Monitoring of Carbon Ion Therapeutic Beams with Thin Silicon Sensors: Status and Perspectives

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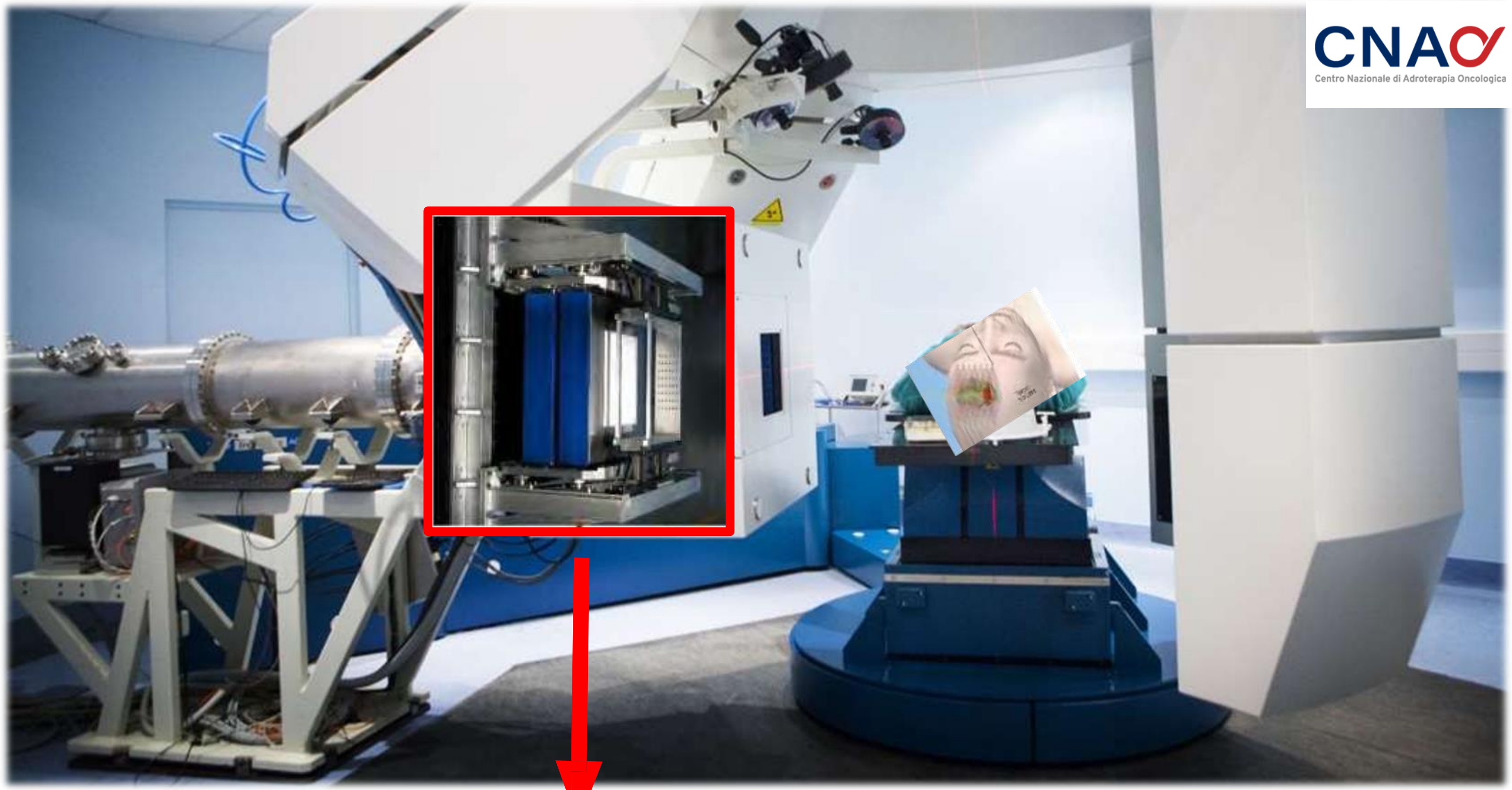

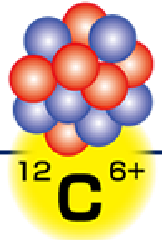

- **CIRT**:
  - Higher LET than protons and photons.
  - Higher Relative Biological Effectiveness (REB).
  - Less radiation dose to adjacent normal tissues.

- The state-of-the-art of **beam monitors** is represented by **gas-filled ionization chambers** (IC):
  - ✓ Large area
  - ✓ Good radiation hardness
  - ✗ Limited sensitivity (~ 10^4 particles)
  - ✗ Slow charge collection times (~ 100 µs)

- Single ion counting in particle therapy demands sensors with:
  - High spatial and temporal resolutions.
  - Capable of handling high instantaneous flux (up to 10^8 carbon/cm^2·s) in the clinical energy range.

In recent years, the University and the INFN of Turin demonstrated the feasibility of counting particles for therapy using thin Ultra-Fast Silicon Detectors (UFSD) segmented in strips.

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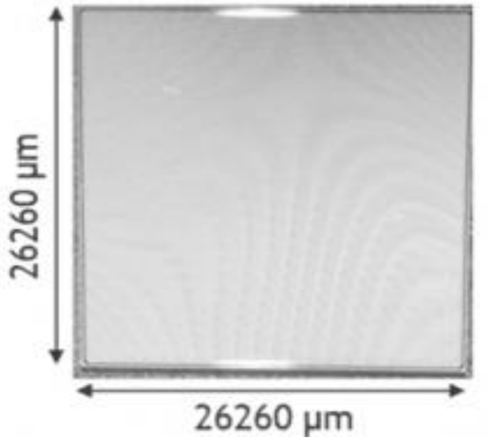
MoVe IT

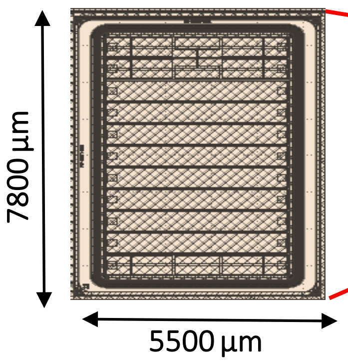
Parameters	Type A	Type T
Dimension (mm)	26.3 x 26.3	7.8 x 5.5
Area (mm²)	690	43
Active thickness (µm)	60	60
Pitch (µm)	180	591
Strips dimension (mm)	26.2 x 0.114	4.0 x 0.5
Strip Area (mm²)	2.9	2.2
Breakdown voltage (V)	**~ 200**	**~ 300**

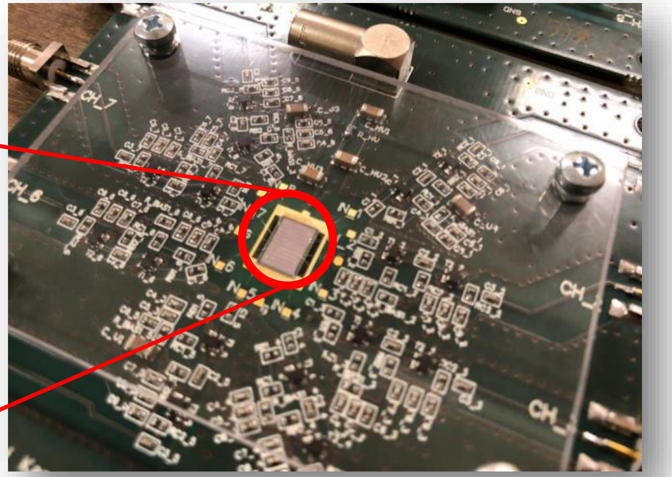
A (146 strips)



- **UFSD**:
  - Sensitivity: single particle
  - Charge collection time: ~ ns
  - Time resolution: ~ 50 ps

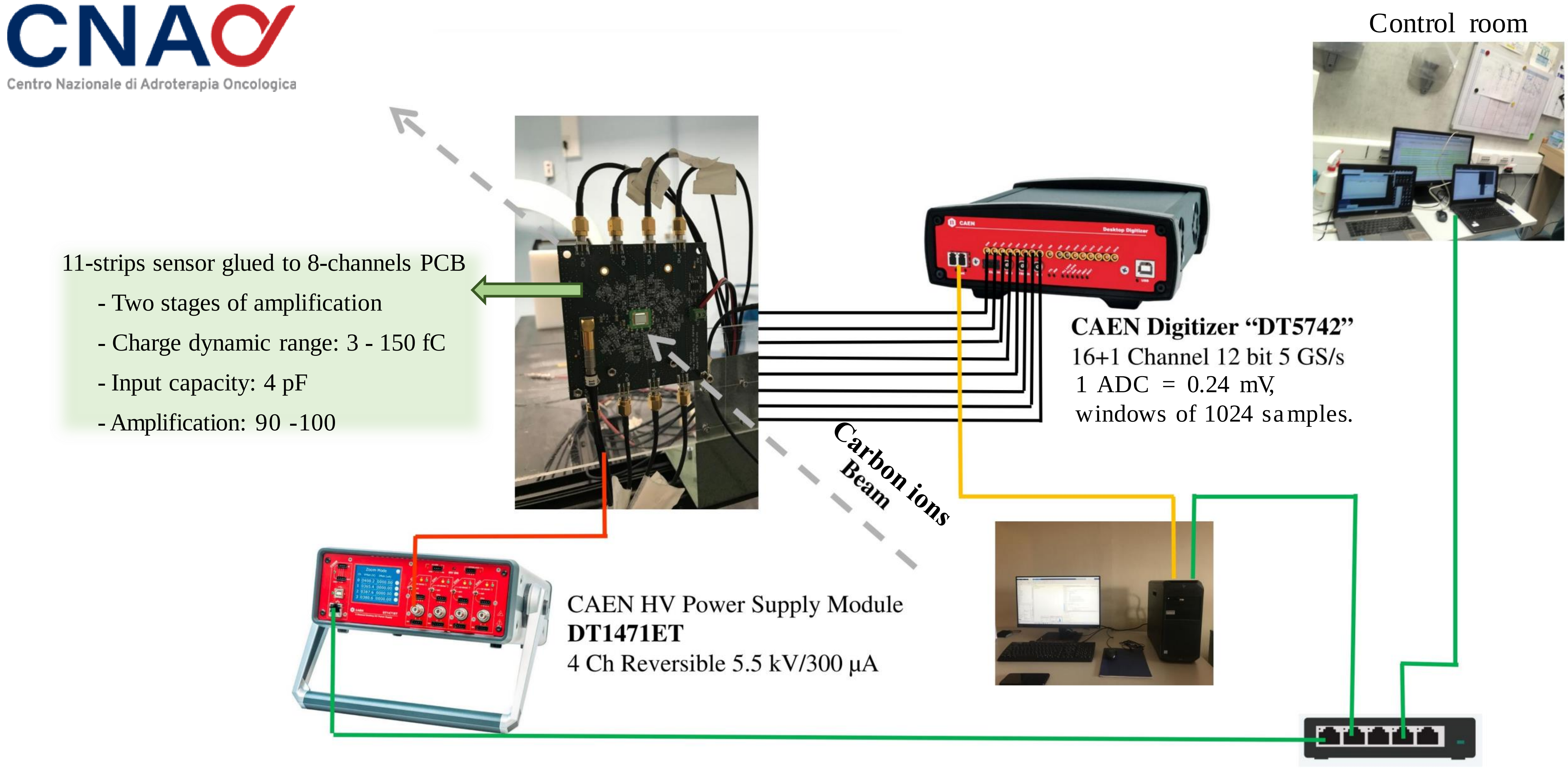
T (11 strips)





Superconducting Ion Gantry

Within the INFN-SIG project, these optimized sensors were used for carbon ion clinical monitoring tests at CNAO.

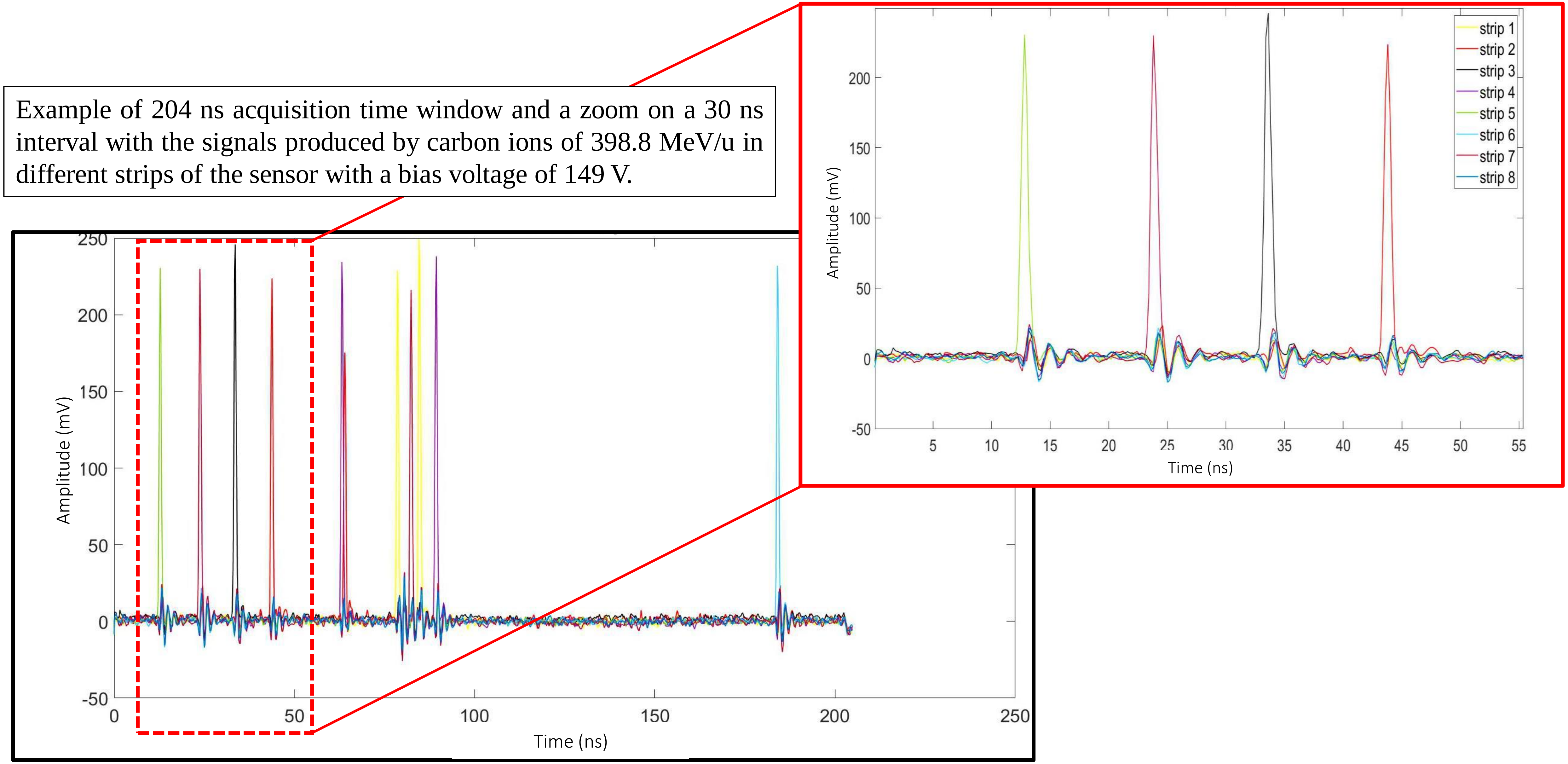

CNAO
Centro Nazionale di Adroterapia Oncologica
Control room
11-strips sensor glued to 8-channels PCB
- Two stages of amplification
- Charge dynamic range: 3 - 150 fC
- Input capacity: 4 pF
- Amplification: 90 -100
CAEN Digitizer "DT5742"
16+1 Channel 12 bit 5 GS/s
1 ADC = 0.24 mV,
windows of 1024 samples.
Carbon ions
Beam
CAEN HV Power Supply Module
DT1471ET
4 Ch Reversible 5.5 kV/300 µA

CNAO
Centro Nazionale di Adroterapia Oncologica

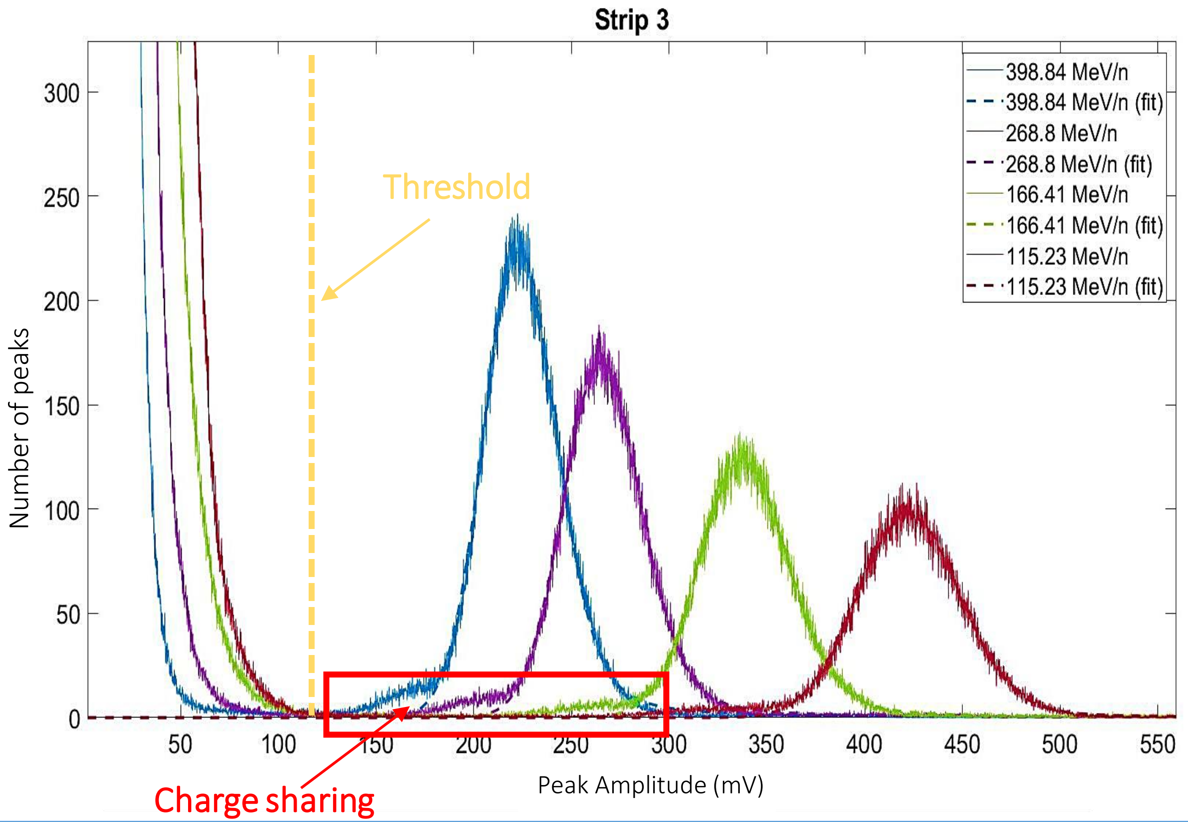
- Measurement conditions:
  - CNAO synchrotron
  - Beam energies (MeV/u): 115.2, 166.4, 268.6 and 398.8.
  - Bias voltage: 9V – 300 V
  - Number of spills: 10 – 20 for each run
  - Number of carbon ions: $8 \cdot 10^{7}$ ions/spill
  - Detector placed at the isocenter
  - Room temperature

- It was studied:
  - ✓ Signal amplitude & duration.
  - ✓ Time resolution.
  - ✓ Deposited charge & Charge sharing.
  - ✓ Beam shape.

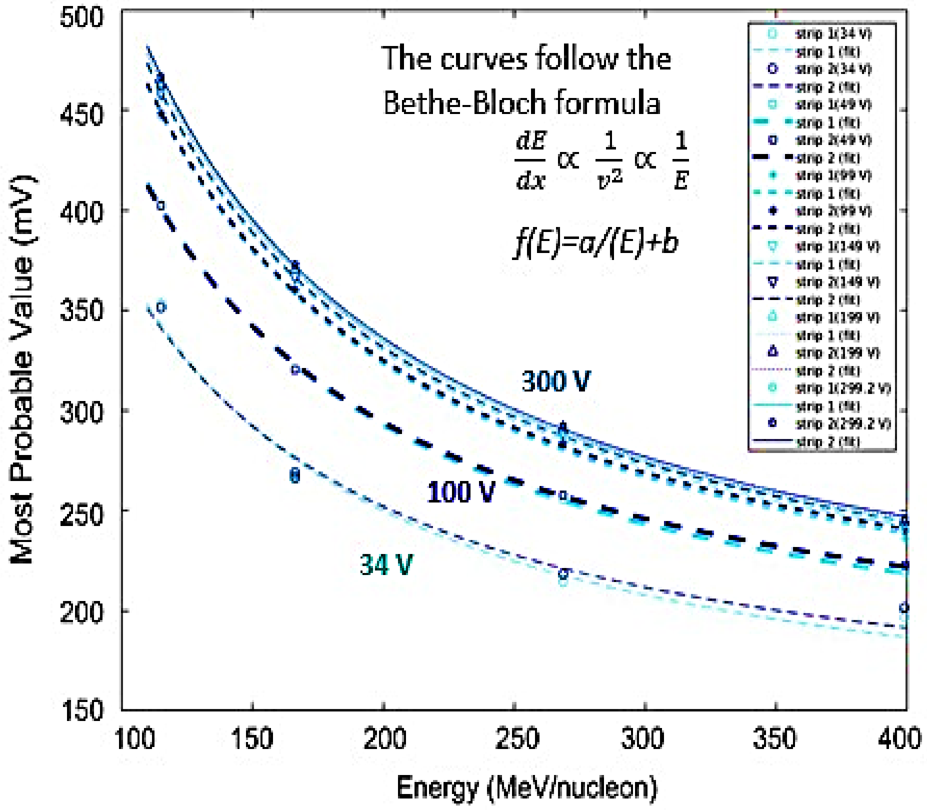
Example of 204 ns acquisition time window and a zoom on a 30 ns interval with the signals produced by carbon ions of 398.8 MeV/u in different strips of the sensor with a bias voltage of 149 V.



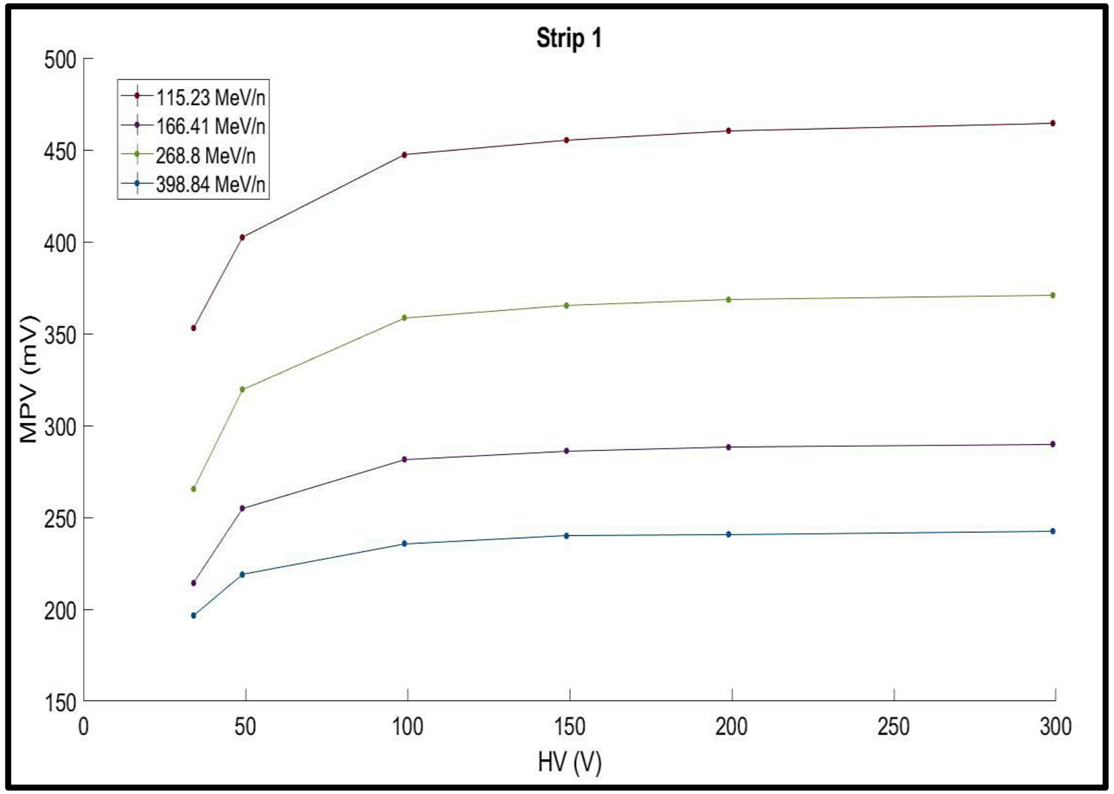
Amplitude distribution for clinical range energies measured on strip 3 at 149 V. **Good signal/noise separation** is achieved by choosing an appropriate threshold.



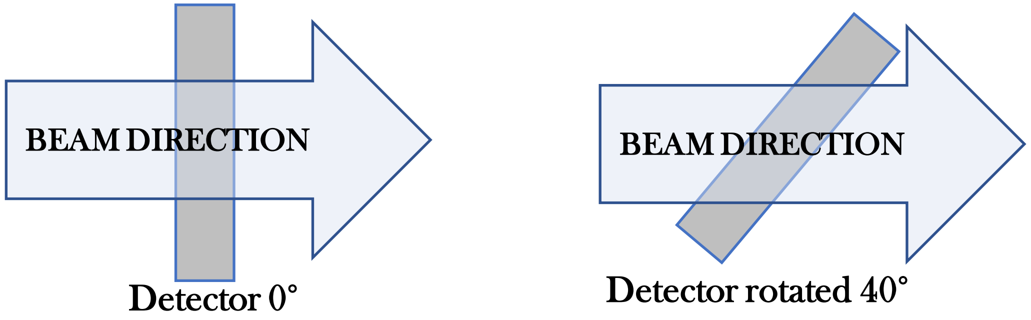
In the range of 34 V to 300 V the most probable values (MPV) calculated from the Langaus distribution fit for strips 1 and 2 were between 200 and 450 mV.

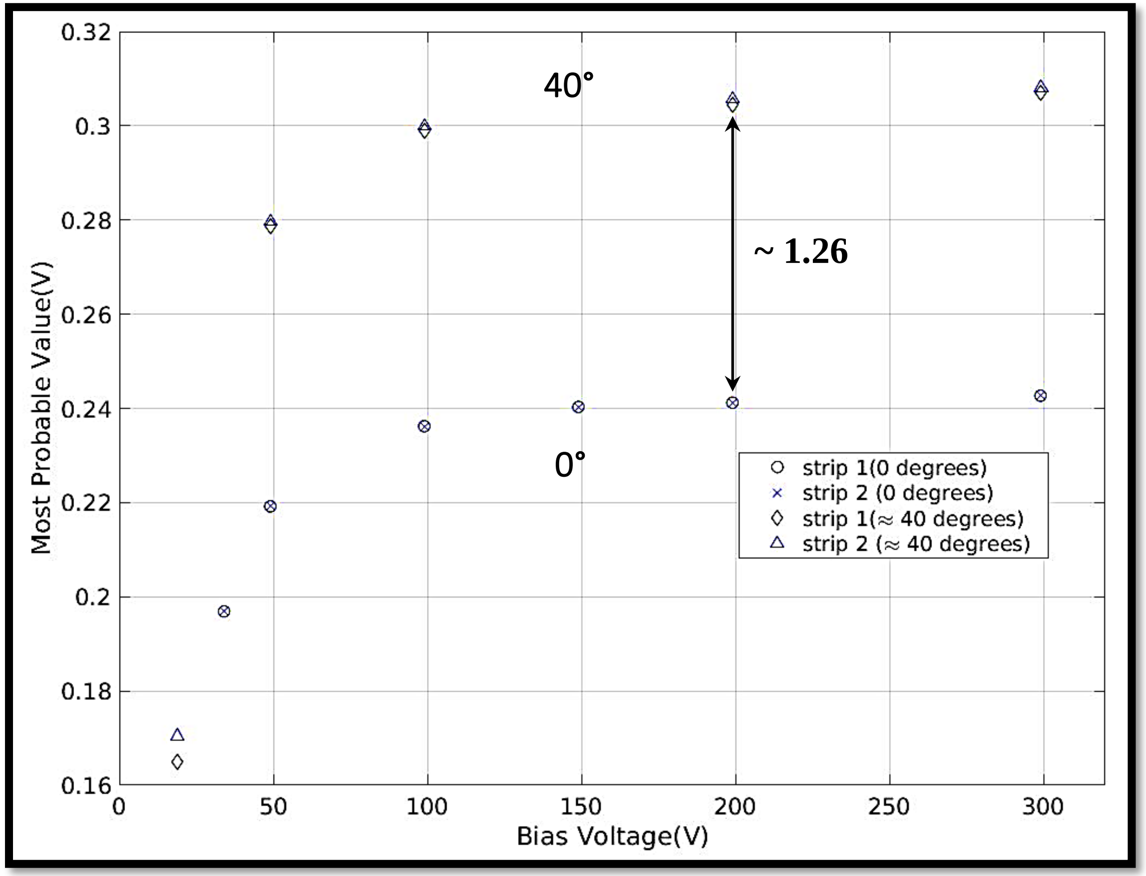


MPV vs. bias voltage for all energies

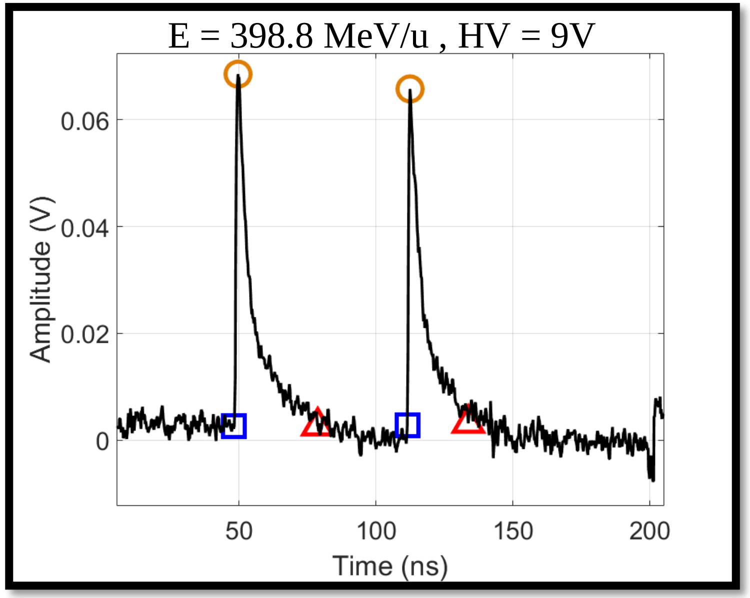


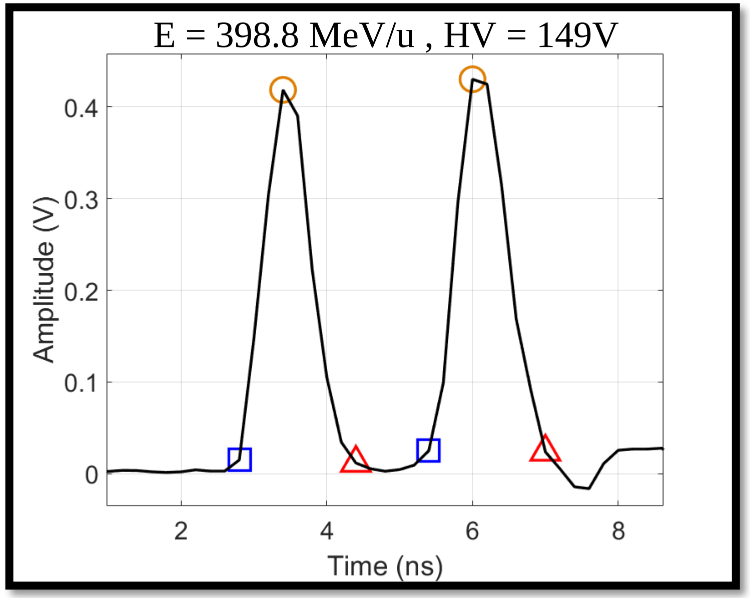
TOP VIEW

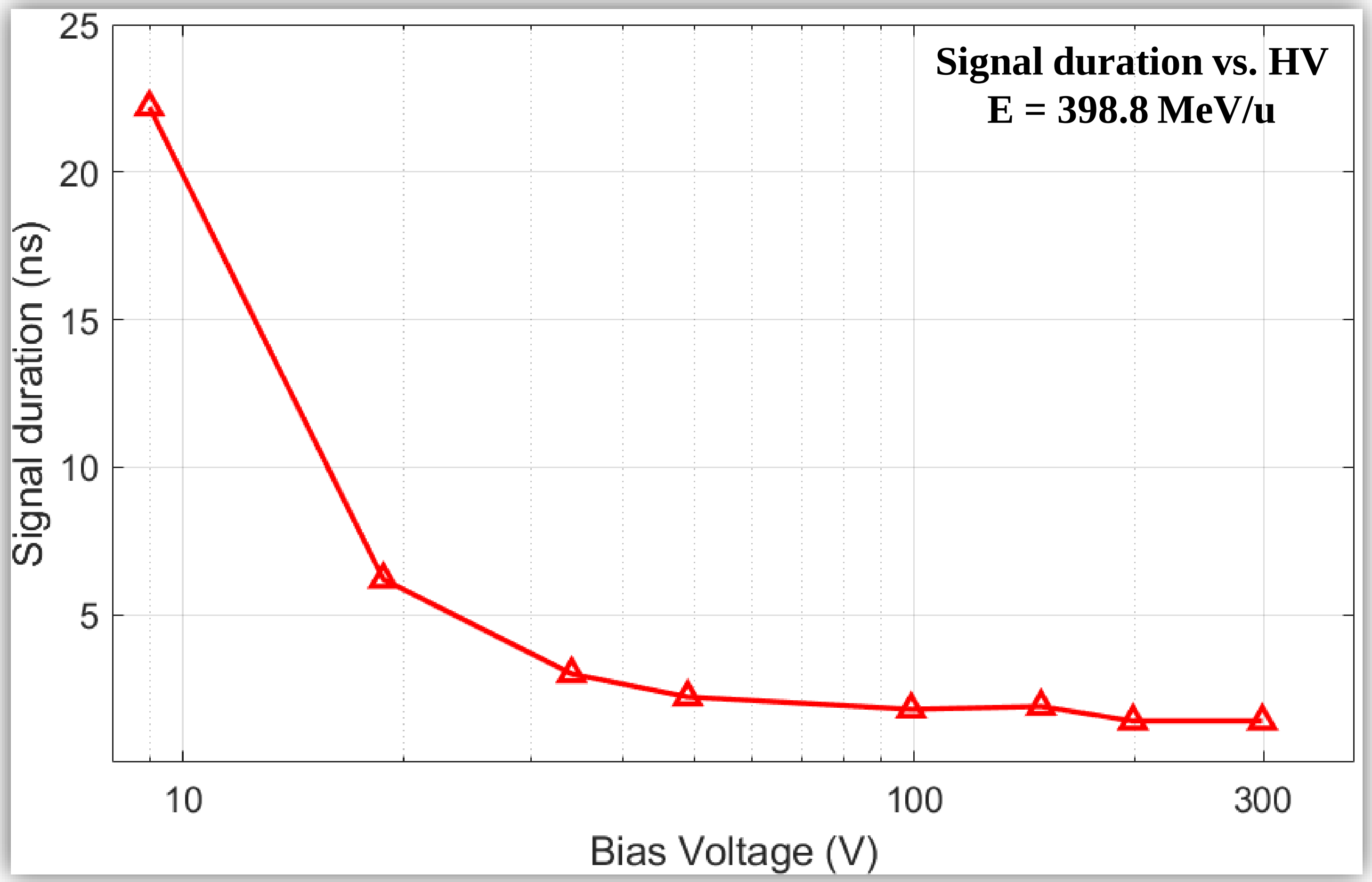




Rotation of the sensor increases the amplitude of the signal due to the longer path of the carbon ions, which creates additional electrons and holes.







For bias voltages greater than 100 V, the **signal duration** is **less than 2 ns**.

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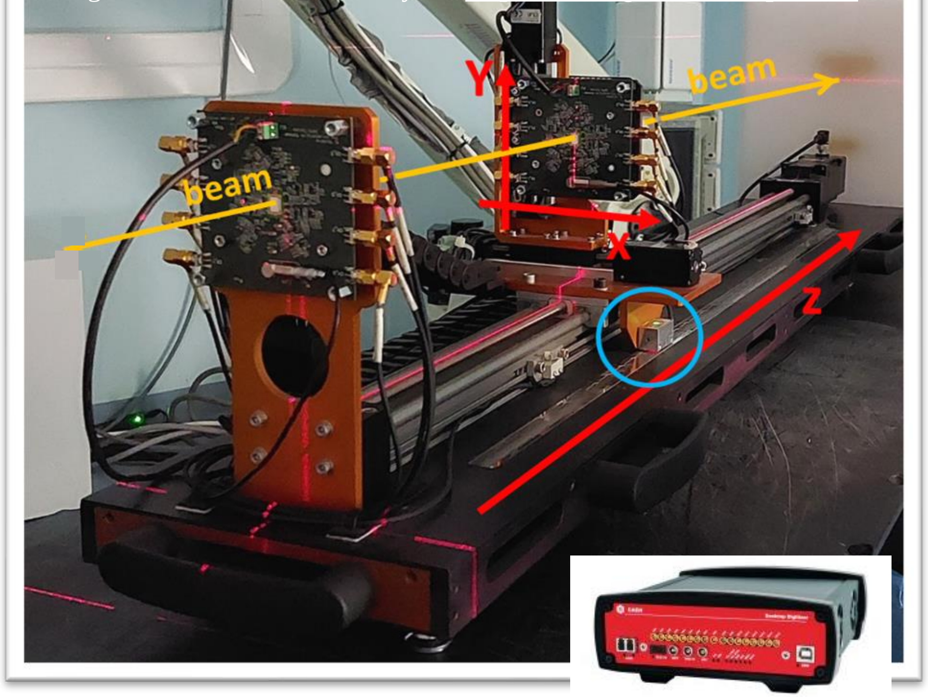
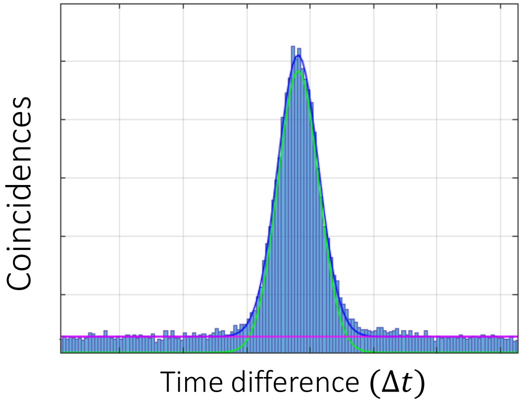
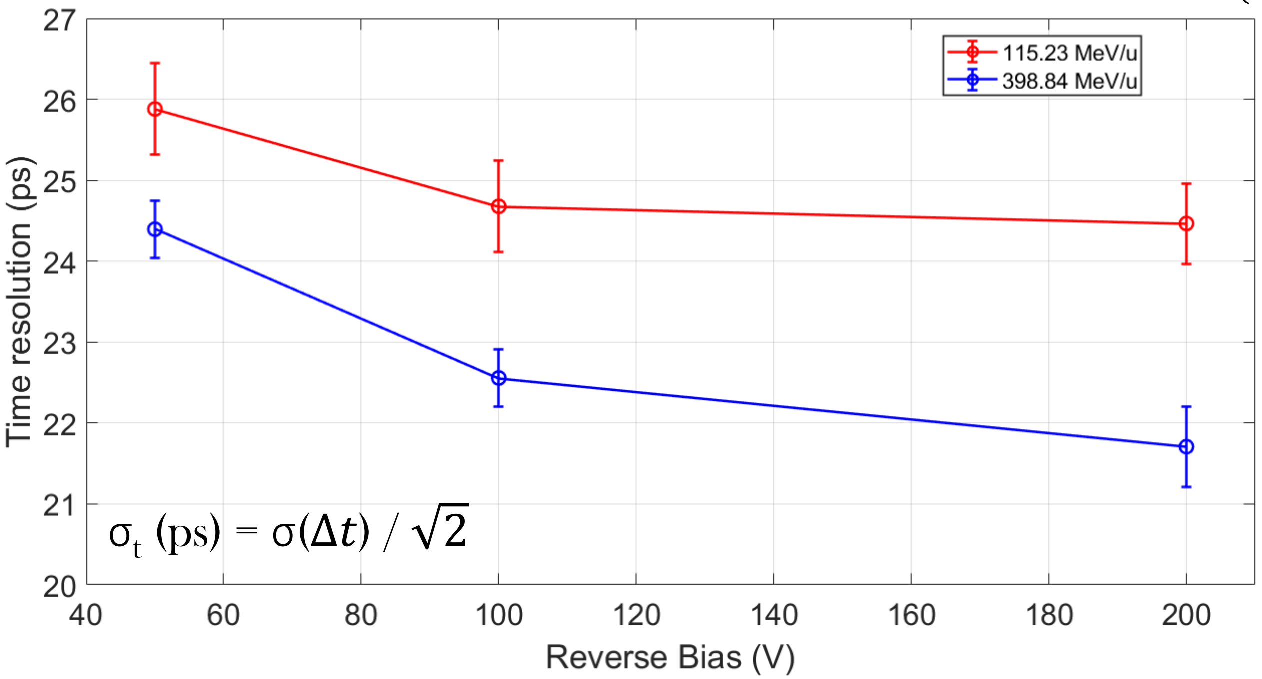


16 channels of the Digitizer DT5742

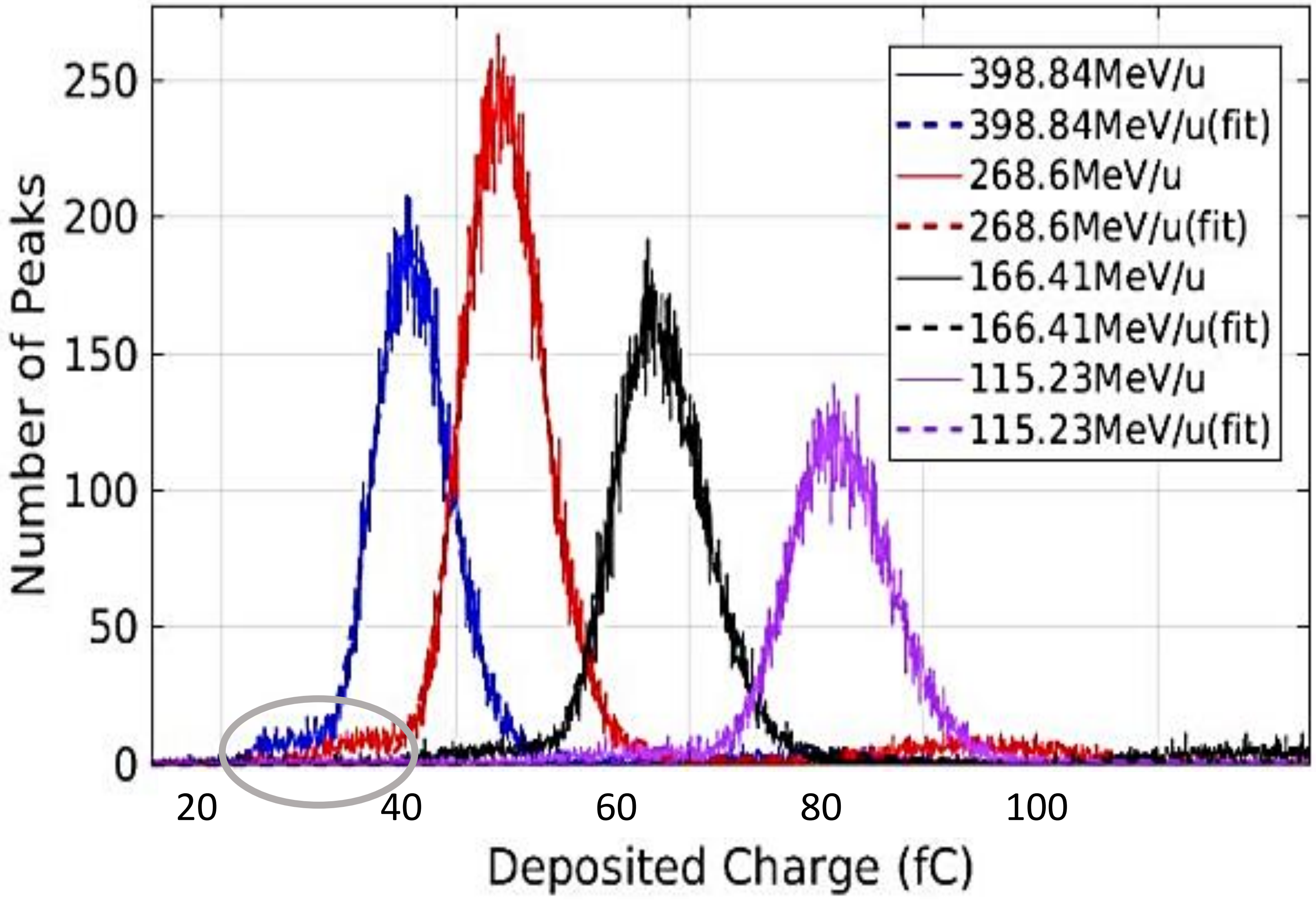
- **Measurements conditions:**
  - Two Si sensors with the same characteristics placed in a telescope configuration 30 cm apart.
  - Beam energies (MeV/u): 115.2 and 398.8.
  - Bias voltage: 50V, 100V, and 200 V.
  - Arrival time determined using CFD.





Time resolution values for single ion crossing were **less than 26 ps** (relative error < 2%)

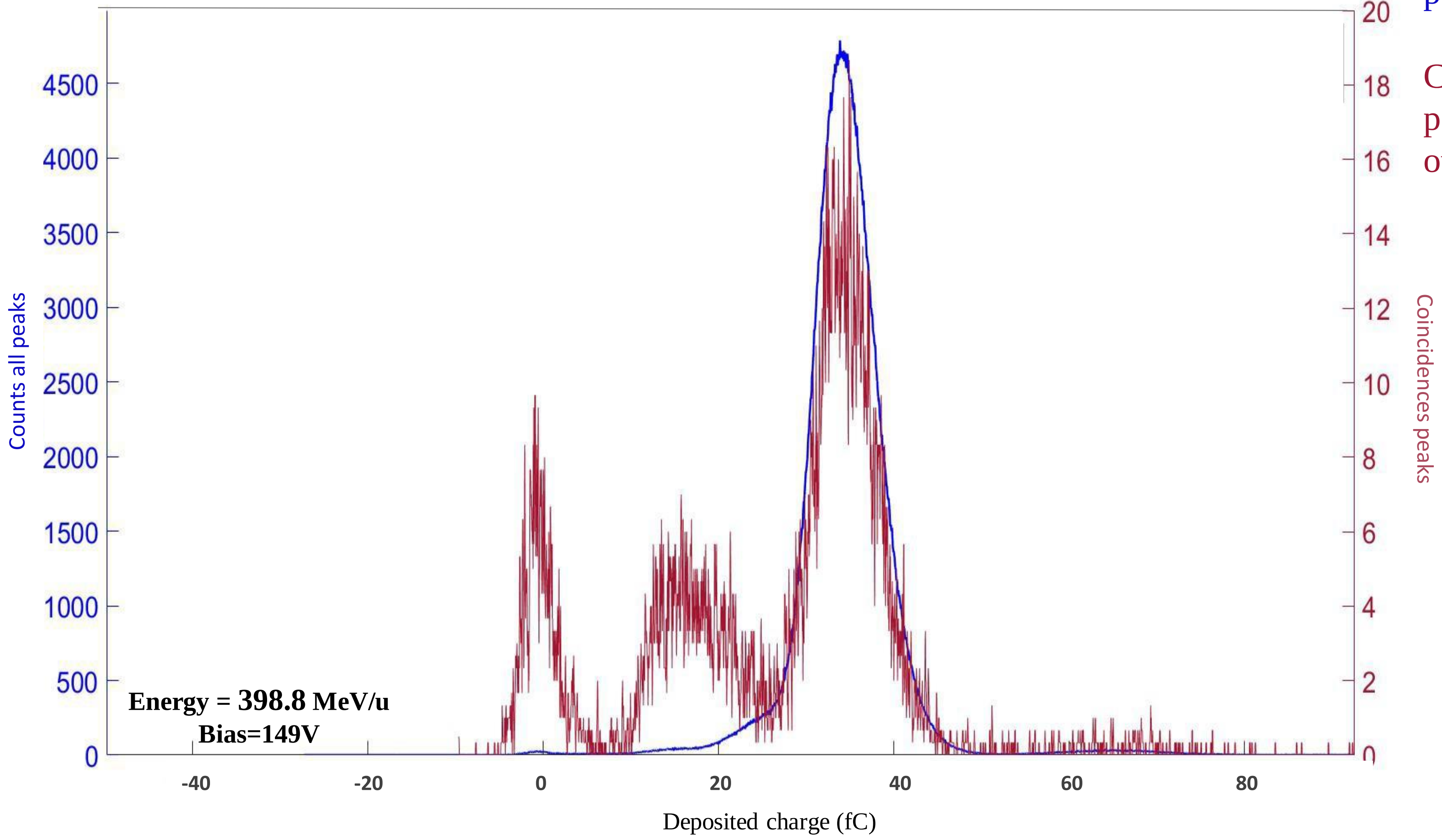
Deposited charge distribution (fC) by carbon ions on strip 1 (HV = 149 V)



$$Q = \frac{\int V \cdot dt}{G_A \cdot Z}$$

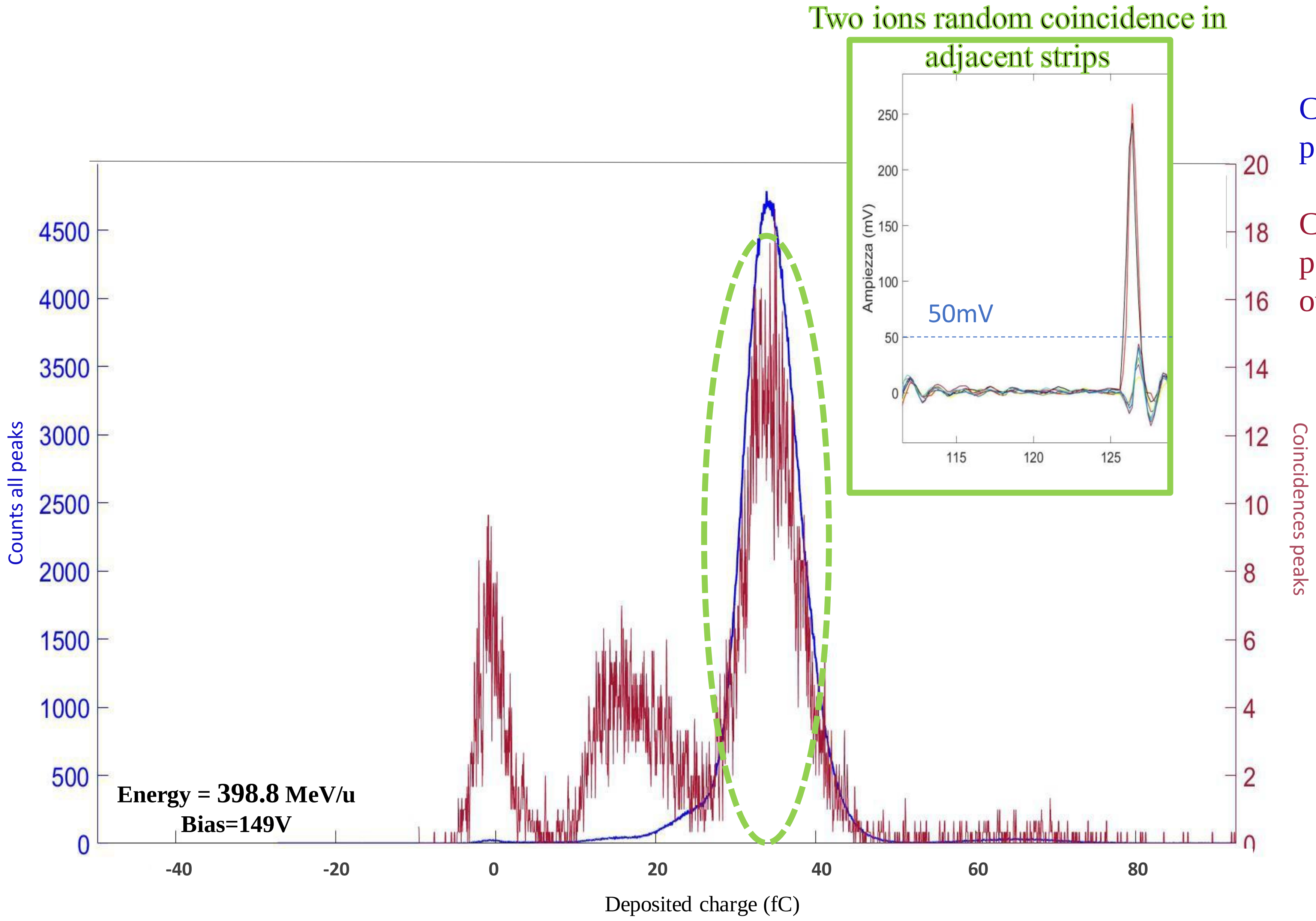
Gain Amplification (G_A): 90 – 100
Input Impedance (Z): 50 Ω

MPV Deposited charge:
37.4 fC – 78.9 fC



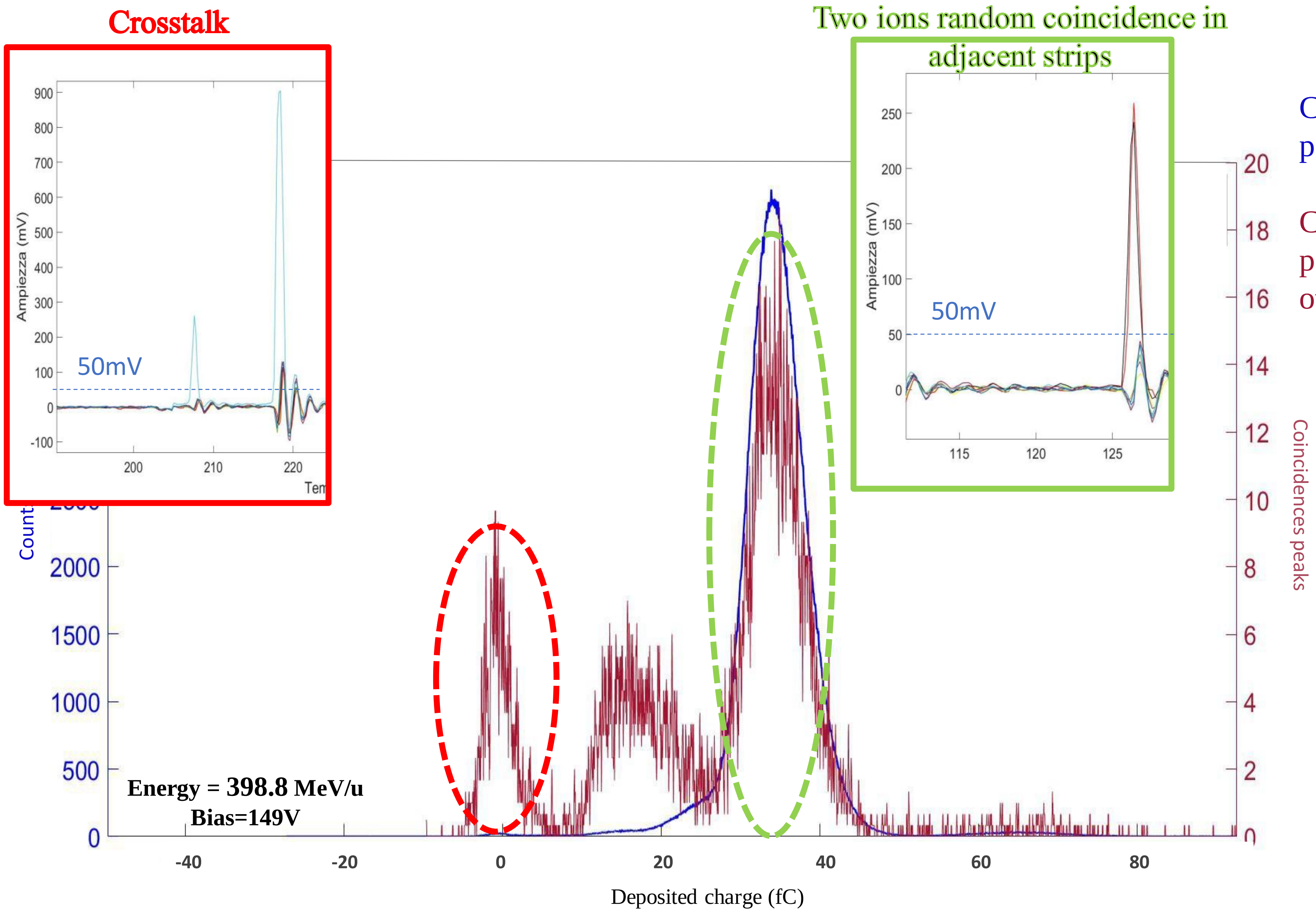
Charge distribution considering all the peaks in all the strips.

Charge distribution considering only the peaks in coincidence ($\Delta t < 0.2$ ns) with other peaks in the adjacent strips.



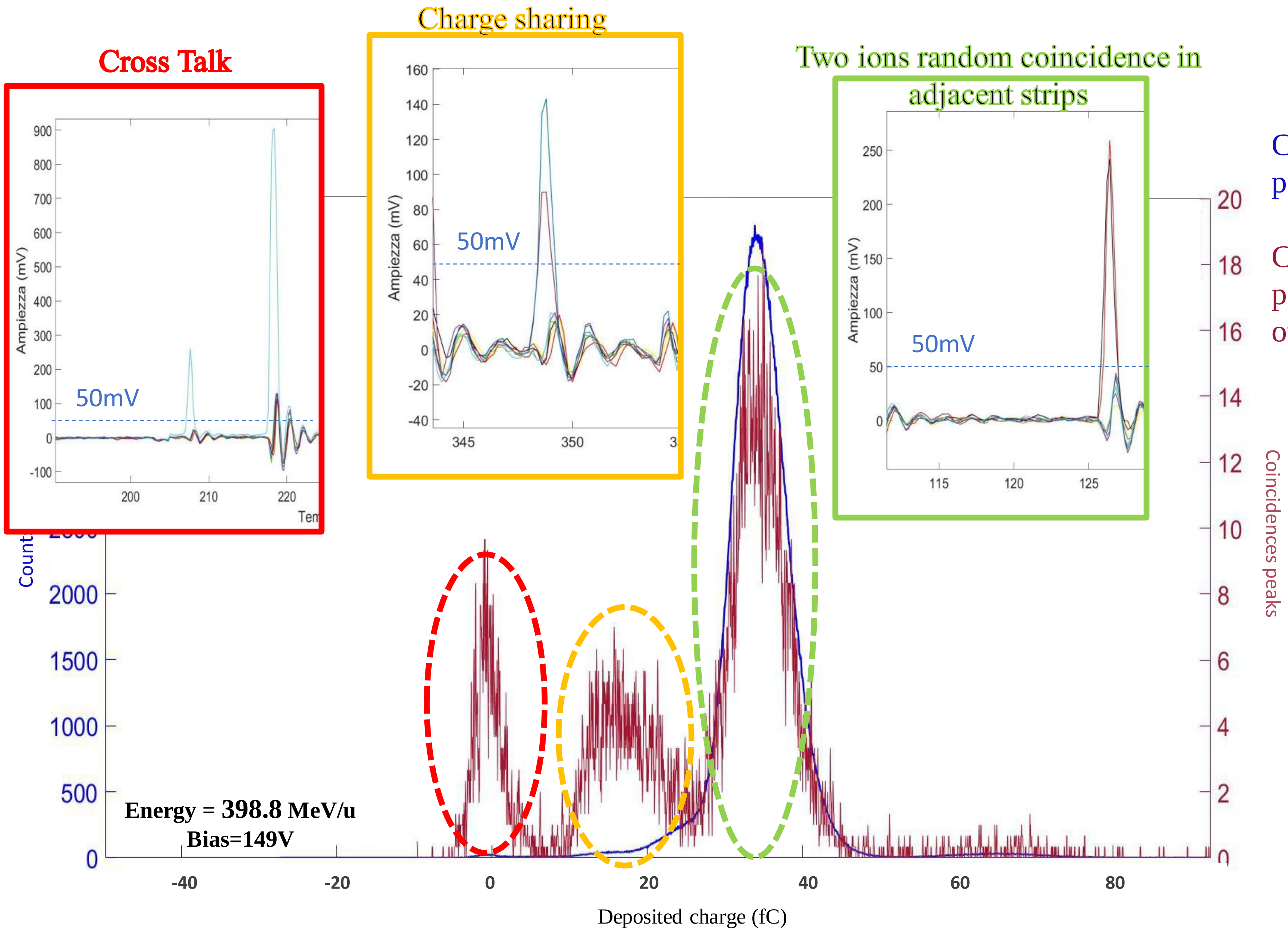
Charge distribution considering all the peaks in all the strips.

Charge distribution considering only the peaks in coincidence ($\Delta t < 0.2$ ns) with other peaks in the adjacent strips.



Charge distribution considering all the peaks in all the strips.

Charge distribution considering only the peaks in coincidence ($\Delta t < 0.2$ ns) with other peaks in the adjacent strips.



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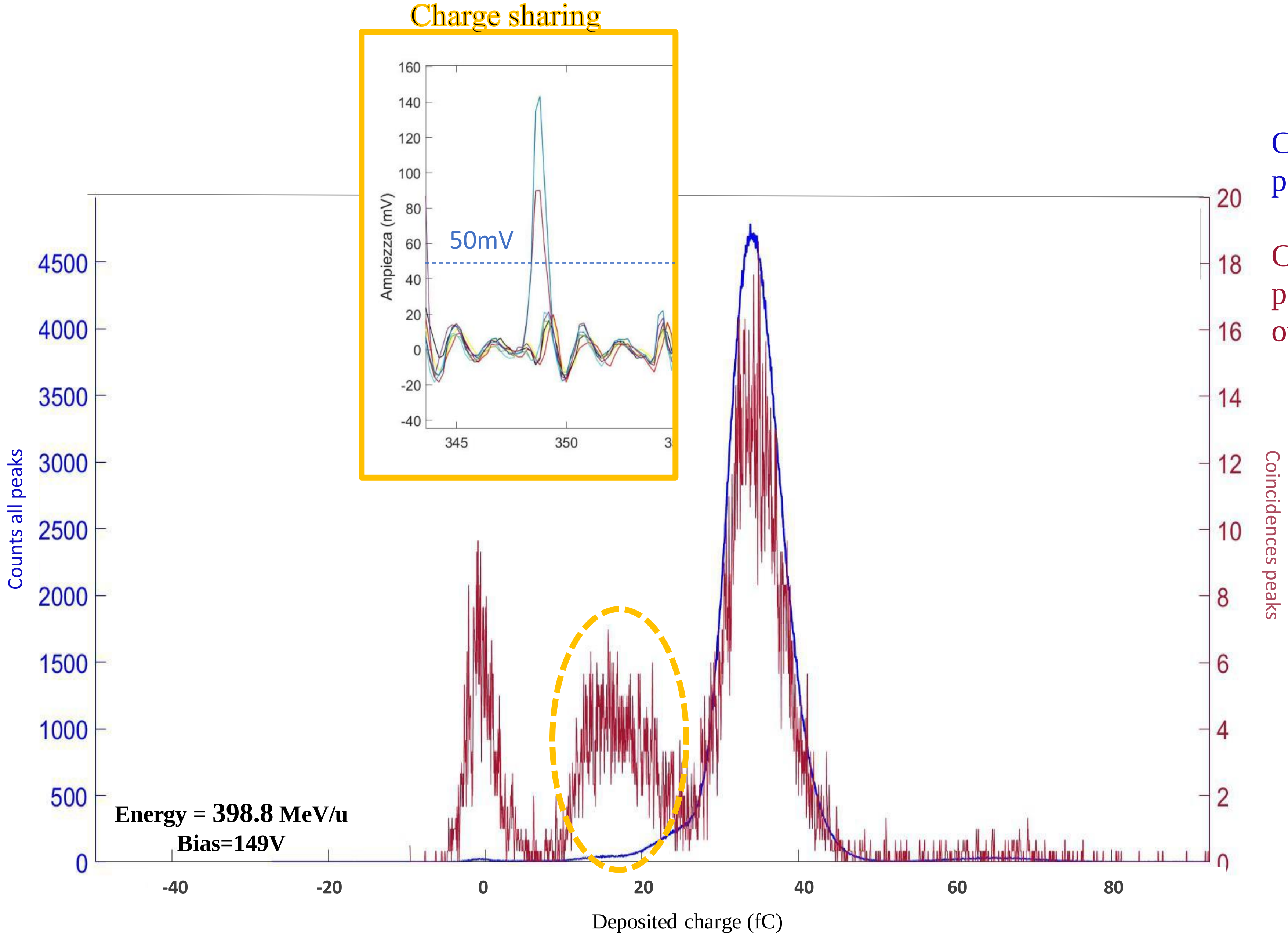


Charge distribution considering all the peaks in all the strips.

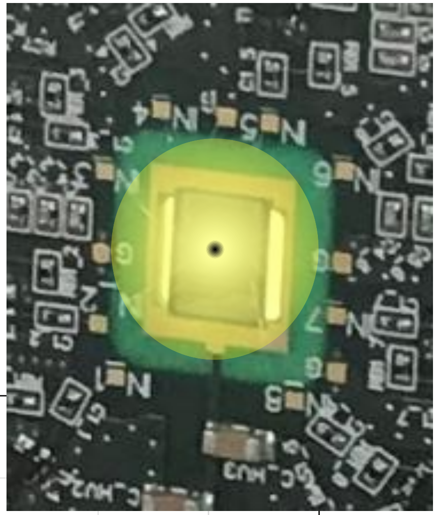
Charge distribution considering only the peaks in coincidence ($\Delta t < 0.2$ ns) with other peaks in the adjacent strips.

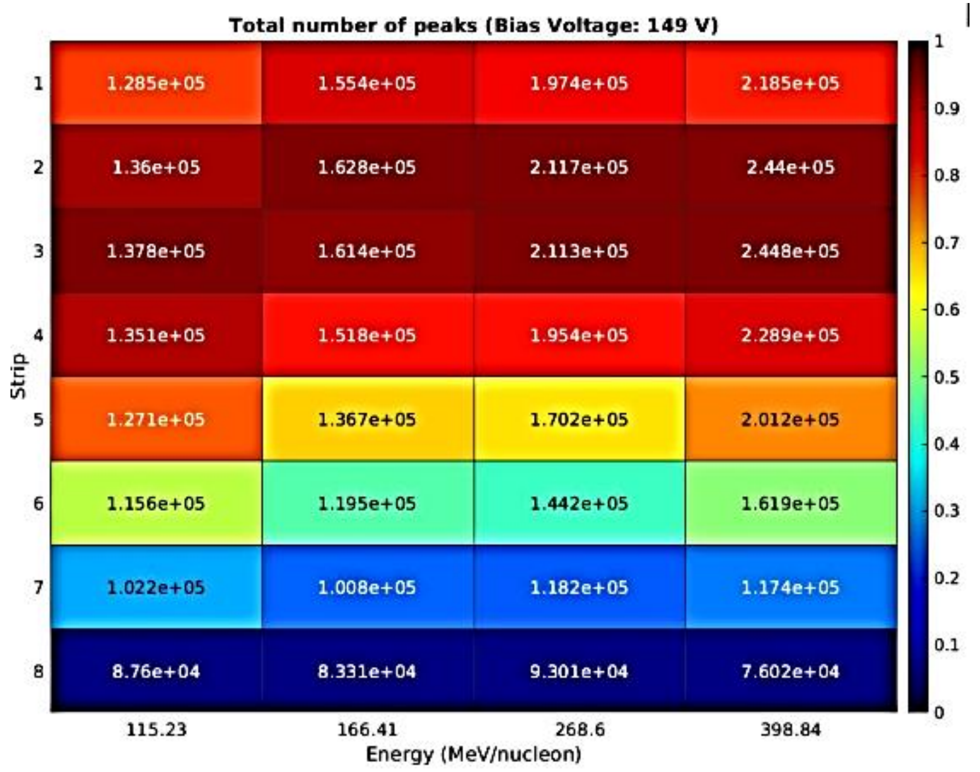
$$\text{Charge sharing} = \frac{A_0}{A_T} \approx 0.1\%$$

The percent of **charge sharing** between adjacent strips are **negligible**.

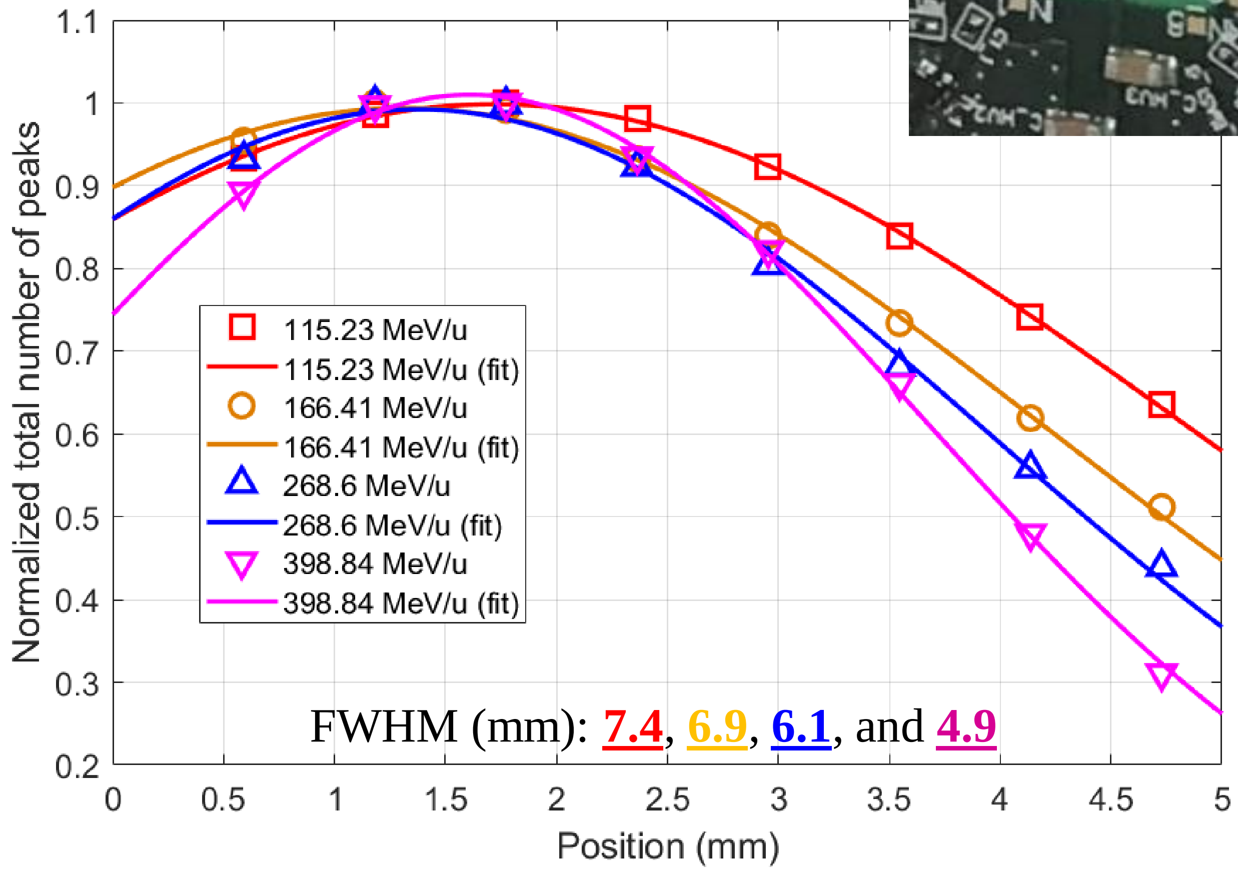
By normalizing the total number of peaks as a function of strip position:

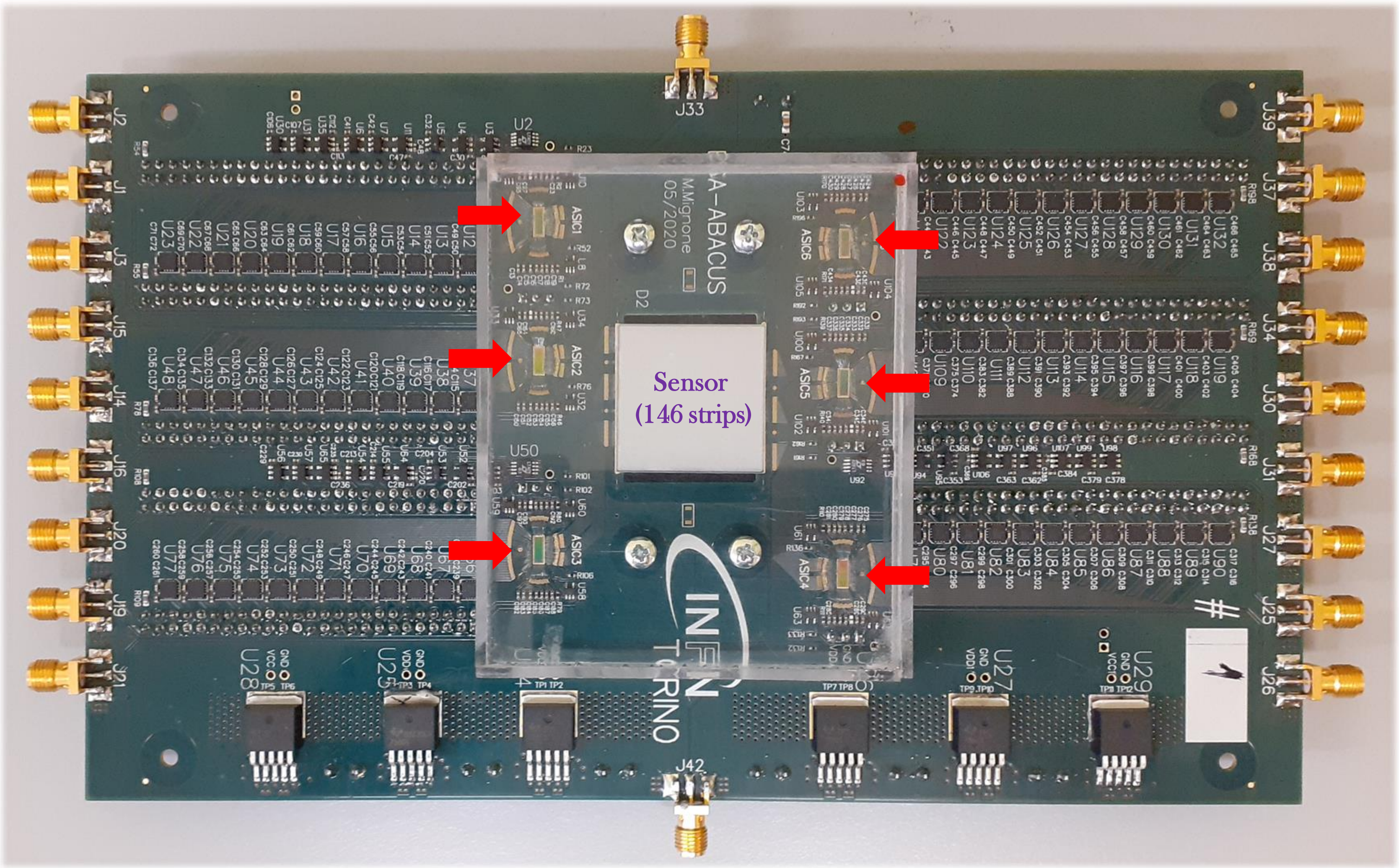
1. The beam was aligned between strips 2 and 4.
2. Beam dimension decreases with increasing energy
3. Beam dimensions extracted from the Gaussian fit agreed with those reported by CNAO.

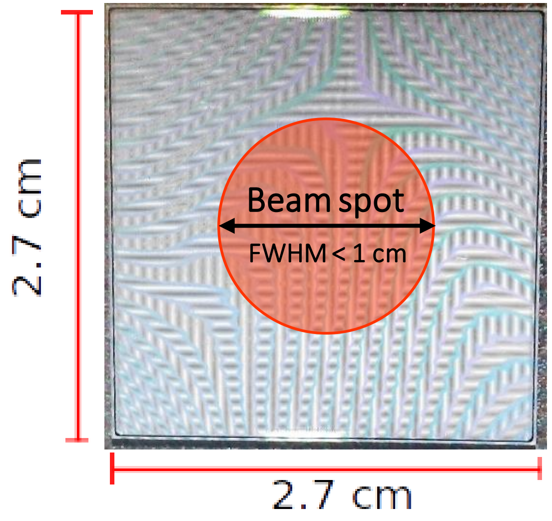




Heatmap of the total number of peaks per strips



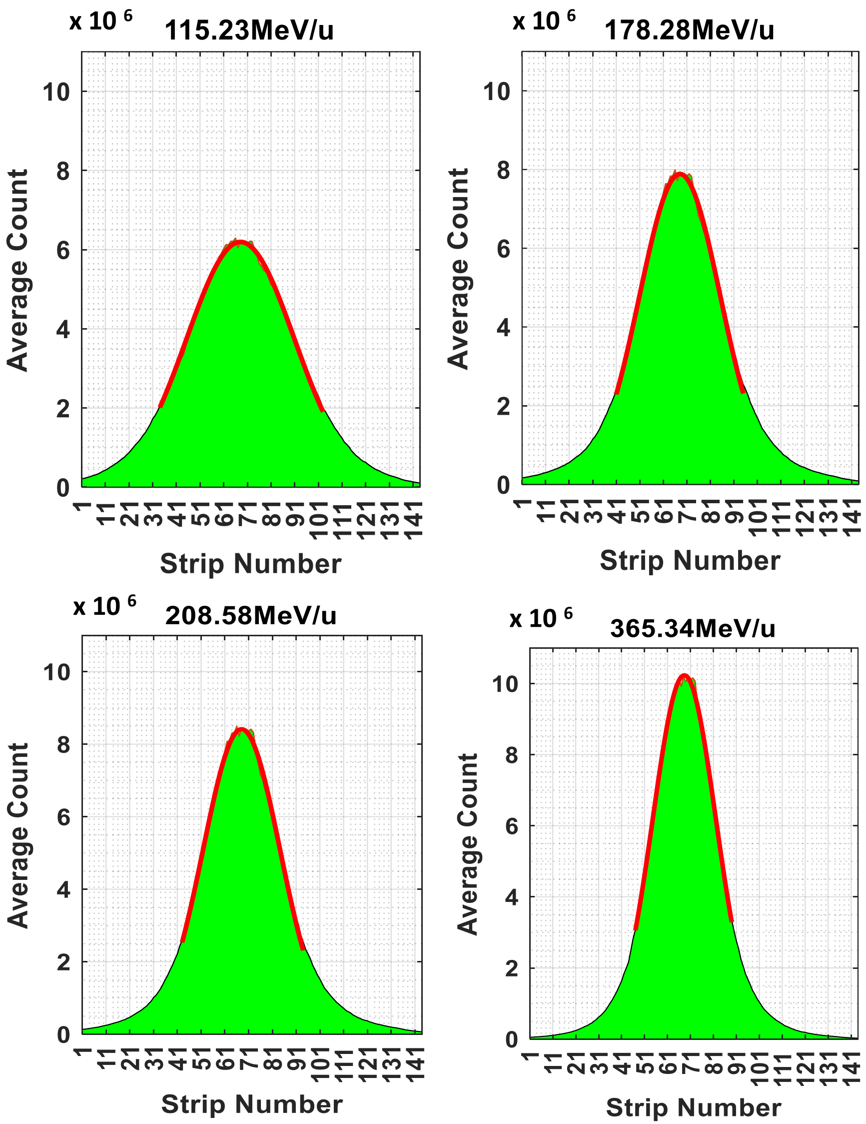


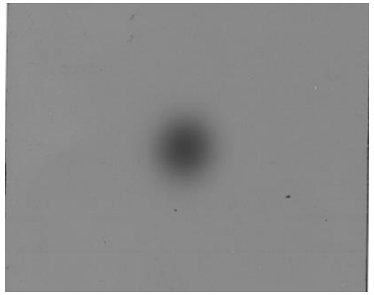


The ABACUS chip (x6)

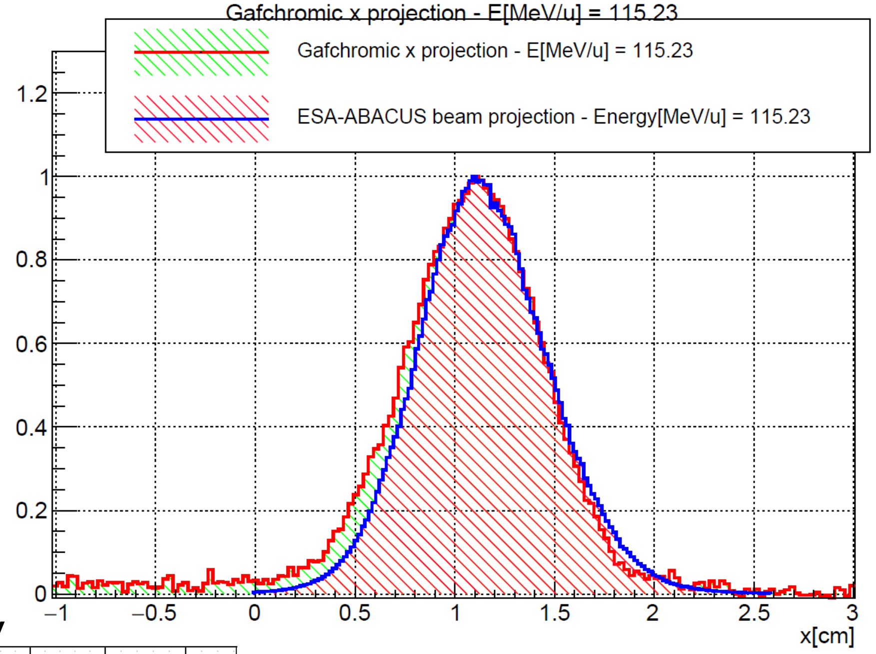
- 110 nm CMOS technology.
- Chip area = 2 × 5 mm^2, 24 channels.
- CSA dynamic range: 4 fC – 150 fC.
- Dead time: ~ 10 ns.

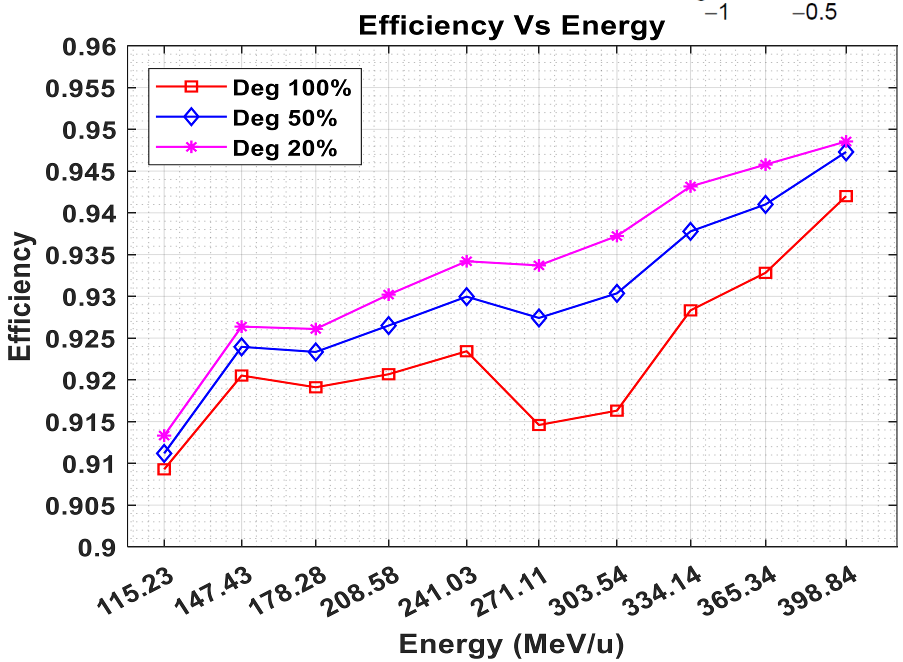
Beam Profile





GAFCHROMIC film for 115MeV/u





The **counting efficiency** for different beam fluences and measured energies is **greater than 90%**.

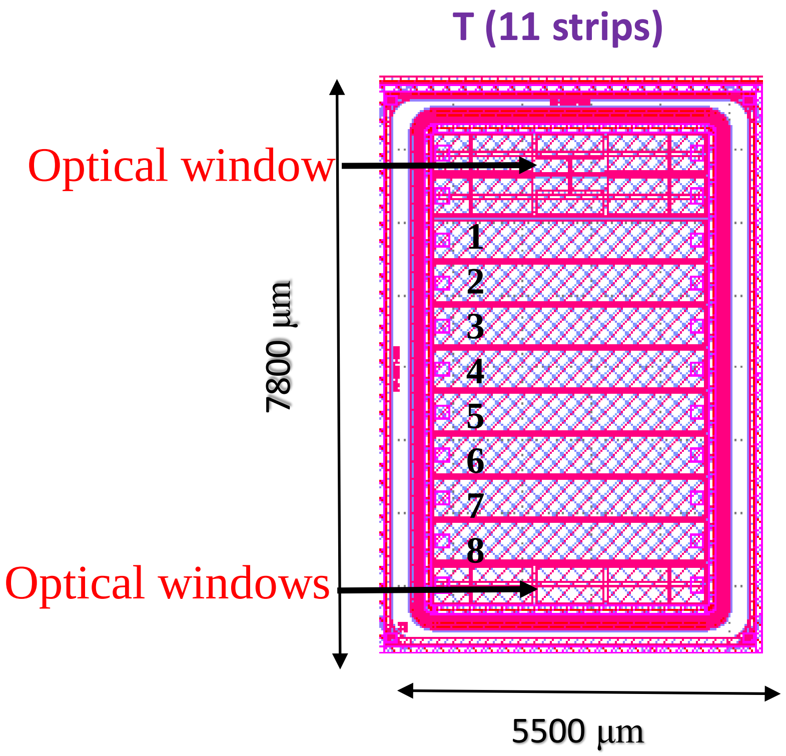
- Tests of thin silicon segmented sensors with therapeutic carbon ions yielded **promising results**:
    1. Good separation between signal and noise for all the clinical energies.
    2. Signal duration that decreases as the bias voltage increases, reaching values of less than 2 ns.
    3. A single hit time resolution of ~25 ps for the two extreme energy values: 115.2 and 398.8 MeV/u.
    4. Charge sharing and signal cross talk indicate a negligible overall effect.
    5. First tests of the ESA-ABACUS board proved the feasibility of directly measuring particle rate and beam shape with high efficiency and uniformity.

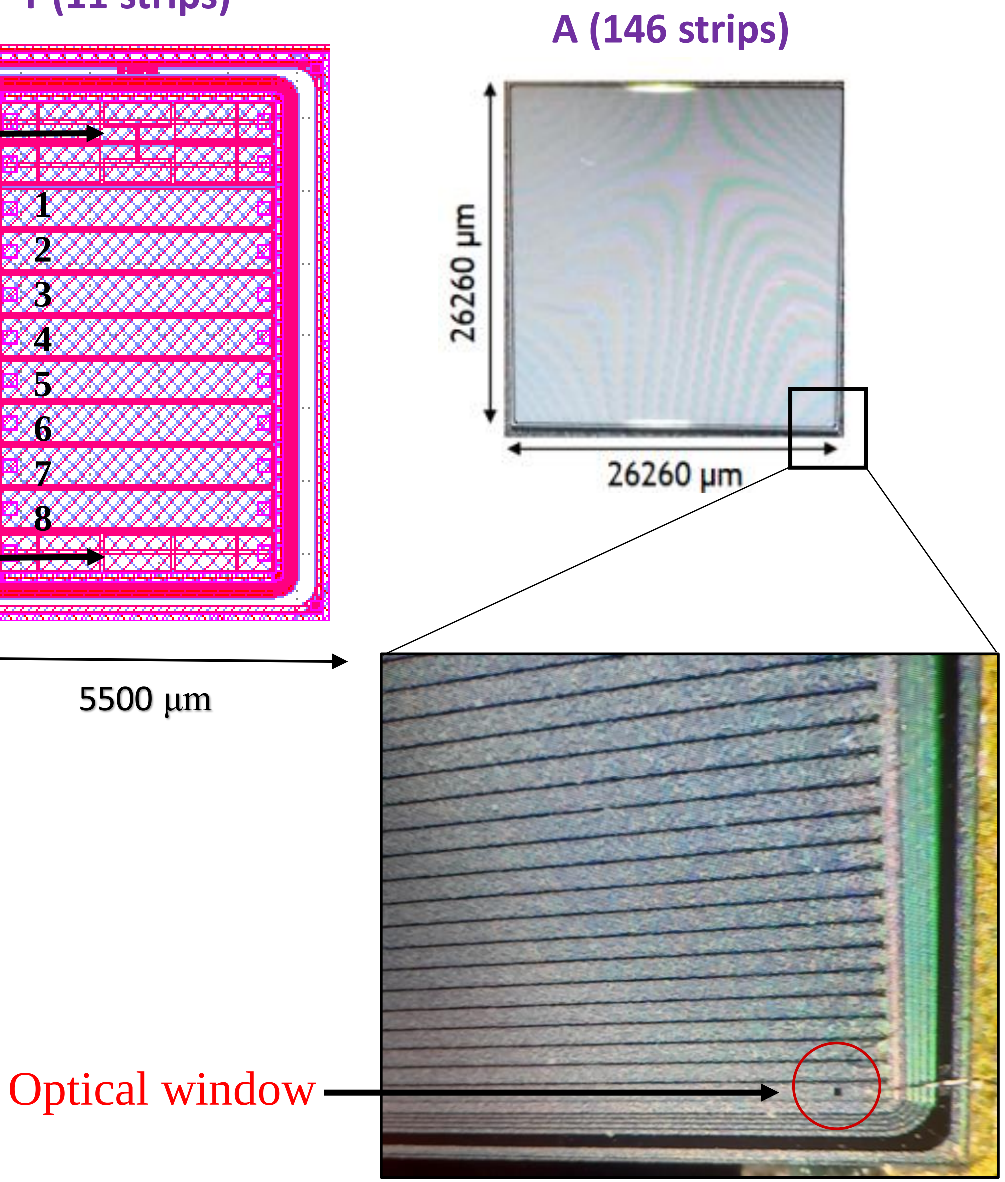
- Next steps:
    - Further studies are ongoing to mitigate the pile-up effect and other sources of systematic errors.
    - Coupling of a PicoTDC to the ESA-ABACUS board to perform time measurements.

THANK FOR YOUR ATTENTION!!

Back-up Slides

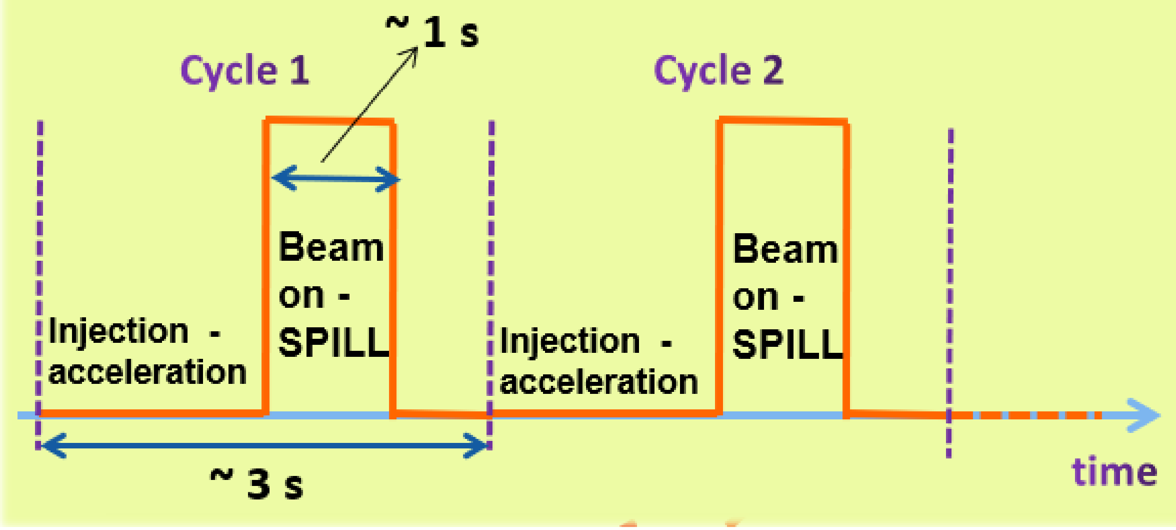
Parameters	Type A	Type T
Dimension (mm)	26.3 x 26.3	7.8 x 5.5
Area (mm²)	690	43
Active thickness (μm)	60	45/60
Total thickness (μm)	630	70/615/630
Substrate	Si-Si	Epi/Si-Si
Number of strips	146	11
Strips dimension (mm)	26.2 x 0.1	4.0 x 0.5
Strip Area (mm²)	2.99	2.20
Breakdown voltage (V)	**~ 200**	**~ 300**

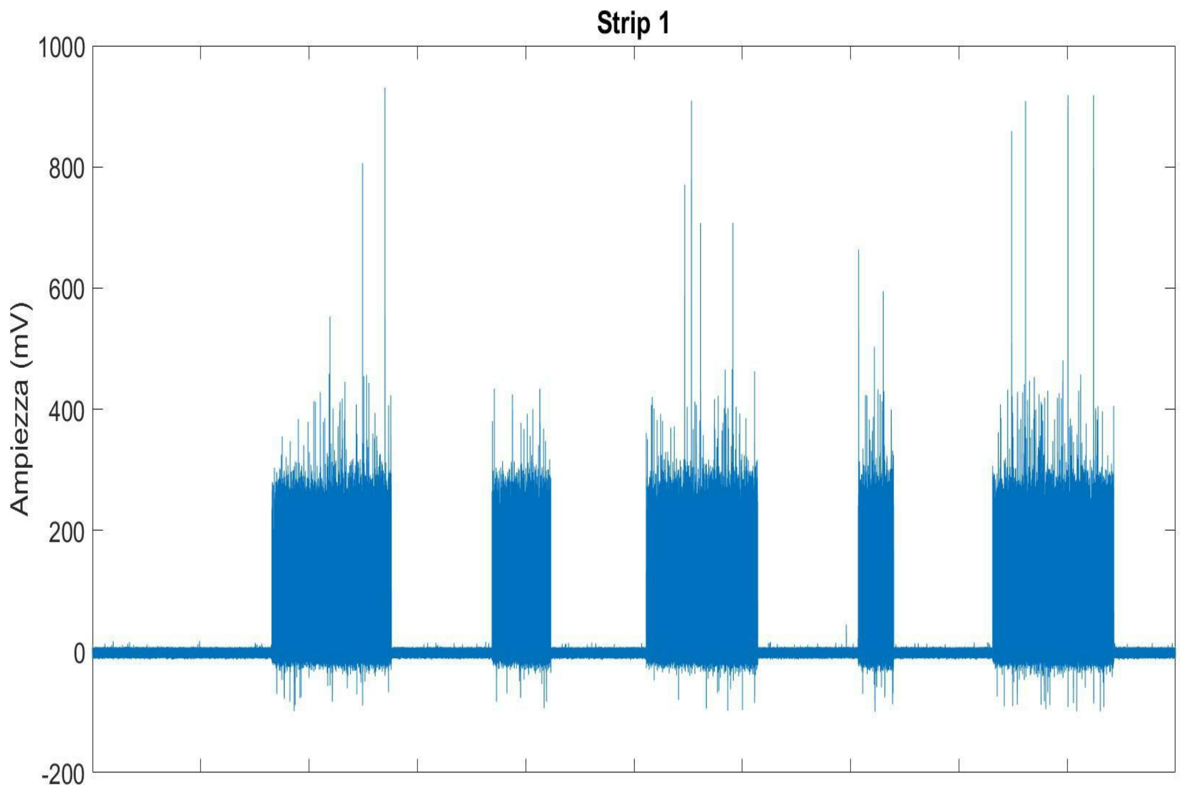




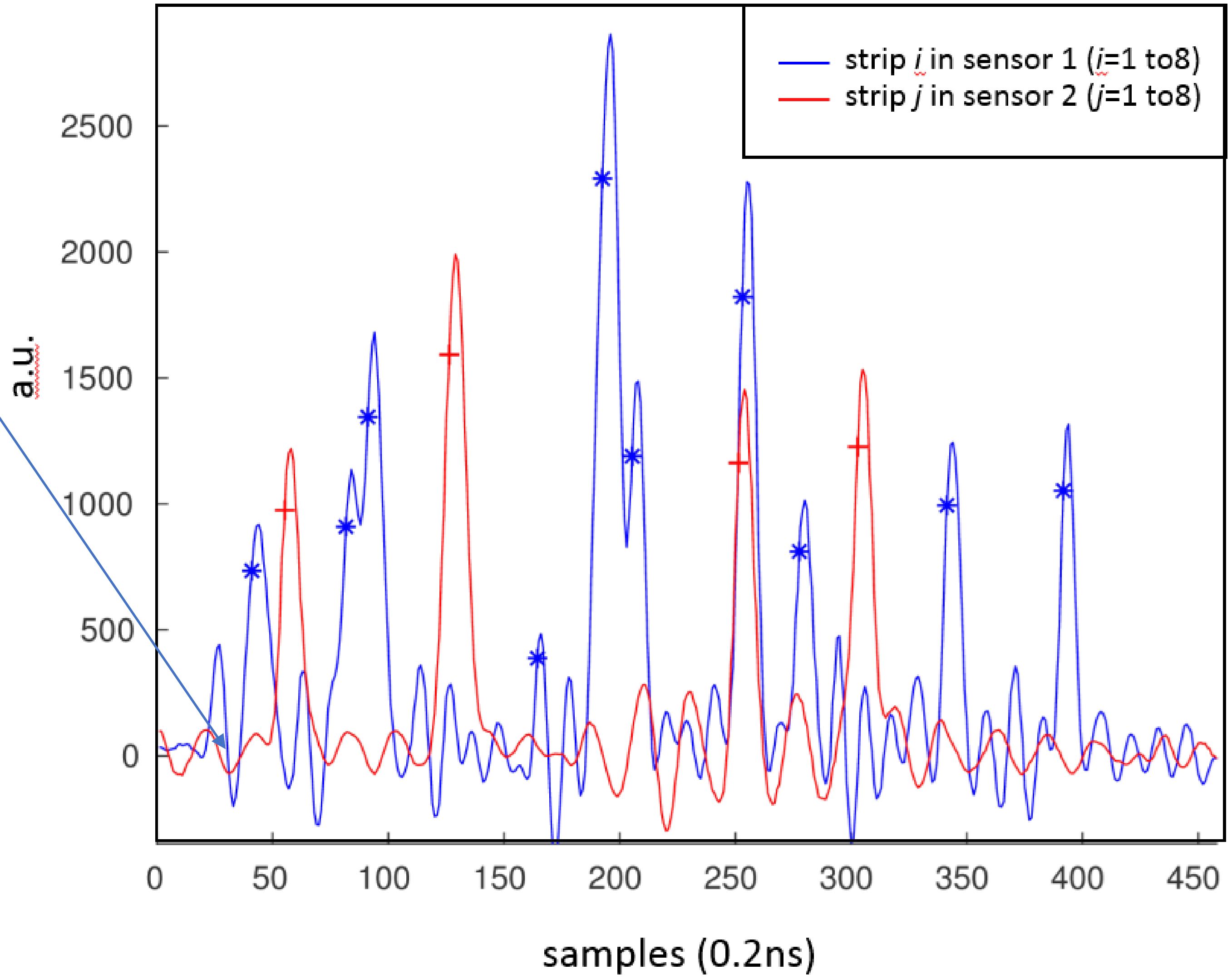
TIME STRUCTURE of the BEAM

The acceleration process in a synchrotron for hadron therapy occurs in *cycles*





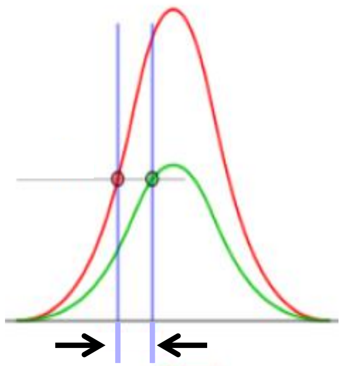
1. Zero level determination



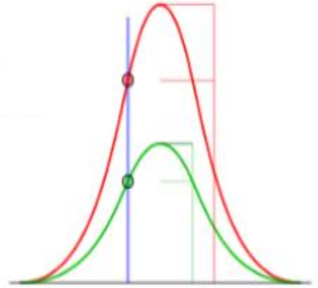
1. Zero level determination

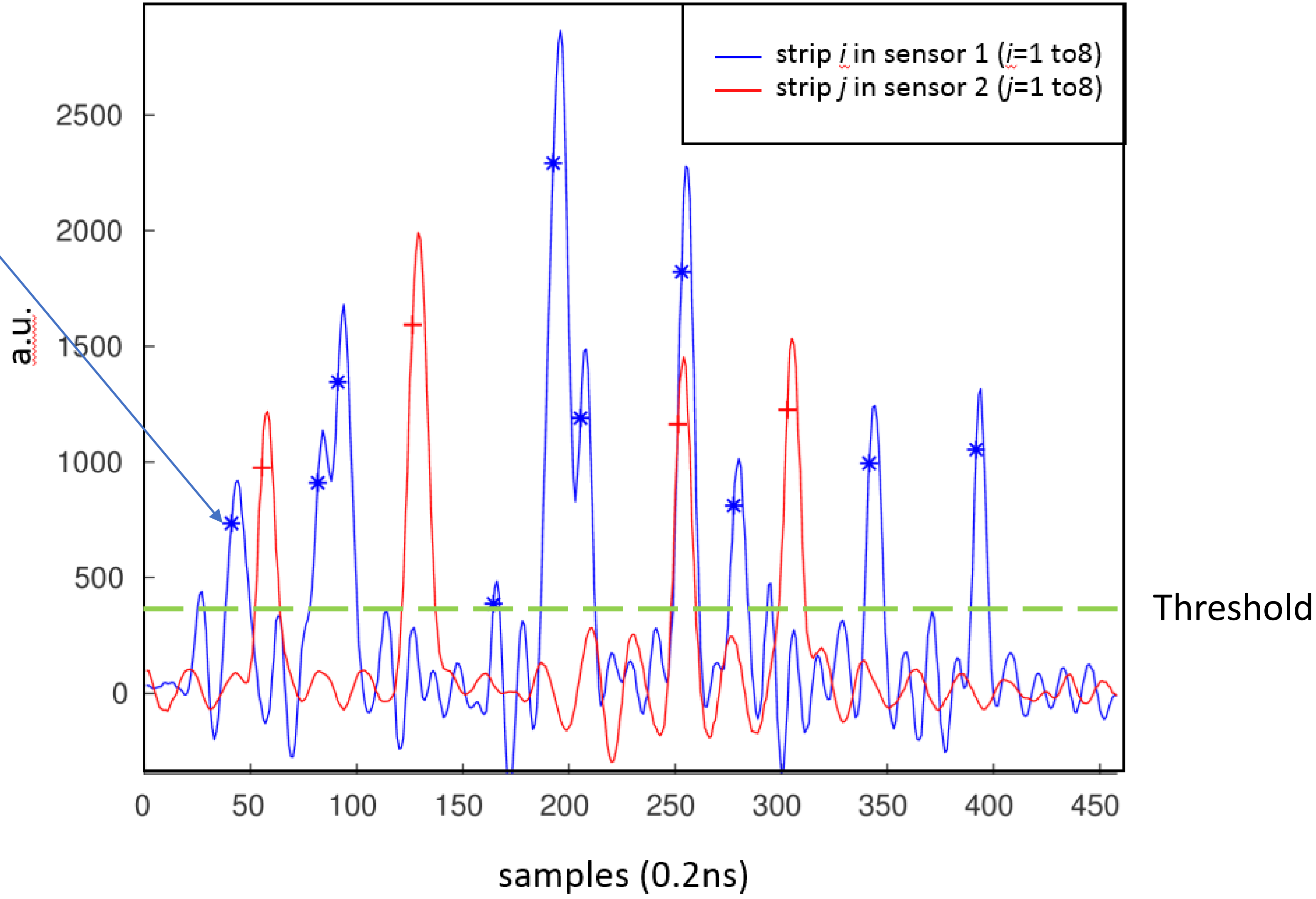
2. If the signal is over a threshold, the proton arrival time is determined as the 80% of the peak maximum. (it was used constant fraction to reduce the time walk effect).

$t_2 \neq t_1$



$t_2 = t_1$

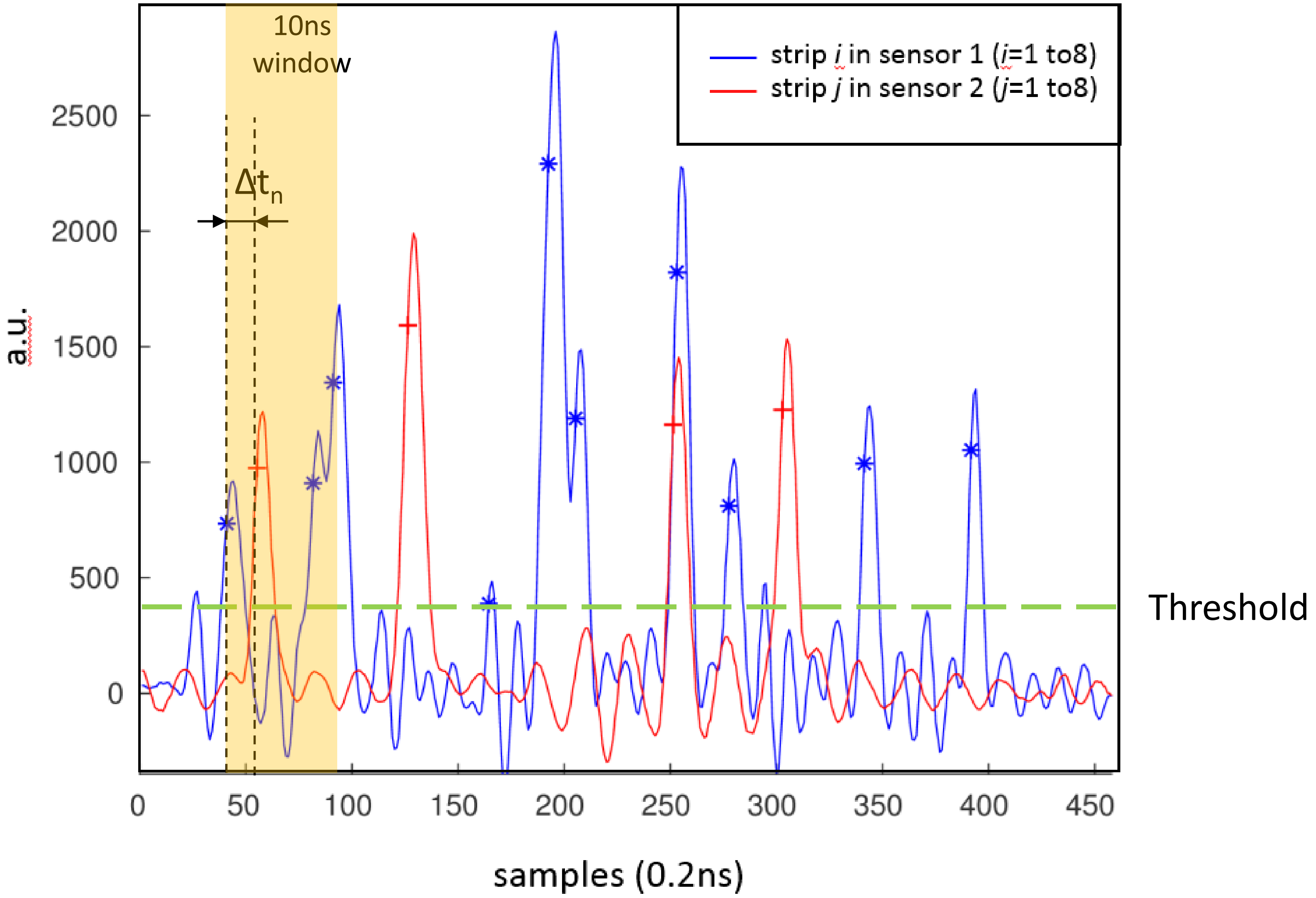




1. Zero level determination

2. If the signal is over a threshold, the proton arrival time is determined as the 80% of the peak maximum. (it was used constant fraction to reduce the time walk effect).

3. A 10ns window is used to extract all the time difference (Δt) between the peaks in sensor1 with those in sensor 2.



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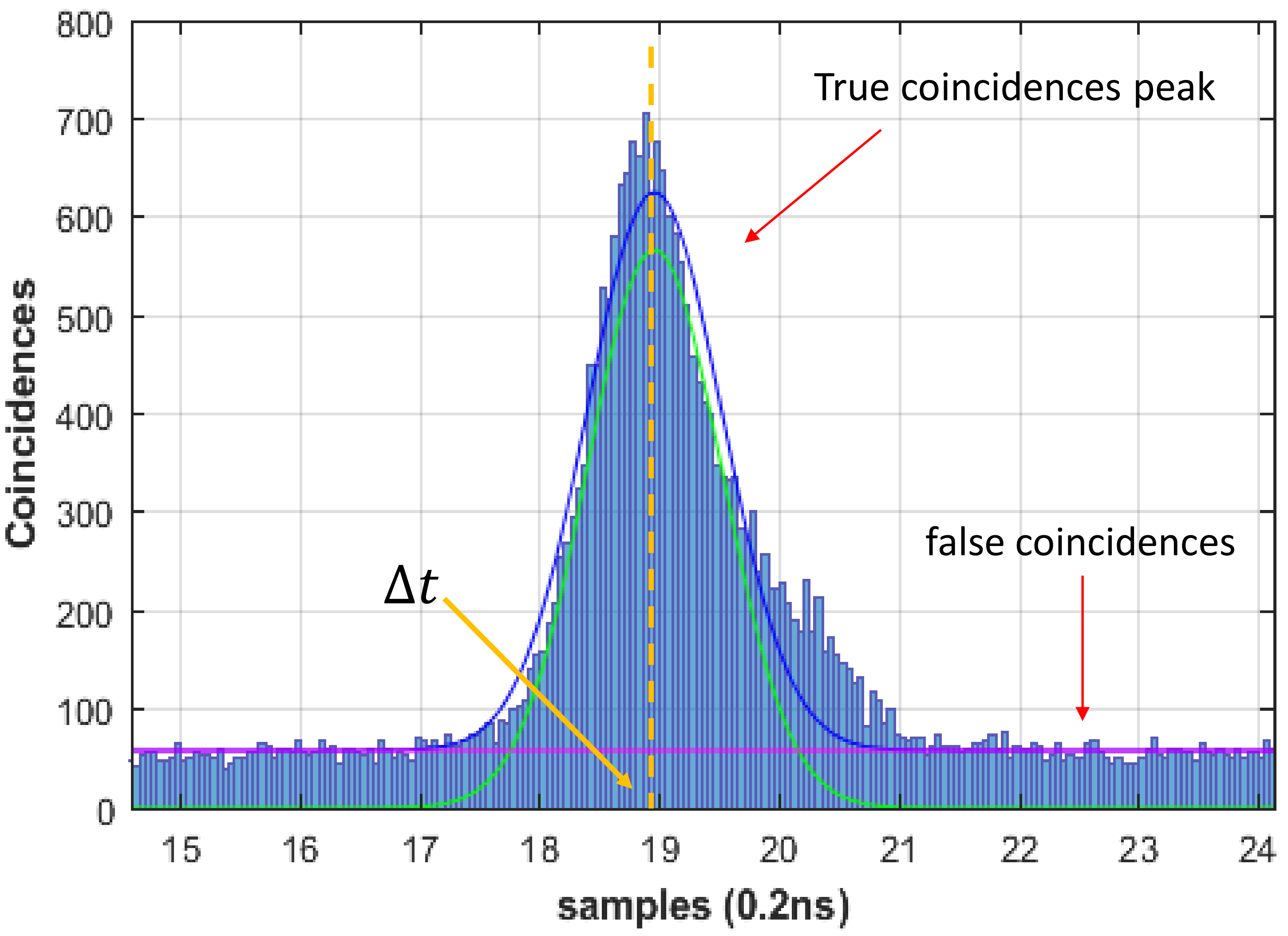
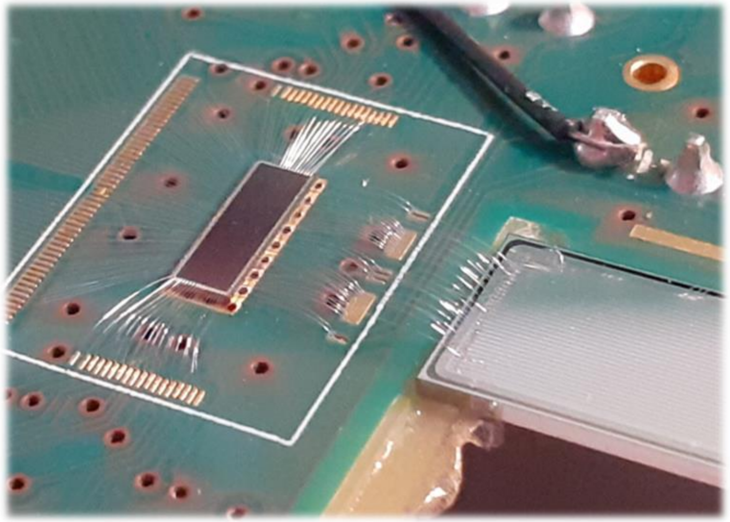
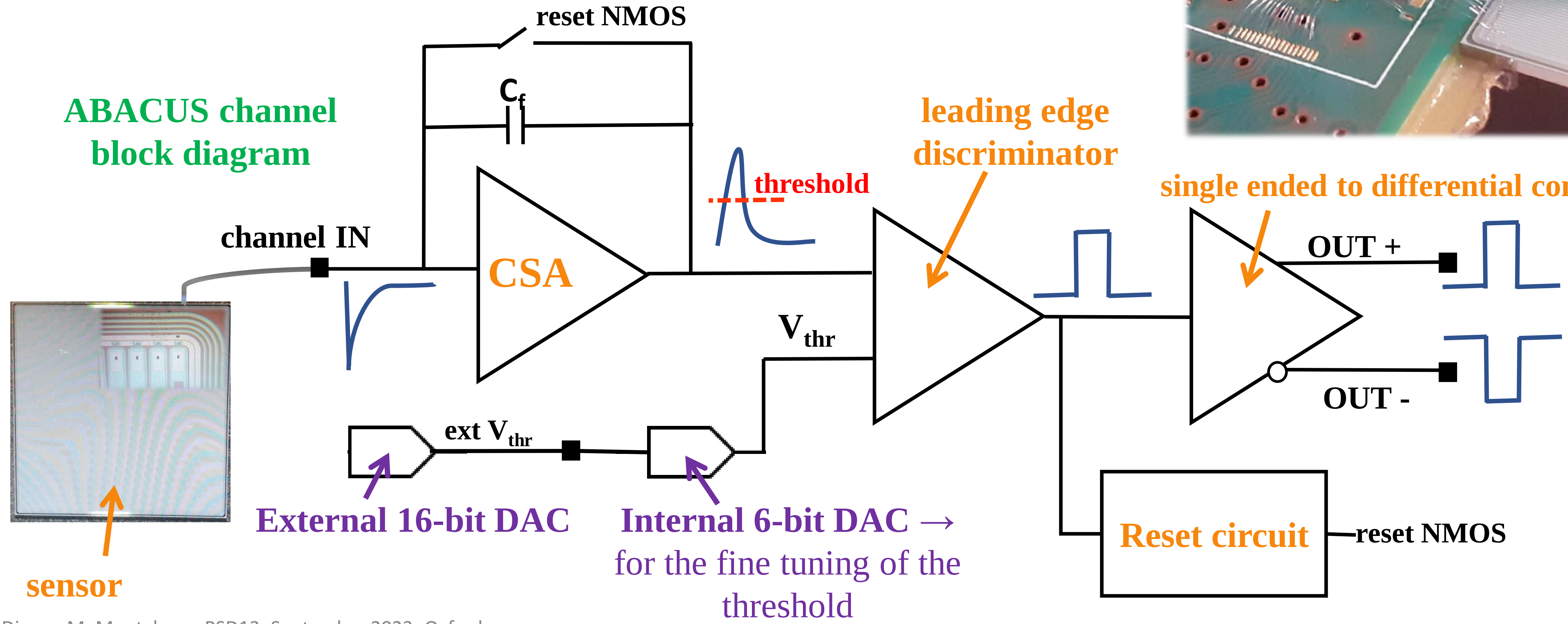
4. All the Δt are grouped in a histogram. A Double Gaussian fit is done to extract the true-coincidences peak.

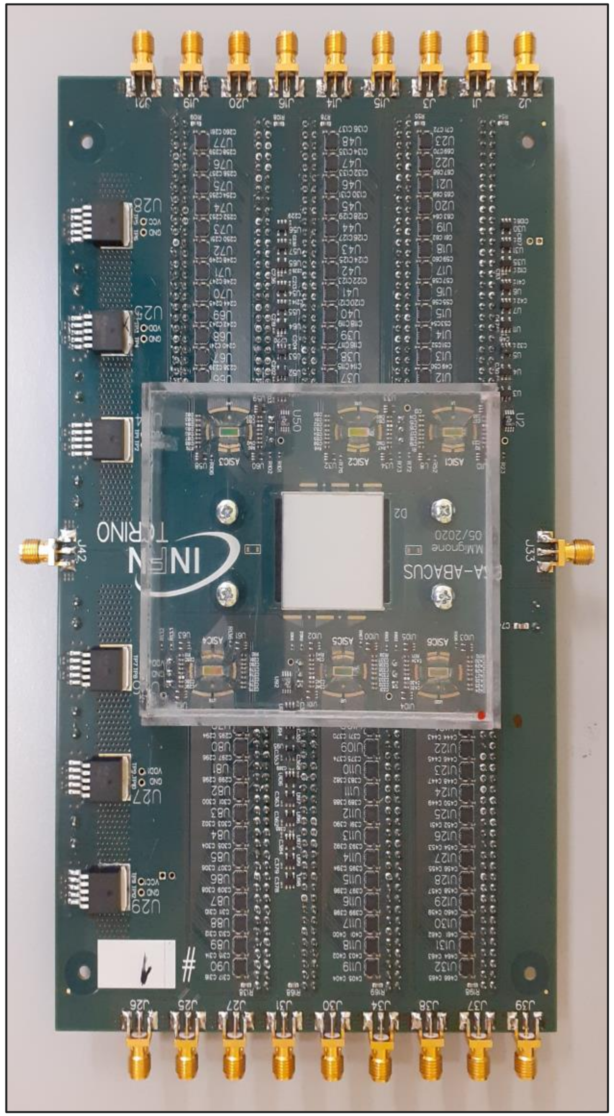


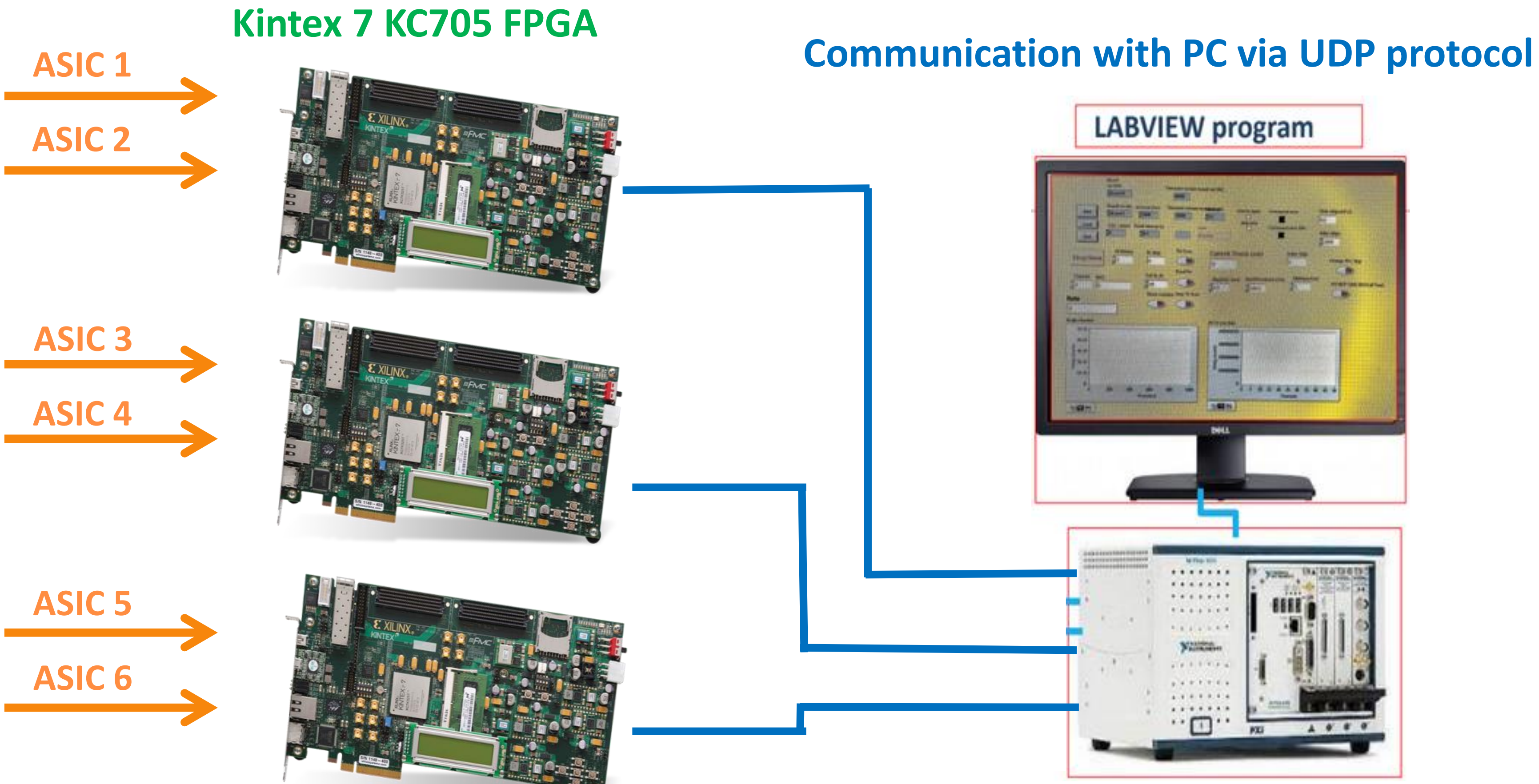
Fausti et Al,10.1016/j.nima.2020.164666



- 110 nm CMOS technology, 24 channels
- CSA dynamic range: 4 fC – 150 fC
- First characterization results:
  - Dead time < 10 ns







On FPGA boards a dedicated firmware implements a counter for each of the 48 channels to store the number of 0-1 transitions.

A LabVIEW program is used for:

- reading counters and time stamps from FPGA boards
- saving data for offline analysis
- setting threshold voltages