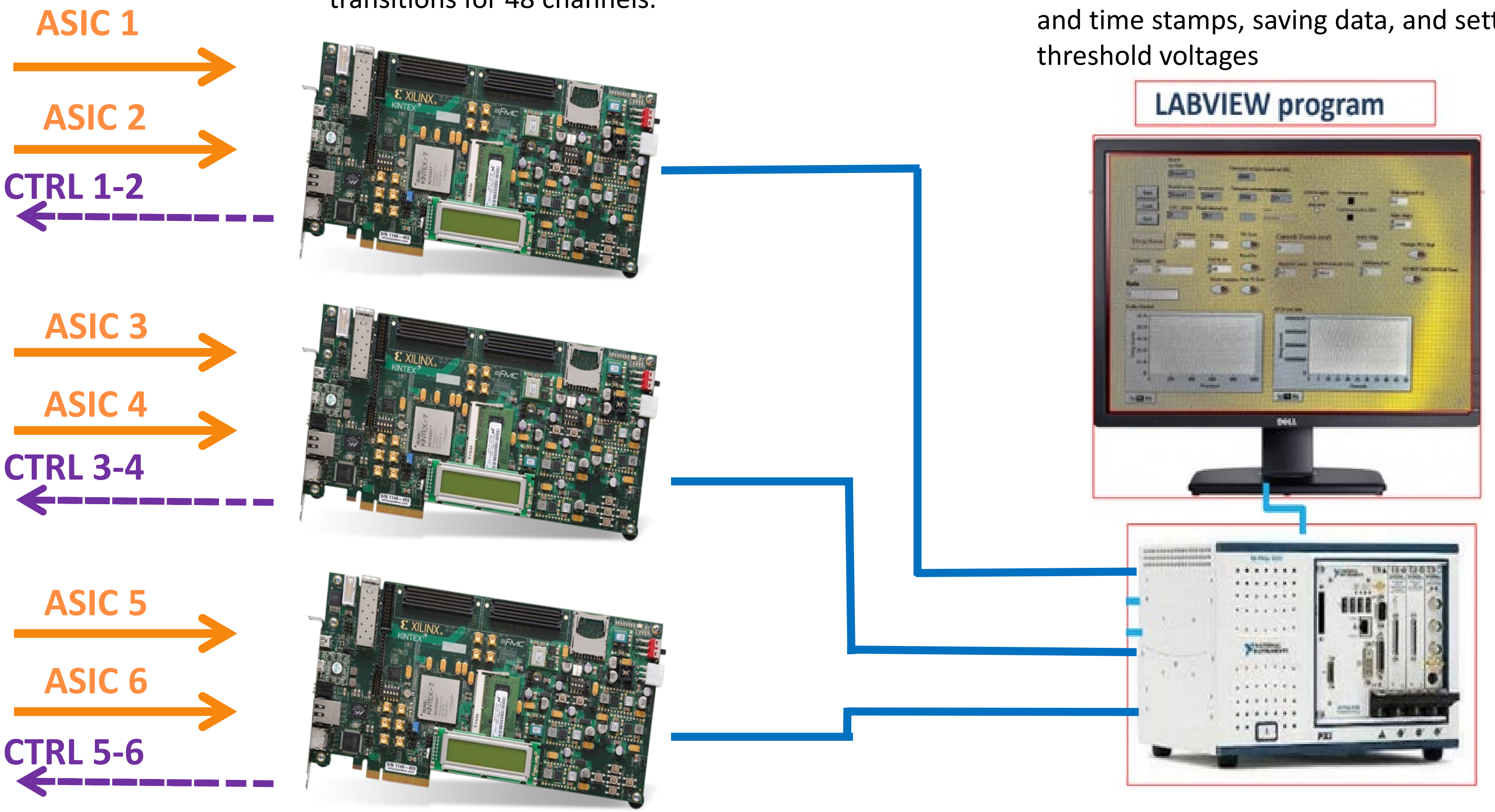
PICOTDC INTEGRATION FOR PRIMARIES





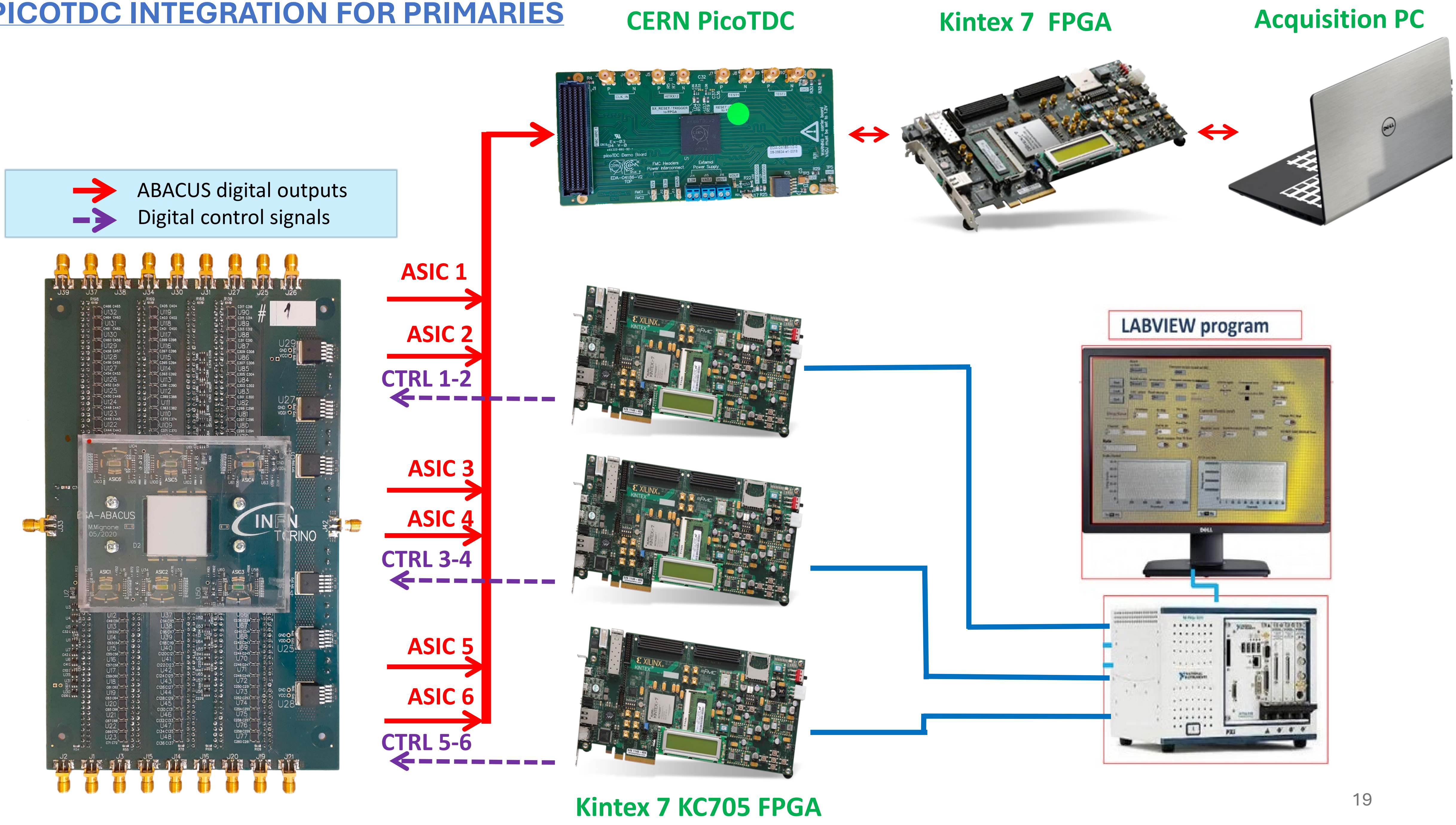
FPGA boards to count 0-1 transitions for 48 channels.

LabVIEW program for reading counters and time stamps, saving data, and setting threshold voltages

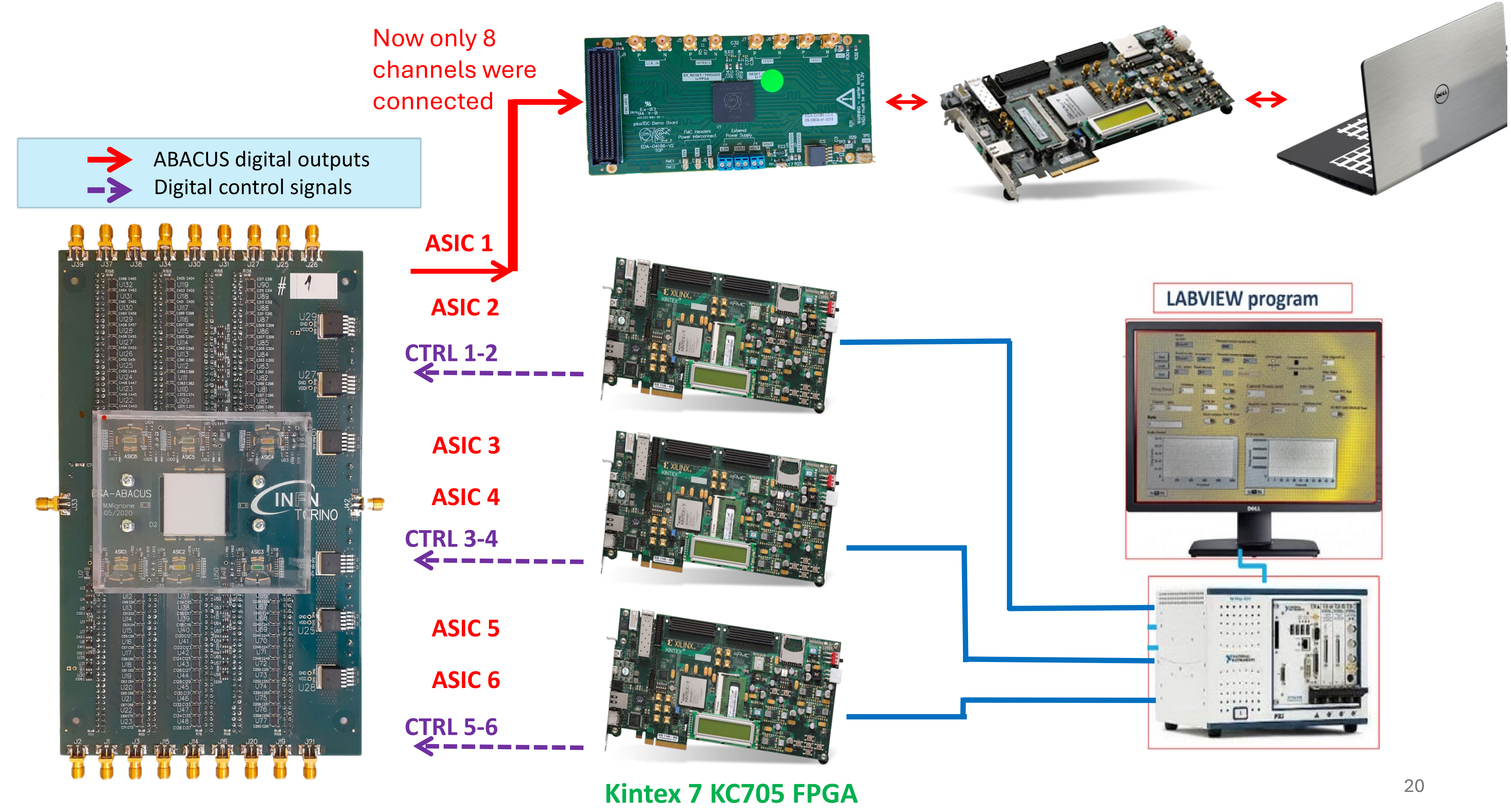


Kintex 7 KC705 FPGA

PICOTDC INTEGRATION FOR PRIMARIES



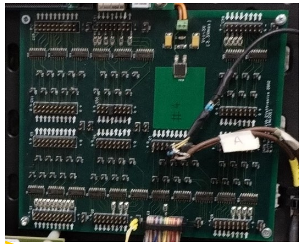
PICOTDC INTEGRATION FOR PRIMARIES

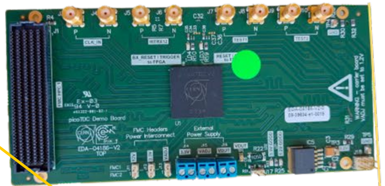


PICOTDC INTEGRATION FOR PRIMARIES

- We were advised not to use LVDS signals with a common mode of 1.25V (LVDS25). A translation level board was constructed to bring it down to 0.9V (LVDS18).
- 8 channels from ESA-ABACUS were connected to PicoTDC Ch0-Ch7.
- Triggered by TTL signals converted into LVDS25 later down to LVDS18.
- PicoTDC Ch8, Ch9, Ch10 used for secondary TTL signals acquisition.

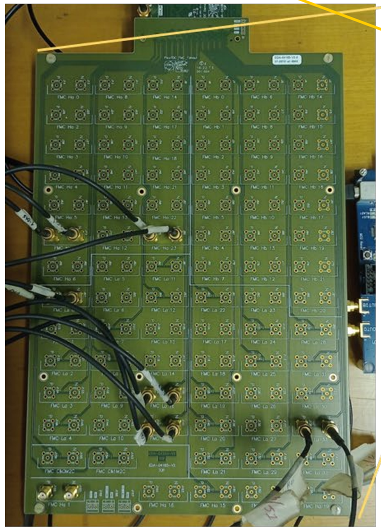
TTL to LVDS
(for secondaries signals)

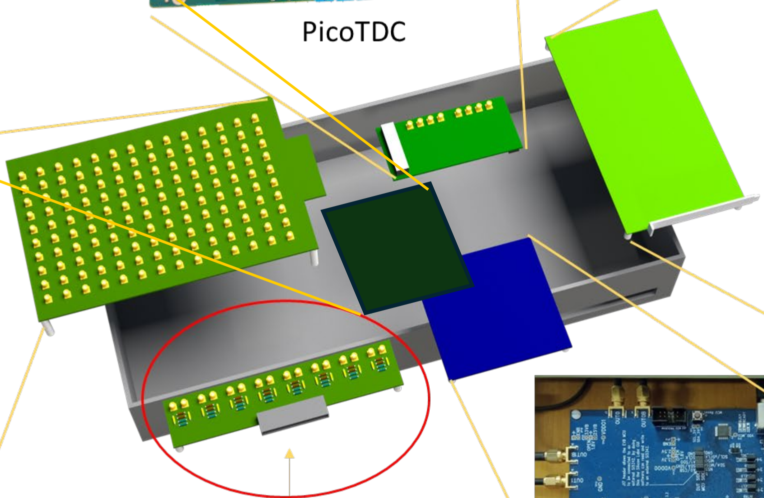




PicoTDC

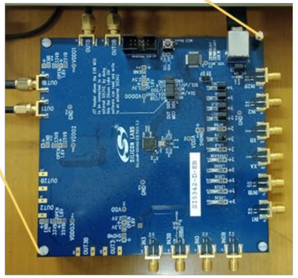
Fan in board



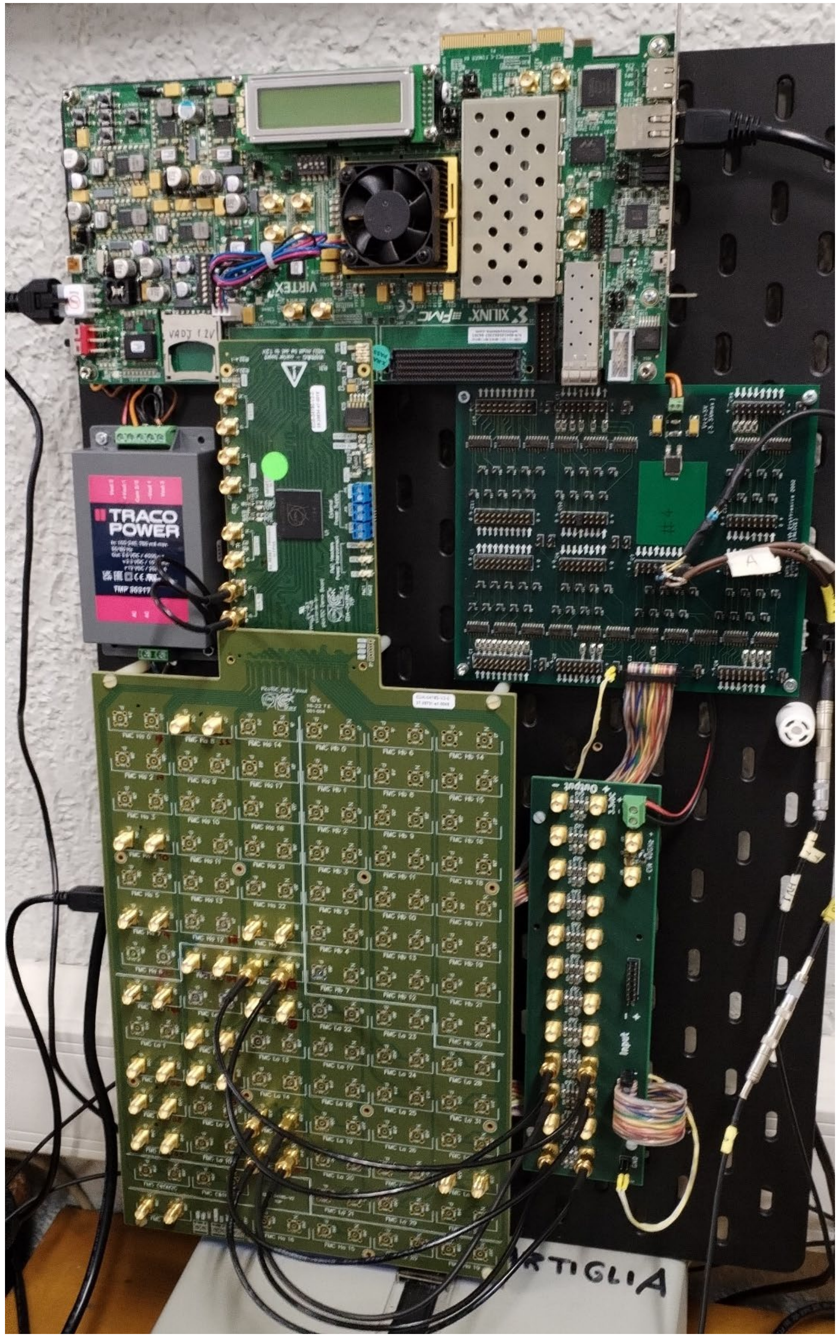


12 ch. level translator board
(reduce common mode from
1.25V to 0.8V.

FPGA VIRTEX7



40MHz clock board



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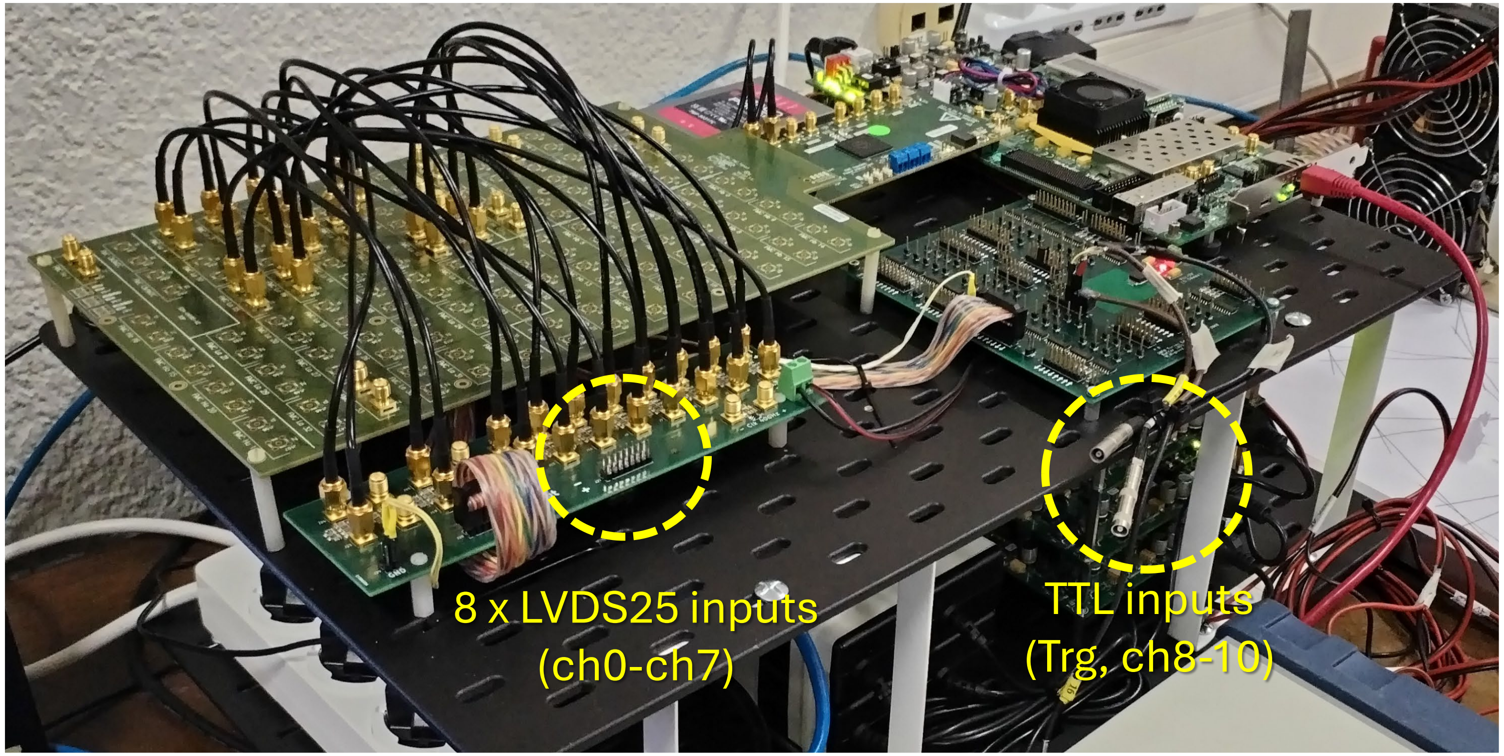
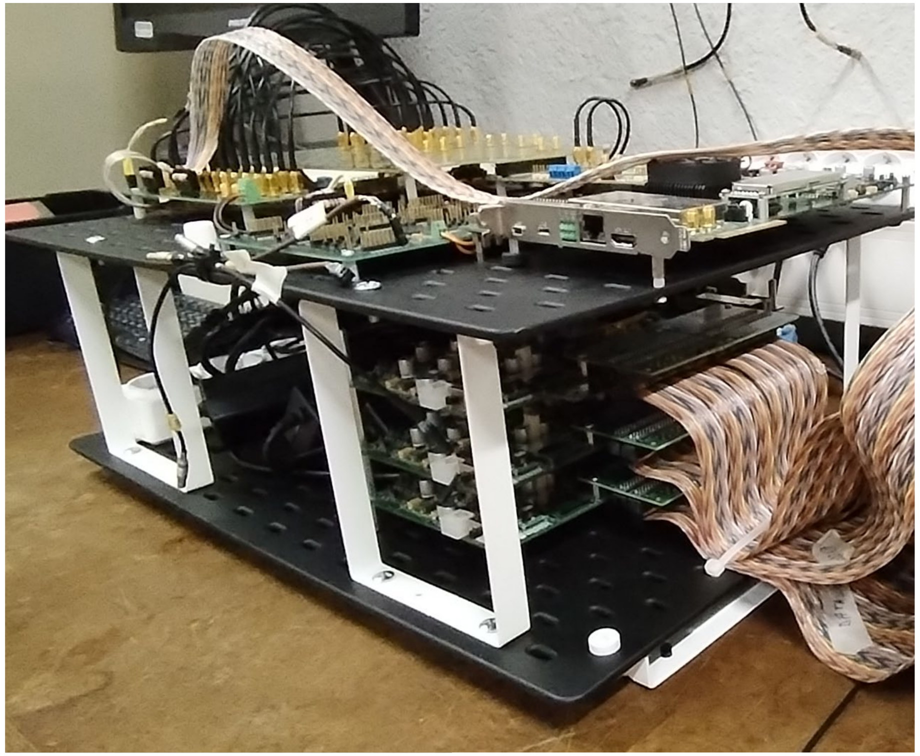
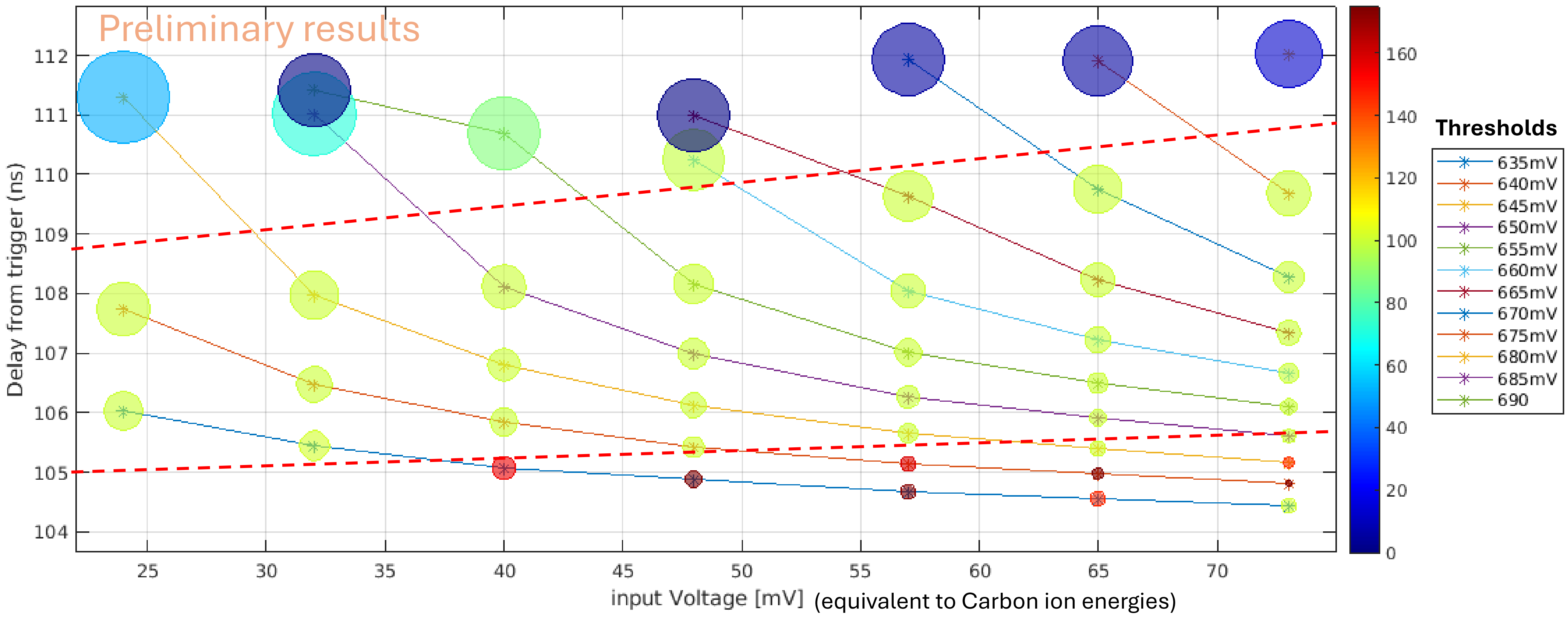


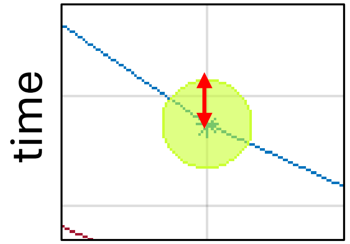


LABORATORY TEST FOR PRIMARIES

Study of the ESA-ABACUS time-walk effect

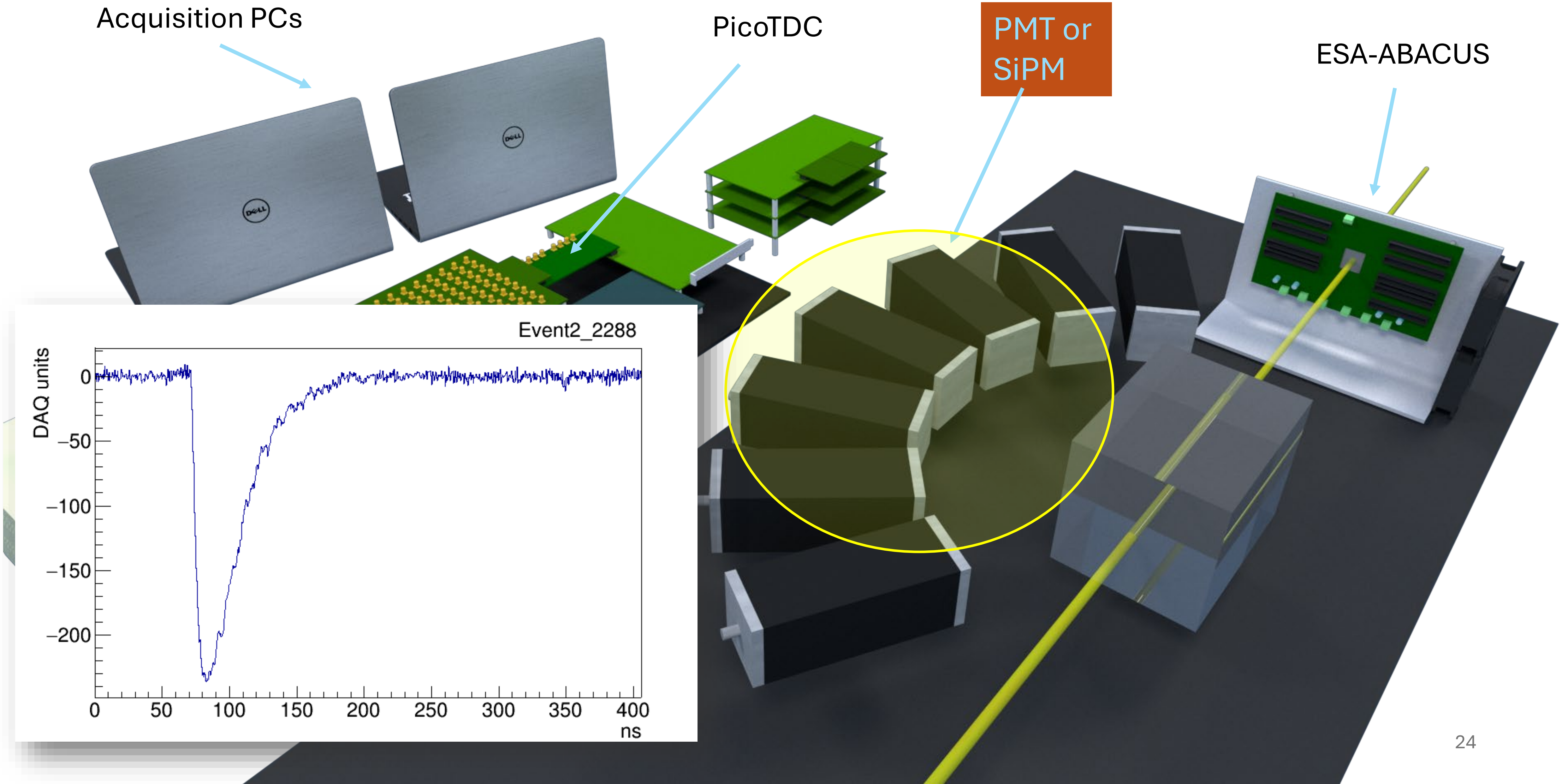
Difference between the pulse trigger and the ESA-ABACUS output



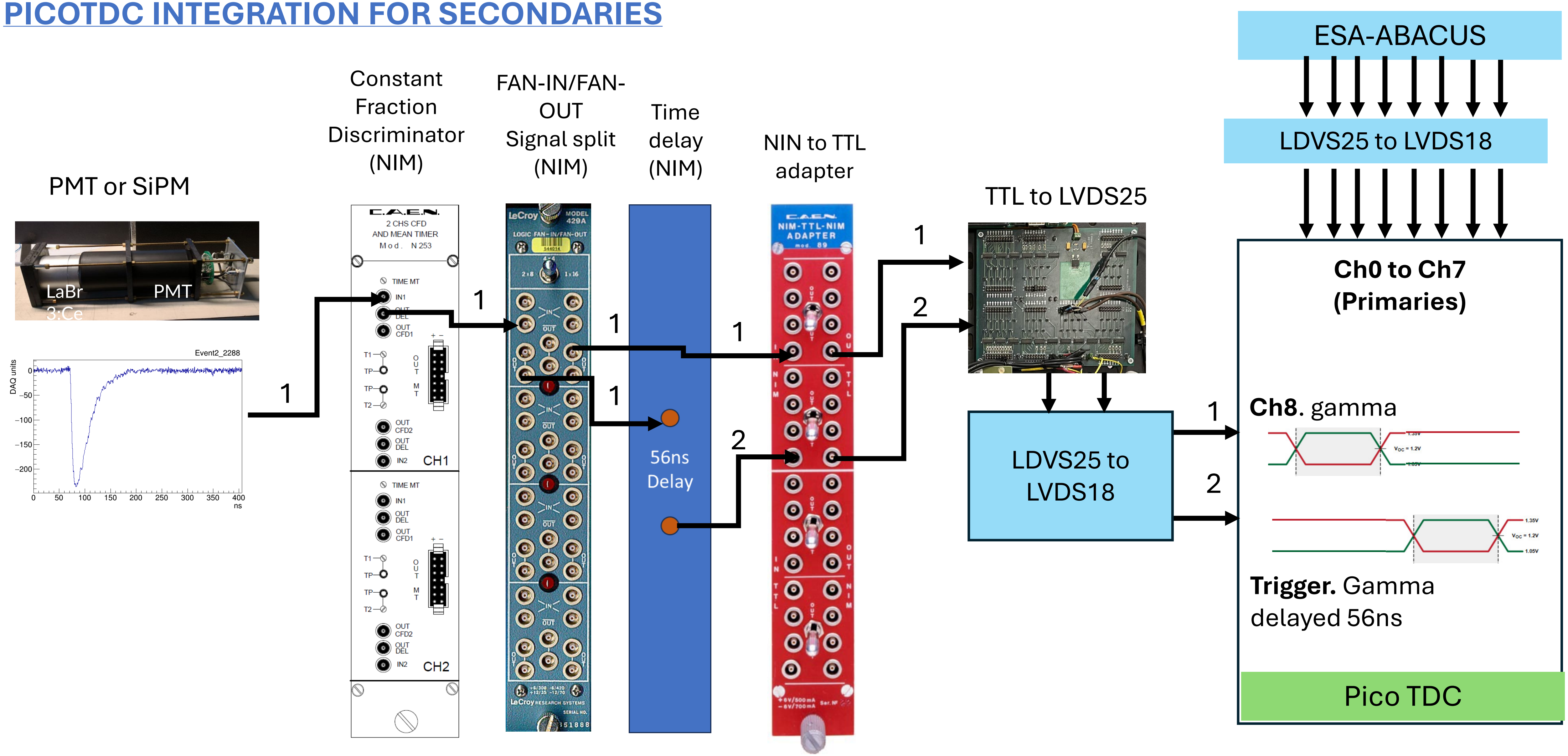


- The color represents the percent of real pulses measured.
- The radius in Y is equal to time resolution.
- In function of the discrimination threshold selected, up to 100 ps resolution can be reached.

PICOTDC INTEGRATION FOR SECONDARIES



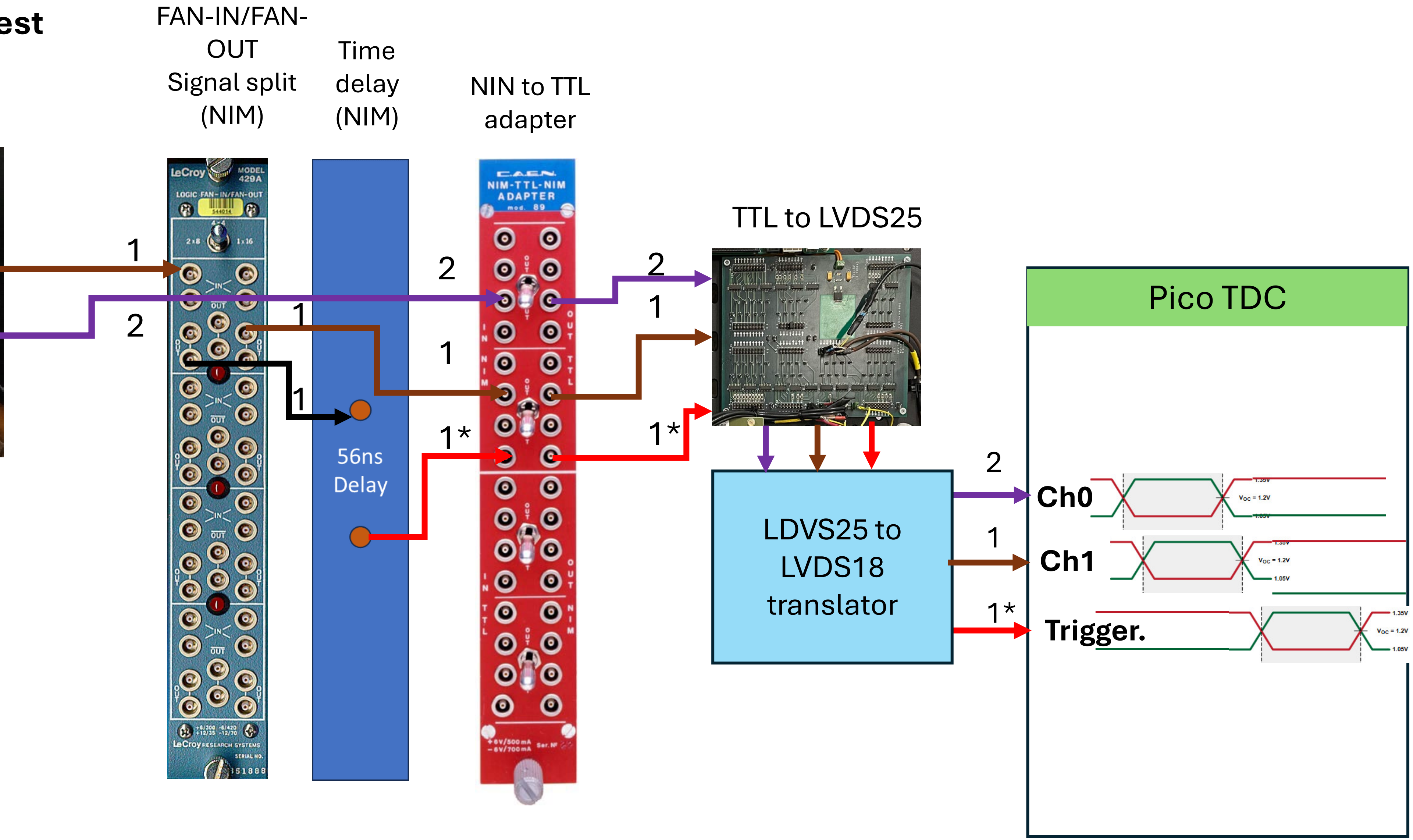
PICOTDC INTEGRATION FOR SECONDARIES



LABORATORY TEST FOR SECONDARIES

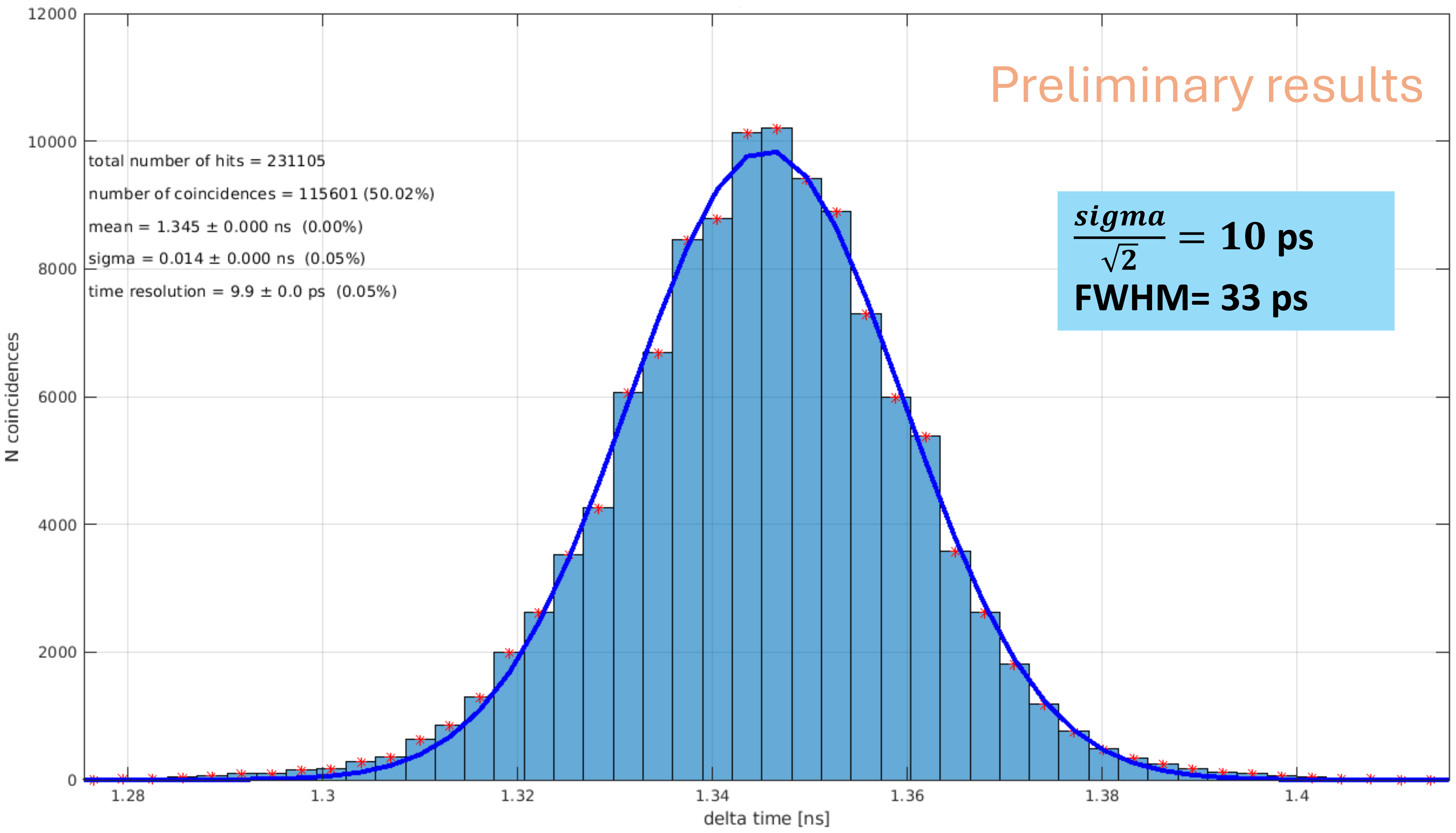
Adapters time resolution test

Active Technologies Pulse generator PG-1072
Output ch0 and ch1: 42ns NIM pulses (simulating the CFD output). 10 kHz.



LABORATORY TEST FOR SECONDARIES

SIGNAL ADAPTERS TIME RESOLUTION

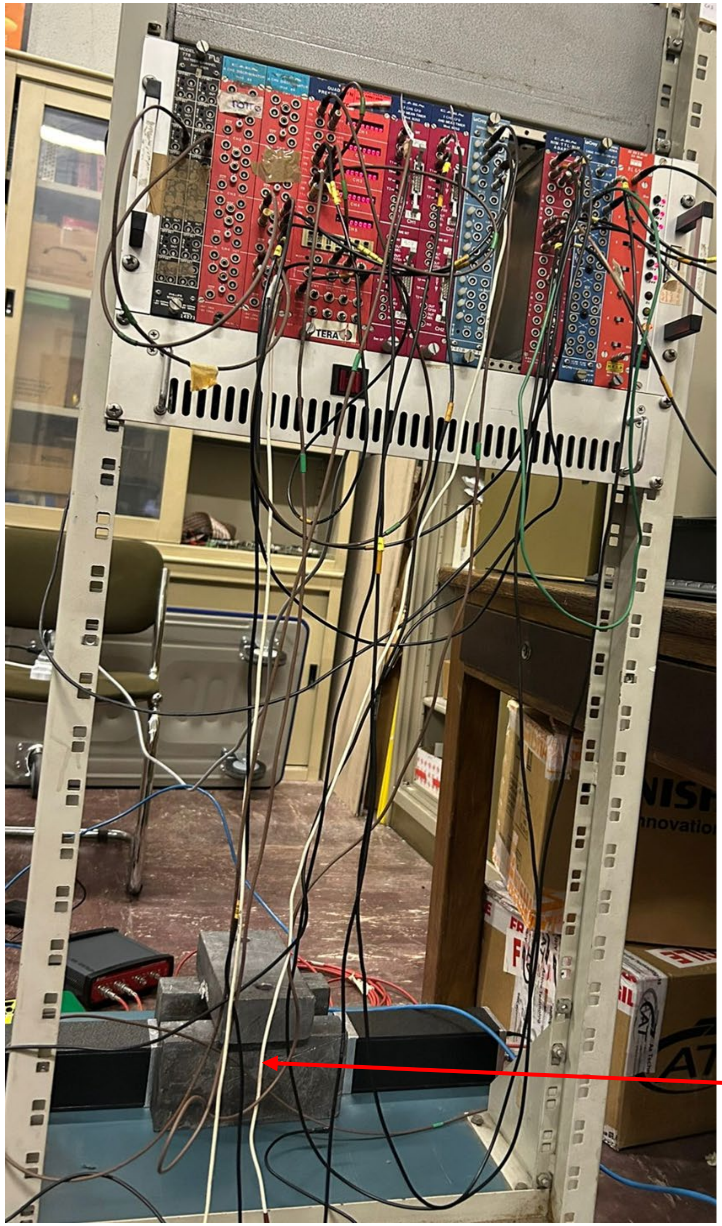


$\frac{sigma}{\sqrt{2}} = 10$ **ps**

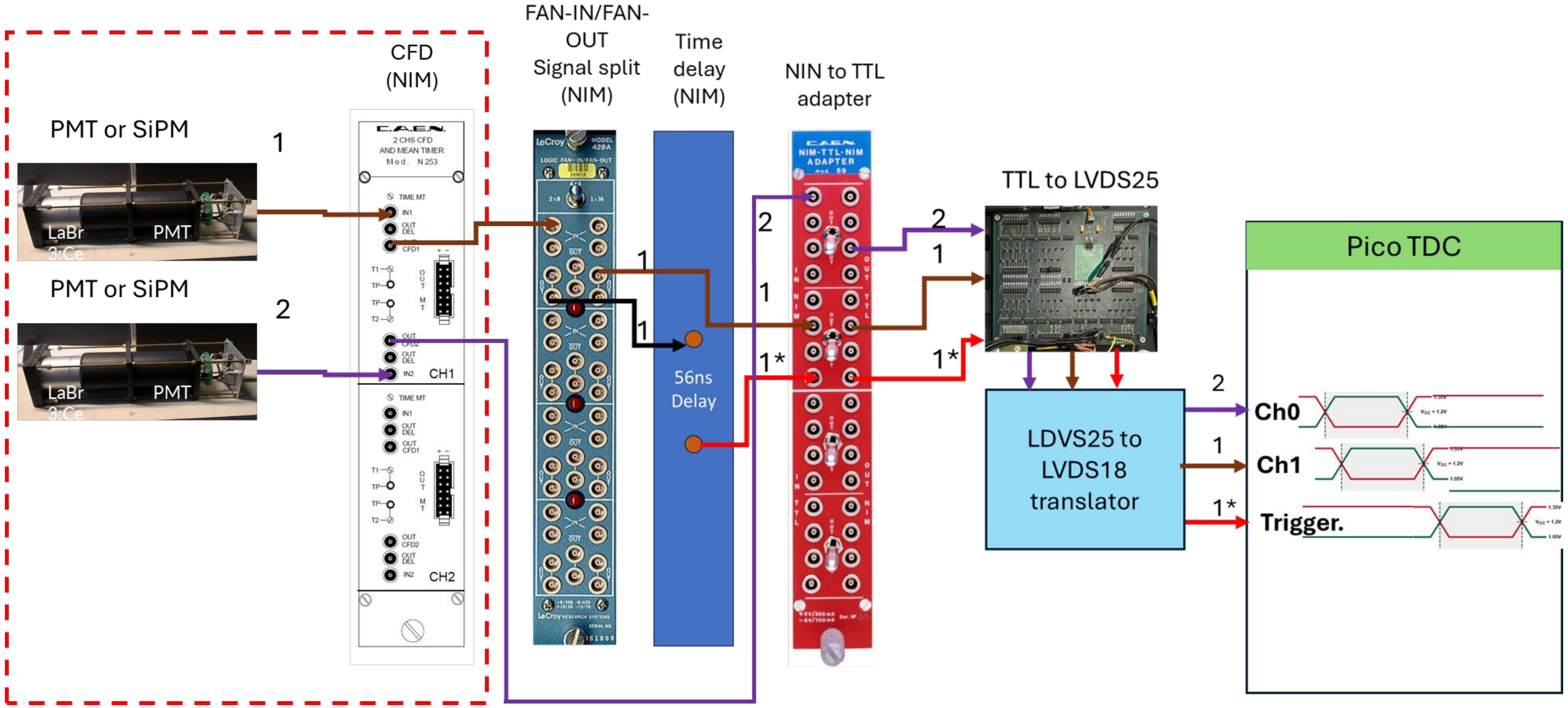
FWHM= 33 ps

(Ch1-Ch0)

LABORATORY TEST FOR SECONDARIES



Secondary detectors time resolution test

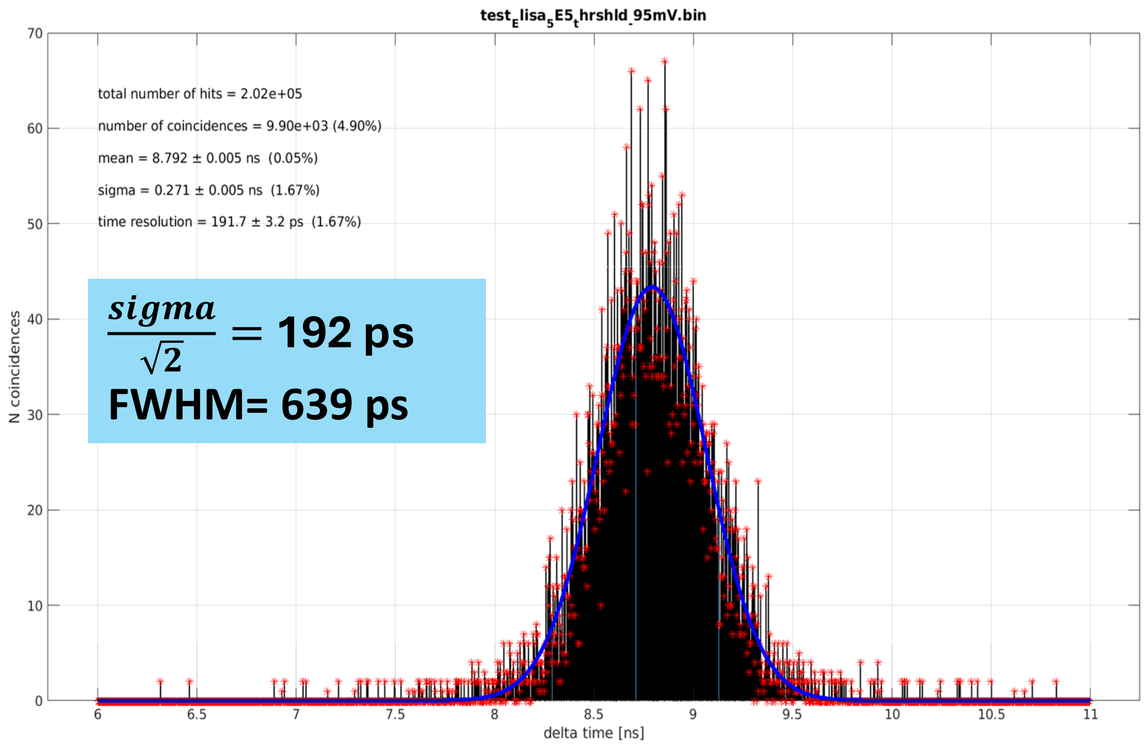


Detectors (= LaBr3 crystals coupled to PMT) + radioactive source (Na22, Co60)

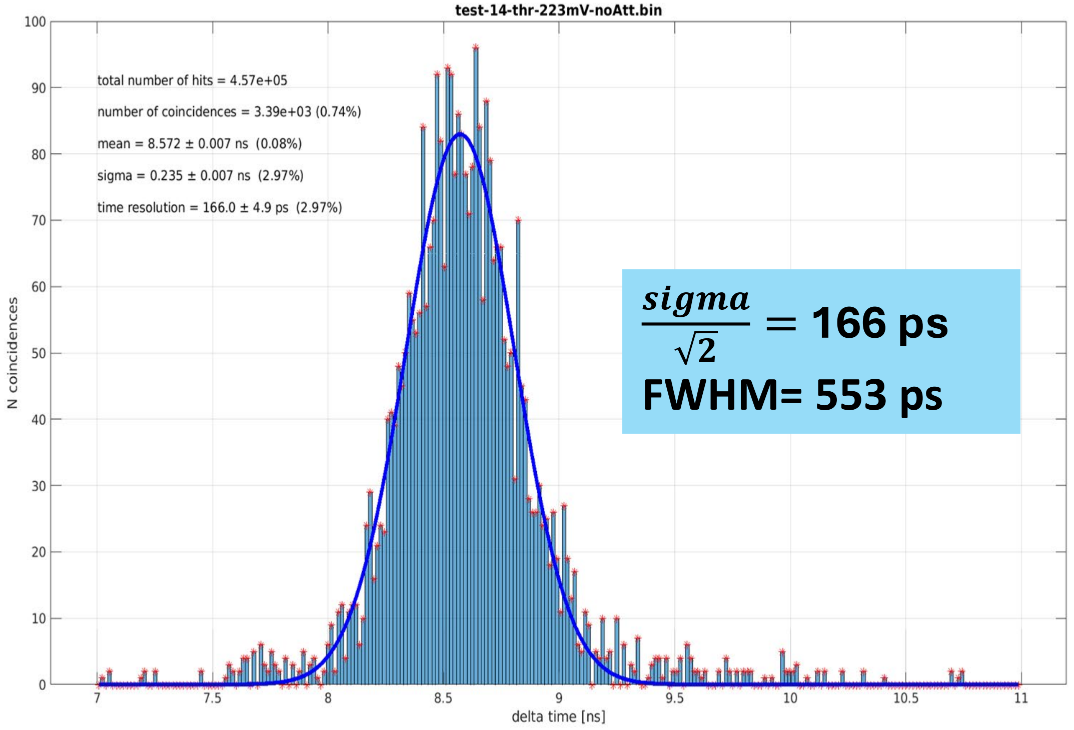
LABORATORY TEST FOR SECONDARIES

Best time resolution for secondary detectors using radioactive sources

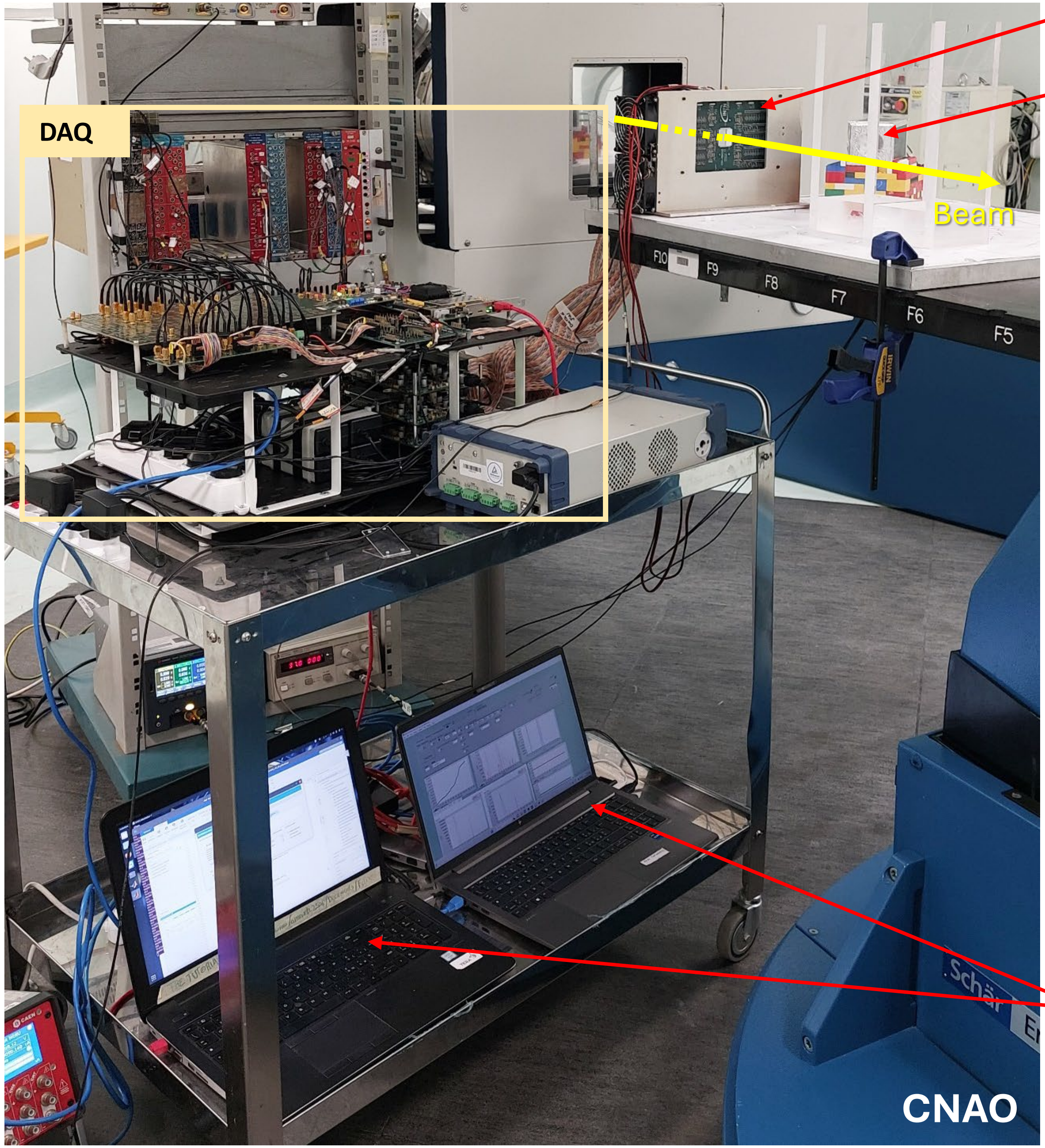
Na22 source



Co60 source



THE CURRENT EXPERIMENTAL SETUP



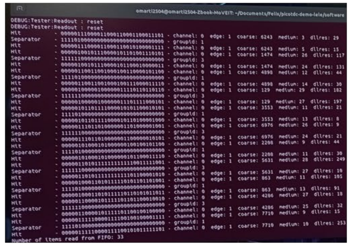
ESA-ABACUS (primaries)

SiPM (secondaries)

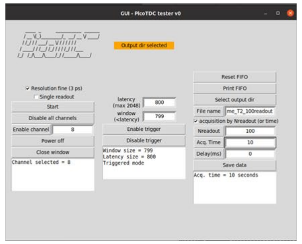
Acquisition PCs controlled remotely with TeamViewer

MEASUREMENT AND ANALYSIS CHAIN

CERN Python program



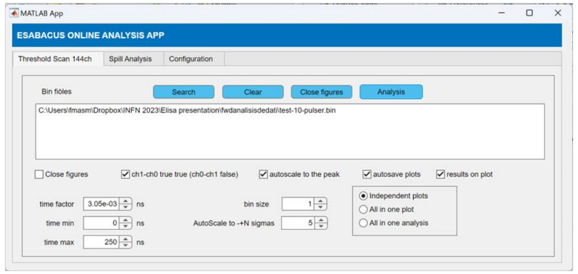
CERN Python GUI (acq. by N_readout or by elapsed time)



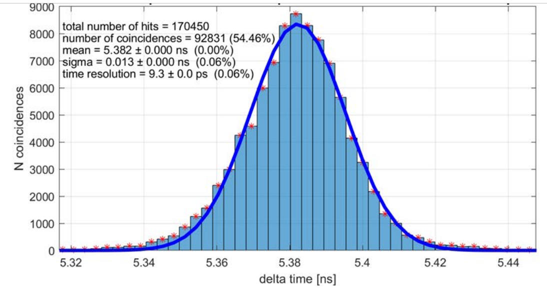
output

Binary files

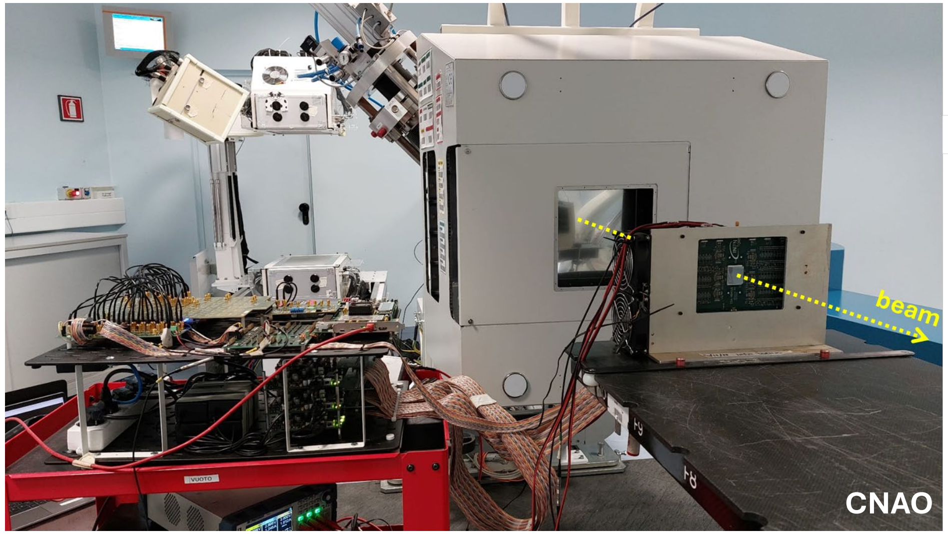
MATLAB App



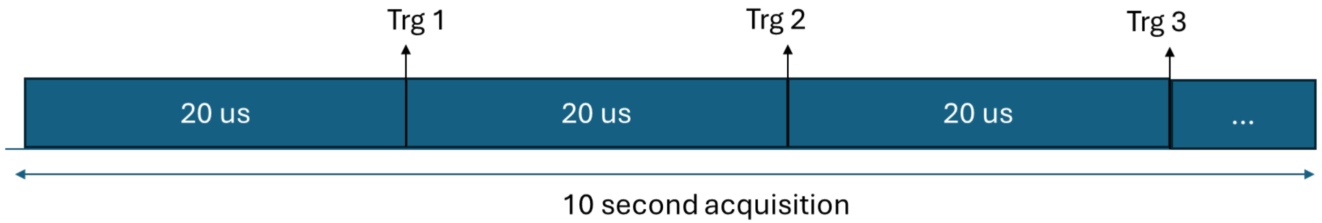
time difference



BEAM TEST WITH PRIMARIES ONLY



- 7 beam energies from 115.23 MeV/u (30 mm) to 398.84 MeV/u (270 mm).
- Carbon clinical rates with degrader 20, 50, 100
- PicoTDC latency 800 clocks, windows 799 clocks (20 us)
- Regular 50 kHz trigger.
- 10-second acquisitions




```
----
Corase= 7727 , TriggerStart= 56745984 , minTrigger= 56745984 , maxTrigger= 63299584 , rollOver= 4041
Init Time= 827293.1795 us, Final Time= 827313.168 us detTime= 19.9885 us , deltaCoarse= 800
-----
Ch= 2, coarse= 6938 , time= 56839111 , ABSTime= 271243758535 , realTime= 827293.4635 us
Ch= 6, coarse= 7677 , time= 62897981 , ABSTime= 271249817405 , realTime= 827311.9431 us
Trailer EventID= 5291 , HitCount= 2 , Overflow= 0
----
----
Corase= 335 , TriggerStart= -3809280 , minTrigger= 63299584 , maxTrigger= 2744320 , rollOver= 4042
Init Time= 827313.168 us, Final Time= 827333.1565 us detTime= 19.9885 us , deltaCoarse= 800
-----
Trailer EventID= 5292 , HitCount= 0 , Overflow= 0
----
----
Corase= 1135 , TriggerStart= 2744320 , minTrigger= 2744320 , maxTrigger= 9297920 , rollOver= 4042
Init Time= 827333.1565 us, Final Time= 827353.1449 us detTime= 19.9885 us , deltaCoarse= 800
-----
Ch= 1, coarse= 789 , time= 6467064 , ABSTime= 271260495352 , realTime= 827344.5108 us
Ch= 2, coarse= 570 , time= 4675820 , ABSTime= 271258704108 , realTime= 827339.0475 us
Ch= 5, coarse= 946 , time= 7753776 , ABSTime= 271261782064 , realTime= 827348.4353 us
```

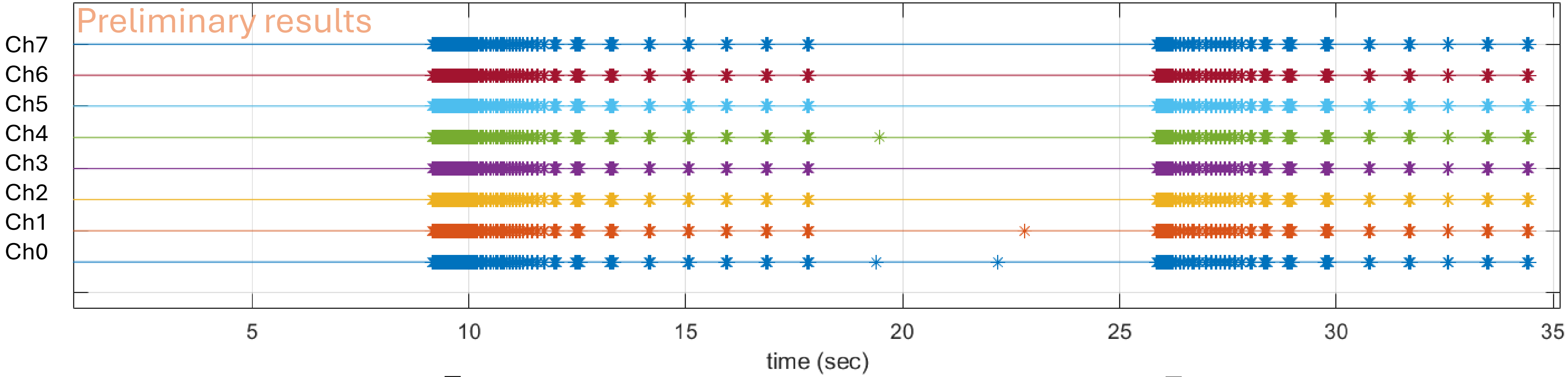
Increase real-time reference in 2^{26} *3.05ps

- We tried to synchronize the channel hits in the function of an absolute time using the trigger time tag (and its rollover) as a global time reference.

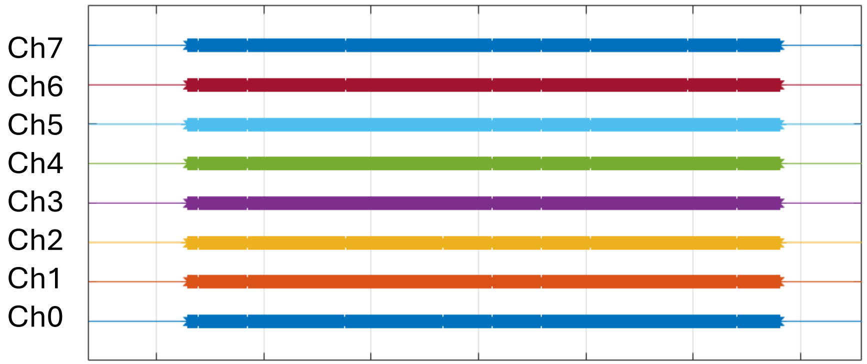
BEAM TEST WITH PRIMARIES ONLY

Example of spills acquisitions with 8 strips in Streaming mode for a Carbon ion beam

Issue: spill acquisition with not real time synchronization

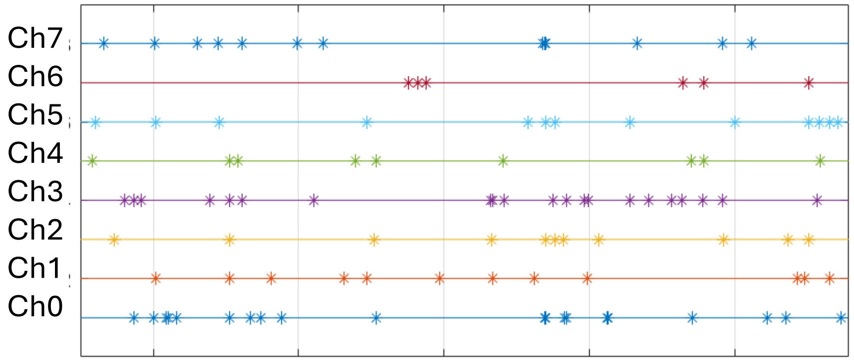


Zoom



72ms

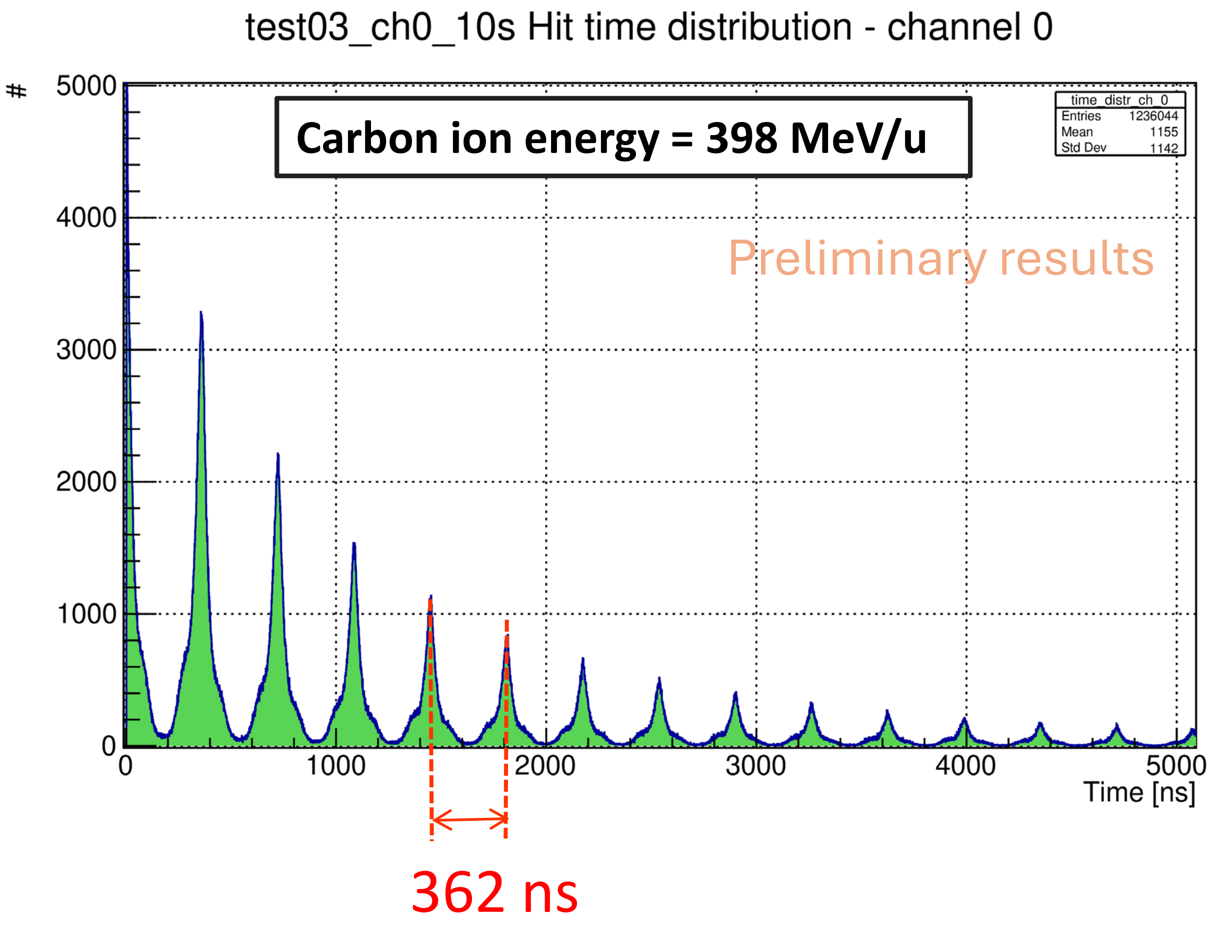
Zoom

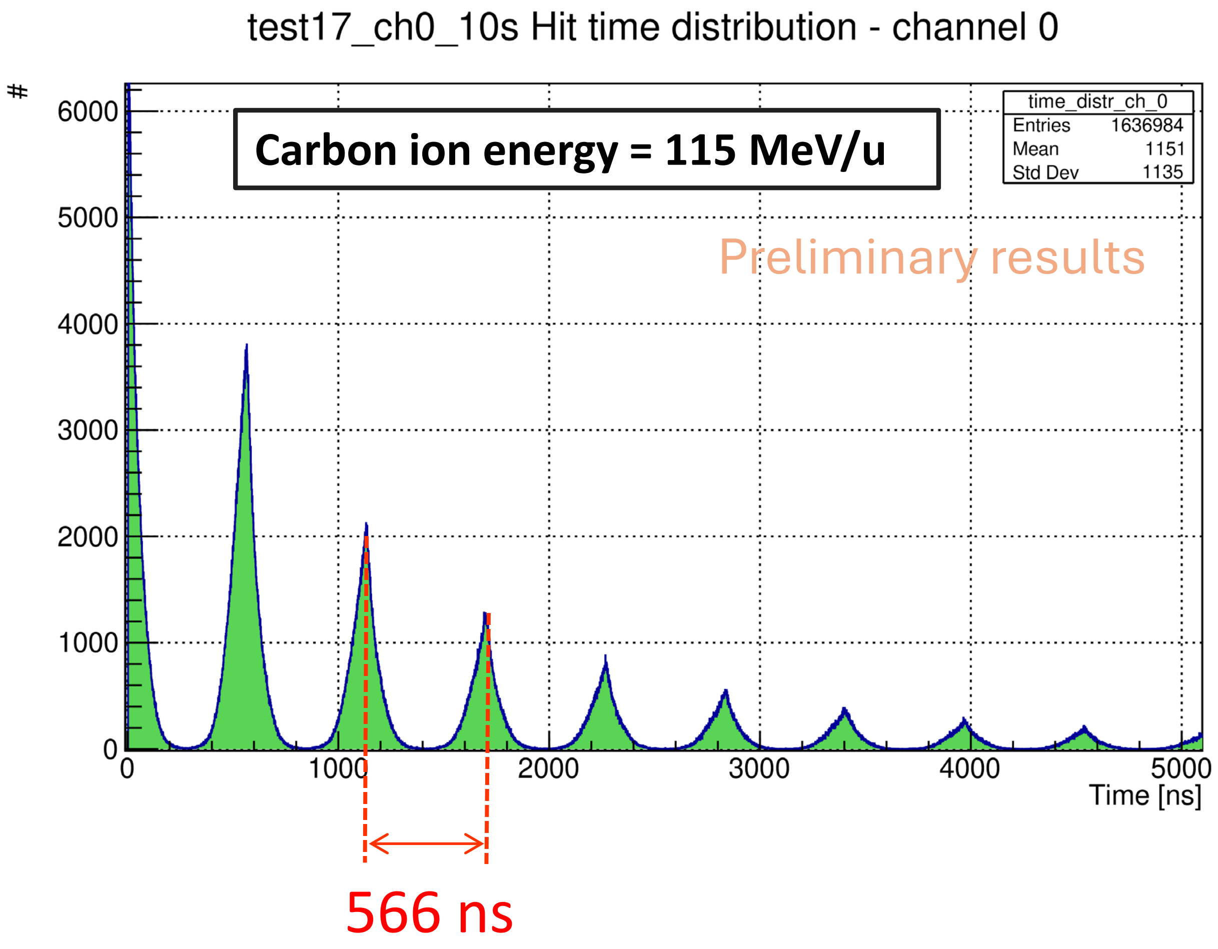


26 us

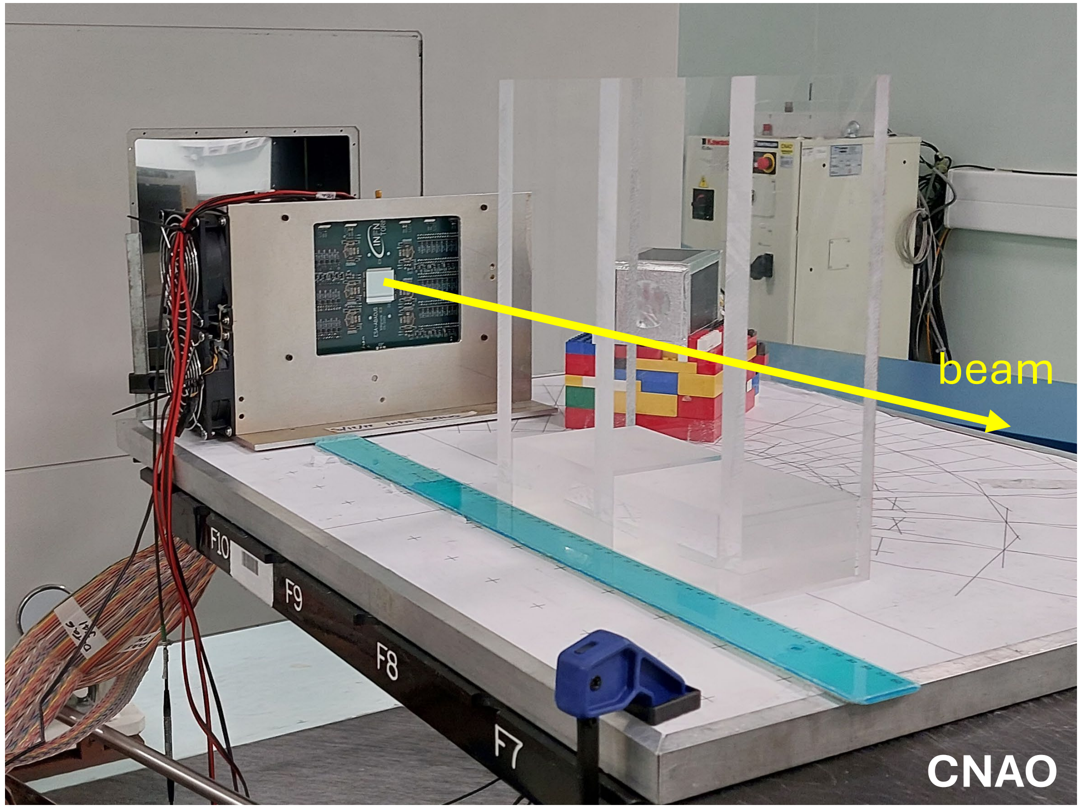
BEAM TEST WITH PRIMARIES ONLY

Distribution of difference of time of consecutive ions crossing one strip. The bunch structure and the accelerator radiofrequency were observed for all the energies





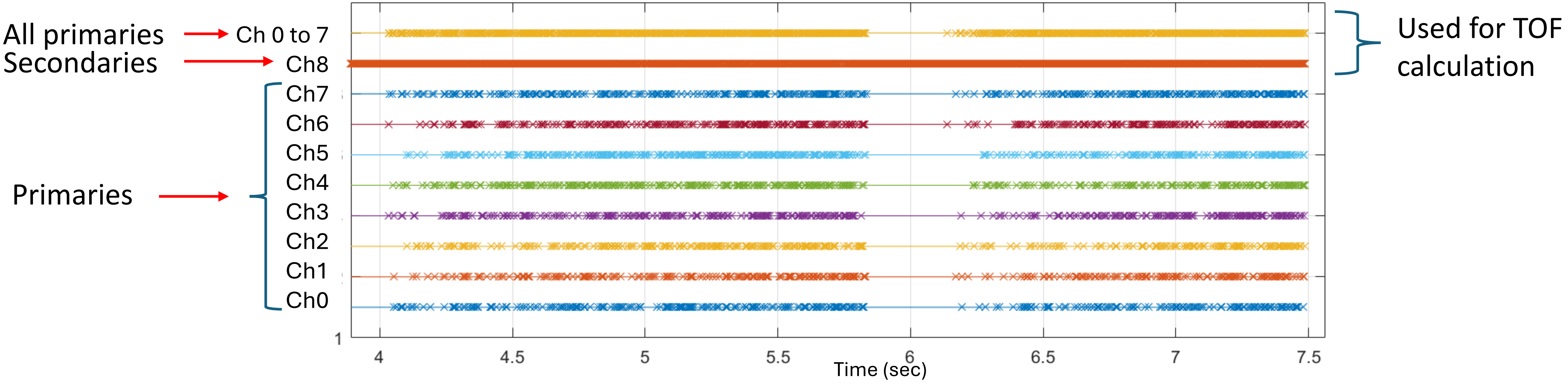
BEAM TEST WITH PRIMARIES AND SECONDARIES

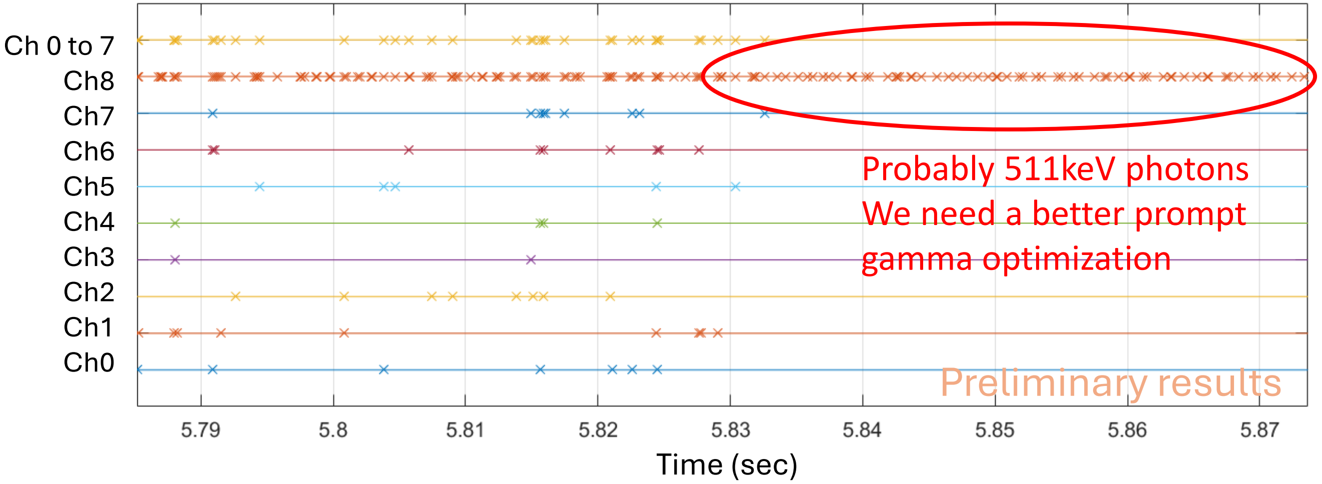


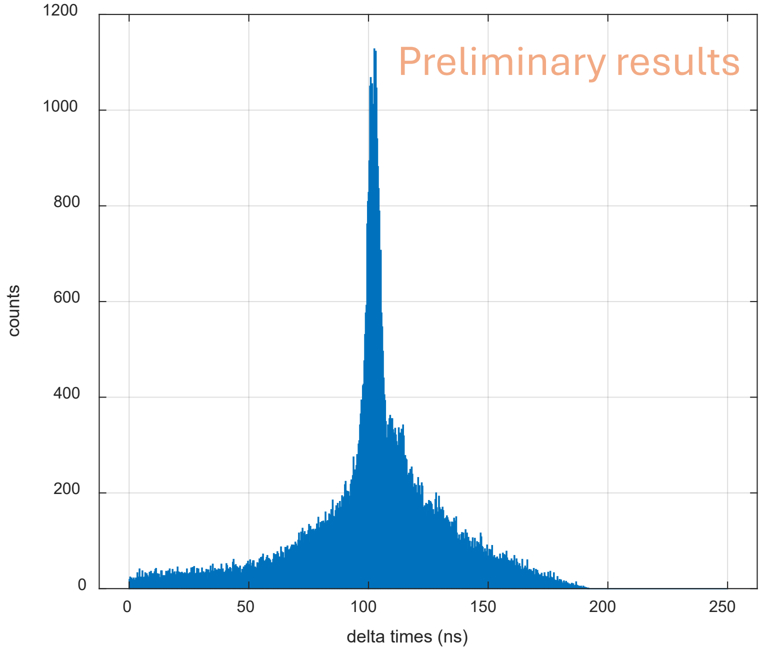
- Carbon clinical rates
- Maximum energy 398.84 MeV/u (270 mm)
- PMMA phantom
- Primaries on PicoTDC Ch0 to Ch7
- PicoTDC latency 10 clocks, windows 9 clocks (250 ns)
- Tigger from a delayed 56ns secondaries signal (on Ch8).
- 10-second acquisitions

BEAM TEST WITH CARBON IONS AND SECONDARIES

Example of spills acquisitions with 8 strips+1 SiPM in Triggered Mode and Clinical rate (empty spaces removed)







CONCLUSIONS

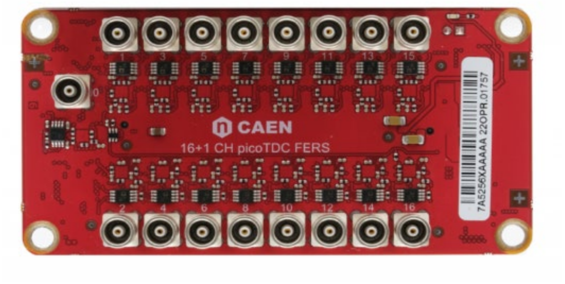
- We have successfully integrated our particle counter and the secondary detector with the PicoTDC.
- With the experimental setup, it was possible to calculate the time difference between the particles with the carbon ion beam and observe the bunch structure as well as the accelerator's radiofrequency.
- It was also possible to calculate the difference between secondary and primary particles, necessary for the range verification system

However, there are still some points that need to be addressed:

- We need to optimize the prompt gamma acquisition.
- We will explore the DT5203 and A5256 recently purchased from CAEN.
- Implement the time-walk correction using the TOT.

DT 5203

A5256



Thank you for your attention!

INFN
TORINO