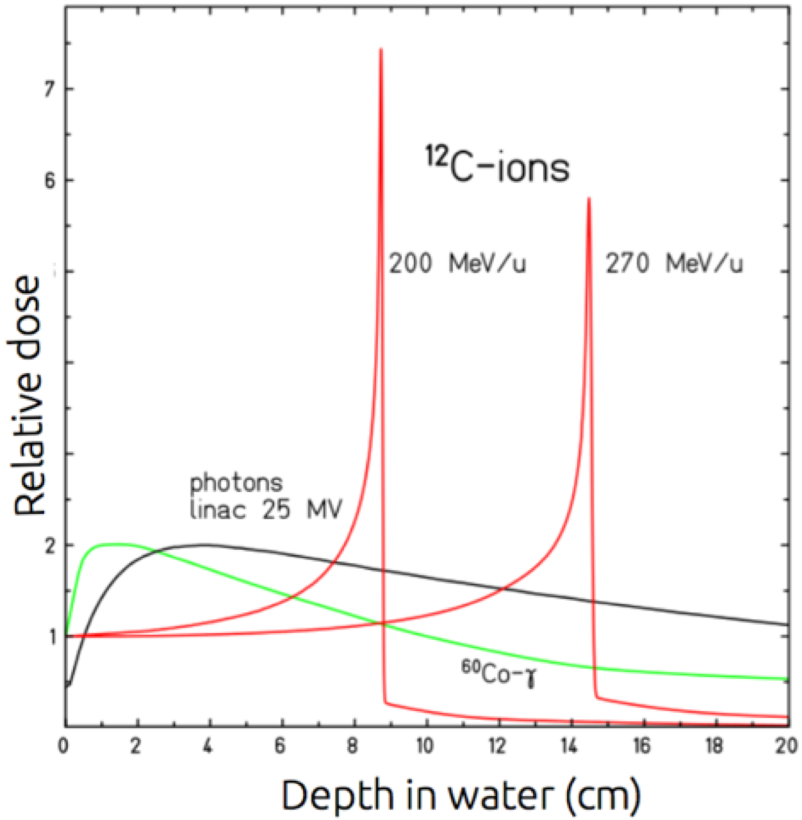
Novel charged particles monitor of light ions PT treatments: results of preliminary test using an anthropomorphic phantom

Giacomo Traini, G.Battistoni, M.De Simoni, Y.Dong, A.Embriaco, M.Fischetti, M. Magi, C. Mancini-Terracciano, I. Mattei, M. Marafini, R. Mirabelli, S. Muraro, V. Patera, A. Schiavi, A. Sciubba, A.Sarti, E. Solfaroli-Camillocci, S. Valle

InSide
INFN Istituto Nazionale di Fisica Nucleare
SAPIENZA Università di Roma
ARPG Applied Radiation Physics Group

Particle Therapy: rationale

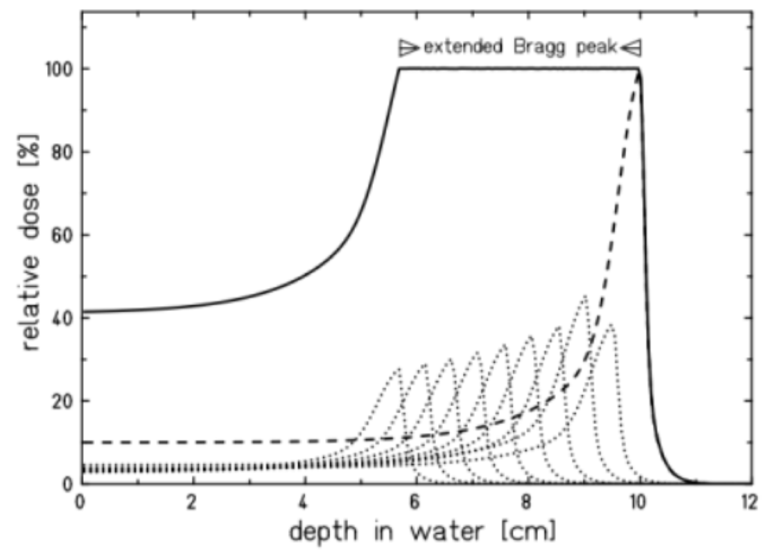
D.Schardt T.Elsasser, Rev. Mod. Phys., 82, (2010)



- Beam penetration in tissue function of the beam energy

- Peak of dose released at the end of the projectile path, **sparing the normal tissues**

- Accurate conformal dose to tumor with **Spread Out Bragg Peak**



The biological damage is related to the **released energy**, **ionization density and type of projectile used**.

Typical treatment flow

3D information (CT, MRI)

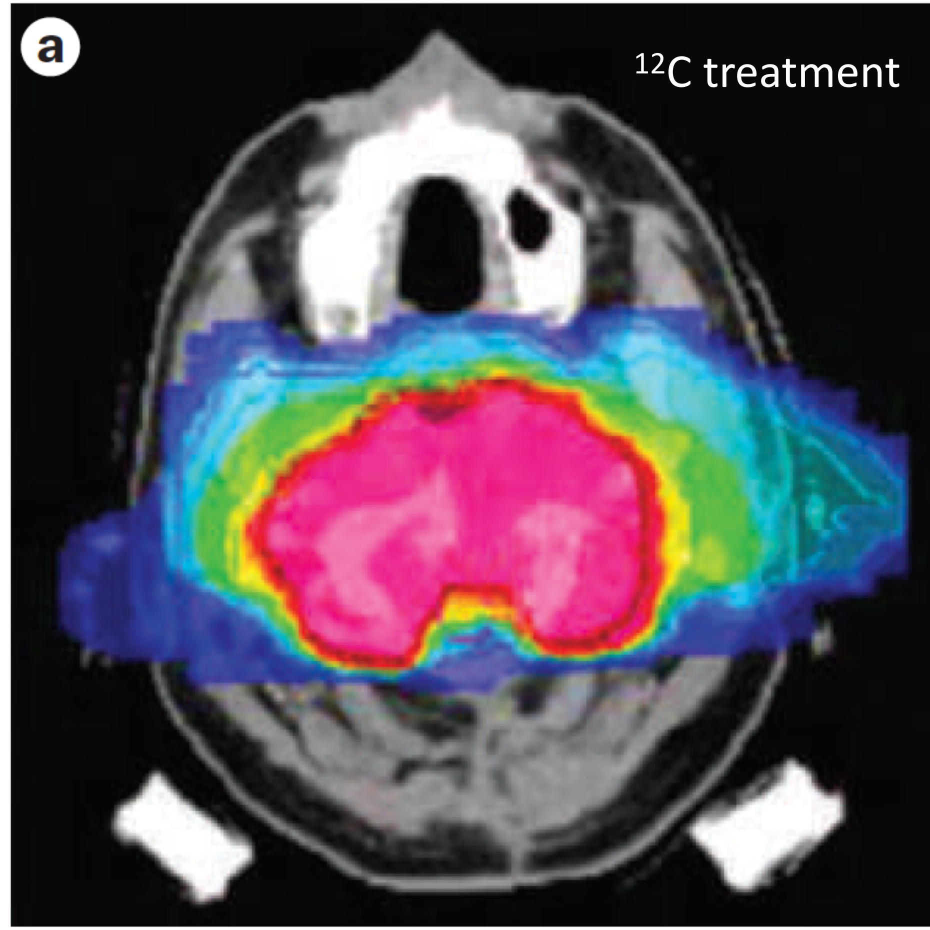
- Tumour localisation inside the body
- Human tissues density map

Treatment planning

- A software tool produces as output the instructions for the accelerator to deliver the prescribed dose in the patient (E, θ, N)

Dose delivery

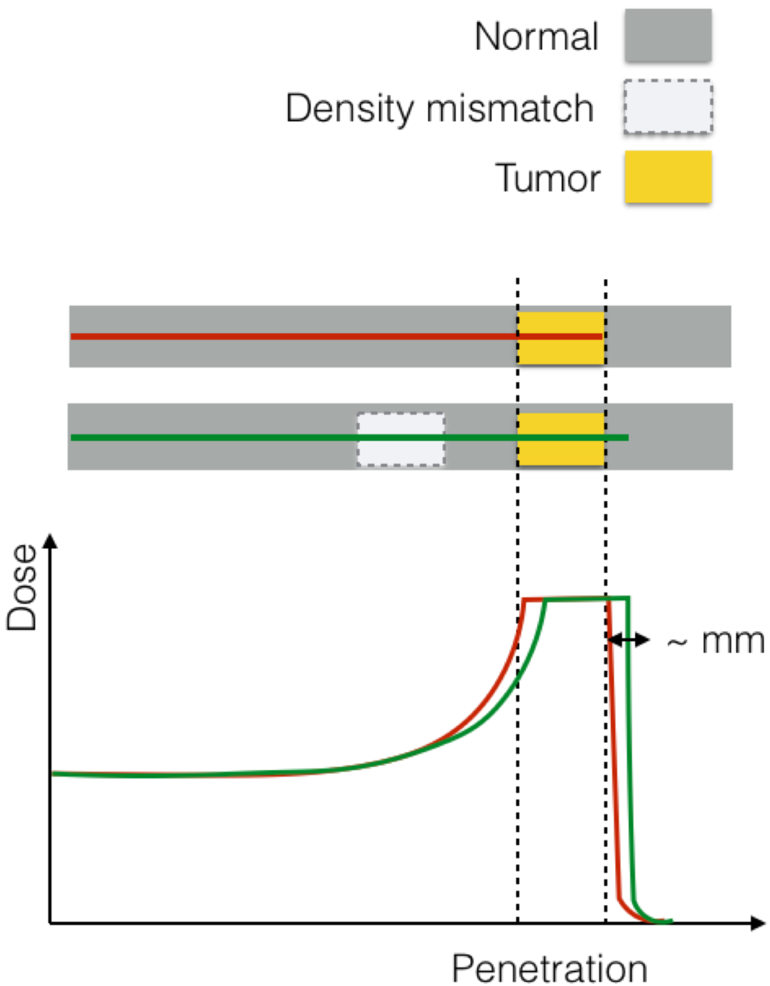
-The total dose is delivered within few weeks (~30 fractions), each one lasting few minutes



Durante, M. & Loeffler, J. S. Nat. Rev. Clin. Oncol. 7, 37–43 (2010), doi:10.1038/nrclinonc.2009.183

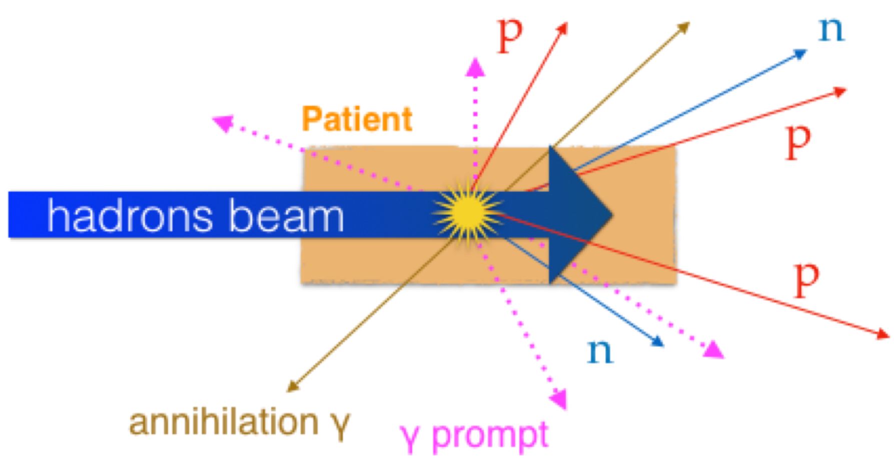
The range monitoring issue

PT is highly sensible to range variations (patient mispositioning, uncertainties on the CT Hounsfield number conversion, anatomical density variation...)



-A range monitor must rely on **secondary particles produced in nuclear interactions** and coming out from the patient, giving a feedback during the treatment (online)

- Generally the Bragg peak position can be correlated with the secondary particles **emission spatial distribution**



Monitoring with charged fragments

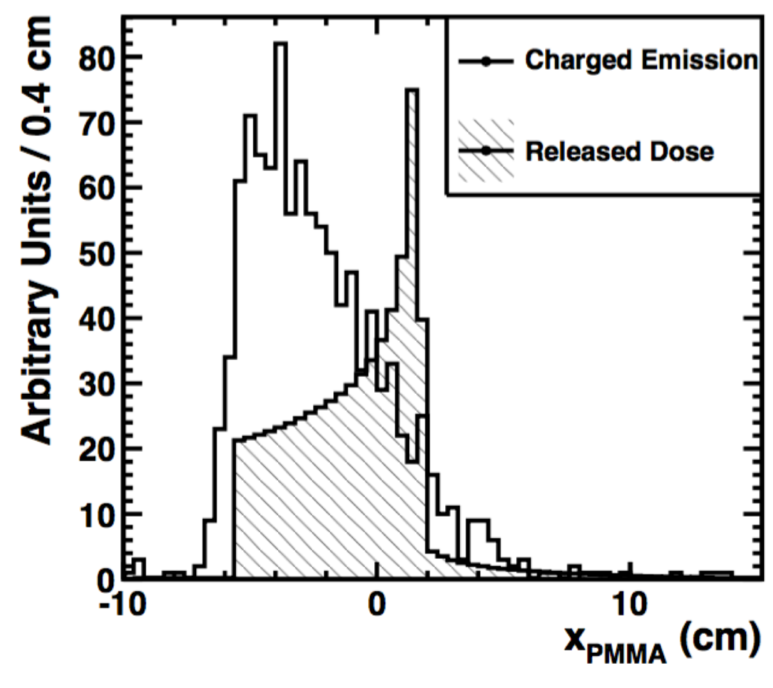
Advantages:

1) Easy to detect (high detection efficiency, low background)
2) Significant production in Z>1 ion treatments (He, C, O) (mainly protons)
3) **Correlated by the Bragg Peak**

Drawbacks:

1) Fragments suffer of abpsorption and Multiple scattering interactions in matter
2) Larger the angle wrt the beam direction, lower the statistic

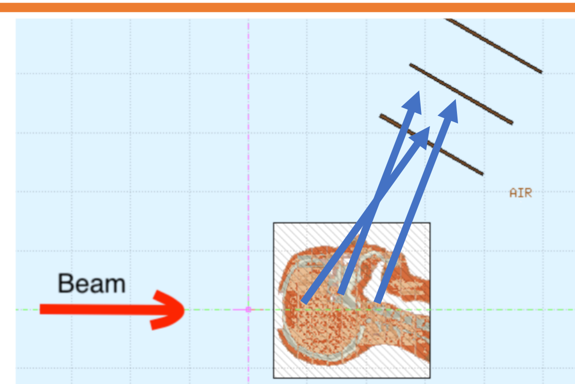
"Measurement of charged particle yields from PMMA irradiated by a 220 MeV/u ^{12}C beam", Phys. Med. Biol. 59 (2014) 1857-1872.



REVIEW ARTICLE

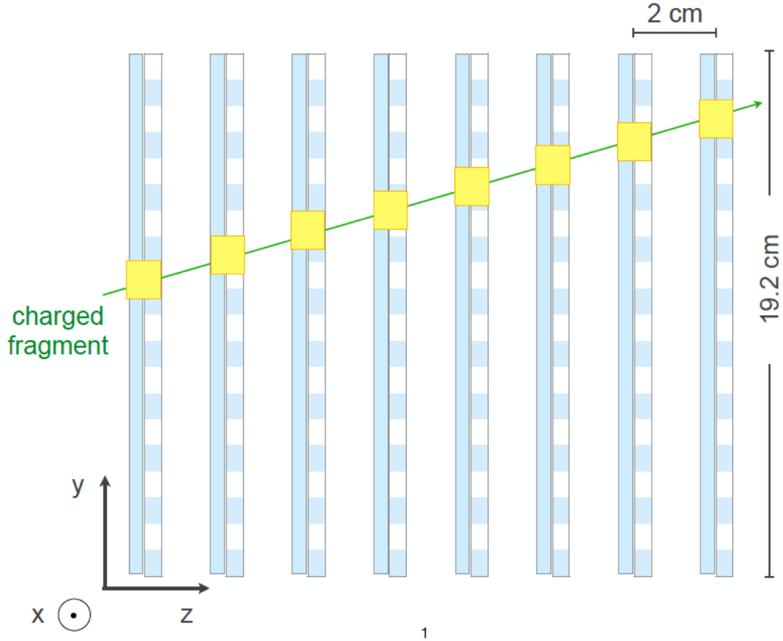
Front. Oncol., 03 August 2016 | https://doi.org/10.3389/fonc.2016.00177

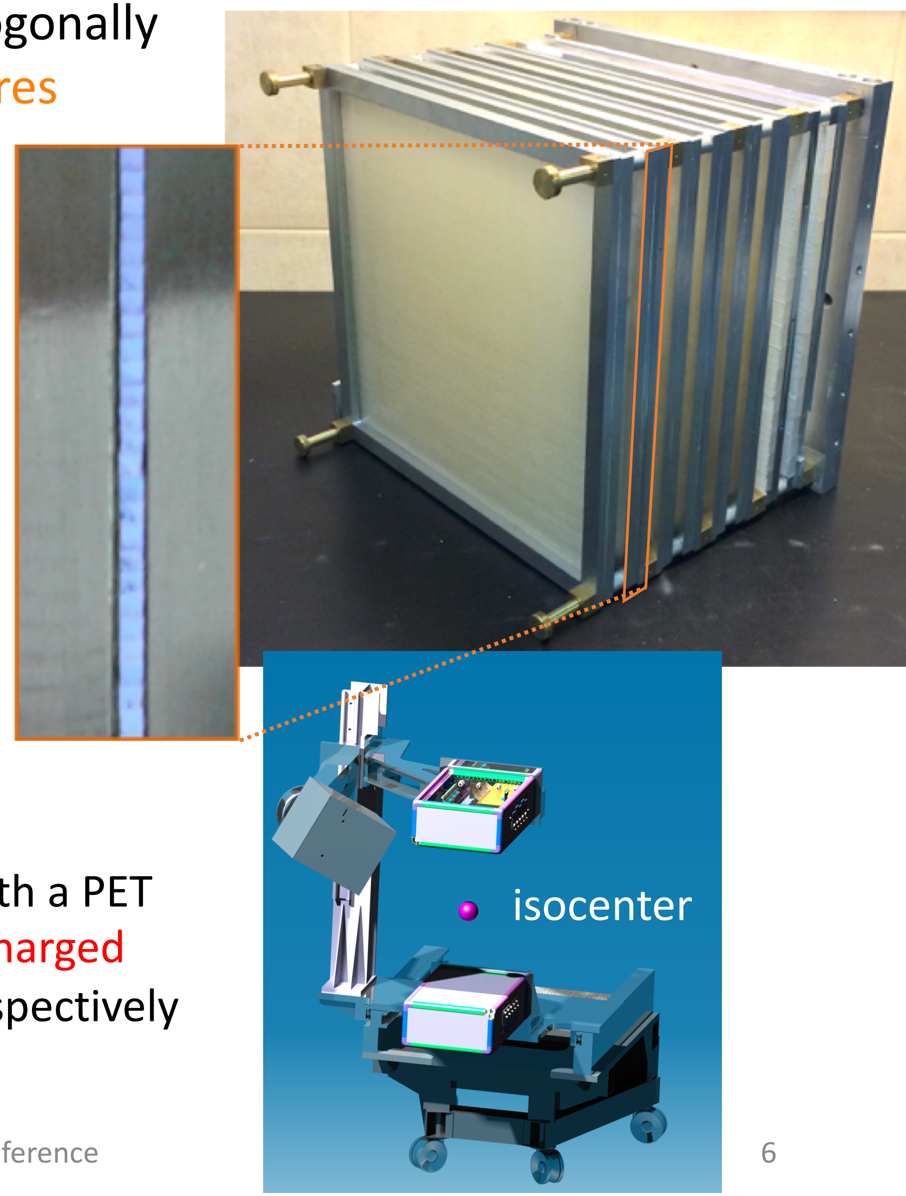
Monitor of Hadrontherapy treatments by means of charged particle detection



The Dose Profiler

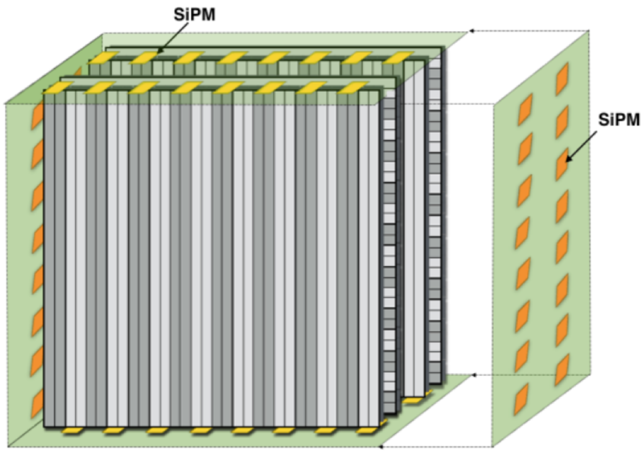
- 8 planes: each one composed of 2 orthogonally oriented layers of plastic scintillating fibres (squared 500 µm, double cladding)

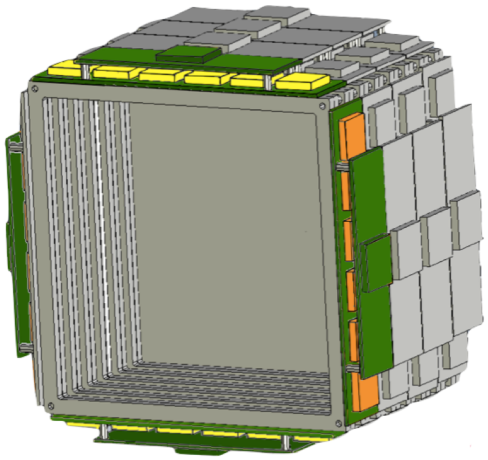




Integrated within the INSIDE project @CNAO with a PET device for a bi-modal simultaneous approach: charged fragments and ß⁺ emitters detection tailored respectively for carbon and proton treatments monitoring

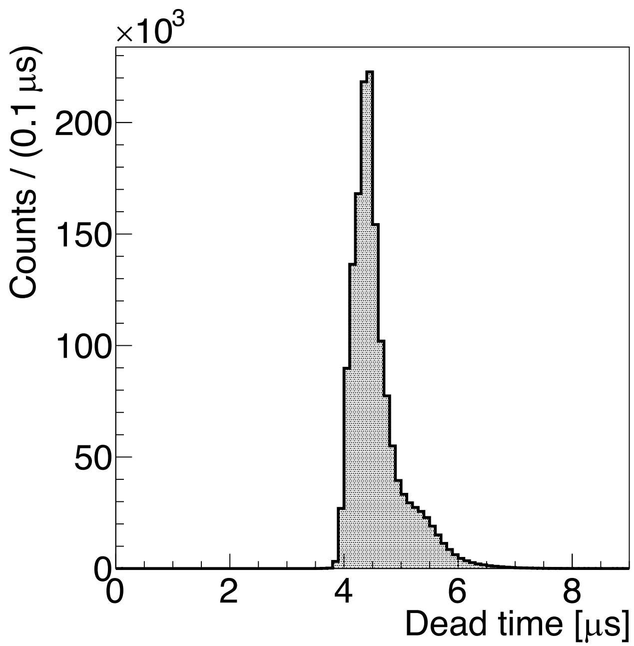
The read-out system

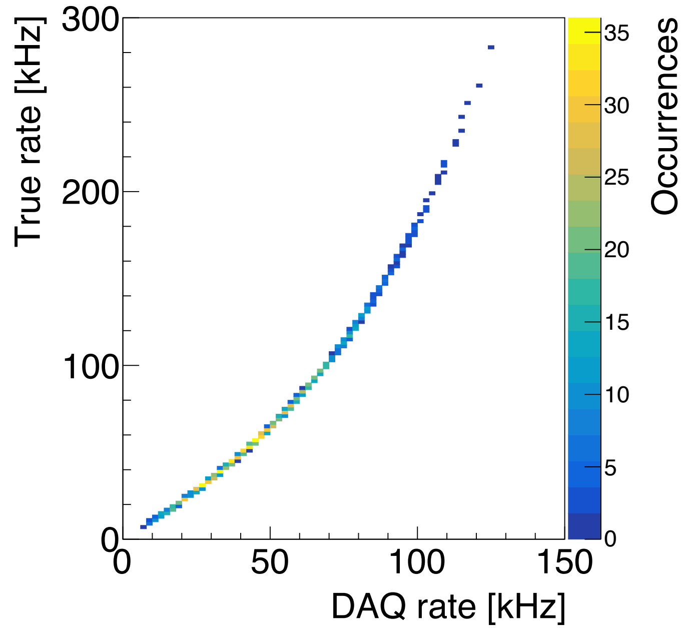




- SiPM (Hamamatsu, 1 mm^2 active area), 3072 channels
- 32 channel ASIC for SiPM read-out
- 16 FPGA for the ASIC readout and configuration
- Commercial embedded system for event-building, triggering and data transfer

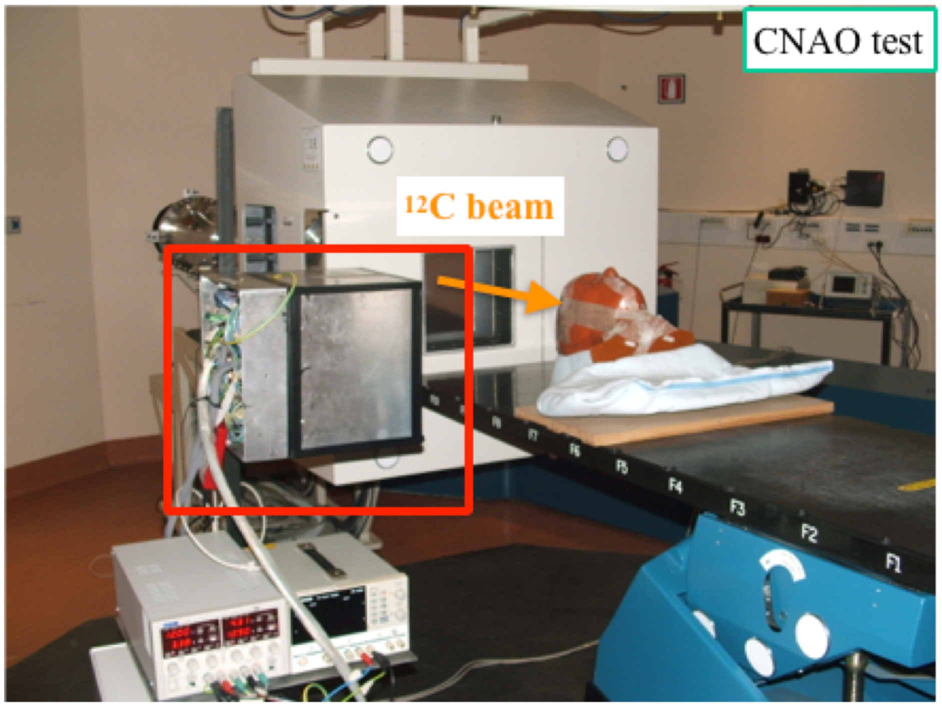
- Data acquisiton rates can reach O (100 KHz)
- Primary ion rate ~ 10^8 Hz



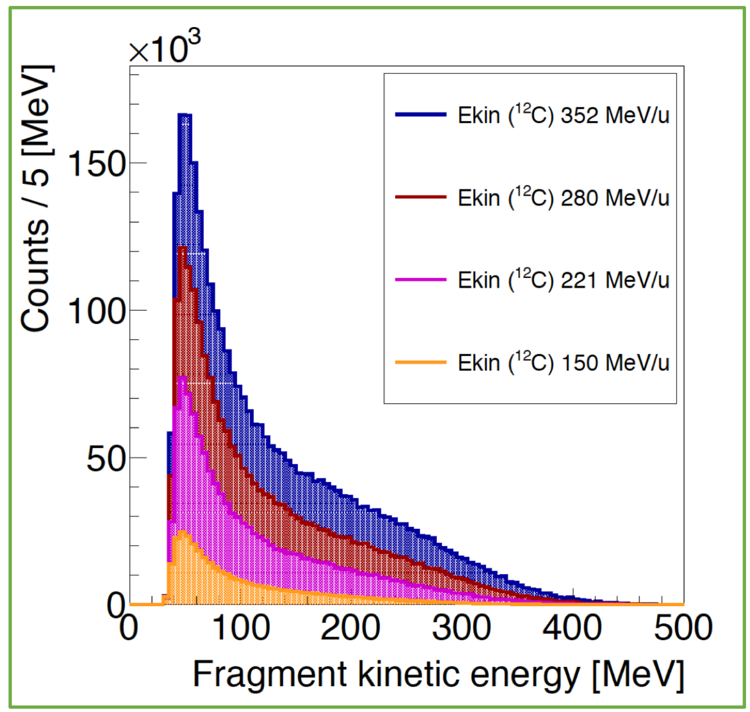


The CNAO data-taking

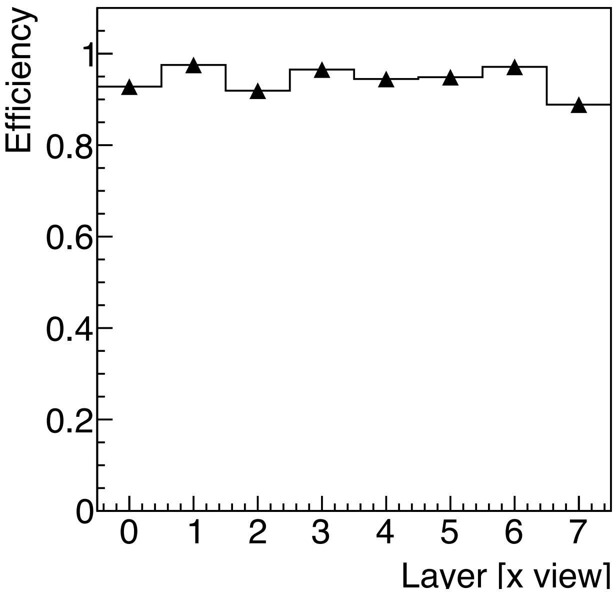
The DP has been tested @ **CNAO** to check the operation in ‘clinical like conditions’, using ^{12}C beams between 150 and 350 MeV/u, impinging on different targets.



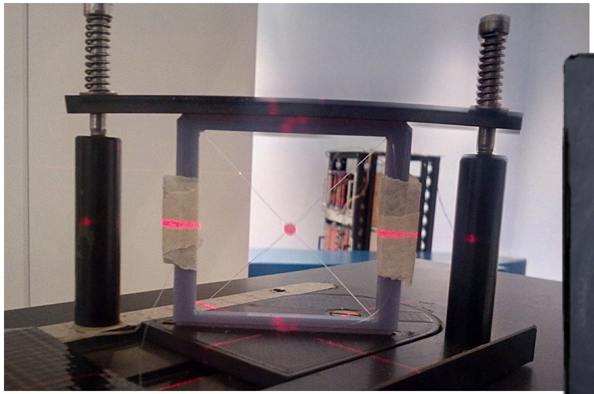
Detected fragments have average kinetic energies of ~ 100-120 MeV

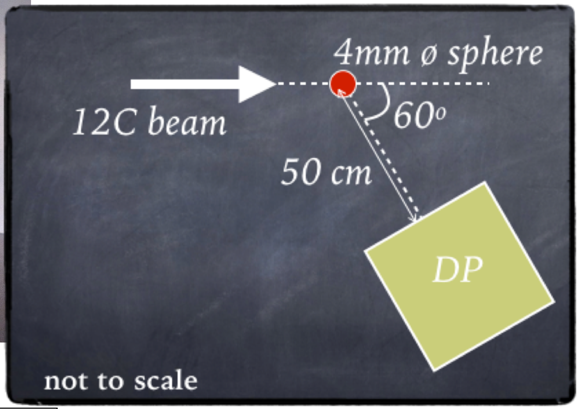


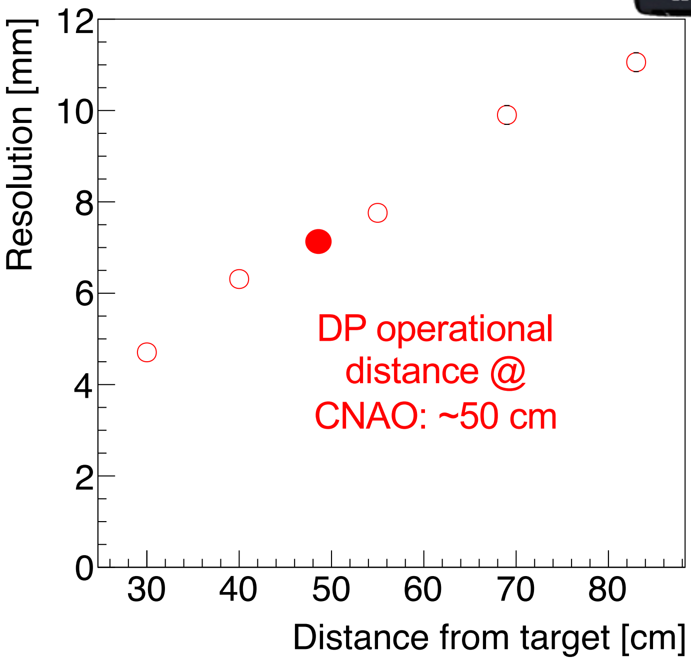
Performances



The **detection efficiency (~90%)** matches what was expected from detector calibration when properly taking into account the fibre cladding and inter-layer alignment







The **'per-track' back-traking resolution** has been evaluated using a small (4mm diam.) plastic spherical target

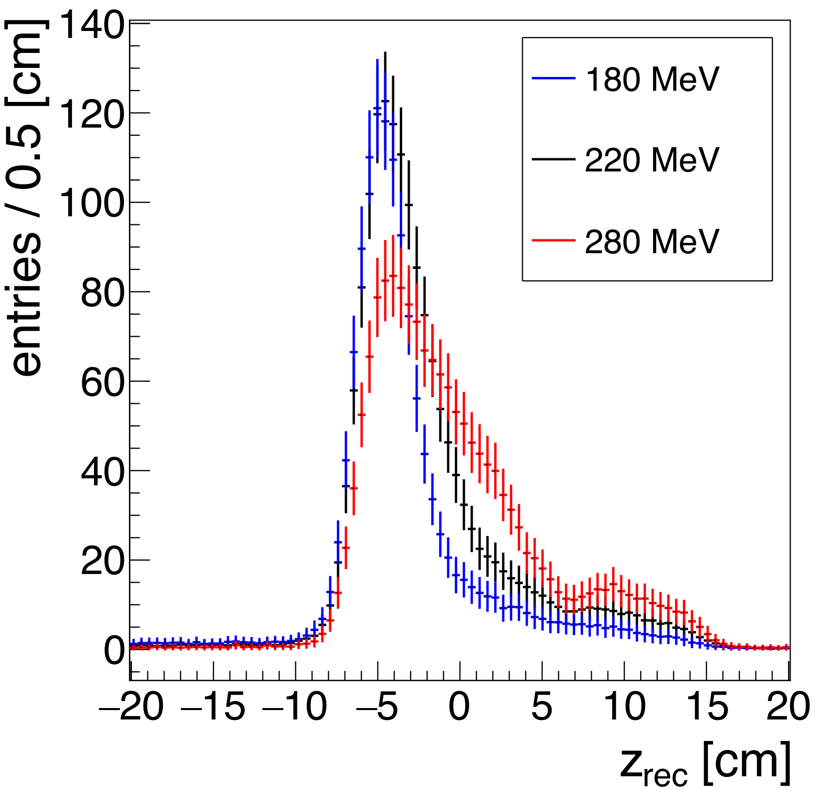
Pencil beam monitoring quest

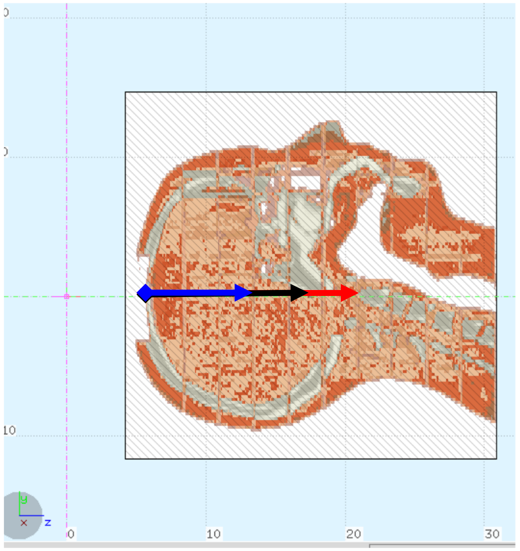
The results are shown for the statistics [number of fragments] expected from ~10 PB together [~1 cm^2 area]

In the following, we assume that (in average) for 1 Gy dose 10^7 ^{12}C are shoot per "slice" and 10^5 per PB [actual numbers can vary a lot in a specific treatment]
Flux depends also on 'depth' (beam energy) and distance from isocenter [50 cm]!

Between 1.2 and 1.6k tracks in total (per cm^2)

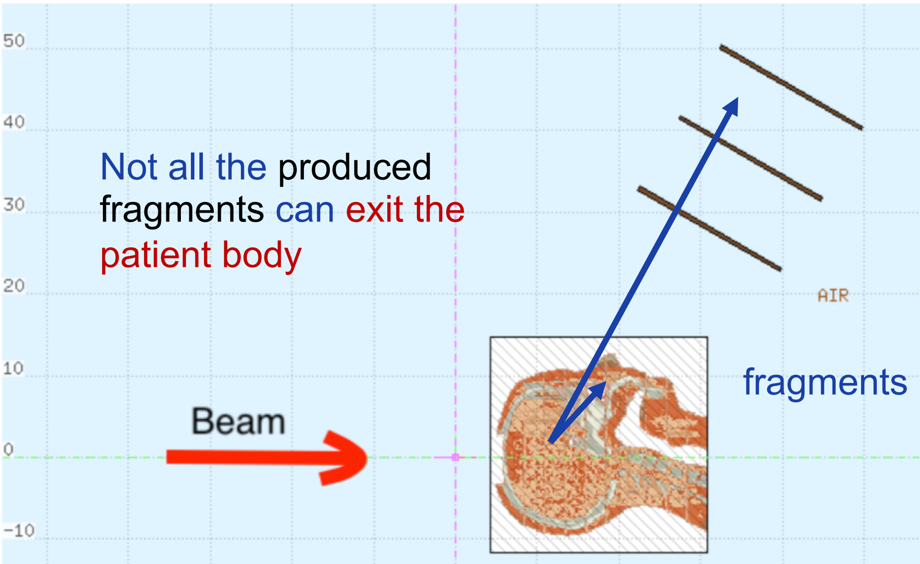
O(100) tracks can be expected per PB in average conditions: strategies for 'PB packing' have to be envisaged in order to reach the desired precision (enough tracks per spot)

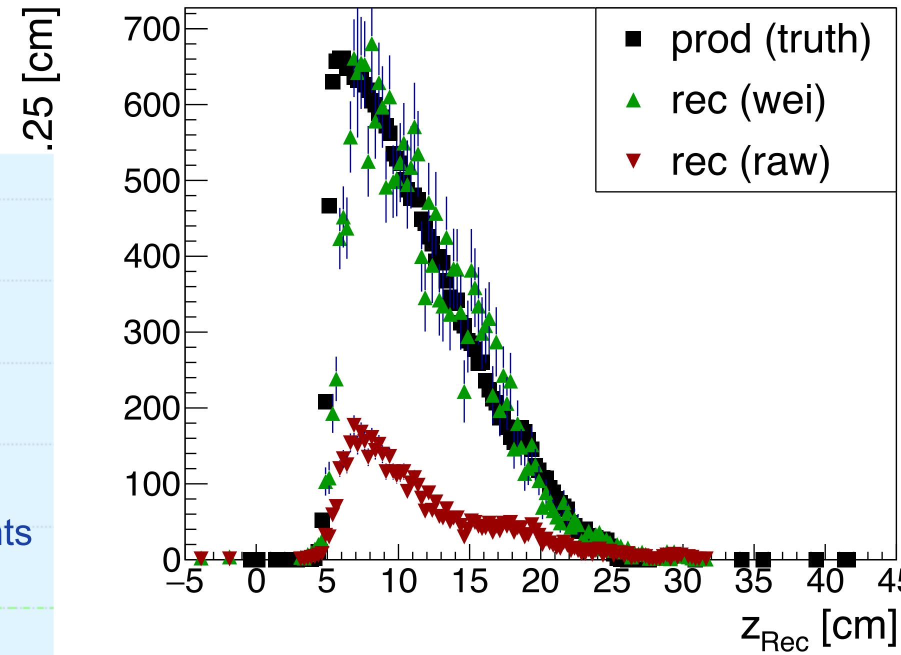




Effect of matter absorption

Charged fragments undergo MS interactions and are absorbed inside the patient body





Statistics: expected tracks from 1 cm^2. Weighing is performed using a full MC approach based on the study of fragments interactions with a water target (allows an experimental calibration)

Another approach under development is a MLEM algorithm: use a fast GPU based MC to compute the A_{ij} MLEM matrix → apply the correction

ML-EM

$$x_i^{(n+1)} = x_i^{(n)} \cdot \frac{1}{\sum_j A_{ij}} \cdot \sum_j A_{ij} \frac{y_j}{\sum_k A_{kj} x_k^{(n)}}$$

Clinical trial preparation

fondazione CNAO

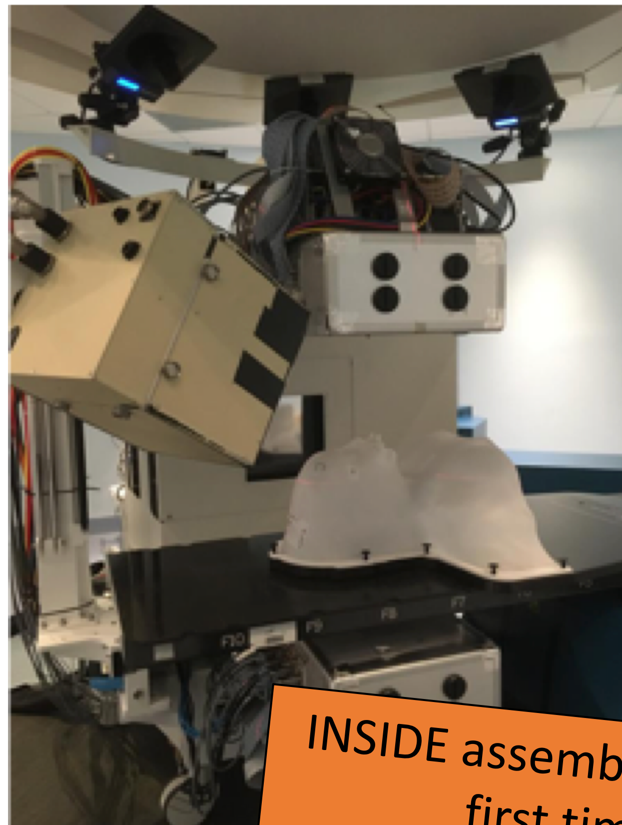
InSide

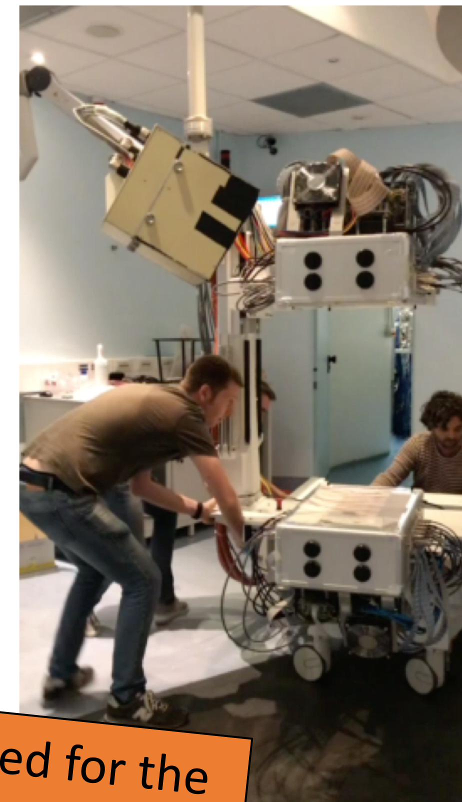
In September 2018 the CNAO - INSIDE2 integration happened!

The system can be used with minimum impact in the treatment time workflow in the clinical routine

Clinical trial @ CNAO (bi-modal operation with PET heads) will start in spring 2019. Four selected pathologies have been identified:

- Meningioma and nasopharynx cancer treated with proton beams
- Adenoid Cystic Carcinoma (ACC) and clival chordoma treated with carbon ion beams



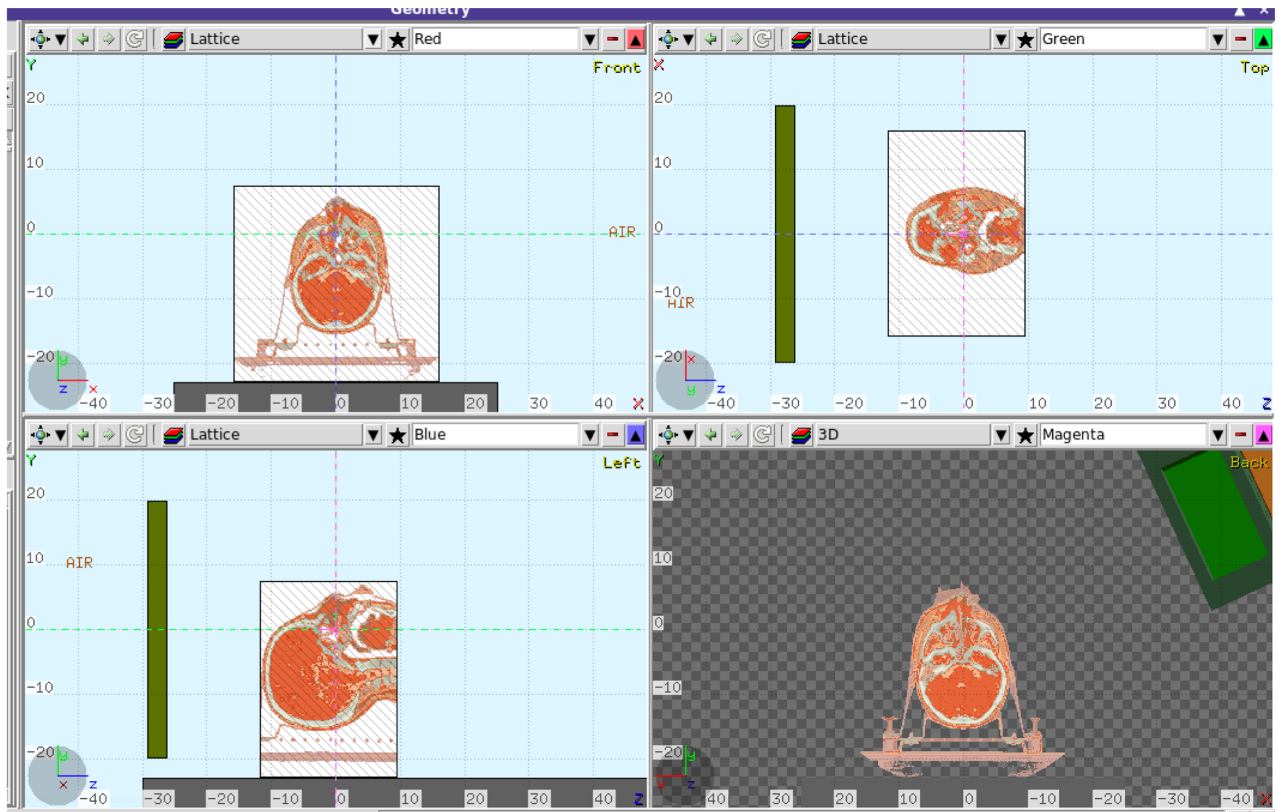


INSIDE assembled for the first time!

Simulation

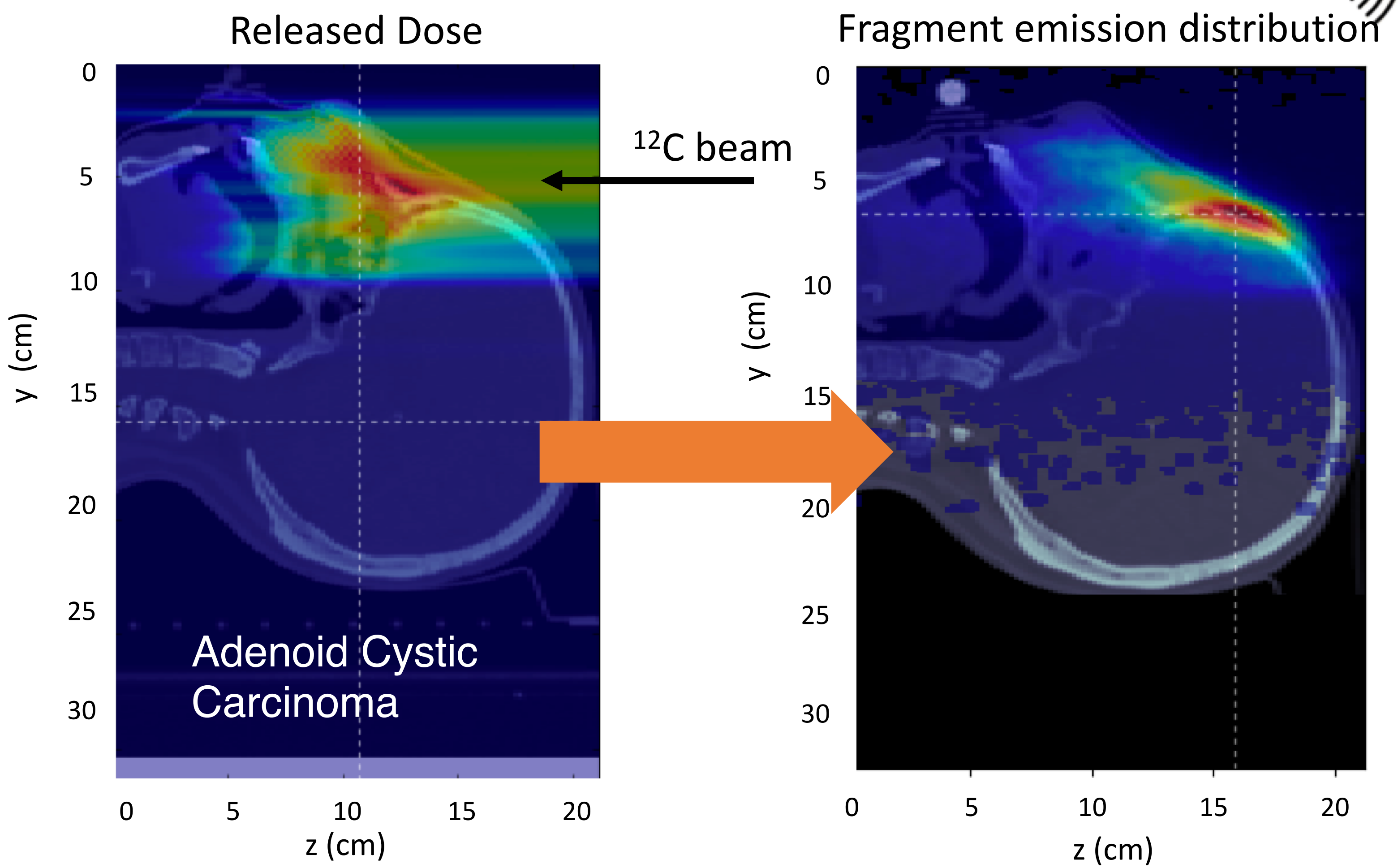
Simulation with FLUKA of a real treatment @CNAO has been performed. Real patient and real positioning (real CT has been acquired)

Clinical trial will help us in understanding which is the best method to "pack" the PB in a real treatment and to test the dishomogenity recognition capability!



More than 25000 pencil beams, with kinetic energies between 145 and 350 MeV/u

Secondary fragment production



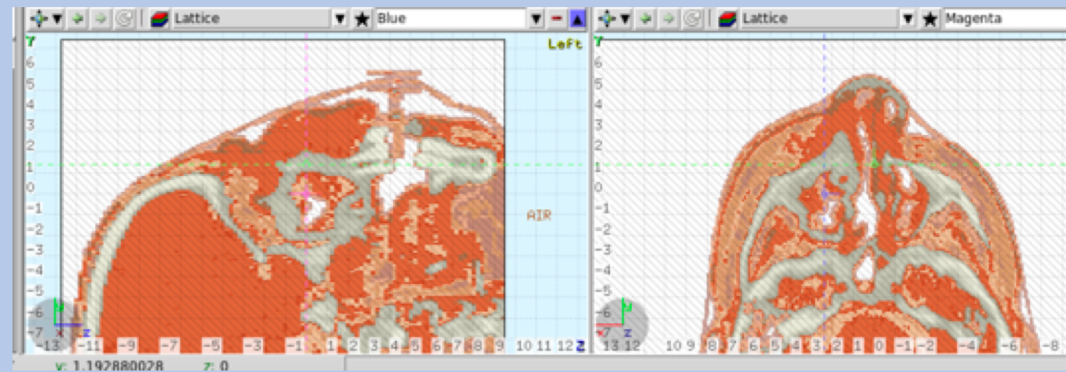
Fragments, as expected, are mostly produced at the entrance point inside the patient and are absorbed by the patient body in their exit path towards the detector

A possible use: interfractional monitoring

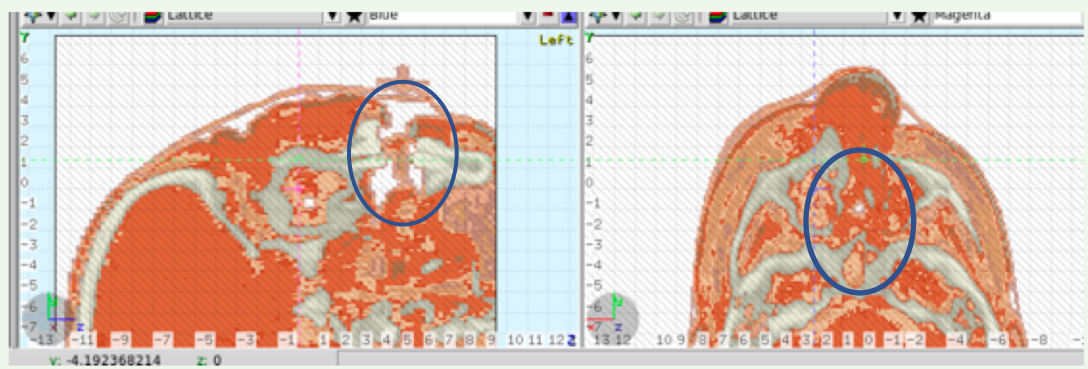
- A study has been performed using MC simulations to assess the DP capability of spotting interfractional morphological changes that will need a re-evaluation CT scan and a re-optimization of the plan

- Two CT scan have been acquired for a patient that had a severe toxicity induced from the treatment and whose plan had to be re-evaluated.

CT scan before the treatment



CT scan after ~ 20 days

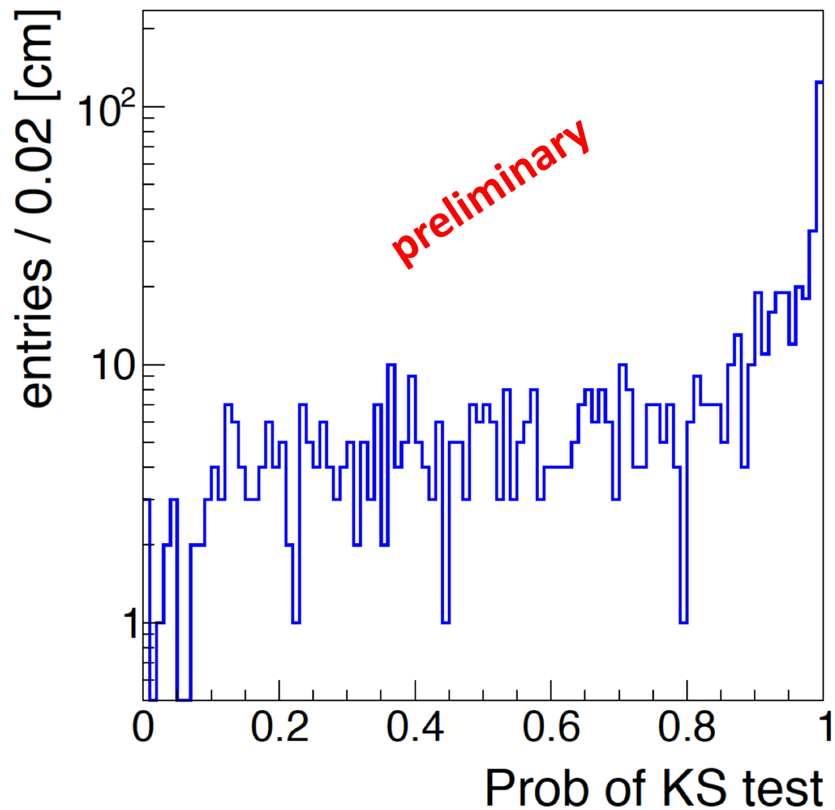


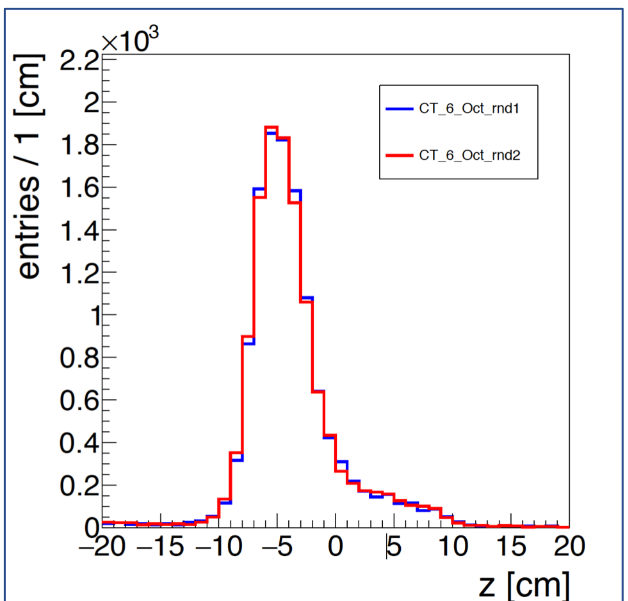
Reproducibility study

- **<u>The same treatment</u>** plan has been simulated and the reconstructed tracks have been analysed.

- The impact of fluctuations has been valuated by producing the same MC with different radndom seeds and comparing the resulintg proflies,.

Kolmogorov test

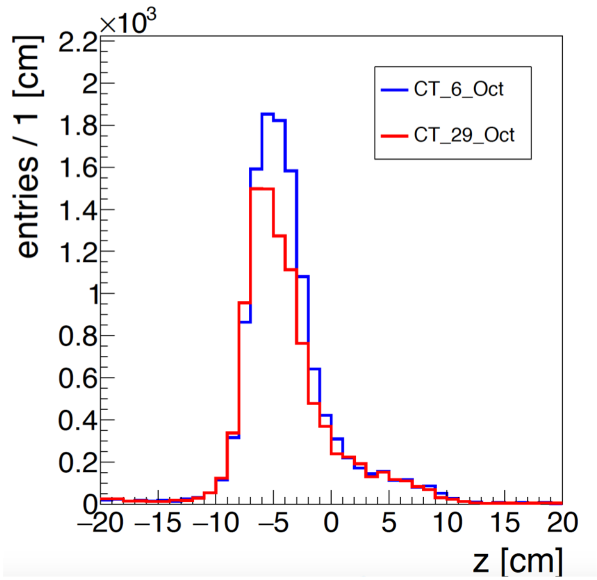




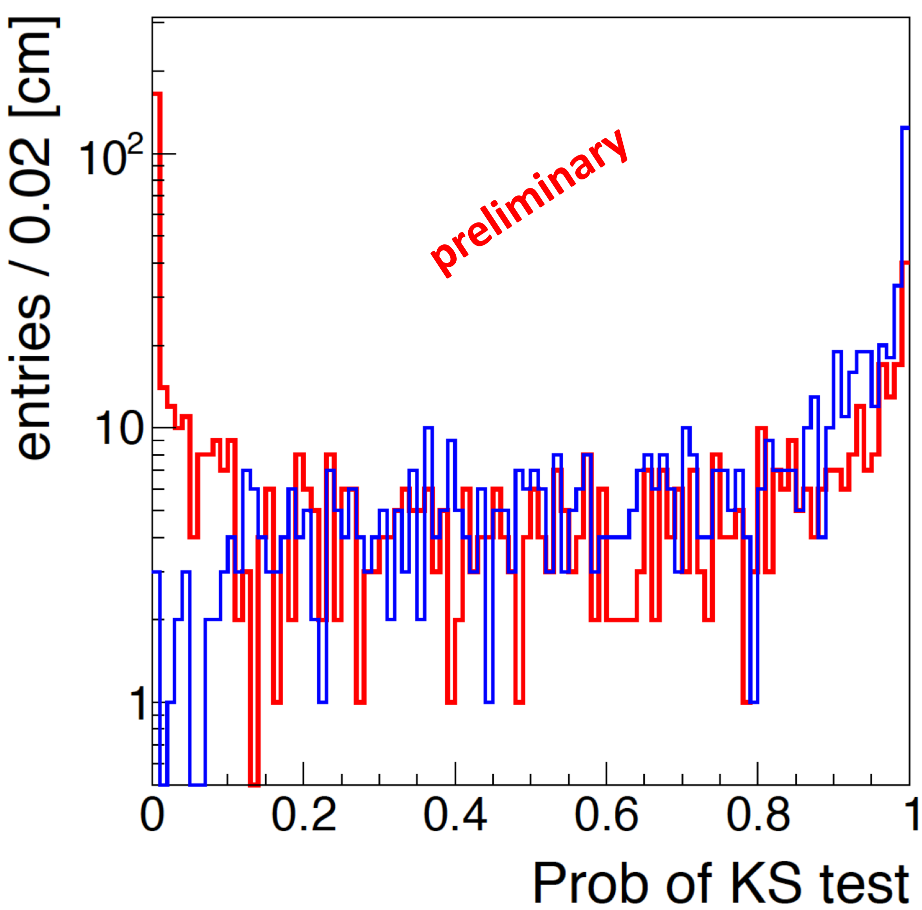
PB belonging from the same target volume of 1cm x 1cm x 6 mm have been summed up

Spotting the differences

- Comparing the reconstructed profiles for the two different CT scans, **differences are observed**.
- ~ 200 pencil beam are significantly different, due to the toxicities developed by the patient



Kolmogorov test

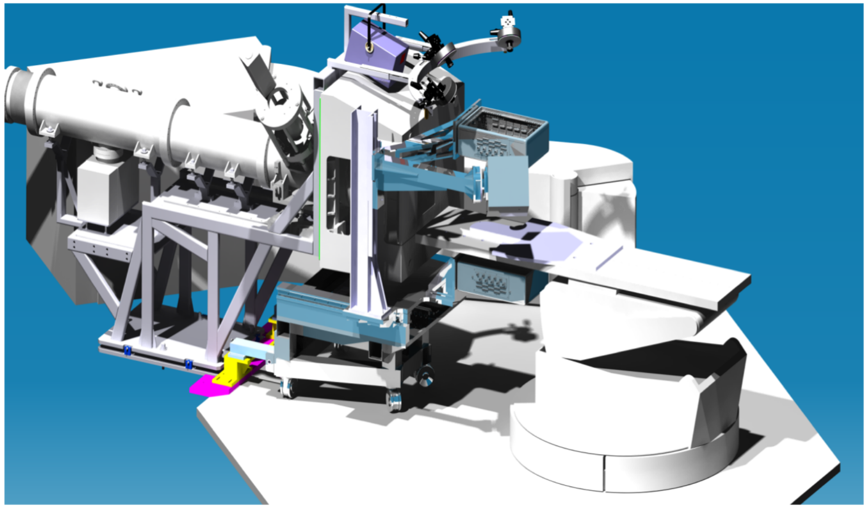


With this approach, unfolding of the matter effect is not needed!

Conclusions

- The Dose Profiler fibre tracker is operational and matches the design expectations (resolution and efficiency)

- The capability to spot toxicities induced by the treatment seems to be very promising



- Clinical trial @ CNAO (bi-modal operation with PET heads) is about to start.
  - Four selected pathologies have been identified: meningioma and nasopharynx cancer treated with proton beams, Adenoid Cystic Carcinoma (ACC) and clival chordoma treated with carbon ion beams

- Data collected during the treatment will be analised offline, finalising the matter studies, and a final word on the BP monitoring precision achievable in clinical conditions with this technique will be said.
  - Online monitoring will be implemented shortly after and tested in the second trial phase