Proton imaging: status and perspectives

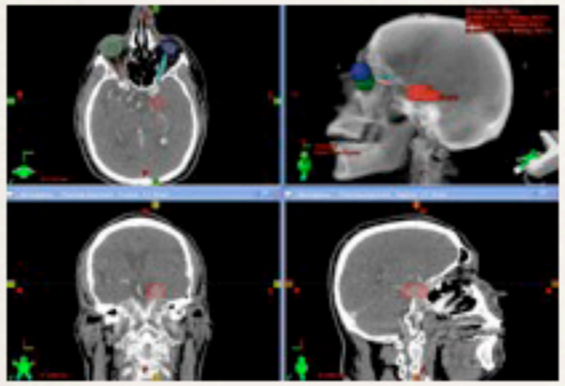
R. Rescigno on behalf of ImaBio task force

Nice, 03-12-2014

Treatment Planning system nowadays

Analytical and Monte Carlo treatment planning

X-ray CT scan



Absorption of an X-ray flux (attenuation coefficients)

Conversions

- Relative Stopping Power (energy loss)
- Scattering Power (beam dispersion)
- Nuclear Interaction Cross Section (fluence reduction of the beam)

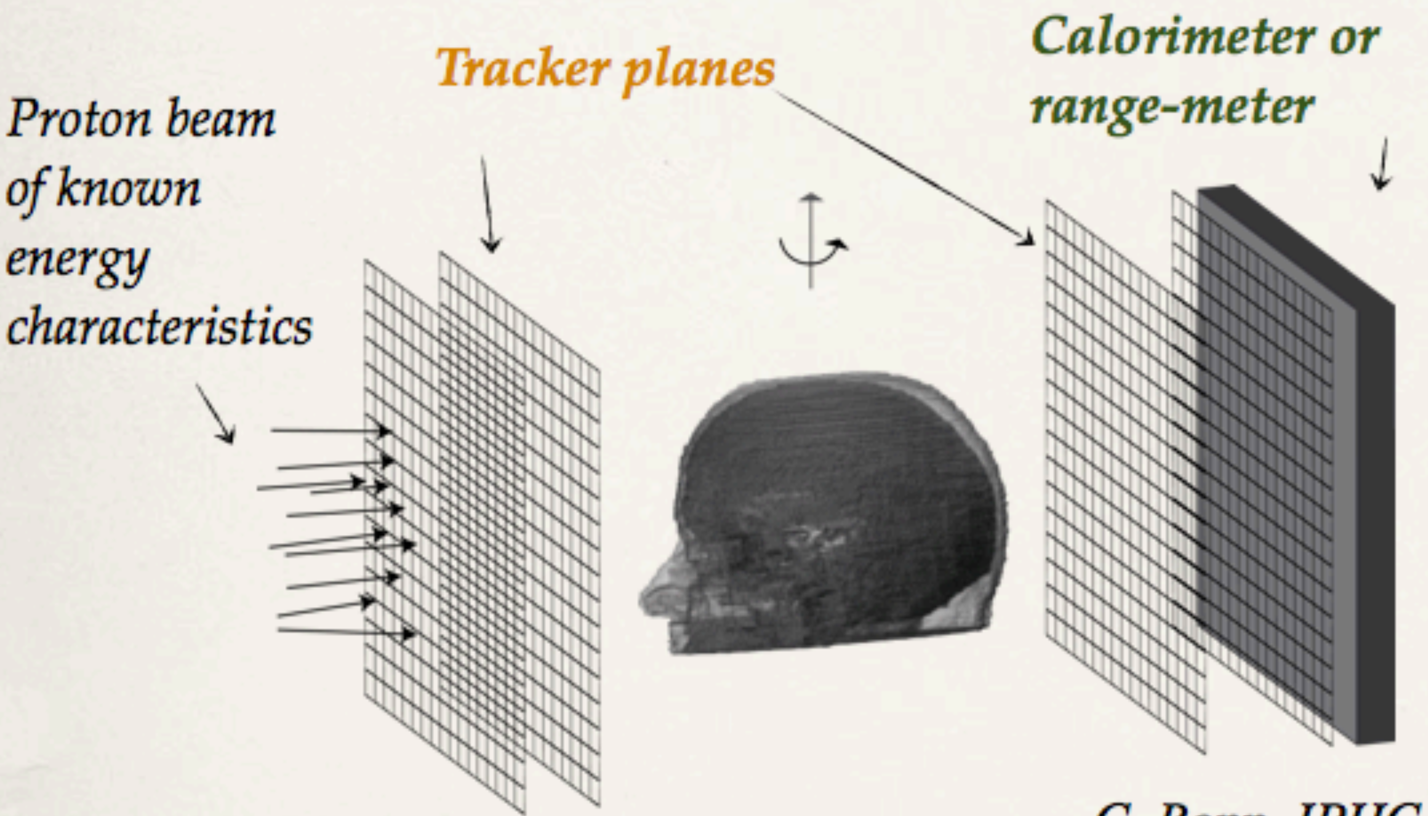
Errors

- ~ 3% on proton range
- Up to 3% uncertainty on the dose

Proton Imaging as possible solution?

Proton Imaging

Improving **charged particle treatment planning** by directly mapping the **relative stopping power** of tissue



C. Bopp, IPHC

Reconstruction problem

$$\int_{E_{in}}^{E_{out}} \frac{dE}{S_{water}(I_w, E)} = \int_l \rho(\vec{r})\, dl$$

Computed from Bethe and Bloch formula

Unknown RSP

Proton path in tissues

Prediction of the **Bragg peak position** in analytical treatment planning

What about beam spread and nuclear interactions?

see next slides on Cecile Bopp works

Proton Imaging: status and challenges

Requirements sheet (Shulte 2004)

Spatial resolution	< 1mm	**MLP** for better approximation of protons paths **Impact of the detection system** on the path estimation can be evaluated[*]
Distance to patient	> 10 cm	
Density resolutions	< 1%	Tradeoff between **dose** and **density resolution** Ratio of 100 between number of particles and voxels
Dose	< 5 cGy	
Data acquisition time	< 5 min	Detection system able to handle data rate of about 2MHz Characteristics of accelerator must be take into account (**data rate ~ 6 MHz**)
Reconstruction time	<15 min	

Which solutions for clinic exploitation?

*C.Bopp, PMB (2014) **59** N197-N210

see next slides on Regina Rescigno works

Proton scanner prototypes in the world

USA

<u>1st generation</u>
Silicon Strip detector
CsI (Tl) crystal

<u>2nd generation</u>
Scintillating fiber
Range meter

Rate ~ 1-2 MHz

PSI -Switzerland

Scintillating fiber
Range meter

Japan

Silicon Strip detector
NaI (Tl) crystal

Rate ~ 1 MHz

PRIMA Collaboration - Italy

Silicon Strip detector
YAG(Ce) crystal

Rate ~ 1 MHz

TERA Foundation - CERN

Triple GEM as tracker
Range meter

Rate ~ 1 MHz

Why a new one?

<u>see next slides on ImaBio task force perspective</u>

What about beam spread and nuclear interactions?

Transmission Rate Imaging

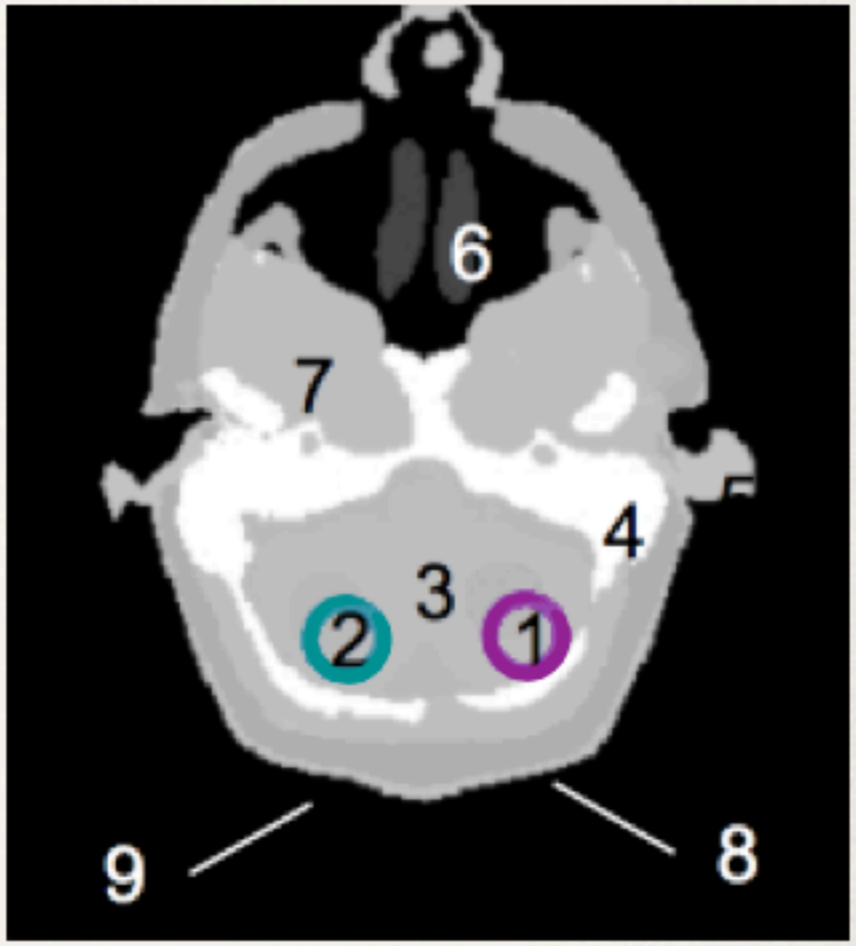
To retrieve information about the **nuclear interactions macroscopic cross section**

like in X-ray imaging

$$\Phi = \Phi_0 \int e^{-\int_l \kappa(x,y,z,E)\,dl} dE$$

Nuclear interactions macroscopic cross-sections

Transverse slice of RSP head phantom



1: Right carcinoma RSP:1 (65% O)
2: Left carcinoma RSP: 1 (35 % O)
3: Brain and withe matter RSP: 1.04
4: Bone RSP: 1.48

Transmission Rate Imaging

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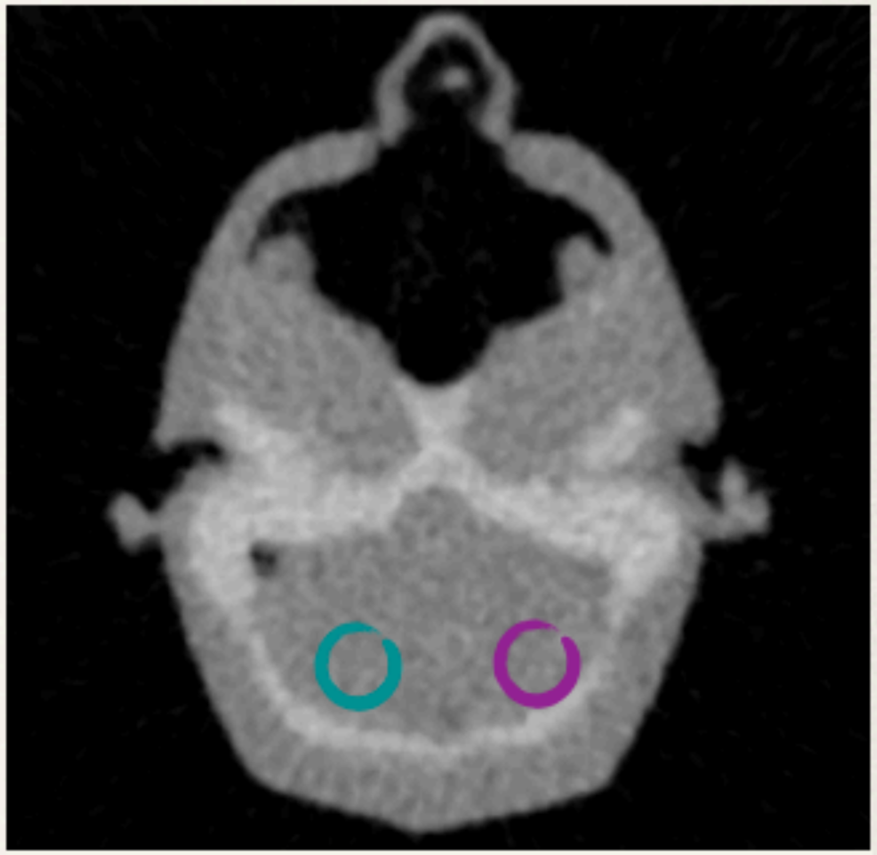

Data binned upstream tracker
Analytical reconstruction (FBP)

- Can distinguish bone-soft tissues air
- Can not see the tumors

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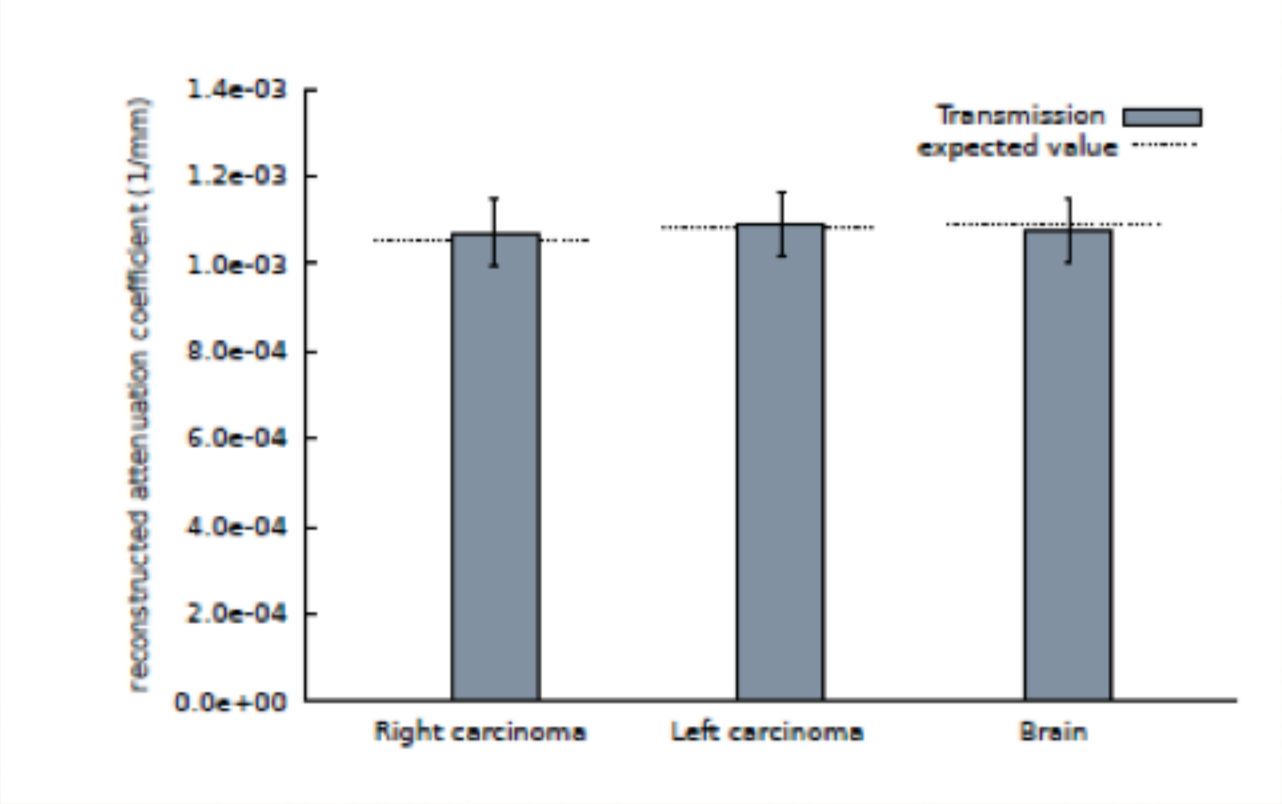

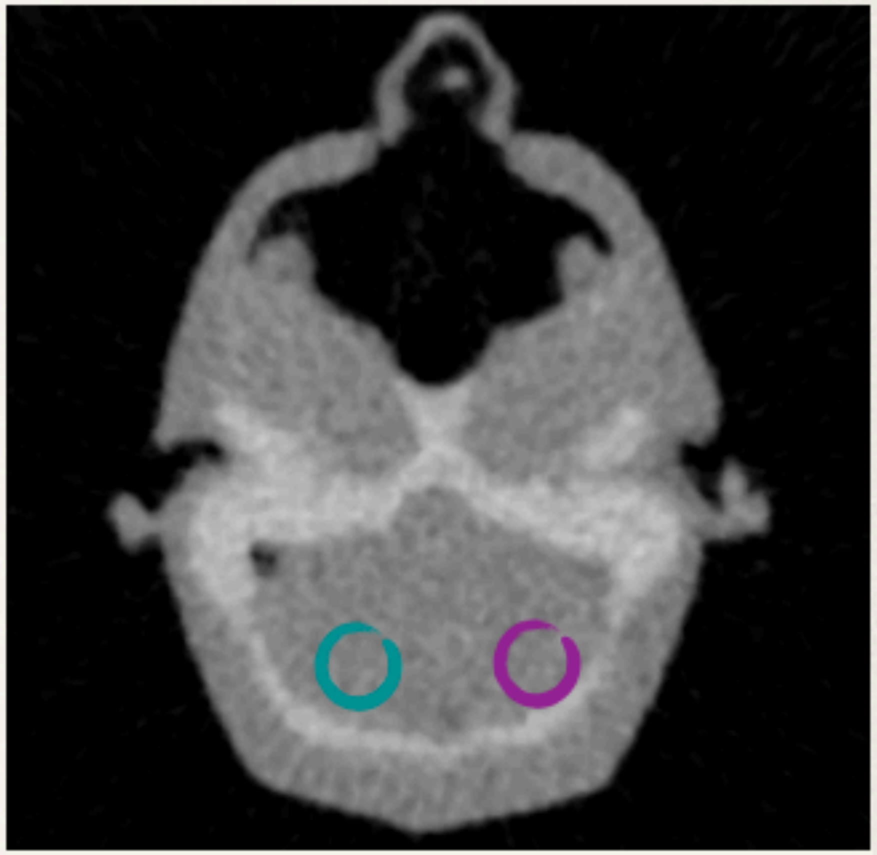

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Quantitative imaging from transmission rate

Scattering Imaging

To retrieve information about the **scattering properties** of tissues

$$\langle \theta^2_{proj} \rangle = \int_0^x f_{dM}(pv, p_1 v_1)\left(\frac{E_S}{pv}\right)\frac{1}{X_s}\,du$$

Measured angular spread

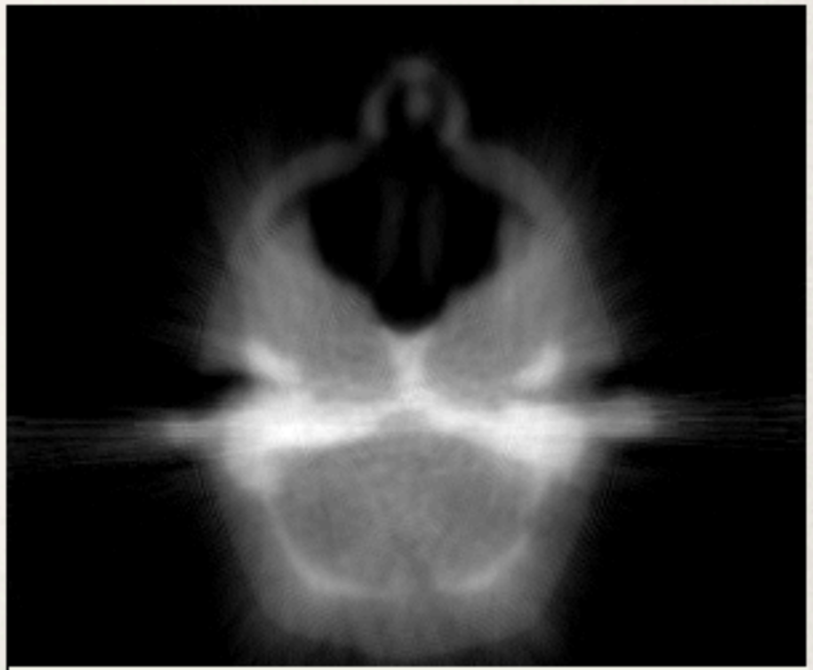
Energy dependent term

Reconstructed quantity

Reconstruction is in two steps

- RSP image reconstruction
- Scattering Length reconstruction

Transverse slice of $1/X_s$ head phantom



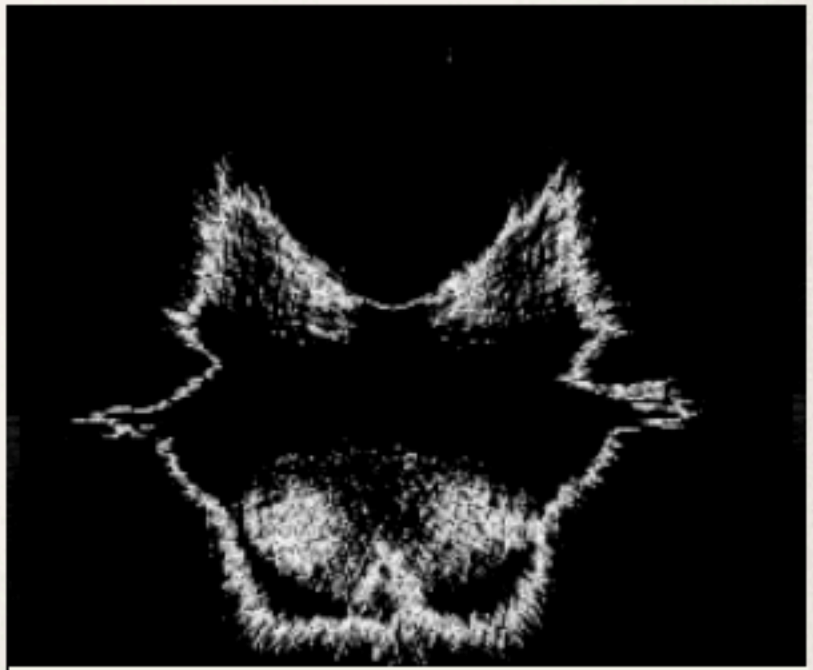
From projections
ART algorithm

Scattering Imaging

To retrieve information about the **scattering properties** of tissues

- Reconstruction process still needs to be optimized
- Can distinguish the tumor from the brain

Transverse slice of $1/X_s$ head phantom



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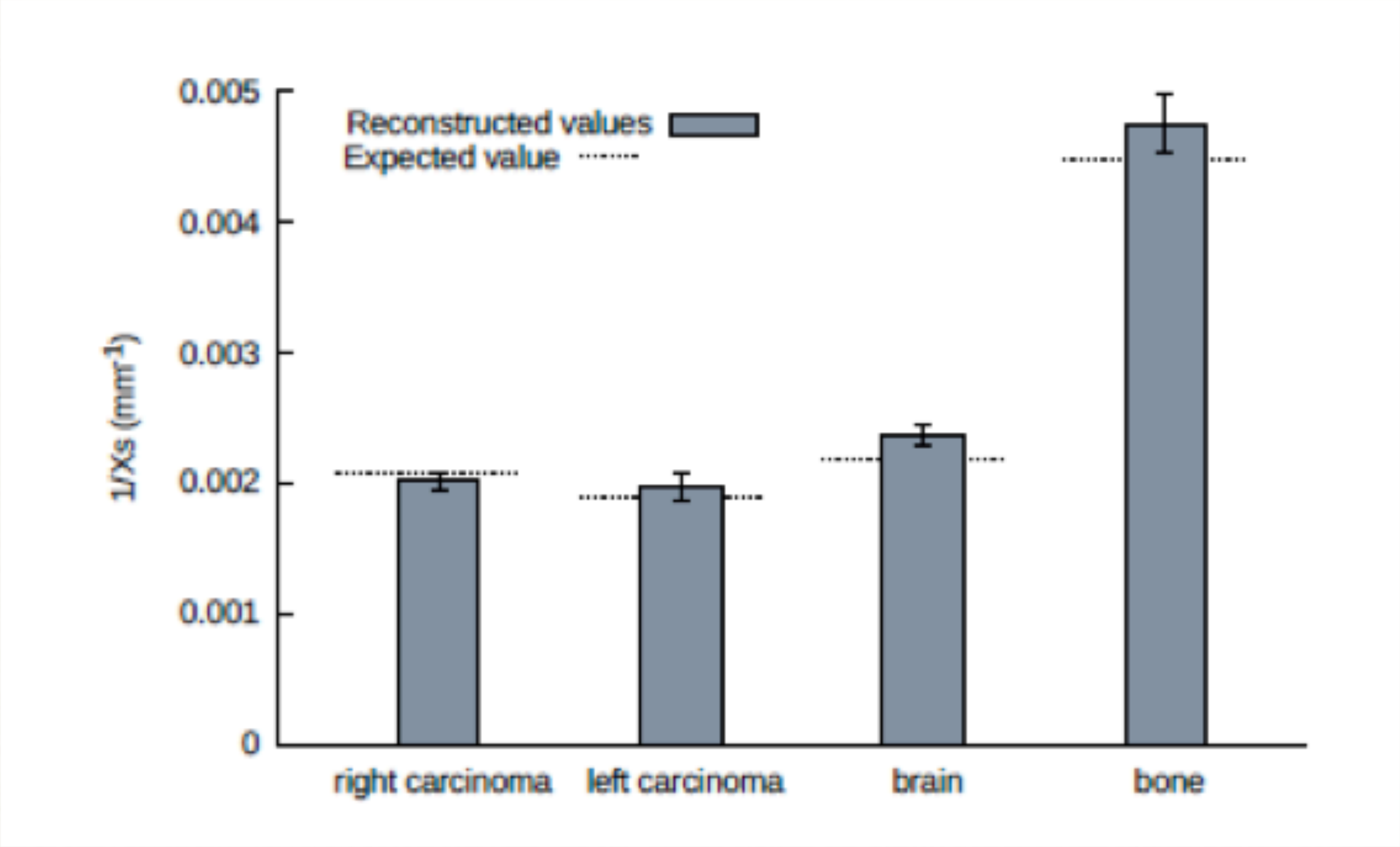

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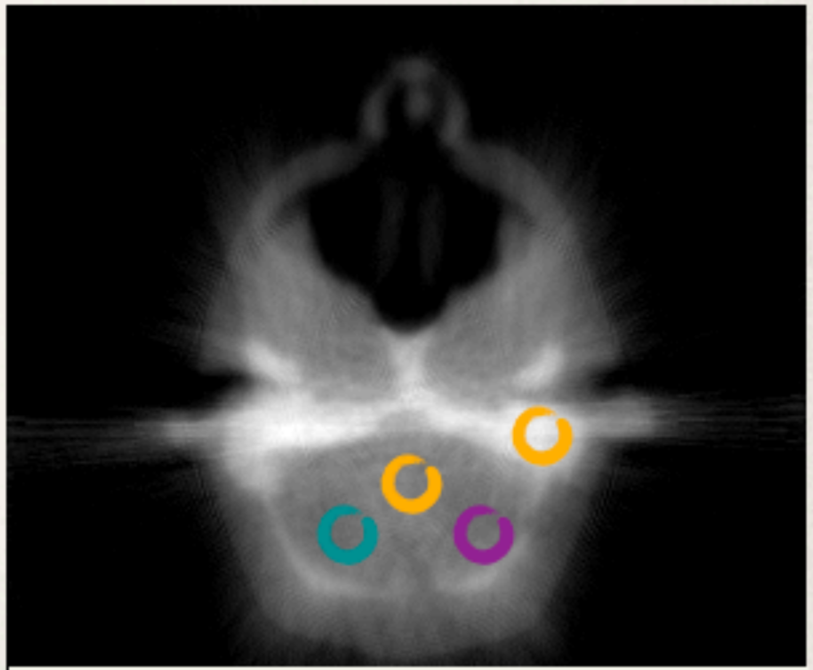


From projections
ART algorithm

Quantitative imaging from scattering

Summary and conclusions

...of Cecile Bopp works

- There is information in scattering and transmission rate of the protons
  - Used to reconstruct images, *qualitative* and *quantitative*
  - Could be of use in analytical treatment planning
  - Not enough to fully characterize the composition of materials
  - *Can provide additional constraints for a conversion*

Publications and communications on the subject

- C. Bopp, **Proton Computed tomography for multiple physics processes**, PMB 2013
- C. Bopp, **Quantitative proton imaging from multiple physics processes,** submitted to PMB

- IEEE NSS/MIC, Workshop on new technologies in hadron therapy, Anaheim, 2012
- IEEE NSS/MIC, **Proton computed tomography: beyond the stopping power**, 2014

Which solutions for clinic exploitation?

Pencil beam (PB) approach to proton imaging

PB approach aims at the reconstruction of the distribution of the RSP using **Pencil Beam information rather single proton histories**

Matrix form of pCT reconstruction problem $$\sum_j a_{ij} x_j = WEPL_i$$

Classical approach

a_{ij} : Length of intersection of i-th proton with j-th voxel

$WEPL_i$: WEPL of i-th protons

x_j : Unknown RSP of j-th voxel

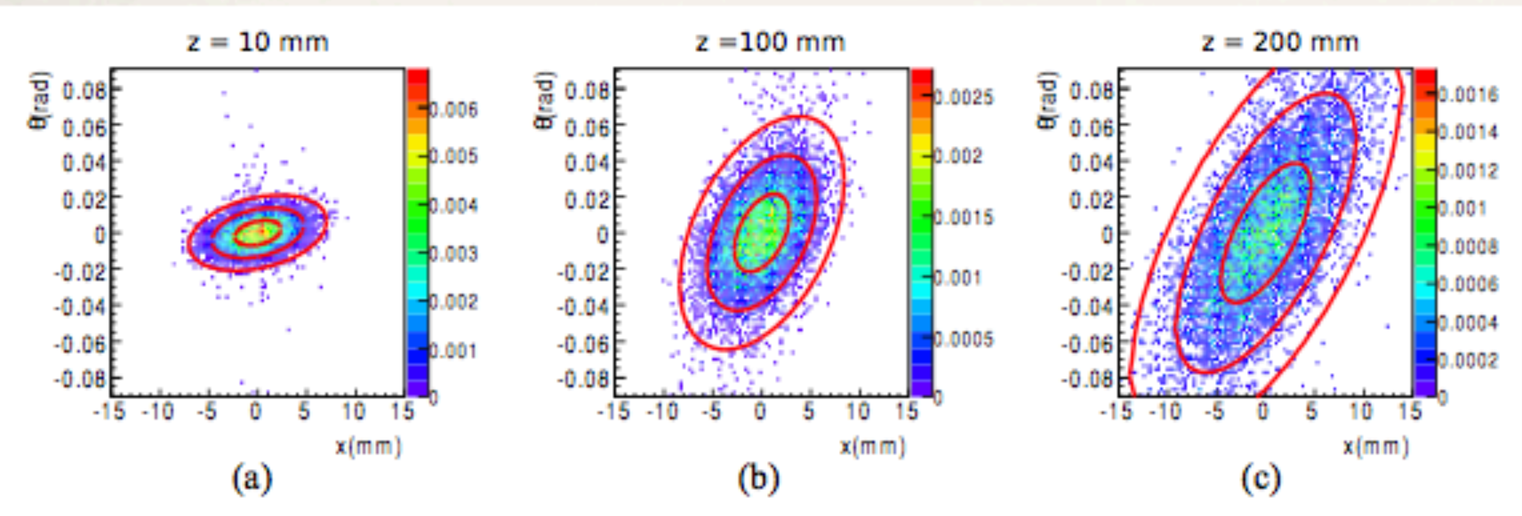
PB approach

a_{ij} : **Probability of i-th beam to traverse j-th voxel**

$WEPL_i$: **Mean** WEPL of i-th **beam**

x_j : Unknown RSP of j-th voxel

Needs for beam modeling and its propagation in matter



Beam in phase space @ three different depth in water

Colored scale: Monte Carlo sample
Red Line : Results from analytical model

R. Rescigno, submitted to Med.Phys.

Why a new prototype @ IPHC?

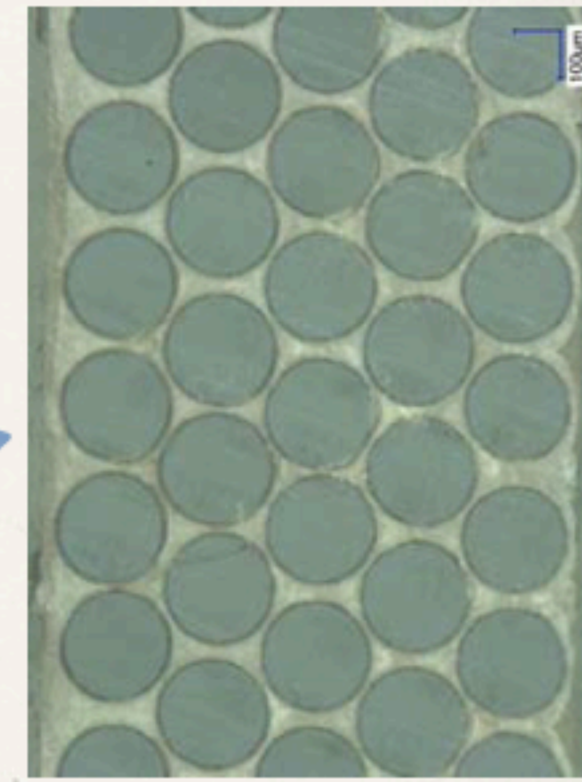
A scanner prototype for the PB approach

Tracker and **range-meter** solution for a proton imaging system with an approach *Pencil Beam*

Fiber-based detector for tracker

Advantages

- High spatial resolution (size : few 100 µm up to mm)
- Fast (length of signal: few tens of ns)
- Several solutions of arrangement



Ongoing study

- Which material?
- Size?
- Design?
- Other solutions?

Expertise of ImaBio

- Scintillation detectors
- PM & SiPM
- Asic development
- Previous patent depositions

\+ <u>Available beam @ Cyrcé for detector test</u>

Range meter solution for energy

ImaBio task force

A three year project : 2015-2017

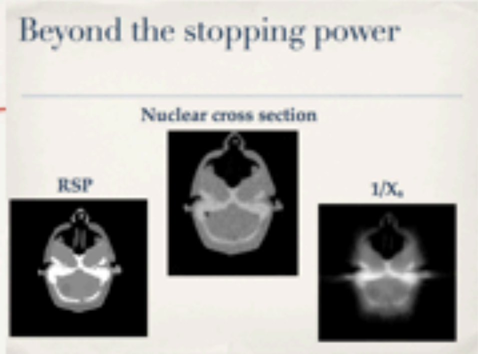
	Number	FTE (man.month)
PhD	1	36
CDD	1	12
MdC	2	12
CNRS	2	29
	<u>Total</u>:	89

Adding IT from ImaBio team: 36-72 FTE (man.month)

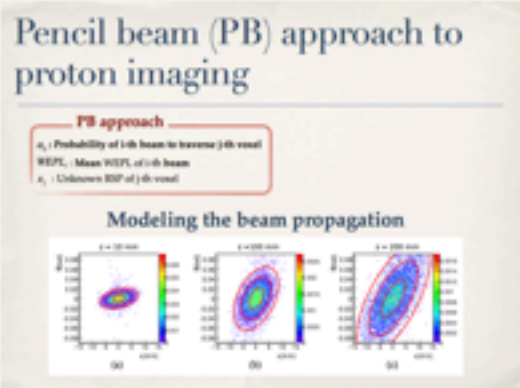
Summary

- ProTom project (2011-2012)
- IdEx (2014-2015)
- AP in2p3

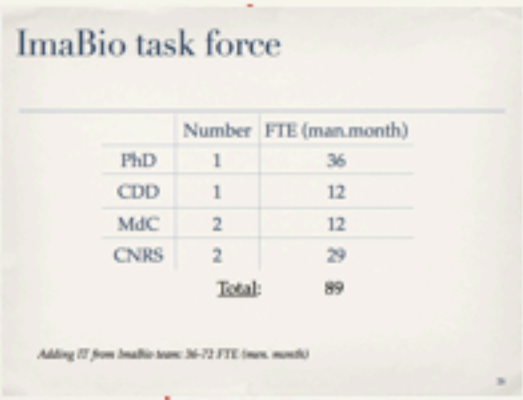
Expertise in pCT problem



New approach to pCT (*Pencil Beam*)



Manpower and support of UdS and IPHC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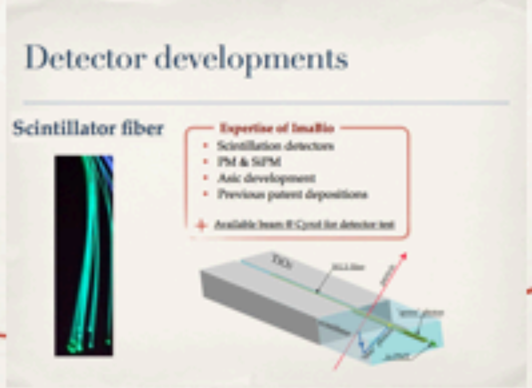

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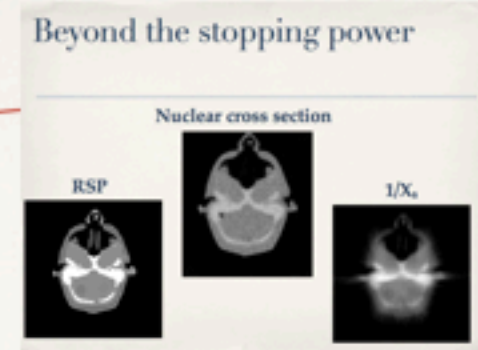

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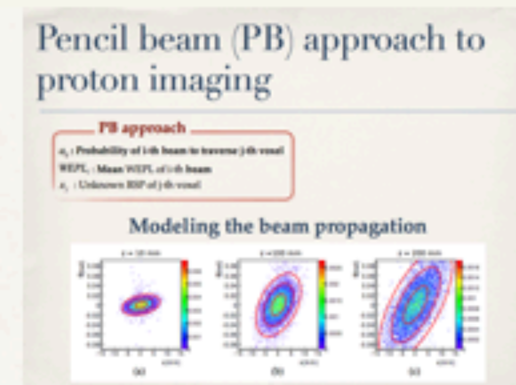

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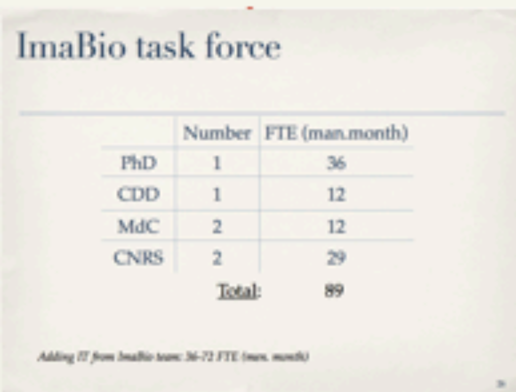

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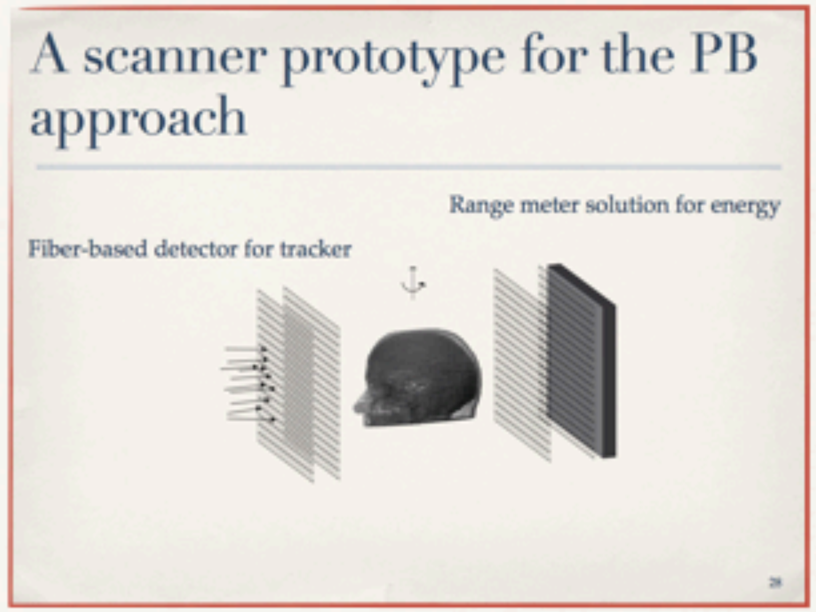

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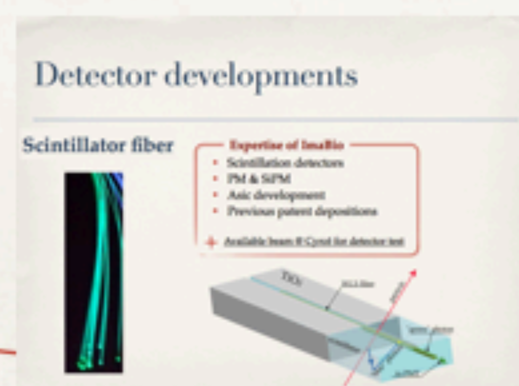
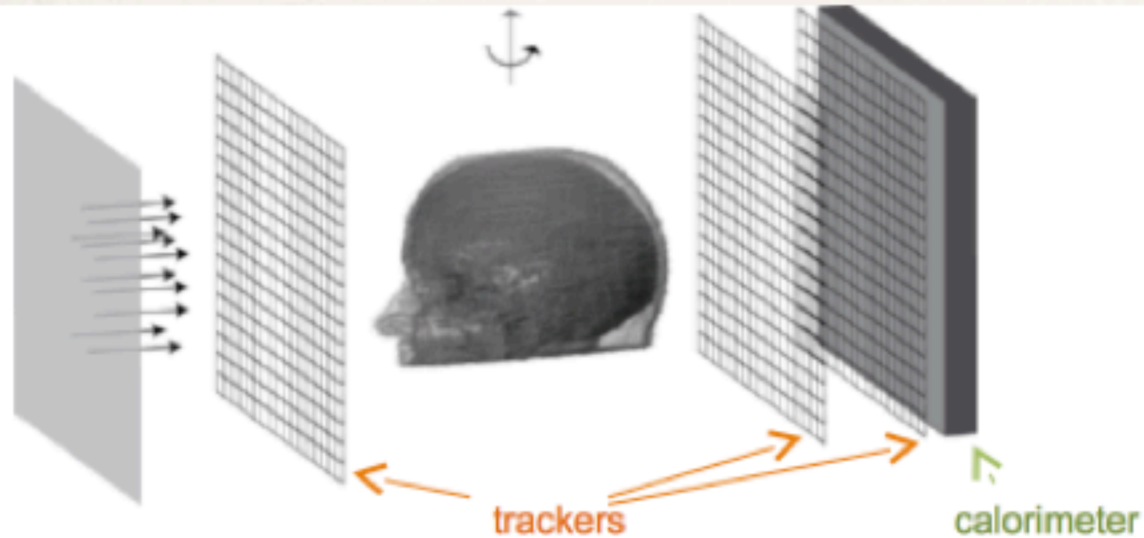


Spares

Simulation features



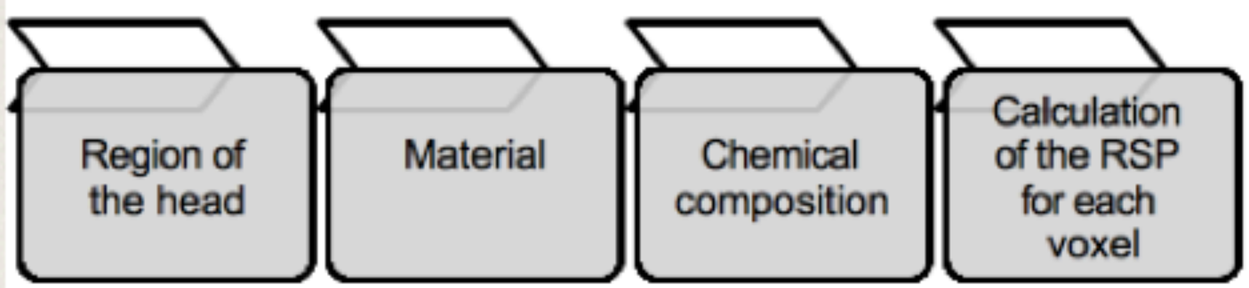
Simulation parameters :

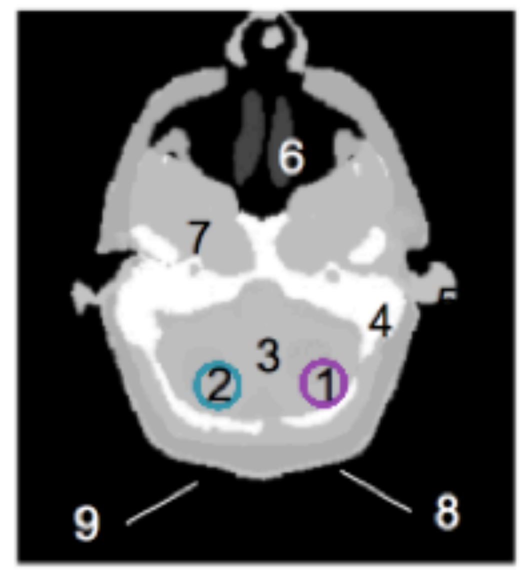
- 200 MeV protons
- 1000 protons/mm²
- 256 projections over 2 Pi
- Parallel
- Perfect trackers and calorimeter

Delivered dose ~ 2.5 cGy

Voxelized head phantom :

- 20 different materials
- Tumors inserted with same electron density but different compositions
- 256x256x128 voxels of 1.1x1.1x1.4 mm3
- 60 regions differenciated





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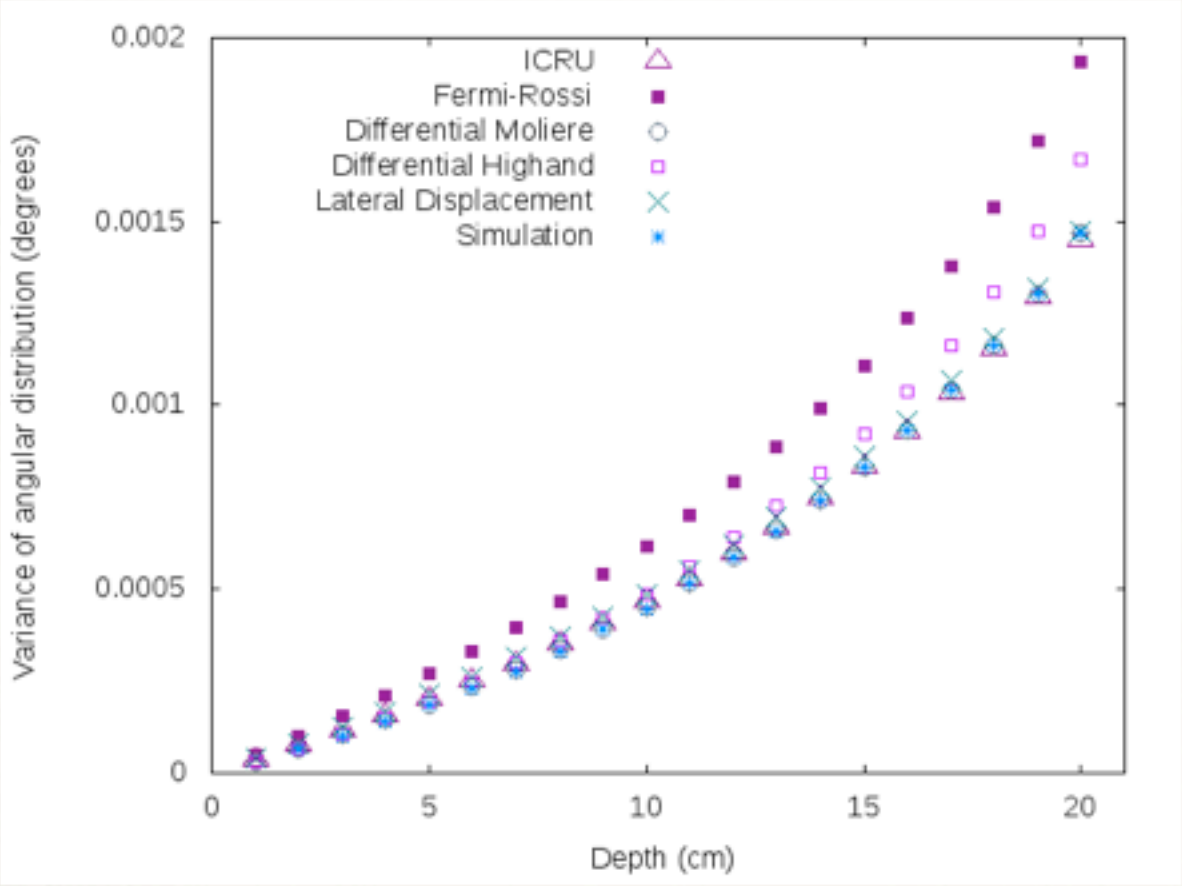
2. Left carcinoma (~35% O) RSP = 1.00
3. Brain (white and grey matter) RSP = 1.04
4. Bone RSP = 1.48
5. Cartilage RSP = 1.09
6. Turbinate RSP = 0.32
7. Skeletal muscle RSP = 1.05
8. Adipose tissue RSP = 0.94
9. Skin RSP = 1.09

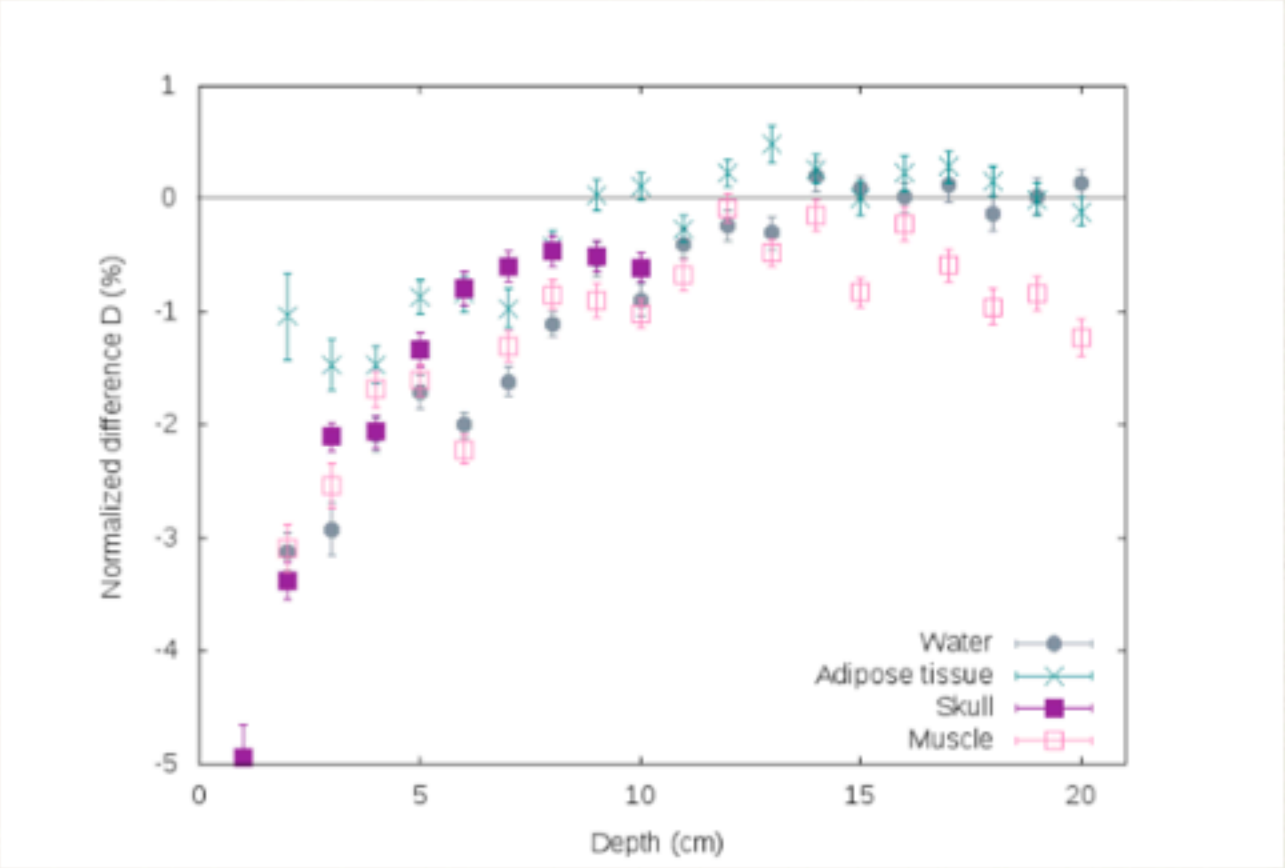
Transverse slice of the relative stopping power head phantom

Stored in list-mode data format

Validation model simulation GATE

in water





Scattering Imaging

To retrieve information about the **scattering properties** of tissues

Definition of reconstruction problem

- Gaussian approximation of MCS process (variance of angular distribution $<\theta^2>$)
- Differential description of MCS through **Scattering Power** $T \equiv \frac{d<\theta^2>}{dx}$

$$T_{dM} = f_{dM}(pv, p_1 v_1)\left(\frac{E_s}{pv}\right)\frac{1}{X_s}$$

Several approximation: differential Molière best fits simulation

$$<\theta^2_{proj}> = \int_0^x T(u)\,du$$

Reconstruction is in two steps

$$<\theta^2_{proj}> = \int_0^x f_{dM}(pv, p_1 v_1)\left(\frac{E_S}{pv}\right)\frac{1}{X_s}\,du$$

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