Proton CT application in X-CT calibration for treatment planning in proton therapy

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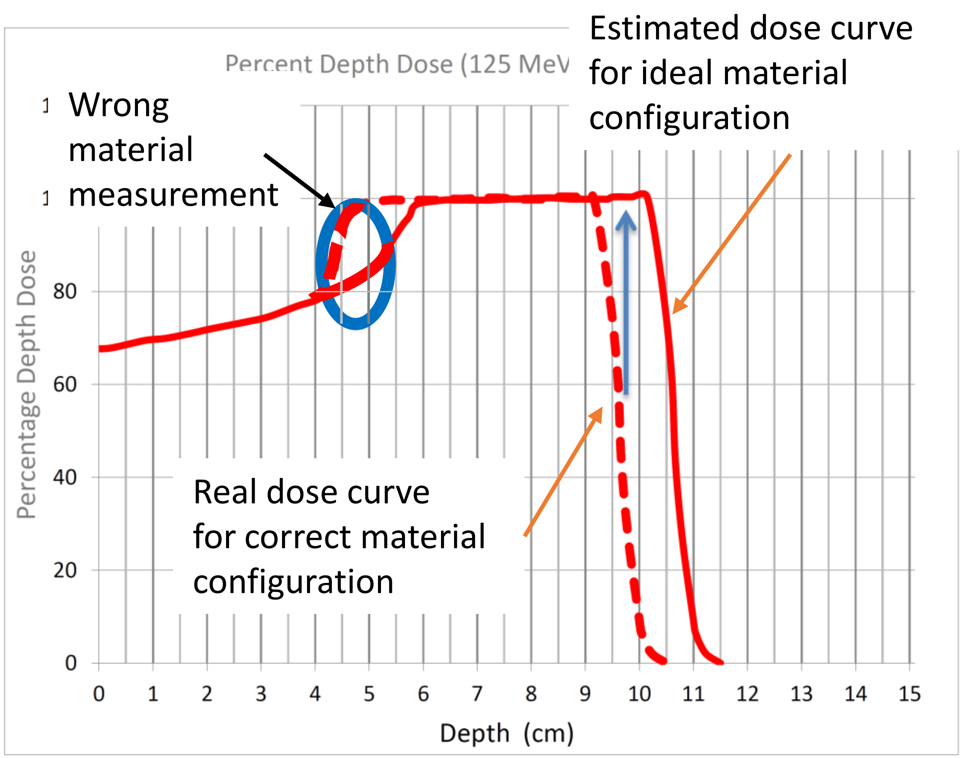
Outline

- Treatment planning in proton therapy
- The INFN proton CT (pCT) apparatus
- The XP-Calib project
- Test beam results
- Perspectives and Conclusions

Proton therapy treatment planning

Treatment planning requires a precise determination of the proton stopping power distribution (relative to water - **RSP**) within the volume crossed by the beam.



- RSP maps are derived form X-CT scans through a calibration procedure
- X-CT calibration introduces errors in RSP estimation
- For this reason the volume to be irradiated is enlarged by a safety margin which is tipically:

  +3.5%*range + 1mm

- This increases the healthy tissues potentially irradiated

x-CT calibration – present methods

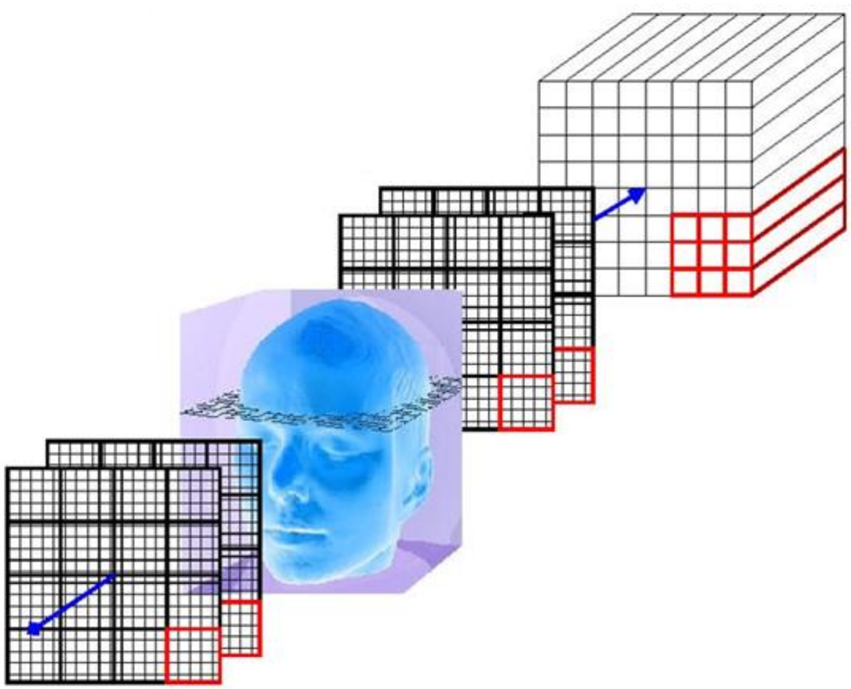
- Single-energy x-CT calibration is obtained by scanning a number of tissue equivalent materials (TEMs), suffering limitations in mimicking the properties of real tissues.
- To partially overcome that issue, a stoichiometric calibration has been proposed or, more recently, dual-energy x-CT methods were investigated.
- These are ‘two steps’ processes:
  1. x-CT scan to compute relative electron or mass densities (for DECT also the effective atomic number is computed);
  2. translation of such quantities into proton RSP using a heuristic function, which depends on specific material related properties affected by large experimental errors such as the mean excitation energy.
- Errors on the proton range using these procedures could be of the order of 1.5-3.3 mm (depending on the tumor location)
  - (*B. Schaffner and E. Pedroni Phys. Med. Biol.* 43 (1998) 1579–1592)

Possible solution: reduce errors in xCT calibration by using pCT to measure RSP maps of test phantoms

How to perform a proton CT

Use a **monoenergetic proton beam** which is able to cross the patient's body (200-230 MeV): the residual proton energy (or range) carries information about the **stopping power distribution** of the traversed material.

The phantom is rotated during data taking to collect protons entering the object from many different (ideally continuous) directions.



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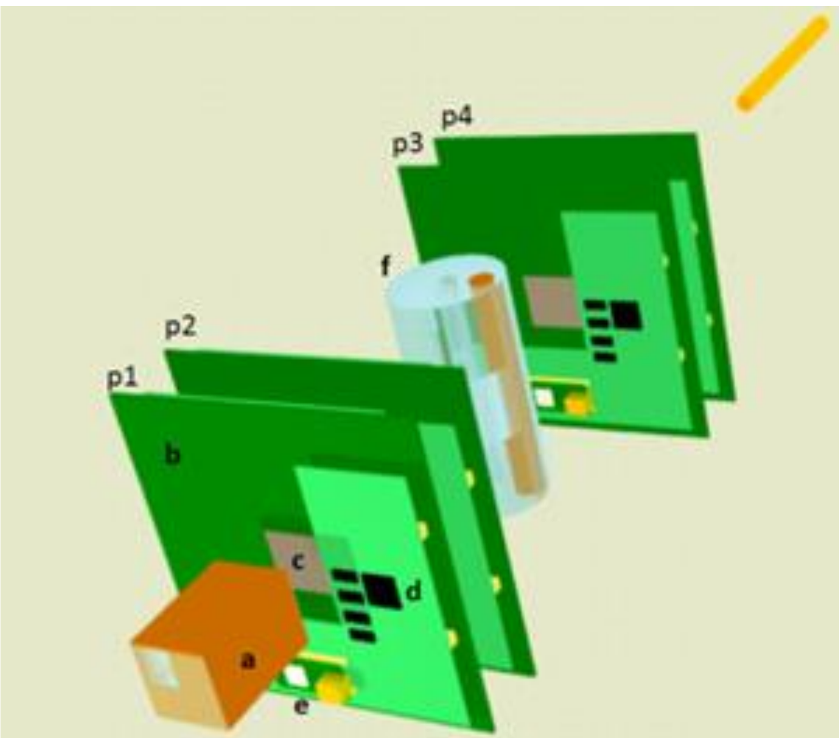

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To mitigate the effect of the multiple Coulomb scattering we need an **event-by-event** measurement:

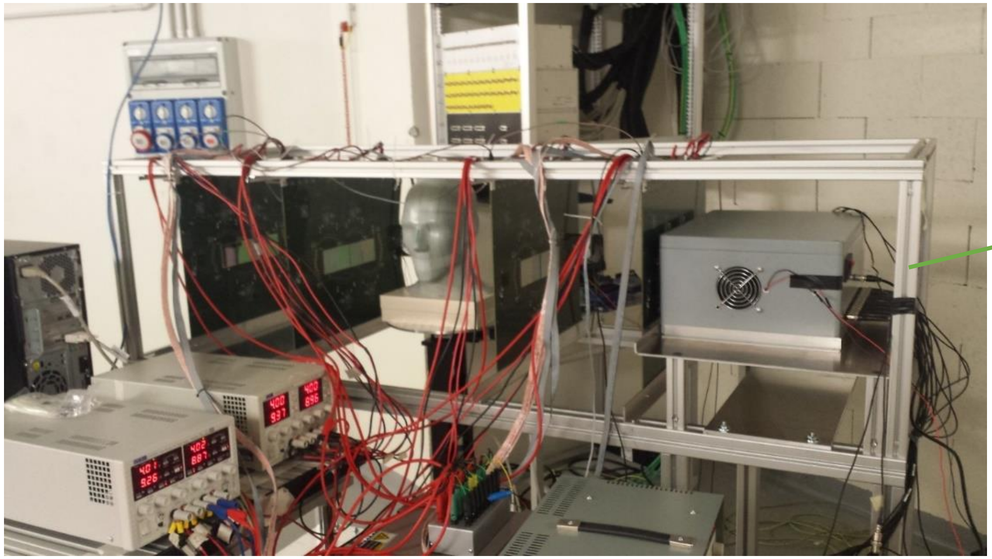
1) **Tracker** to measure the proton Most Likely Path (MLP) → Silicon microstrip detectors (~70 μm point resolution);

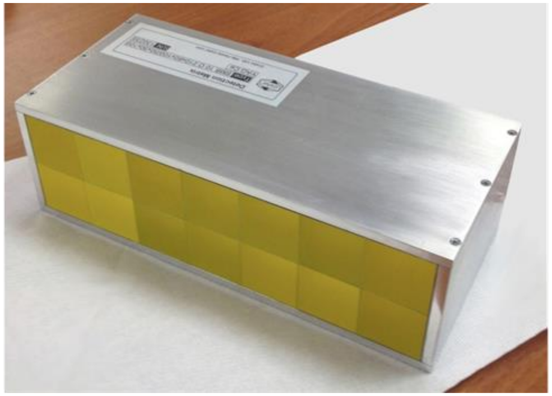
2) **Calorimeter** to assign an energy loss to each proton track → YAG:Ce scintillating calorimeter (~1% energy resolution @ 200 MeV);

3) Process data with reconstruction algorithms (ART, FBP) to obtain CT images

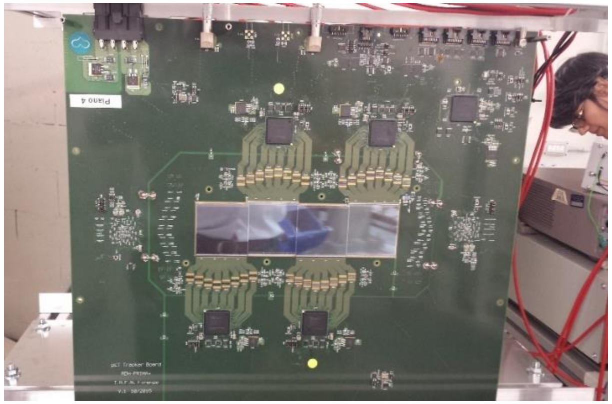
The INFN pCT apparatus

INFN pCT apparatus mounted at APSS Trento experimental beam line





Calorimeter
2x7 YAG:Ce Crystals Array
$3x3x10cm^3$ each



Tracker composed of 4 xy planes
Each xy plane based on 4x2 silicon microstrip p-on-n detectors, 200μm pitch, 320μm thick
$5x20\ cm^2$ active area

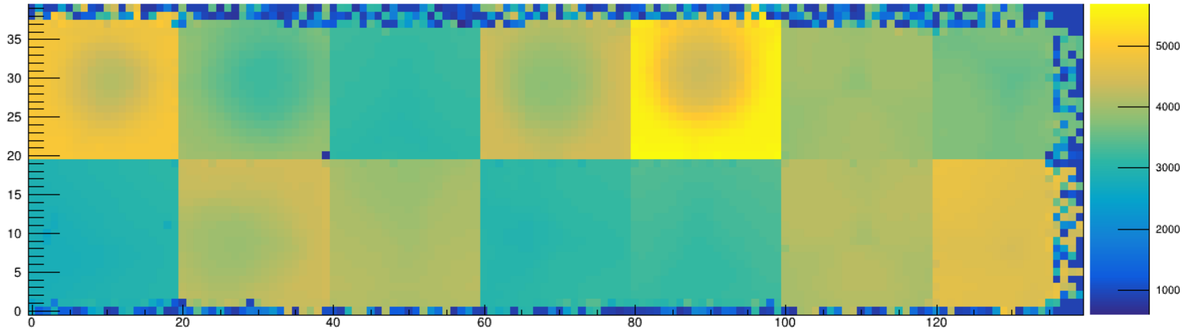
Carlo Civinini *et al. Phys. Med. Biol. 65 (2020) 225012*

Detectors read-out

- Silicon tracker
  - Custom front-end board equipped with 6x8 front-end chips (discriminators - 32 channels each), single channel I^2C programmable thresholds
  - 2 levels FPGA: data reduction + event building
- Calorimeter
  - Hamamatsu 18x18 mm^2 photodiodes (S3204)
  - Analogue amplifier + shaper (1μs)
  - Custom Analogue to digital readout board
- Serial transmission of digitized data to Central DAQ through source-synchronous serial protocol on 8 data lines + clock @ 1.6 Gbps
- Central DAQ board
  - ML605 Xilinx Virtex 6 development board equipped with custom FMC interface board with PCIe link to acquisition PC

Energy calibration

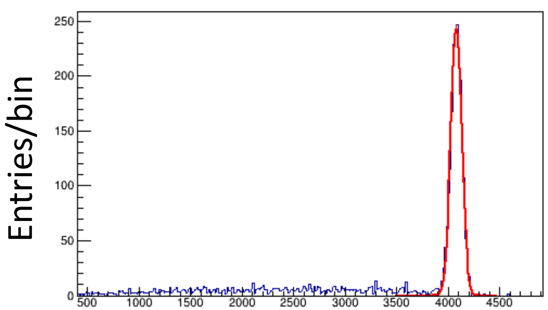
ADC counts map at 200 MeV



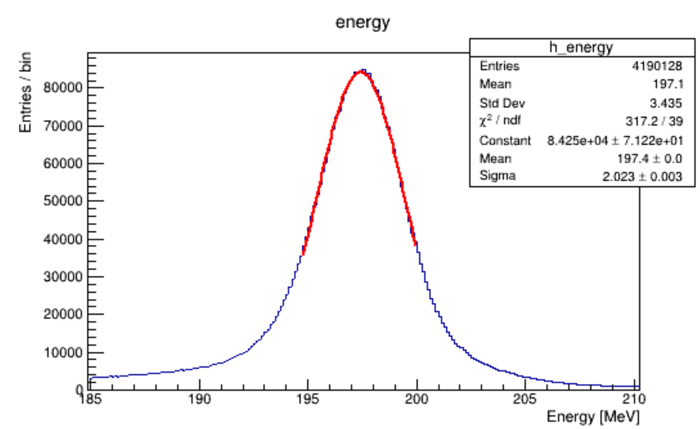
6 runs with no phantom at energies from 80 to 200 MeV

- Each crystal is divided in 20x20 bins ($1.5 \times 1.5 mm^2$)
- For each bin and energy the ADC count distribution is fitted with Gaussian function
- For each bin a calibration function is extracted by polynomial fit

Gaussian fit for one bin

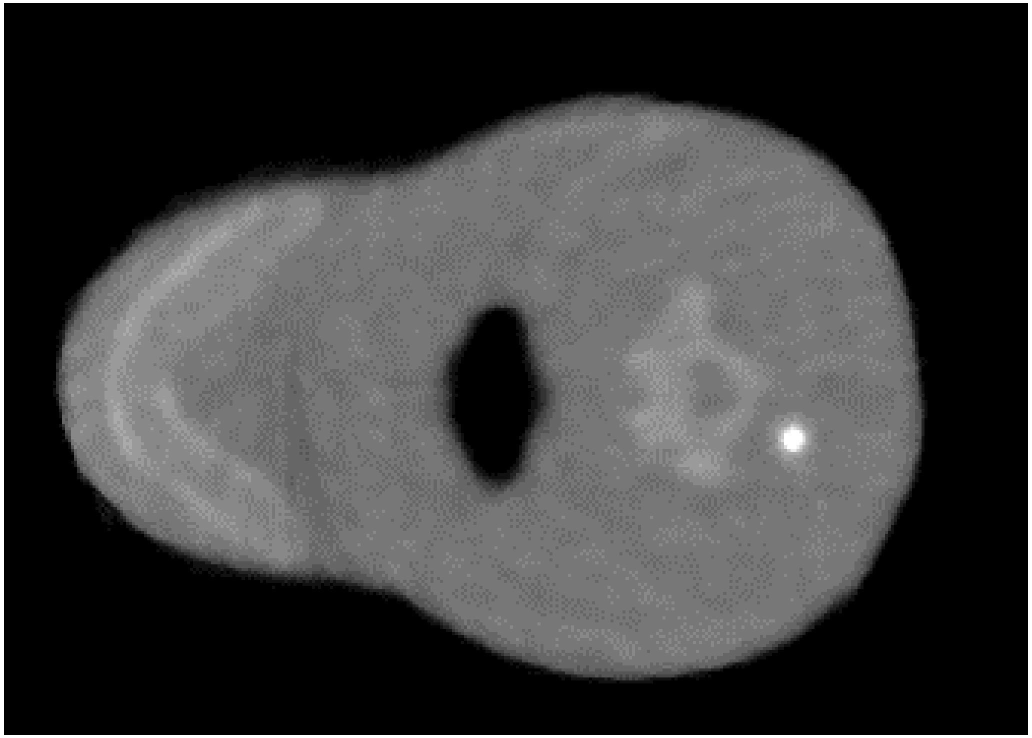


Overall resolution after calibration ~ 1% at 200 MeV



Anthropomorphous phantom proton tomography

Proton Tomography



X-ray radiography

Tomography region

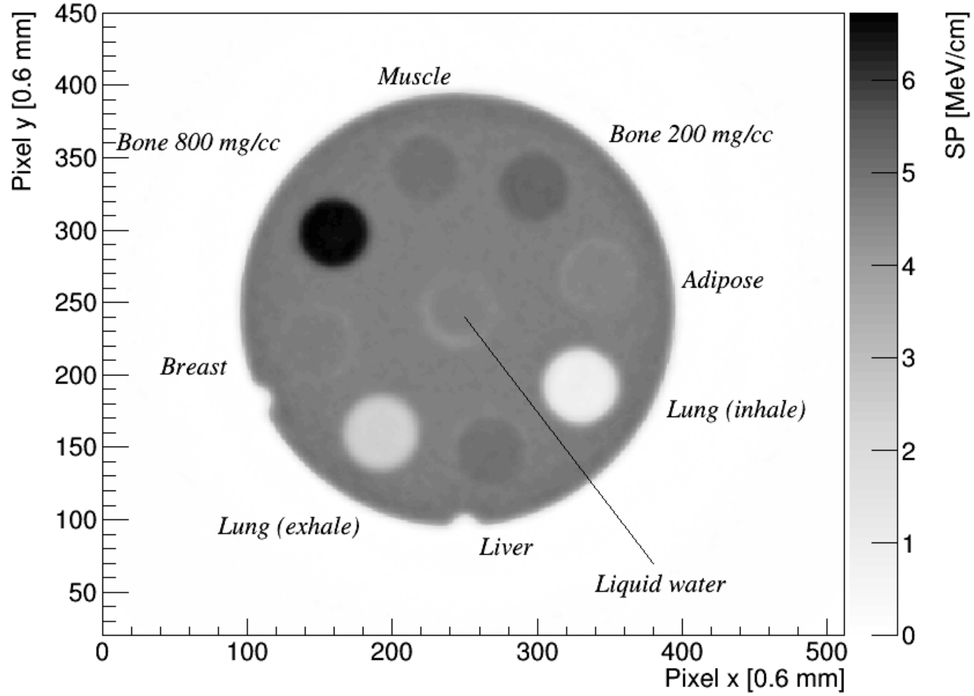
Algebraic reconstruction: 64 axial slices
voxels: $600 \times 600 \times 812 \mu m^3 \sim 0.3 mm^3$
400 angles (0.9 deg. uniform spacing)
3.7×10^7 events (selected)

Movie starts from lower jaw ends at upper teeth (5.2 cm range).

Total dose $\sim$ 1.5mGy

Data have been collected using the experimental beam line of the Trento Proton Therapy Centre (June 2018) – 211 MeV proton energy

Electron density phantom

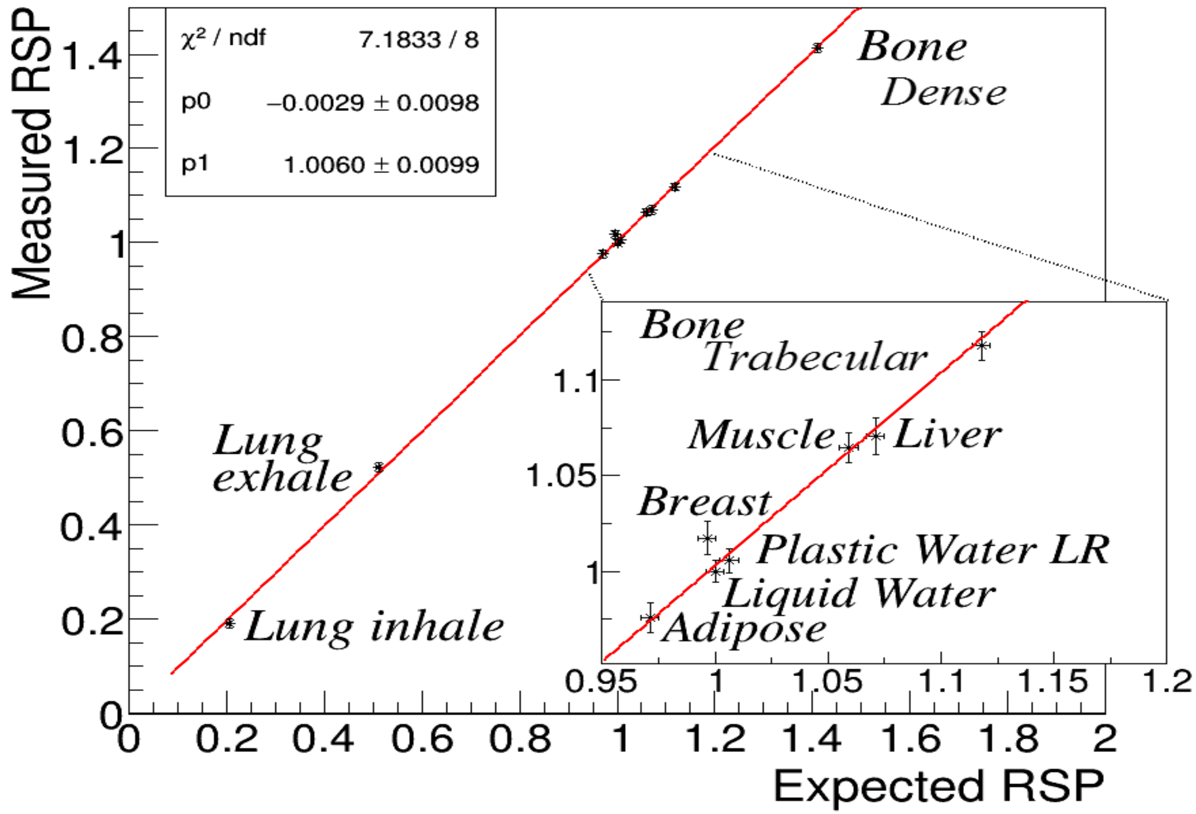


1.6mm thick central slice of the tomography

Algebraic reconstruction: 75th iteration

RSP correlation

Carlo Civinini *et al. Phys. Med. Biol. 65 (2020) 225012*

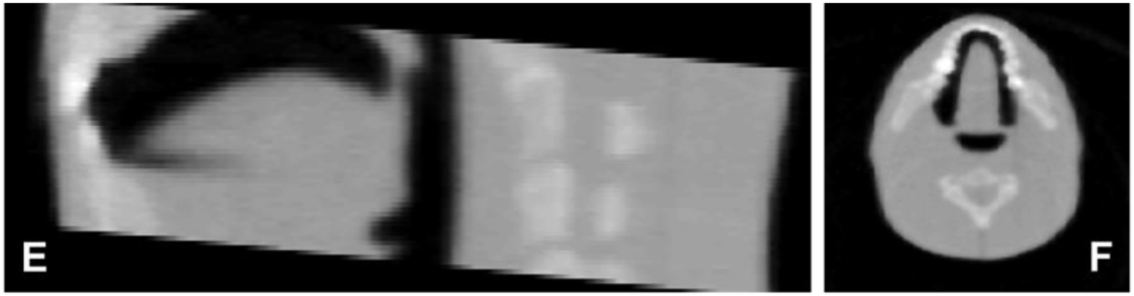


Measured Relative Stopping Power are compatible with the predicted ones at 1% level

The XP-Calib project: x-CT calibration by pCT

- This project aims at a performing a x-CT calibration using direct RSP measurements on heterogeneous biological tissues performed by the INFN pCT apparatus
- This procedure has the potentiality of reducing the calibration errors arising from the use of tissue equivalent synthetic samples and material specific quantities such as the mean excitation energy.
- The experimentally tested INFN pCT apparatus could then be used in the proton therapy treatment planning setup

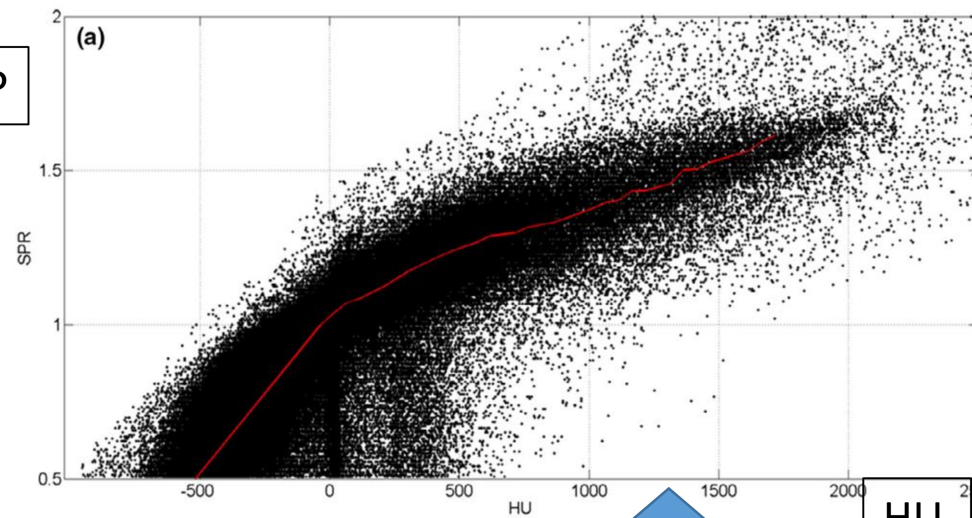
Implementation of the x-CT calibration by pCT



Best correlation curve from Voxel-by-voxel scatter plot

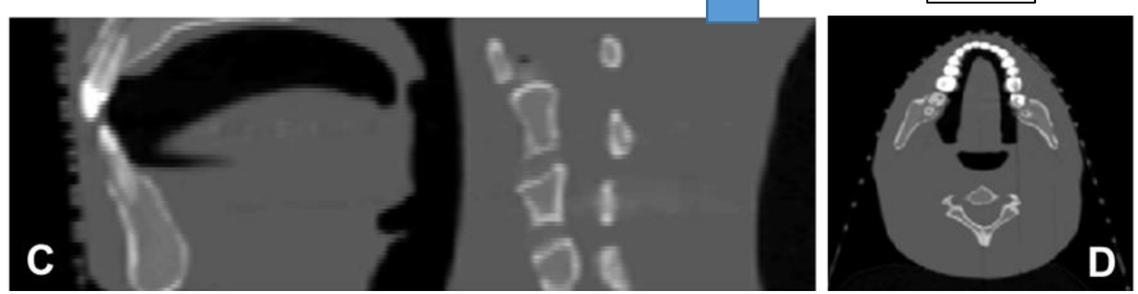
pCT image

RSP



HU

Register the two different images → same reference systems, same unit length, possible deformation correction by the TPS reg. tool (RaySearch Lab.)



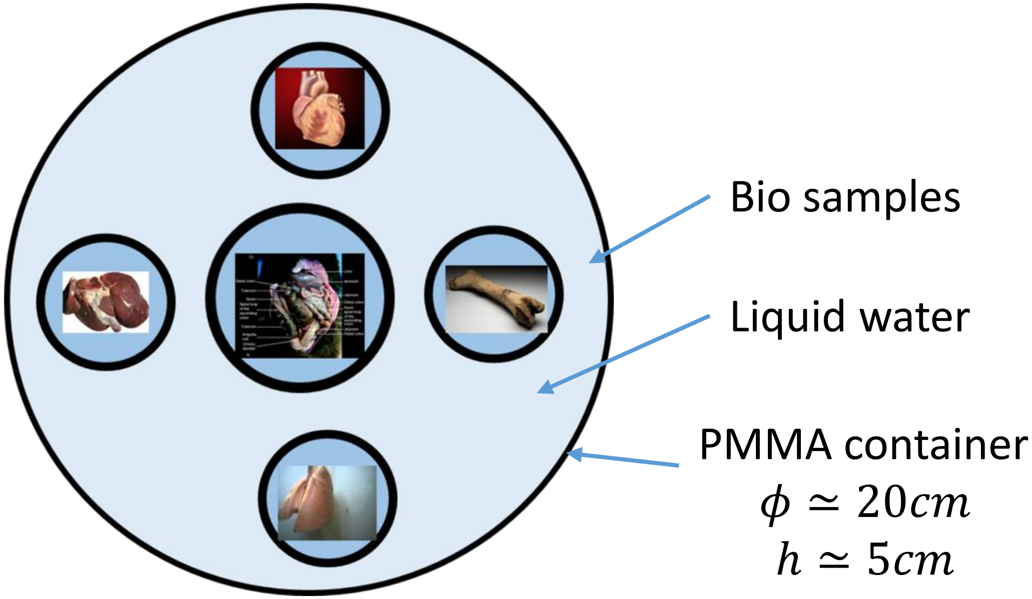
Technical Note: CT Calibration for Proton Treatment Planning by Cross-Calibration with Proton CT Data

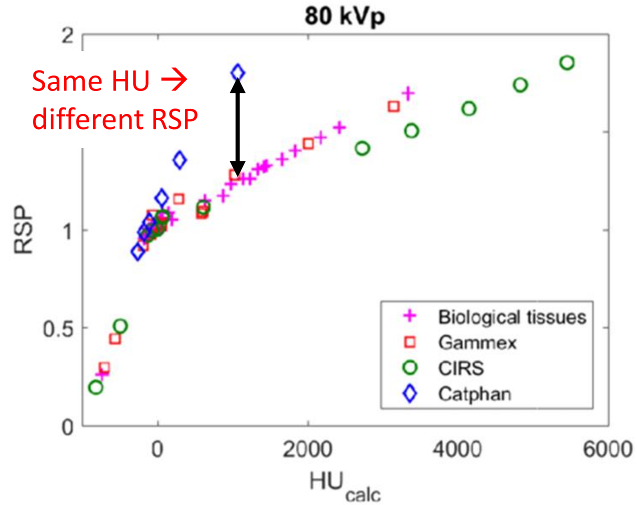
Paolo Farace *et al.* Med Phys 48 (3), March 2021

x-CT image

Biological phantom

- To avoid problems arising from the use of the synthetic tissue equivalent material we decided to implement a biological phantom





Phys. Med. Biol. 63(23) · Nov. 2018

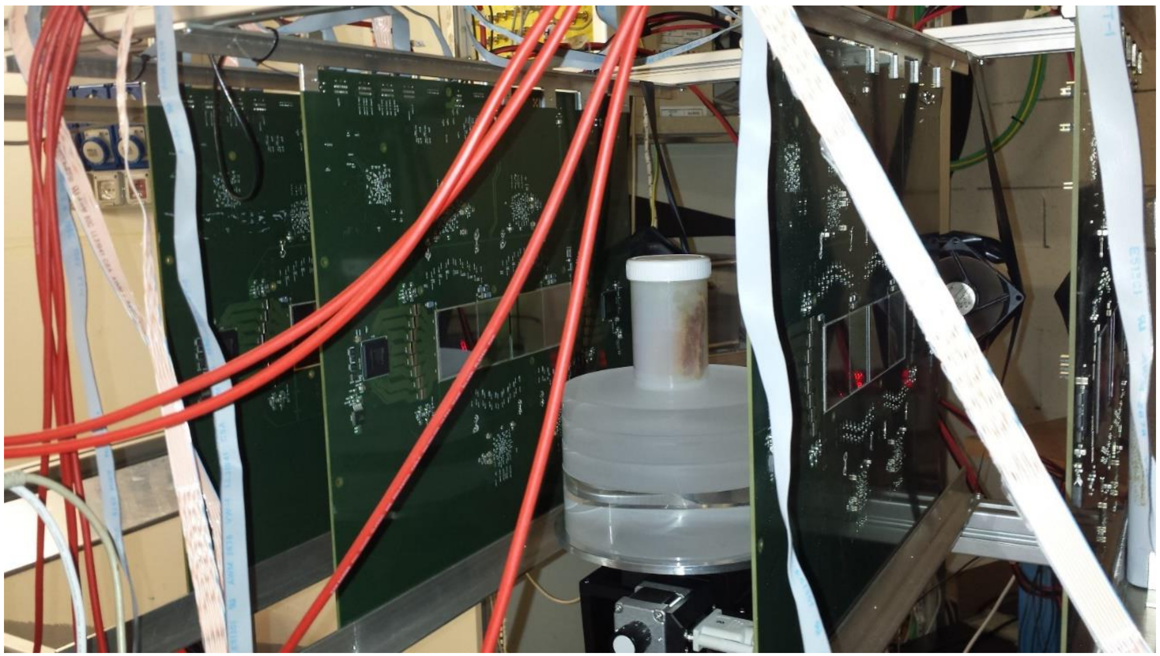
- Animal tissue samples are stabilized in formaline, rehydratated and finally suspended in hydrogel.
- The samples are hosted in a container filled with water mixed with a bacteriostatic agent.

Perspectives:
XpCalib for other therapy centres

- The x-CT calibration via pCT is easily exportable to other proton therapy centres:
    1. pCT scan of the bio-phantom @ Trento
    2. Shipping the bio-phantom to the remote centre
    3. x-CT scan of the bio-phantom at the remote centre
    4. x-CT back to Florence/Trento
    5. Calibration curve
    6. Shipping the bio-phantom back to Trento
    7. Verification radiography at Trento
- No new hardware
    - One x-CT image + one pCT image + one radiography

Beam test at Trento APSS Proton Therapy Center May 2021

Several tomographies acquired, analysis in progress

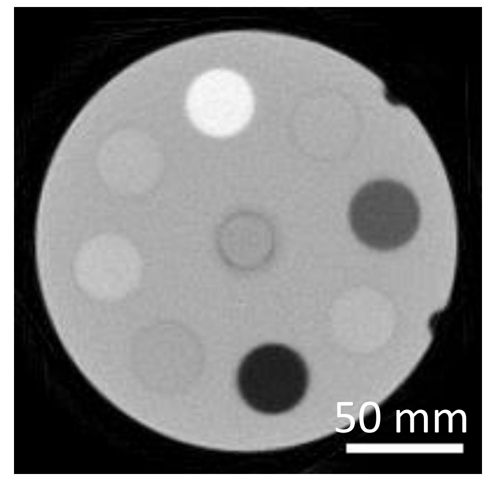


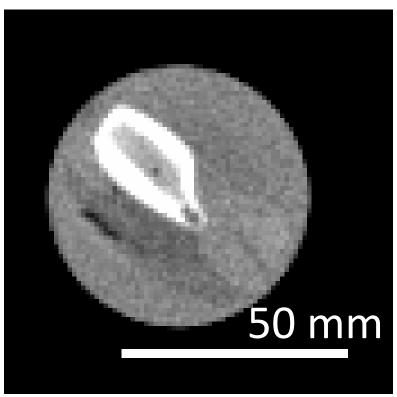
Biological phantom on the rotating platform of the pCT apparatus

Preliminary results

Preliminary pCT image obtained with open-source reconstruction algorithm (Filtered Backprojection along Most likely paths [1]) developed by Simon Rit group at CREATIS Research Lab, Lyon
https://github.com/SimonRit/PCT
Thanks to Simon for his support in adapting the software to our data set

Electron density phantom





Biological phantom

10^8 protons at 150 kHz acquisition rate
~ 2 mSv dose to phantom

[1] Simon Rit et al. "Filtered backprojection proton CT reconstruction along most likely paths" Med Phys 40(3), March 2013

Conclusions

- A novel method of xCT calibration for treatment planning in proton therapy using pCT has been proposed
- Phantoms composed of stabilized biological samples have been designed and are under development
- xCT calibration procedure could be extended to other proton therapy centers
- First tomographies of biological and tissue substitues phantoms have been acquired, analysis in progress