Status of Simulation R&D in Strasbourg

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Work in collaboration with the LPC Caen

pCT meeting, Nice, April 25th 2013

- pCT scanner specifications
- Analysis of a pCT scan outputs

- pCT scanner specifications
  - Tracking system?
  - Calorimeter ?
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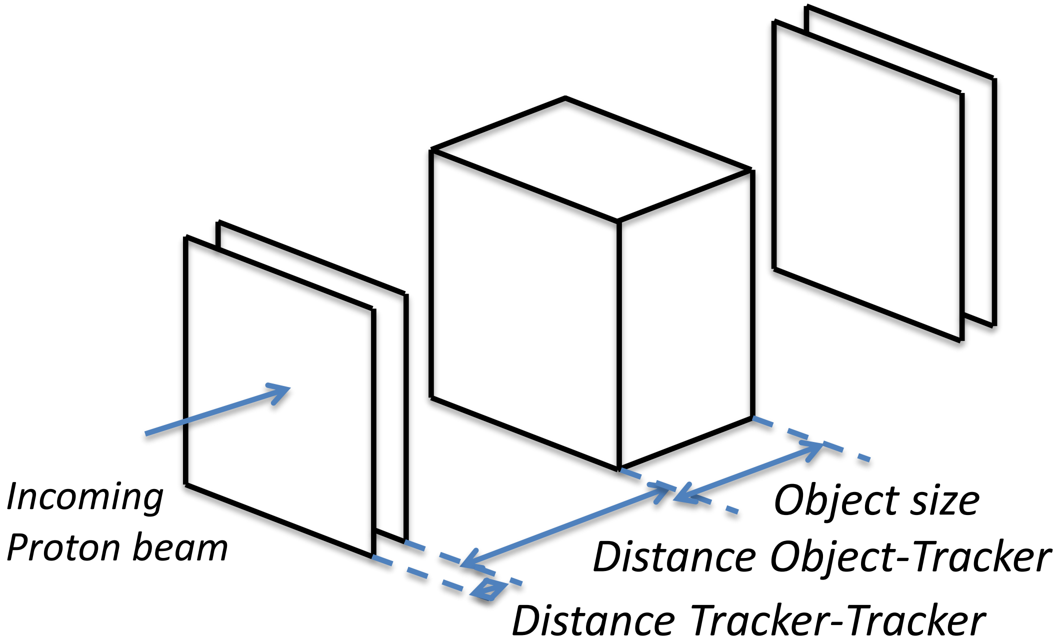
Tracking system requirements

Tracking system
=
four tracker planes

Positions and directions of protons before and after the object

Estimation of the Most Likely Path of each particle



Need for optimization of different parameters:

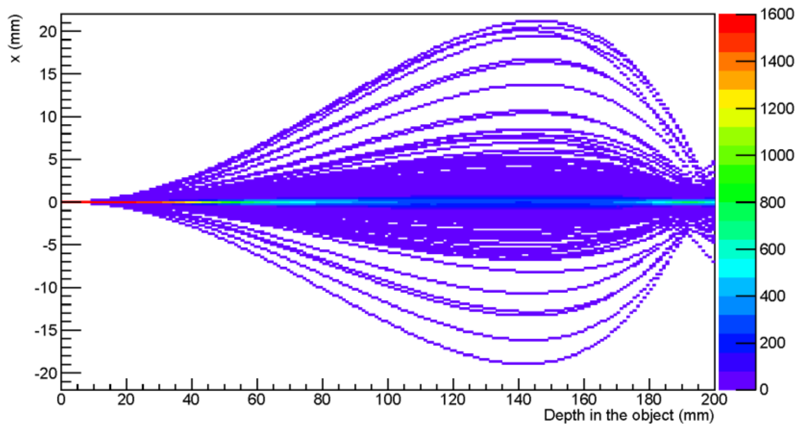
- Spatial resolution of the tracking planes
- Distance between the tracking planes
- Distance to the object

Impact of the parameters on the MLP: Monte Carlo Simulation

Object: 200 mm deep cube of water
The input vector for the proton beam along the z-axis (0,0,1)

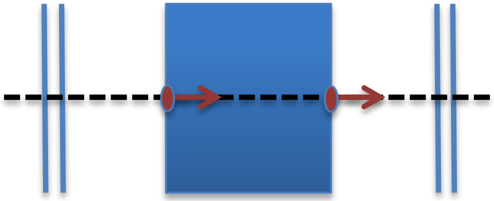
The output vector is given by a Geant4 Monte Carlo simulation
2000 protons sent, 1602 recorded

- The entrance and exit points of the object are given by Monte Carlo simulations (Geant4)
- For each proton, two MLP are computed, one "exact" and one "noisy", affected by the system



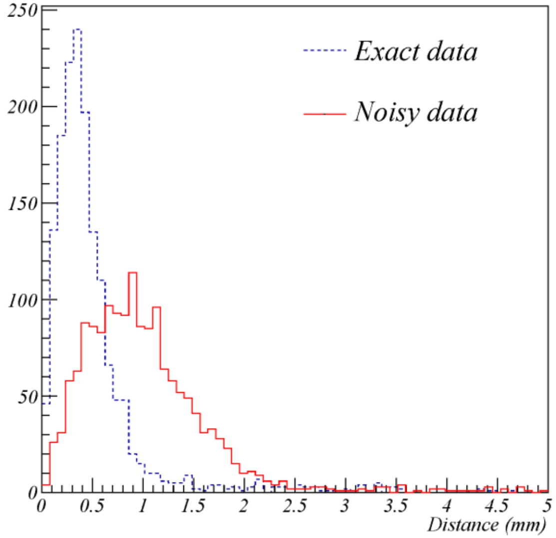
1602 MLP calculated using the exact information

Impact of the parameters on the MLP



For each incident proton, 4 interaction points are considered: one for each tracker

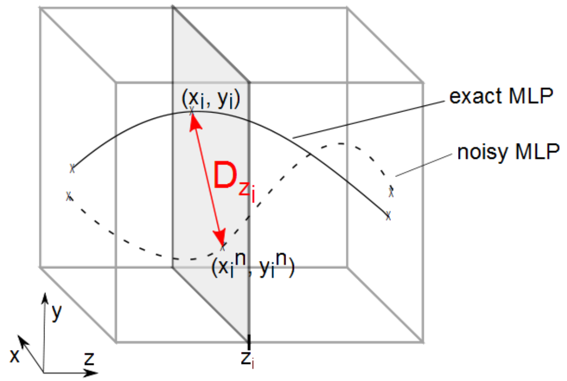
- The entrance and exit points are projected on the trackers using the directions (MC simulation data)
- The obtained positions on the trackers are blurred
- Directions are re-calculated and positions are then projected on the object
- The “noisy” MLP is then computed using the blurred information



Distance tracker-tracker	= 10 mm
Distance tracker-object	= 100 mm
Resolution	= 0.1 mm

Distance distribution on the exit face of the cube for the exact and noisy data

Impact of the parameters on the MLP

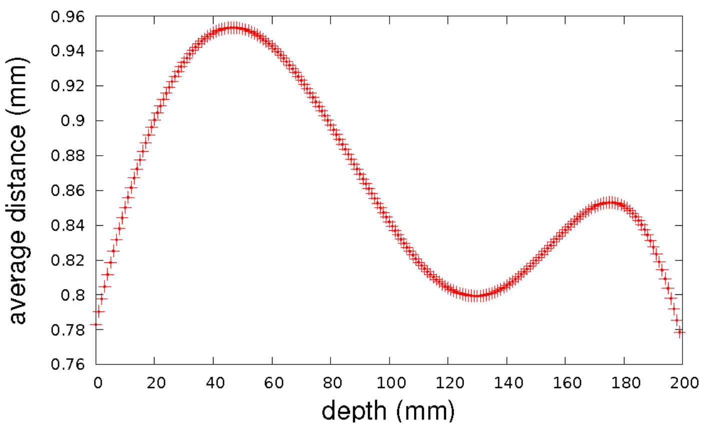


For a given depth, the distance between the two paths is calculated as

$$D_{zi} = \sqrt{\left(x_i^n - x_i\right)^2 + \left(y_i^n - y_i\right)^2}$$

Average distance between the exact and noisy MLP as a function of the depth

Distance tracker-tracker	= 10 mm
Distance tracker-object	= 100 mm
Resolution	= 0.1 mm



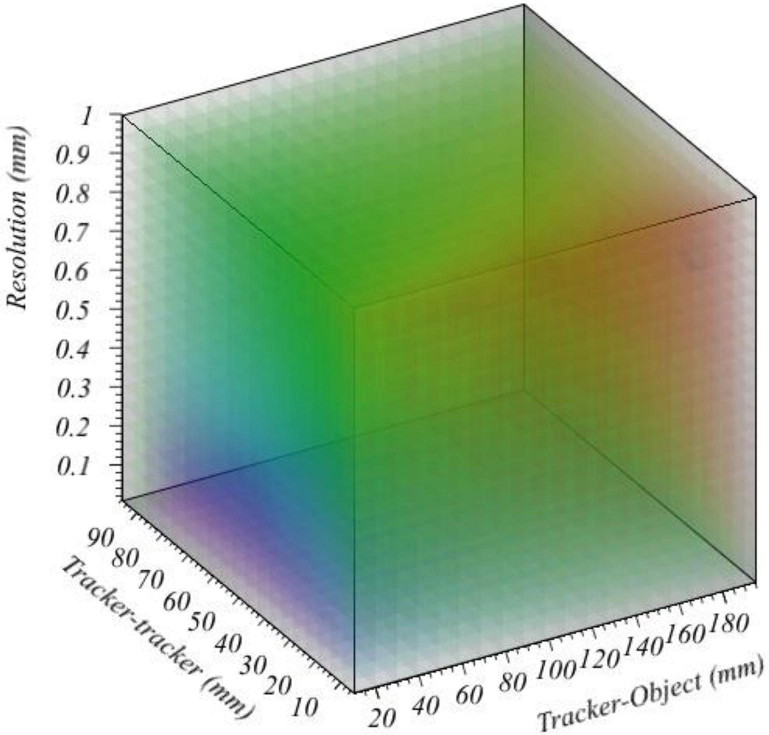
Impact of the parameters on the MLP: systematic study

Distance tracker-tracker	1 mm to 100 mm
Distance tracker-object	10 mm to 200 mm
Resolution	0.01 mm to 1.0 mm

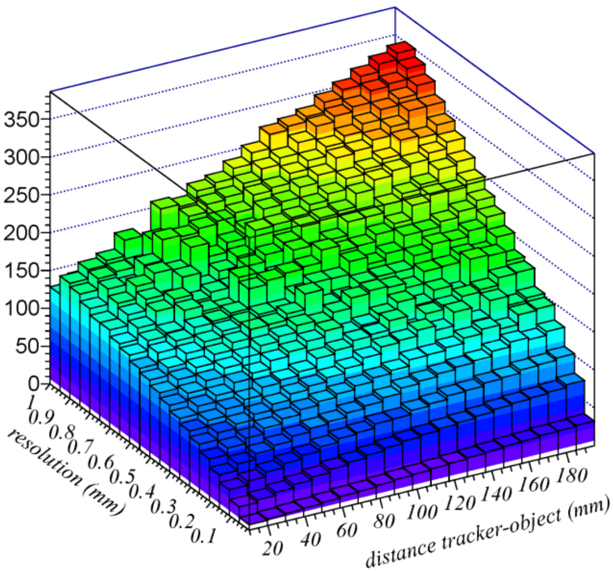
Average value of the distance for each realization:

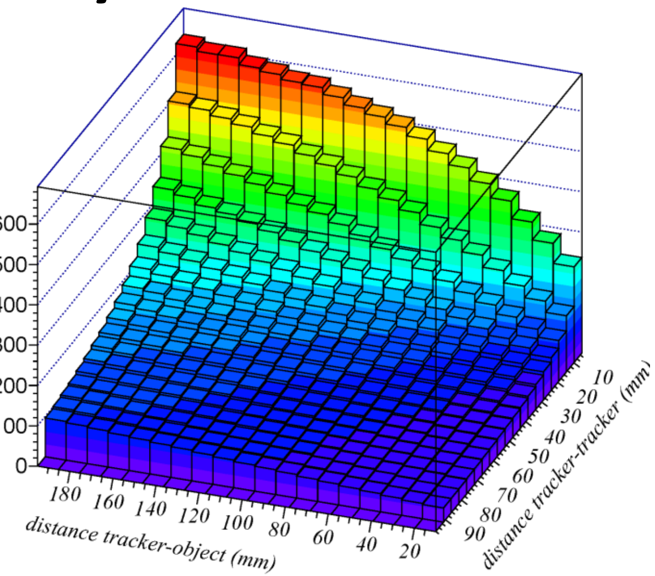
$$Err = \frac{1}{N}\sum_{i=1}^{i=N} D_{zi}$$

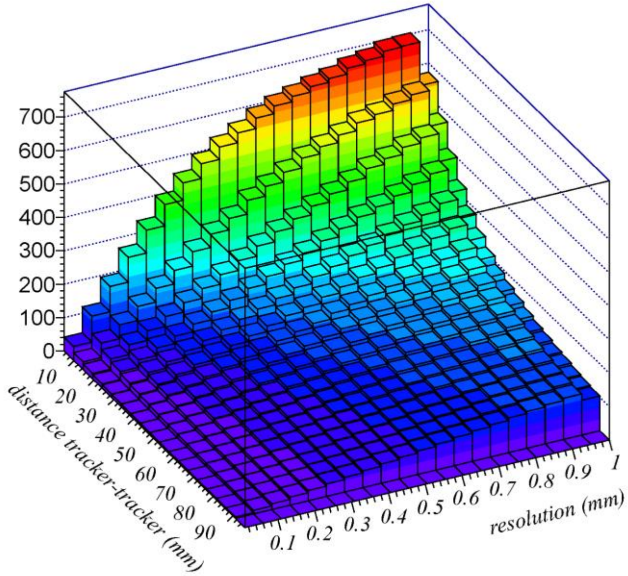
Average on all protons



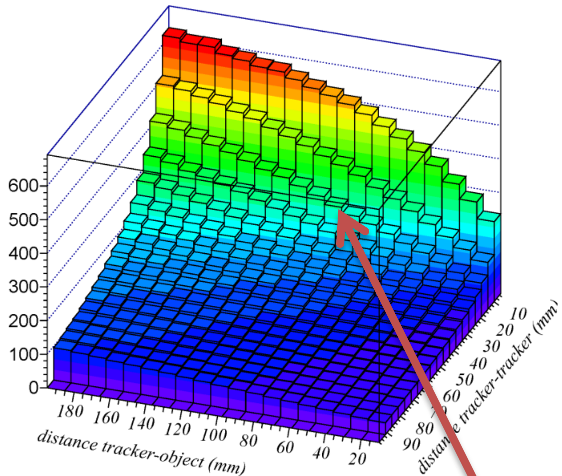
Impact of the parameters on the MLP: systematic study



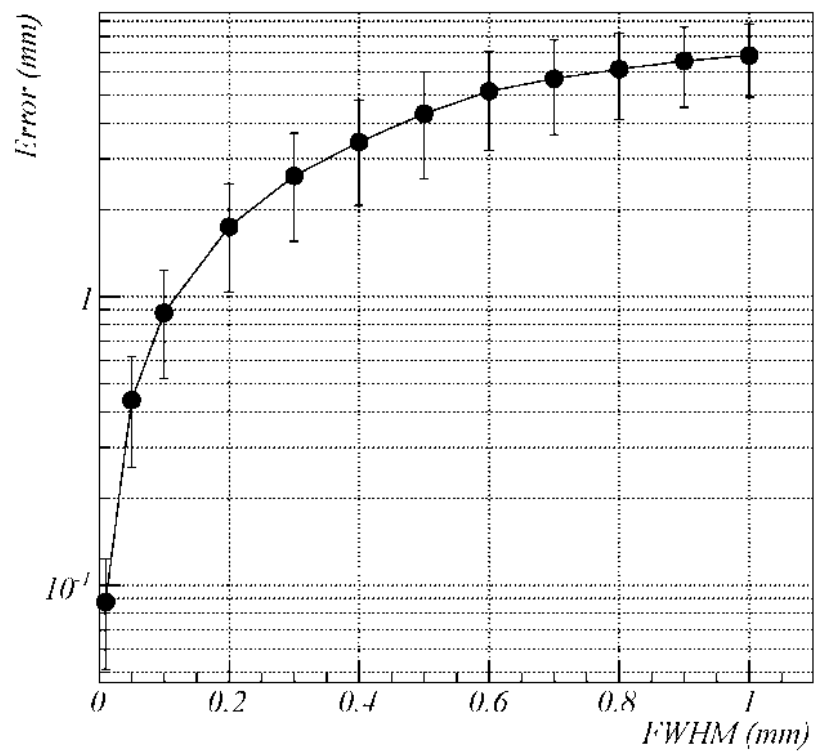




Impact of the parameters on the MLP: Resolution



Distance tracker-tracker = 10 mm
Distance tracker-object = 100 mm



This work was submitted for publication to Medical Physics

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  - Tracking system?
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- Analysis of a pCT scan outputs

Motivations for this work

Proton CT nowadays :
Improving hadron therapy treatment plans by **mapping the Relative Stopping Power (RSP)** of the materials in order to predict the position of the Bragg peak

➡ Energy of protons

➡ Spatial and angular deviation

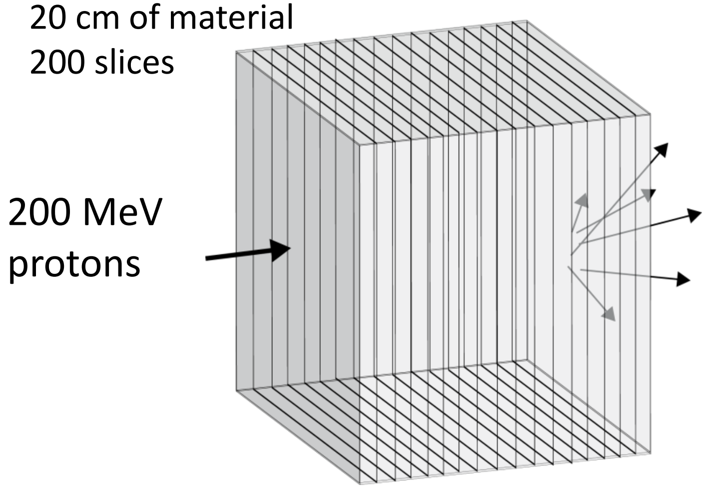
➡ Transmission rate

Question : Could pCT bring other information on the materials, that could be used in diagnostic ?

- How much information can we get from the transmission rate and the deviation ?
- Could it be used to identify materials, determine their chemical composition ?

Concept

Geant4 simulations



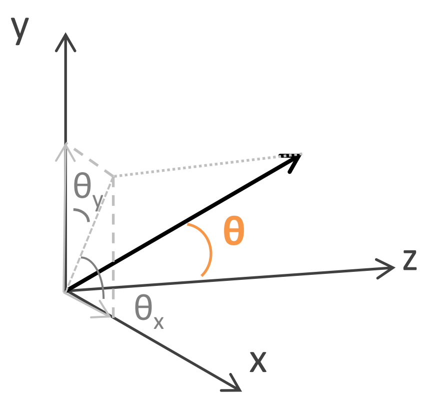
List of materials:

- Water
- Adipose tissue
- Skeletal muscle
- Grey matter
- White matter
- Brain
- Brain (less Oxygen)
- Carcinoma
- Carcinoma -10% O
- Carcinoma -20% O
- Carcinoma -30% O

Same CT number (Skeletal muscle, Grey matter)

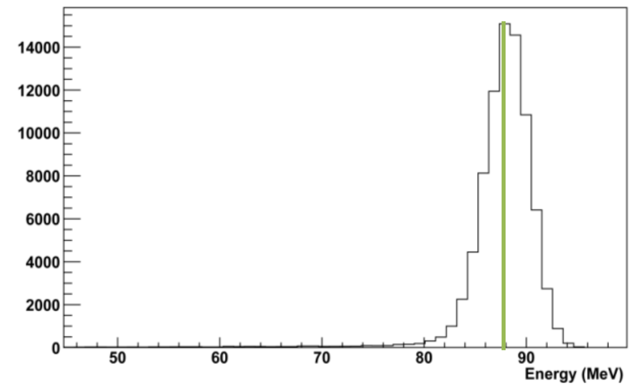
Same electron density (Brain, Brain (less Oxygen))

Same electron density (Carcinoma, Carcinoma -10% O, Carcinoma -20% O, Carcinoma -30% O)

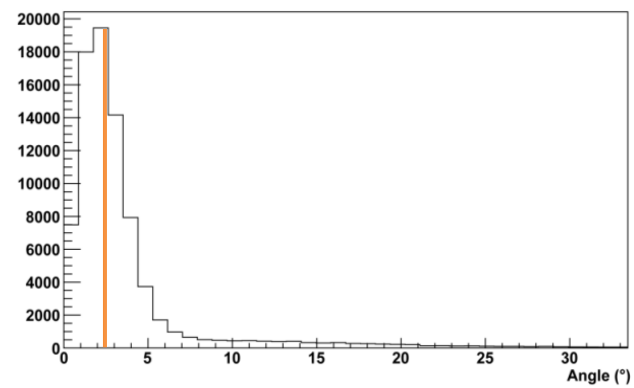


Definition of the observables

Average of energy distribution



Average of 2D angular distribution



Transmission rate

Study of the outputs

- ✓ Different materials give different outputs for the defined observables
- ✓ The three observables bring three different information about the materials
- ➢ Need for a 3D study ?

Energy loss

Deviation

Resolution : $\frac{2.35\,\sigma_{distribution}}{\mu_{distribution}}$		
After 200 mm of Water	**100 protons**	**25000 protons**
Energy	0.94 %	0.059 %
Transmission rate	10.58 %	0.67 %
Deviation	50.76 %	3.21 %

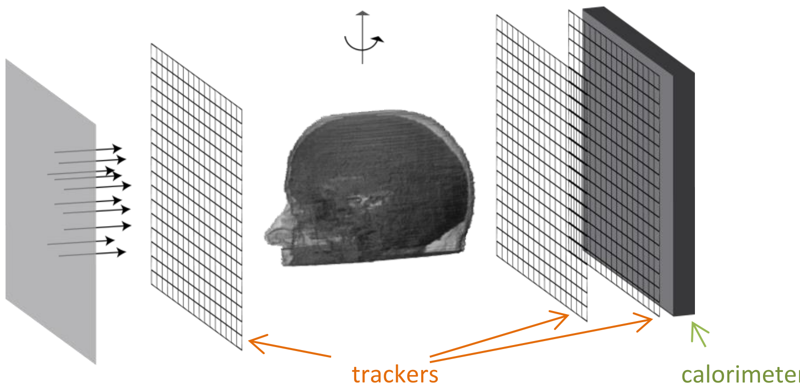
Much higher uncertainty on transmission and deviation than on the energy

Can those observations be transferred to 3D ?

NEED FOR A TOMOGRAPHIC AQUISITION

Reconstruction strategy ?

Simulation of a pCT Acquisition



Simulation parameters :

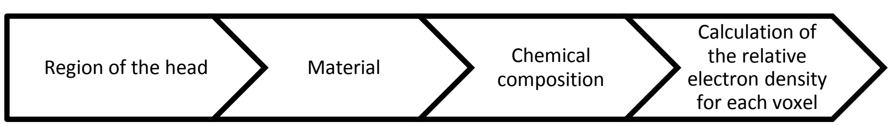
- 200 MeV protons
- 100 protons/mm^2
- 256 projections over 2 Pi
- Parallel
- Perfect trackers and calorimeter

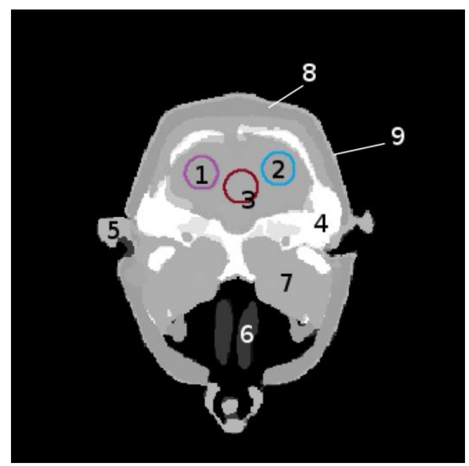
Delivered dose ~ 2.5 mGy

Stored in list-mode data format

Voxelized head phantom :

- 20 different materials
- Tumors inserted with same electron density but different compositions
- 256x256x128 voxels of 1.1x1.1x1.4 mm^3
- 60 regions differentiated





Transverse slice of the relative electron density head phantom

1. ROI 1 - Carcinoma $\rho_e = 0.989$
2. ROI 2 - Carcinoma (different chemical composition) $\rho_e = 0.989$
3. ROI 3 - Brain (white and grey matter) $1.034 \le \rho_e \le 1.035$
4. Bone $\rho_e = 1.527$
5. Cartilage $\rho_e = 1.083$
6. Turbinate $\rho_e = 0.329$
7. Skeletal muscle $\rho_e = 1.040$
8. Adipose tissue $\rho_e = 1.951$
9. Skin $\rho_e = 1.078$

Reconstruction Pre-processing

From the energy : Reconstruction of the RSP

$$\int_{E_{in}}^{E_{out}} \frac{1}{S(I_{water}, E)} dE = \int_L RSP(\boldsymbol{r}) dl$$

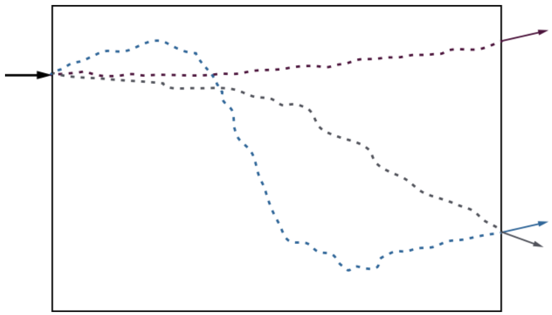
Ein, Eout : Energy of the proton before and after the object
$S(I_{water}, E)$: Stopping power of water at energy E
L : proton path, chosen for this study as the straight line along the incidence angle of the particle

From the transmission rate : Reconstruction of the attenuation

$$P_i = -\log(\frac{1}{T_i})$$

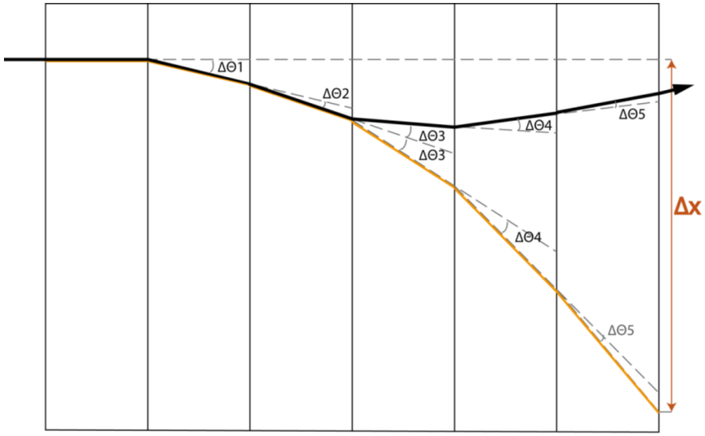
P_i value in projection pixel i
T_i transmission rate calculated for pixel i

Reconstruction from the deviation



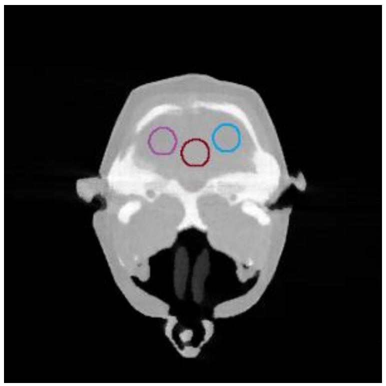
Angular deviation or spatial deviation do not represent the history of the particle

Integration on the MLP

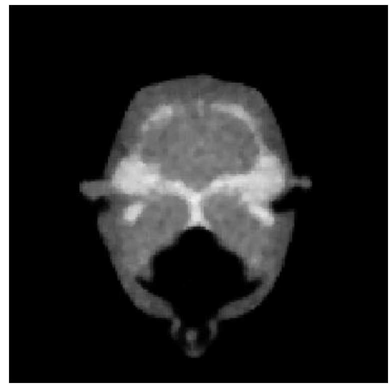


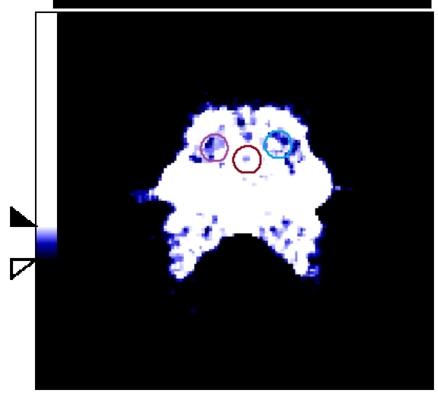
Reconstructions

RSP
ART + TV (50 iterations)

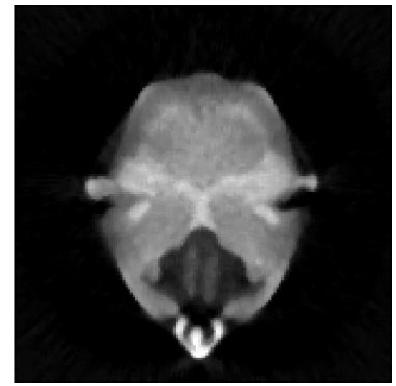


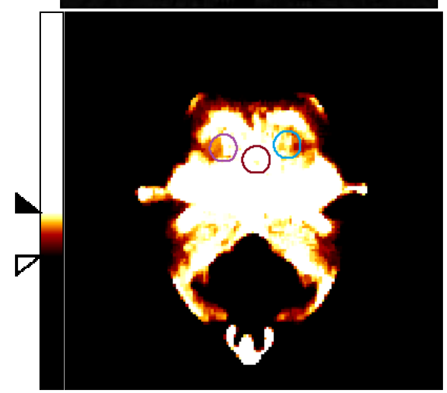
Transmission
ML-EM (150 iterations)





Deviation
FBP





Contrast study :

$$\text{Contrast} = \frac{\overline{\text{Brain ROI 3}} - \overline{\text{Carcinoma ROI 1,2}}}{\overline{\text{Brain ROI 3}}}$$

	Electron density phantom	ART+TV RSP	ML-EM transmission	FBP deviation
Carcinoma	2.9%	2.9%	11.5 %	10.2%
Carcinoma (less oxygen)	3.0%	2.3%	12.3 %	11.5%

Conclusion and Prospects

The study of the attenuation and the deviation of the protons opens new perspectives

The optimal way to reconstruct each observable is still being studied (list-mode reconstruction, from deviation to radiation length, use of the transmission…)

A more appropriate reconstruction algorithm needs to be developed

The key might be a statistical algorithm taking into account more than one of the observables.

Part of this work was submitted for publication to PMB