TOFpRad: a novel proton radiography prototype based on Time Of Flight measurements

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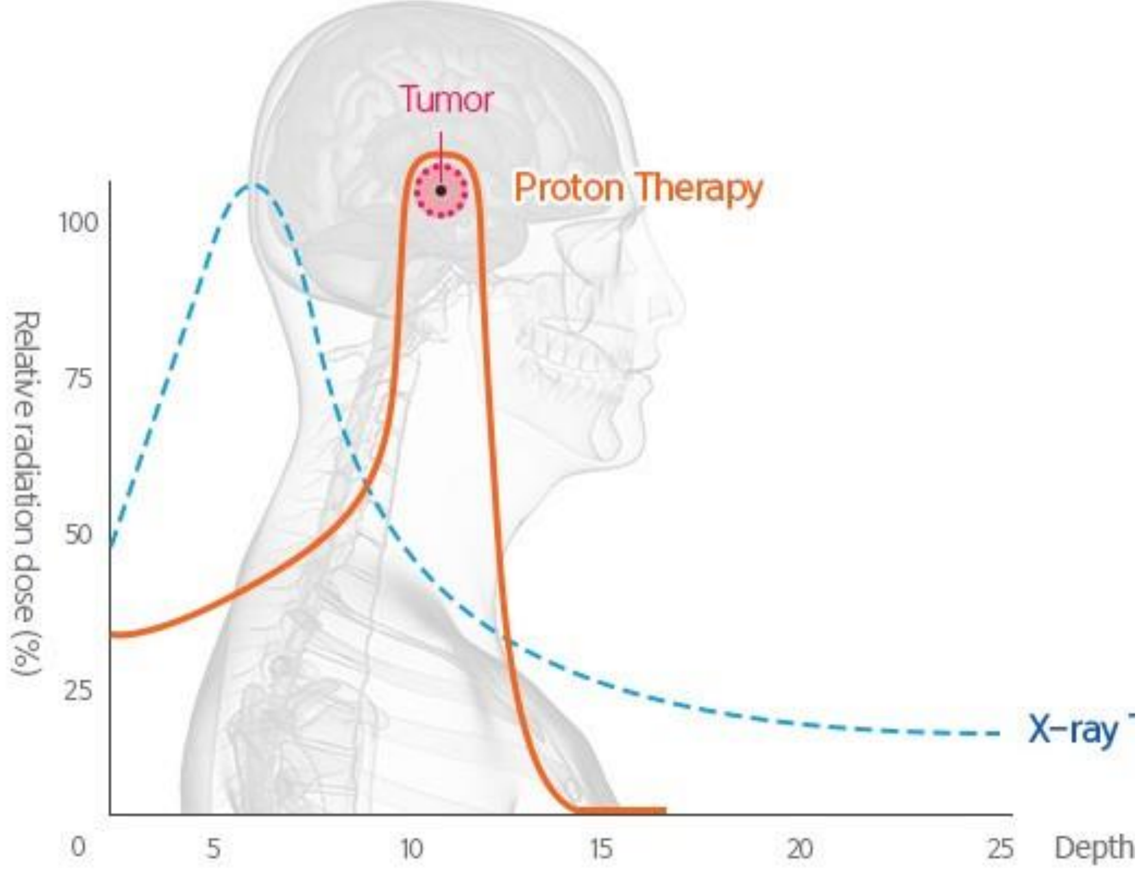
Hadrontherapy

- Hadrontherapy, or particle therapy, is a type of **cancer treatment** that uses **protons or heavier ions** to **kill tumor cells minimizing exposure to surrounding healthy tissues**
- It is preferred for **treating radiation-resistant and deep-seated tumors** due to its ability to deliver high doses at depth and the high biological effectiveness of heavier ions
- Large dose gradients **require a thorough planning** and verification of the treatment
- Wide safety margins, imposed by current technology, reduce therapy efficacy.



Particle range uncertainties

Stochastic

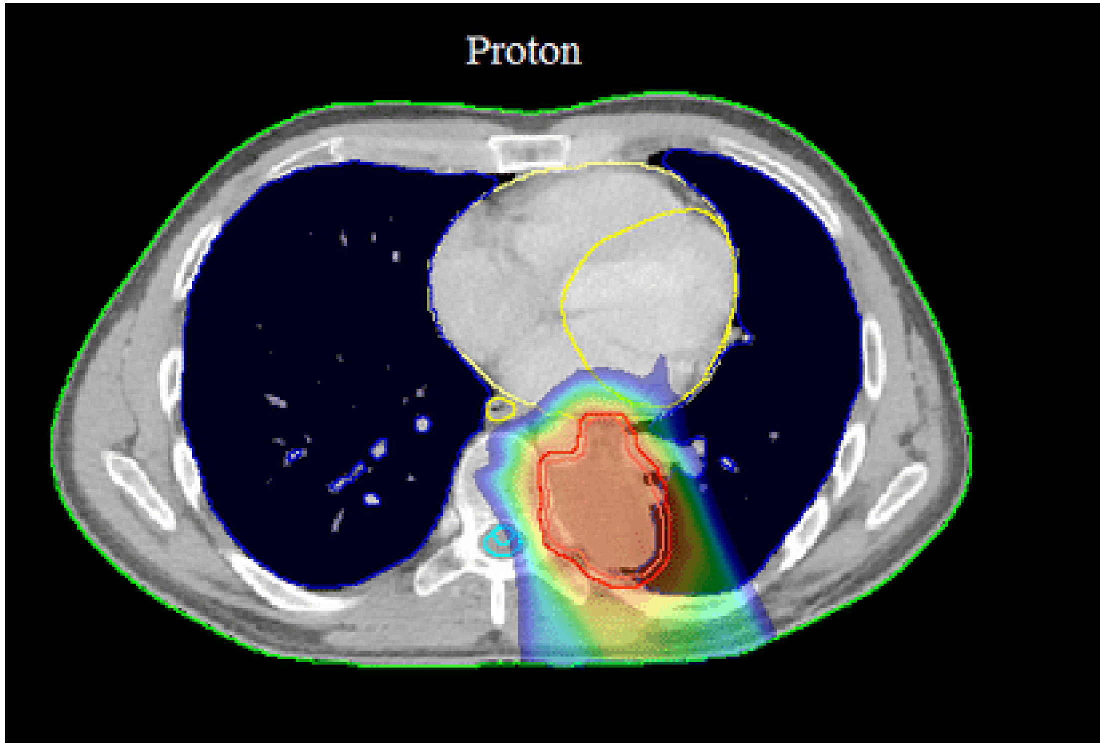
- Energy uncertainty
- Patient positioning
- Moving target

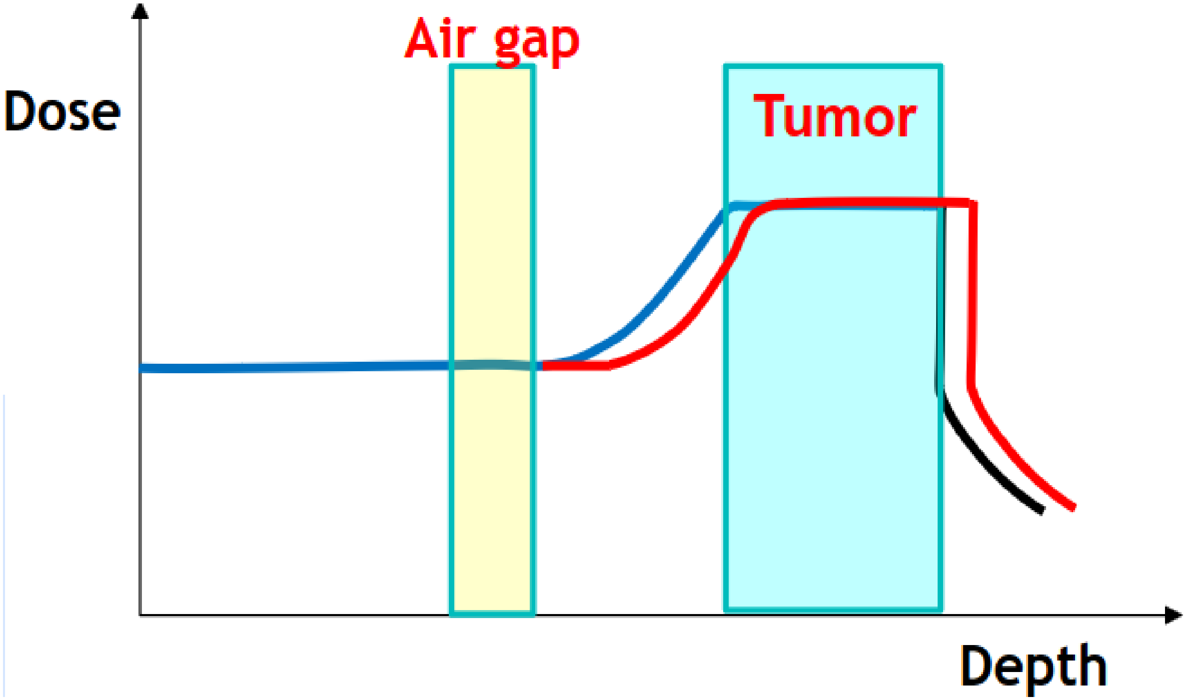
Anatomical changes

Systematic

- CT scan calibration
- CT artefacts
- RBE changes

Particle range uncertainties

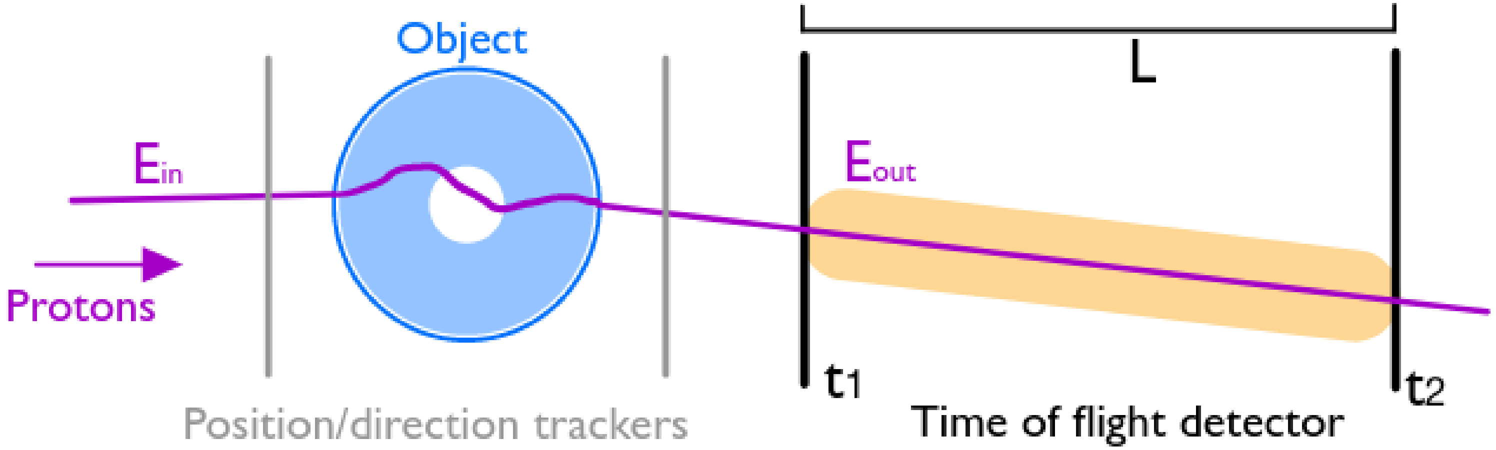




Reference: Pettersen H. E., "A Digital Tracking Calorimeter for Proton Computed Tomography"

The TOFpRad project

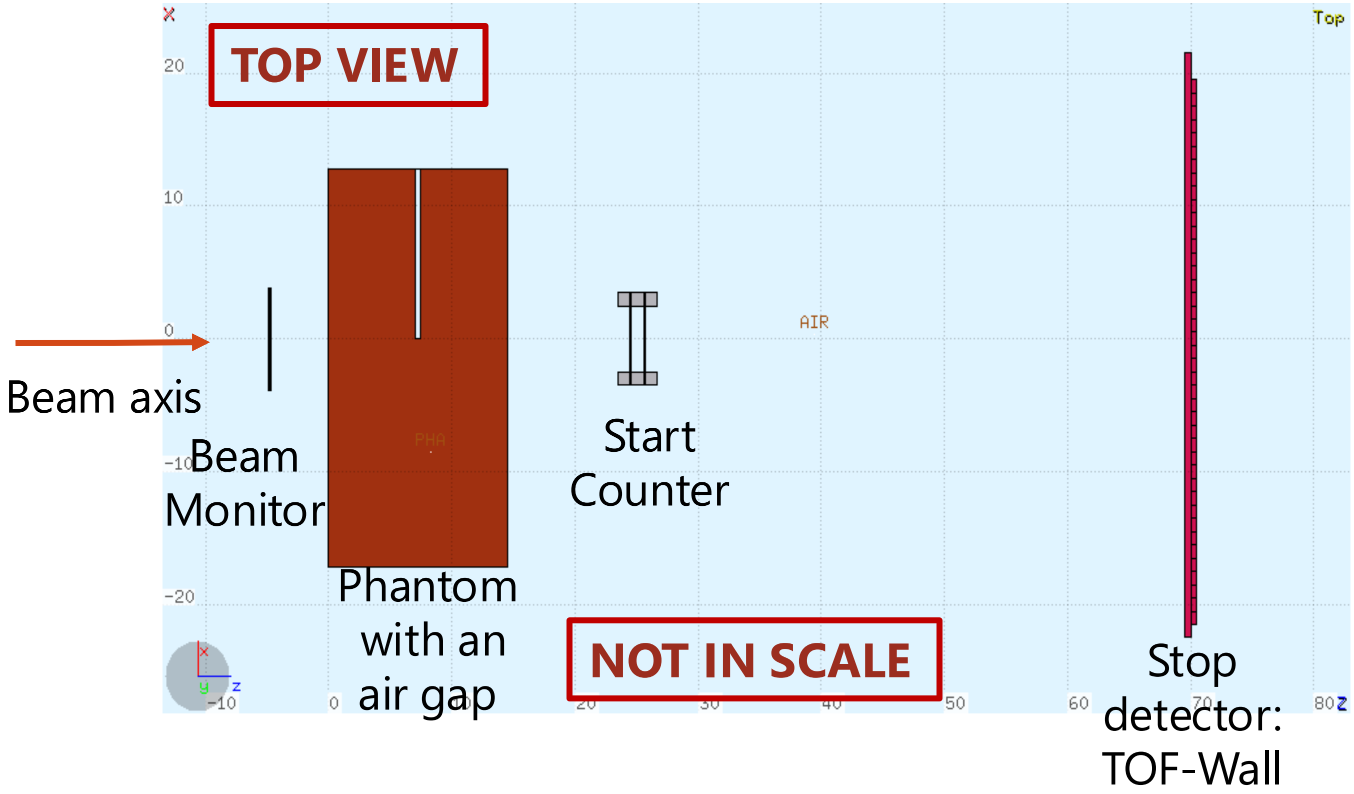
- **Proton transmission imaging**, using protons instead of x-rays for image acquisition, is pivotal for precise treatment planning by **directly probing the proton stopping power**, reducing uncertainties, and enabling a **fast verification for the treatment accuracy**
- In the last 15 years, proton imaging prototypes have primarily used calorimeter detectors. An alternative method measures proton Time Of Flight (TOF)
- The TOFpRad project aims to create a **proton radiography prototype integrating a Time Of Flight (TOF) system and plastic scintillating fibers** to reconstruct the position, direction, and residual energy of the protons.

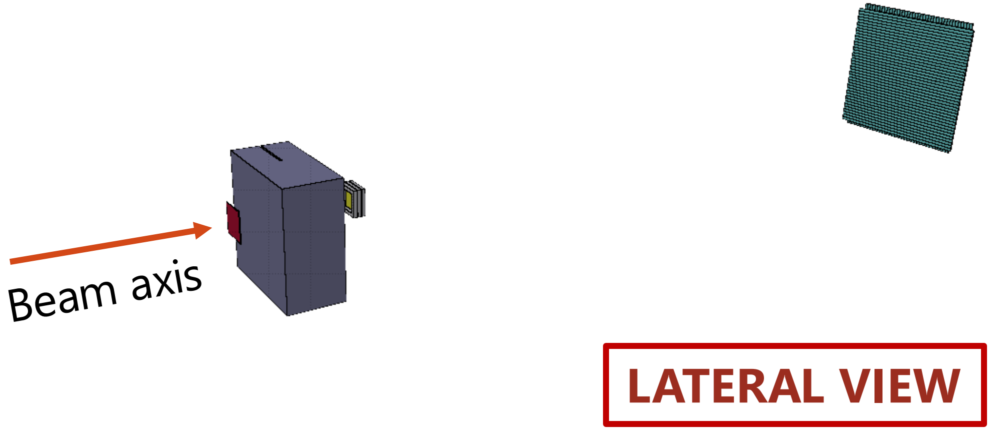


Reference: Krah Nils et al. "Relative stopping power precision in Time-Of-Flight proton CT", 2021
Doi: https://doi.org/10.48550/arxiv.2112.11575

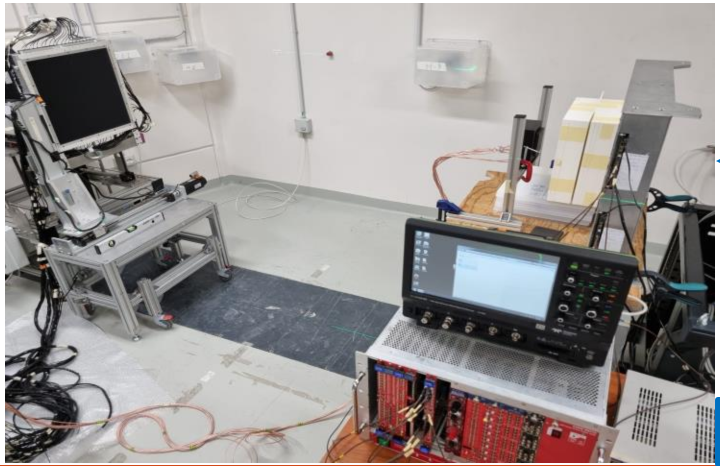
TOFpRad Monte Carlo simulation

In order to estimate the performance of the system, a Monte Carlo simulation setup was built using FLUKA.





First data taking



Beam axis

LATERAL VIEW

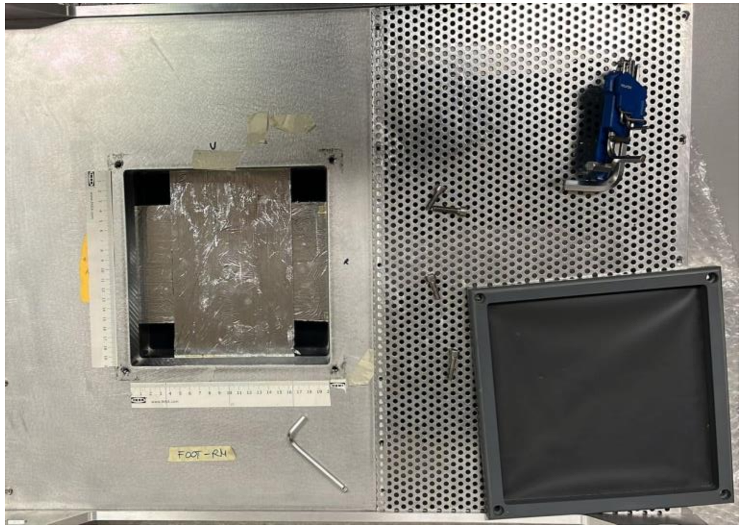
A preliminary experimental apparatus was developed and tested at the National Center for Oncological Hadrontherapy (CNAO, Pavia), consisting of the following components:

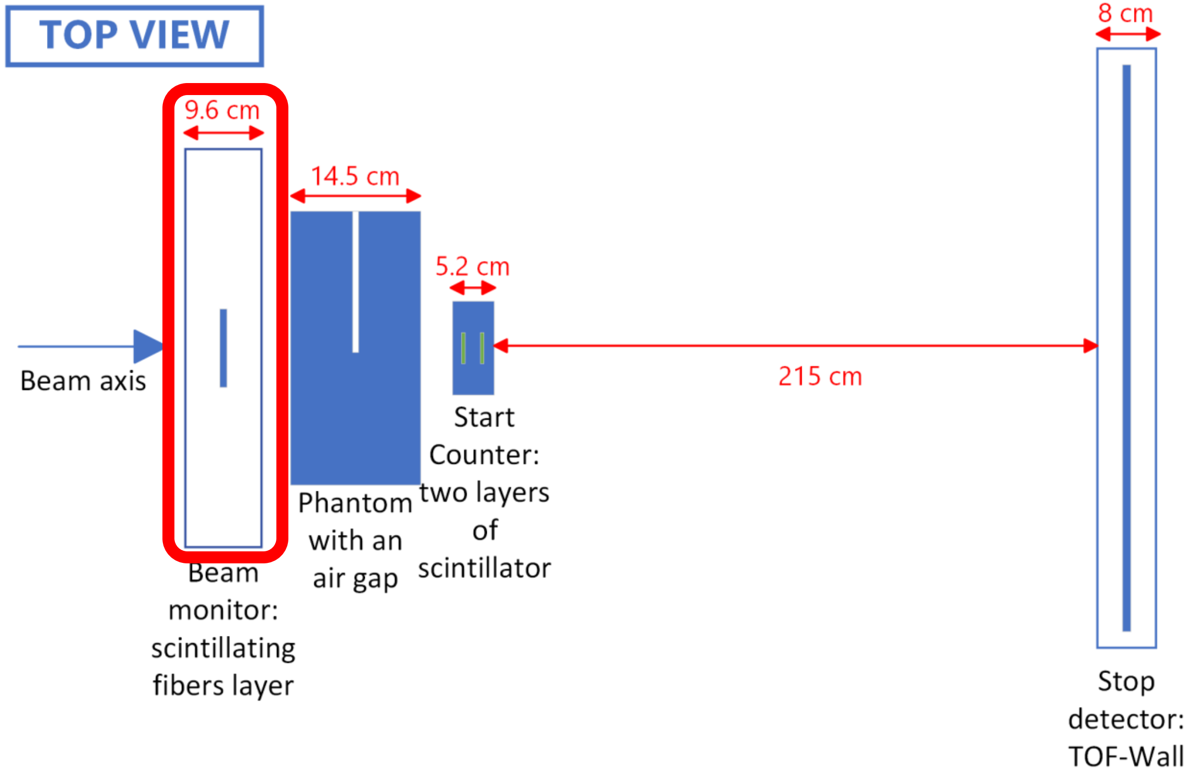
- layers of scintillating fibers at the beam exit, serving as a **beam monitor**;
- a water-equivalent **phantom**;
- a plastic scintillator **start counter** at the phantom exit;
- the **TOF-Wall** detector of the FOOT experiment, serving as the **stop detector.**

Experimental apparatus

BEAM MONITOR

Layers of scintillating fibers at the beam exit used to identify the position of the particles with a granularity of about 1 mm

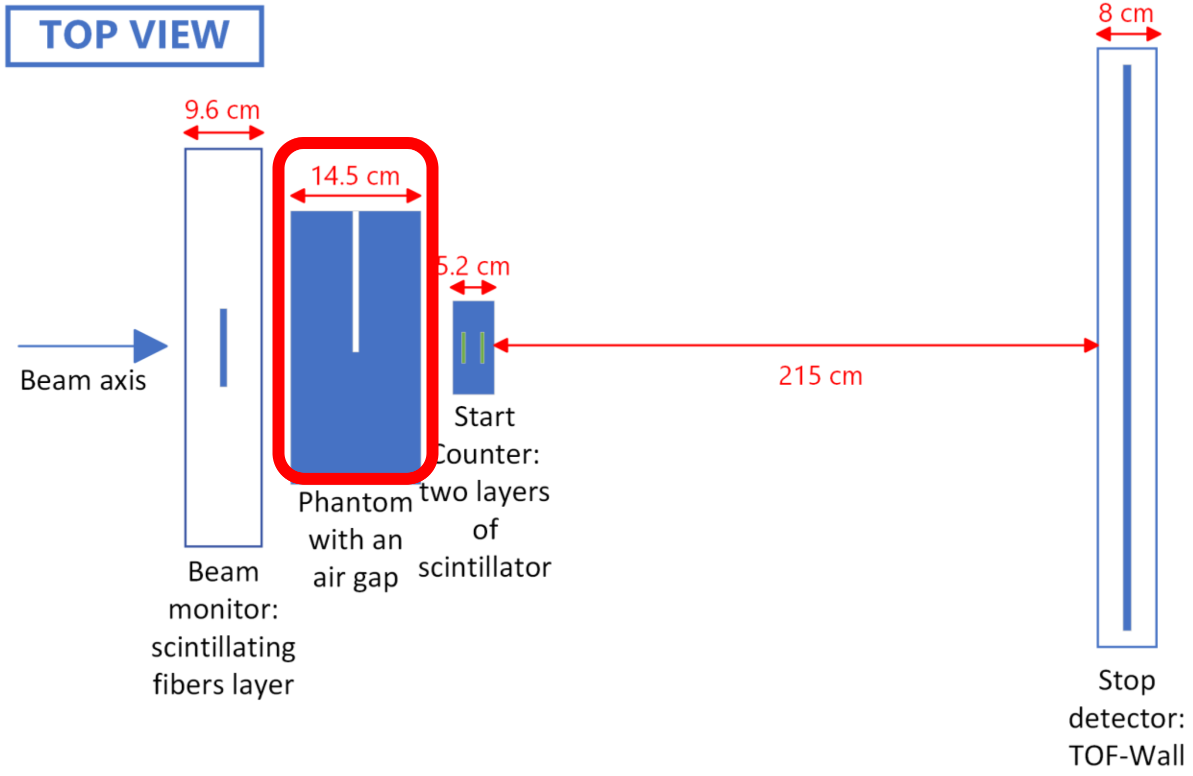




Experimental apparatus

WATER-EQUIVALENT PHANTOM (RW3)

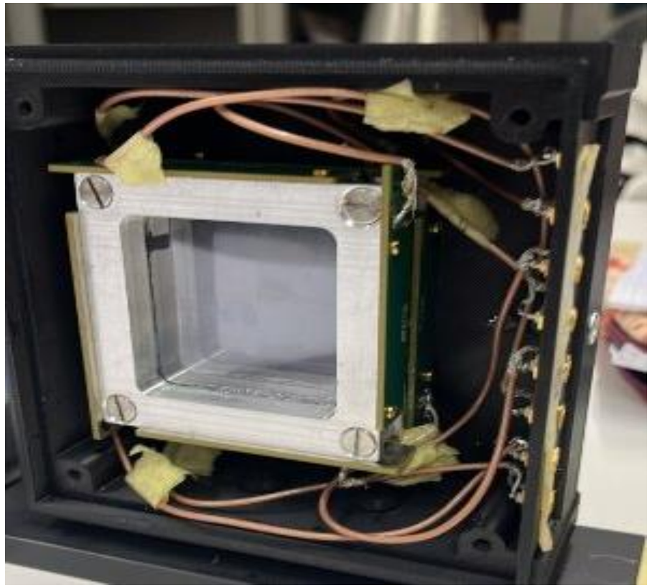
RW3 type, with the possibility of creating an air gap

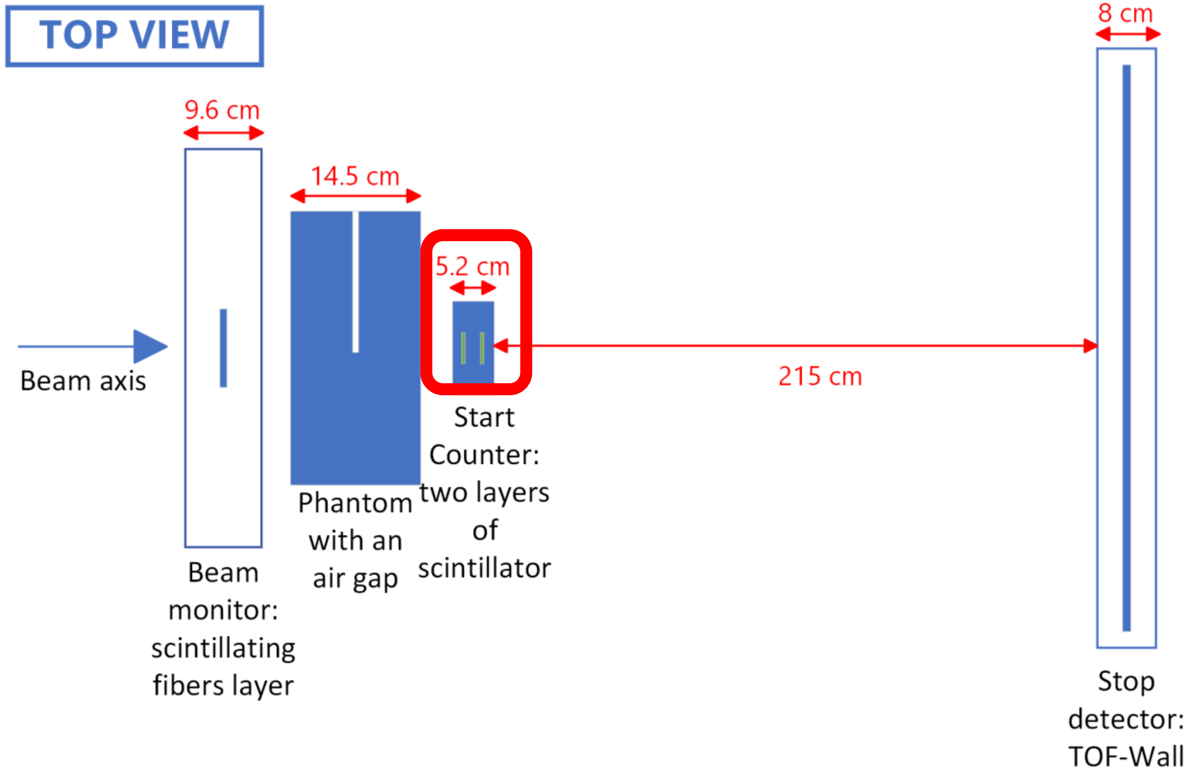


Experimental apparatus

START COUNTER

Two homogeneous layers of plastic scintillator (EJ-232 by Eljen Technology), each with a thickness of 500 µm, read-out by SiPMs (Advansid NUV3S)



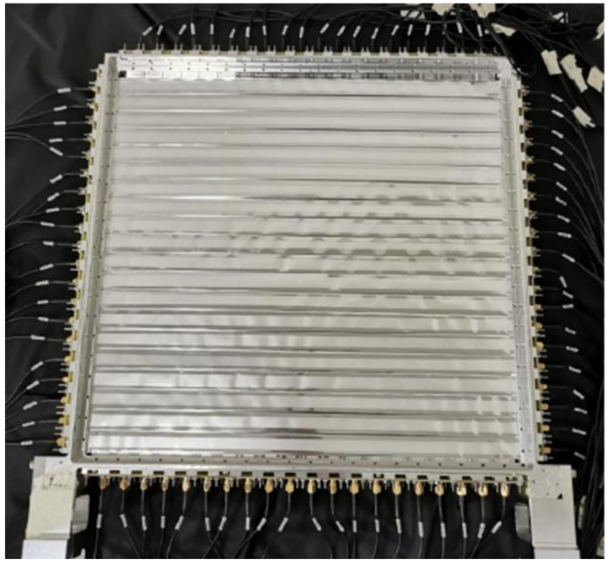


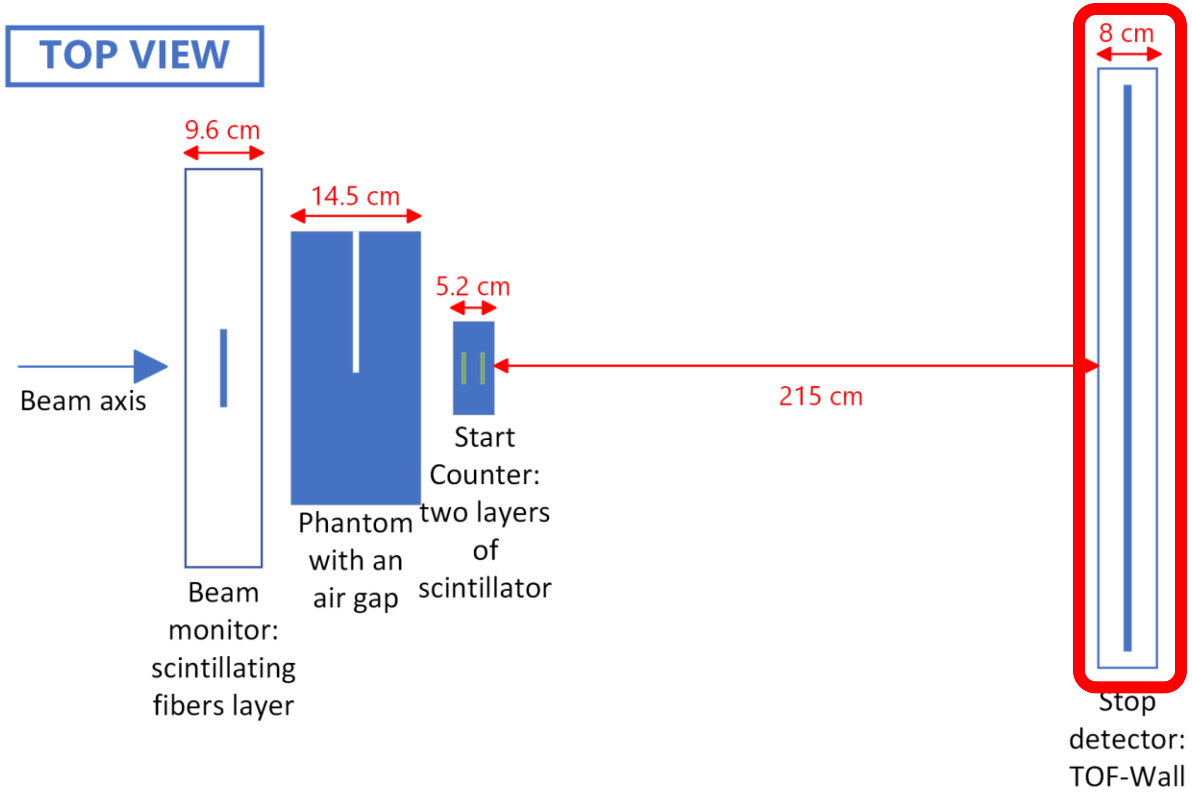
Experimental apparatus

STOP DETECTOR: TOF-WALL

Two orthogonal layers of 20 plastic scintillating bars (EJ200 by Eljen Technology) wrapped with Enhanced Specular Reflector film (ESR) to maximize the light output, read-out on both sides by SiPMs

Reference: 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

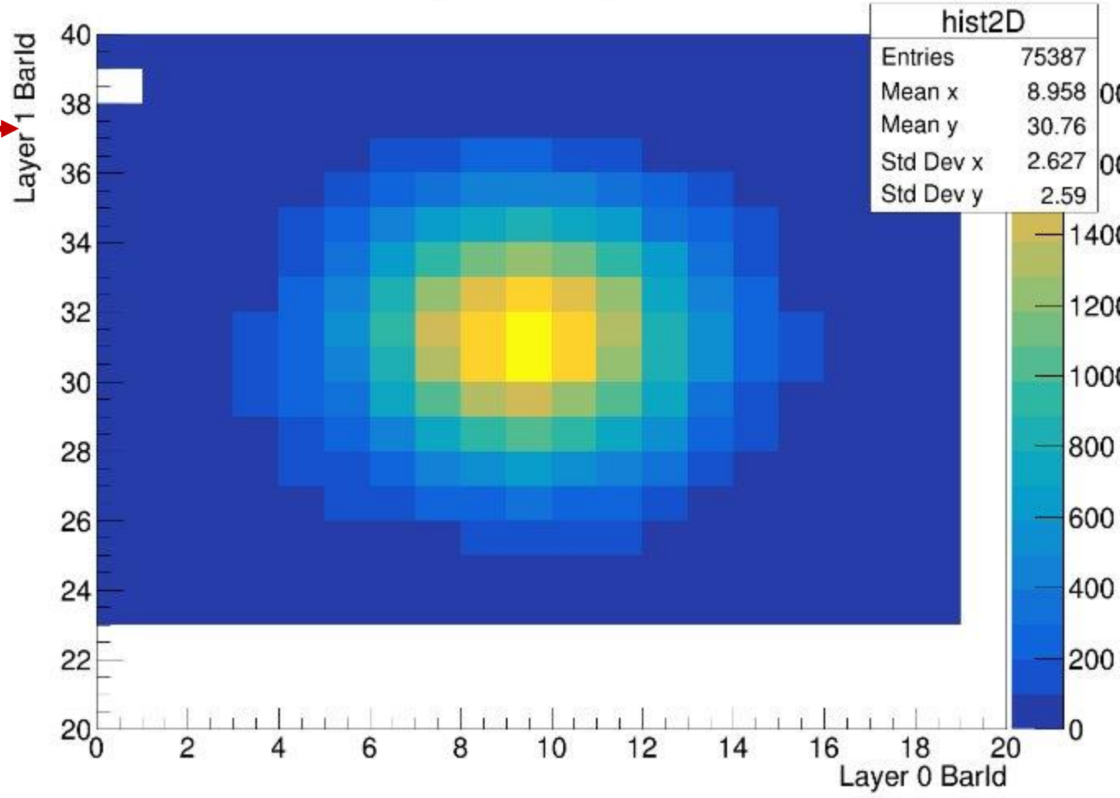




Performed measurements

- TOF measurements in air were performed using proton beams with energy ranging from 62 to 228 MeV
- Measurements with a uniform water-equivalent phantom
- Other measurements were carried out by varying the size of the air gap and its position along the phantom axis.

Summary	Phantom	Beam energy [MeV]	Irradiated field
1.	No	From 62 to 228	At center
2.	Uniform	228	At center
3.	With air gap at different positions	228	3 cm x 3 cm scan
4.	With air gap of different sizes	228	3 cm x 3 cm scan



Comparison of the responses

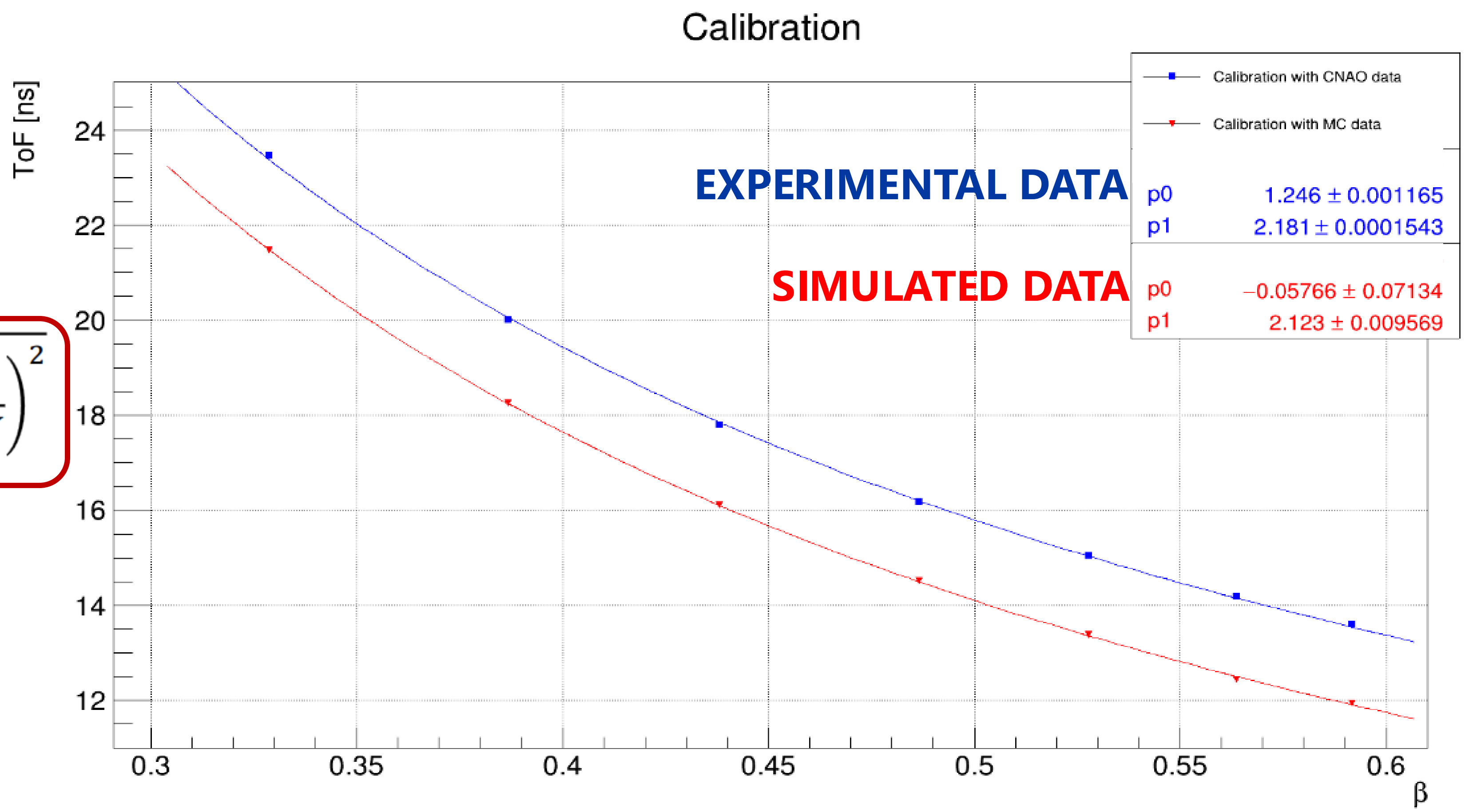
Fit function:

$$ToF = p_0 + \frac{p_1}{(\beta c)}$$

where:

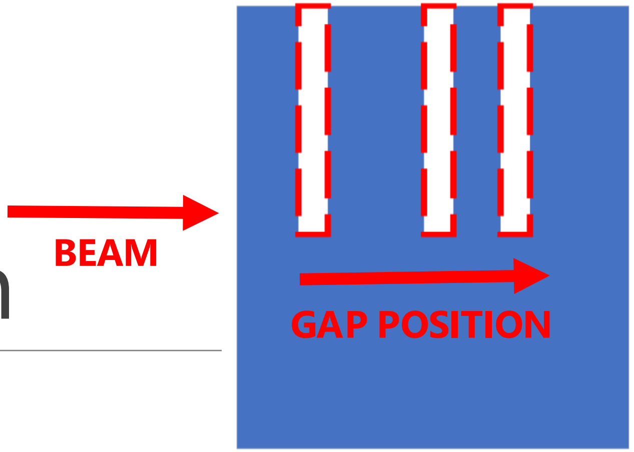
- p_0 is a time, [ns]
- p_1 represents the distance between the start counter and the TOF-Wall, [m]

$$\beta = \sqrt{1 - \left(\frac{m_0c^2}{m_0c^2 + K}\right)^2}$$



MC results:

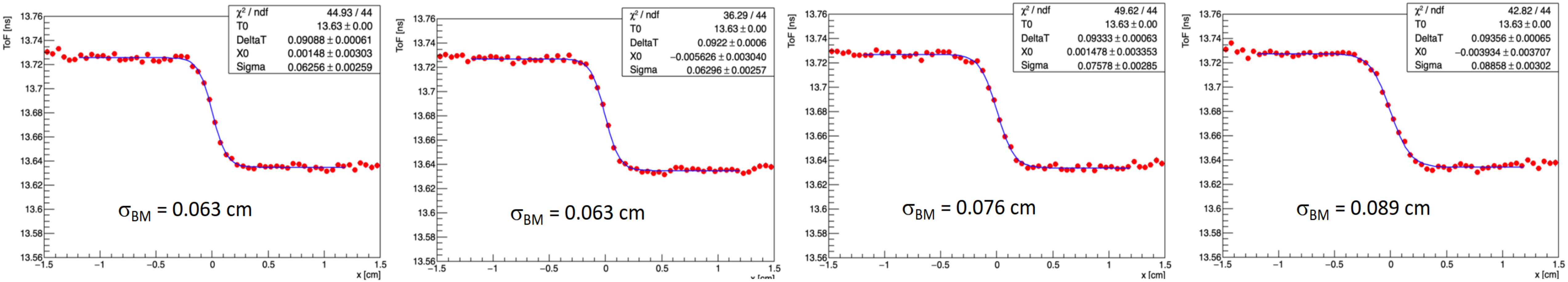
TOF profiles as a function of gap position



Fit function:

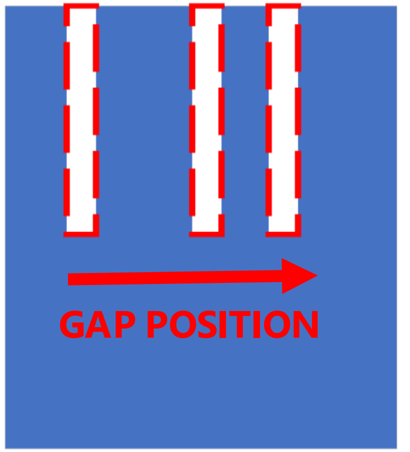
$$f(x) = t_0 + \Delta t \left(\frac{1}{1 + e^{\frac{x - x_0}{\sigma}}} \right)$$

2 cm **4 cm** **7 cm** **10 cm**



- **Δt** of the TOF profiles remains constant at different air gap positions
- **σ** increases with an increasing depth from the beam monitor

MC results:
TOF profiles as a function of gap position



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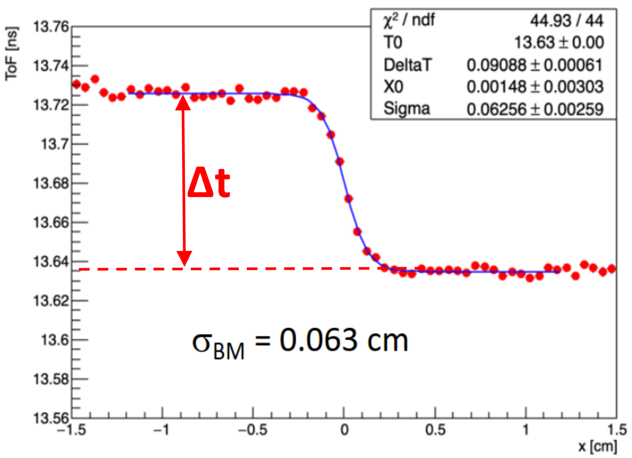
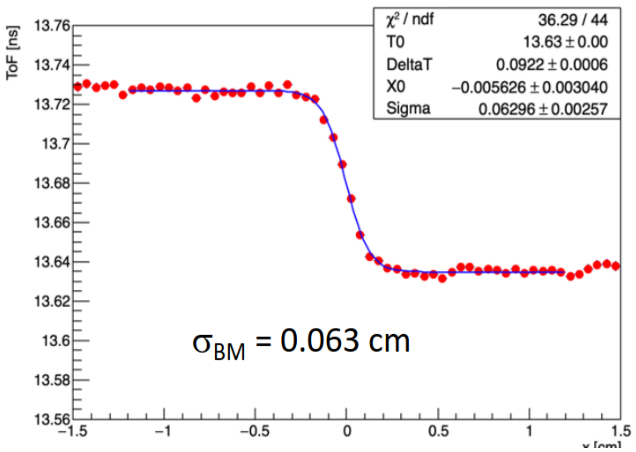
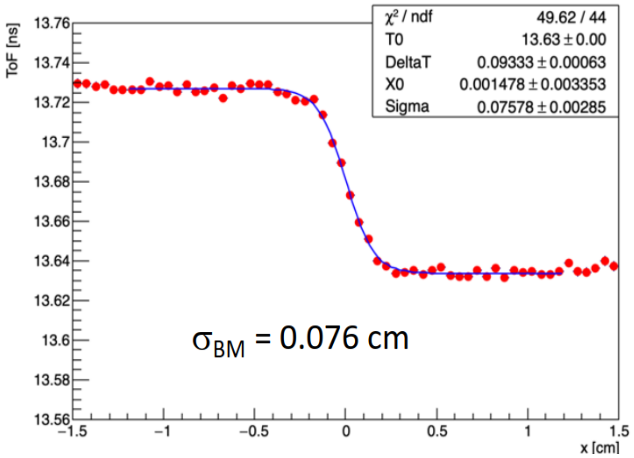
2 cm



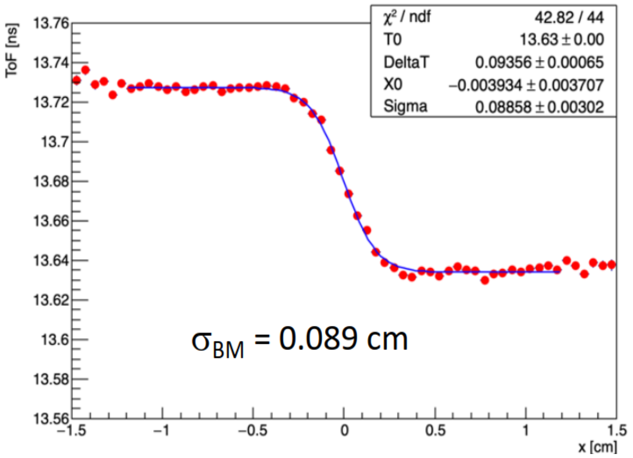
4 cm



7 cm

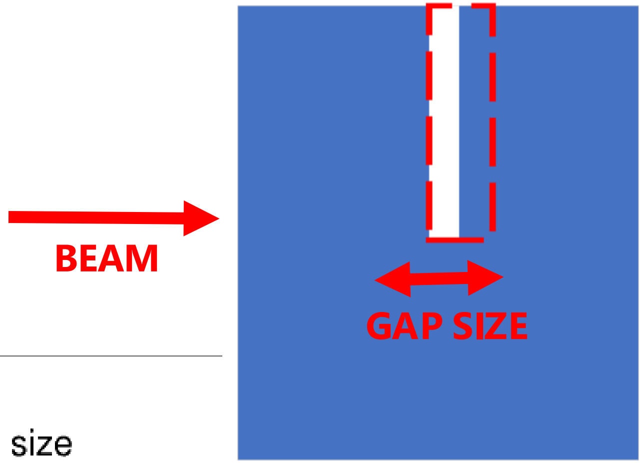


10 cm

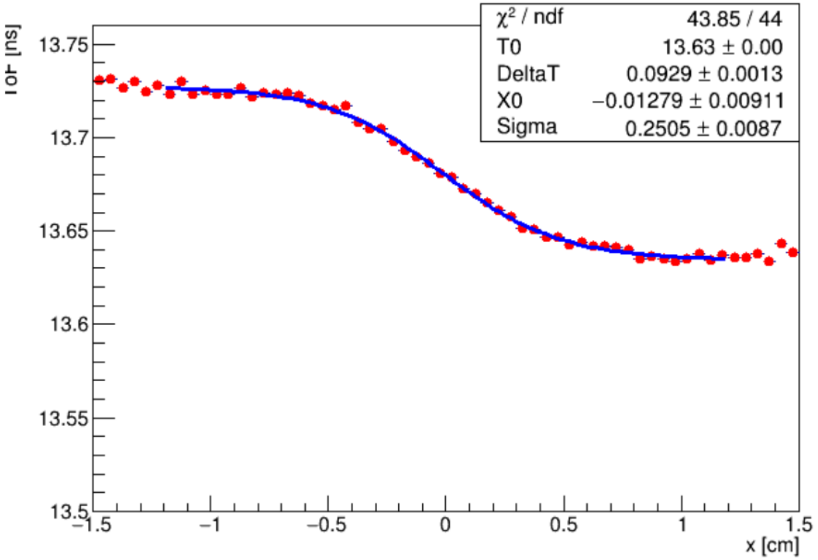


- **Δt** of the TOF profiles remains constant at different air gap positions
- **σ** increases with an increasing depth from the beam monitor

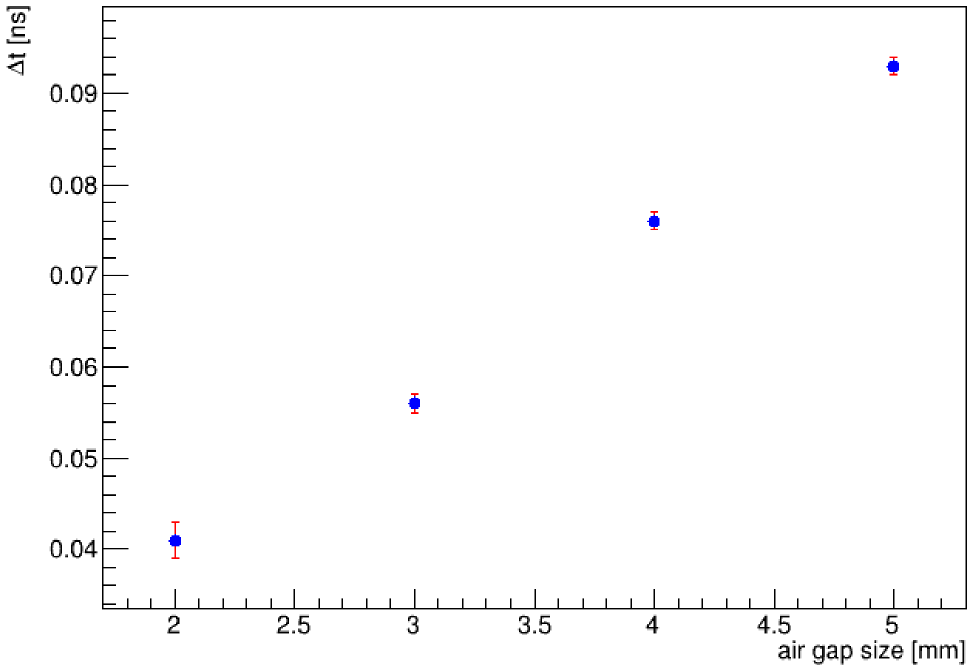
MC results:
TOF profiles as a function of gap size



TOF profile - 5 mm air gap

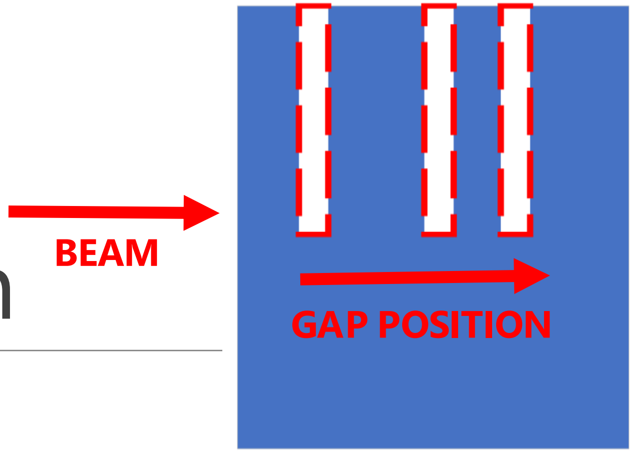


Simulated data: Δt vs air gap size

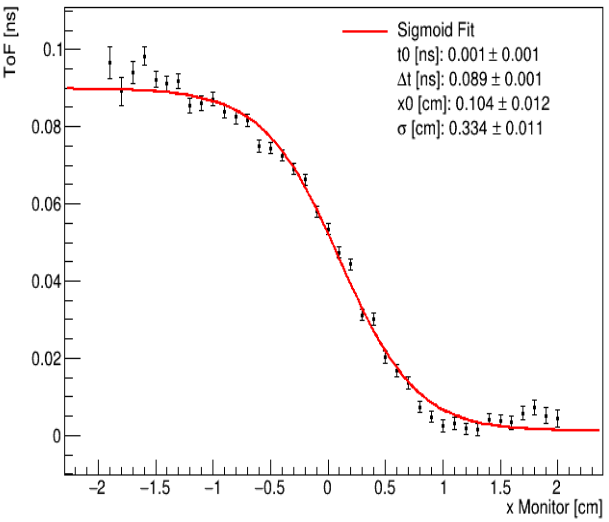


Δt of the TOF profiles increases with an increasing air gap size

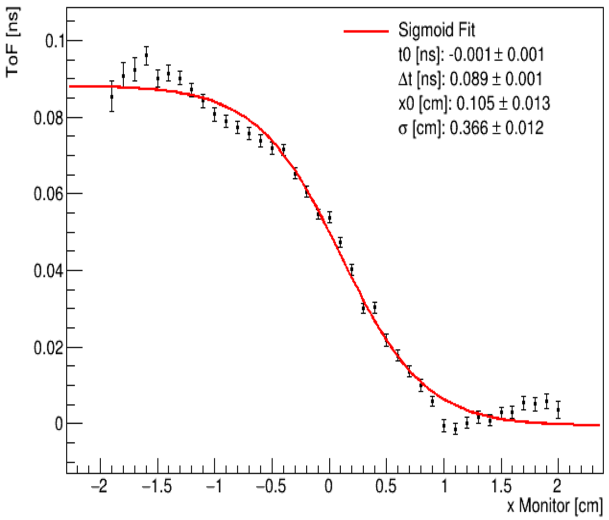
Experimental results:
TOF profiles as a function of gap position



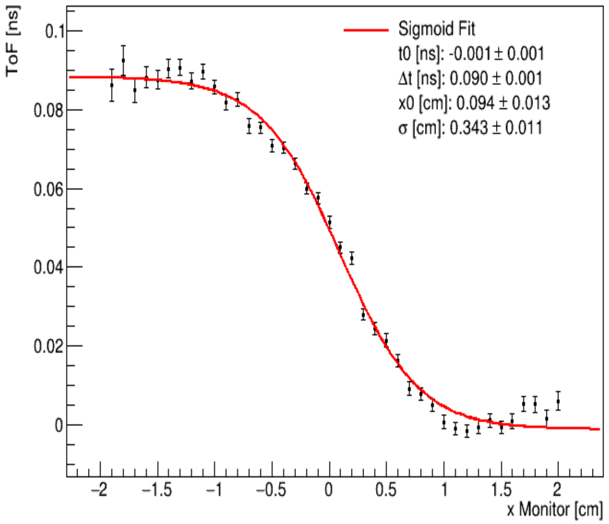
2 cm



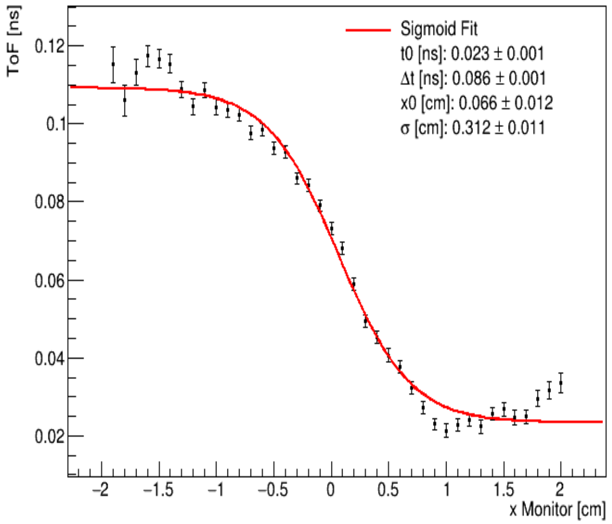
4 cm



7 cm

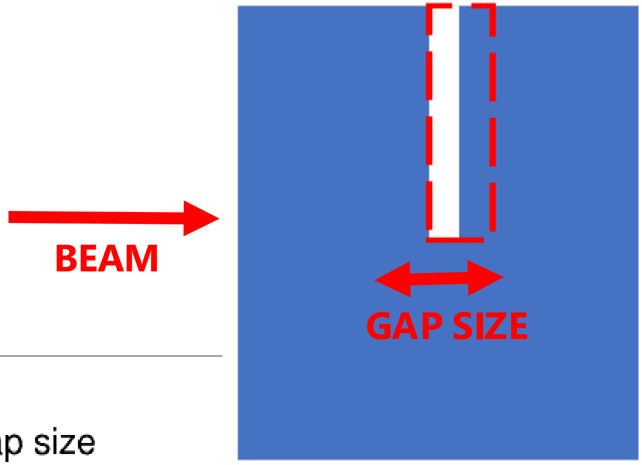


10 cm

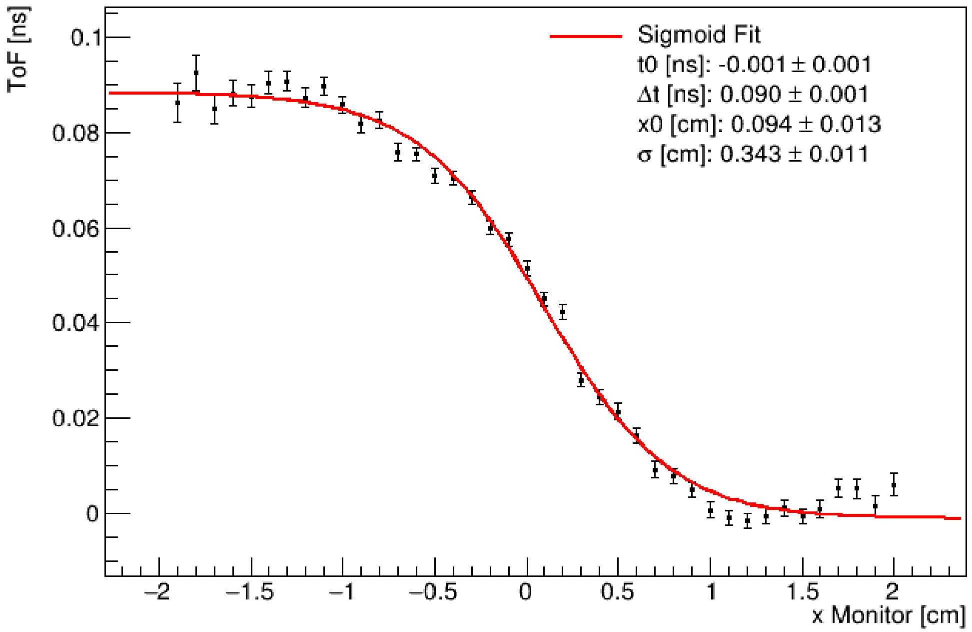


Δt of the TOF profiles remains constant at different air gap positions

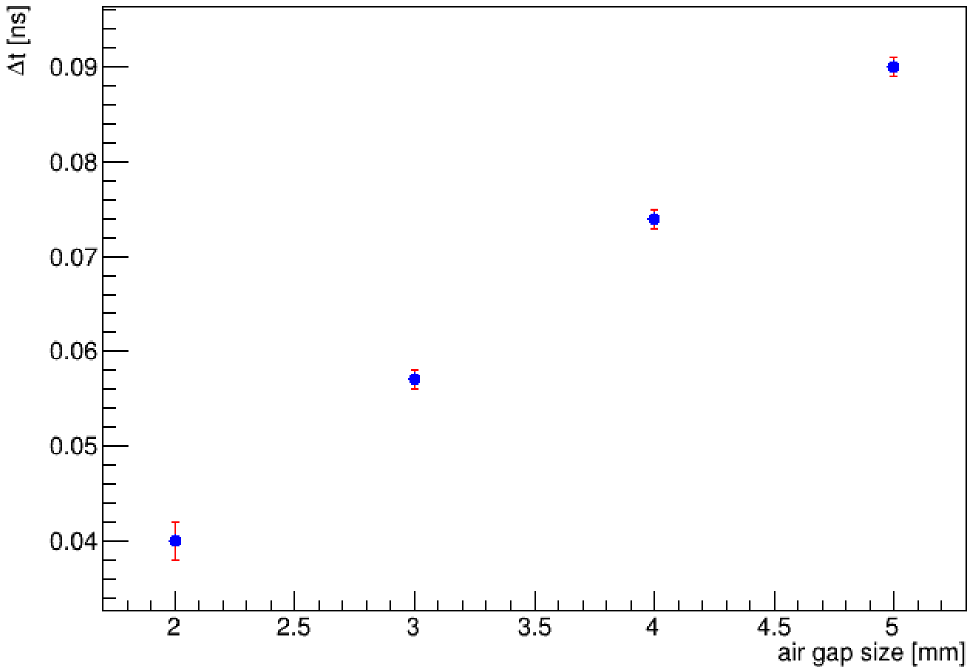
Experimental results:
TOF profiles as a function of gap size



TOF profile - 5 mm air gap



Experimental data: Δt vs air gap size



Δt of the TOF profiles increases with an increasing air gap size

Summary of the results

Δt values as a function of gap position

	Air gap @ 2 cm in RW3	Air gap @ 4 cm in RW3	Air gap @ 7 cm in RW3	Air gap @ 10 cm in RW3
Δt_{exp}[ns]	0.089 ± 0.001	0.089 ± 0.001	0.090 ± 0.001	0.086 ± 0.001
Δt_{MC} [ns]	0.091 ± 0.001	0.092 ± 0.001	0.093 ± 0.001	0.093 ± 0.001

Δt values as a function of gap size

	2 mm air gap	3 mm air gap	4 mm air gap	5 mm air gap
Δt_{exp}[ns]	0.040 ± 0.002	0.057 ± 0.001	0.074 ± 0.001	0.090 ± 0.001
Δt_{MC} [ns]	0.041 ± 0.002	0.056 ± 0.001	0.076 ± 0.001	0.093 ± 0.001

Conclusions and future perspectives

- A **good agreement** between the system response and the Monte Carlo simulation was found
- The first data taking shows that the developed system is **able to detect an air gap** of a few millimeters in a water-equivalent phantom
- The experimental Δt of the TOF profiles is compatible with the Monte Carlo one
- In order to be compatible with proton radiography applications, a **new DAQ system able to reach higher data rates** is under investigation
- Optimized TOF and tracking detectors are under development
- **Further tests with an upgraded prototype will be performed at CNAO** in the next months.

Thank you for the attention!

Acknowledgment:

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