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Carbon ions tracking in particle therapy: first tests with thin silicon sensors

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MOTIVATION

MoVeIt project: Development and upgrade of the INFN irradiation facilities including advanced monitoring systems.

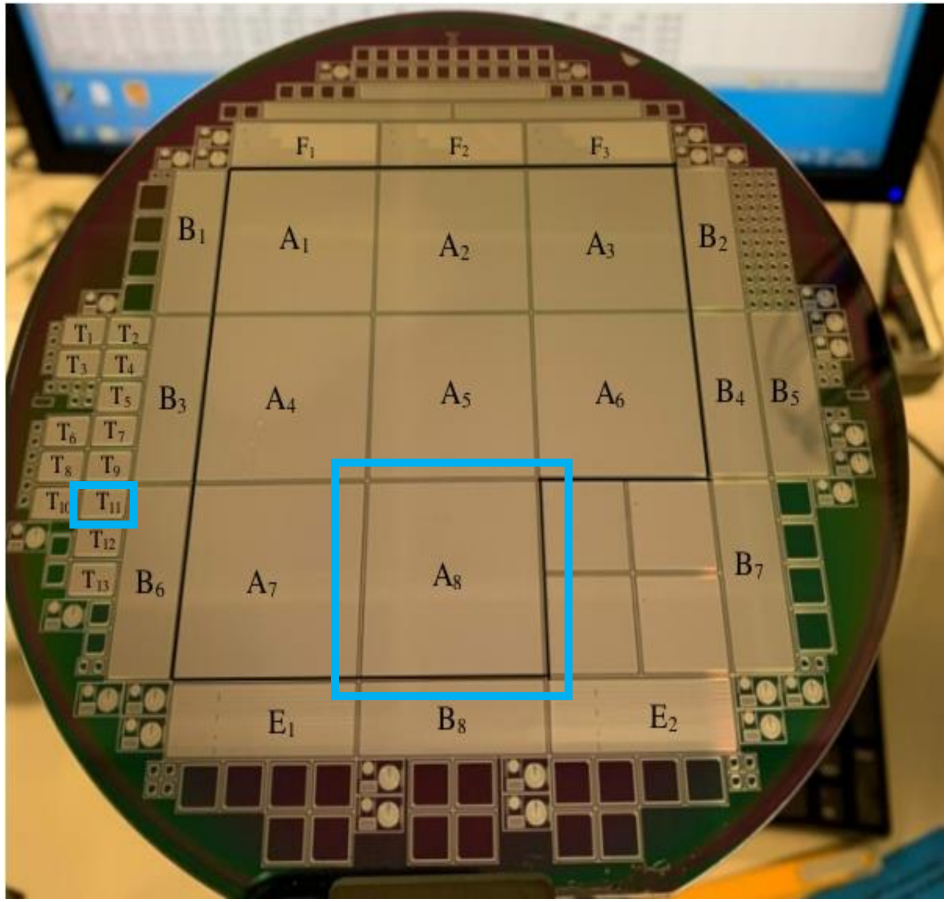
Development of two prototypes using UFSD (LGAD optimized for time resolution) for beam monitoring:

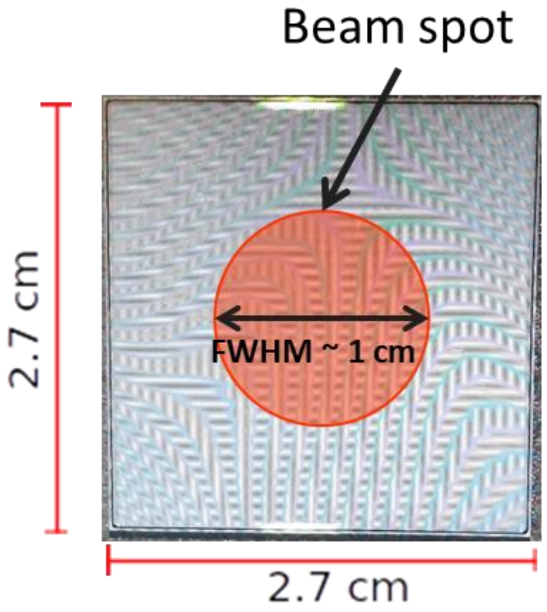
1. **to directly count individual protons.**
2. to measure the beam energy with time-of-flight techniques, using a telescope of two UFSD sensors.

Actual project: Superconducting Ion Gantry (SIG)

THE MoVeIT SENSORS

Silicon sensors used for the first tests with carbon ions. Designed and produced by the Fondazione Bruno Kessler (FBK, Trento, Italy).





Sensors T10-T11

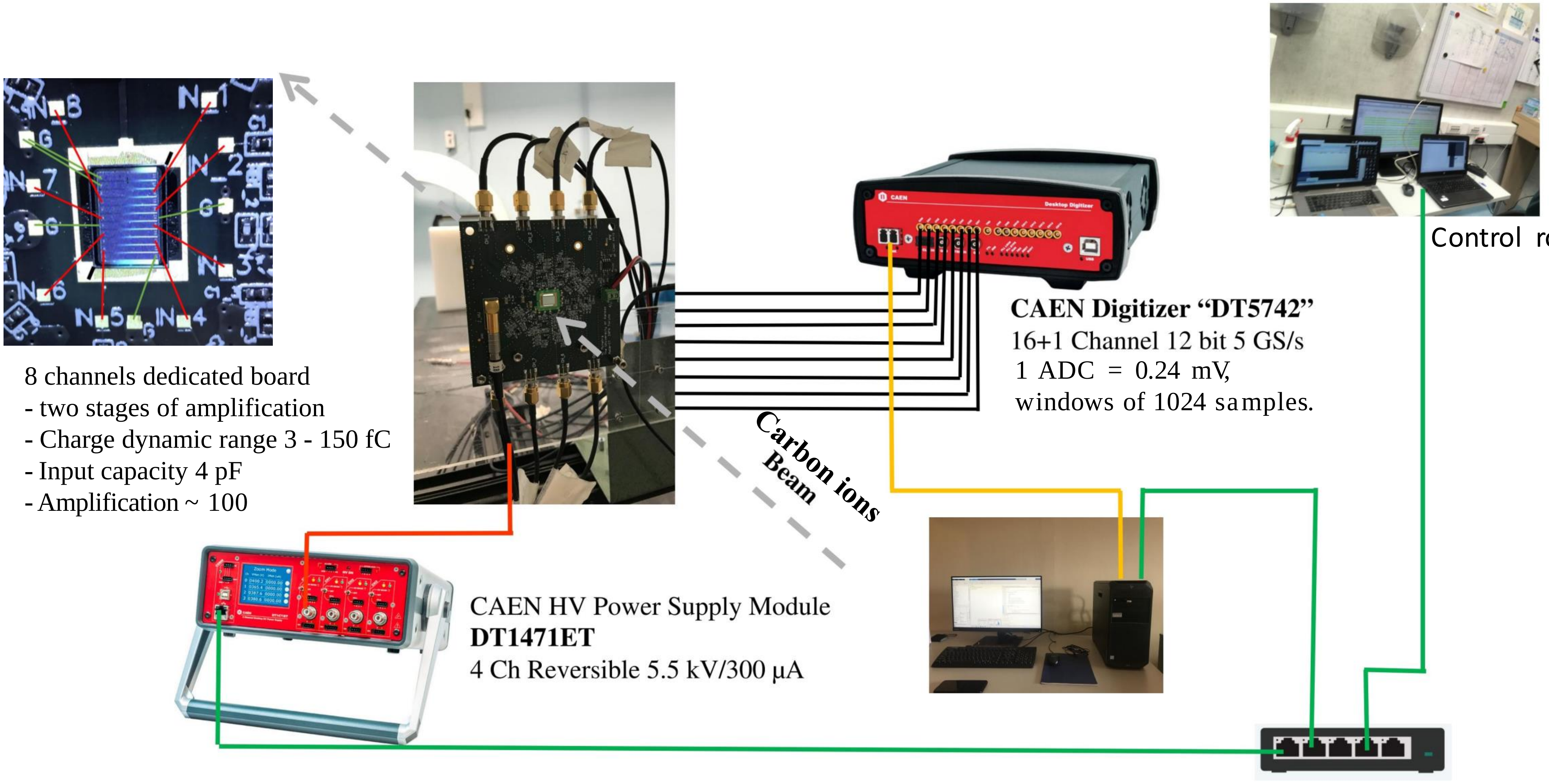
- 11 strips
- 0.55 mm width
- 4.00 mm length,
- 591 μm pitch,
- 2 mm^2 area/strip
- 60 μm active thickness.
- No gain sensors were used for carbon ions
- Si-Si substrate

Sensor A1-A8

- 146 strips
- Width → 114 μm
- Pitch → 180 μm
- Thickness → 50 μm
- Internal gain → 5-20
- Capacitance → 7 pF

EXPERIMENTAL SETUP FOR SIGNAL CHARACTERIZATION

Experimental setup used to characterize the thin silicon sensor with Carbon ions beams



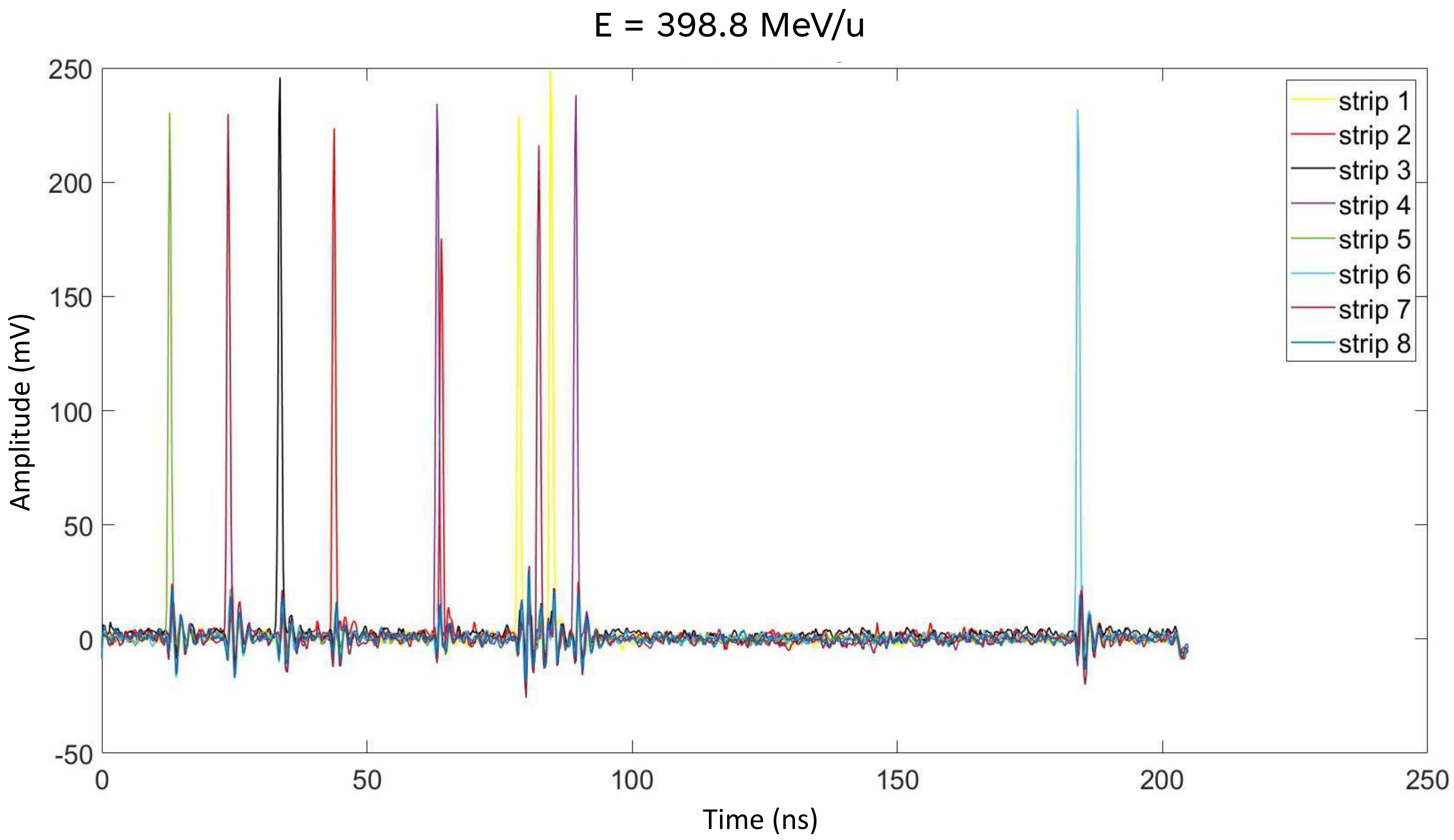
EXPERIMENTAL CONDITIONS

Measurements were performed at the CNAO synchrotron with different bias voltages to study: signal amplitude, signal to noise ratio, signal duration, time resolution and charge sharing.

Four beam energies: 115.2, 166.4, 268.6, 398.8 MeV/u; Number of spills: 10-20 for each run; Number of carbon ions per spill: 8×10^{7}; Room Temperature; Nine bias voltages: values from 9V to 300V. Detector placed at the isocenter.

EXAMPLE OF WAVEFORM

Example of 204 ns acquisition time window produced by ions of 398.84 MeV/u in different strips of the sensor with a bias voltage of 149 V.



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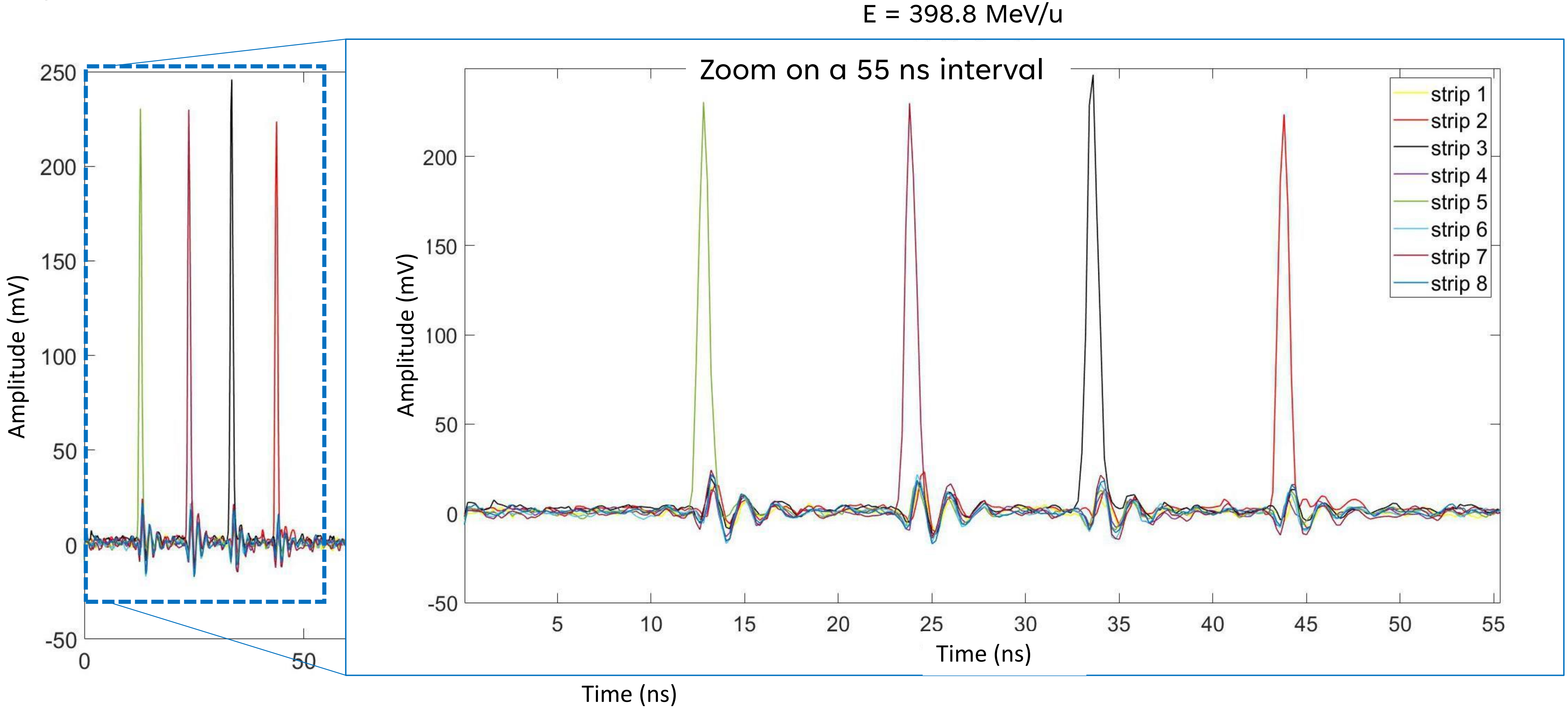
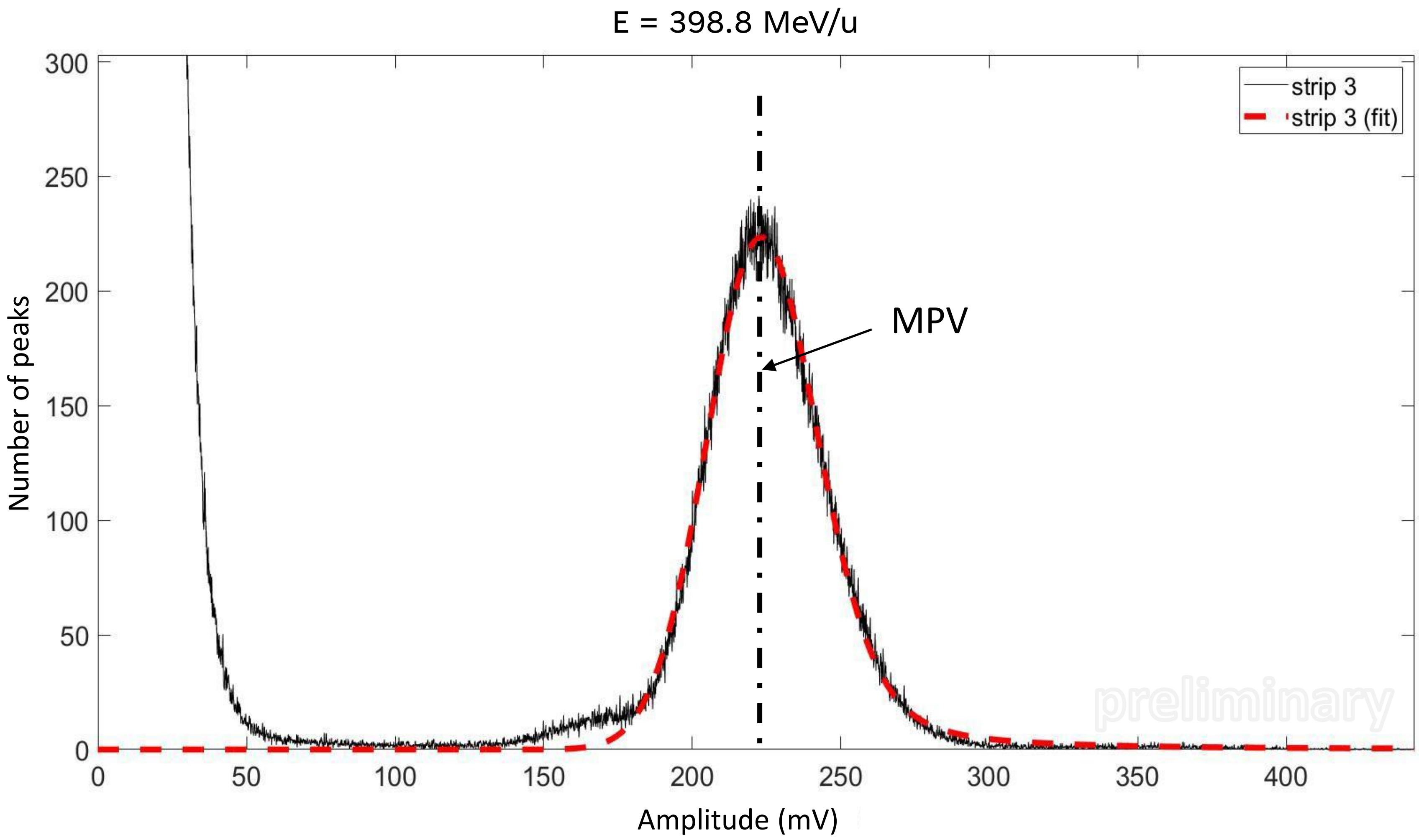


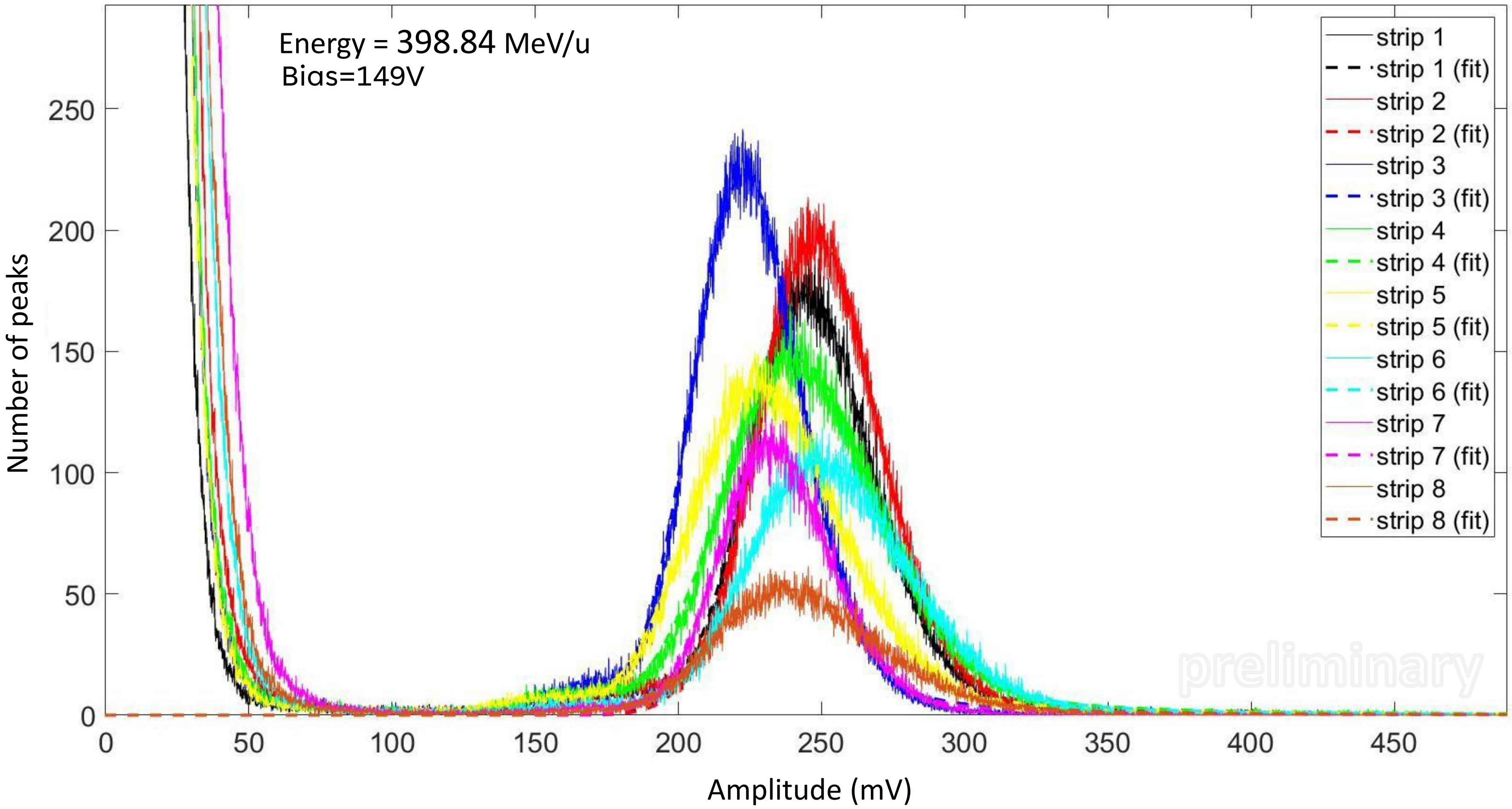
AMPLITUDE DISTRIBUTION

Amplitude distribution for highest energy in strip3. Good separation between signal and noise. The MPV extracted from a Langaus fit. It was observed a charge sharing effect.



AMPLITUDE DISTRIBUTION BY CHANNELS

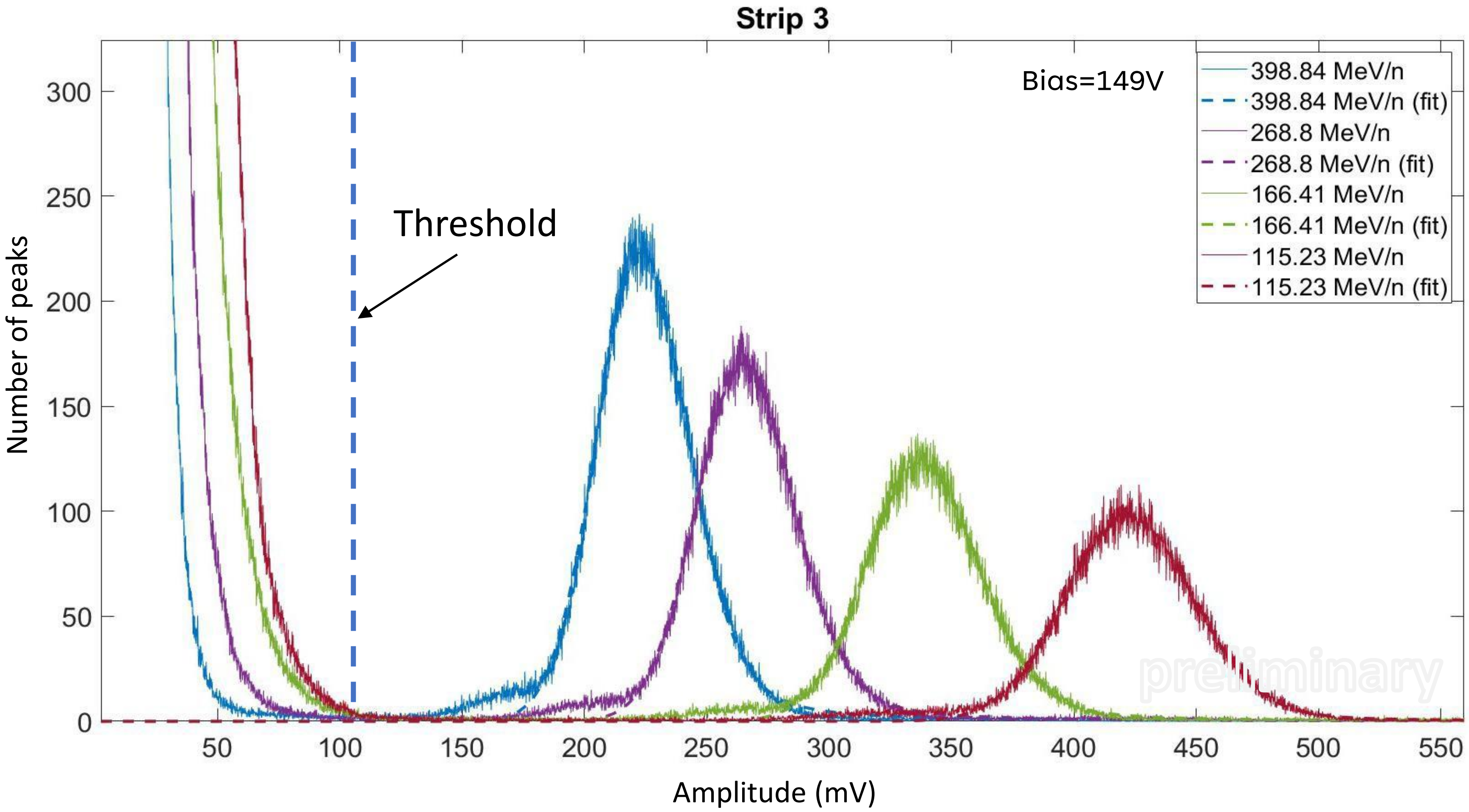
Number of peaks vs. peaks amplitude for carbon ions with an energy of 398.84 MeV/u and using a bias voltage of 149V.



The variation of the MPVs between 220 to 240 mV is related to the tolerance of the electronics on the front-end board, which makes the gain for each channel different.

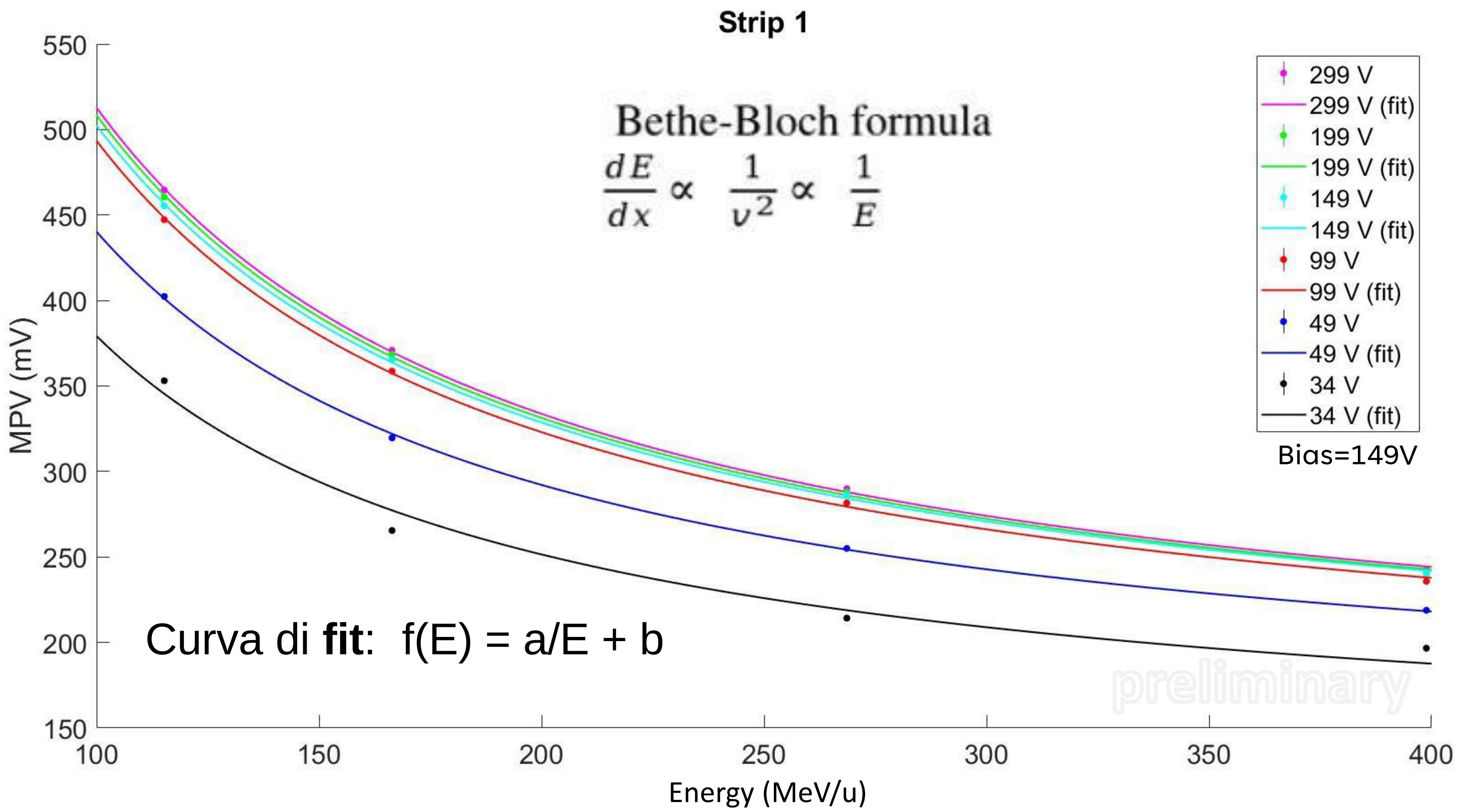
AMPLITUDE DISTRIBUTION FOR DIFFERENT BEAM ENERGIES

Amplitude distribution for the clinical range energies in the strip 3 and 149V bias voltage. Signal/noise separation could be achieved by choosing an appropriate threshold. The MVP increases with decreasing carbon ion energy beam, as expected.



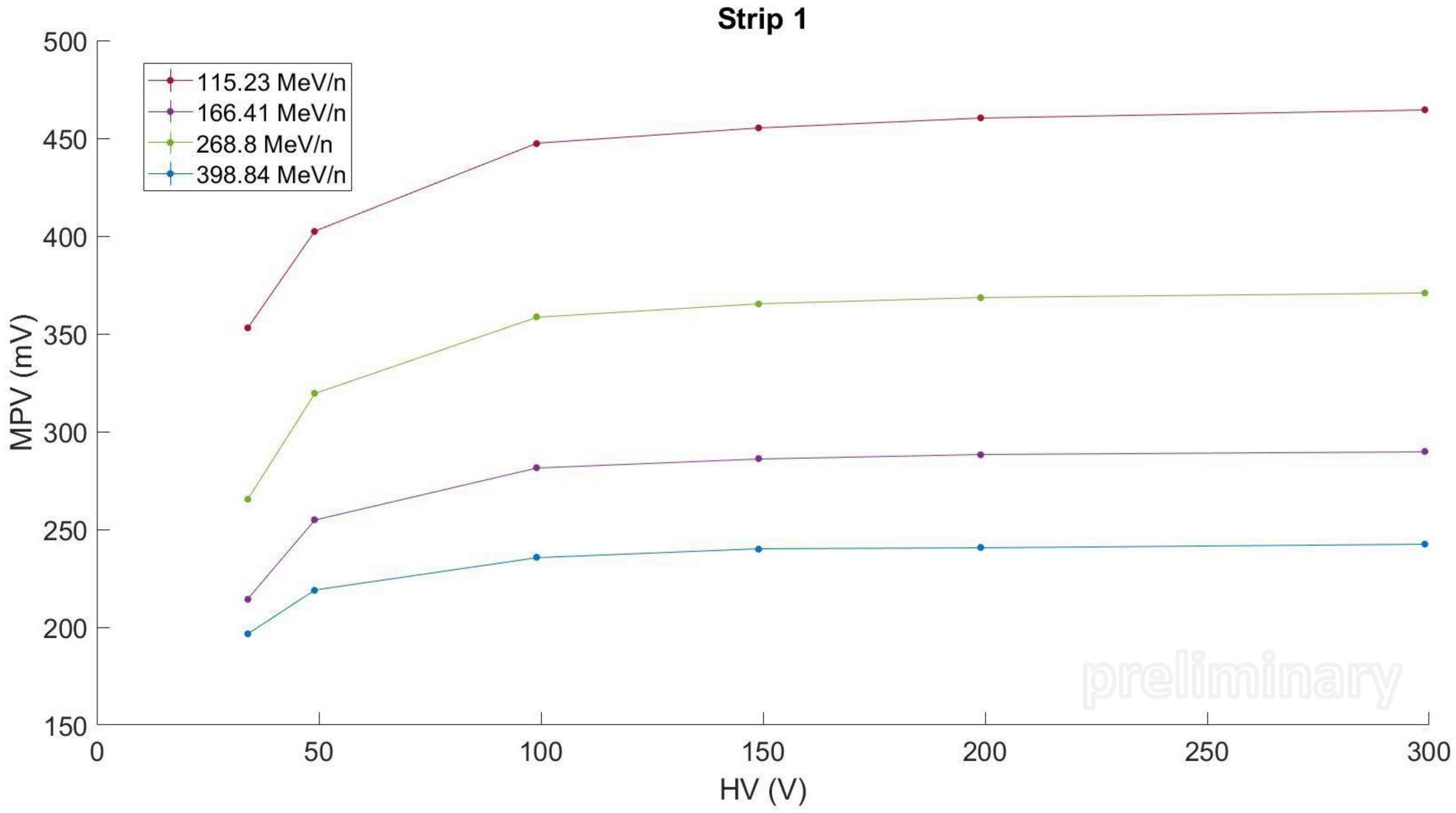
MPV VS BEAM ENERGY

MPV in function of energy for different bias voltages for strip 1. Decreasing the bias, the MPV decrease due to no saturation of the drift velocity.

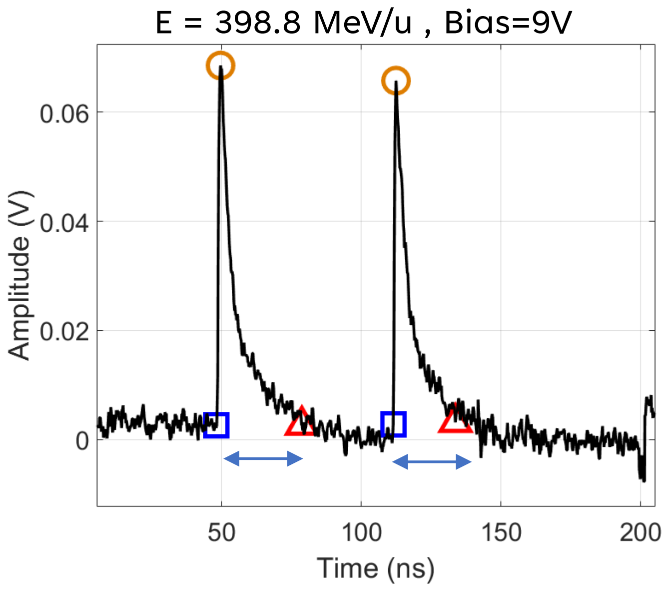


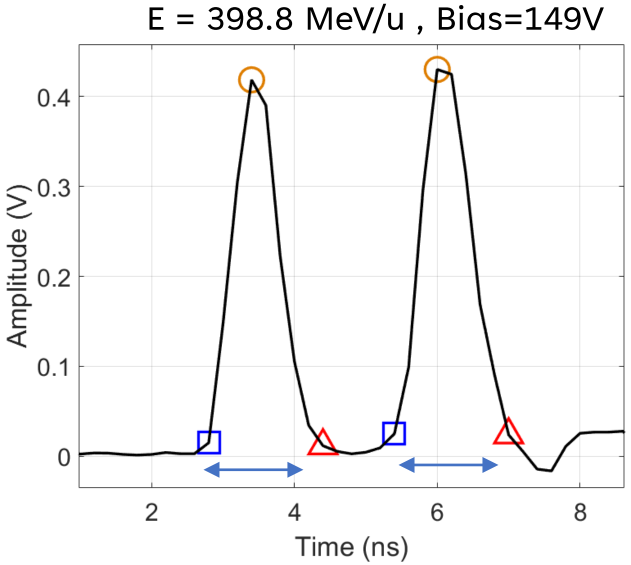
MPV VS BIAS VOLTAGE

MPV vs bias voltage for all energies. A plateau was observed for more than 150V or 30 kV/cm which is necessary to saturate the drift velocity for electrons. The slight increasing is because the drift velocity for the holes in not yet reached (100kV/cm needed).

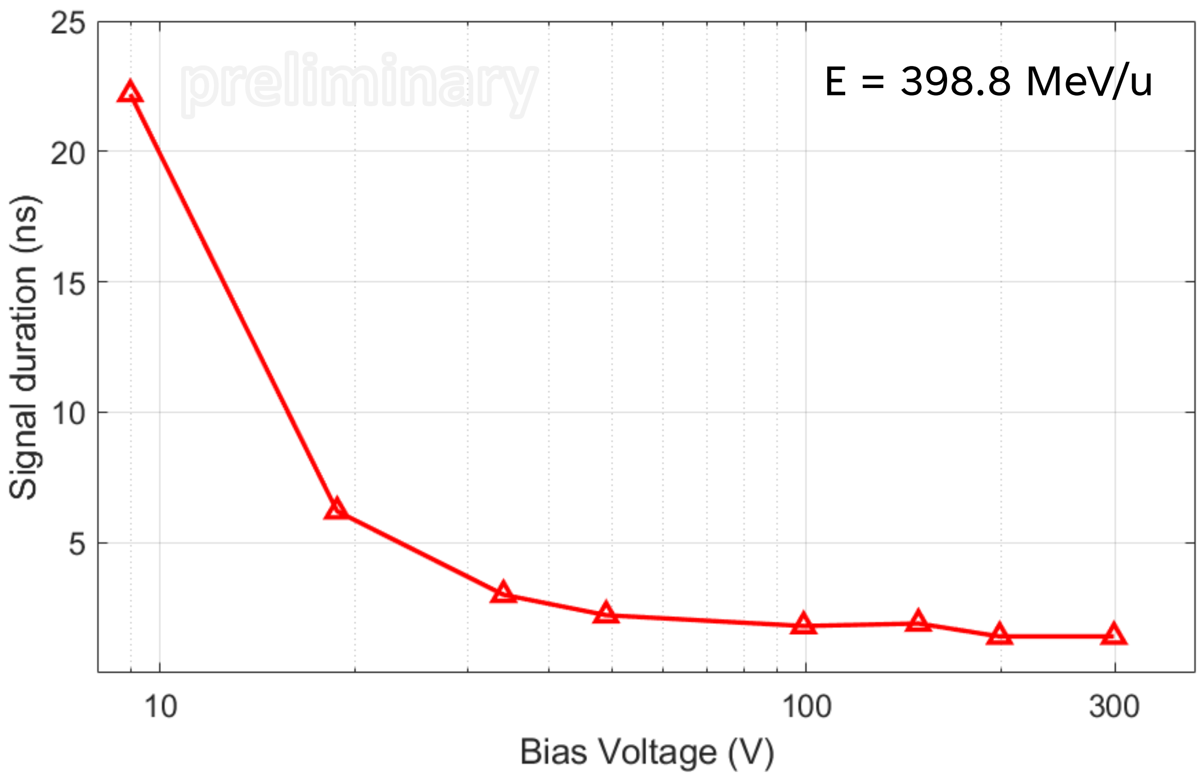


SIGNAL DURATION





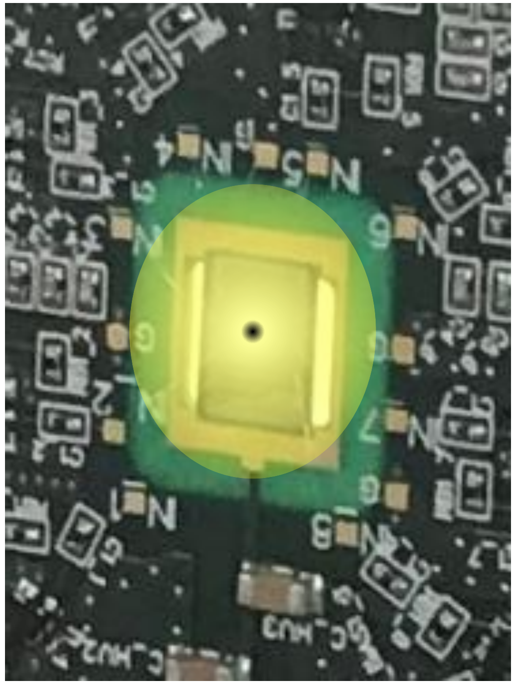
The difference are related with the electric field inside the silicon, which drifts the electron and holes.

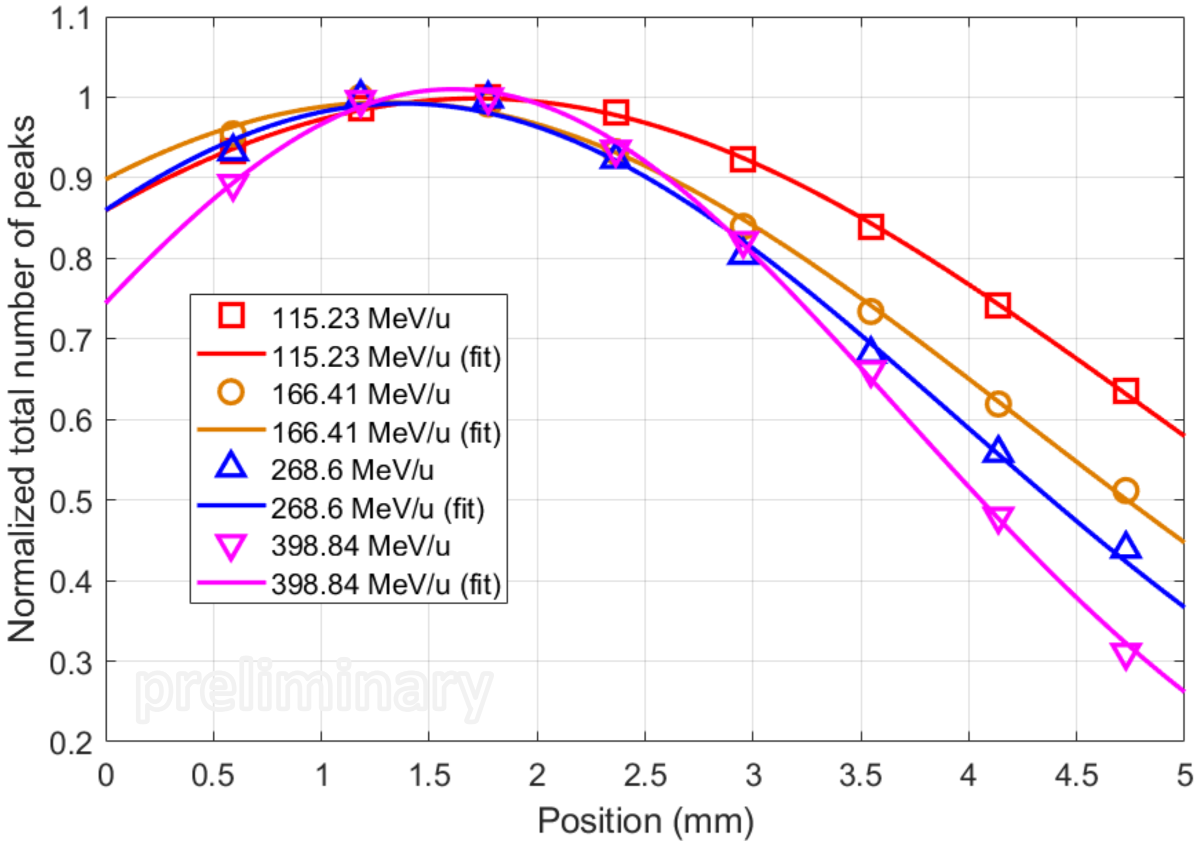


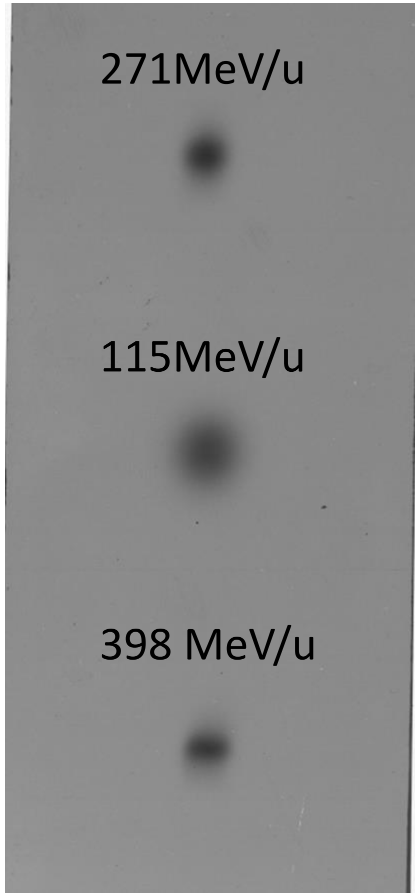
Signal duration increasing the Bias from 0 to 300 V. For bias voltage higher than 100 V the signal is shorter than 2 ns

BEAM SHAPE

Normalized total number of peaks in function of the strip position for all the energies with 149V bias voltage.





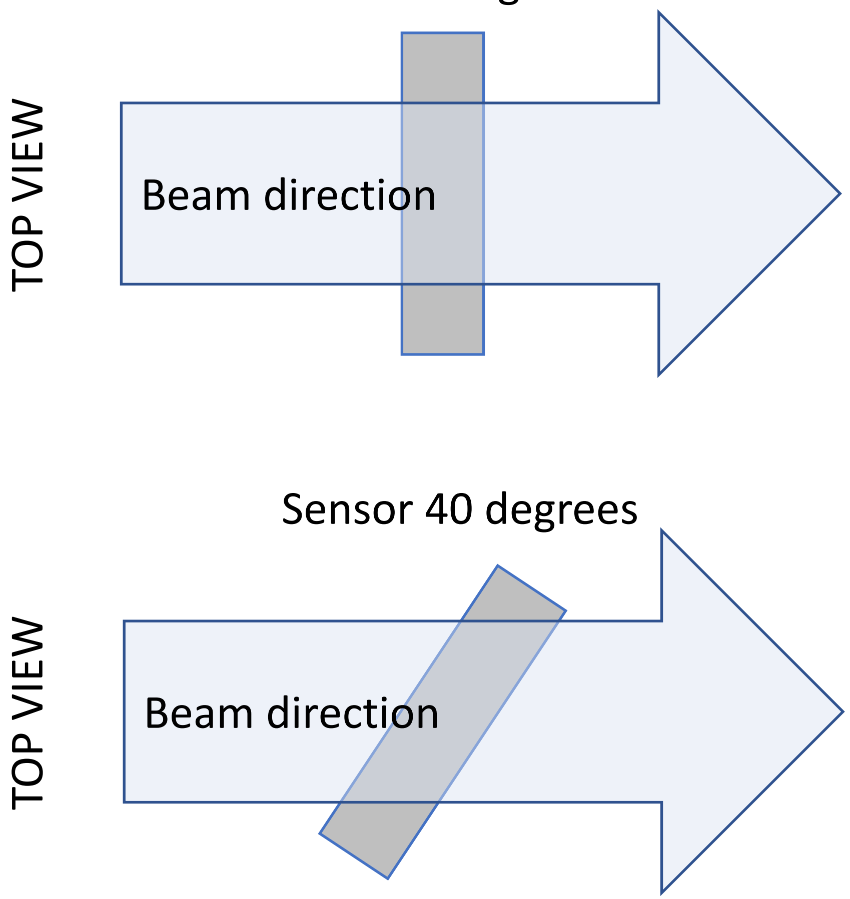


Gafchromic film for three carbon ions beams

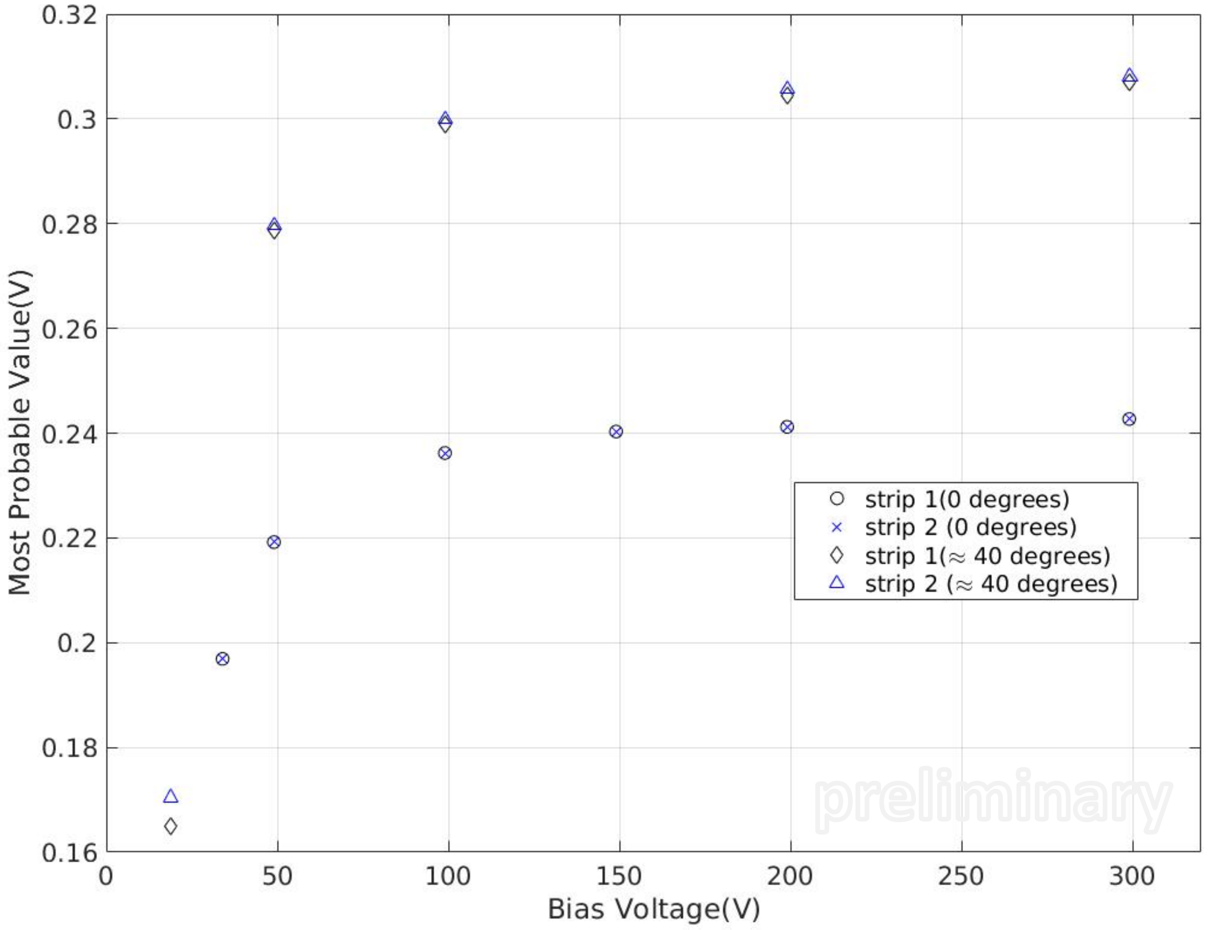
The beam was aligned between strip 2 and 4. The beam dimensions extracted from the Gaussian fit agree with those reported by CNAO, decreasing in size with increasing energy.

SIGNAL AMPLITUDE FOR DIFFERENT SENSOR ANGLE

The board was placed at two different angles with respect to the beam direction, 0° and 40°, To evaluate the effects of a different travel path inside the sensor



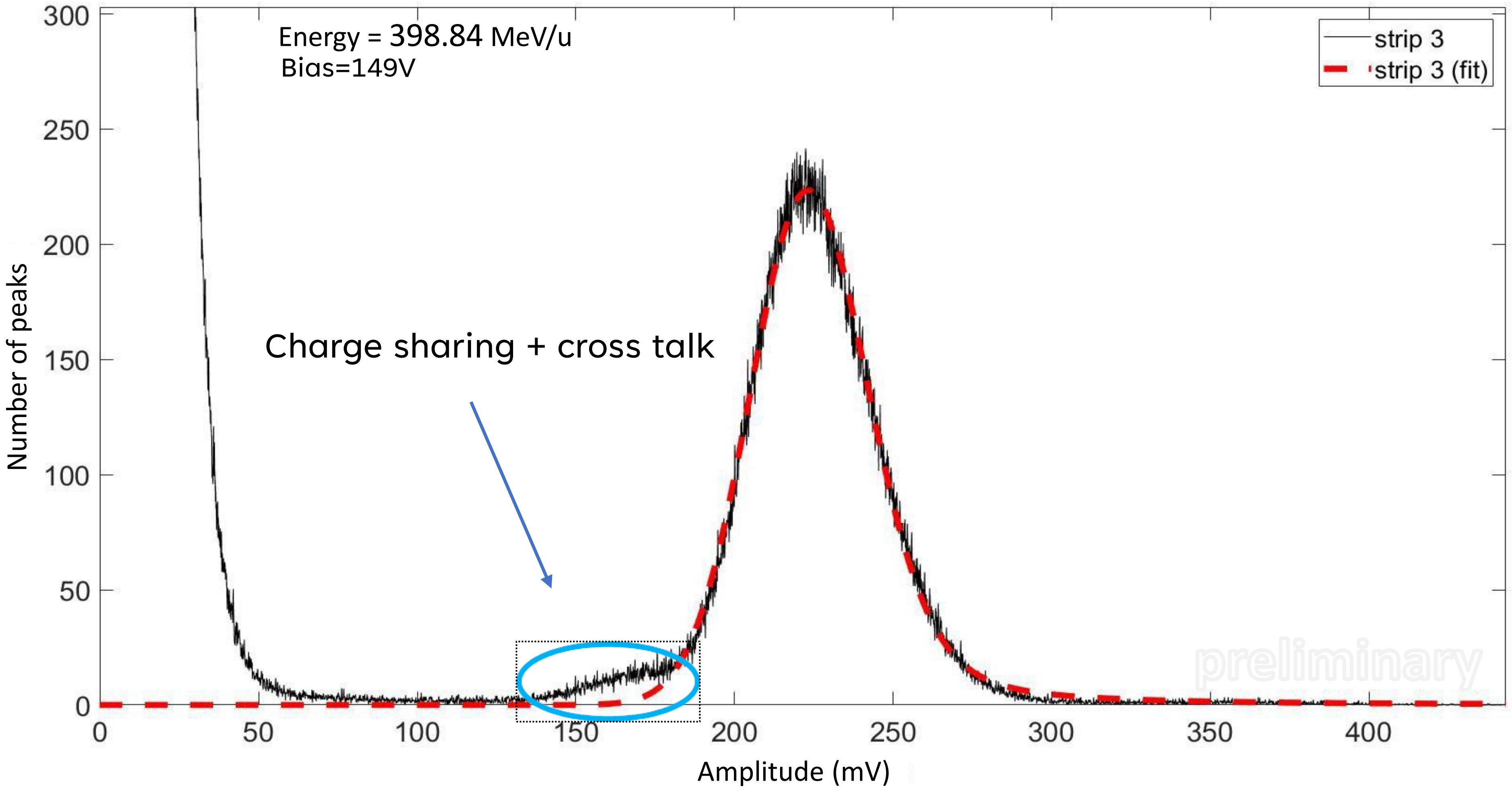
(E = 398.8 MeV/u)



As expected, rotating the sensor increases the signal amplitude, reflected in a higher MPV due to the larger path travel for the carbon ions, creating additional electrons and holes.

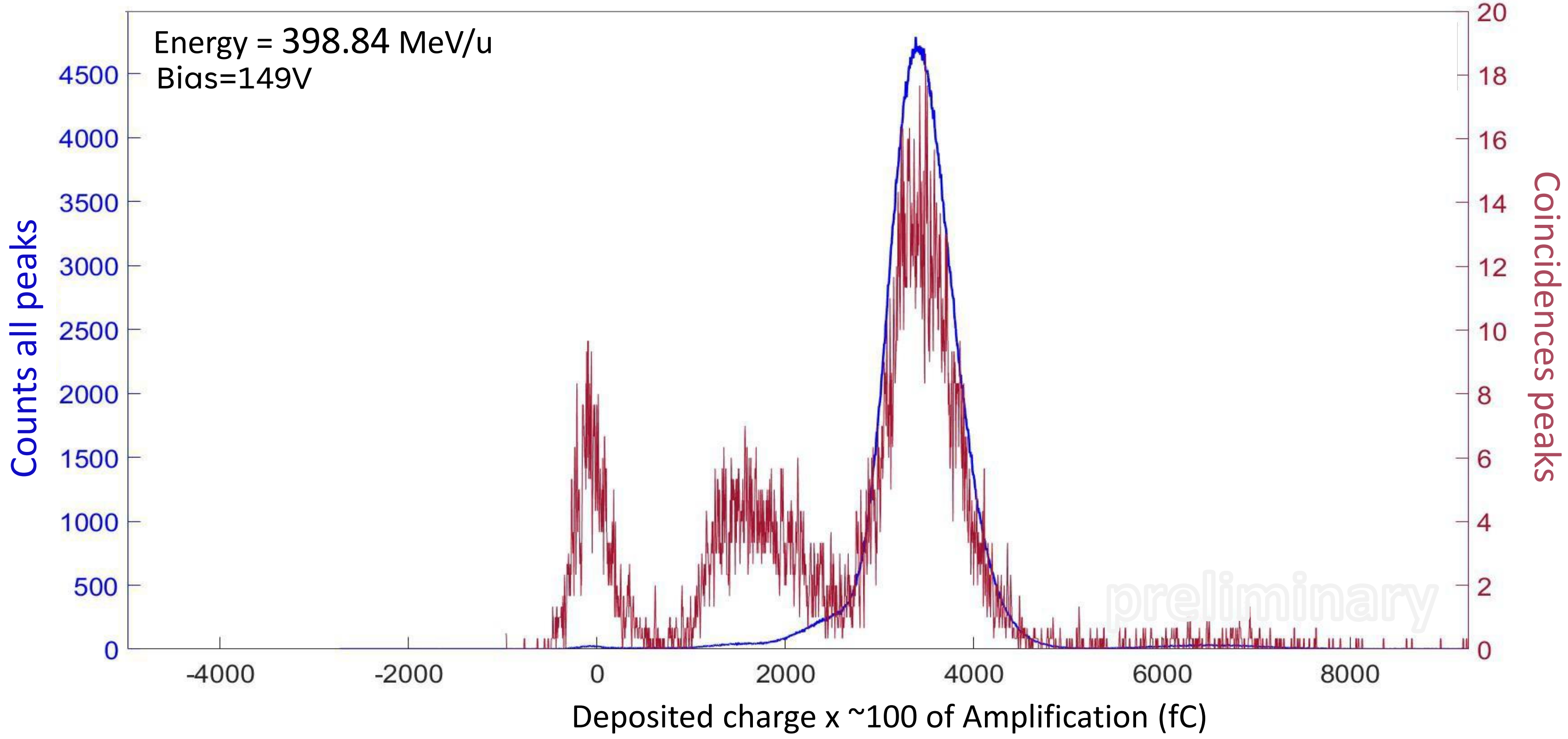
CHARGE SHARING AND CROSS TALK

Regarding the charge sharing and cross talk.



CHARGE DISTRIBUTION FOR TIME OVERLAPPING SIGNALS

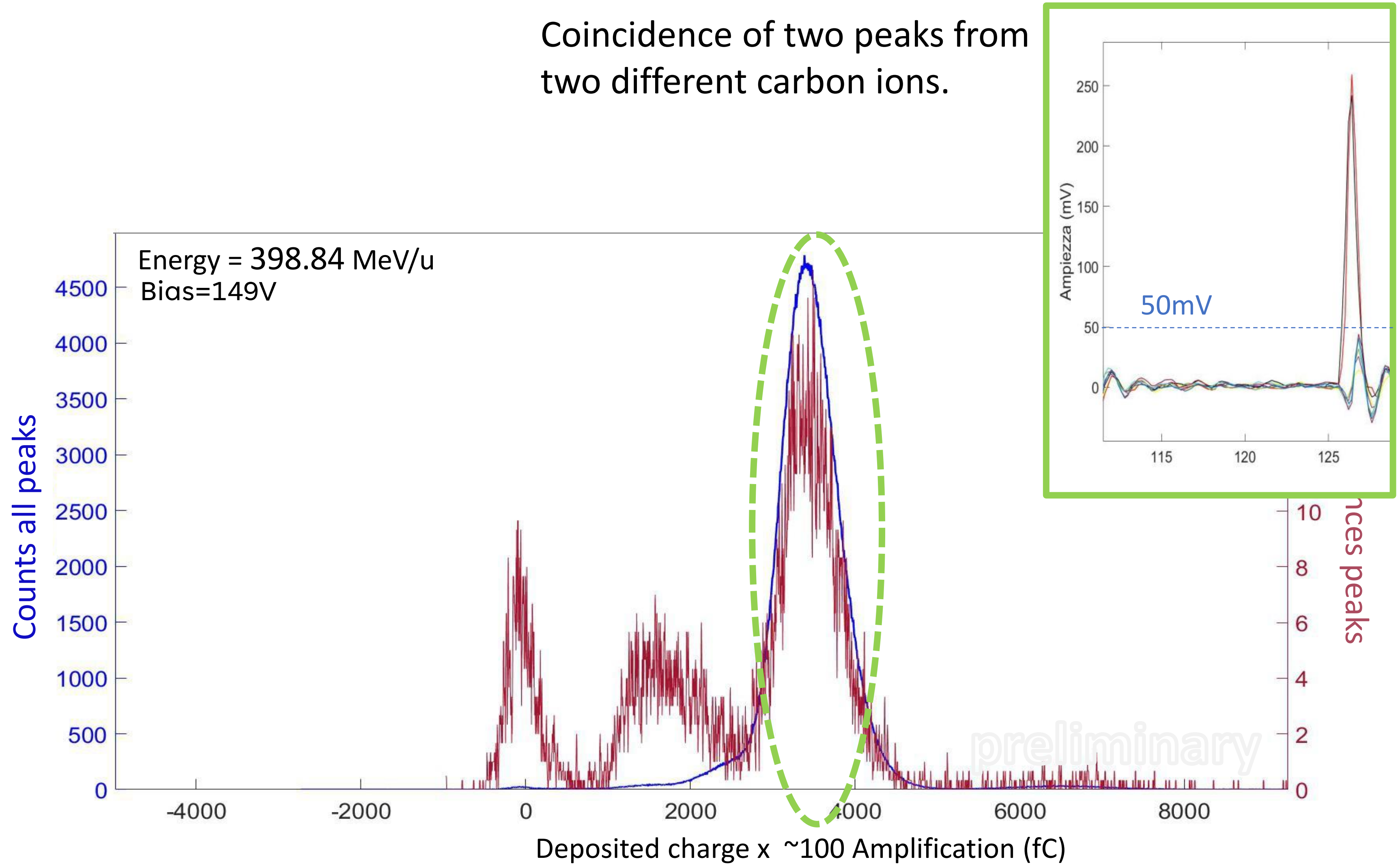
Deposited charge by peaks all the peaks (blue line, left axis) and in two neighboring strips within a time difference less than 0.2 ns (red line, right axis). The released charge was calculated in first approximation as the integral of the peak divided by 50 Ohms.



CHARGE DISTRIBUTION FOR TIME OVERLAPPING SIGNALS

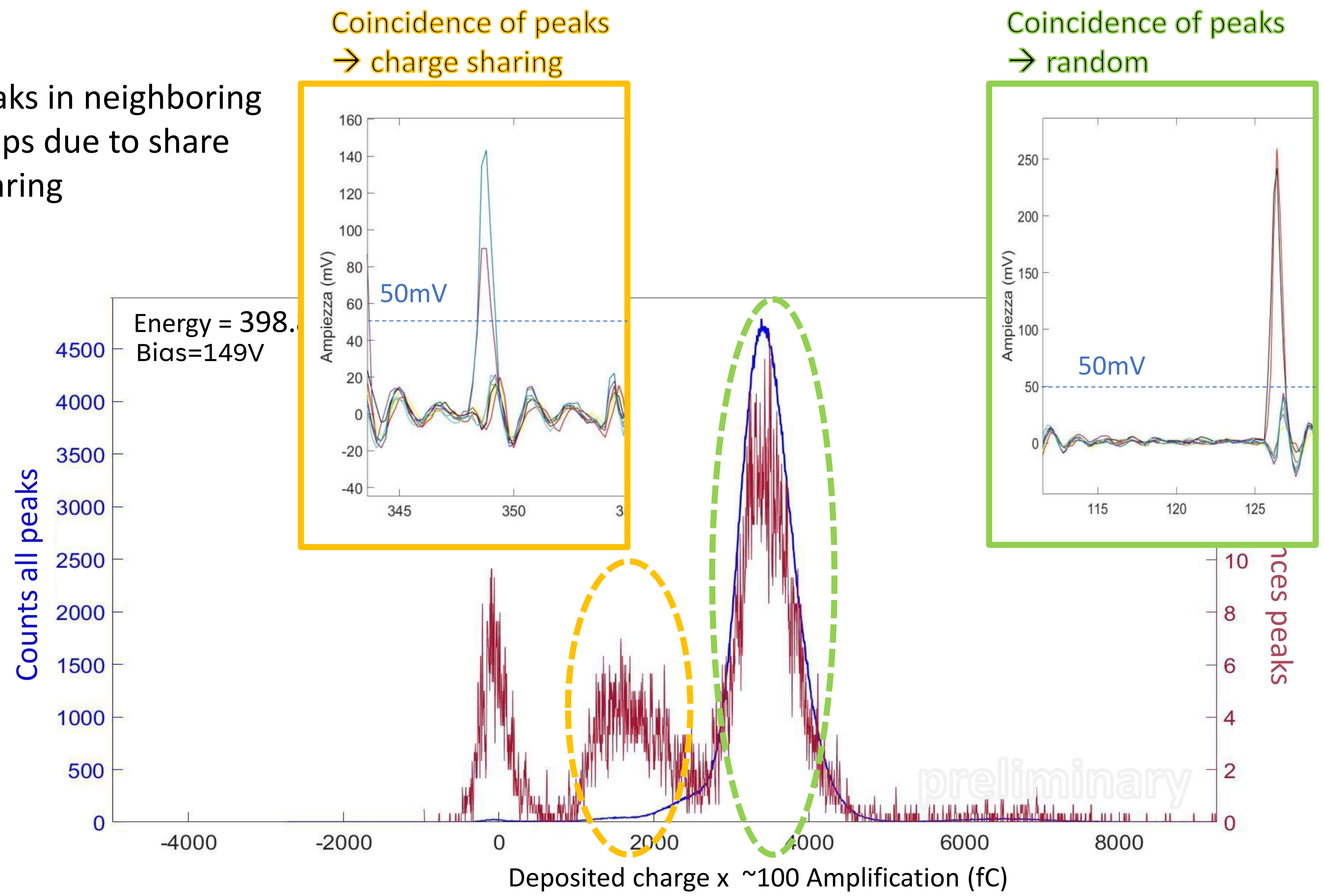
Coincidence of two peaks from two different carbon ions.

Coincidence of peaks → random

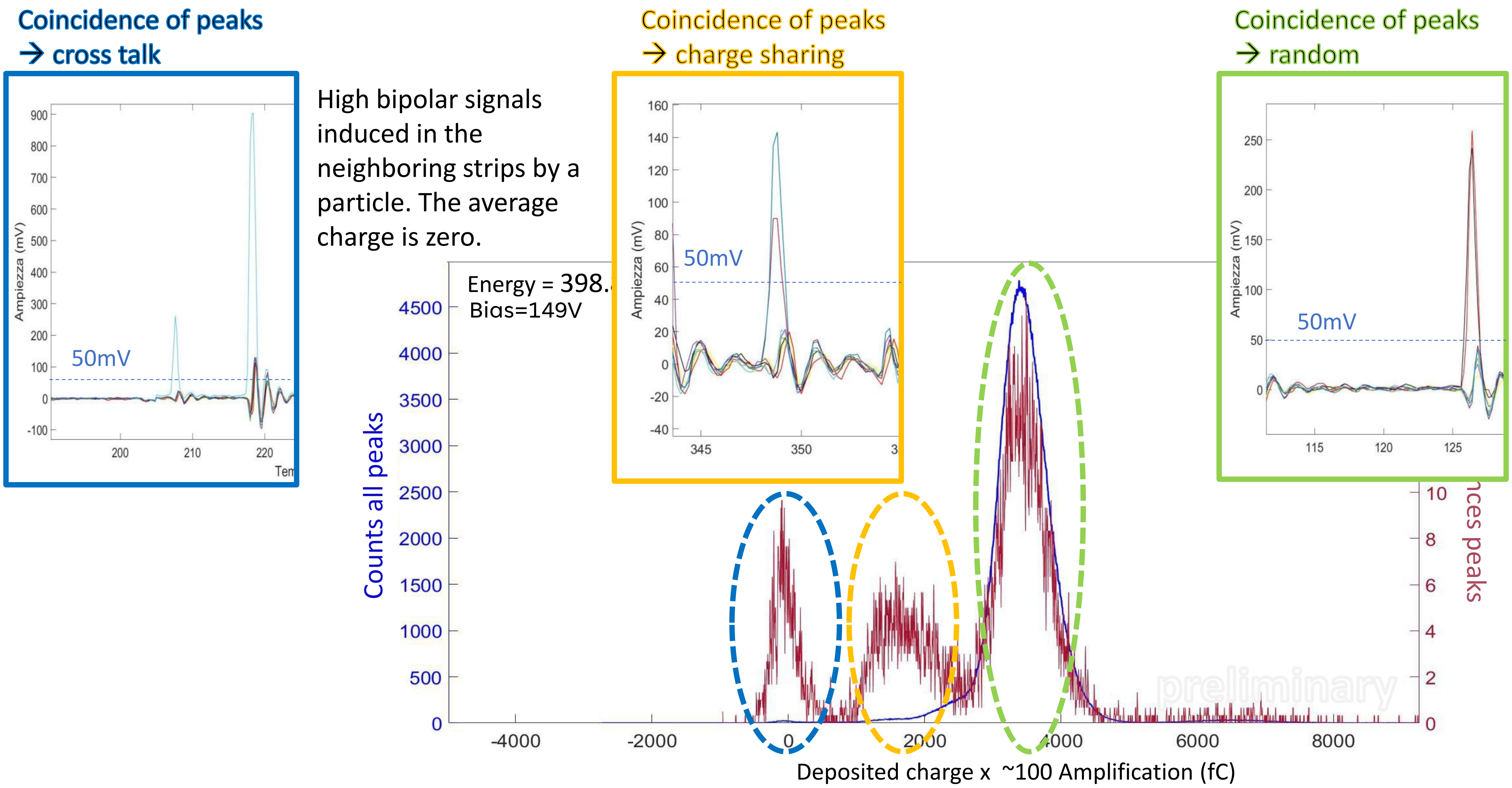


CHARGE DISTRIBUTION FOR TIME OVERLAPPING SIGNALS

Peaks in neighboring strips due to share sharing



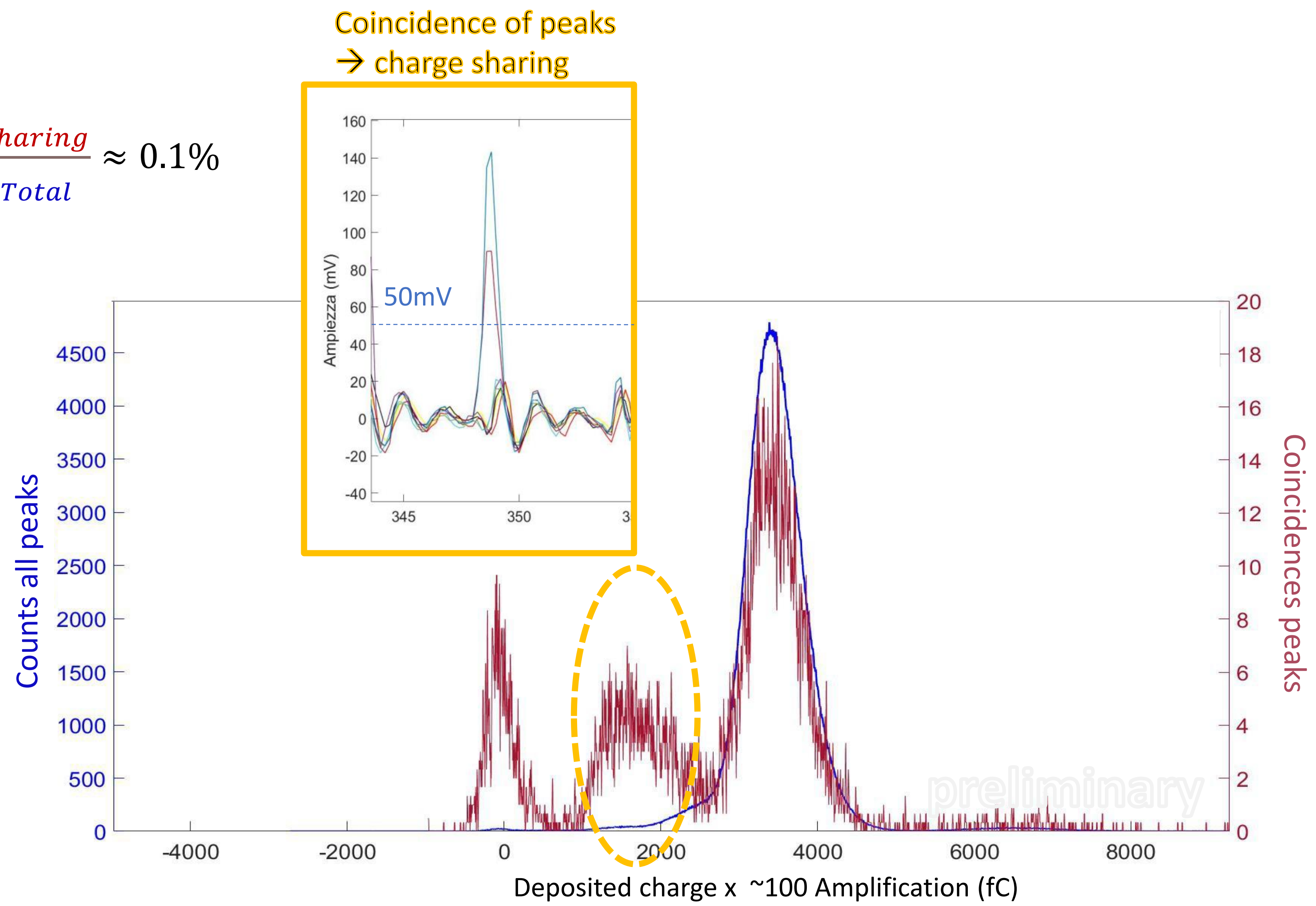
CHARGE DISTRIBUTION FOR TIME OVERLAPPING SIGNALS



CHARGE DISTRIBUTION FOR TIME OVERLAPPING SIGNALS

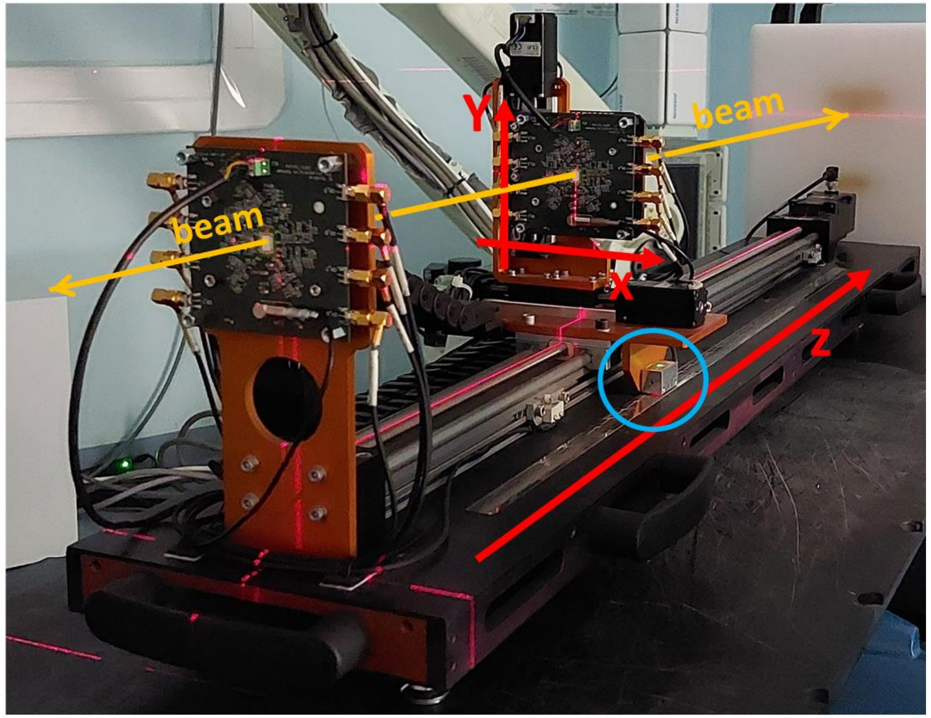
$$Percent_{charge\_sharing} = \frac{Q_{sharing}}{Q_{Total}} \approx 0.1\%$$

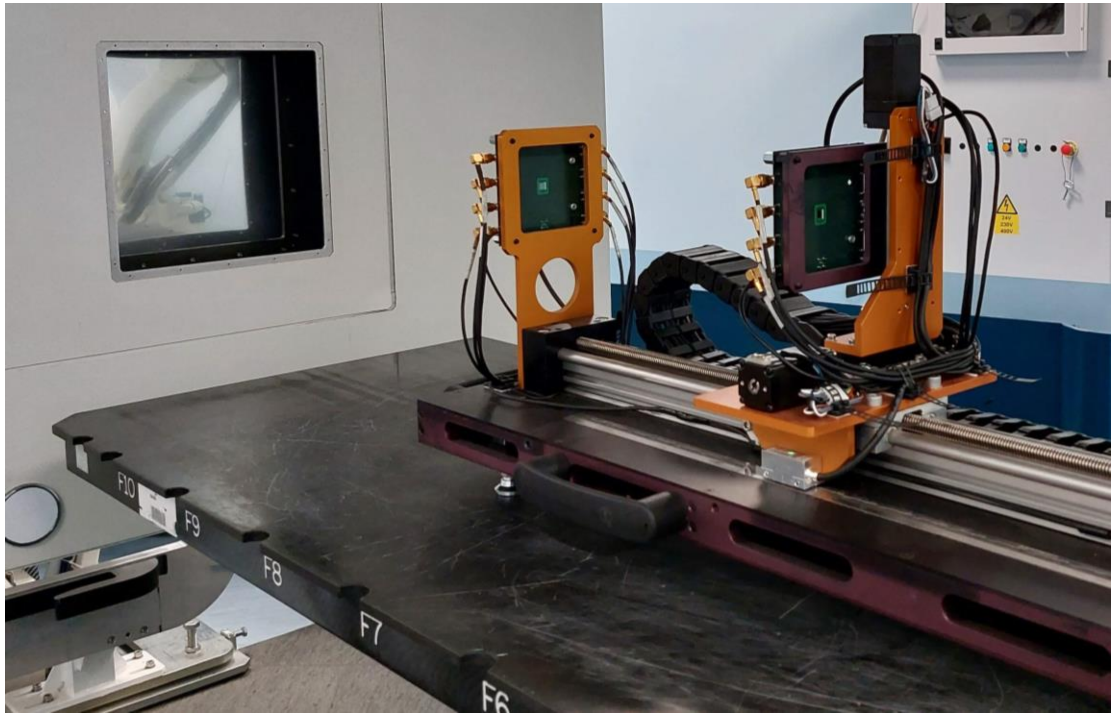
The percent of charge sharing between adjacent strips are negligible.



TIME RESOLUTION

Second experimental setup to measure the time resolution with two silicon sensors placed in a telescope configuration They were aligned along the beam direction at 30 cm of distance, measured with an optical encoder (0.1 um resolution).





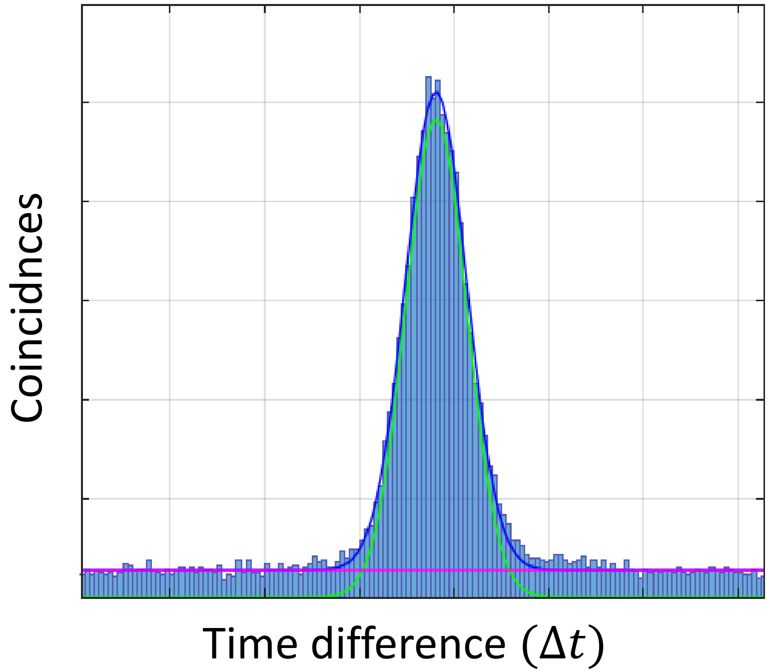
The 16 waveforms from the first and second sensors were used to extract the delta time analyzing the coincident peaks.
Beam energies: 115.23 MeV/u and 398.84 MeV/u
Bias voltages: 50 V, 100 V, and 200V

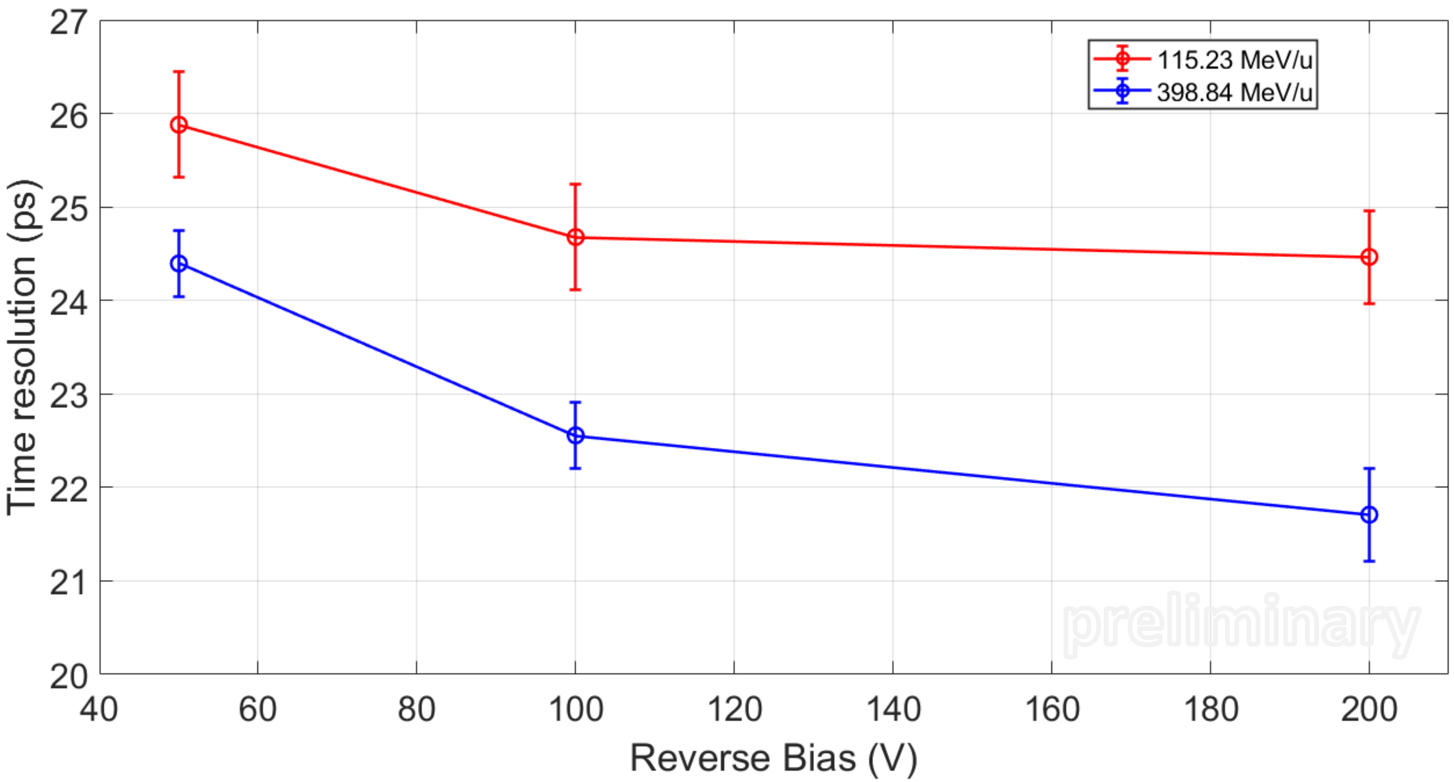
16 channels of the Digitizer DT5742

TIME RESOLUTION

The Δt was obtained from the combination of ions time of arrival on each sensor, determined using the constant fraction. On the right, the time resolution for single crossing measured at 115 and 398.8 MeV/u with HV from 50 to 200 V. The values are al less than 26 ps.

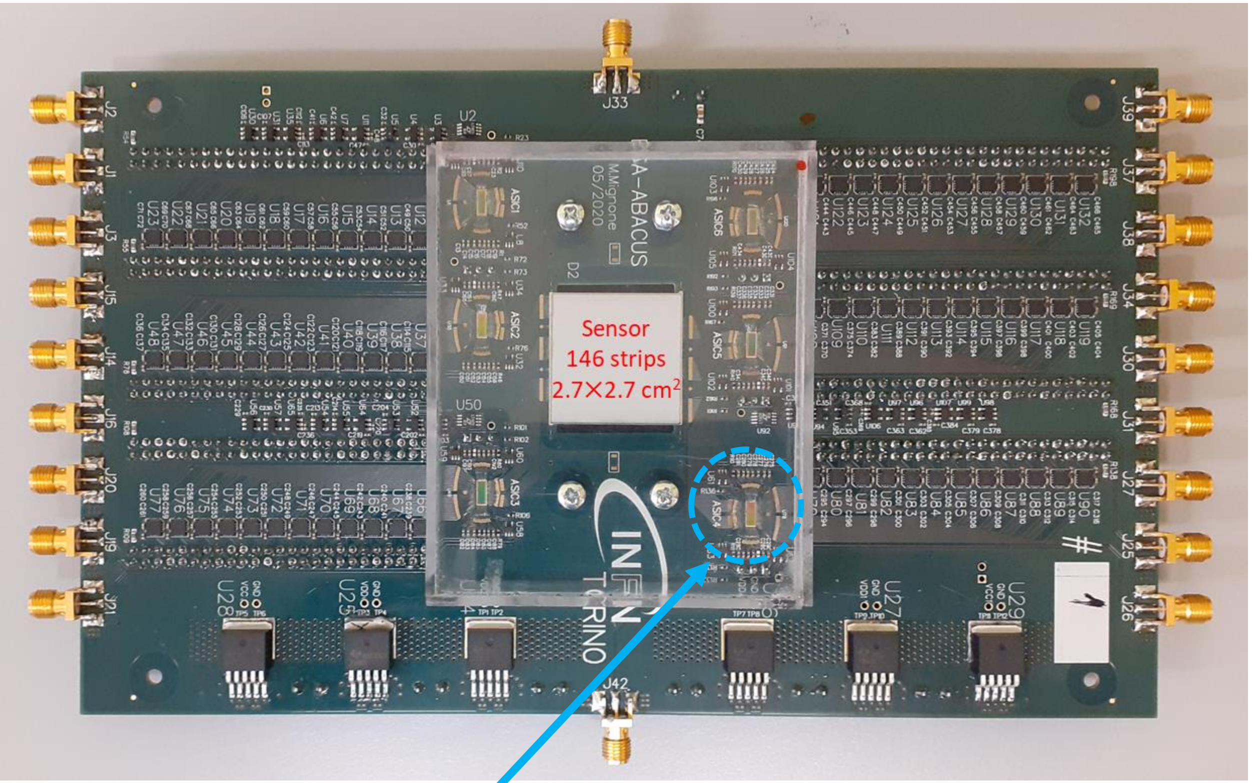
$$\sigma_t \text{ (ps)} = \sigma(\Delta t) / \sqrt{2}$$

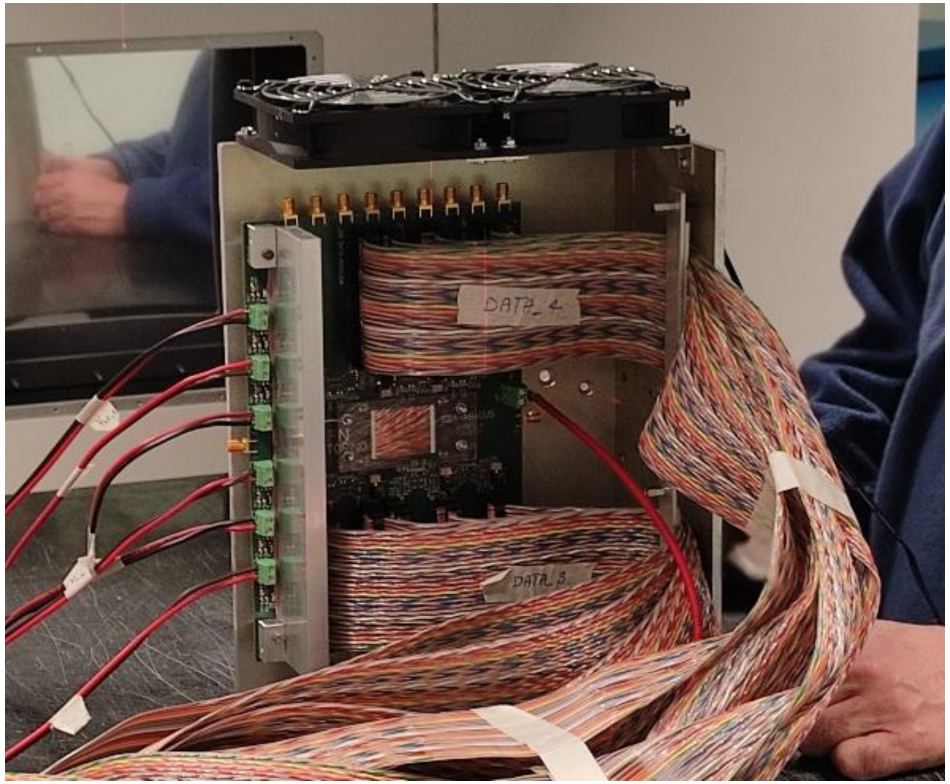




ONGOING WORKS

ESA-ABACUS board





The ABACUS chip (x6)

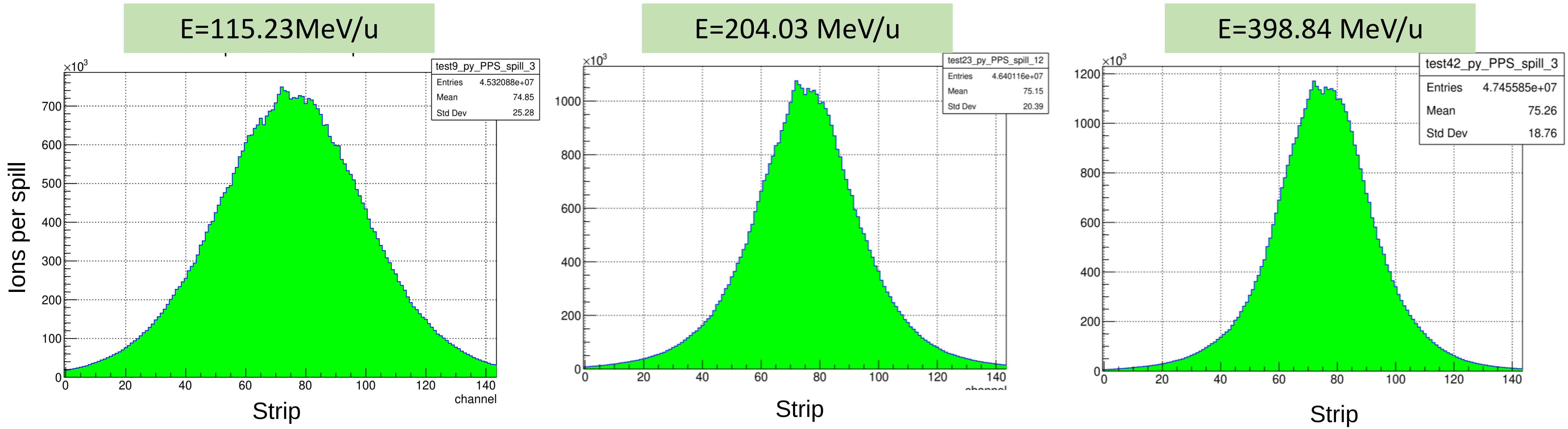
- 110 nm CMOS technology, chip area = 2 × 5 mm^2, 24 channels
- CSA dynamic range: 4 fC – 150 fC
- First characterization results:
- Dead time → ~ 10 ns
- Counting efficiency > 98 %

Firsts experimental measurements in 2022, at CANO, with different beam energies and intensity

ONGOING WORKS

ESA-ABACUS board

Preliminary test shows promising results and good uniformity in the measured beam profile.
Further studies are ongoing to investigate charge sharing and cross talk effect between strips



Outlook: Radiation hardness to clinical ions

Radiation hardness of silicon sensors with respect to light ions (He+, Li+2, O+6, C+6, and C+4) at clinical energies (< 500 MeV/u) must be tackled.

Expected carbon ions/cm^{2}year < 10^{13} →Energy range (100-400 MeV/nucleon)

Open questions:

1. Where to irradiate?
2. Existing measurements/models?
3. How to extrapolate from proton/neutron results?

Need help from sensor community.

CONCLUSIONS

- Good separation between signal and noise for all the clinical energies
- The MPV was sensitive to the incidence angle increasing with the crossed thickness.
- The signal duration decreases with the increase of the bias voltage up to 100 V, where it reaches a value of less than 2 ns.
- A single hit time resolution of about 25 ps is achieved at the two extreme energy values of 115 and 399 MeV/u.
- Studies of charge sharing and signal induction between adjacent strips indicate an overall negligible effect.

Initial tests of two different thin silicon sensors segmented in strips irradiated with therapeutic carbon ion beams show very promising results, preparing the groundwork for future devices and applications.

THANK YOU FOR YOUR ATTENTION

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