Plastic-scintillator based proton radiography relying on time of flight measurement: the tofprad project

Giacomo Traini, R. Anzalone, G. Battistoni, E. Ciarrocchi, Y. Dong, M. Francesconi, L. Galli, N. Krah, M. Magi, A. Mereghetti, S. Muraro, A. Muscato, M. Pullia and M. Morrocchi

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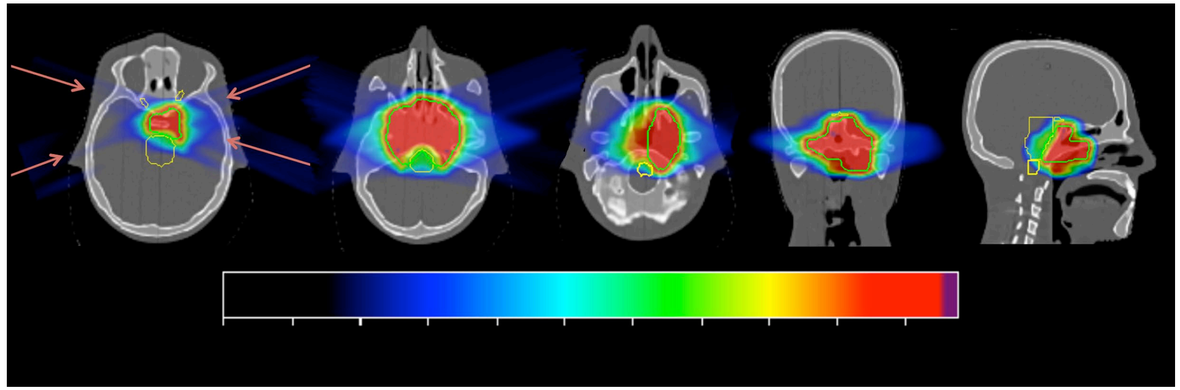
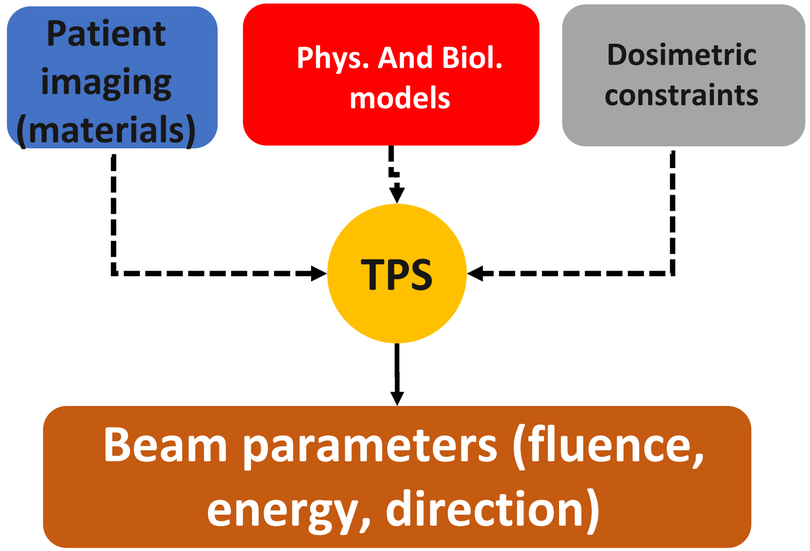
CNAO Centro Nazionale di Adroterapia Oncologica

Treatment in particle therapy

- **Goal**: optimizing beam (proton, C ion) E,θ to maximize dose conformity to tumor boundaries while preserving healthy tissues



- **Planning workflow**:
  - Image acquisition before the treatment start **(CT)**
  - Contouring Planned Target Volume and Organs at Risk by radiotherapists
  - Dose optimization against a set of constraints on PTV and OAR through dedicated software (Treatment Planning System) which exploit analytical model or MC models



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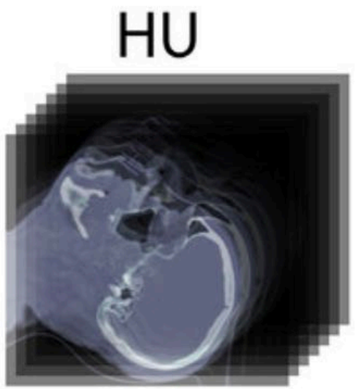
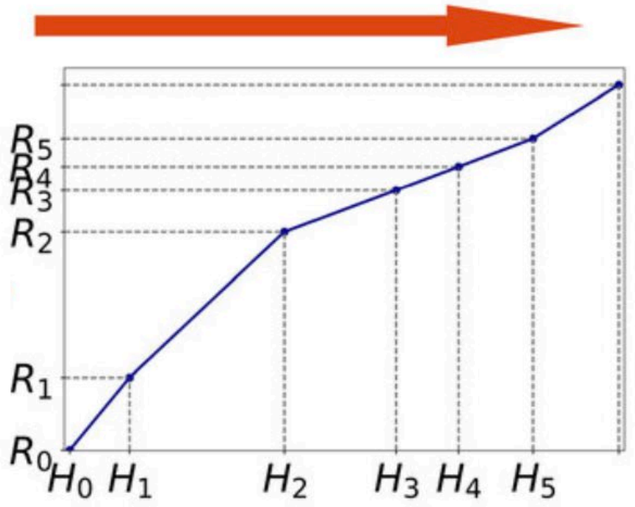
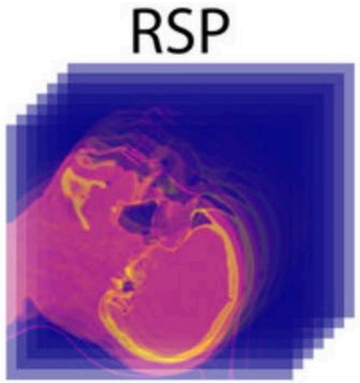
Plan robustness: range uncertainties

- The dose delivered to the patient is strongly affected by **range uncertainties:**
  - Relative Stopping Power (RSP) (with respect to water) <-> **HU conversion**. Today based on Schneider-Parodi conversion doi: 10.1118/1.1833041.







Up to 5-7% uncertainty

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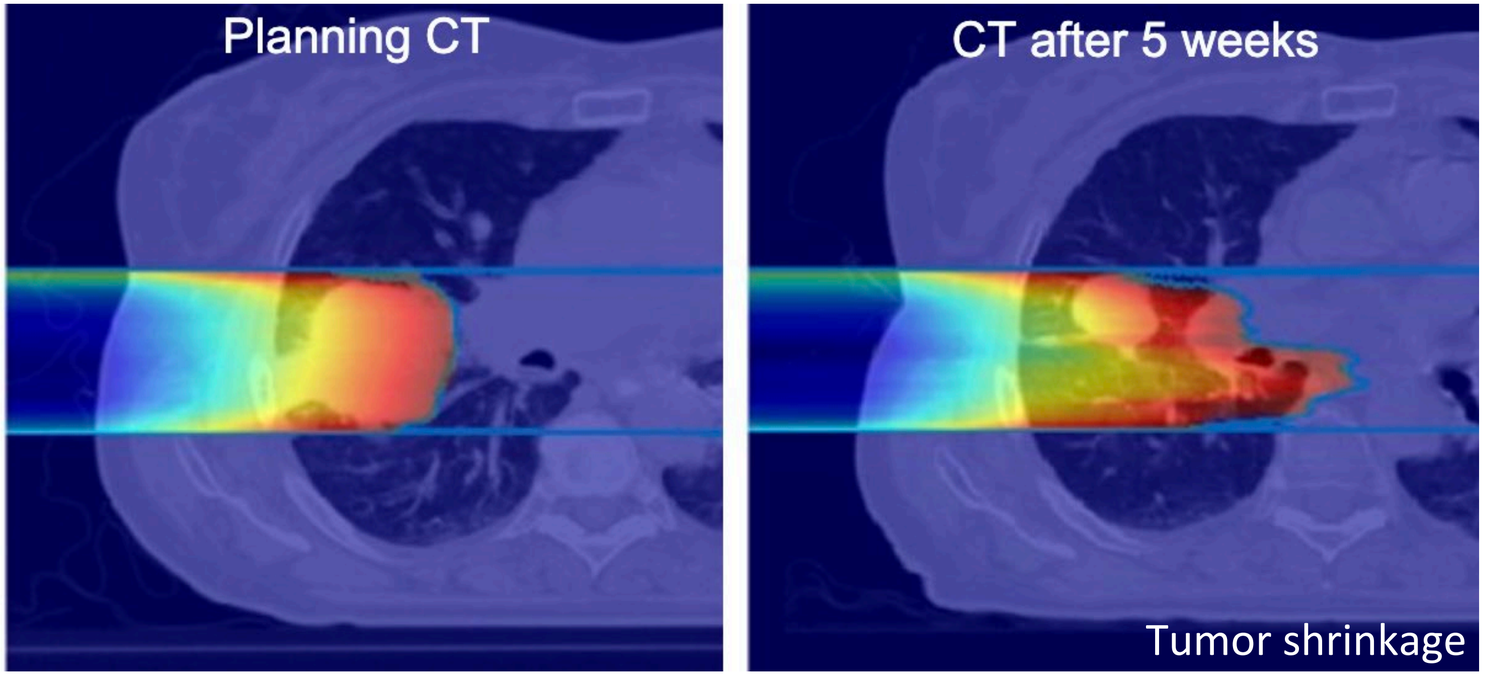
  - Morphology changes (inter-fraction, mis-alignment, breath-induced movement)

Future direction of particle therapy, Tony Lomax, Oxford 2008



There is no system capable of taking account to that!

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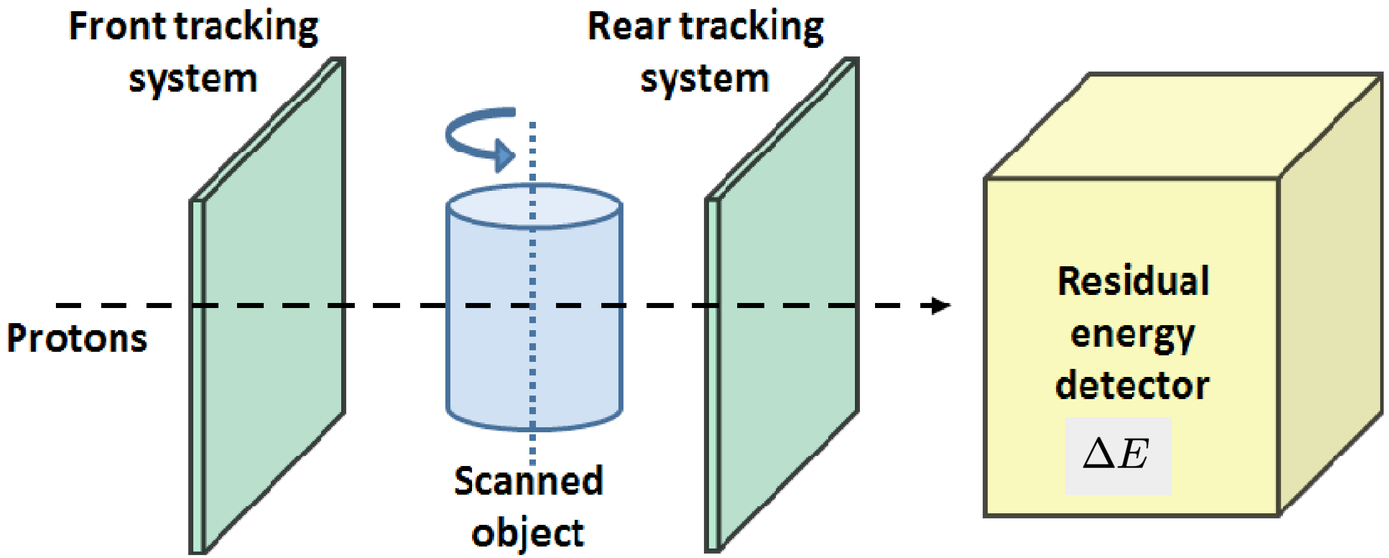
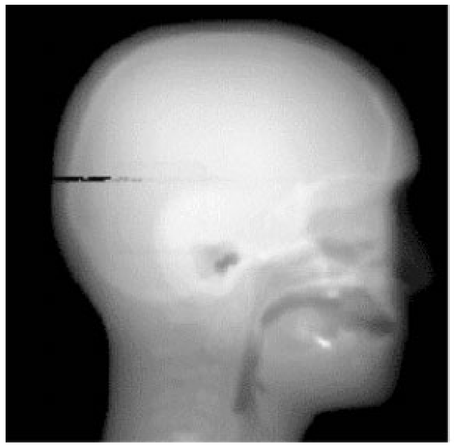
A possible solution: proton-imaging



$$\Delta E = \int \frac{dE}{dz}(z,\rho)dz$$

reconstruction



RSP(x,y,z)

- Direct image of RSP (no uncertainties on HU conversion)
- Low-dose, in-situ imaging system capable of periodical verification of the patient morphology
- Calorimeters made of **inorganic scintillators** are typically used to measure the residual energy, but suffer from a **limited rate capability** so that acquiring asufficiently large number of individual protons (to achieve the desired accuracy) would take too long to be clinically acceptable

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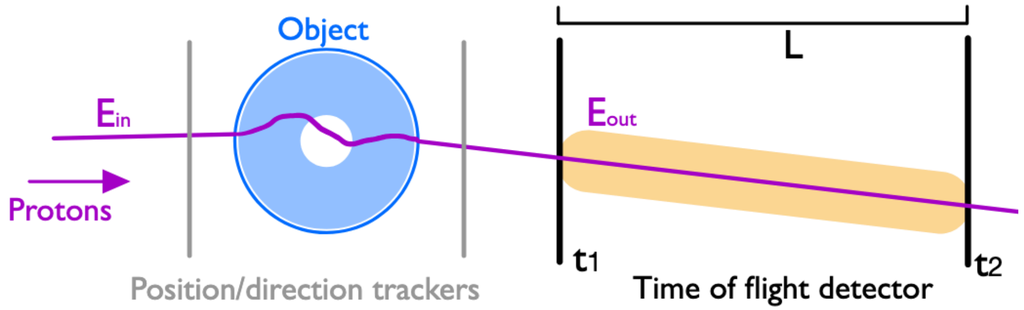
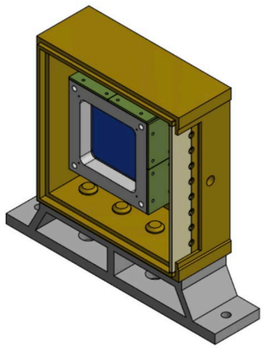
The TofPrad project

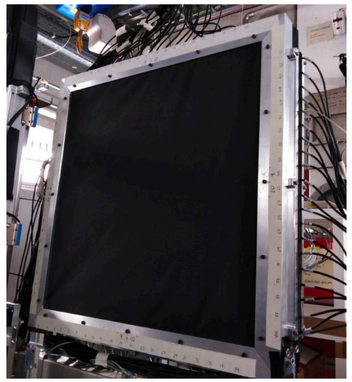


Goal: development of a **proton radiography prototype** integrating a **Time Of Flight (TOF)** system based on **plastic scintillators + SiPM** to reconstruct the position, direction, and residual energy of the protons.

Start counter

Plastic scintillator 5x5x0.2 cm^3





Plastic scintillator 20x20x0.6 cm^3

Tof-wall

- The ToF system of FOOT is tailored to detect nuclear fragments with energy of 50-400 MeV/u with a $\sigma_t < 100$ ps
- Readout (WaveDAQ) not suitable for clinical application (rate capability ~ 1KHz)

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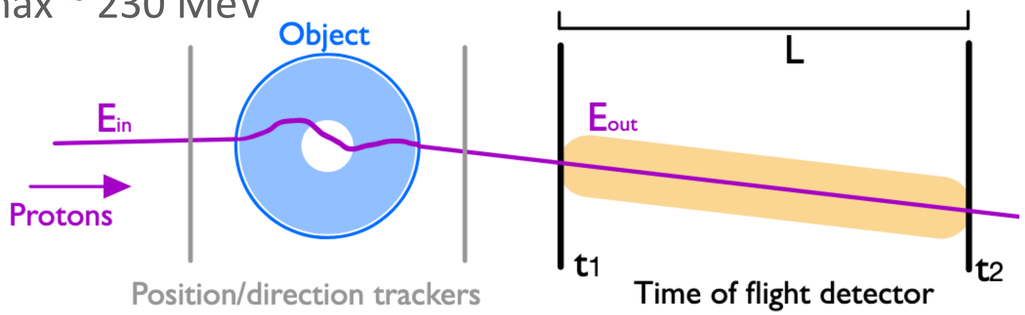
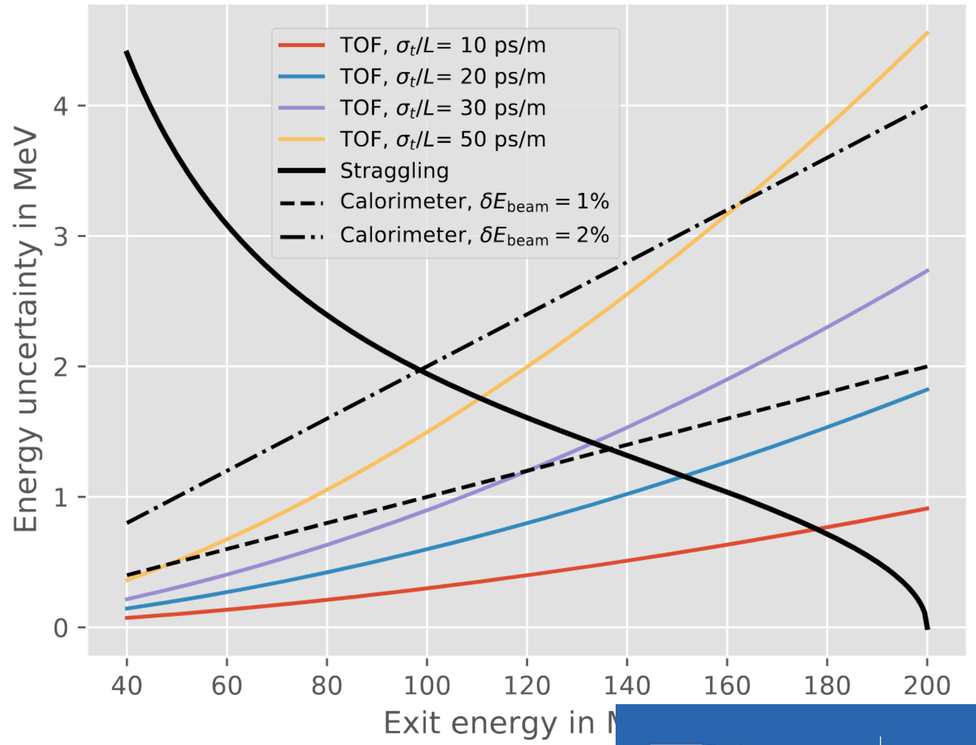
Requested performance

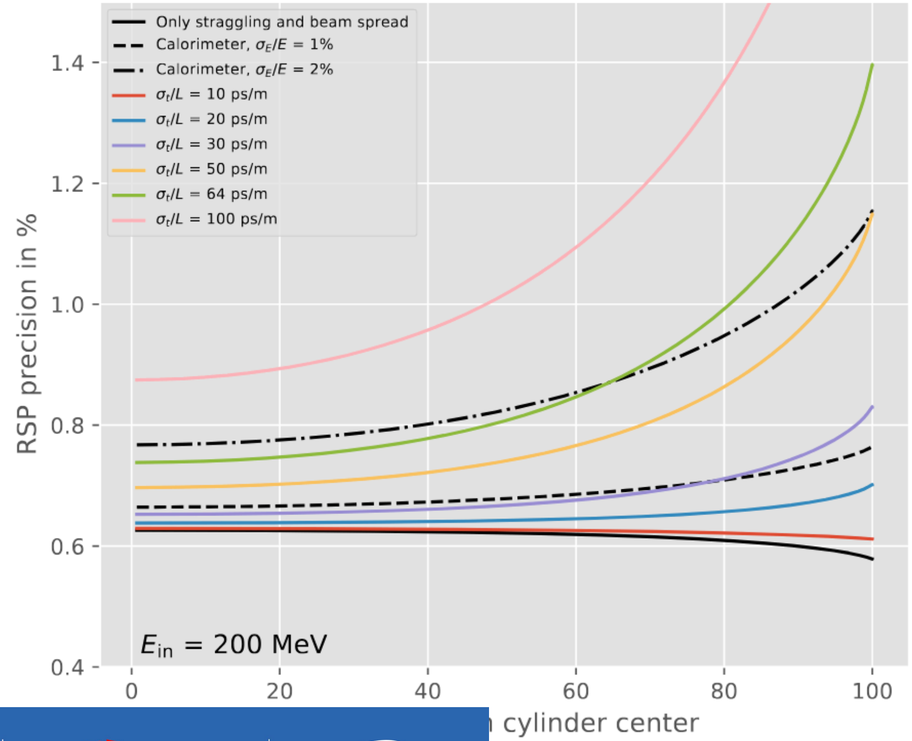
Ekin max ~ 230 MeV



- Tracking system needed to reduce the impact of **multiple scattering** in image reconstruction (requested resolution ~ 2mm)
- With a time resolution of **50 ps/m** we can match the performance obtained by calorimeter



Krah et al, DOI: 10.48550/arXiv.2112.11575



300 p/mm^2

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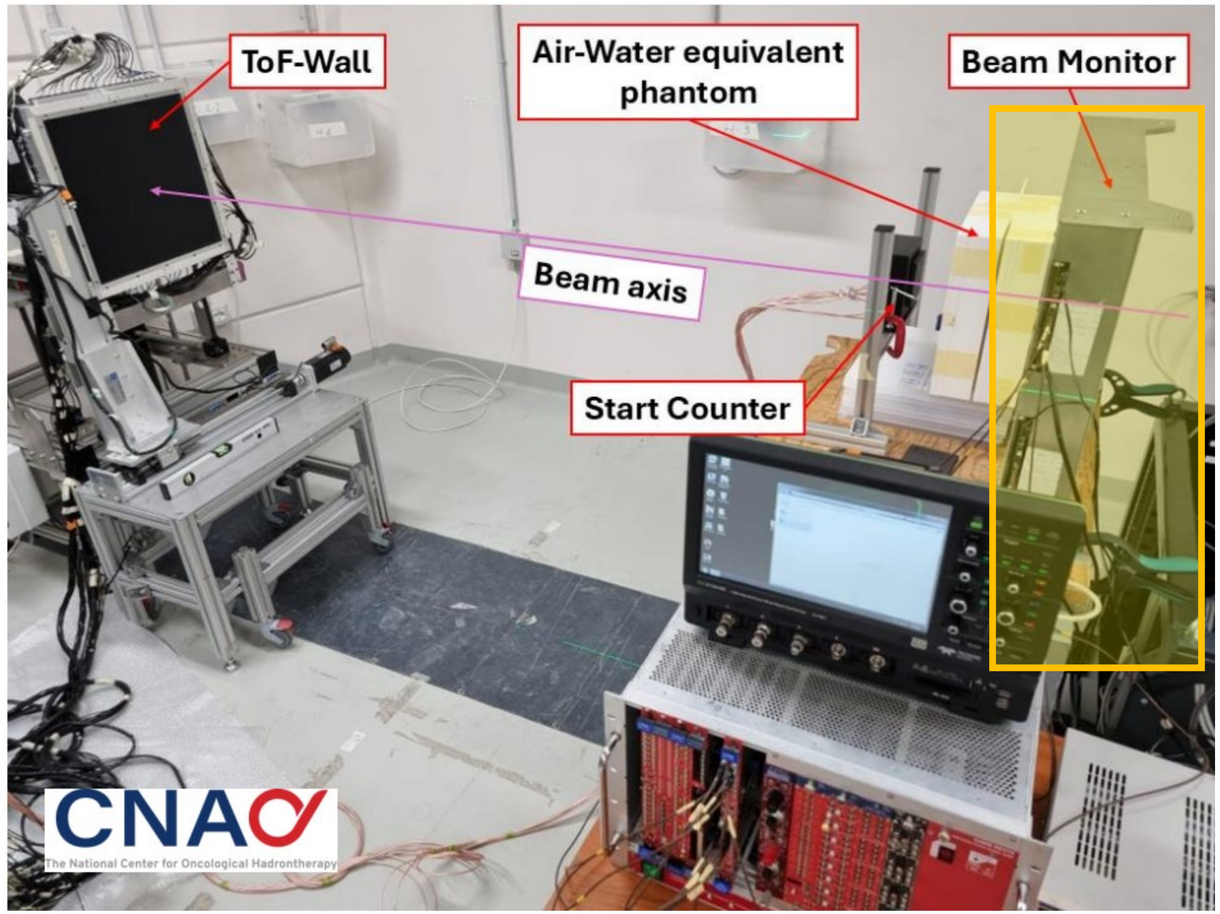
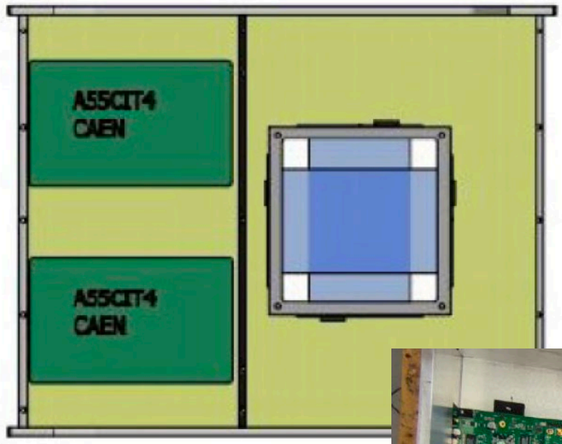
Test beam @ CNAO with FOOT detectors: setup

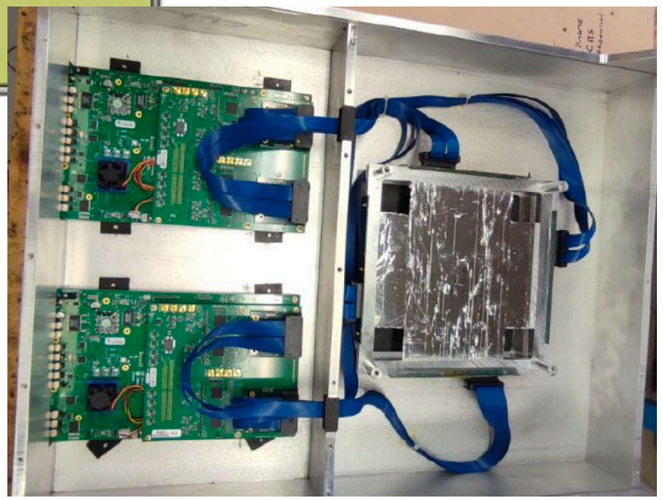


Tracker: LENTO (Low intEnsity moNiTOr)



1 x-y fiber planes
(12x12 cm^2)

CAEN DT5550w
(Citiroc-based)



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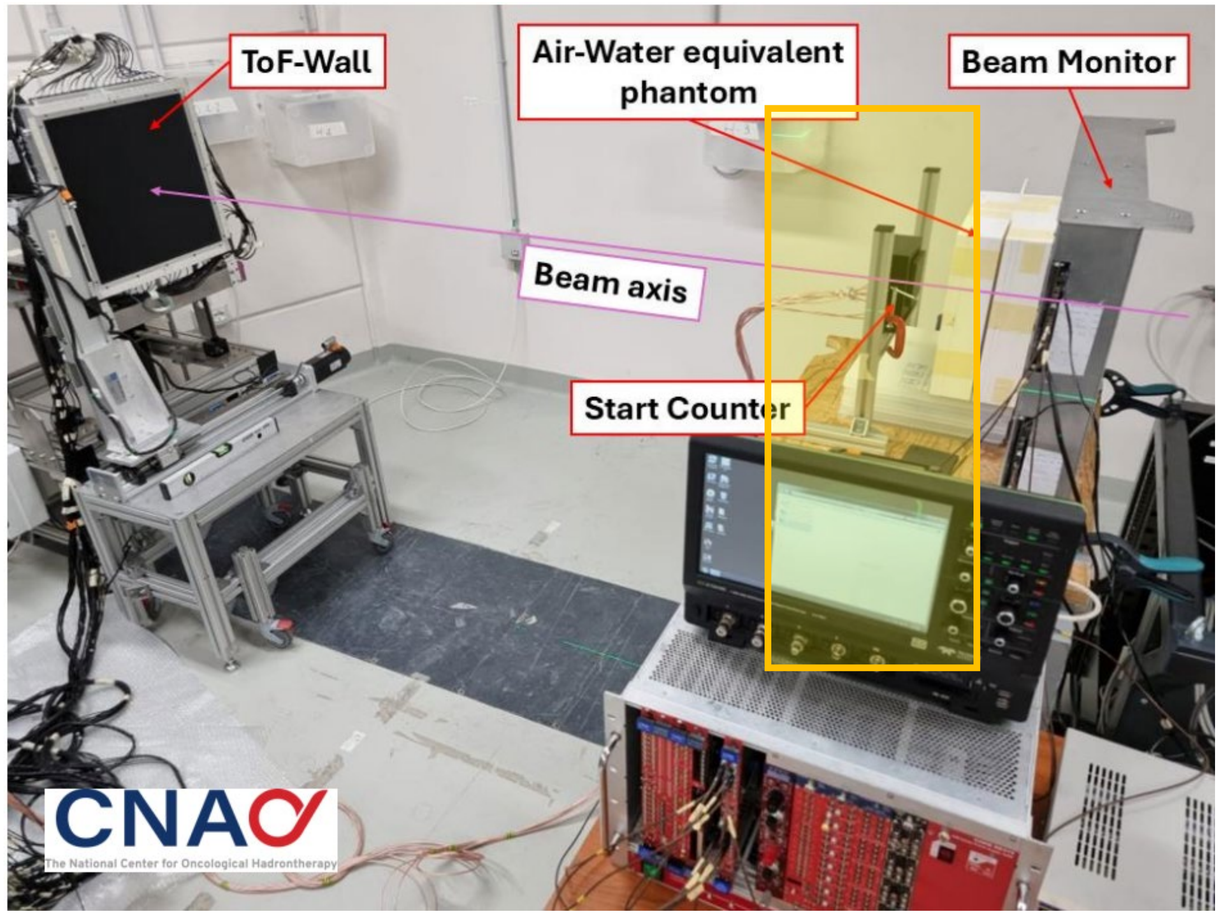
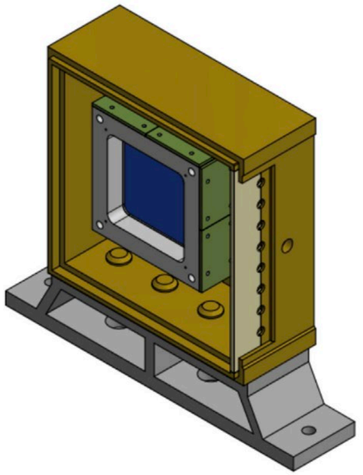
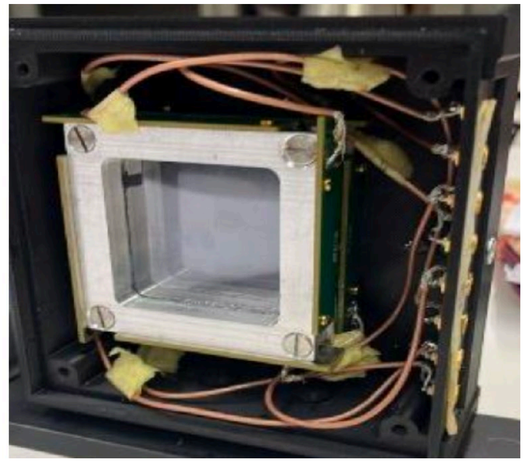


Start of ToF: the FOOT start counter





Homogeneous layer of plastic scintillator (EJ-204) 2 mm thick read out by 48 SiPM (8 channels of 6 seried SiPM)

Traini G. et al., "**Performance of the ToF detectors in the FOOT experiment**", 2020 DOI:10.1393/ncc/i2020-20016-5

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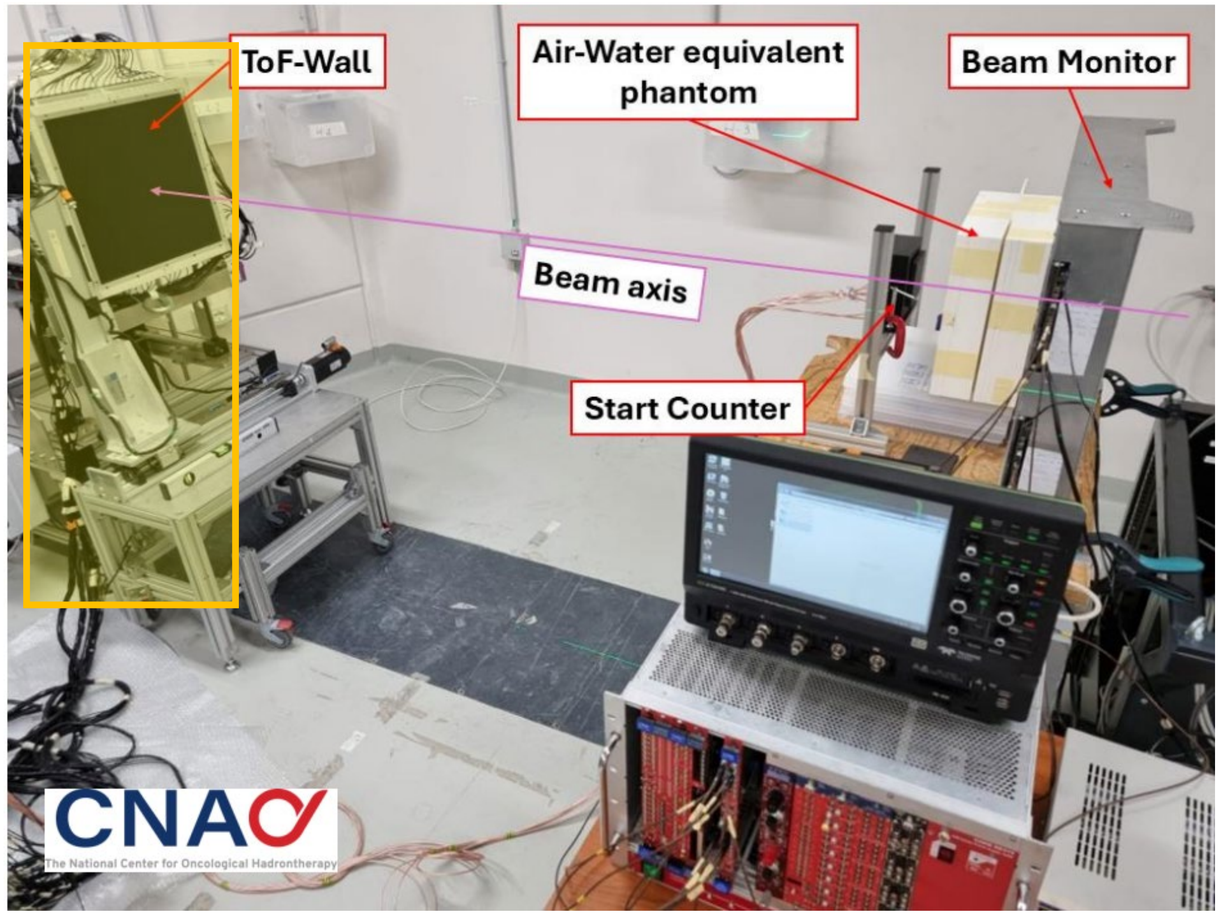
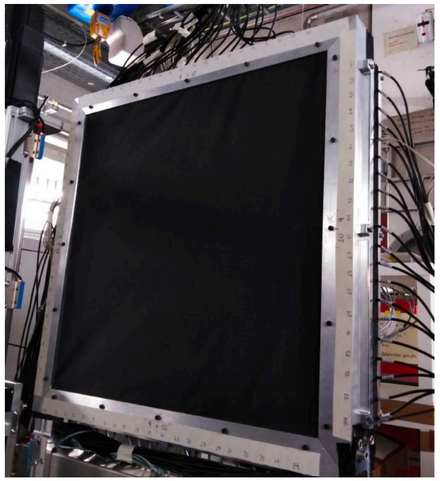
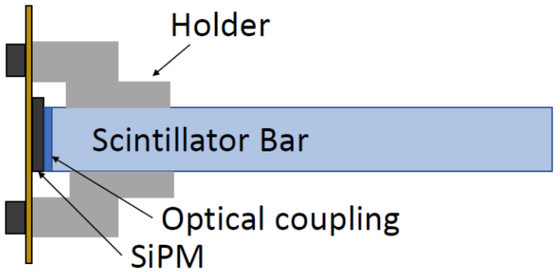
Test beam @ CNAO with FOOT detectors: setup



Stop of ToF: ToF-Wall





Two orthogonal layers of EJ-200 plastic scintillating bars (20 bars of 44x2x0.3 cm3 each) read with SiPMs on both sides

Morrocchi M. et al., "Performance evaluation of the TOF-Wall detector of the FOOT experiment", 2020 Doi: https://doi.org/10.1109/ TNS.2020.3041433

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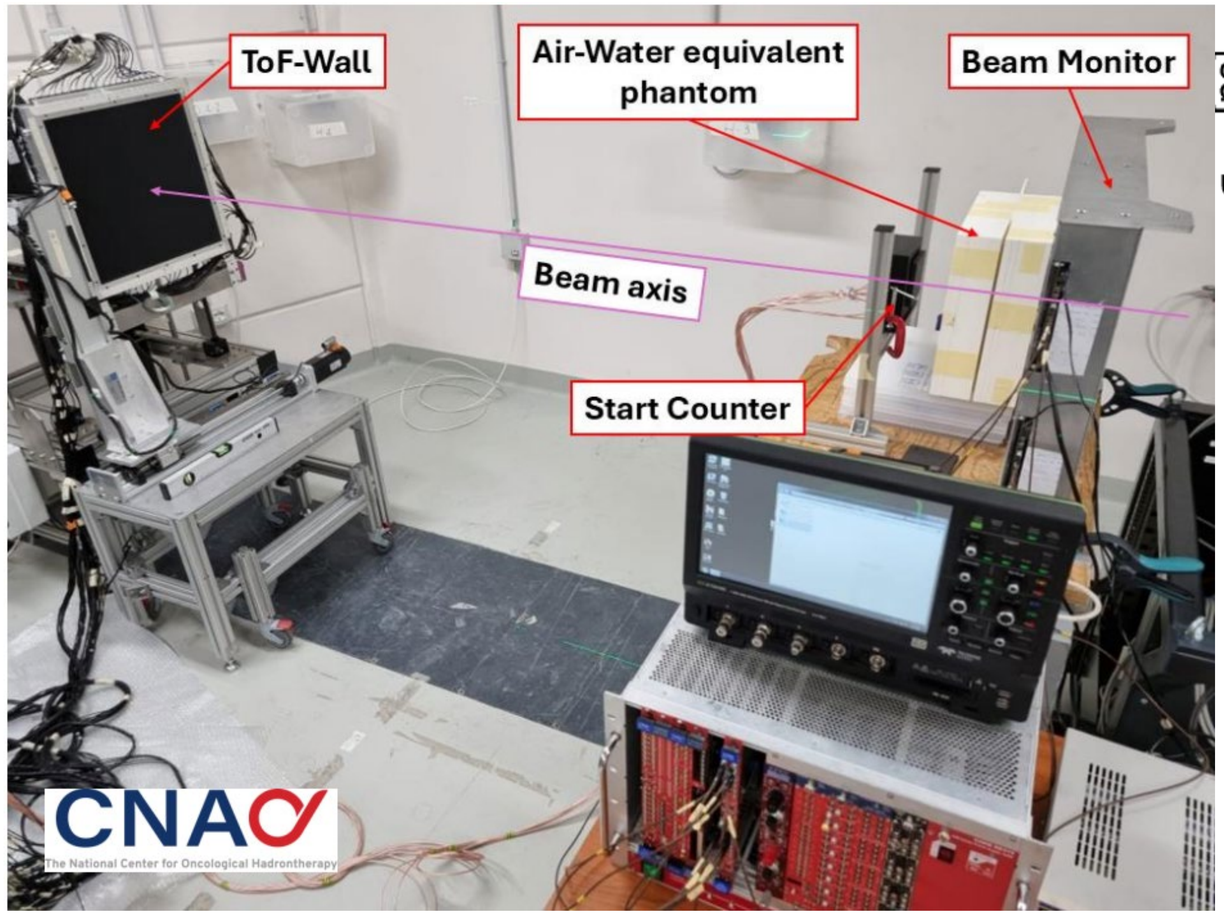
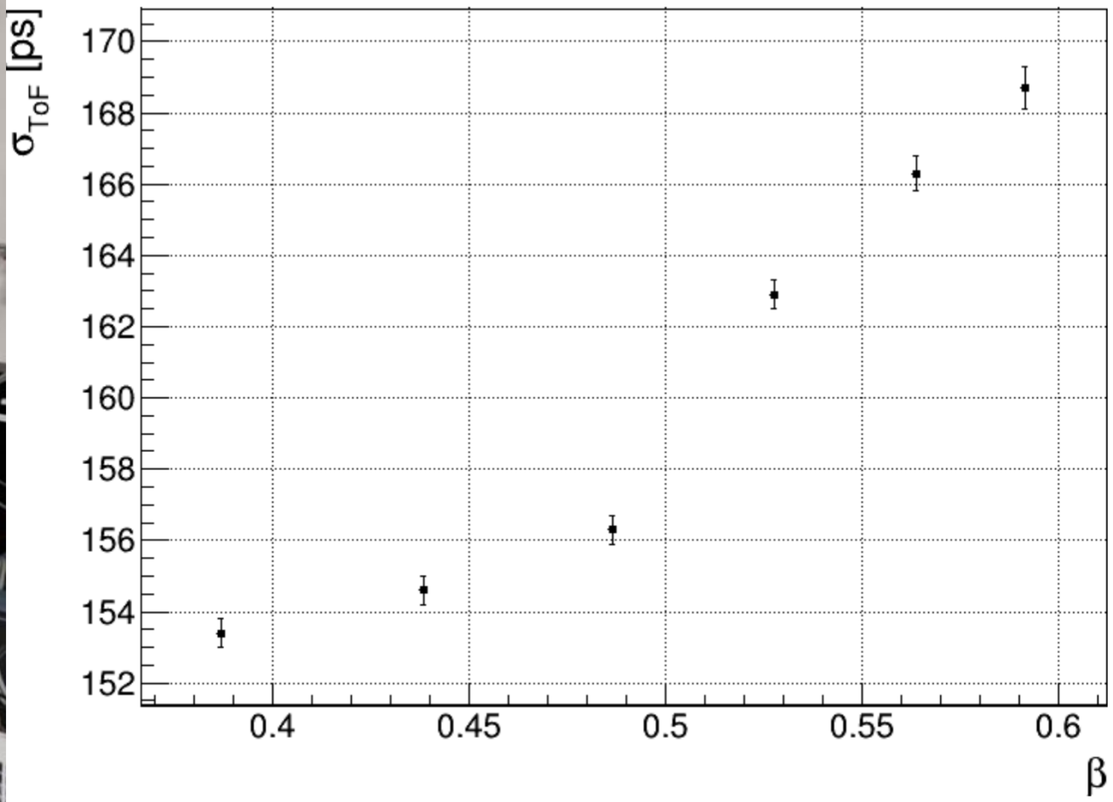
Test beam @ CNAO with FOOT detectors: results



Ekin 70-230 MeV



Goal of TofPrad → <100 ps

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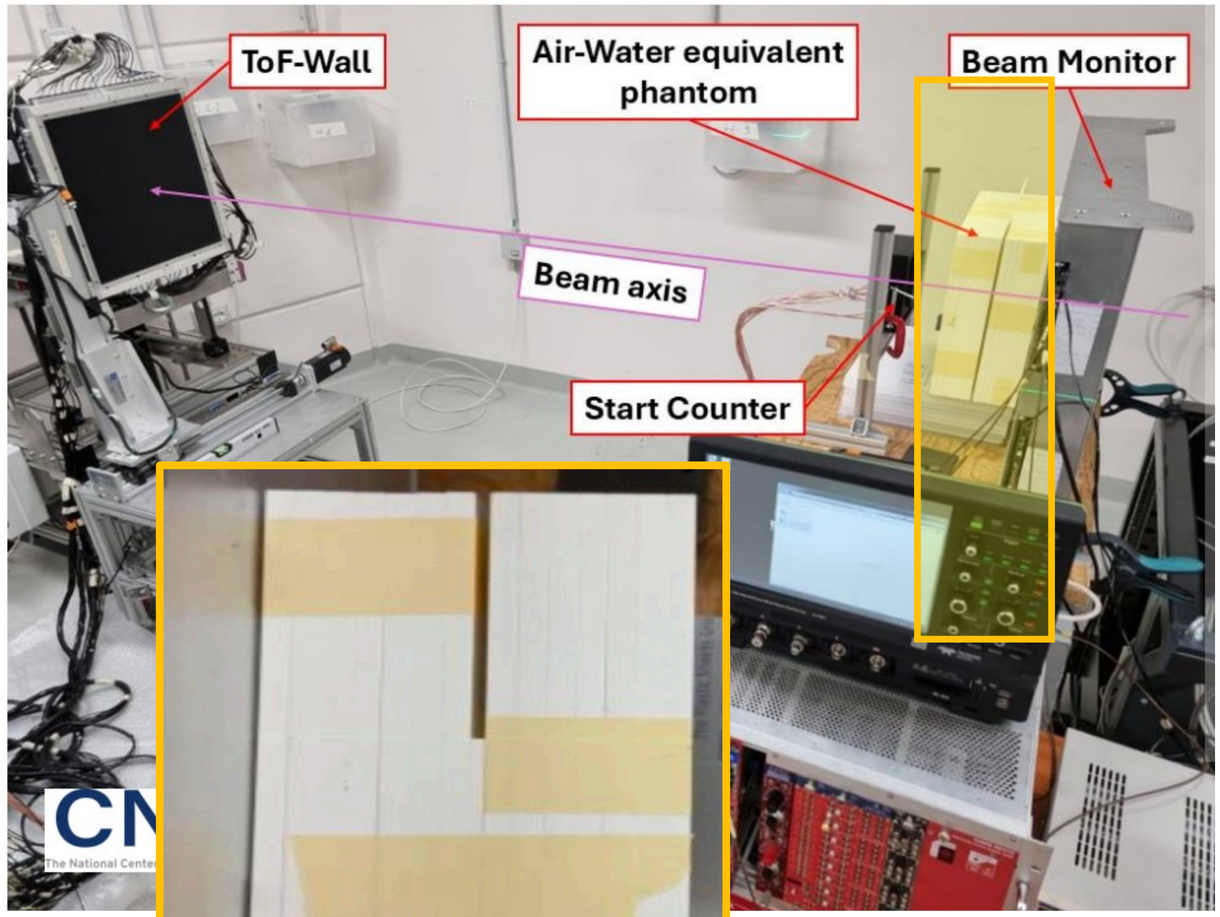
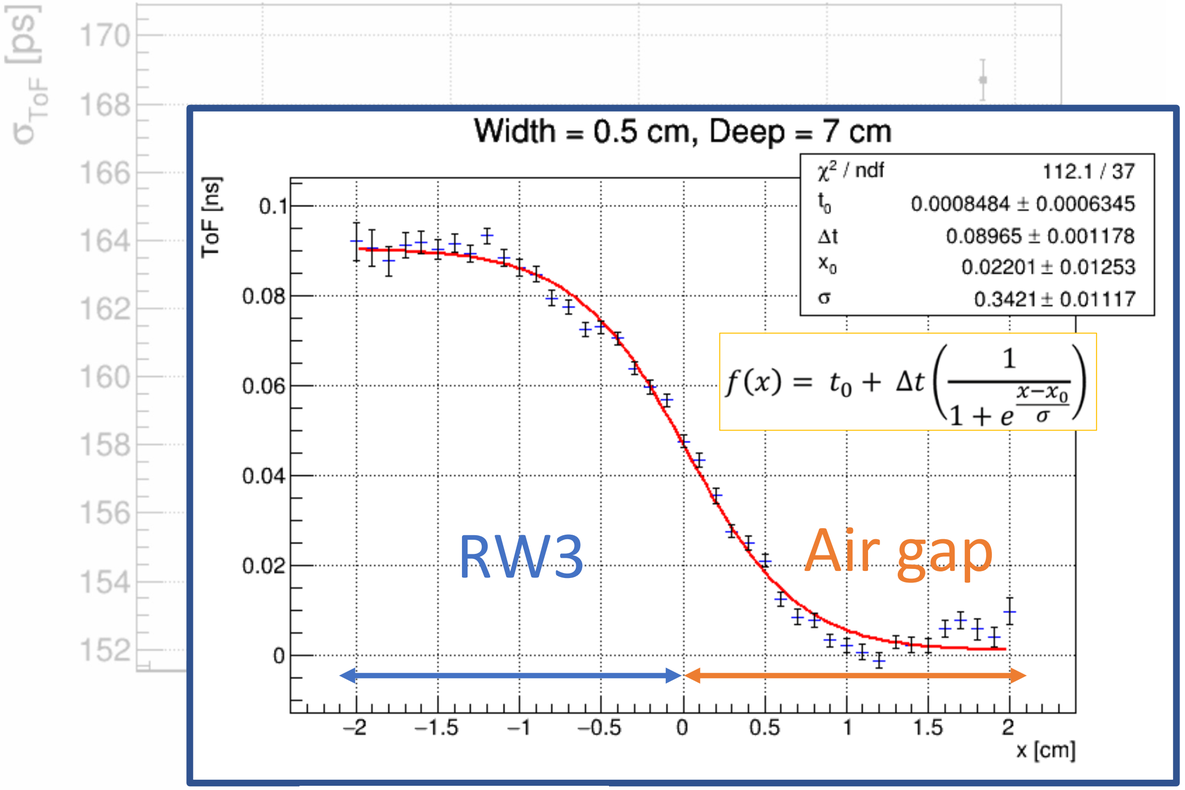
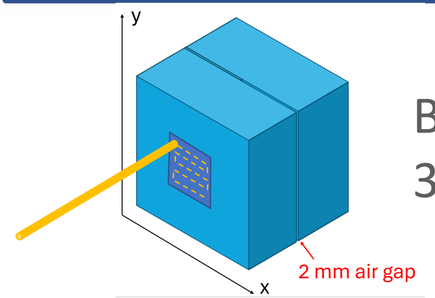


Phantom





Beam scan in an area of 3x3 cm^2

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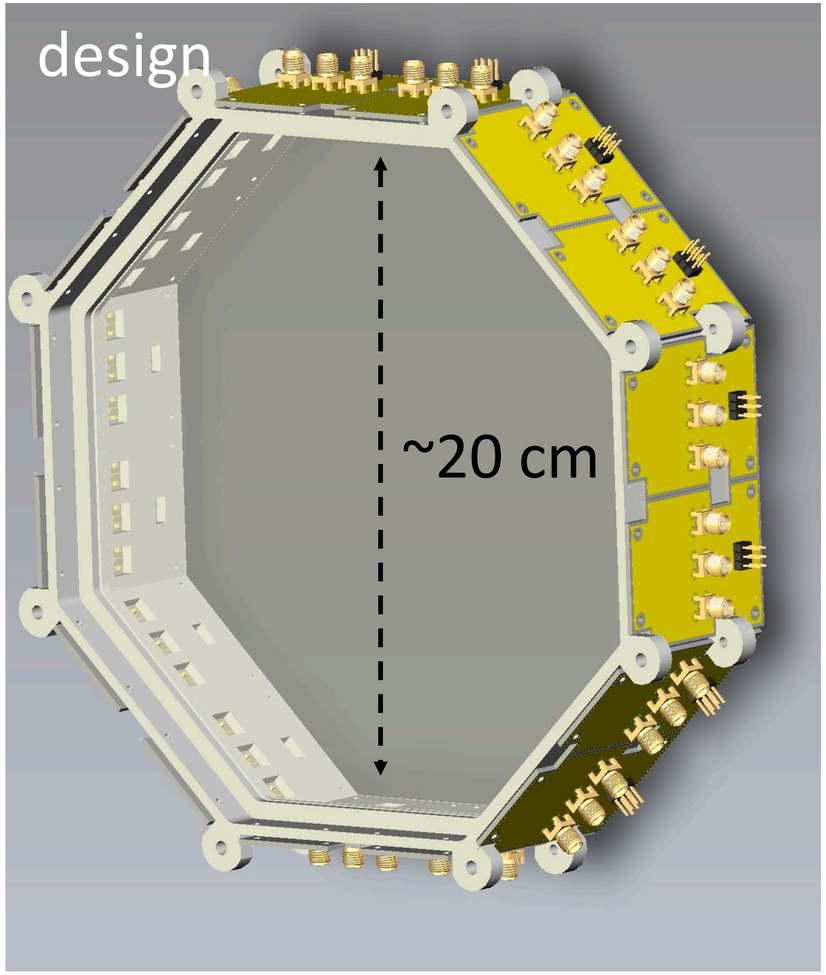
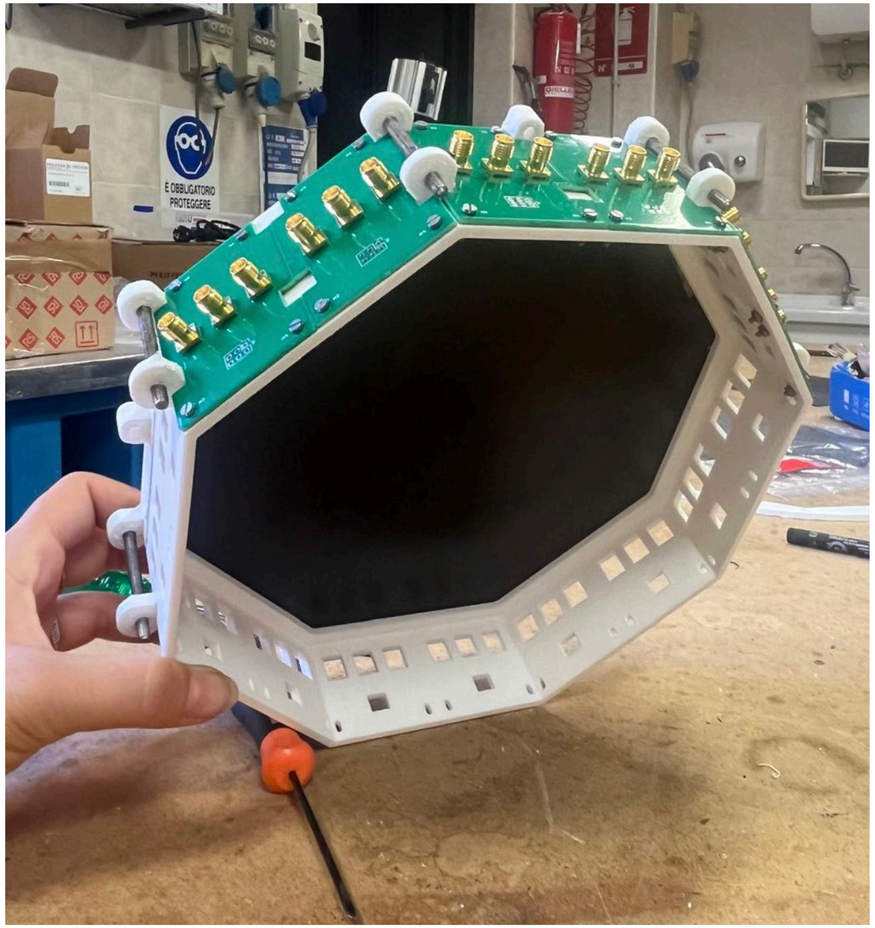
New start detector





- Currently adopting 1 mm thick EJ-212 cut by Marco Magi @ Sapienza Mechanics Workshop (final scintillator 6 mm, cut and polished by ELJEN)
- SiPM glued by INFN-Pi
- Just **3 sides** instrumented at today (second delivery of SiPM expected in September)

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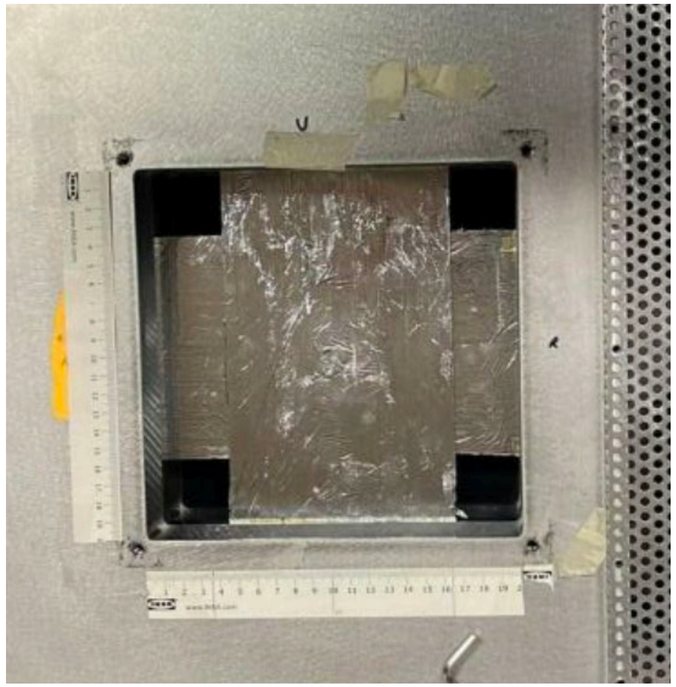
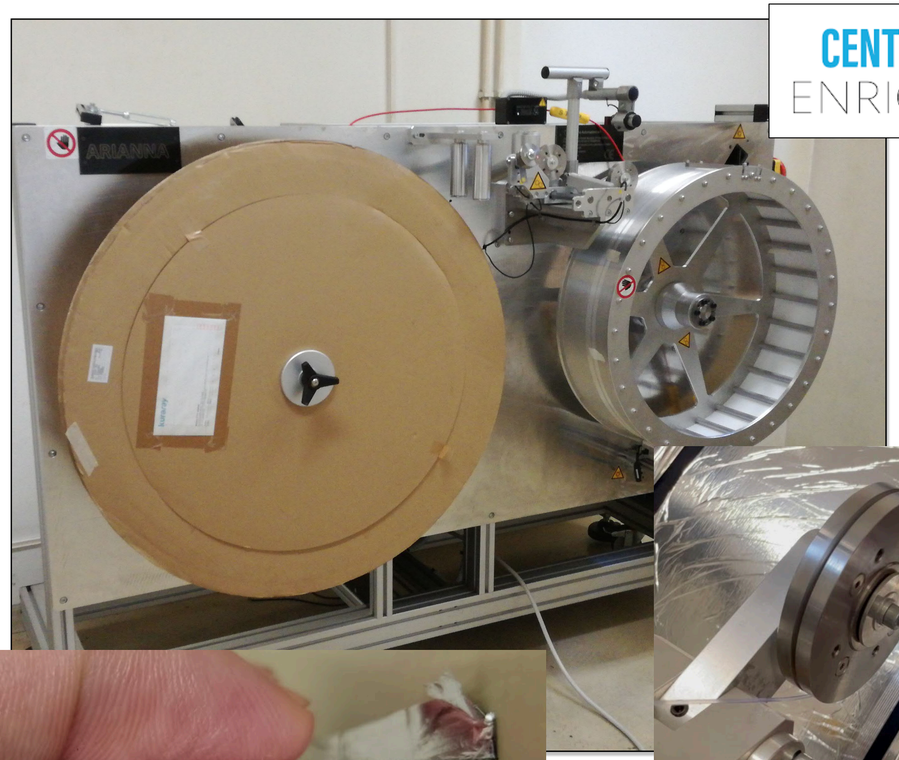
New tracker planes





- Scintillating fiber planes (squared fibers 1 mm side) read-out by SiPMs area 10x10 cm2

https://sites.google.com/studenti.uniroma1.it/construction-of-an-hodoscope#h.bb25and05ap1

Built @ SBAI department

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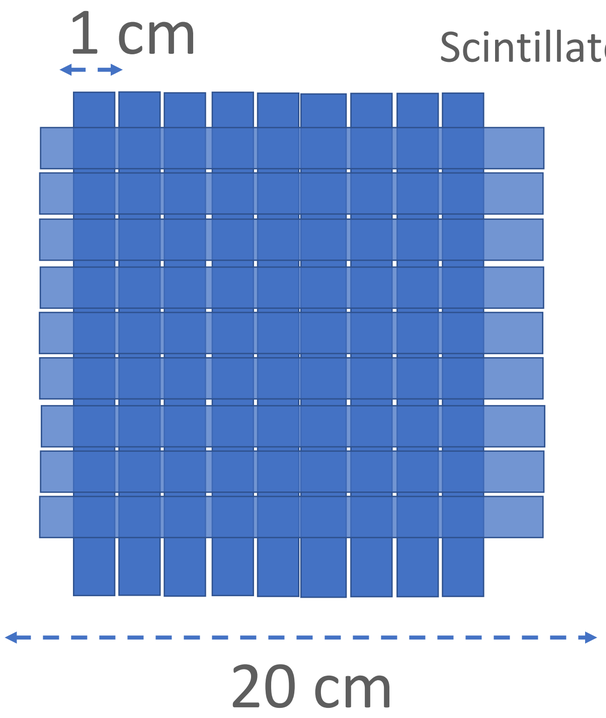
New stop detector

- Built @ University of Pisa
- Same acceptance but higher granularity wrt the FOOT detector



The higher granularity is needed to improve spatial resolution (~ 3 mm)

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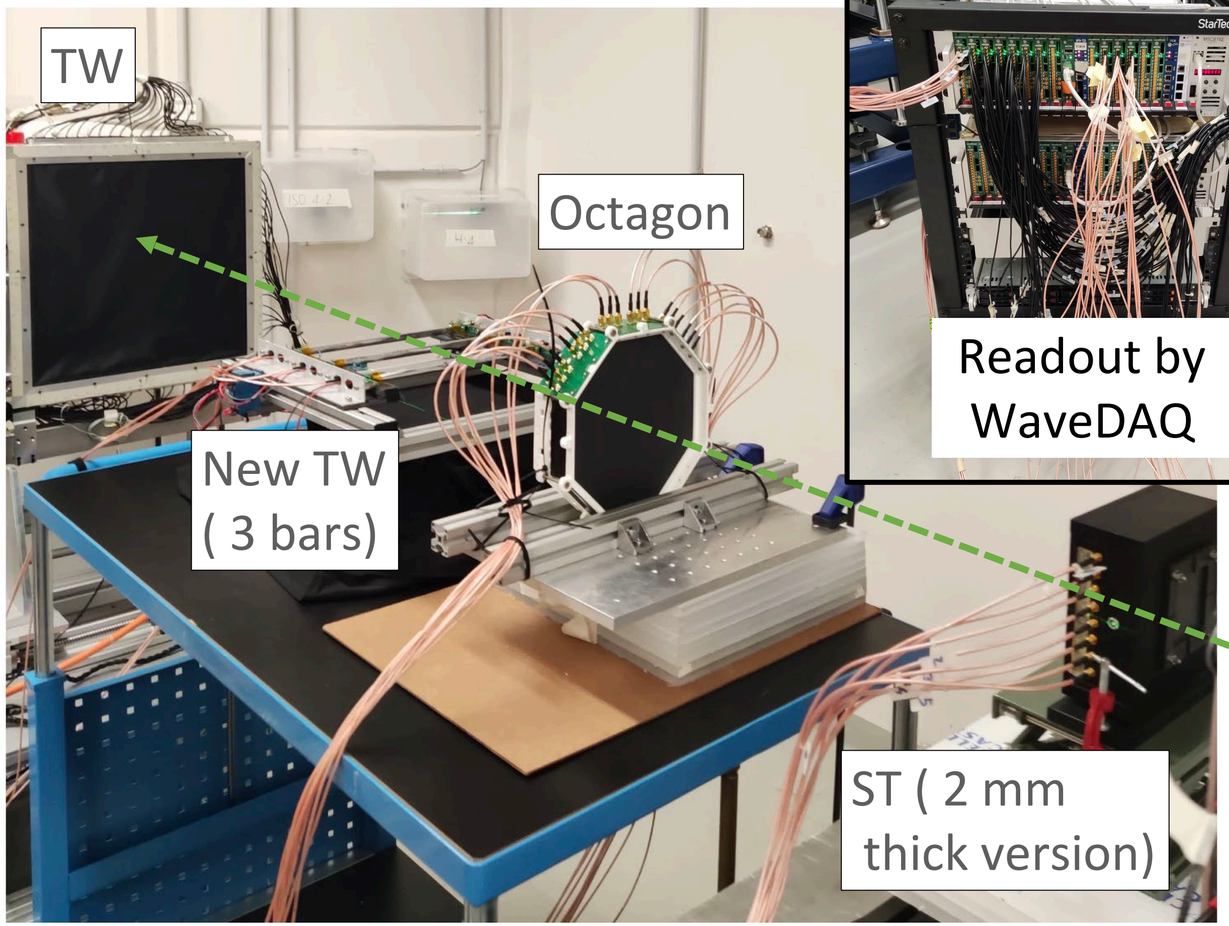
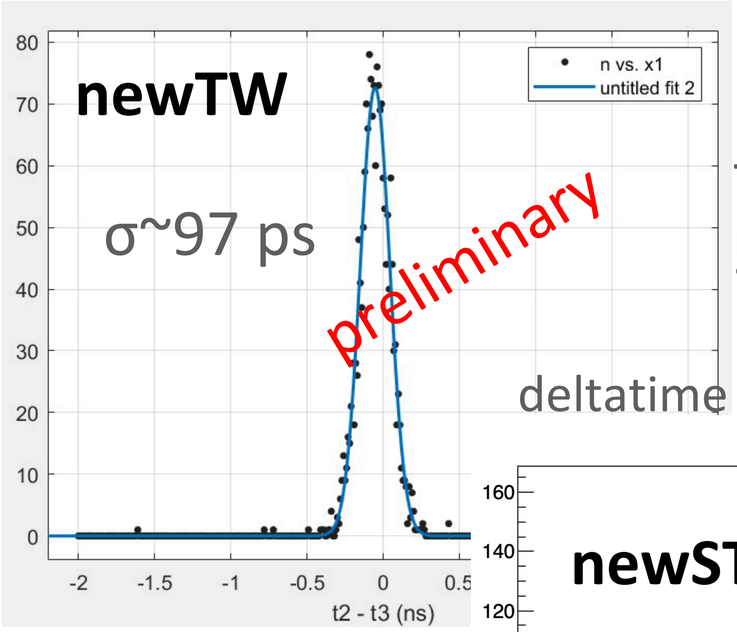
Test @ CNAO



beam

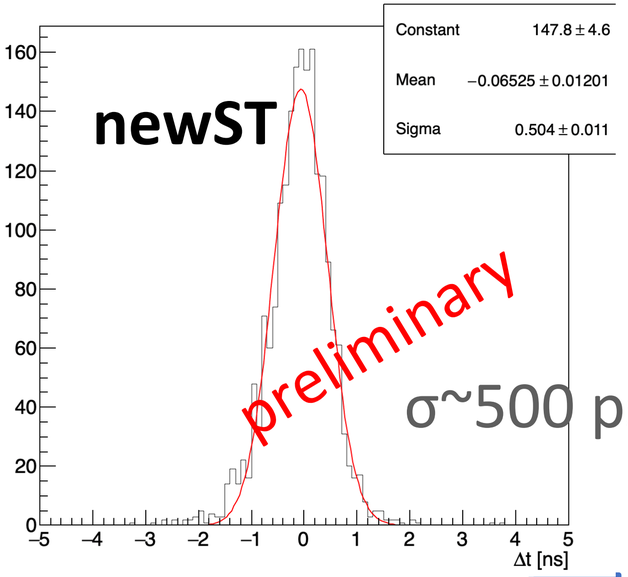
deltatime btw the two extremities



when using the average → 50 ps

when using the average of 48 channels → 50 ps

deltatime btw two channels



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Next steps

- Test beam @ CNAO in 2026 with the final prototype, with the aim to take a radiography of a non-homogeneous phantom

- Use a commercial solution for the read-out system with **a higher rate capability** (~100 kHz)

- Evaluate the system performance with **He beam** (available soon @ CNAO) (better time resolution, less multiple scattering

- 64-ch TDC unit for **high-resolution timing** applications housing the CERN picoTDC
- Part of **FERS-5200**, the CAEN platform for the readout of **large arrays of detectors** (SiPM, MA-PMTs, Gas Tubes, Si detectors, ...)
- Timing resolution: **LSB = 3.125 ps, RMS typ. ~ 7 ps**
- TDC dynamic range: **up to 26 bit (~ 210 µs). Extendable to 56 bit in the FPGA**
- Inputs: **differential LVDS signals** (max common mode = 1.2 V; max absolute voltage = 1.45 V). **NIM, TTL or analog signals through dedicated adapters**
- Acquisition of **leading/trailing edge Time of Arrival (ToA)**, or **leading edge ToA plus Time over Threshold (ToT)** of the input signals
- **Scalability** and **easy-synch**: up to 128 cards (**8192 channels**) can be managed

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