IWORID-8

Pisa July 2–6, 2006

The Italian project for a proton Computed Tomography (pCT) device

G.A.P. Cirrone

and the PRIMA collaboration

Laboratori Nazionali del Sud

Istituto Nazionale di Fisica Nucleare

CATANIA - I

TALK OUTLINE

1. Why the pCT?

2. The proton Computed Tomography: history, physical principles and status of the art

3. Design of the detector

4. Role of Monte Carlo simulation

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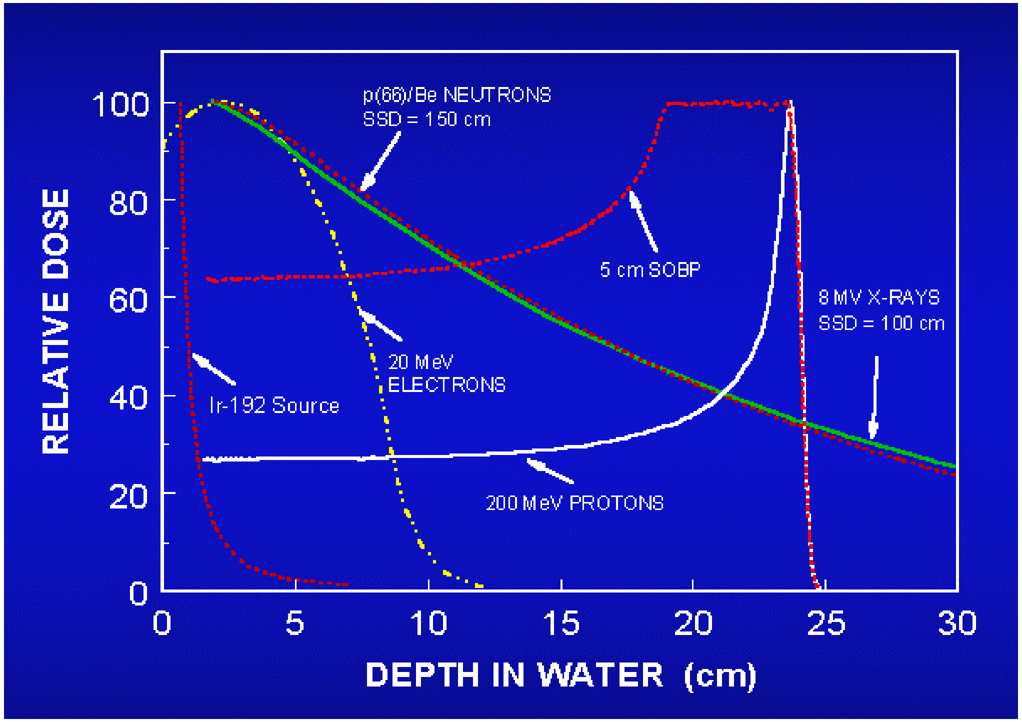
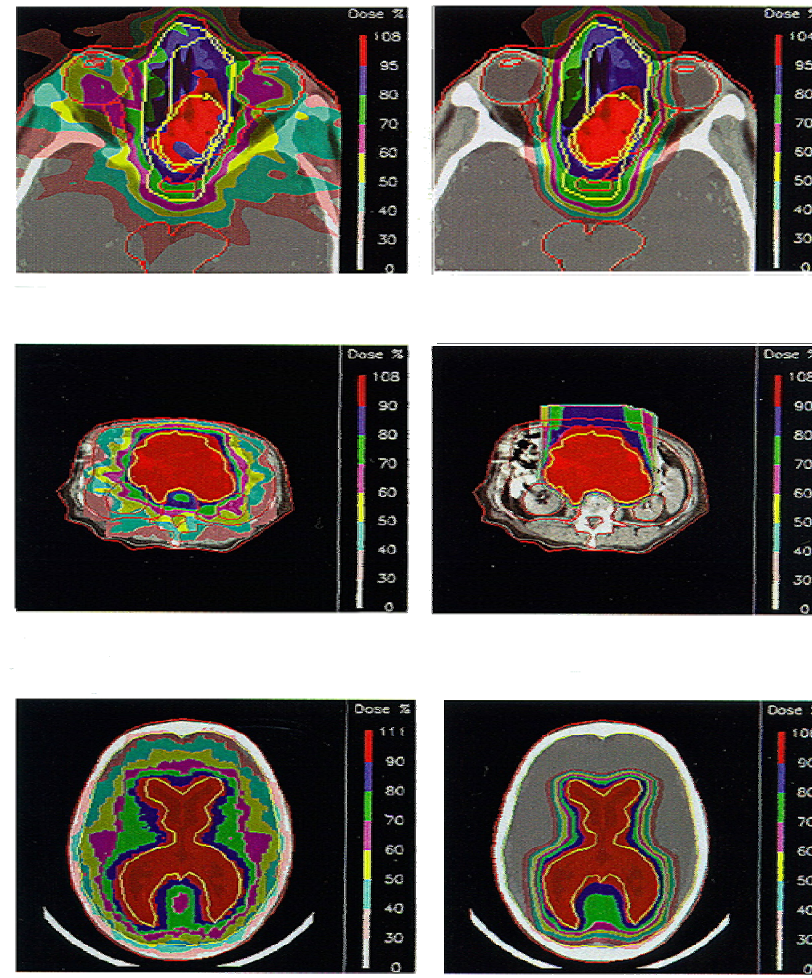
WHY A pCT DEVICE ?

Proton therapy is a growing radiation treatment technique (more 35 centers today)





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WHY A pCT DEVICE ?

MAIN IUSSUES IN PROTON THERAPY QUALITY

- Patient positioning
- Dose planning

Actually TPS are based on the xCT images as input and this bring a sensible amount of imprecision

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WHY A pCT DEVICE ?

DOSE PLANNING IN PROTON THERAPY

The *stopping powers* represent the main parameter for the dose calculation in a proton treatment planning

In proton therapy they are indirectly derived measuring and converting, following some calibration curves, the attenuation coefficients μ derived from a conventional CT

THE ERROR INTRINSIC IN THIS CONVERSION

OWN TO THE NOT SIMPLE DEPENDENCE OF μ FROM η_e AND Z OF THE MATERIAL

IS THE PRINCIPAL FACTOR LEADING TO THE RANGE INDETERMINATION OF PROTON

WHY A pCT DEVICE ?

Studyes by PSI researchers on phantom and animal models demostrated that the used conversion

μ ↔ stopping power

and with actual calibration model produce an average indetermination on proton range of 3%

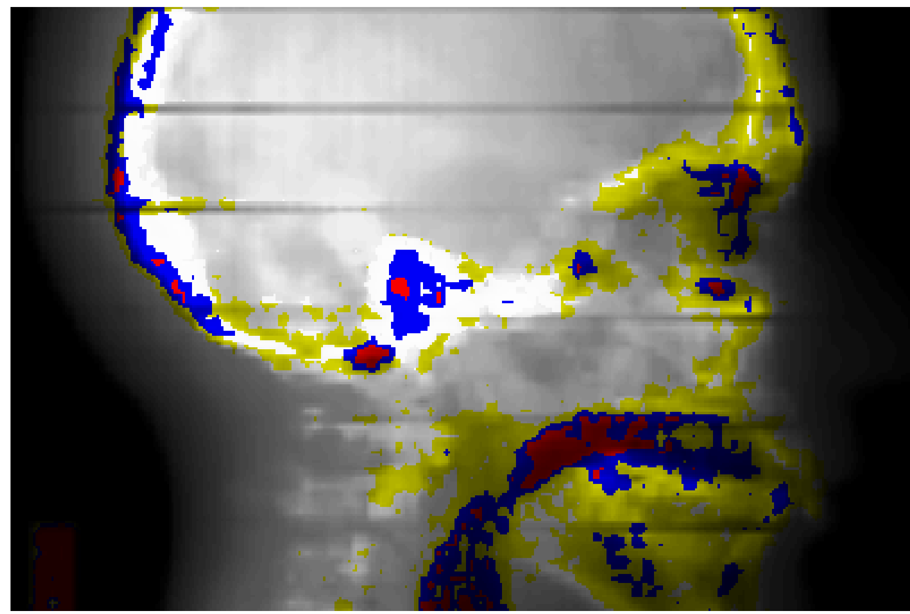
(up to 10 mm in the head)

Range uncertainty

> 5 mm

> 10 mm

> 15 mm



Alderson Head Phantom

Schneider U. (1994), "Proton radiography as a tool for quality control in proton therapy," Med Phys. 22, 353.

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pCT: THE IDEA AND PRINCIPLES

Already in his Nobel lecture, for the computed tomography realisation, Allan Cormack shown his studies carried out with Andreas Koehler and published on J. of Appl. Phys. nel 1963 e 1976, on the possibility of a protonComputed Tomography

<< Why use proton? First there is the question of dose…… There is an agreement with theoretical calculation that the dose required for proton scans is five to ten times less than for X-Ray scans for the same amount of informations.>>

<< Second: due to the different mechanism of interaction with matter one ought to see different things using different radiations…….>>

TWO MAIN REASONS STOPPED THE INTEREST OF PCT IN THE NEXT YEARS:

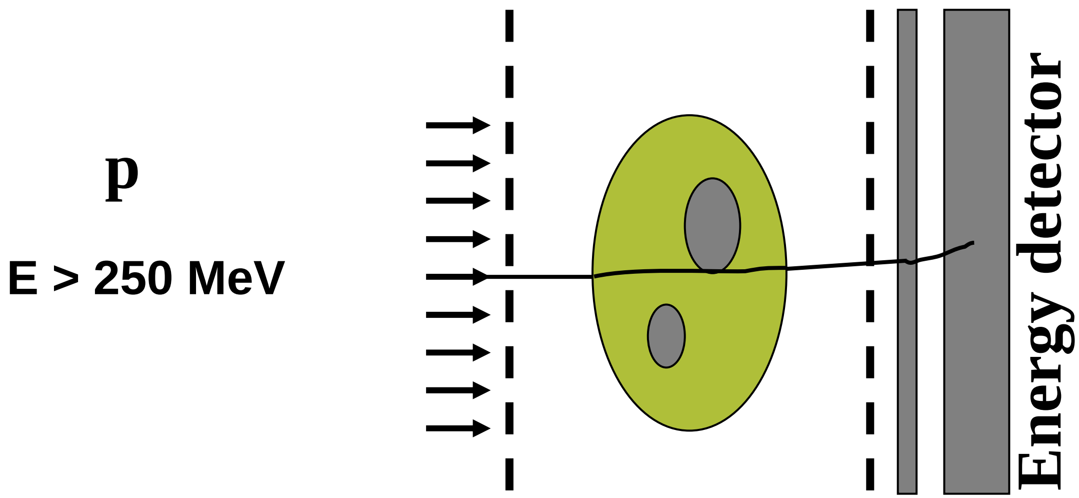
- **A VERY SMALL NUMBER OF PROTON-THERAPY CENTERS**

- **THE IMPOSSIBILITY TO REACH SUFFICIENT LEVELS OF SPATIAL AND DENSITY RESOLUTION OWN THE INTRINSIC PRESENCE OF THE COULOMBIAN MULTIPLE SCATTERING**

pCT: THE IDEA AND PRINCIPLES

pCT: THE IDEA AND PRINCIPLES

METHOD EQUIVALENT TO THE X-RAYS IMAGING BUT HERE THE MAIN INFORMATION IS ENERGIES OF TRAVERSING PROTONS DESPITE ATTENUATION COEFFICIENTS OF PHOTONS



•Proton Computed Tomography

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Knowledge of entry and exit energy of a proton allow the estimation of the integrated (projected) relative electron density along a path L

The mean rate of energy loss is given by the Bethe-Bloch equation, written in a useful for pCT:

$$-\frac{dE}{dx}(r) = \eta_e(r) S\left[I(r), E(r)\right]$$

$$\int_L \eta_e(\vec{r}) d\vec{r} = K \int_{E_{out}}^{E_{in}} \frac{dE}{S(E)}$$

Integrated electron density

Inverse of Stopping Power

Like in xCT the pCT image reconstruction is the inversion of right integral for the unknown electron density distribution

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pCT: THE IDEA AND PRINCIPLES

BUT

the exact path L in the pCT in unknown due to Multiple Coulomb Scattering and only initial and final information can be measured for each proton

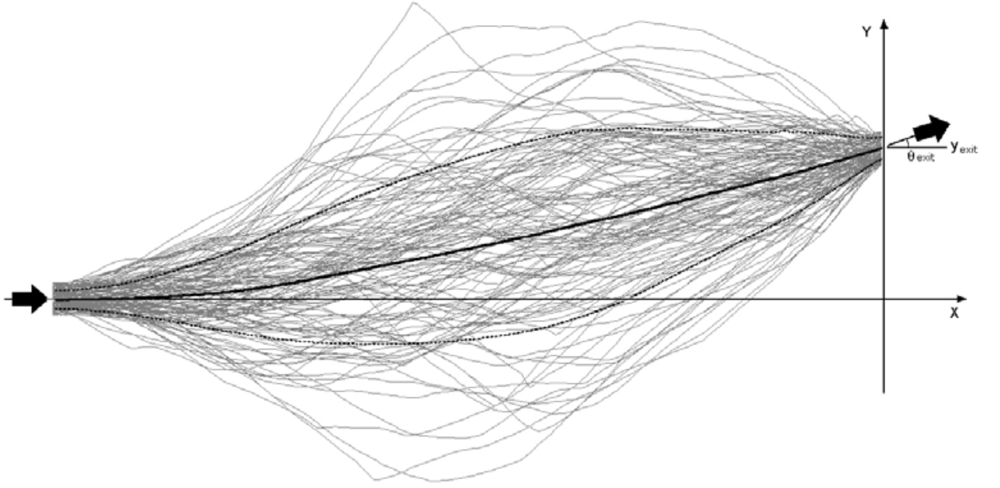
MAIN TASK:

ESTIMATION OF PROTON PATH INSIDE MEDIUM

OR BETTER → A MEDIUM PATH

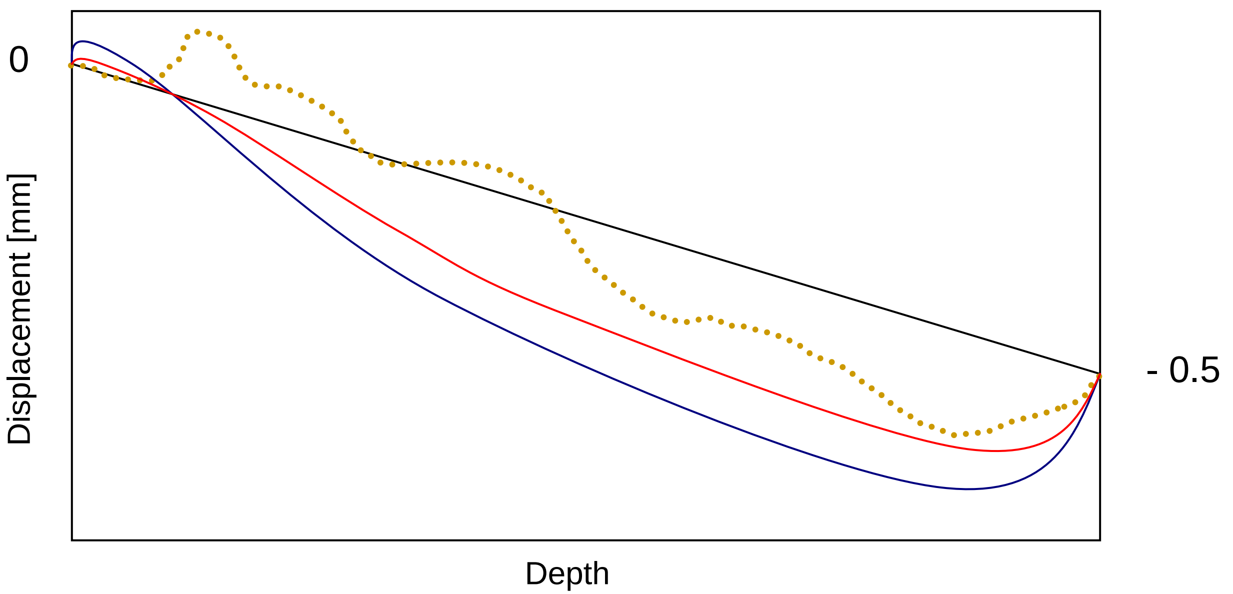
Geant4 simulation of 250 MeV protons in water

THE SINGLE TRACKING APPROACH



MEDIUM PROTON PATH ESTIMATION

1. Straight-line path
2. Most Likely Path (MLP): from Moliere MCS theory
3. Cubic Spline path
4. Monte Carlo path



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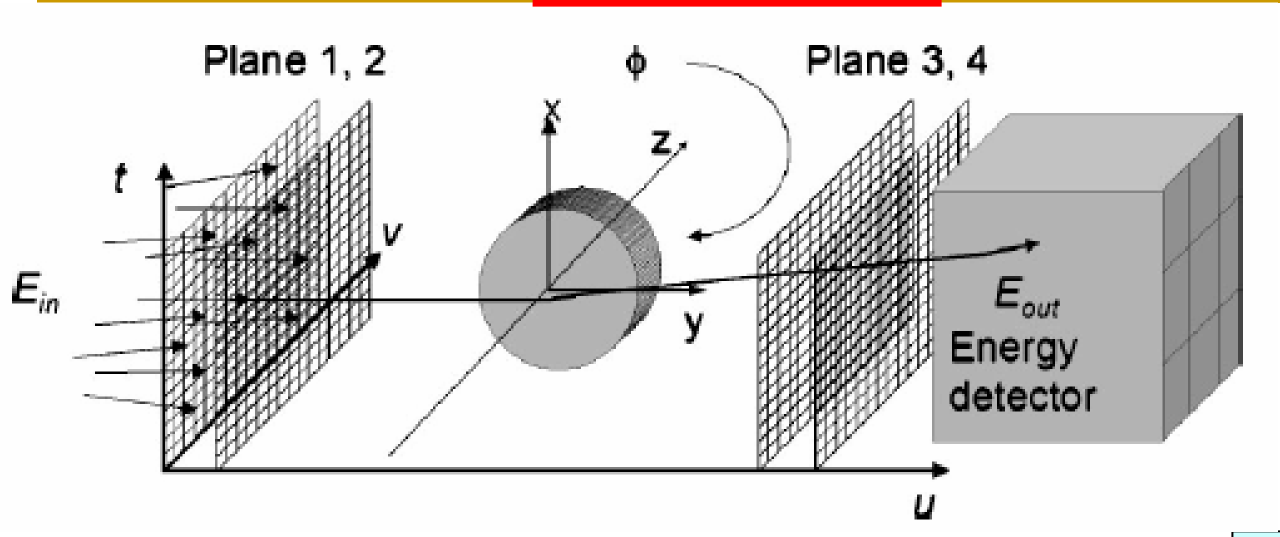
EXPERIMENTAL SOLUTION FOR SINGLE TRAKING

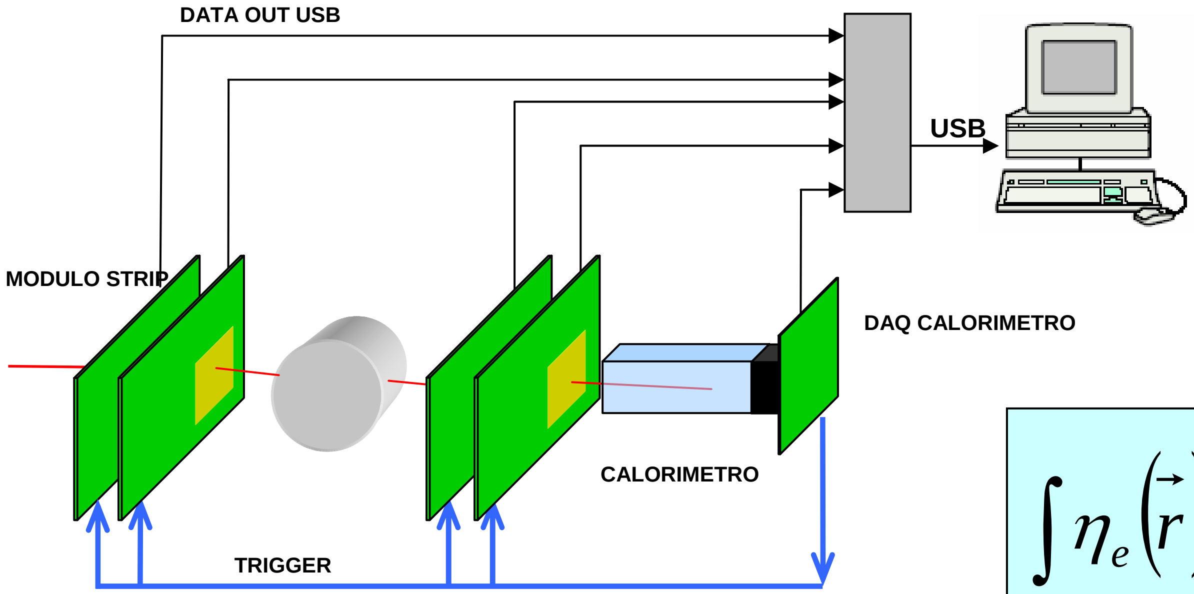
All the studies and prototypes developed in the last years are based on the principle of follow each single proton traversing the medium to investigate



The "single tracking" approach should permit to improve the spatial risolution up to 1 mm or less

$$\int_L \eta_e(\vec{r})\,d\vec{r} = K \int_{E_{out}}^{E_{in}} \frac{dE}{S(E)}$$

THE PRIMA DETECTOR



$$\int_L \eta_e\left(\vec{r}\right) d\vec{r} = K \int_{E_{out}}^{E_{in}} \frac{dE}{S(E)}$$

Single tracking

Acquisition rate up to 1 MHz

Detector: 2 orthogonal microstrip; 200 um picth x 256 strips; about 5x5 cm of active area

Trigger from the calorimeter

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Requirements for a pCT device

Category	Parameter	Desired Value
Proton source	Energy Energy spread Beam intensity	≃200 MeV (head) ≃250 MeV (trunk) ≃ 0.1% 10^3 - 10^5 protons/sec
Accuracy	Spatial resolution Electron density resolution	< 1 mm < 1%
Time Efficiency	Installation time Data acquisition time Reconstruction time	< 10 min < 5 min < 15 min (treatment planning) < 5 min (dose verification)
Reliability	Detector radiation hardness Measurement stability	> 1000 Gy < 1%
Safety	Maximum dose per scan Minimum distance to patient surface	< 5 cGy 10 cm

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THE ROLE OF MONTE CARLO

1. Test the estimation of the proton path
2. Evaluate of image quality
3. Evaluate the released dose (as function of image quality!)
4. Evaluate the different reconstruction algorithms

OUR COMPUTATIONAL TOOL

- GEANT4 MC toolkit:
- Electromagnetic processes
- Elastic nucrear scattering
- Inelastic nuclear scattering

THE ROLE OF MONTE CARLO

First tests of the Williams analytical approach to MLPs

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G4 vs Experiment

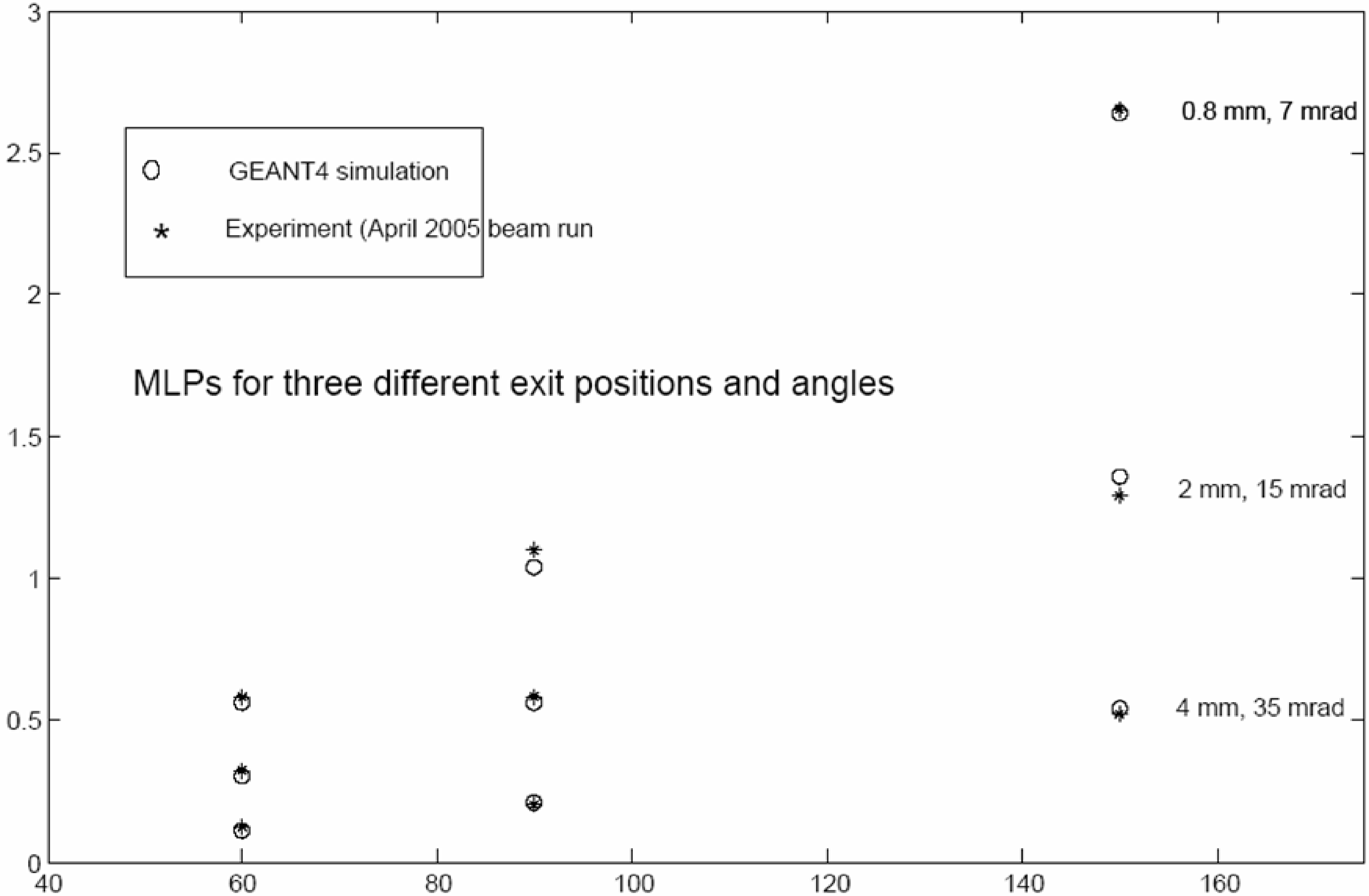
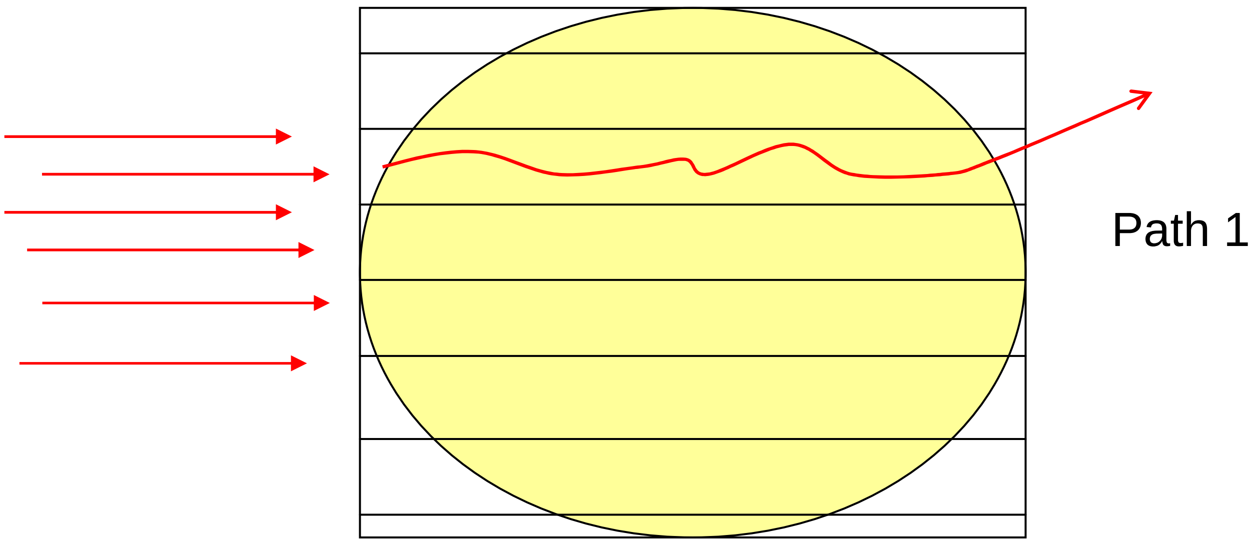


IMAGE RECONSTRUCTIONS WITH THE FBP ALGORITHM



Object is ideally divided in channel and only protons do not exceed the bin AT ANY POINT are considered. Its path can be approximated to a straight line and FBP is applicable

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THE ROLE OF MONTE CARLO

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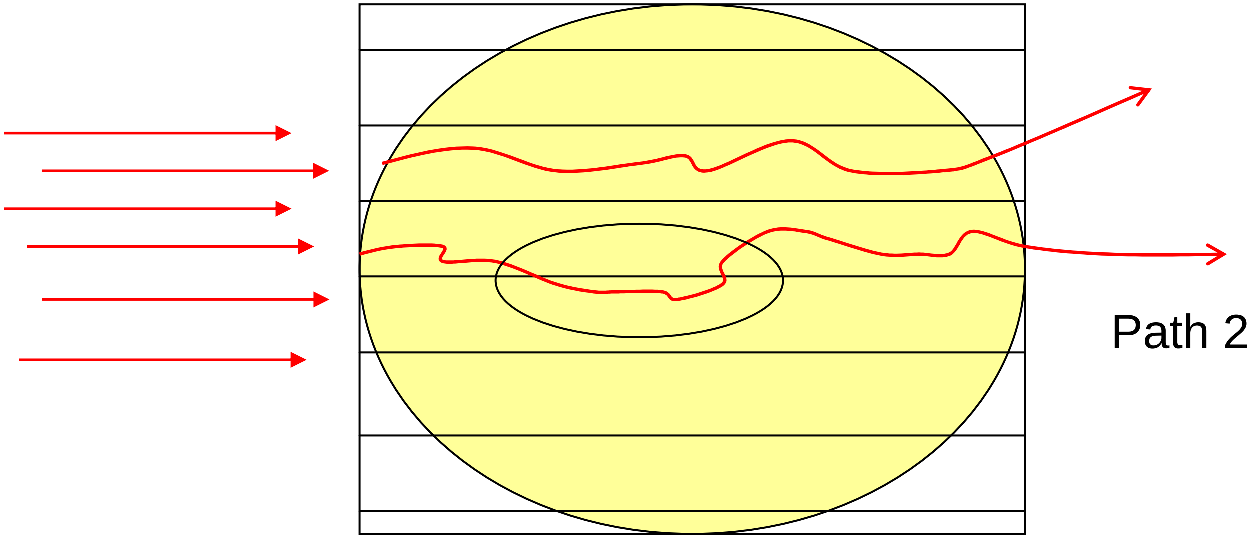
A different possibility is consider protons entering and exiting in the same channel but not limit their paths inside it (Path 2). Eventually a constraint on exit angle can be introduced

This permit to increase the number of protons for image reconstruction decreasing the total dose



THE ROLE OF MONTE CARLO

200 MeV, 179 projections at 1°, 5M Histories, 20 cm circular phantom

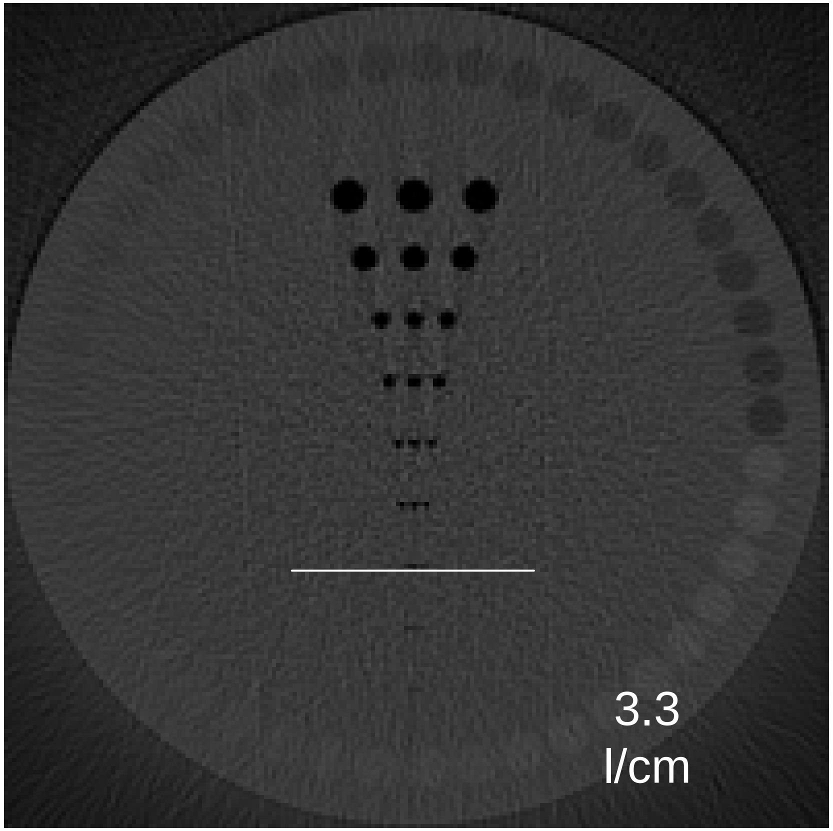
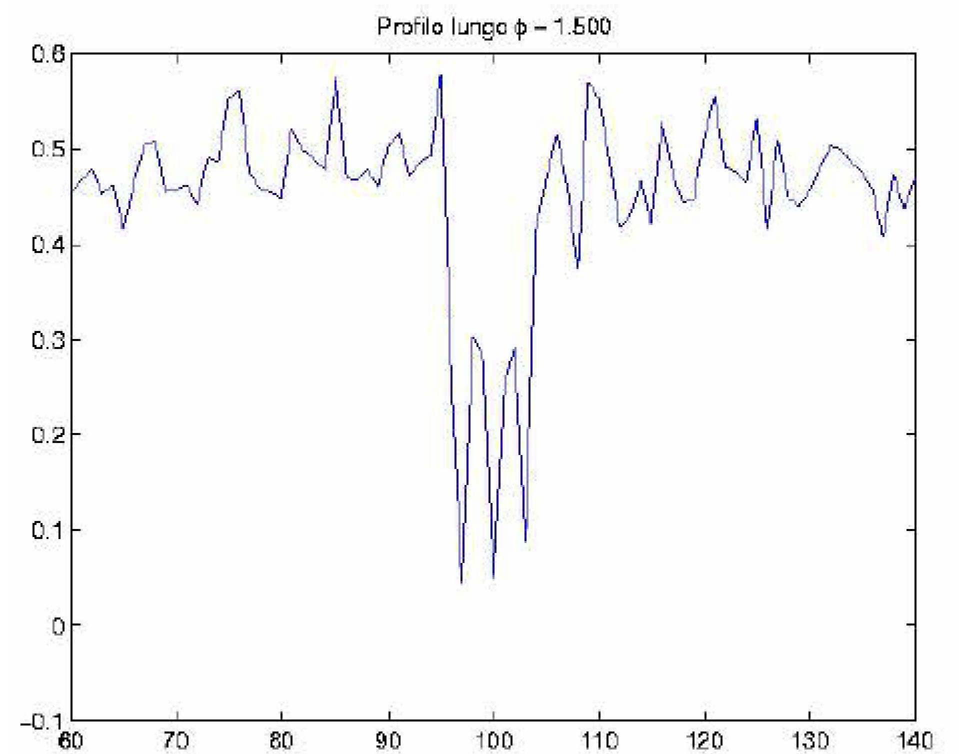
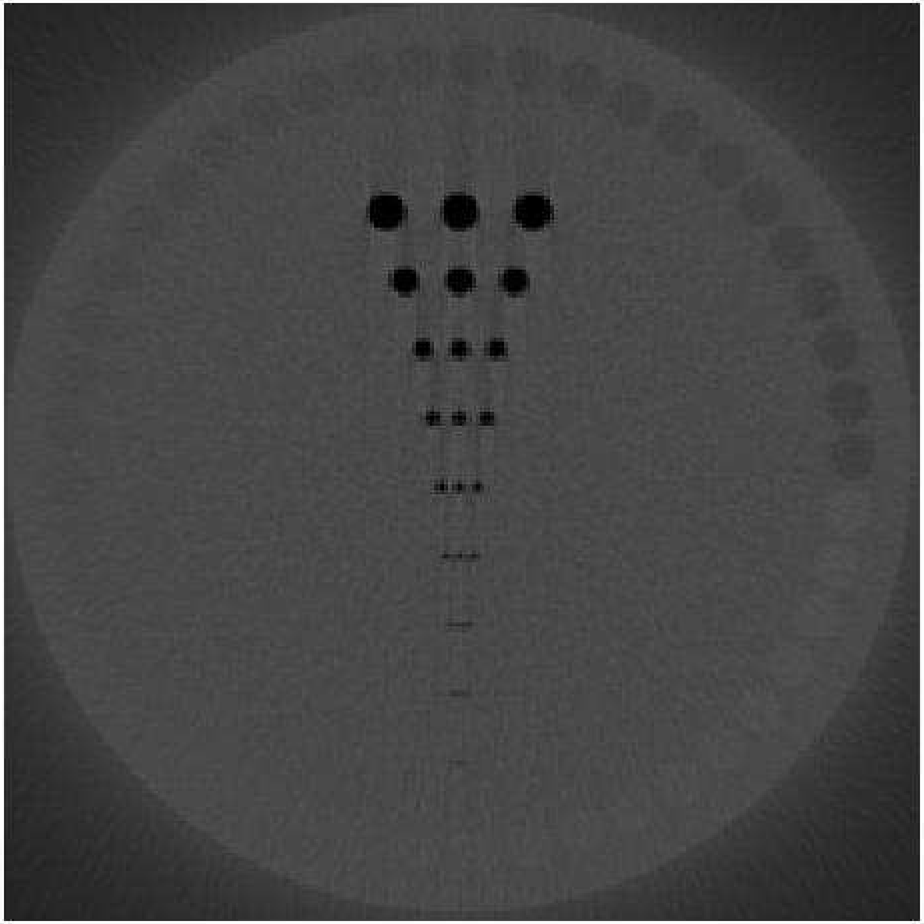


Image relative to path1



THE ROLE OF MONTE CARLO

200 MeV, 179 projections at 1°, 250K Histories, 20 cm circular phantom



Maximum exit angle: 1°

Image relative to path2

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Table relative to image with path1

$N_p (x10^6)$	2.5	5	7.5
Dose(cGy)	15.5	31.08	46.62
$R_A (l/cm)$	3.3	3.3	3.3
$R_B (\Delta\rho/\rho_{H2O})$	4%	2%	2%

Table relative to image with path2

2.5×10^5

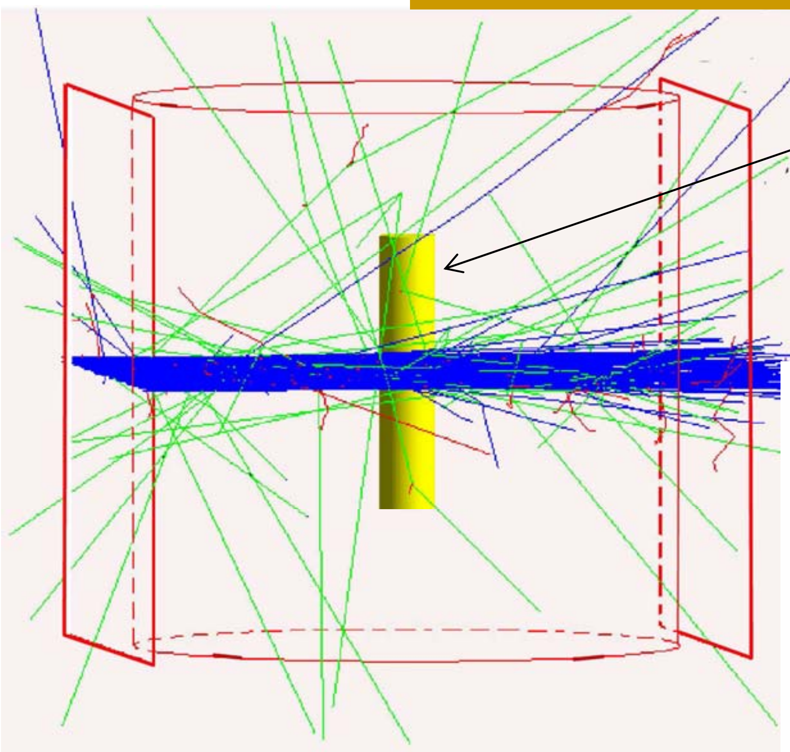
Dose (cGy)	5.1
$R_A (l/cm)$	2.5
R_B	4.5%

R. Shulte et al. *Reconstruction for proton computed tomography by tracing proton trajectories: A Monte Carlo study* Med. Phys. 33, 699 (2006).

→ **3-4 l/cm**

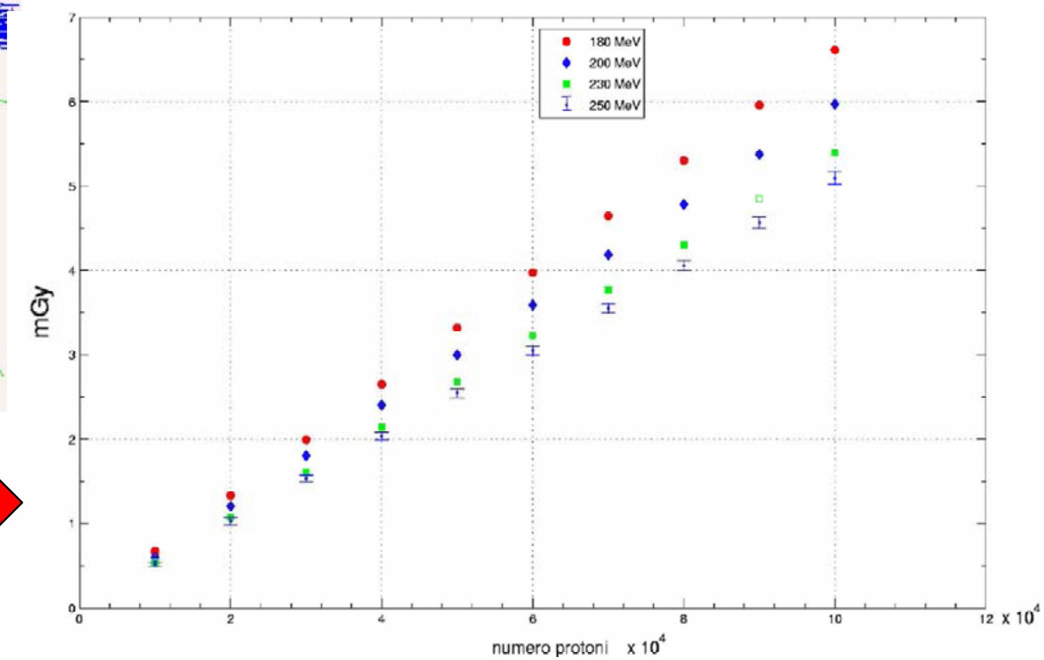
THE ROLE OF MONTE CARLO

Dose estimation: calculation of CTDI



Ionisation chamber

Dose versus number of histories



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CONCLUSION & FUTURE

- ✓ Patient positioning
- ✓ Improvement of input information of TPS and, consequently, improvement in dose control
- ✓ Lower dose level as respect the conventional xCT

Good density resolution and very small dose levels

Not so good spatial resolution → improvement of path estimation and of reconstruction algorithms (ART)

ISTITUTION INVOLVED IN THE pCT

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- Reinhard Shulte group at the Loma Linda University Medical Center

- Eros Pedroni group at Paul Sherrer Institute (actually they stopped the program)

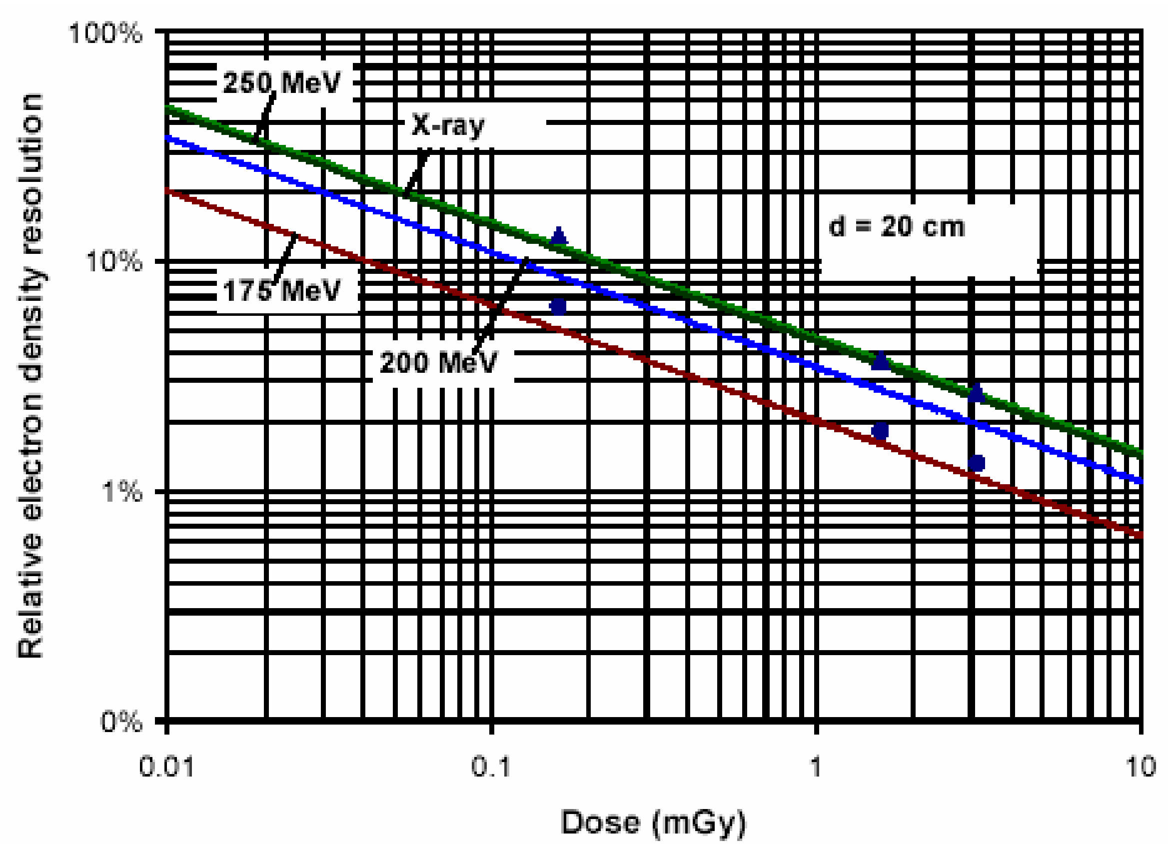
- The Italian group author of the work I am presenting:
  - Laboratori Nazionali del Sud – INFN, Catania
  - Physics Department e INFN Section, Catania
  - Clinic Phisiophatology Department, Florence University
  - Energetic Department, Florence University

} PRIMA

Thank you for your attention

LA RISOLUZIONE IN DENSITA’

Si richiede una accuratezza della conoscenza della densità elettronica in ogni voxel minore o uguale all’1%



GEANT4 studies:

R. Shulte et al.
Density resolution of proton computed tomography

Med. Phys. 32 (4), April 2005

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PER ENERGIE OPPORTUNE E’ POSSIBILE OTTENERE RISOLUZIONI IN DENSITA’ EQUIVALENTI ALLA X-CT MA CON UN RISPRMIO DI DOSE