6th Annual Loma Linda Workshop. July 20-22, 2020

Beam energy measurement using Time-of-Flight and innovative Ultra-Fast Silicon Detectors in proton therapy

F. Mas Milian[1,2,3], A. Vignati[1,2], S. Giordanengo[2], Z. Ahmadi Ganjeh[4], M. Donetti[5], F. Fausti[2], M. Ferrero[6], O. Hammad Ali[1,2], O. A. Martì Villarreal[1,2], G. Mazza[2], Z. Shakarami[1,2], V. Sola[2], A. Staiano[2], R. Cirio[1,2], R. Sacchi[1,2], V. Monaco[1,2].

[1]Università degli Studi di Torino, Italy
[2]INFN - National Institute for Nuclear Physics, Torino, Italy
[3]Universidade Estadual de Santa Cruz, Ilheus, Brazil
[4]Yazd University, Yazd, Iran
[5]CNAO - Centro Nazionale di Adroterapia Oncologica, Pavia, Italy
[6]Università del Piemonte Orientale, Novara, Italy

fmasmilian@gmail.com

INFN Istituto Nazionale di Fisica Nucleare

FONDAZIONE BRUNO KESSLER

MoVe IT INFN project

Outline

- Motivation
- Ultra Fast Silicon Detector (UFSD)
- Energy measurement using Time of Flight (TOF)
- Experimental setup and Fast waveforms analysis
- UFSD telescope
- Validation and experimental measurements
- Conclusions
- Ongoing works

Motivation

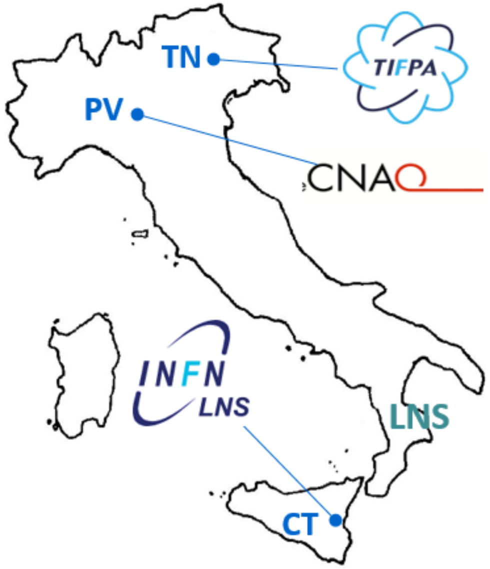
MoVe IT **:Mo**deling and **Ve**rification for **I**on beam **T**reatment planning (INFN)

- Implementation of advanced radiobiological models in ion TPS, experimental verification in-vitro and in-vivo
- **Development and upgrade of the INFN irradiation facilities incl. advanced monitoring systems**

Development of two prototypes of UFSD beam monitoring devices for radiobiological applications @ three irradiation facilities:

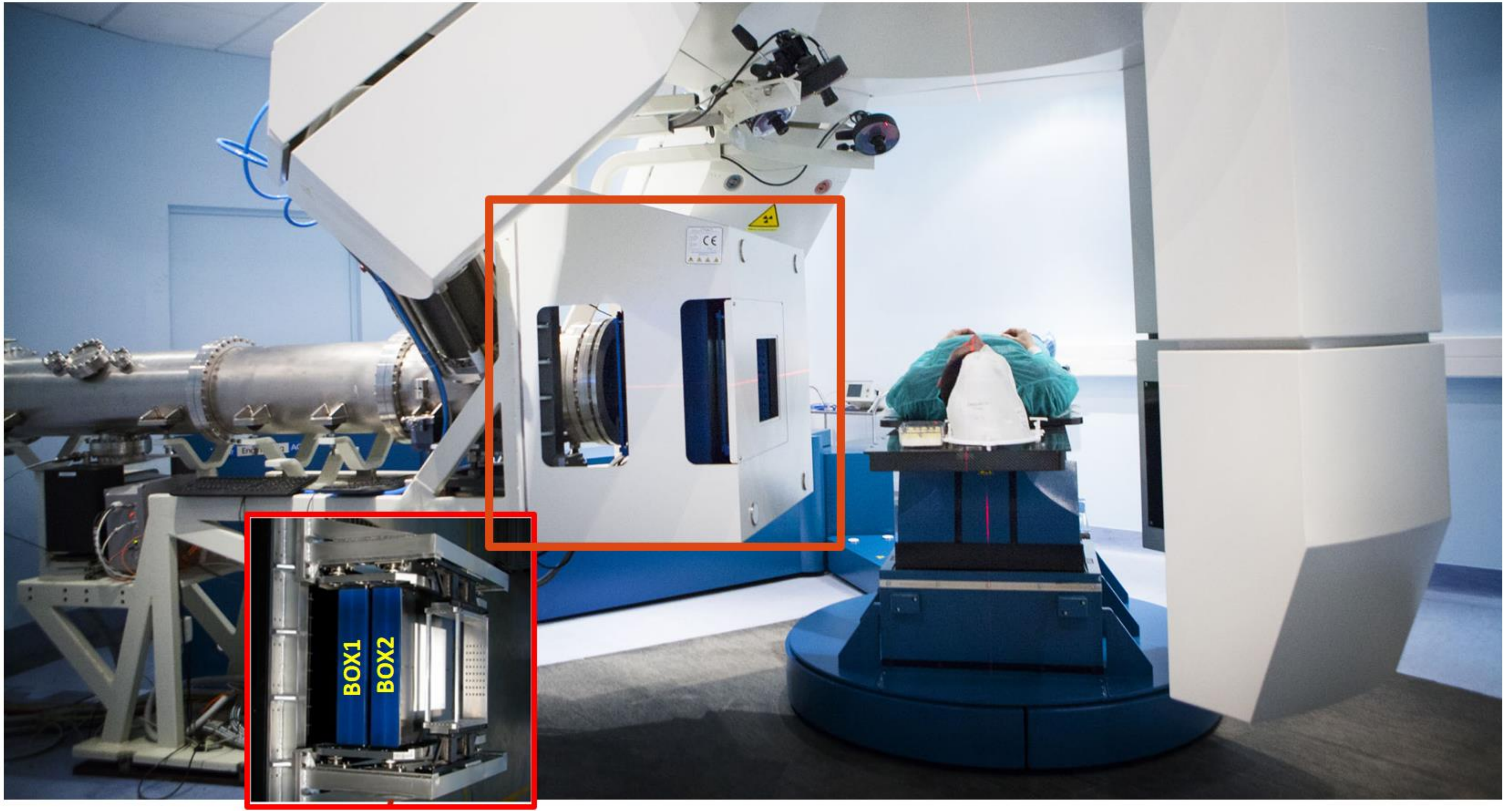
1. to **directly count** individual protons.

2. to **measure the beam energy** with time-of-flight techniques, using a telescope of two UFSD sensors
   - error < 1 mm range in water

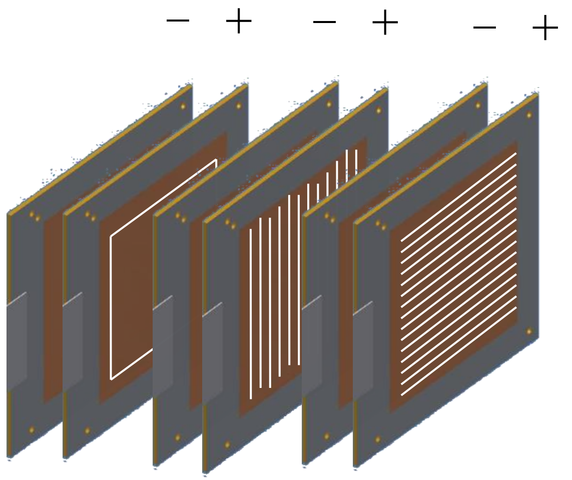


For additional details
http://www.tifpa.infn.it/projects/move-it/

Motivation



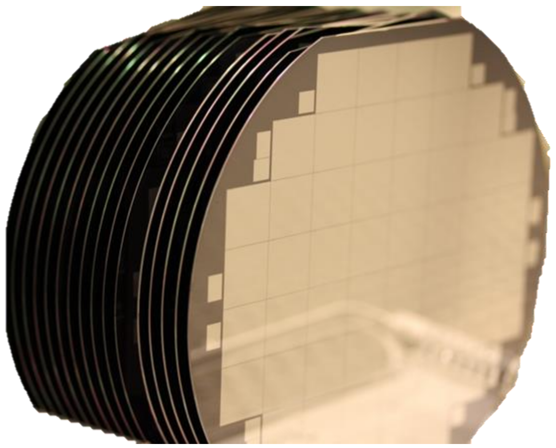
Motivation



ionization chambers, MWPC, ...

Gas detector

versus



silicon detectors

Solid state detectors

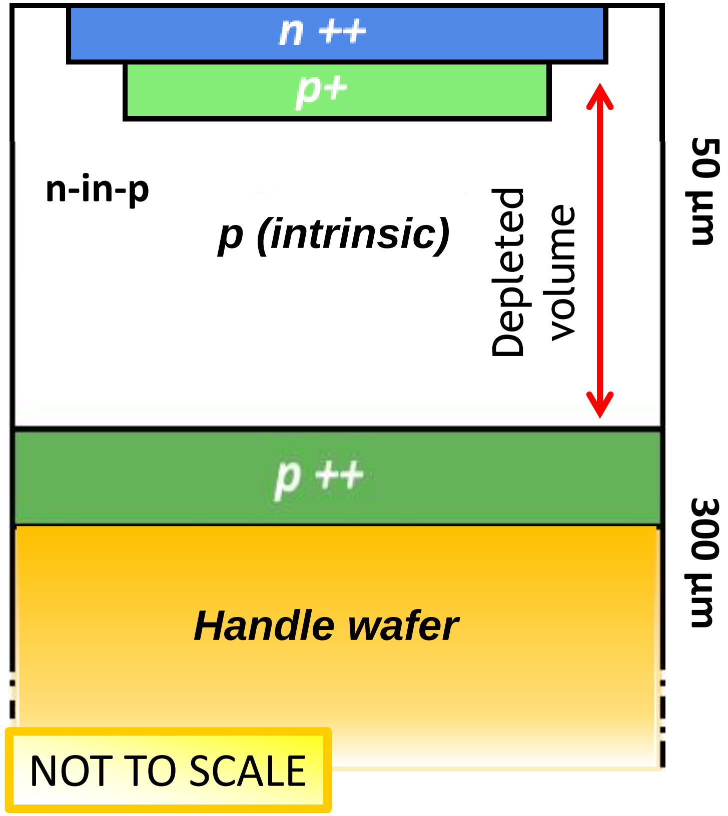
- Robust
- Simple construction and readout
- Large area
- Radiation resistance
- Low thickness

- Slow response time
- Limited sensitivity
- Indirect measurement of number of particles
- Dependance on beam energy, environmental parameters

- Fast response time
- High time resolution
- Large granularity (spatial resolution)
- Sensitivity to single particles

- Radiation resistance
- Pile-up effects
- High readout complexity

Ultra Fast Silicon Detector (UFSD)



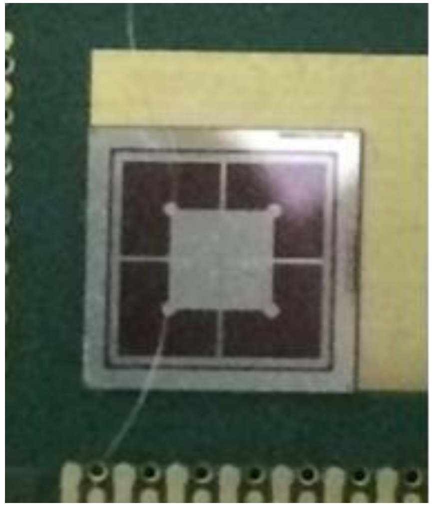
Controlled low gain (~ 10)
→ **Fast electronics with low power consumption**

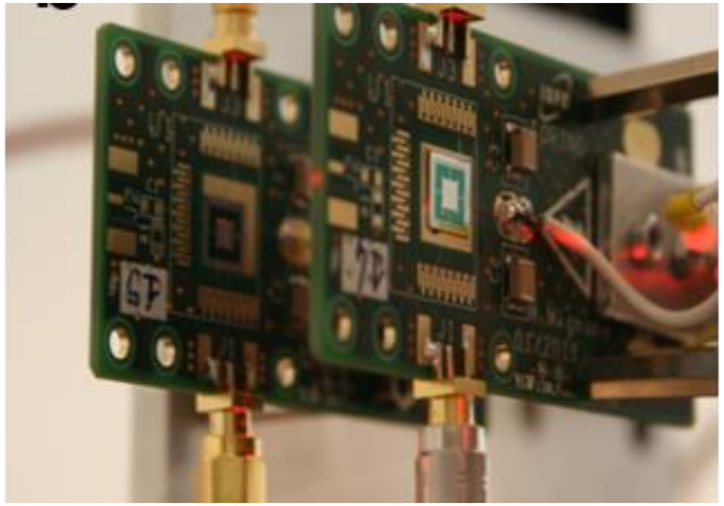
Short signal duration (1 ns)
→ **Single particle detection capability**

Excellent time resolution (tens of ps)
→ **Energy measurement from Time of Flight (ToF)**

(Look at the references for more details about UFSD)

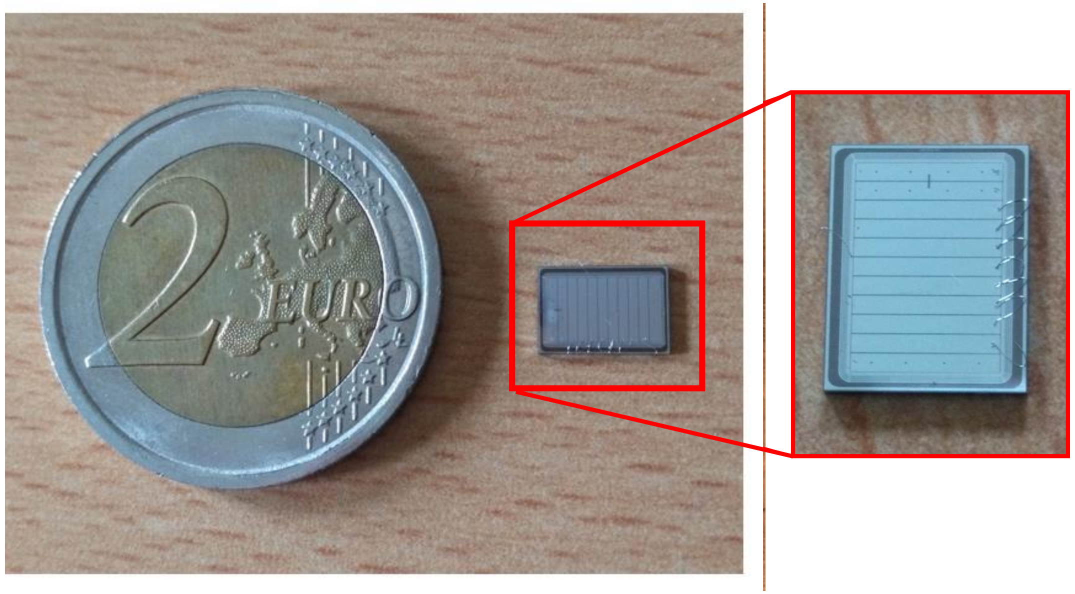
Ultra Fast Silicon Detector (UFSD)

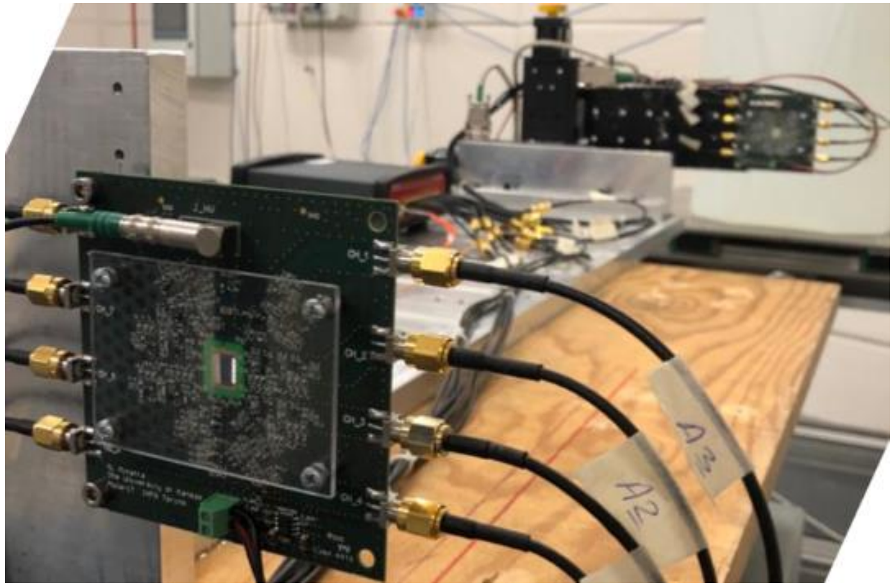




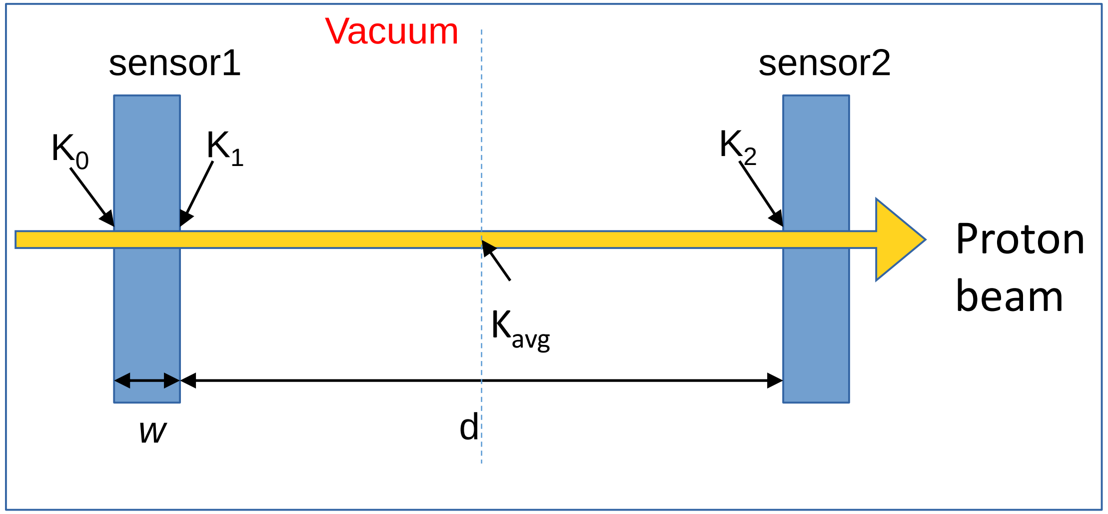
Hamamatsu 4 pad (3x3) mm^2, 80 µm active thickness (2018)

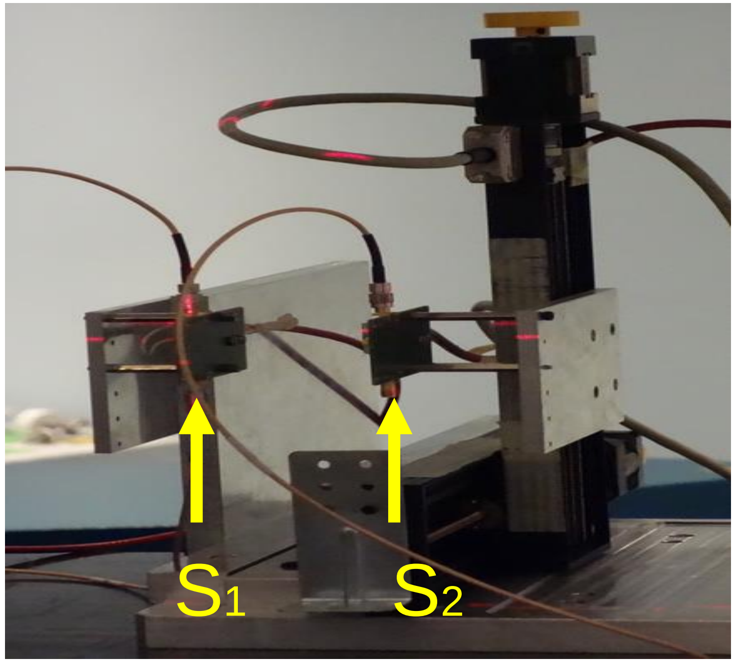
11 strips,
pitch 590 µm
50 µm active thickness
(2019-2020)





Energy measurement using TOF





- In Vacuum $K_1 = K_2 = K_{avg}$

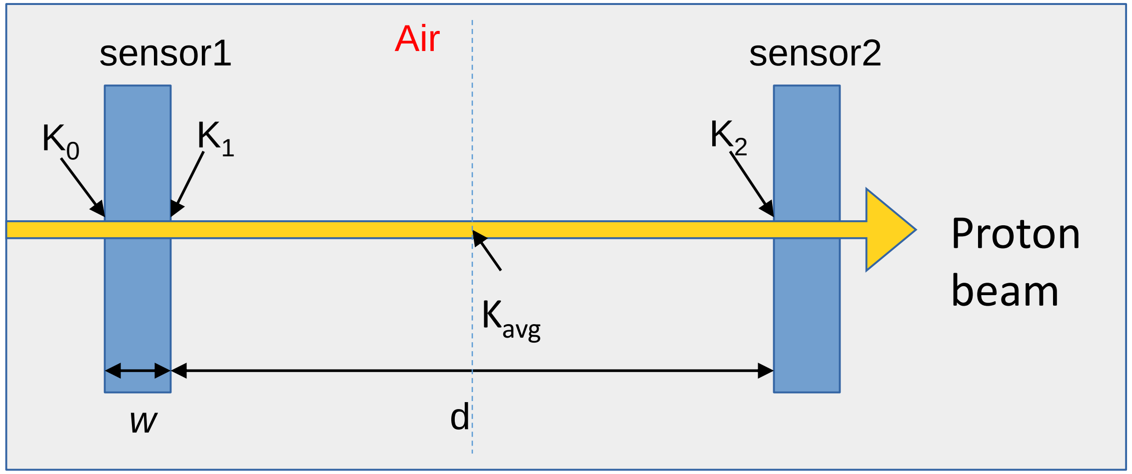
$$v_{avg} = \frac{d}{TOF}$$

$$K_{avg} = E_o\left(\frac{1}{\sqrt{1-\left(\frac{v_{avg}}{c}\right)^2}} - 1\right)$$

- We are interested in K_0. Need to consider the energy loss in sensor 1.
- The telescope will work in the air. Need to consider the energy loss in the air. $K_1 \neq K_2 \neq K_{avg}$.
- We have a time offset added to the TOF due to electronics. What we really measure is: $\Delta t = TOF + offset$, then $TOF = \Delta t - offset$

- We need to include some corrections!!!

Energy measurement using TOF



- Here we consider $\frac{S}{\rho}(K_1) \cong \frac{S}{\rho}(K_{avg})$

and the $\frac{S}{\rho}(K)$ for Air and Silicon were taken from PSTAR and fitted to the equation:

$$\frac{S}{\rho}(K) = y + A \cdot K^{(-p)}$$

- These terms represent the energy lost in *d/2* of Air, and in the thickness *w* of Silicon

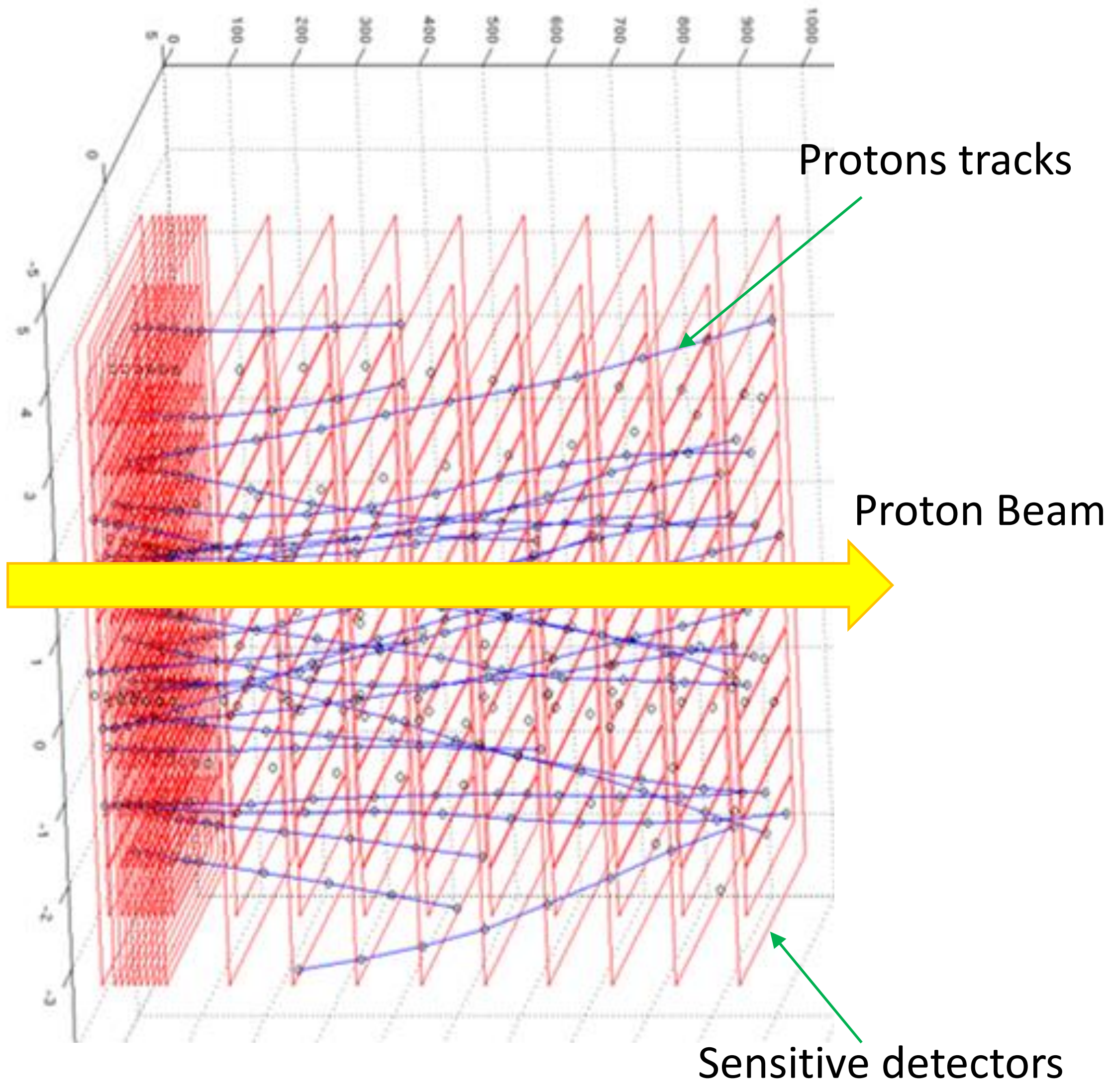
$$v_{avg} = \frac{d}{\Delta t - offset}$$

$$K_{avg} \cong E_o \left(\frac{1}{\sqrt{1 - \left(\frac{v_{avg}}{c}\right)^2}} - 1 \right)$$

$$K_1 = K_{avg} + \left(\frac{S}{\rho}(K_{avg}) \right)_{air} \cdot \rho_{air} \cdot \frac{d}{2}$$

$$K_0 = K_1 + \left(\frac{S}{\rho}(K_1) \right)_{Si} \cdot \rho_{Si} \cdot w$$

Energy measurement using TOF



Data used to test the theoretical equations with and without corrections

A protons info database was done with Monte Carlo simulations using GEANT4.

- Protons energies: 60 MeV to 230 MeV (1 MeV steps). 10^6 protons by energy.

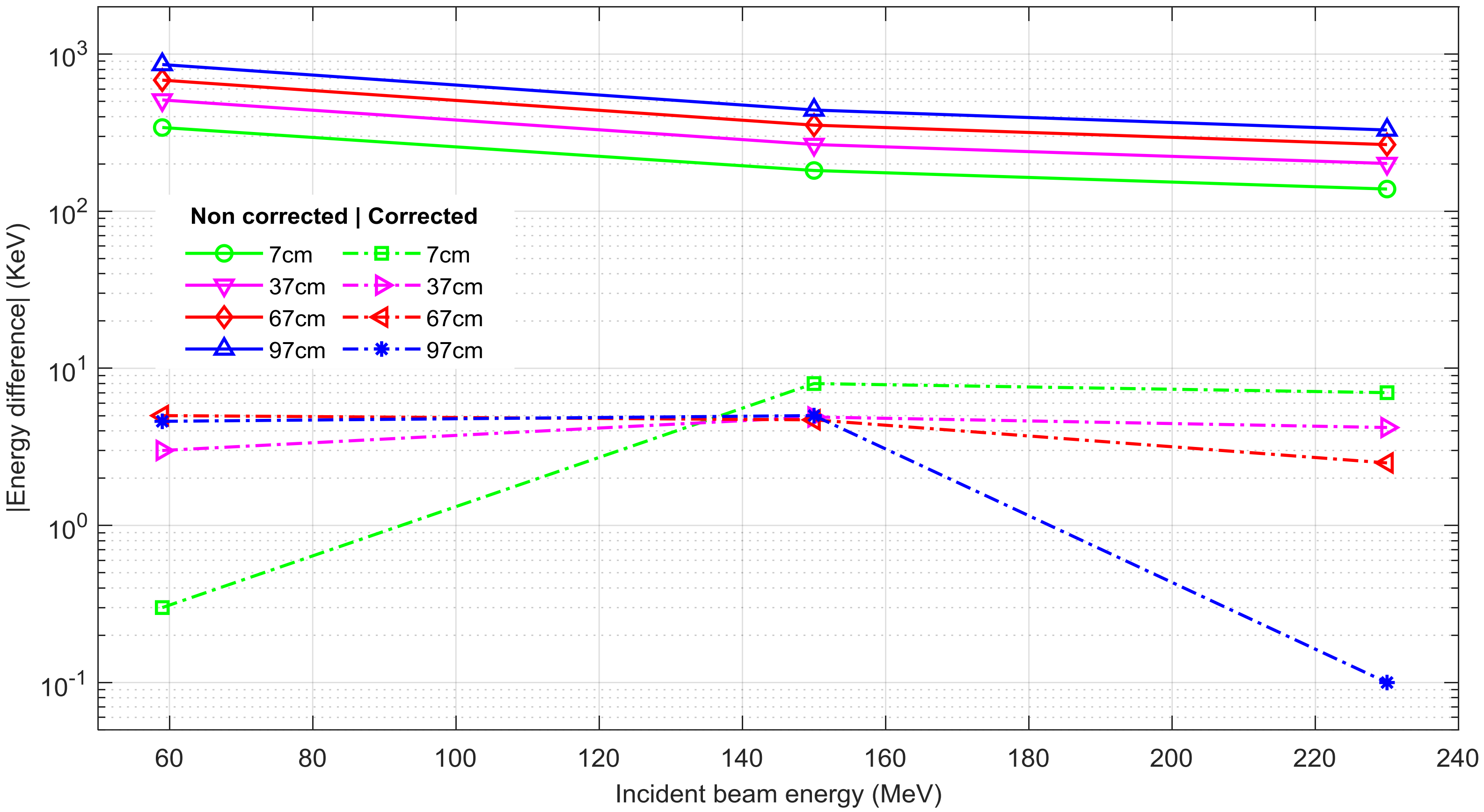
- 15 positions between 2 cm to 100 cm (red planes).

- Information saved in the sensitive detectors:

  - X, Y coordinates
  - Global time
  - Particle energy

Energy measurement using TOF

Energy difference calculated using the simulated TOF at the possible telescope distances (7cm, 37cm, 67cm and 97cm):



The correction works well with simulated data!!!

But in practice we have:

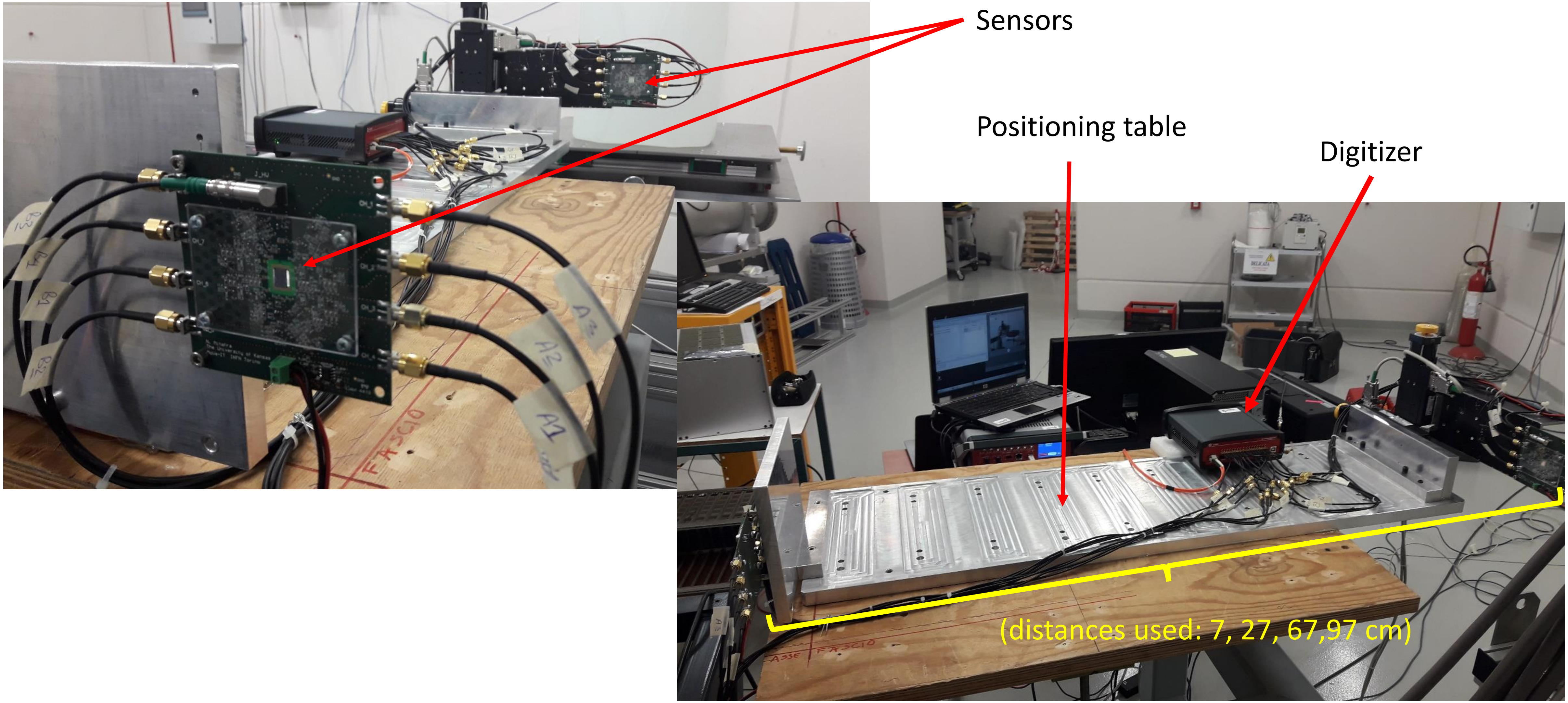
- An unknown time offset added to the TOF.

- Systematics errors in the sensor's distances and positioning.

- And the most important: How is it possible to identify individual protons in the signals from S1 and S2 to extract the TOF?

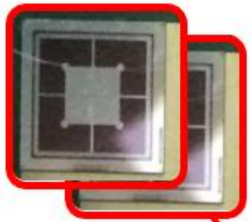
- Without the corrections: the energy differences are hundreds of keV
- With the corrections: the differences are less than 10 keV.

Experimental setup



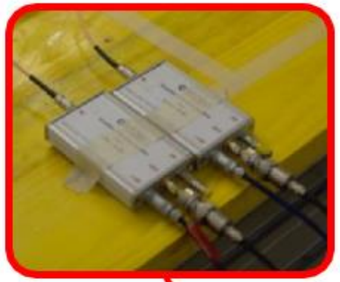
Experimental setup

2 signals configuration



Or

Two CIVIDEC broadband 40 dB amplifiers



2 channels

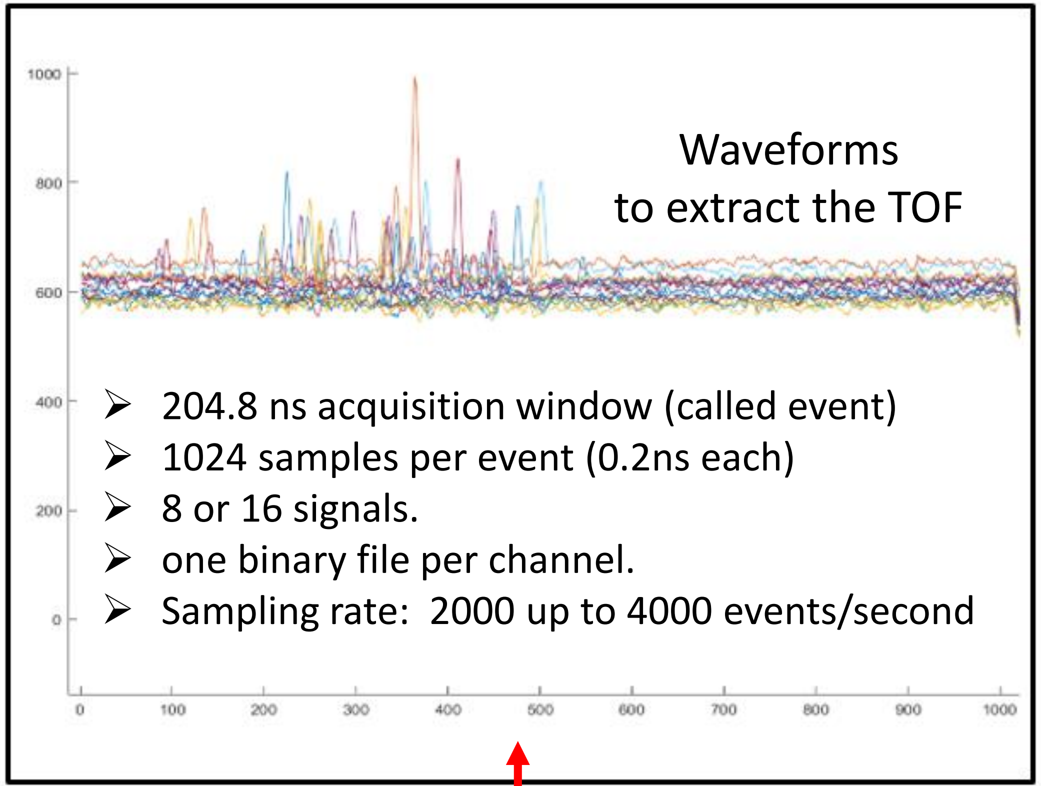
16 signals configuration

8 channels Minafra Board

16 channels

CAEN DT5742 digitizer (5 Gs/s,12 bits)

Optical link (80 MB/s)

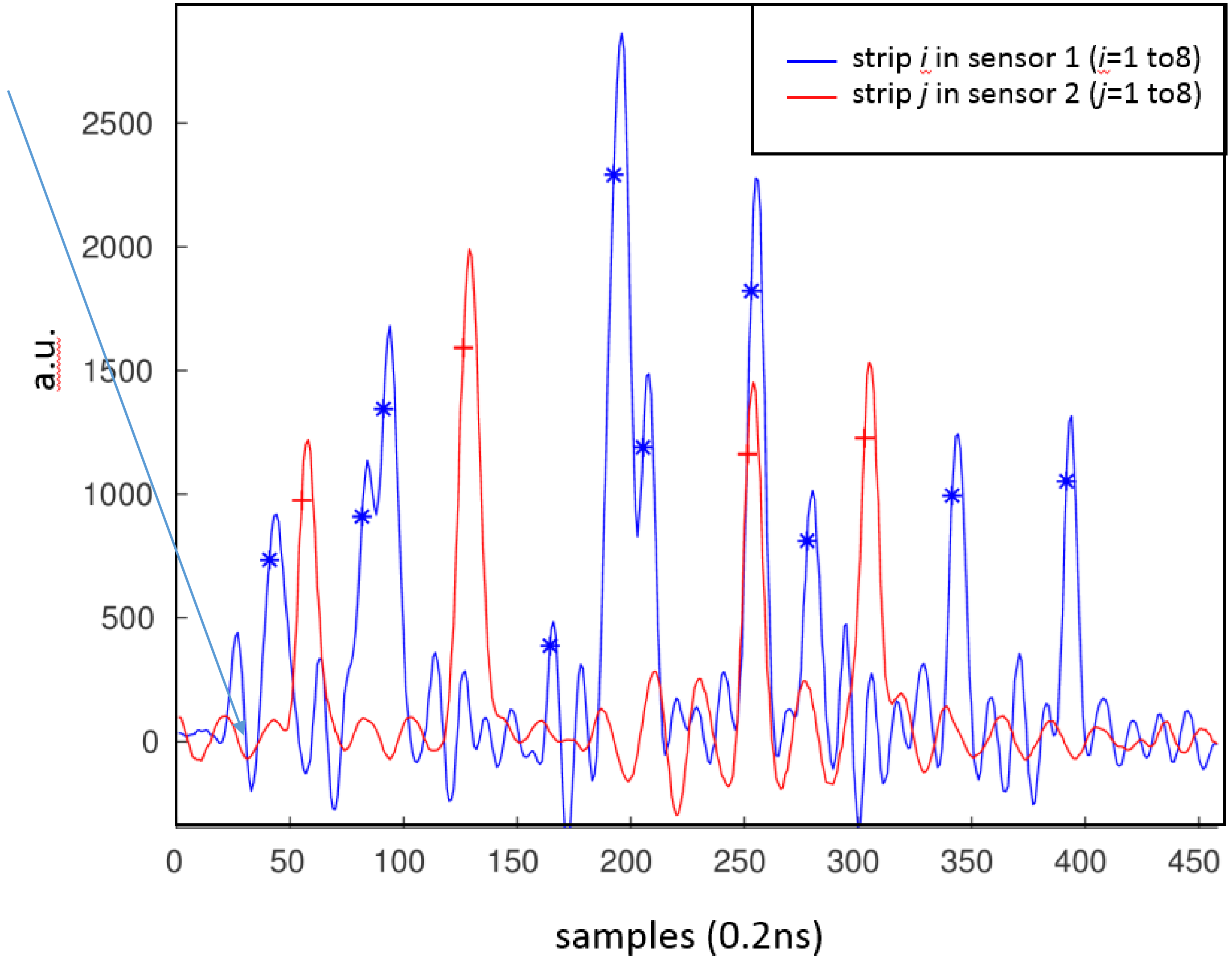


Waveforms to extract the TOF

- 204.8 ns acquisition window (called event)
- 1024 samples per event (0.2ns each)
- 8 or 16 signals.
- one binary file per channel.
- Sampling rate: 2000 up to 4000 events/second

Fast waveforms analysis

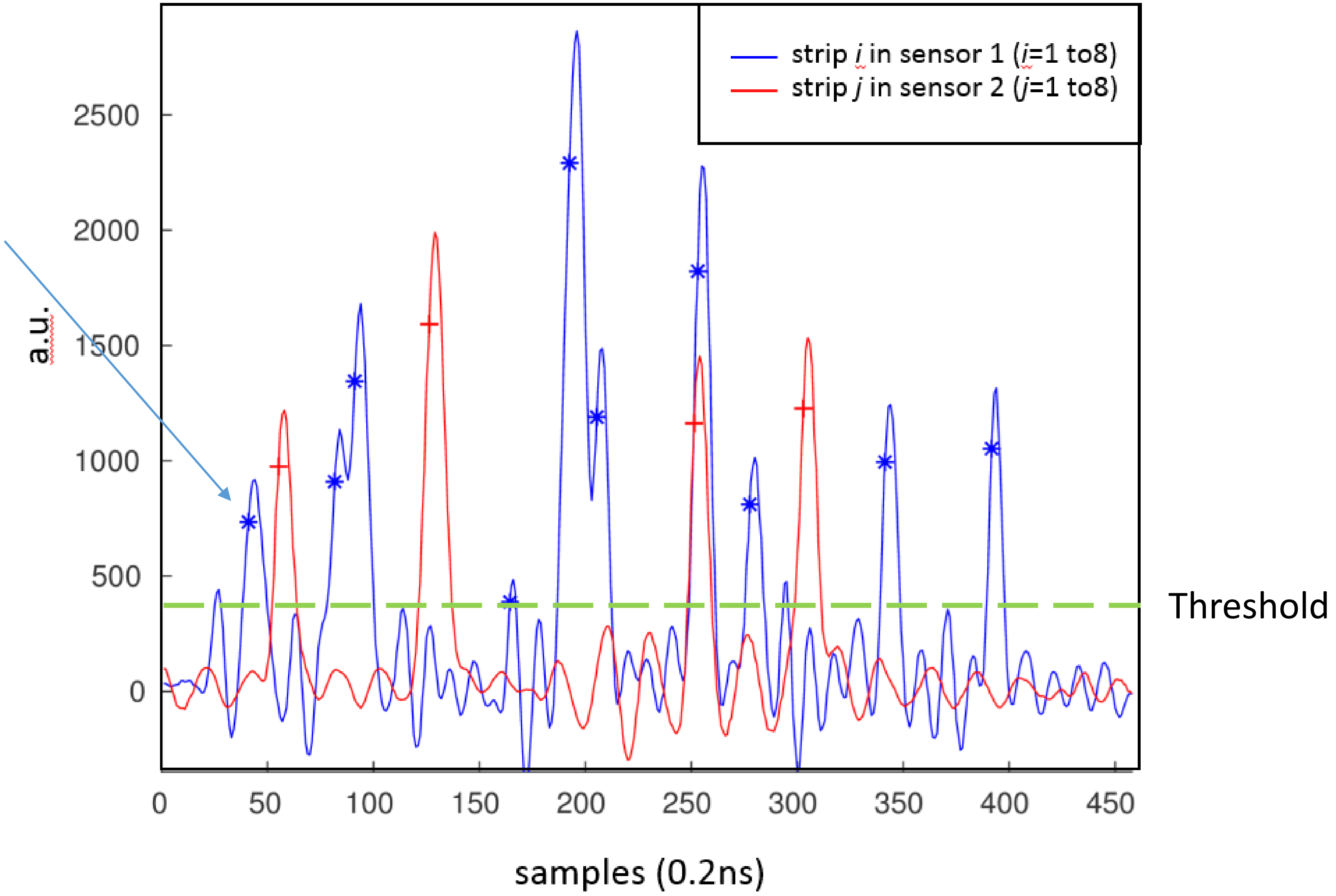
1. Zero level determination using the mode.



Fast waveforms analysis

1. Zero level determination using the mode.

2. If the signal is over a threshold, the proton arrival time is determined as the 80% of the peak maximum. (constant fraction).

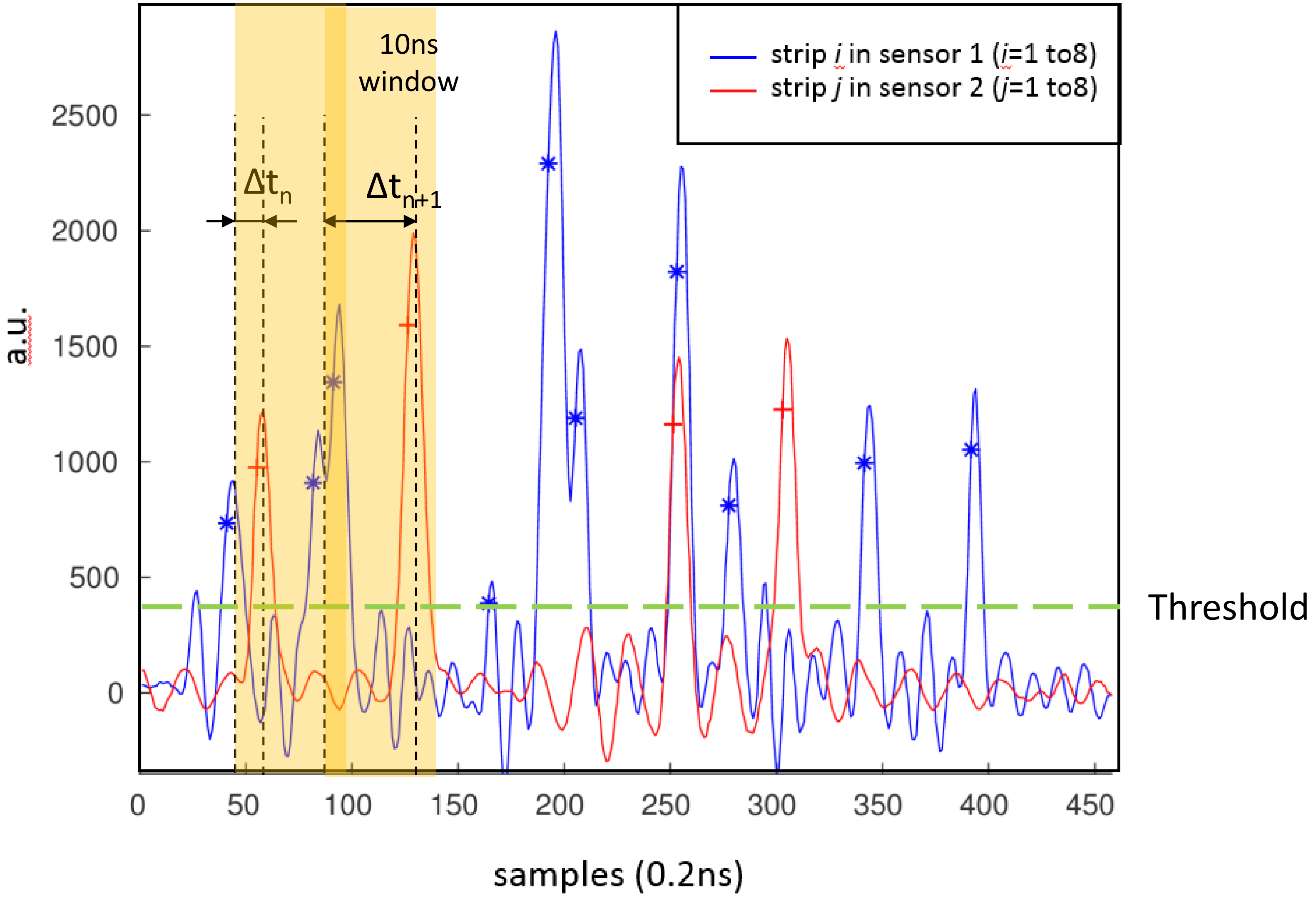


Fast waveforms analysis

1. Zero level determination using the mode.

2. If the signal is over a threshold, the proton arrival time is determined as the 80% of the peak maximum. (constant fraction).

3. A 10ns window is used to extract all the time difference between the peaks in sensor1 with those in sensor2 (the maximum TOF at 1m is less than 10 ns).



Fast waveforms analysis

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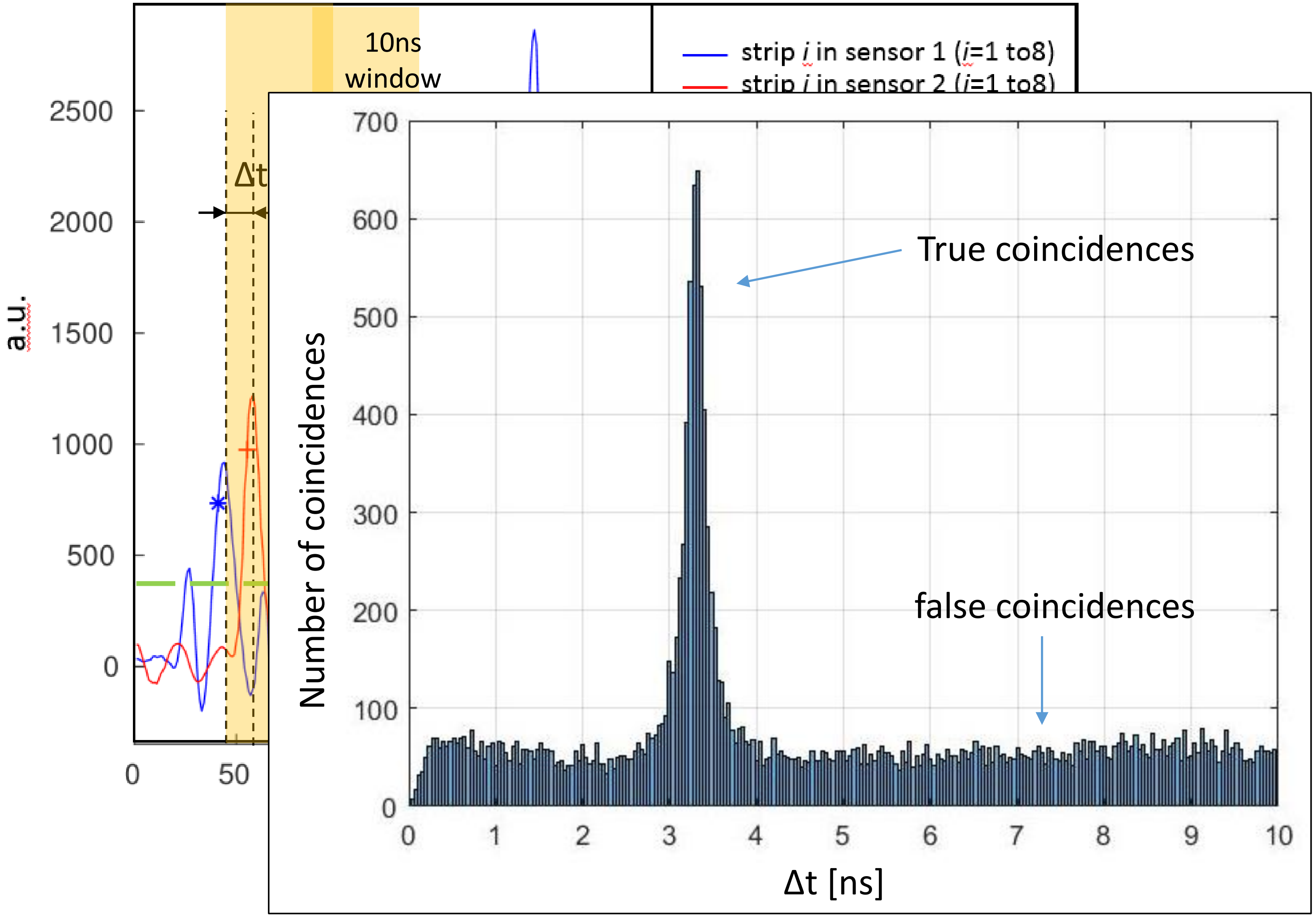
3. A 10ns window is used to extract all the time difference between the peaks in sensor1 with those in sensor2. (the maximum TOF at 1m is less than 10 ns).
4. All the Δt are then grouped in a histogram.

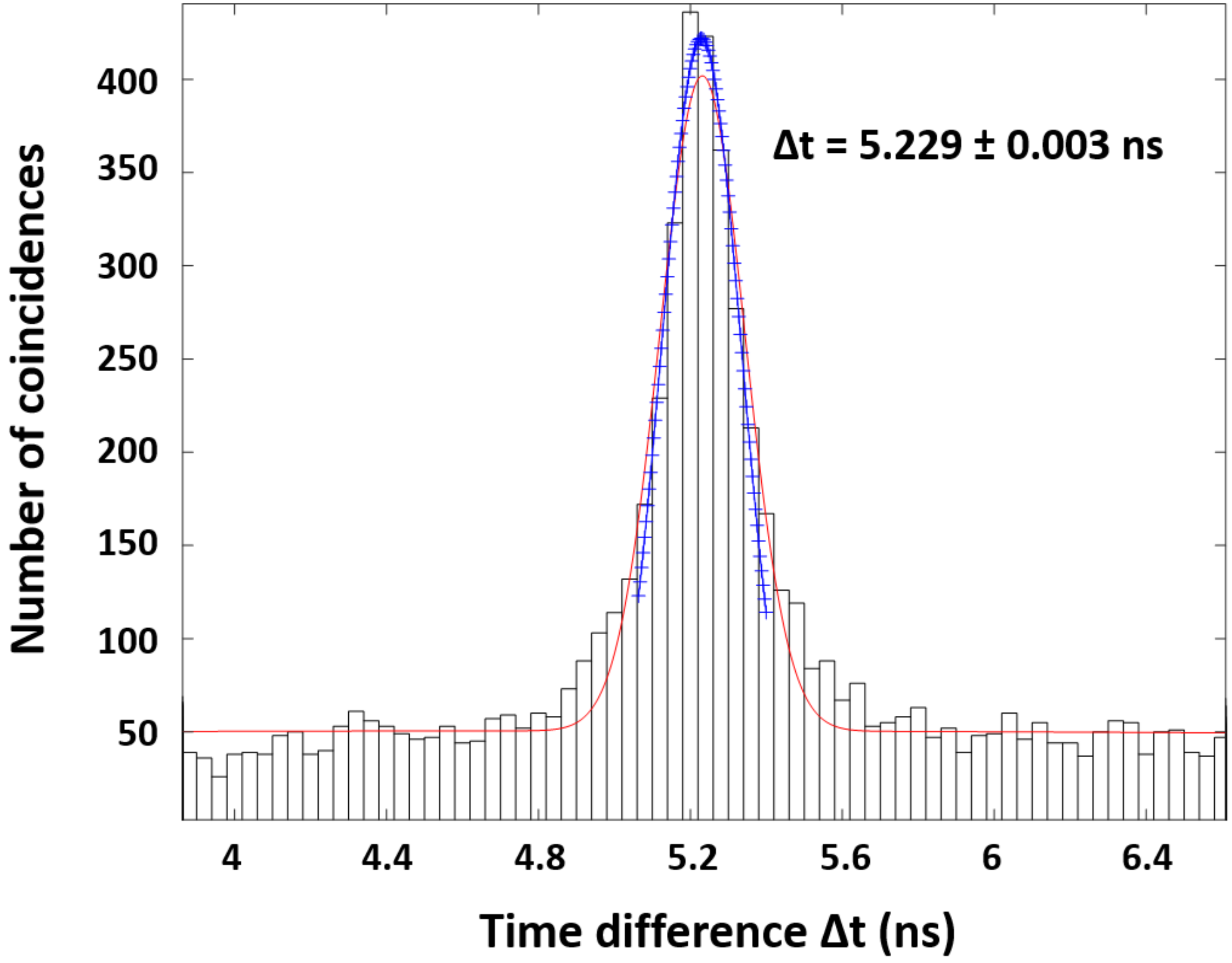


Fast waveforms analysis

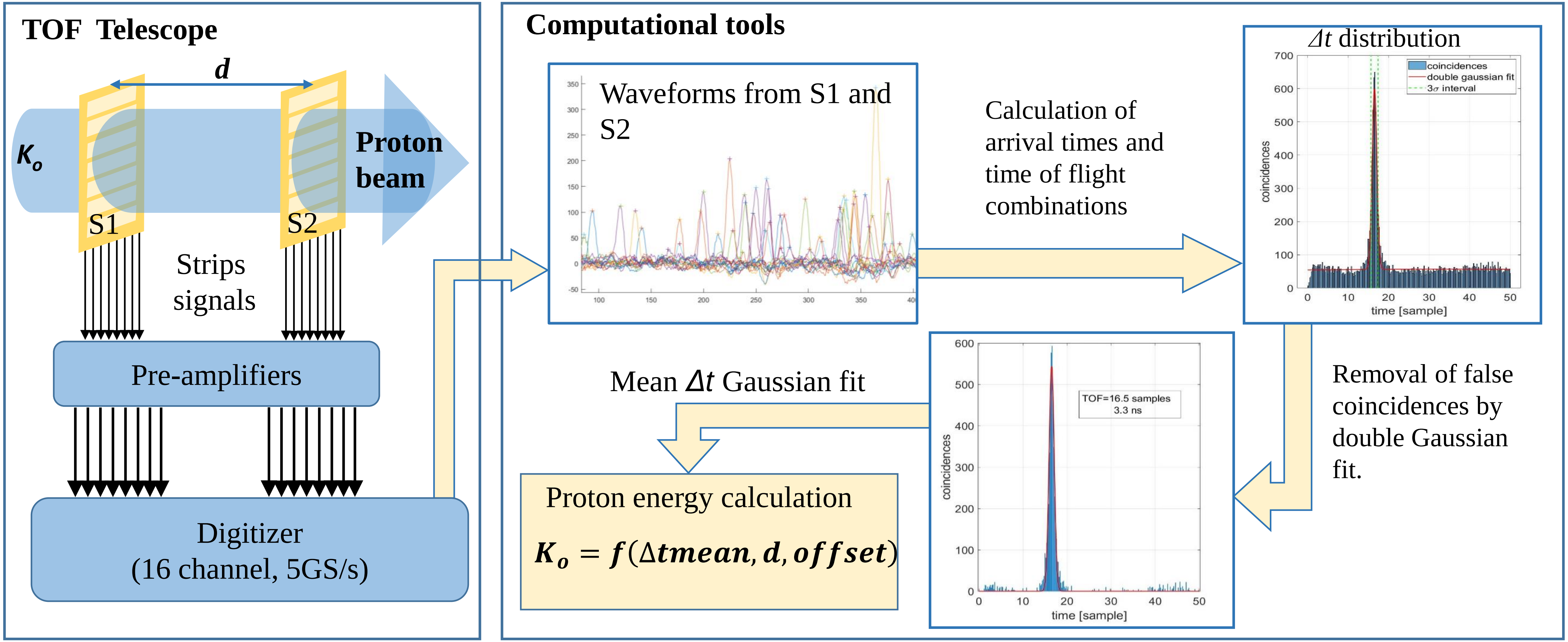
5. Double Gaussian fit (red curve) to extract the true-coincidences peak.

6. Additional Gaussian fit to determine Δt_{mean} within 1.5 σ of the true-coincidences peak.

- Using this method we are able to analyze the data at the same transfer rate they are received from the digitizer (for 2 signal configuration). Making possible the online analysis in the future. Now we are doing only offline analysis, saving the waveforms.
- For the 16 signals configuration, parallel computing could be explored in the future for online analysis.

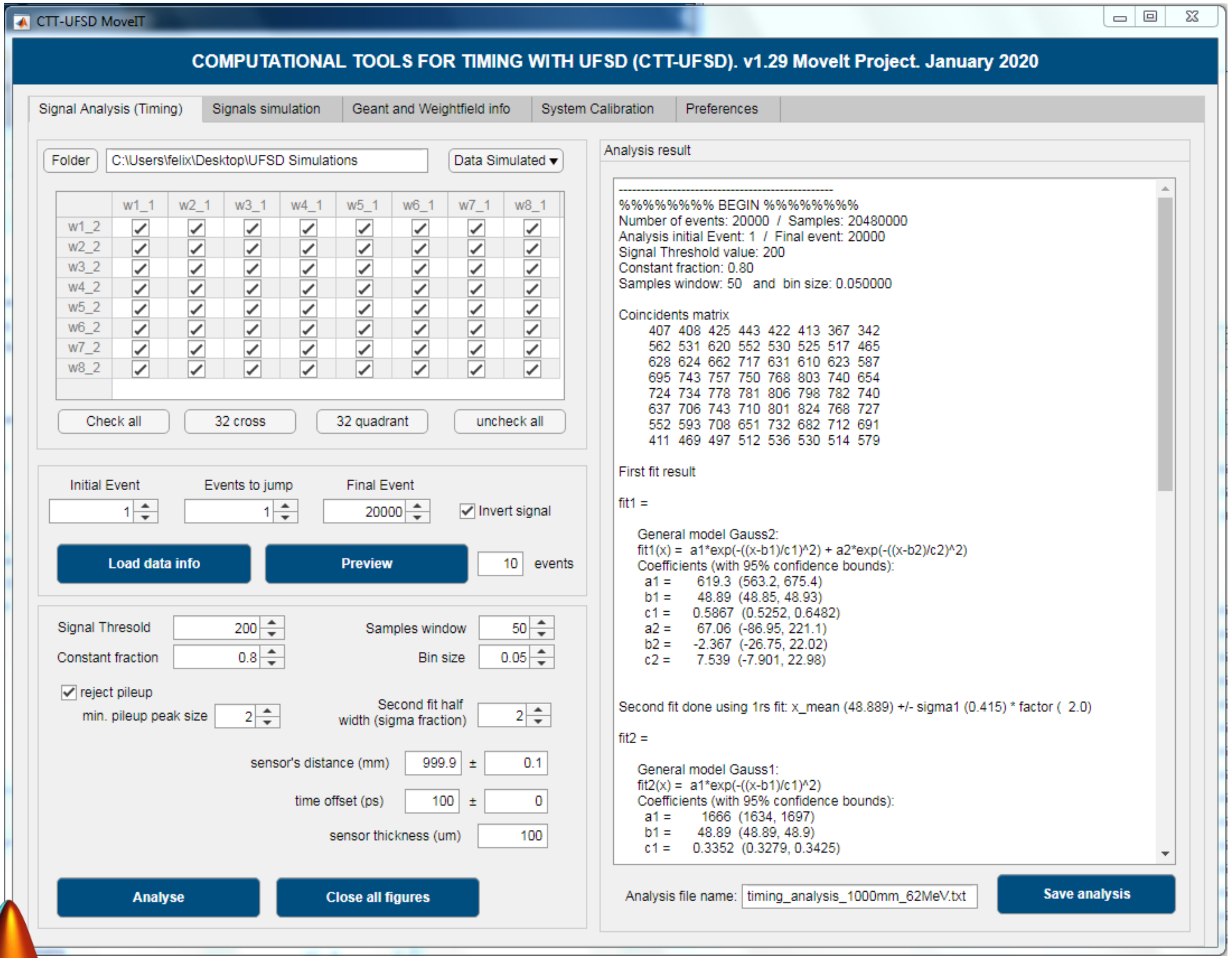


UFSD telescope overview



UFSD telescope software

SIGNAL ANALYSIS APP (MATLAB)

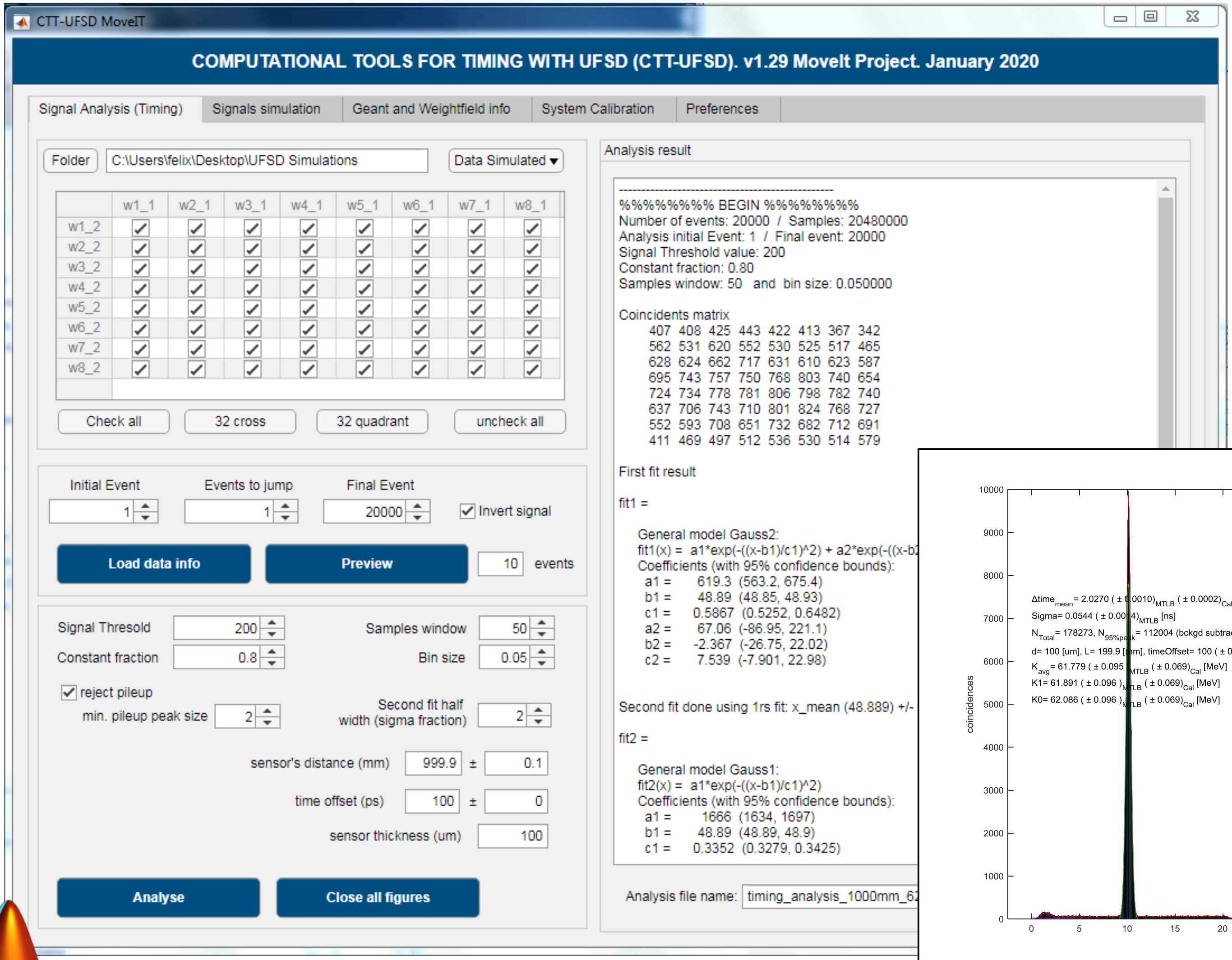


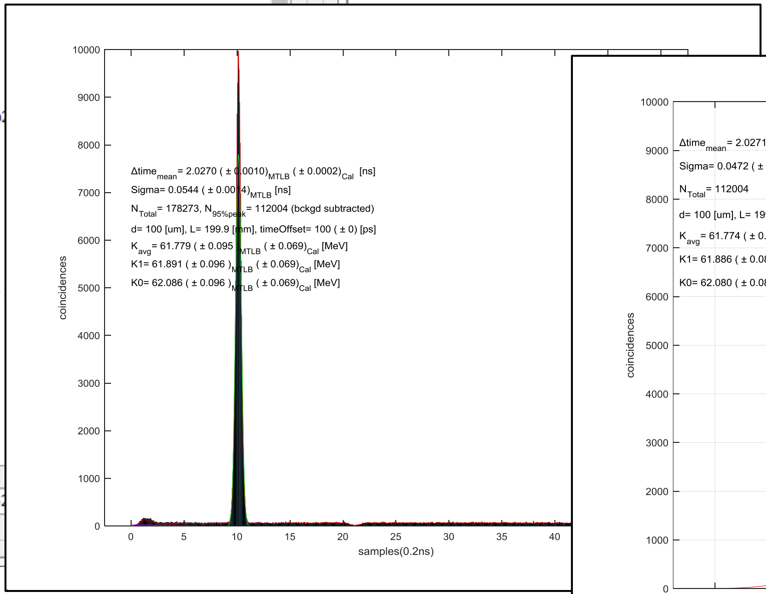
Settings:

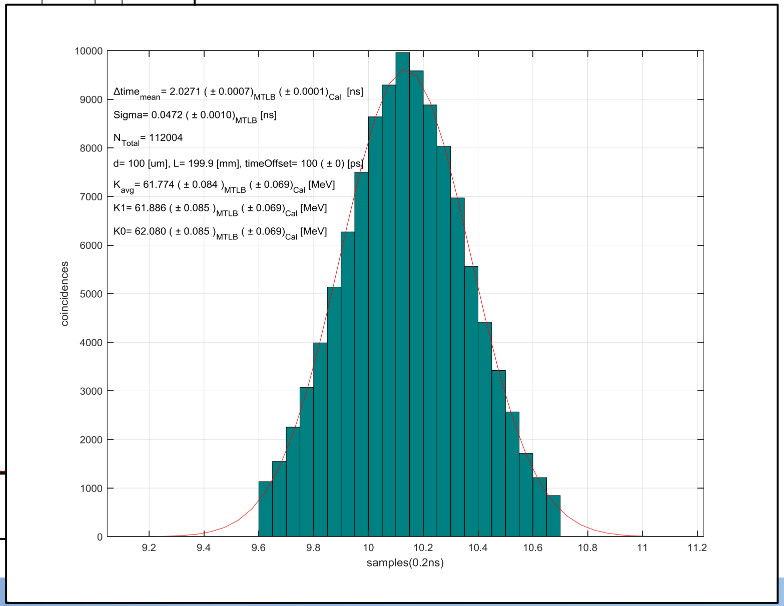
- Combinations, event range, threshold, samples window (10 ns default), constant fraction (80% def.), bin size, pile-up removal.

UFSD telescope software

SIGNAL ANALYSIS APP (MATLAB)







Settings:

- Combinations, event range, threshold, samples window (10 ns default), constant fraction (80% def.), bin size, pile-up removal.

Output:

- mean delta time (Δt_{mean}), pre-calculated proton energy (if time off-set and sensor's distances are defined), and its errors.
- Figures of histograms and its fits.

How can the system be validated?

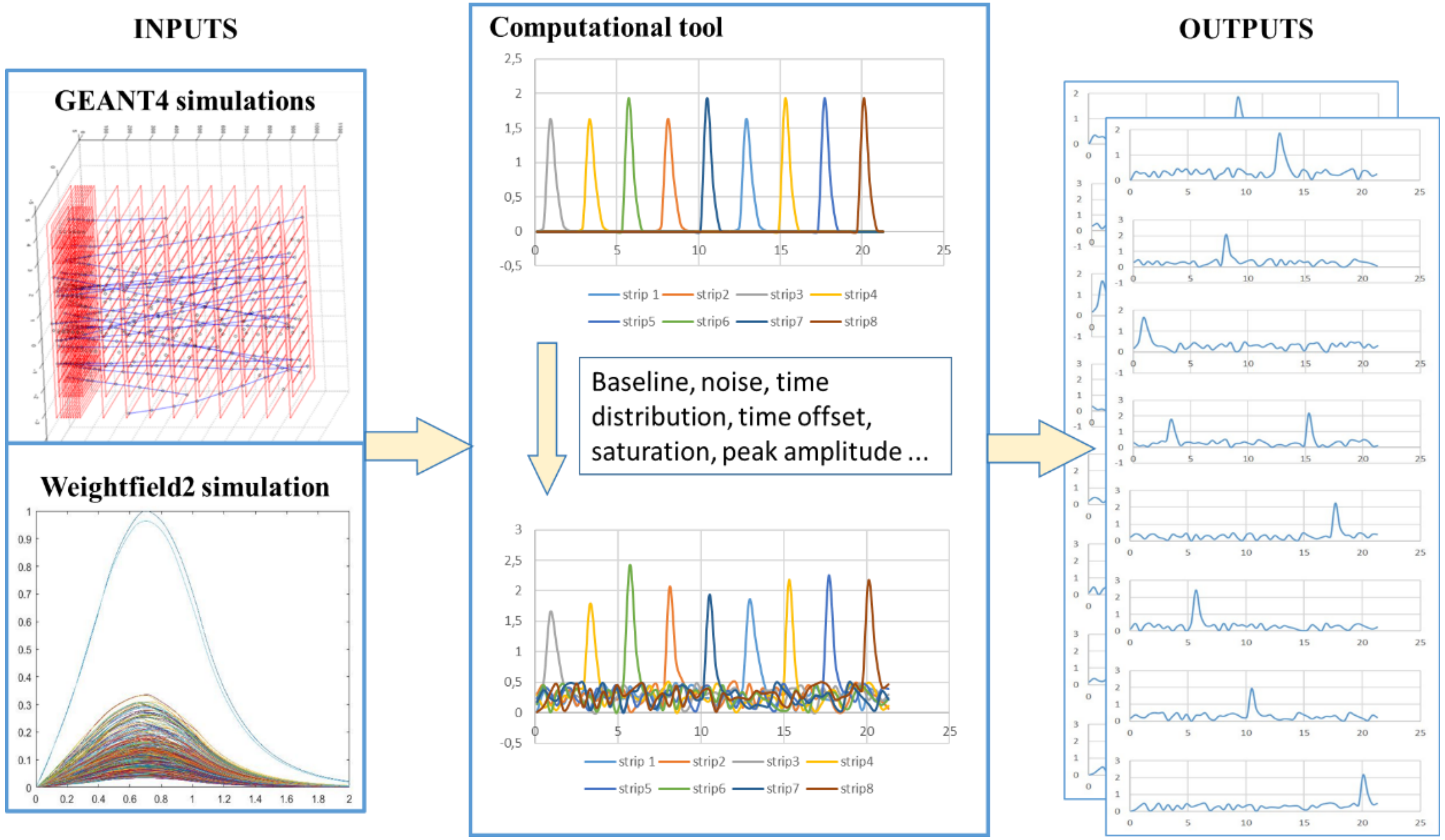
1- Using simulated data.

A MATLAB application was prepared to simulate the UFSD telescope response to different proton beams and sensor distances.

2- Measuring well-known proton energies.

Five beam energies were measured at CNAO (Pavia, Italy) using the UFSD telescope at four different distances. The CNAO nominal energy precision is 0.1%.

Validation with simulated data



Input:

- Proton GEANT4 database to extract the TOF.
- Simulation of the signals generated by protons in the UFSD using (Weighfield2)

Settings:

- time distribution (Poissonian by default.)
- Noise level and type, signal level offset, delta time offset, sampling frequency, peaks amplitude, sensor's distance, number of events.

Validation with simulated data

SIGNAL SIMULATION APP (MATLAB)

Input:

- Proton GEANT4 database to extract the TOF.
- Simulation of the signals generated by protons in the UFSD using (Weighfield2)

Settings:

- time distribution (Poissonian by default.)
- Noise level and type, signal level offset, delta time offset, sampling frequency, peaks amplitude, sensor's distance, number of events.

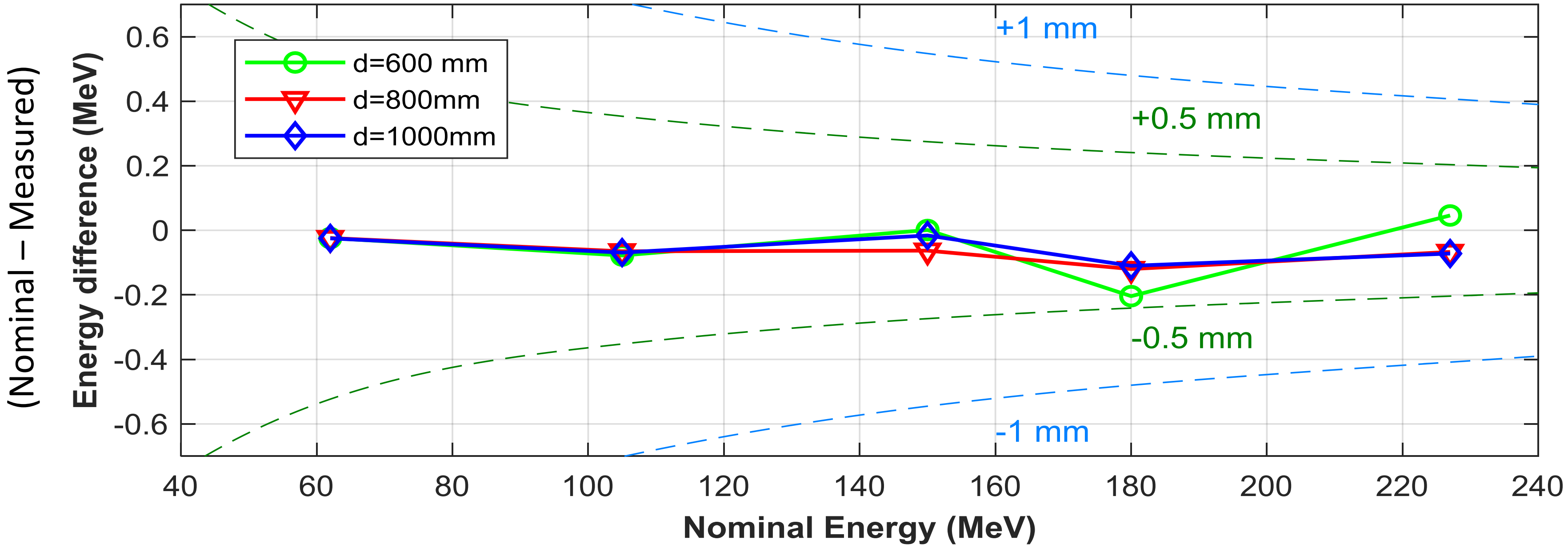
Output

- 16 simulated waveforms, in the same CAEN digitizer format. (easy to analyse).
- 8x8 matrix of true Δt_{means}
- 8x8 matrix of true numbers of coincidences

Validation with simulated data

	Distance between sensors (x_i) [mm]					
Nominal K_0 [MeV]	200	300	400	600	800	1000
62	2,027 ns	2,993 ns	3,960 ns	5,896 ns	7,836 ns	9,778 ns
105	1,626 ns	2,391 ns	3,155 ns	4,684 ns	6,214 ns	7,745 ns
150	1,415 ns	2,074 ns	2,733 ns	4,051 ns	5,371 ns	6,689 ns
180	1,326 ns	1,939 ns	2,553 ns	3,780 ns	5,007 ns	6,235 ns
227	1,223 ns	1,786 ns	2,349 ns	3,474 ns	4,600 ns	5,726 ns

extracted Δt_{mean}



- The deviations are found to be always smaller than 200 keV for all the distances.
- The range discrepancies remained within half millimetre complying with the clinical requirements of 1mm tolerance.

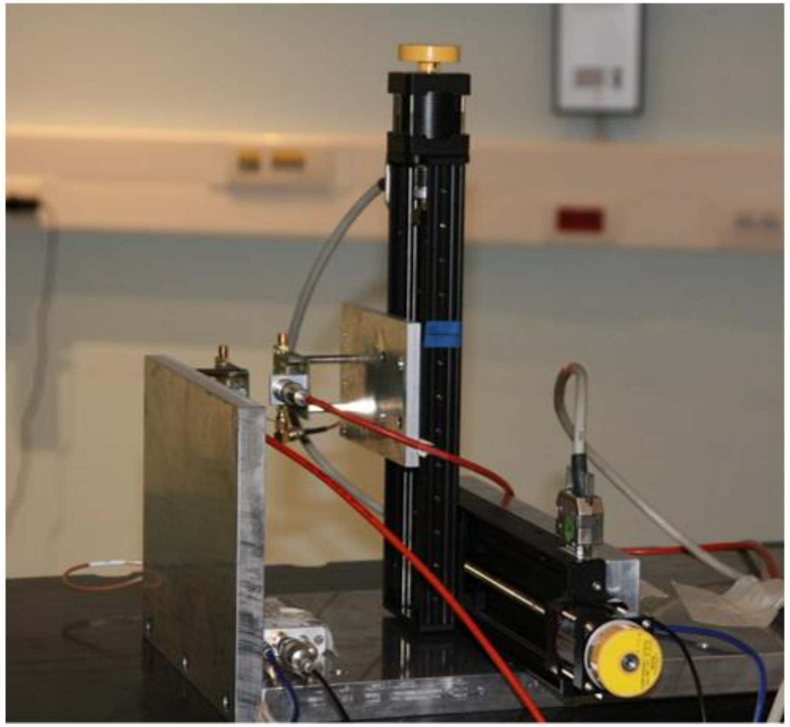
Energy to water range conversion done by the empirical Bragg-Kleman rule.

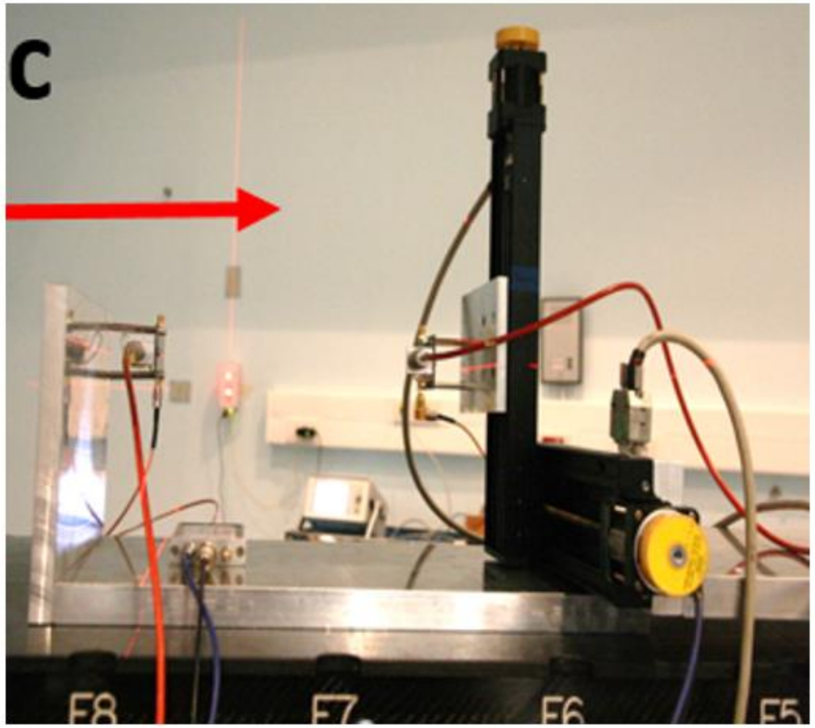
Validation with experimental measurements

CNAO

Proton Beam from synchrotron

- **Beam FWHM** ~ 10 mm
- **Max flux**
  ~ 10^9 p/s delivered in spills
- **Beam flux** range:
  20% - 100% of max flux.
- **Beam energy** range:
  58 – 227 MeV (5 – 2 MIPs)

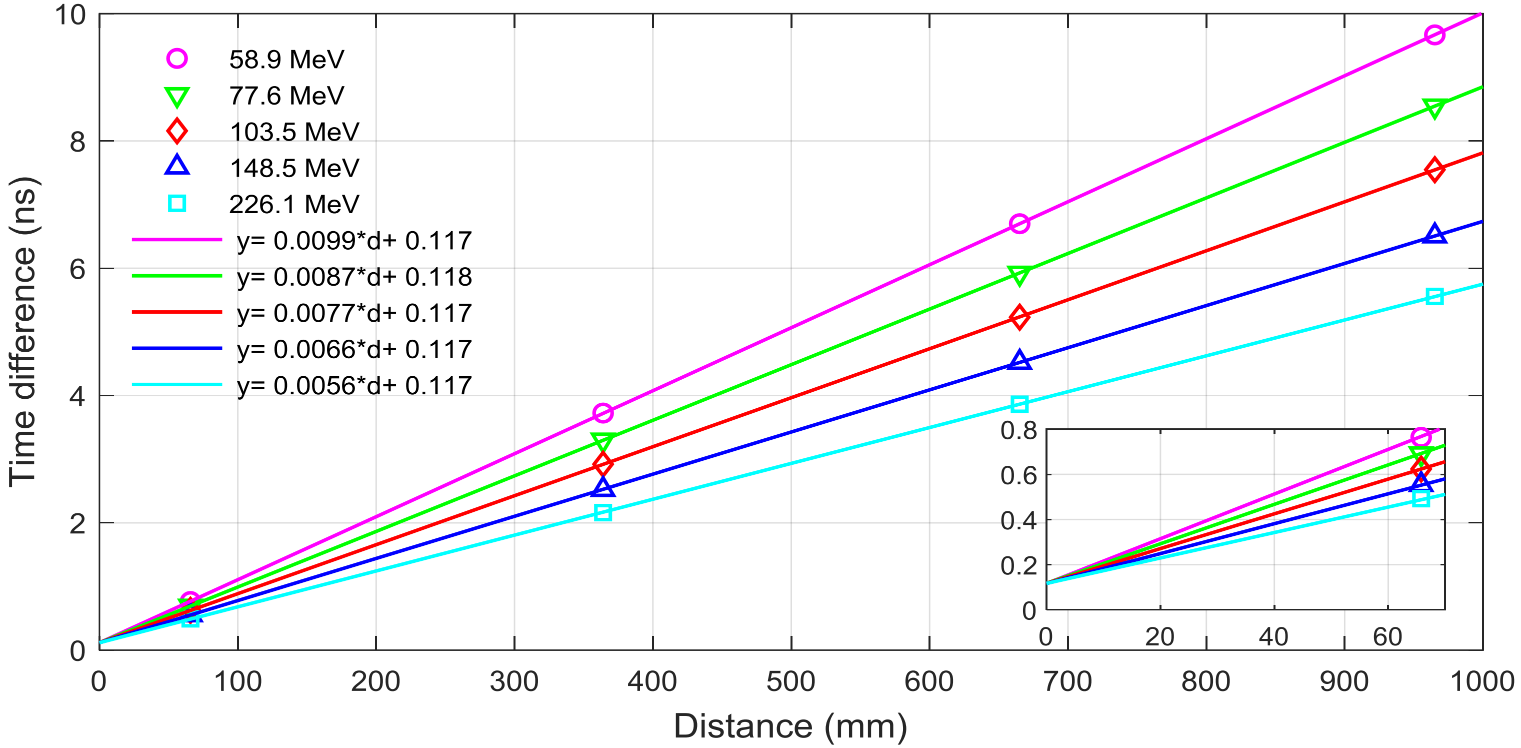




- 4 distances= 7, 27, 67, 97 cm
- 5 energies= 58 - 227 MeV
- 2 HPK pad sensors (150 mm total thickness, 80 mm active thickness)
- 1 pad from each sensor

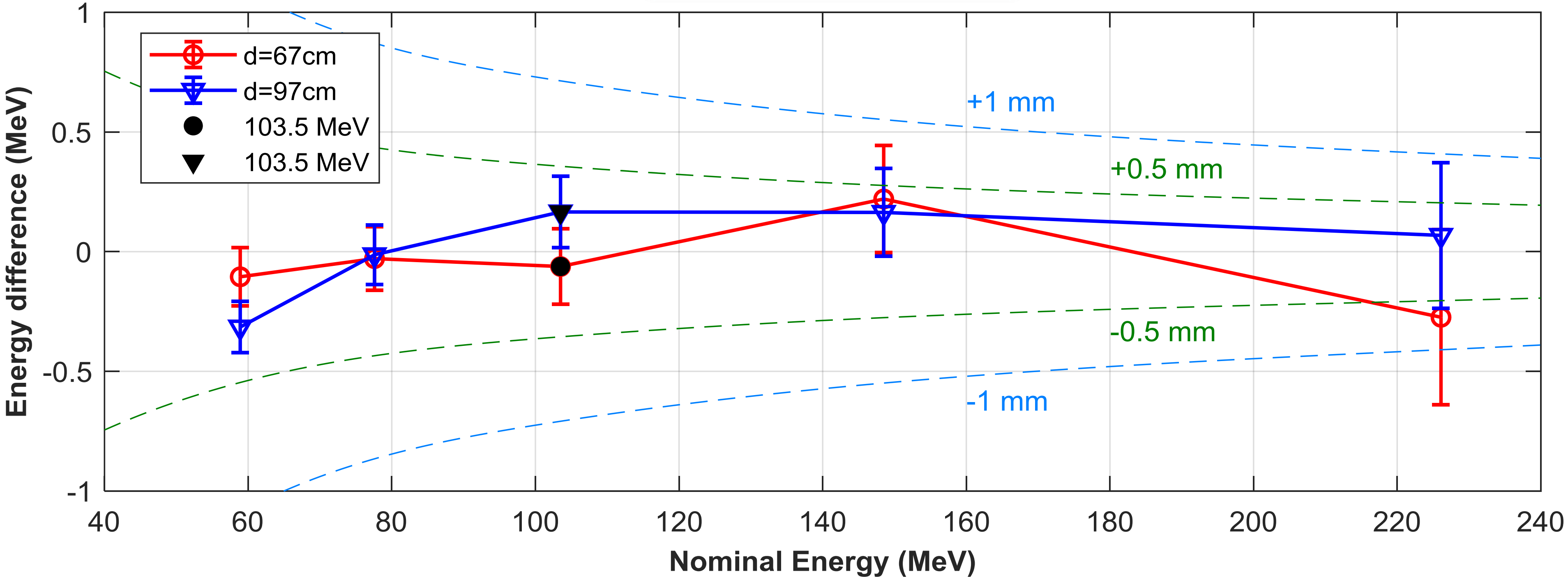
Validation with experimental measurements

CNAO



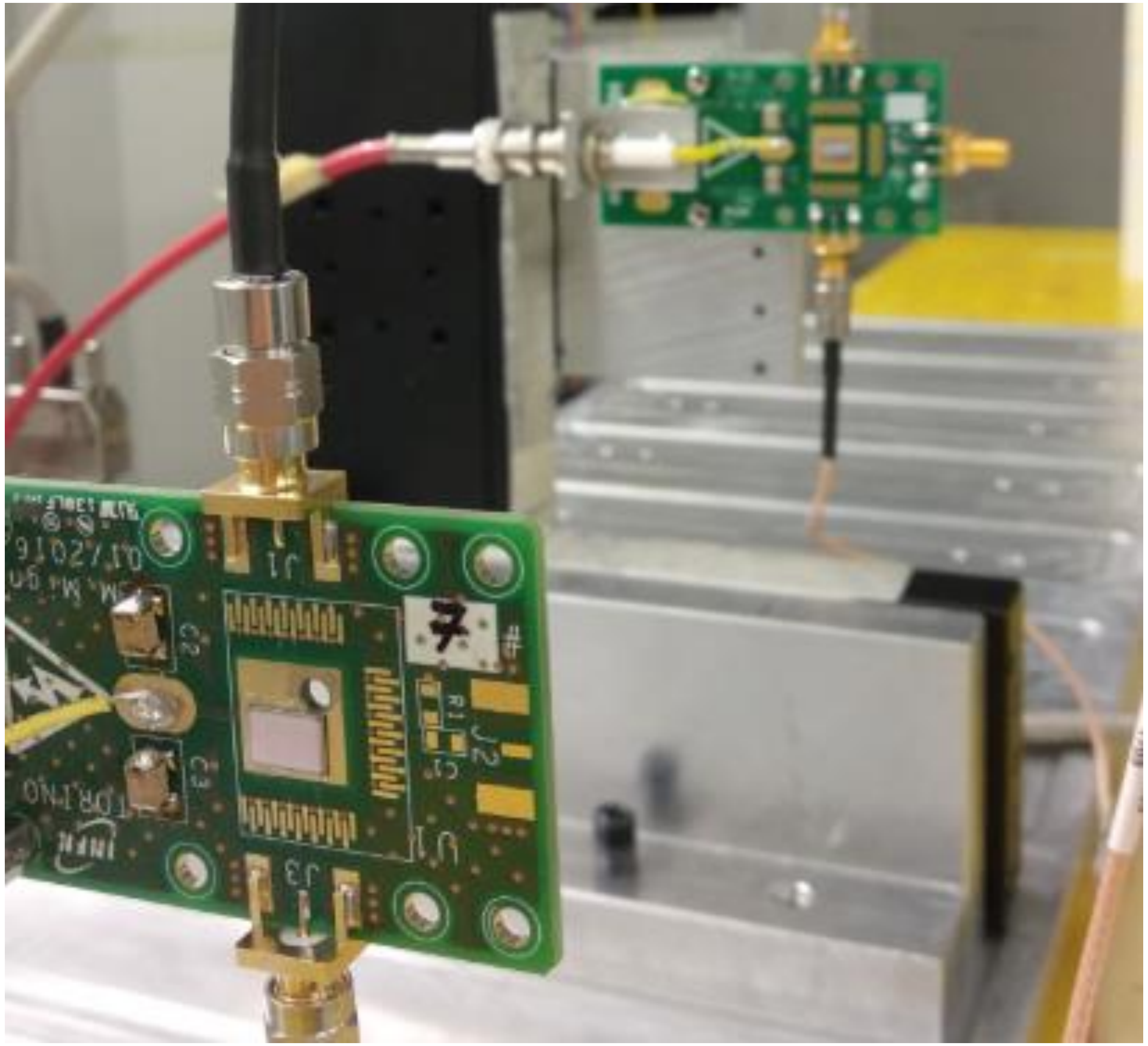
Δt_{mean} measured at CNAO for the 5 different beam energies and the 4 distances between the 2 sensors. They were linearly interpolated for each beam energy. The intercepts provide the time offset, however the final value comes out from a global calibration done using all the data.

Validation with experimental measurements



The deviations for the tests at 67 and 97 cm are found to be always smaller than 0.5 MeV. The range discrepancies remained within half millimetre for the lower energies and within 1 millimetre for the maximum energy, complying with the clinical requirements.

Energy measurement at TIFPA (TRENTO - IT)



TIFPA PROTONTERAPIA TRENTO

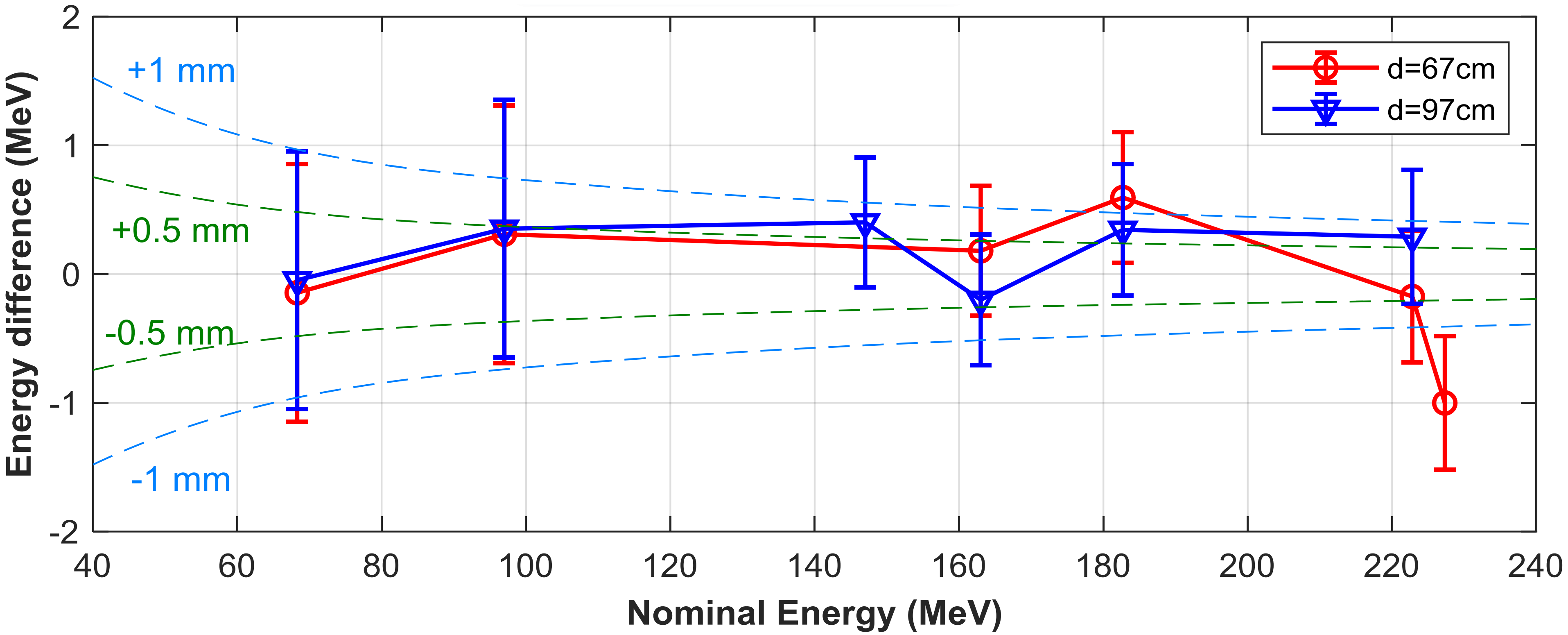
Proton Beam from cyclotron

- **Beam FWHM** 3-7 mm
- **Beam flux**
  10^6 - 10^{10} p/s
- **Beam current** range:
  1 nA – 320 nA
- **Beam energy** range:
  68 – 228 MeV

- 3 distances= 27, 67, 97 cm
- 6 energies= 68 - 228 MeV
- 2 FBK thinned sensors (70 and 120 μm total thickness, 50 μm active thickness)
- 2 strips from each sensor

Energy measurement at TIFPA (TRENTO - IT)

TIFPA PROTONTERAPIA TRENTO



Here the deviation of the measured beam energy lies within the clinically acceptable range uncertainty (< 1mm), for the largest distance 97cm. However there are large error bars comes from the uncertainties on the nominal energies. They were measured using ionization chamber with 0.5MeV- 1MeV uncertainty.

Conclusion

- UFSD is a promising new technology for beam qualification and monitoring in Particle Therapy because of its excellent time resolution and very short signal durations.

- A methodology to determine the beam energy, which accounts for the energy loss in the sensors and in the air, was developed and benchmarked against Monte Carlo simulations.

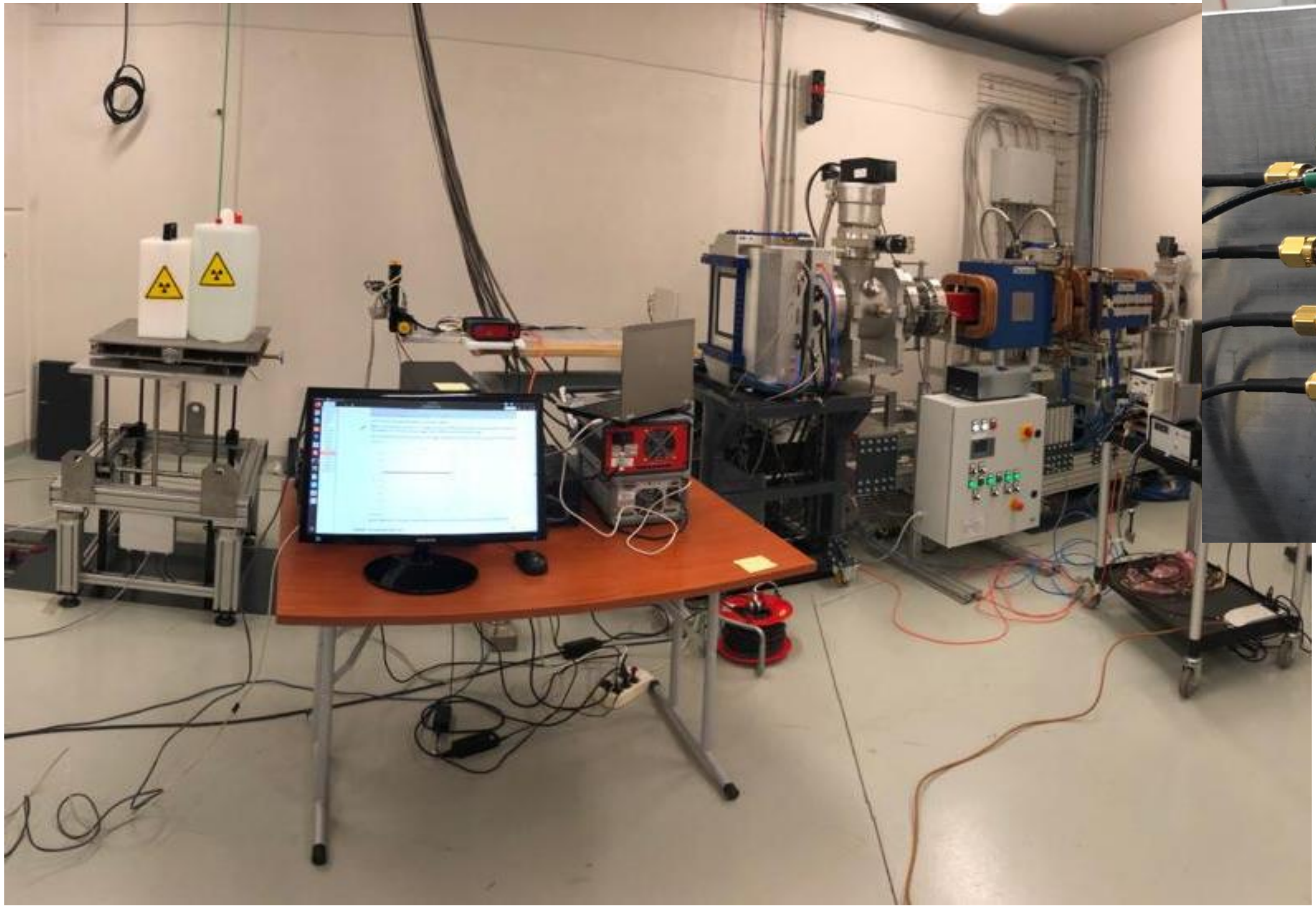
- Measurements were performed at CNAO at TIFPA. The energies determined with the system were compared with nominal values.

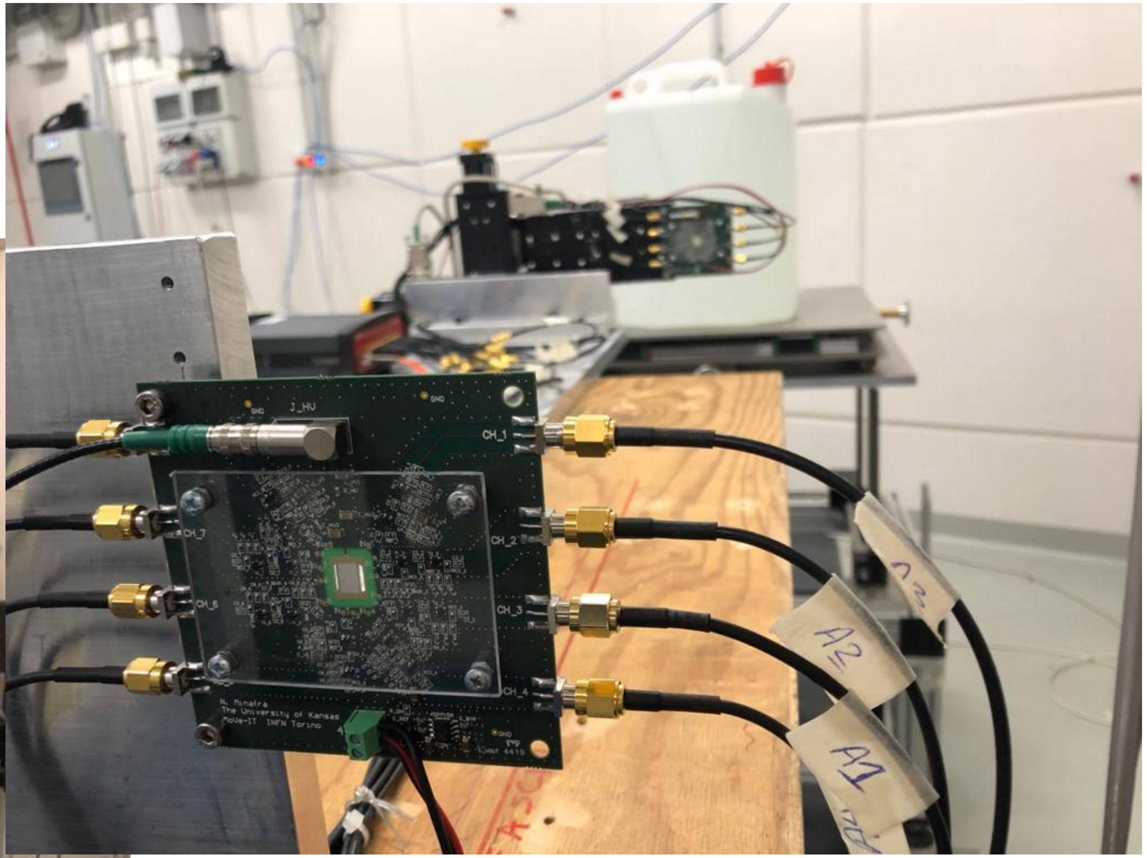
- For distances between sensors of 67 cm and 97 cm, the deviations and errors are of hundreds of keV, corresponding to range in water smaller than the clinical tolerance of 1 mm.

- Ongoing works are improving the system accuracy increasing the number of strips and positioning precision. On the other hand, their translation into clinics needs several improvements, such as, correction algorithms for pile-up effects at therapeutic fluxes, and dedicated efficient electronics.

Ongoing works

16 channel acquisitions and analysis





Measurements with proton beam in the new experimental room at CNAO (March 2nd, 2020)

Ongoing works

A new self-calibration method (no external data needed)

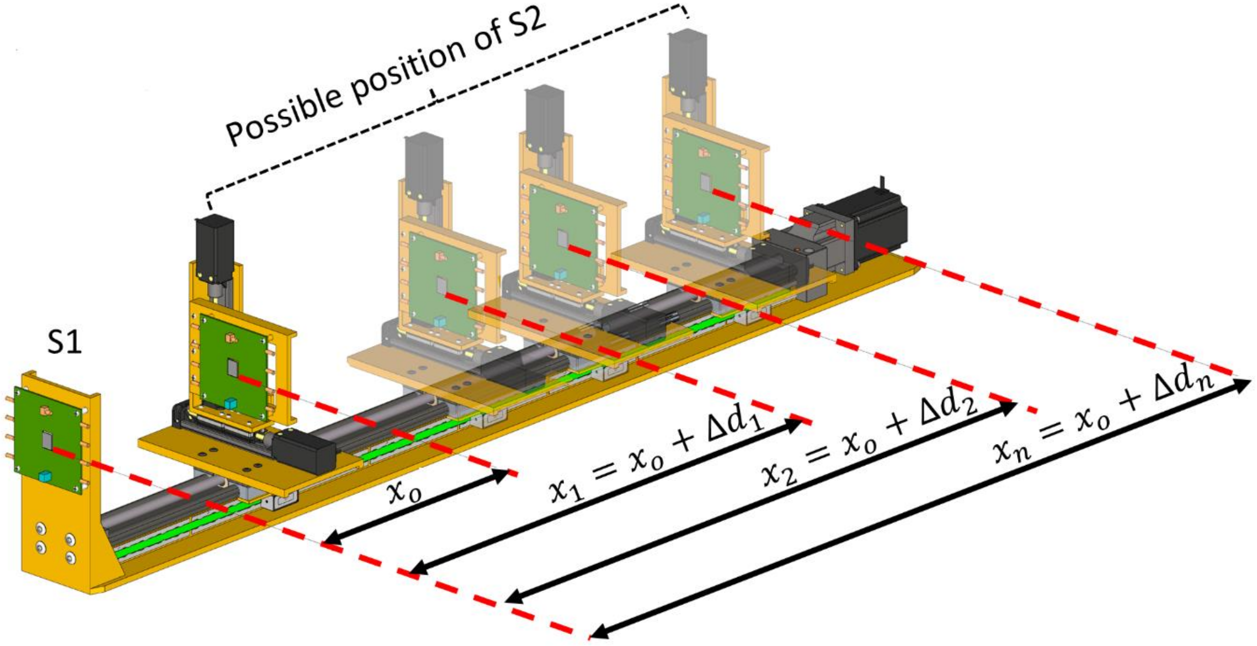
$$v_{ij}^{avg} = \frac{\Delta d_j - \Delta d_i}{TOF_j - TOF_i}$$

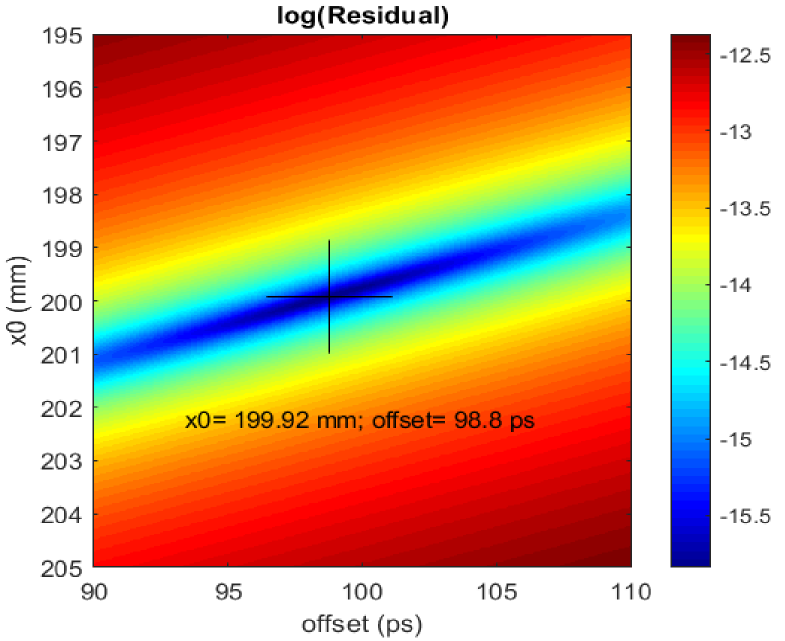
$$K_{1,ij}^{1}(x_o) \approx K_{ij}^{avg} + \left(\frac{S}{\rho}\left(K_{ij}^{avg}\right)\right)_{air} \cdot \rho_{air} \cdot \left(x_o + \frac{\Delta d_j - \Delta d_i}{2}\right)$$

$$d_{ijk}(x_o, offset) \approx v_{ij}^{1}(x_o) \cdot (\Delta t_k - offset)$$

$$res(x_0, offset) = \sum_{k=0}^{n-1} \sum_{j>i}^{n-1} \sum_{i=0}^{n-1} \left(\frac{d_{ijk}(x_o, offset) - x_k}{\sigma_{ijk}}\right)^2$$

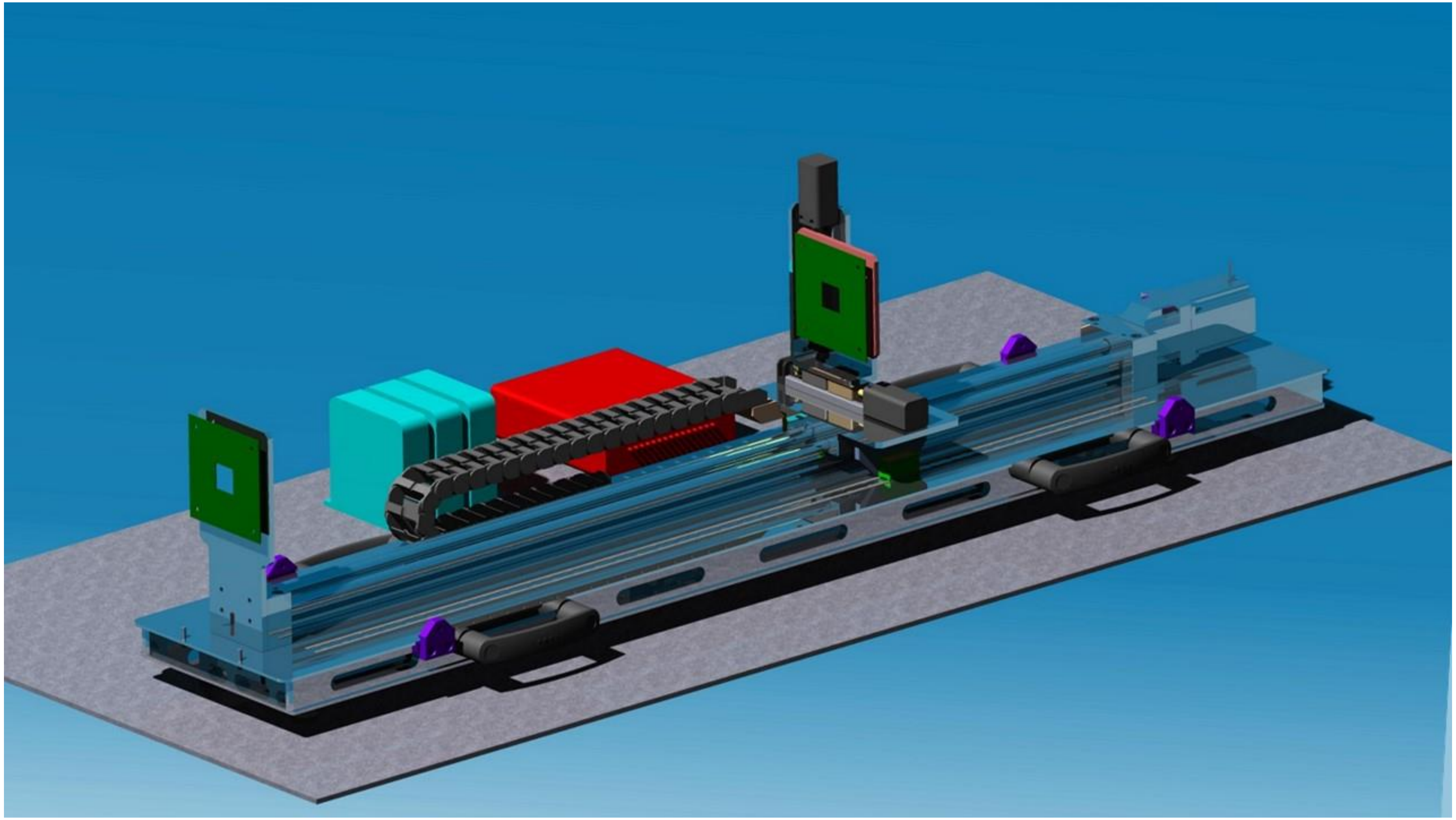
$$RES(x_o, offset) = \sum_{E=K_{min}}^{K_{max}} res_E(x_0, offset)$$





Ongoing works

Construction and test of the final prototype



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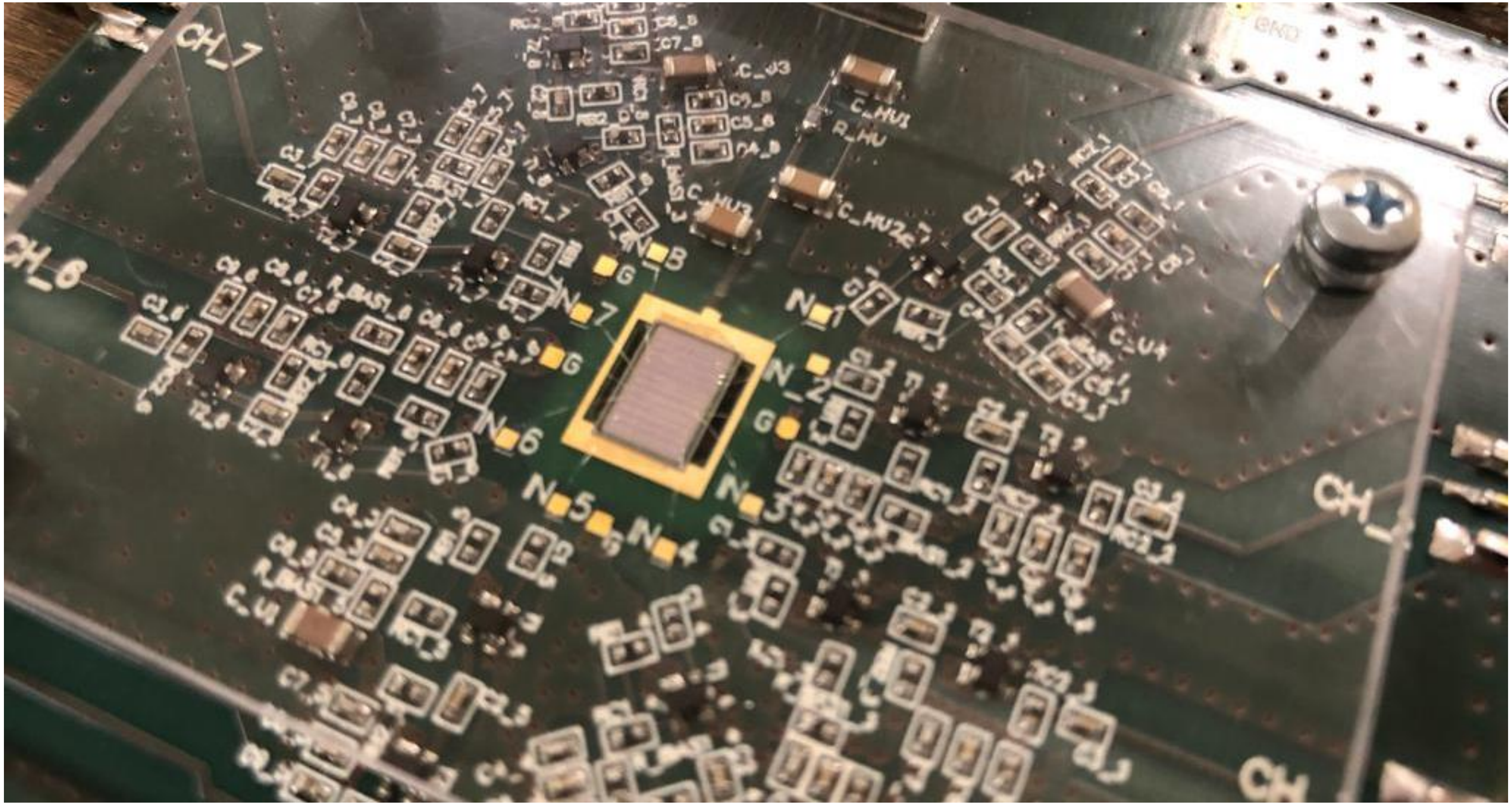

Thank you