Design of a tracking device for on-line dose monitoring in hadron therapy

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for

INSIDE collaboration

Outline

Particle Therapy (PT) and monitoring

The INSIDE Project: the Dose profiler

The Dose profiler performances

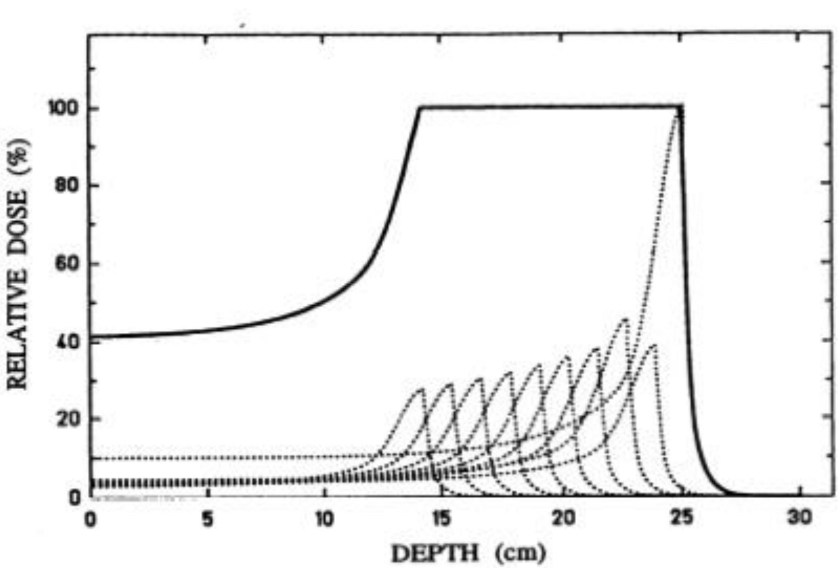
Particle therapy VS Photon RT

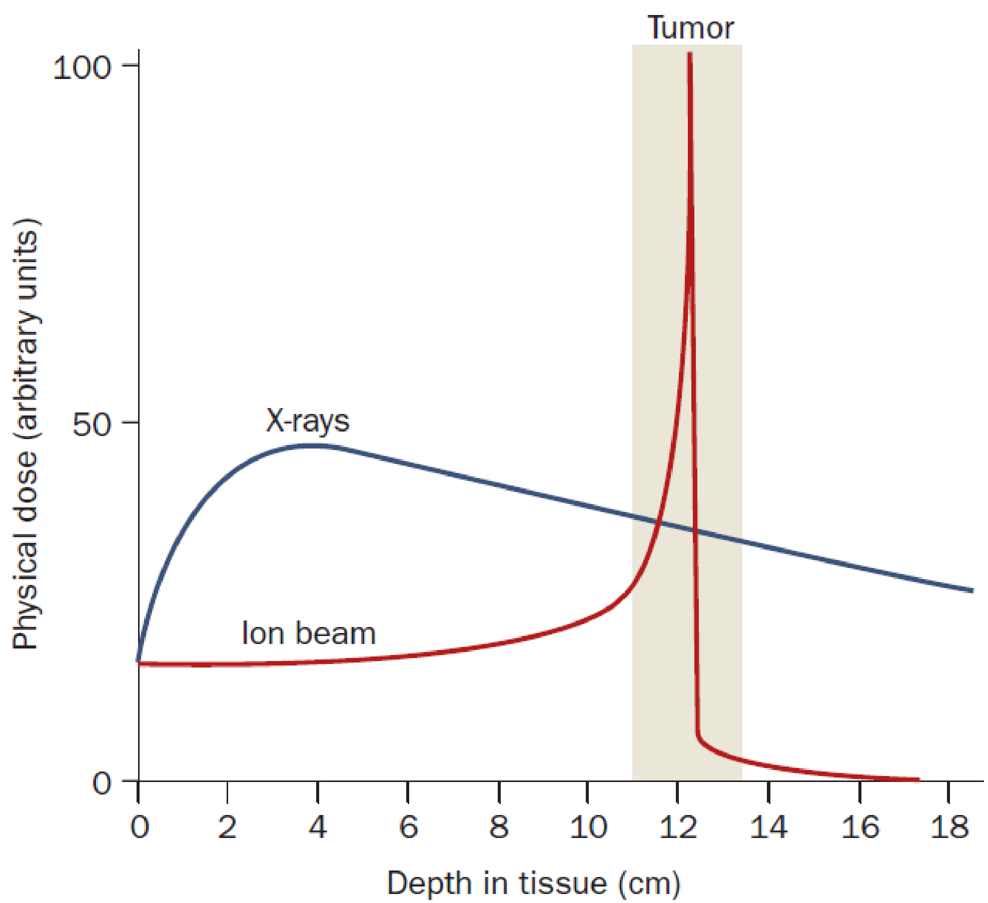
Protons and ^{12}C beams are presently used to treat many different solid cancers.

Photon RT: small, reliable and not so expensive, 40 years R&D

Particle therapy:

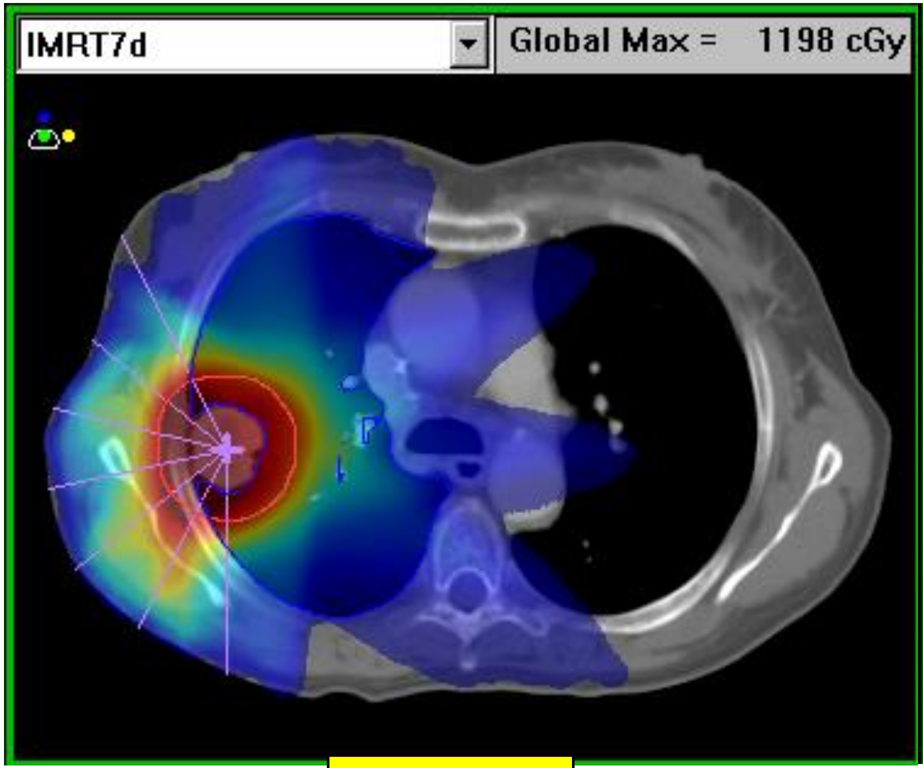
- Peak of dose released at the end of the track, sparing the healty tissues
- Accurate conformal dose to tumor with Spread Out Bragg Peak
- Greater RBE (radioresistant tumors)



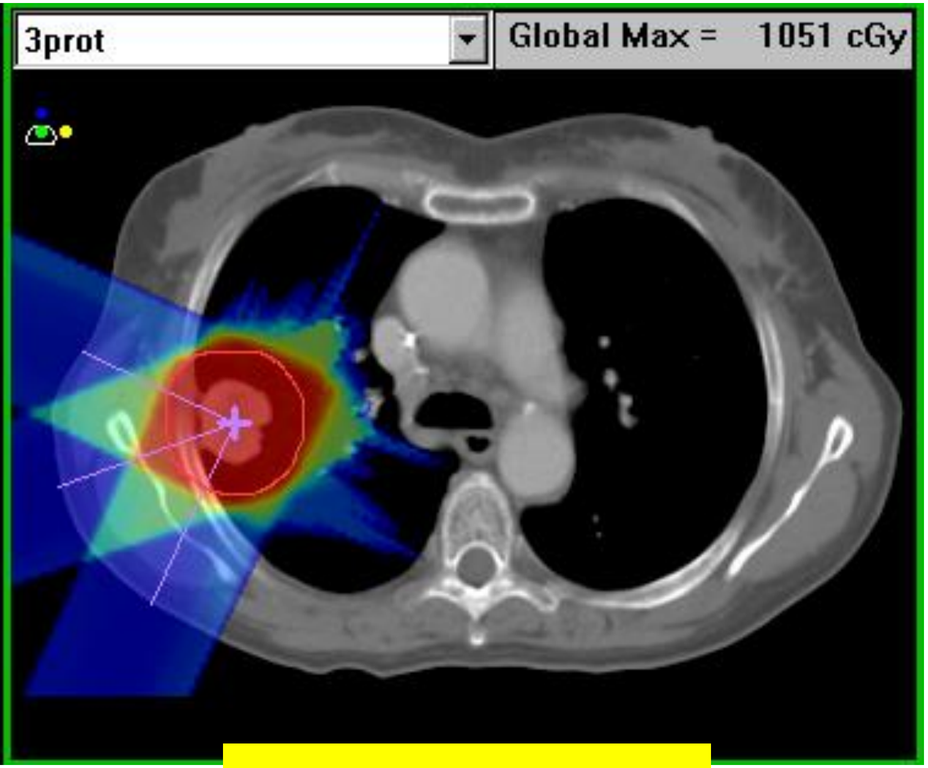


Examples of Photons vs Particle therapy

Particle therapy can show better selectivity with respect to photon techniques



IMRT

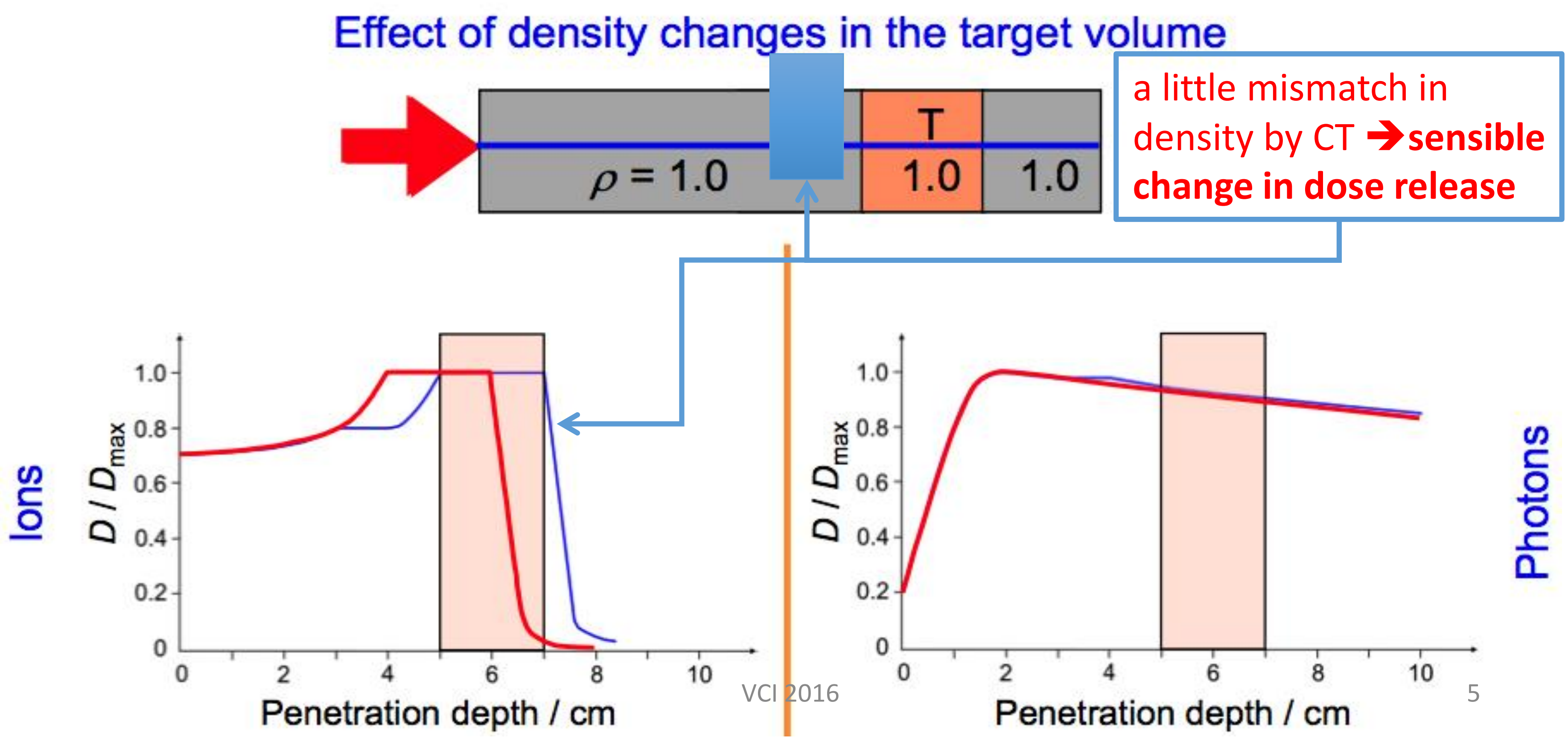


Particle therapy

Quality Assurance & Range monitoring in PT

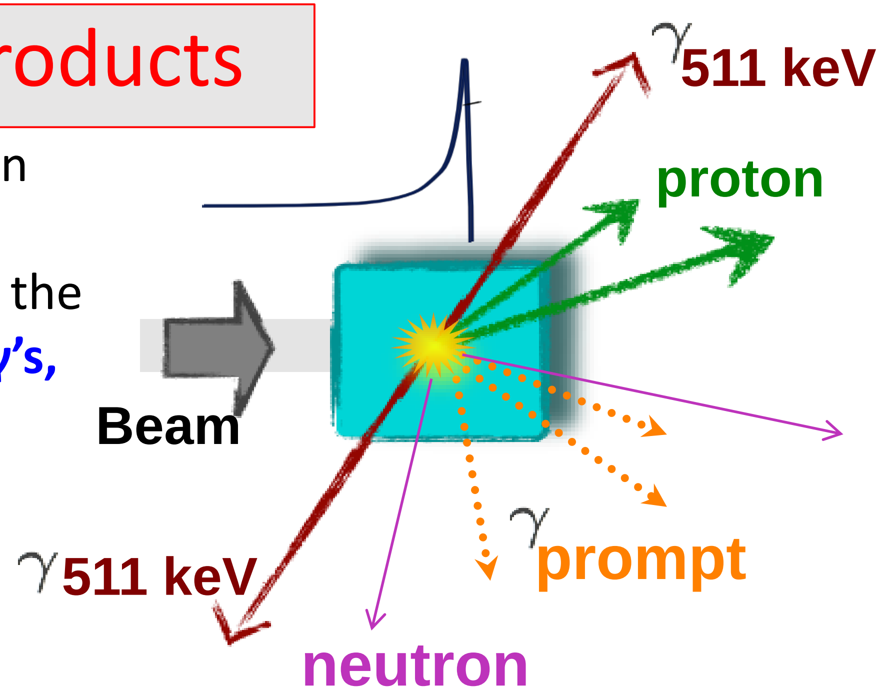
The peculiarity height dose release at the end of the range in PT with respect to photon RT, make crucial the dose monitoring in PT.

Inhomogeneities, metallic implants, CT artifact, HU conversion, inter session anatomical/physiological changes -> **range variations**



Beam range & secondary products

The p,^{12}C beam is dumped inside the patient. In order to monitor the beam the secondary particles generated by the beam interaction in the patient can be used: **prompt γ's, annihilation γ's, neutrons and charged particles**



Activity of β^+ emitters

- Baseline approach
- Isotopes of short lifetime ^{11}C (20 min), ^{15}O (2 min), ^{10}C (20 s) with respect to diagnostic PET (hours)
- Low activity → long acquisition time (~minutes) with difficult in-beam feedback
- Metabolic wash-out of β^+ emitters

Prompt nuclear de-excitation γ's

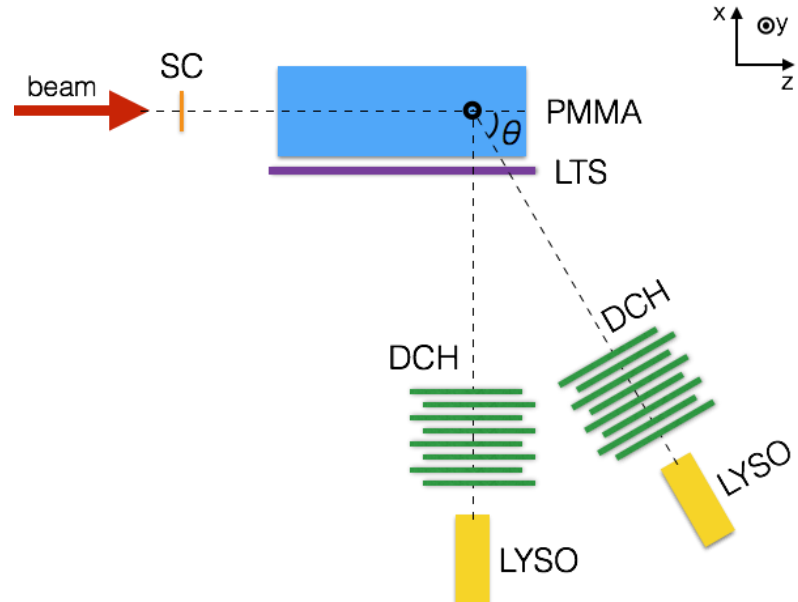
- ~1-10 MeV
- emission profile correlated with dose profile
- Specific detector at present under development: collimated slit cameras or Compton cameras

Charged secondary particles (ion therapy):

- The detection efficiency is almost one
- Can be easily back-tracked to the emission point -> can be correlated to the beam profile & BP
- They are forward peaked
- Enough energy to escape from patient
- MS inside the patient -> worsen the back-pointing resolution

Experimental campaign

Charged fragments production is an **high cross section process** in the interactions of He, C and O beams and is hence particularly suited for **monitoring** applications of those beams.



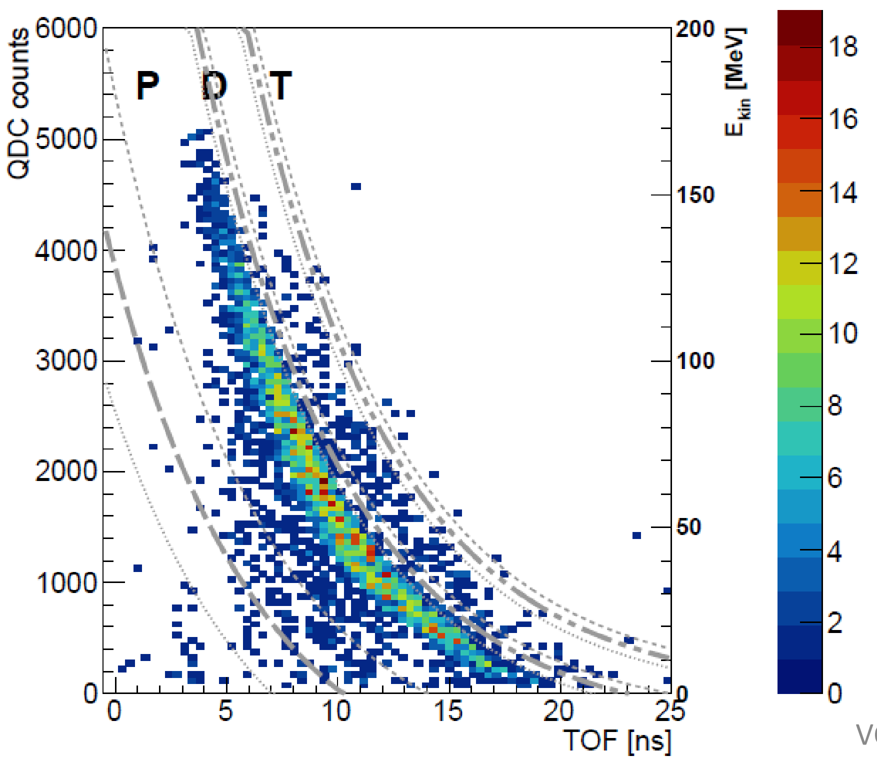
The experimental campaigns:
Since 2011 the ARPG collaboration started a systematic characterization of the beam interaction with PMMA phantoms:

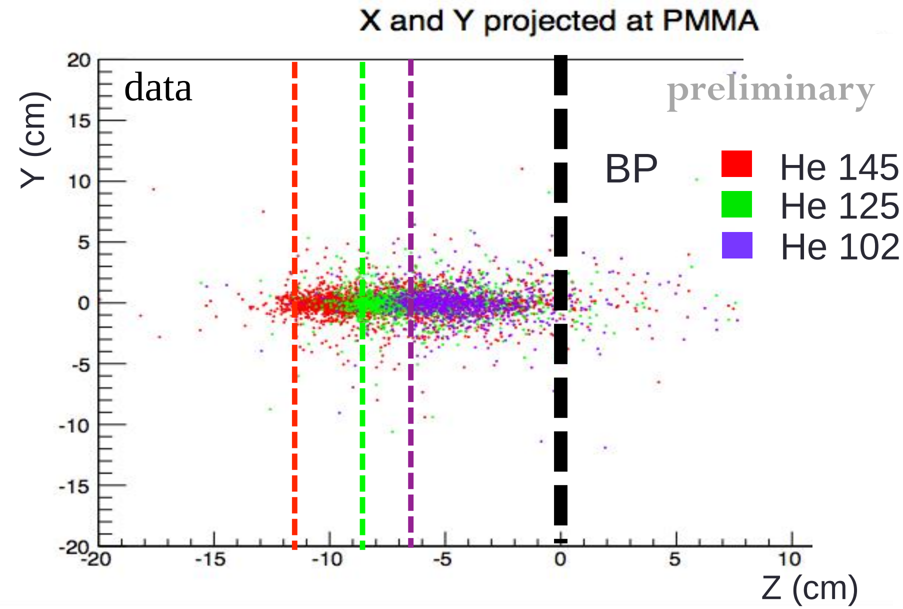
- @LNS 80 MeV/u ^{12}C
- @GSI 220 MeV/u ^{12}C
- @HIT several energies: ^{4}He, ^{12}C, ^{16}O

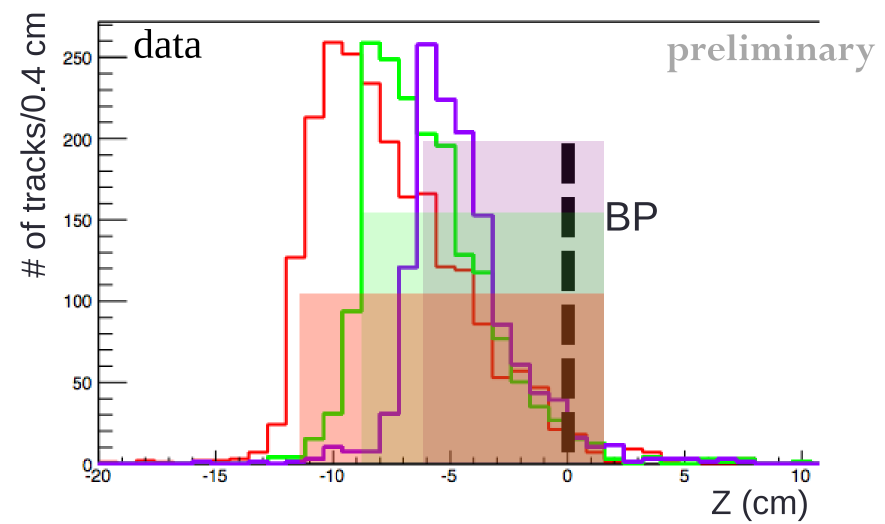
θ	Ion	Energy (MeV/u)	B_{FWHM} (mm)	Range (cm)	t_{PMMA} (cm)
90°	^{12}C	120	7.9	2.9	10.00
		160	6.2	4.9	
		180	5.5	6.0	
		220	4.7	8.5	
60°	^{4}He	102	9.3	6.0	7.65
90°/60°		125	7.8	8.5	10.00
		145	6.9	11.0	12.65
90°/60°	^{16}O	210	4.6	6.0	7.65
		260	3.9	8.5	10.00
		300	3.6	11.0	12.65

BP monitoring

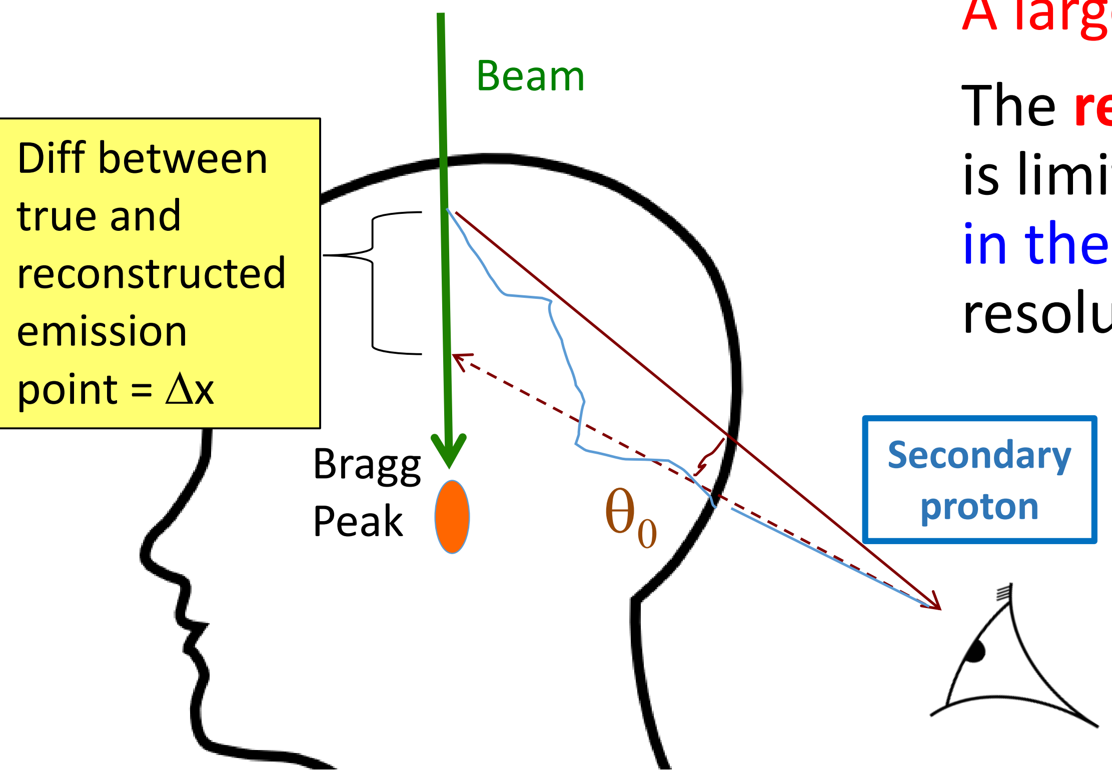
- A non negligible production of charged particles at large angles is observed for all beam types
- The emission shape is correlated to the beam entrance window and BP position







Which detector should be used?



A large area detector.

The **resolution** of the back-tracking is limited by the multiple scattering in the patient, not by the detector resolution.

Typical resolution on Δx is of the order of 6-8 mm

Integrating enough statistic (~ 10^3 events) helps to lower the accuracy on the emission point distribution (and then on the beam profile) to mm level ➔ detector size

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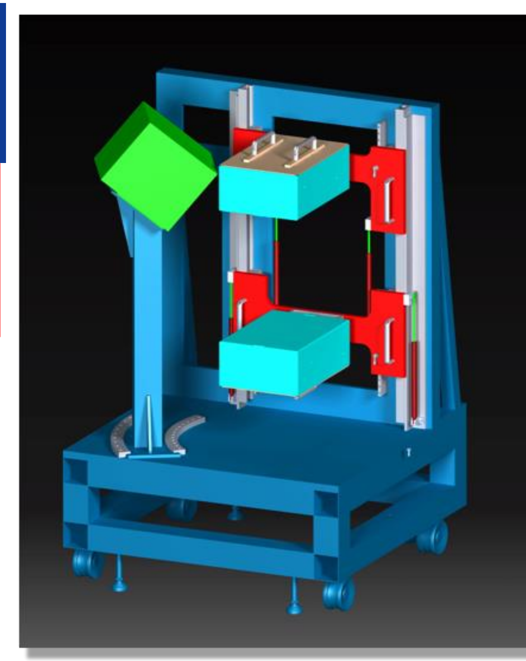
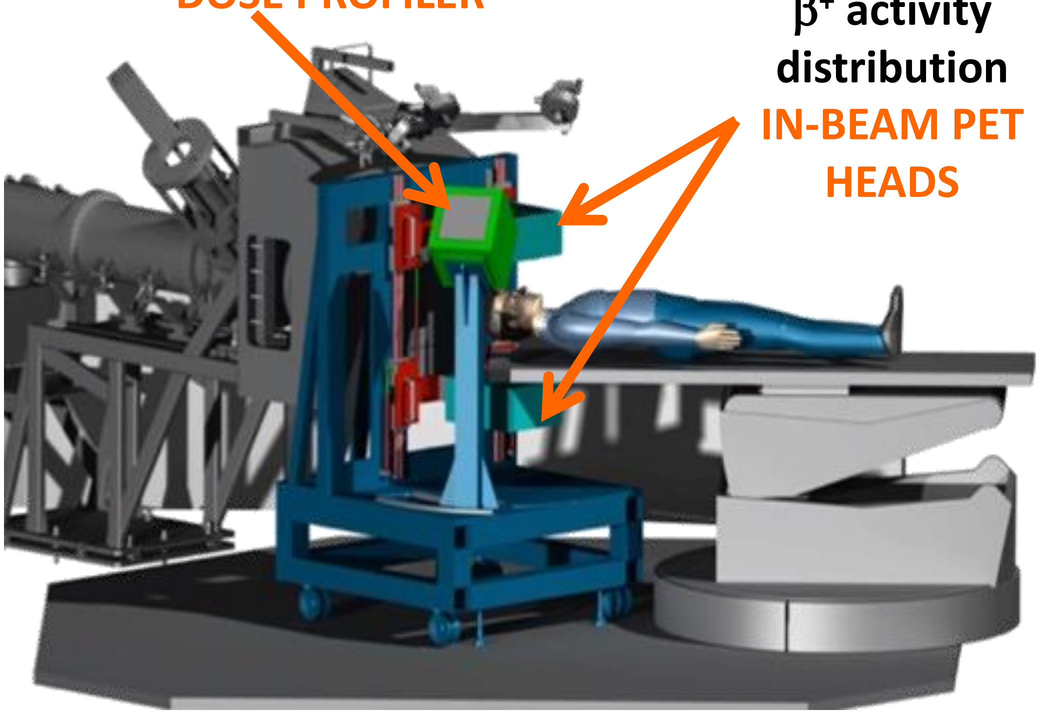
The InSide Project @ CNAO

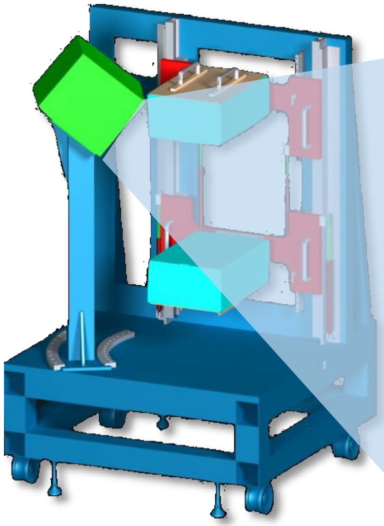
INnovative **S**olutions for **I**n-beam **D**osim**E**try in Hadrontherapy

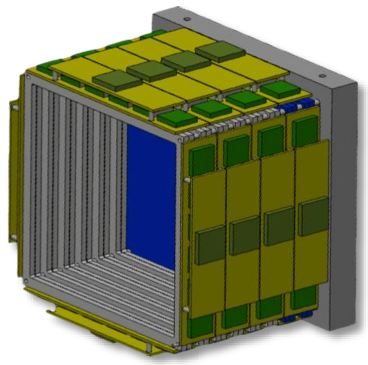




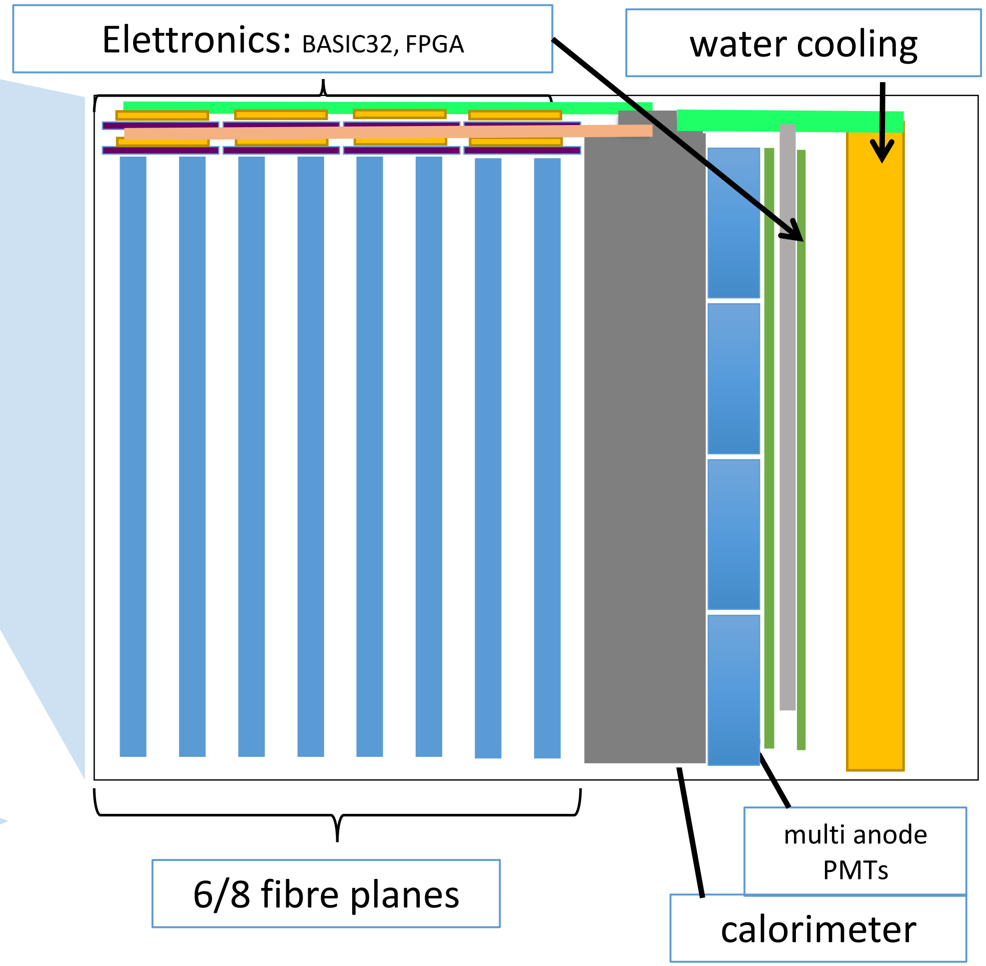
- ✓ **Integrated in treatment room** of Centro Nazionale di Adroterapia Oncologica (CNAO)
- ✓ Operate **in-beam**
- ✓ Give an **IMMEDIATE feedback** on the particle **range**
- ✓ Effective both on **p**roton and **^{12}C** beam

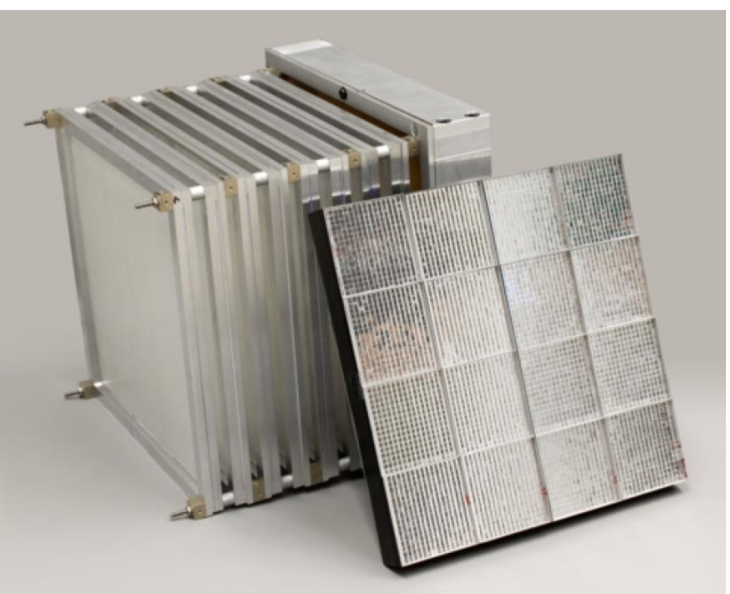
Dose Profiler (DP)





28 x 28 x 35 cm^3

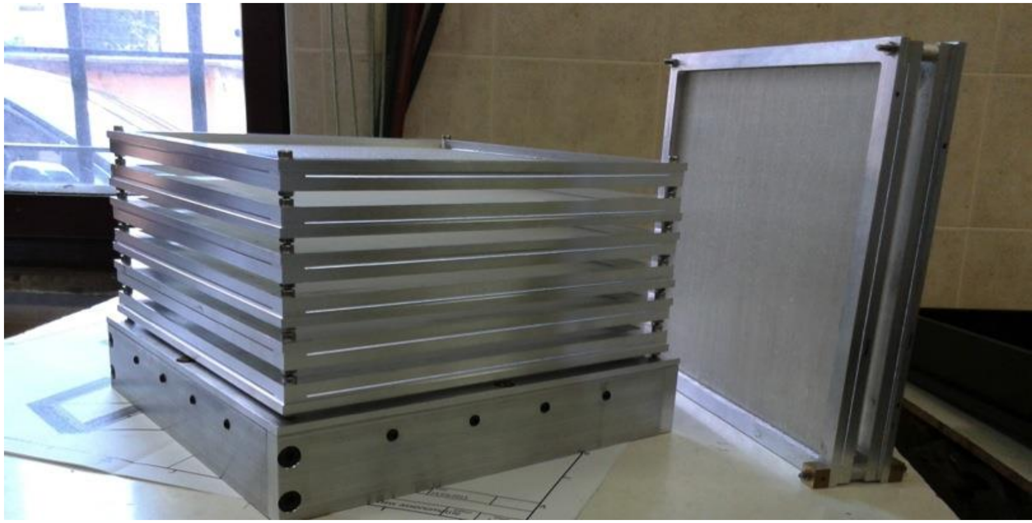


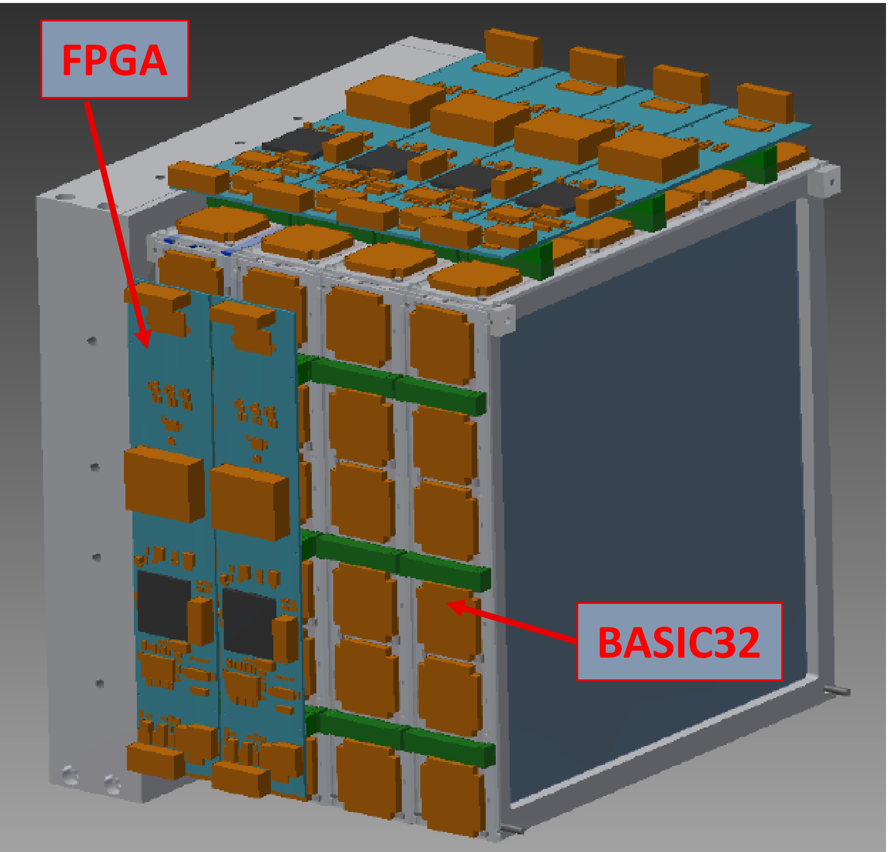


- 6/8 planes of orthogonal squared **scintillating fibers** coupled to SiPMs
- a **calorimeter** coupled to Position Sensitive PMTs.

Tracker

6/8 XY tracking planes: 384 scintillating fibers (0,5 mm) per side, with the minimal plane separation (2 cm) allowed by fibers front-end electronics readout in order to increase the geometrical acceptance and the compactness of the detector.





Readout:

- Hamamatsu 1mm SiPM.
  Each SiPM coupled with two adjacent fibers.
- In total the 19.2 x 19.2 cm^2 sensitive area is read by 192 channels per layer.
- 32 SiPMs feed a 32 channels custom ASIC (BASIC32_ADC; F.Corsi, C.Marzocca et al. Politecnico and INFN Bari).
- Plane controller: 1 FPGA every 6 BASICS32

Tracker

The **system** is designed to sustain a **rate of 20 kHz**.

- rate of single p.e. is 100kHz per SiPM
- BASIC integration time of 100 ns
- threshold of 3 p.e.

→ **noise rate of 10 Hz**

The **overall noise** will be **reduced at trigger level to a negligible rate** by using the coincidence of 3 planes.

The **spatial single hit resolution is ~ 300 µm** (double fiber readout).

Calorimeter

The role of the high density compact crystal scintillator placed behind the tracker is to **measure the protons energy** helping in track reconstruction (trigger and event selection).

- 64 x 64 matrix of pixelated **LFS** (**L**utetium **F**ine **S**ilicate) **crystals** arranged in 4 x 4 blocks (16 x 16 matrices 5 cm x 5 cm x 2 cm from Hamamatsu).

- The crystal **readout** will be performed by means of Multi Anode Photo-Multiplier (MAPMT H8500 from Hamamatsu).

- On the back, the MAPMT (MultiAnode PhotoMultiplier Tubes), the **acquisition board** (based on BASIC32_ADC) and the **data concentrator.**

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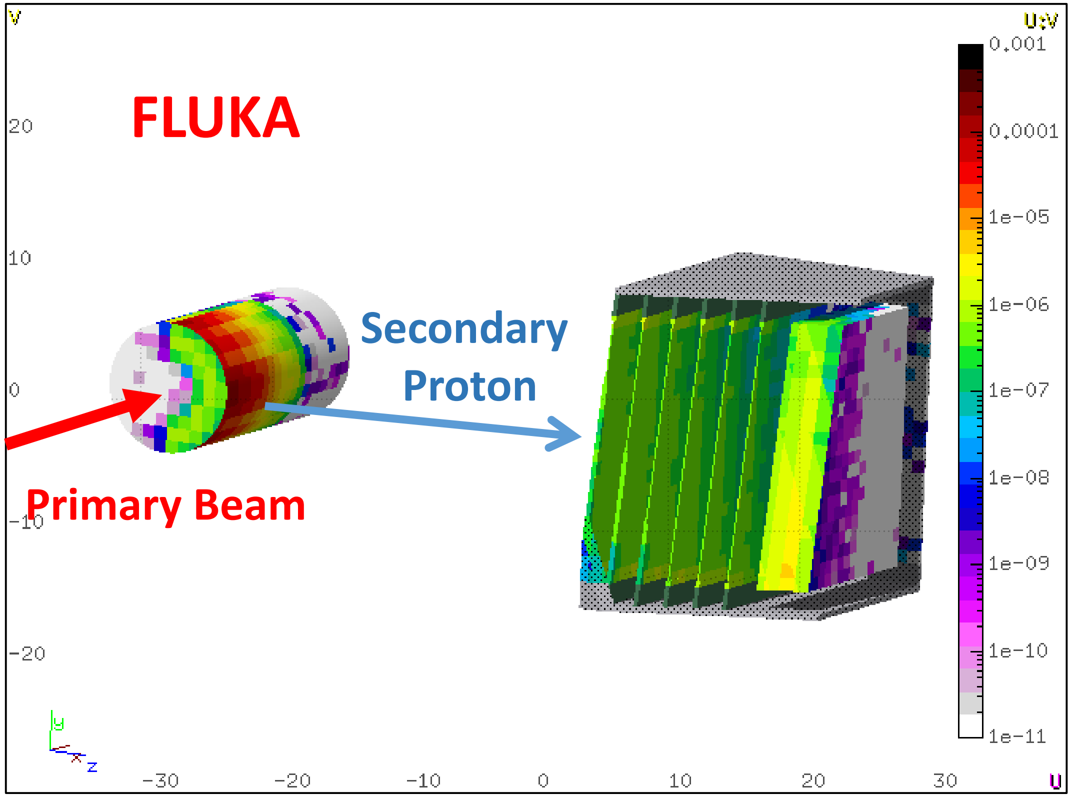
Simulation

The Monte Carlo software used for simulations is **FLUKA** (release 2011.2)

The real data from the GSI data taking has been used to parametrize a **MC generator.**

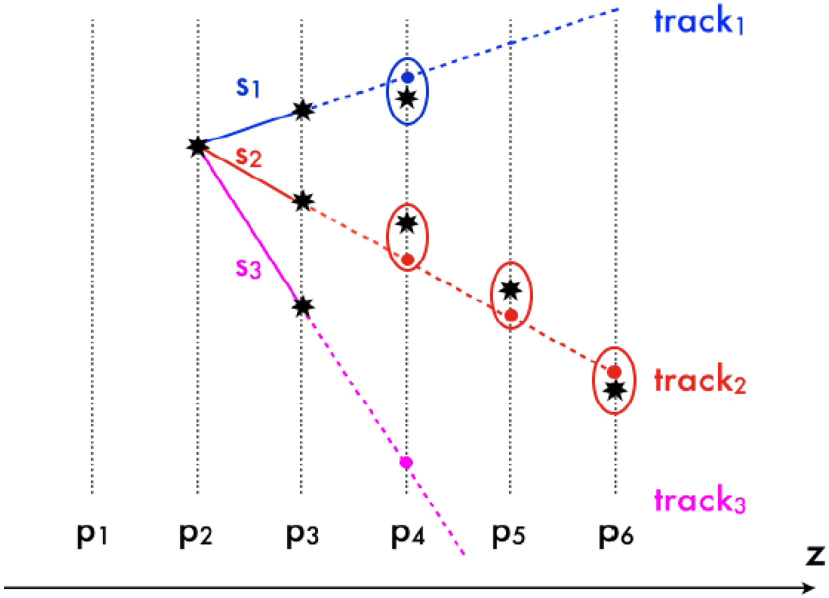
L. Piersanti et al. Phys. Med. Biol. 59 (2014) 1857

The **average kinetic energy** of the protons of interest is about **75 MeV**.



Event reconstruction and analysis

Charged secondary particles are reconstructed with a ***track finding algorithm*** that starts from deposits in the fibers grouped together to form 3D clusters.



2D clusters:
fiber hits in the xz and yz views are clustered separately by grouping consecutive hit fibers.
3D clusters: formed with all the possible combinations of x and y clusters in a plane.

Track finder algorithm: starts from the list of 3D clusters.
Initial guess: a simple linear fit and Kalman filter is applied to take into account the multiple scattering in the detector material.

A **backtracking** **extrapolation towards the patient** is performed to reconstruct the point of closest approach (x,y,z coordinates) of the proton to the primary beam axis.

Performances

Protons detected at 90°

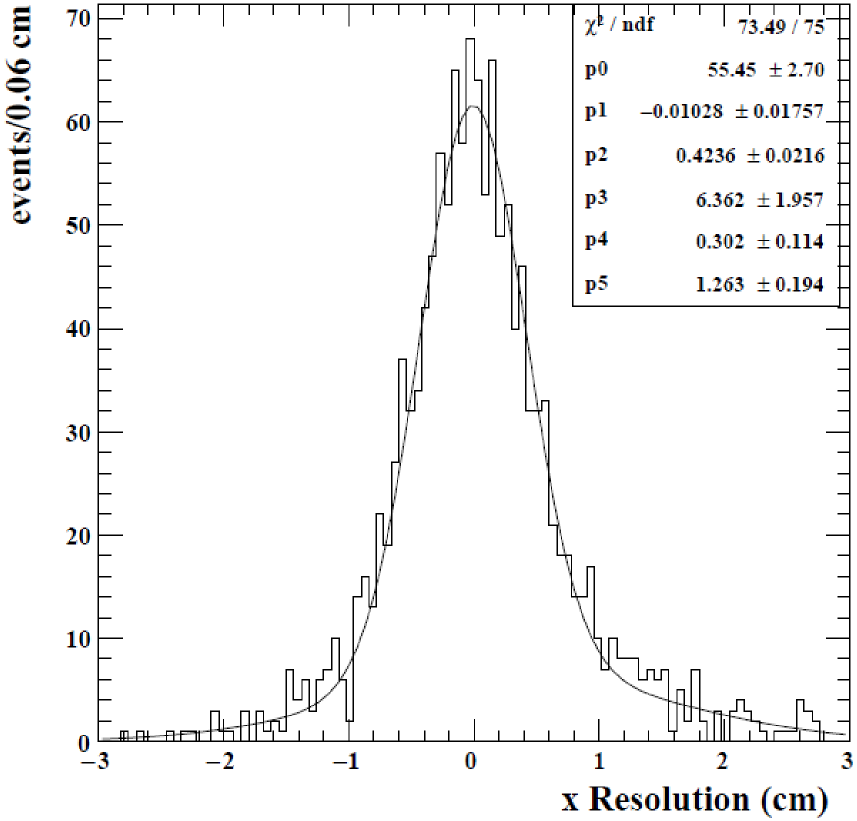
Average resolution on the proton emission point along the primary beam direction

$\sigma \cong 0.4$ cm

For **angles different from 90°** the spatial resolution on the emission shape worsen , due to the transverse spread of the primary beam.

The **resolution** for protons detected **at 60° with respect to the beam axis is worsen by a factor** $\frac{1}{\sin(60^o)}$.

Resolution **along the beam direction** for protons detected at **90°**



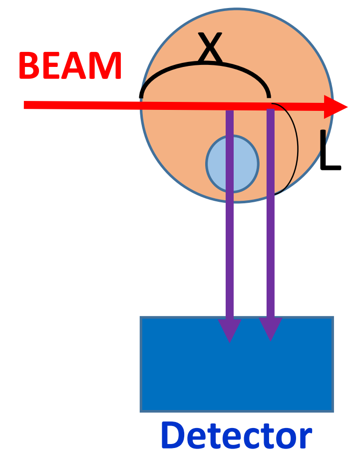
Proton track angular resolution in agreement with the expected Multiple Scattering of the proton in the patient and in the tracker.

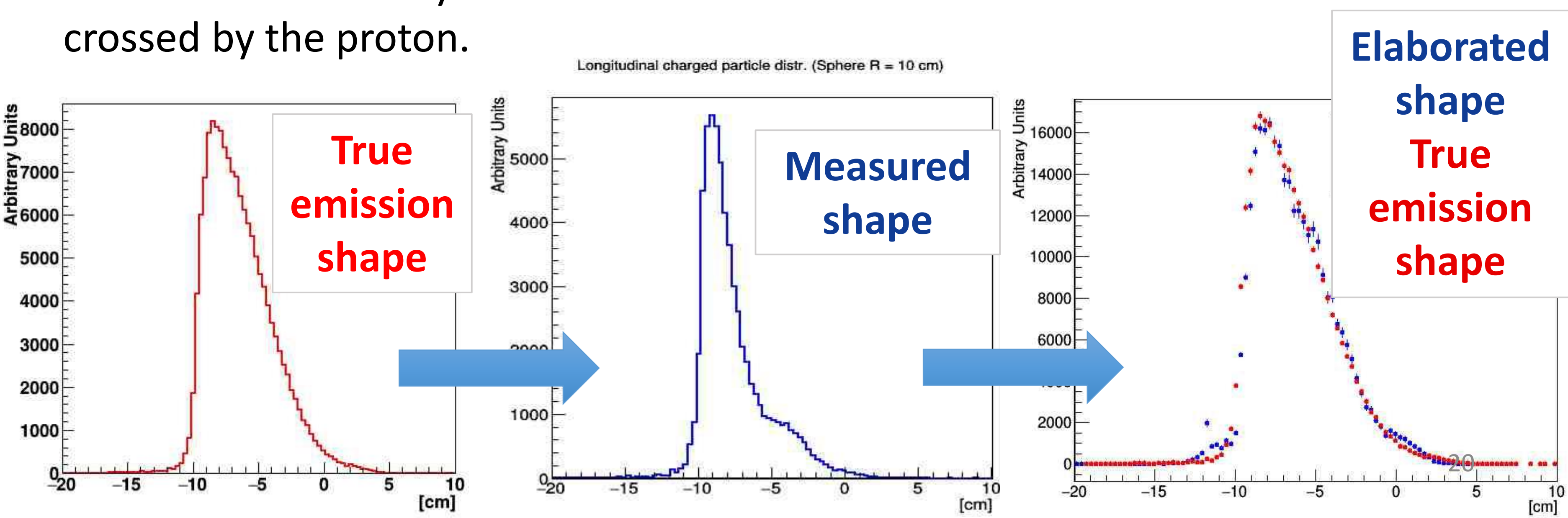
Proton emission shape attenuation inside the patient

By means of the **attenuation study** of the proton emission shape for different material thickness, we get a method to correlate the shape detected by the profiler coming out from the patient with the **B**ragg **P**eak position.

We apply to each reconstructed track a weight which takes into account the thickness and density of the material crossed by the proton.

Example: inhomgeneous PMMA sphere containing a smaller sphere of lighter material





Conclusions

We designed a **new device**
capable of dose pattern online measurements that is tailored for particle therapy applications.
It detects and reconstructs charged particles, mainly protons, coming out from the patient.

The software tools needed for the **full simulation** and the **event reconstruction** have been developed.

The detector expected **resolution,**
estimated by means of a detailed MC simulation,
meets the requirements set for online dose range monitoring applications for particle therapy.

Conclusions

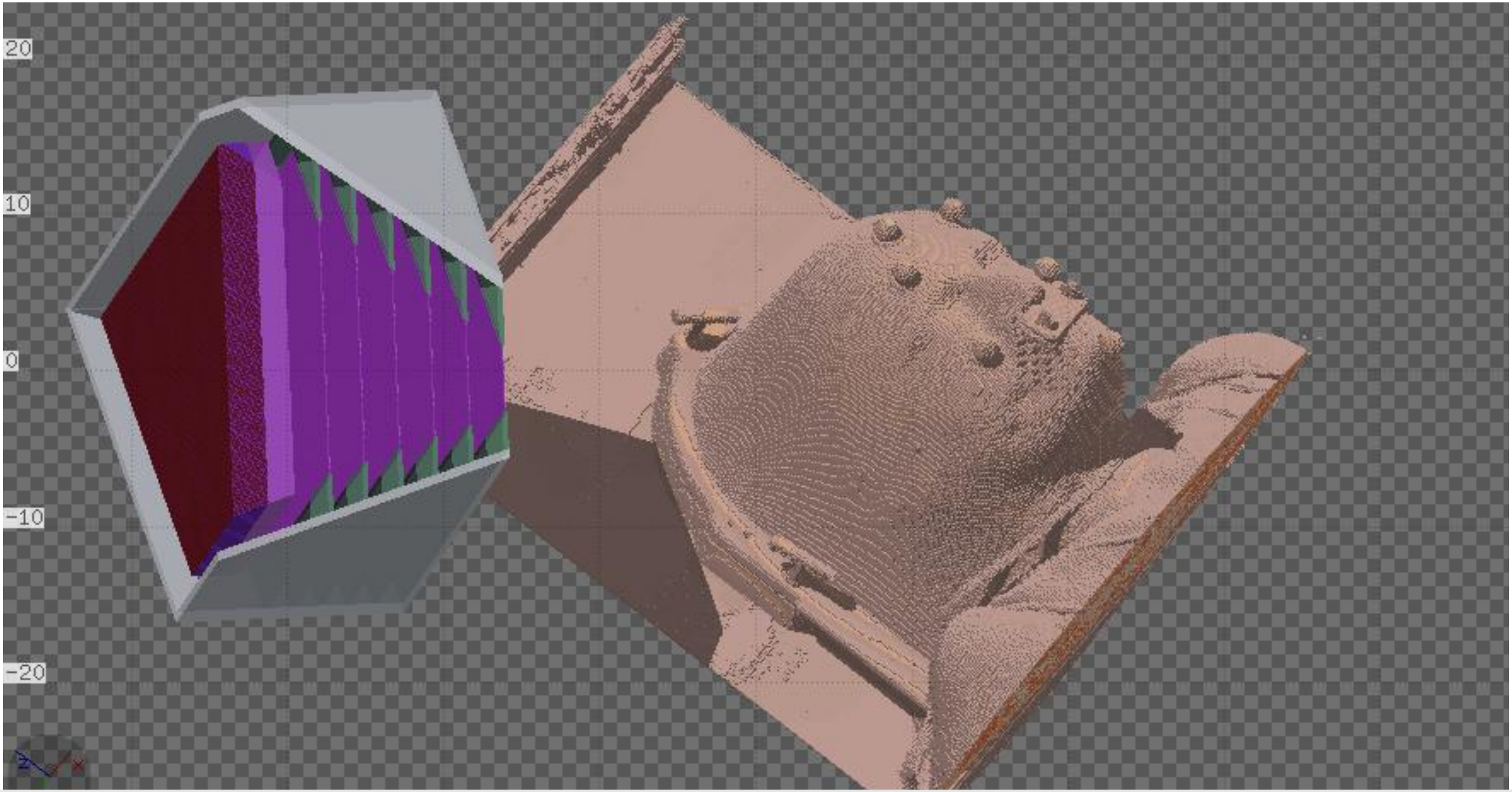
We develop a **method** to correlate the charged particles emission shape with the measured one, taking into account the **matter absorption effect** and **complex geometries**.

This detector, particularly suited for carbon ion beams, is under construction.
At present readout electronics is under test.

A prototipe will be installed at CNAO within 2016.

The collaboration:

G. Battistoni, F. Collamati, E. De Lucia, R. Faccini, M. Marafini, I. Mattei, S. Muraro, R. Paramatti, V. Patera, D. Pinci, A. Rucinski, A. Russomando, A. Sarti, A. Sciubba, E. Solfaroli Camillocci, M. Toppi, G. Traini, C. Voena



Thank you for the attention