Development of a preclinical proton CT scanner: current status

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OUTLINE

- From proton therapy to proton computed tomography (pCT)
- LLU/UCSC prototype pCT scanner
  - Tracking planes & energy detector
  - Preprocessing & calibration & image reconstruction
  - Software simulation platform
- pCT image reconstruction
- pCT dosimetric evaluation
- Conclusion & future work

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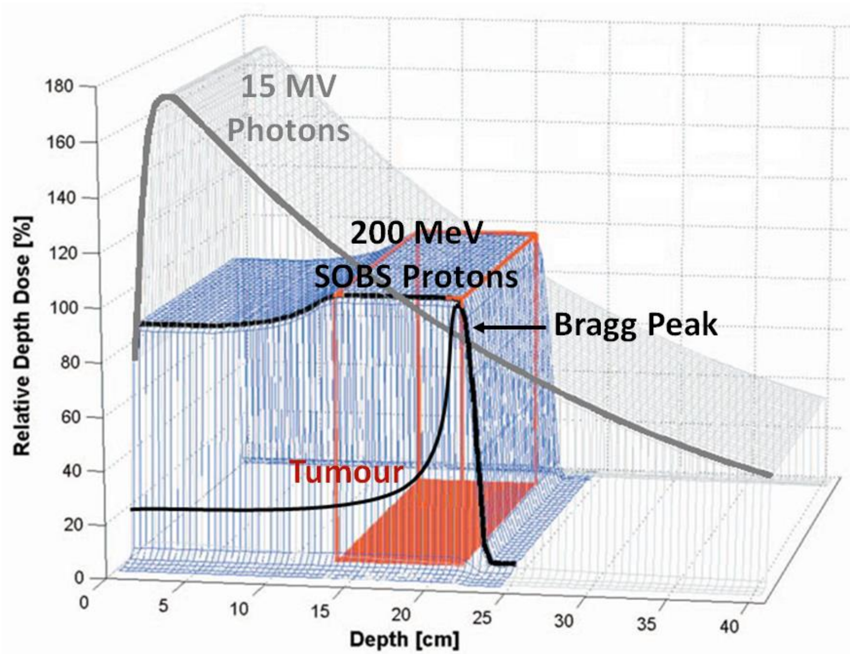
From Proton Therapy to Proton Computed Tomography

- Bragg Peak --› high sensitivity of proton therapy to tissue distribution --› proton therapy relies on accurate imaging.
- OAR closed to rapidly changing tumours, requires daily imaging and continuous replanning.
- Nowadays, both photons and protons therapy are based on x-ray CT images - **map of Hounsfield (HU) values**.
- Treatment planning for proton therapy requires a **map of protons stopping power** relative to water (RSP).



Depth vs dose curve for photons and protons.

Proton Computed Tomography

Proton Computed Tomography (pCT) is an **imaging technique** in which protons **substitute x-rays** to produce tomographic relative stopping or scattering power images of the patient.

Advantages:

- Lack of beam hardening artefacts;
- Improved range estimation of proton therapeutic beams:
  - x-ray CT scan + proton therapy = 3% error in the depth at which the protons stop.
  - pCT scan + proton therapy = less than 1% of error in the depth at which the protons stop.
- Lower dose required, good for daily verification.

Drawbacks:

- Only useful for particle therapy (protons accelerators are more expensive and complex than x-ray sources);
- Multiple Coulomb Scattering (MCS) reduces the spatial resolution;
- Proton energies larger than 300 MeV for complete scans of adult (trunk) abdomen and pelvis.

K. M. Hanson, et al., *The application of protons to computed tomography*, IEEE Trans. Nucl. Sci., 1978.

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Proton Computed Tomography

Primary pCT goal: calculation and reconstruction of the distribution of the **relative stopping power (RSP)** with respect to water of a 3D object.

$$RSP(E) = \frac{SP(E)_{material}}{SP(E)_{water}}$$

- **Preclinical pCT scanner prototype** realized at Loma Linda University (California, USA) in collaboration with University of California Santa Cruz (California, USA) and Baylor University (Texas, USA). Other institutions have joined the collaboration.

- **Experimental measurements** conducted first at **Loma Linda University** and later at **Northwestern Medicine Chicago Proton Center** (Warrenville, Illinois, USA).

- pCT scanner **simulated** to study/optimize the performance --› **software simulation platform.**

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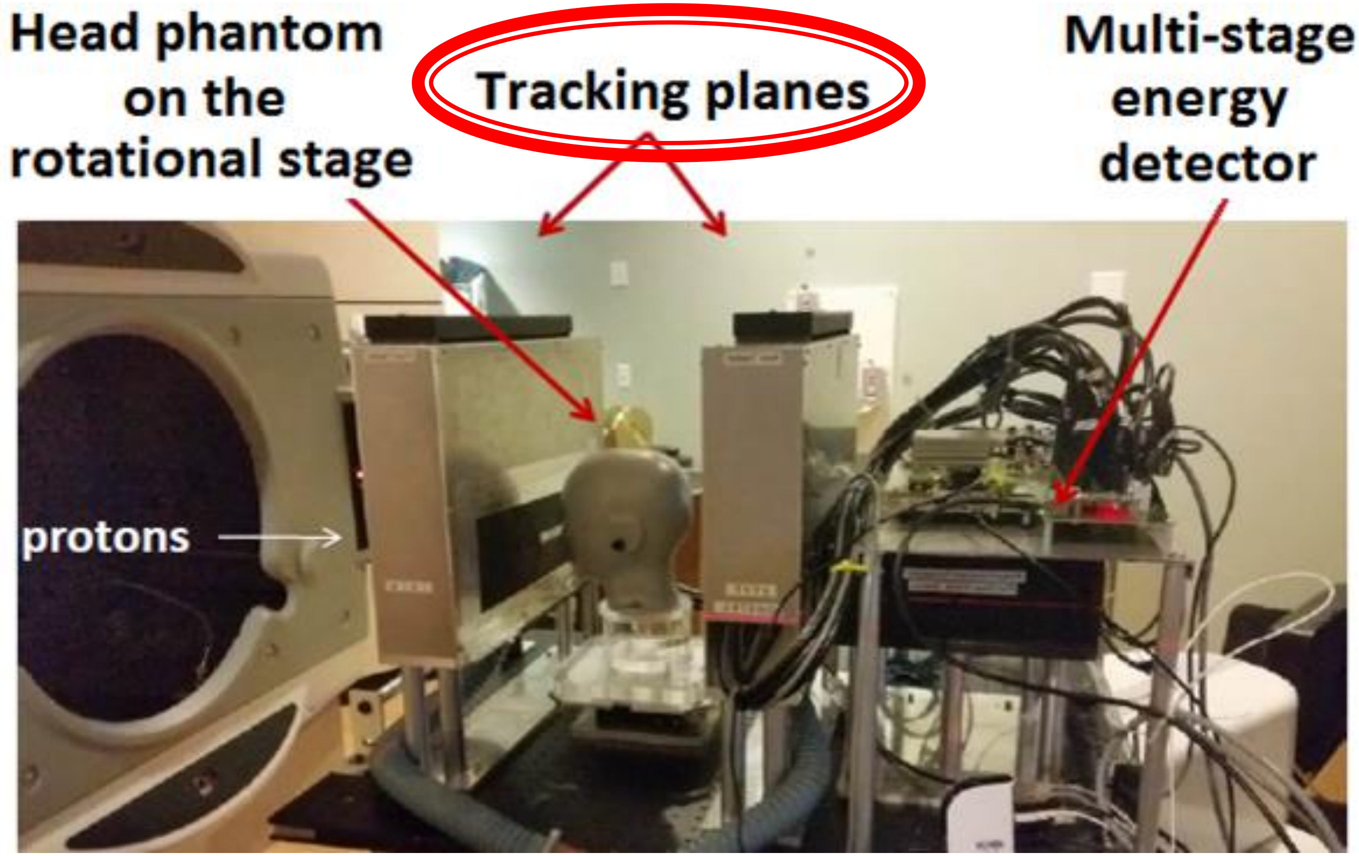
LLU/UCSC pCT scanner prototype



pCT scanner with a paediatric head phantom installed at the proton beam line at the Northwestern Medicine Chicago Proton Center.

Courtesy of R. P. Johnson

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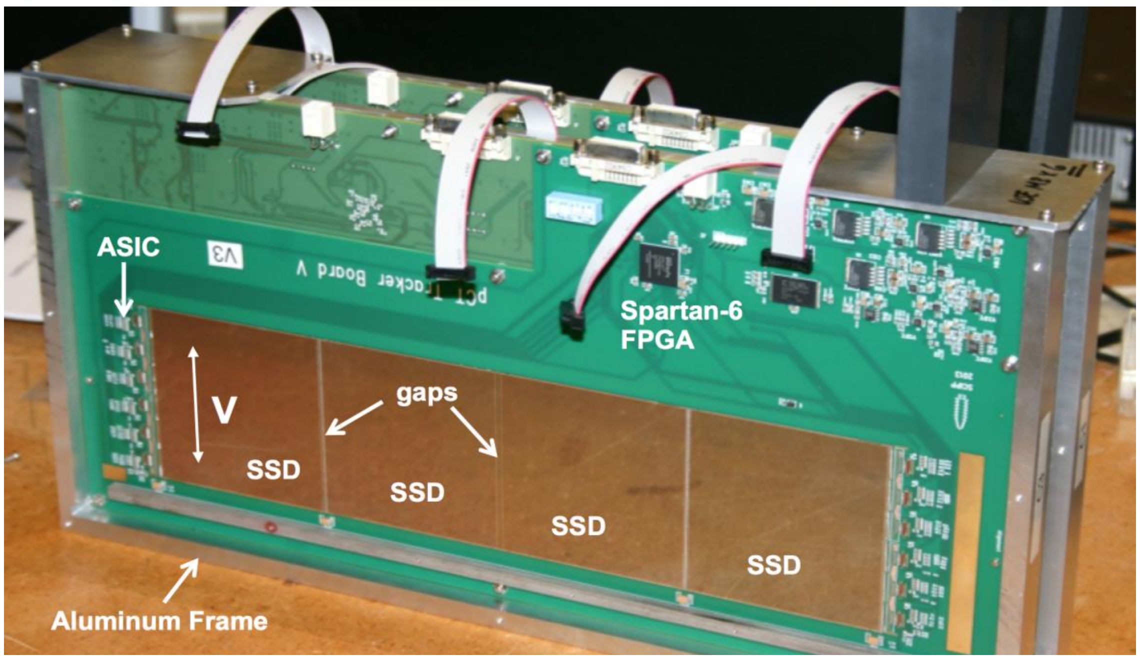
pCT scanner prototype: tracking planes

- Front and rear tracking planes consist of **two paired silicon strip detector (SSD) planes** with vertical and horizontal strip orientation, respectively.
- Each tracker plane consists of **four square SSDs** with individual sensitive areas of 8.6×8.6 cm^2 (**total sensitive area of 34.9×8.6 cm^2 per plane**)
- The **thickness** of each SSD is **0.4 mm**, and the **strip pitch is 0.228 mm**.



Tracking plane of the pCT scanner prototype (V-plane horizontal strips).

R. P. Johnson, et al., *A fast experimental scanner for proton CT: technical performance and first experience with phantom scans*, IEEE Trans. Nucl. Sci., 2016.

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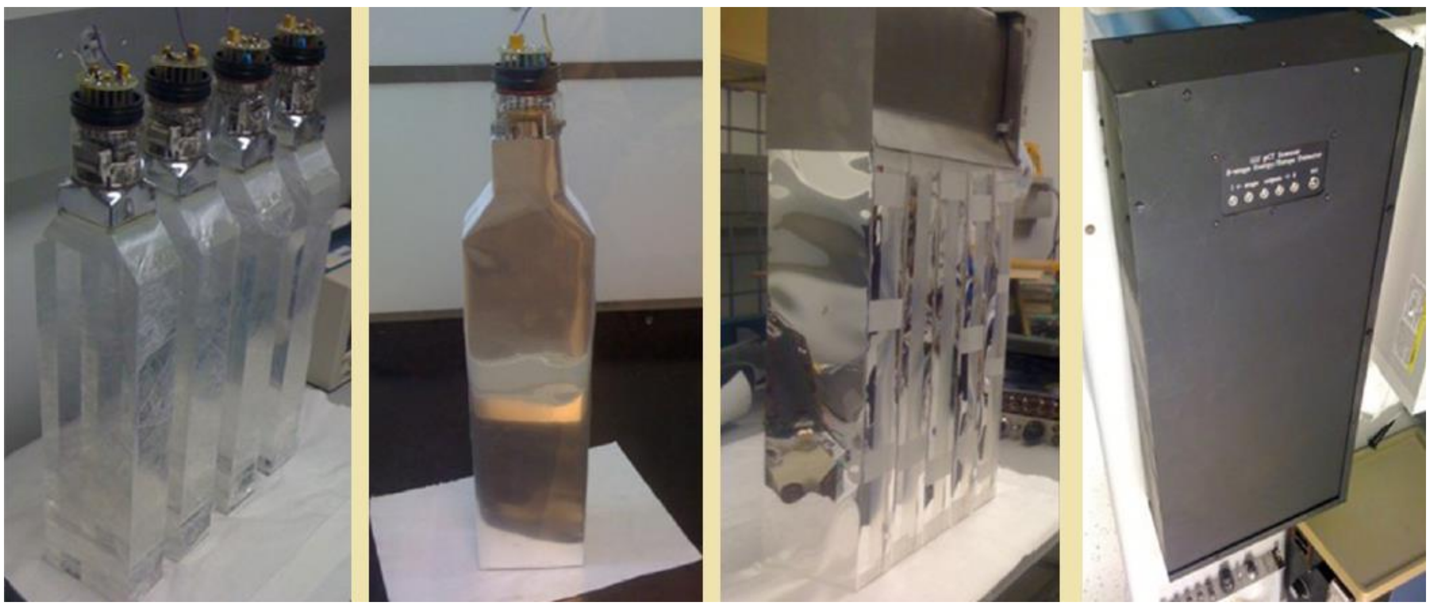
pCT scanner prototype: energy detector

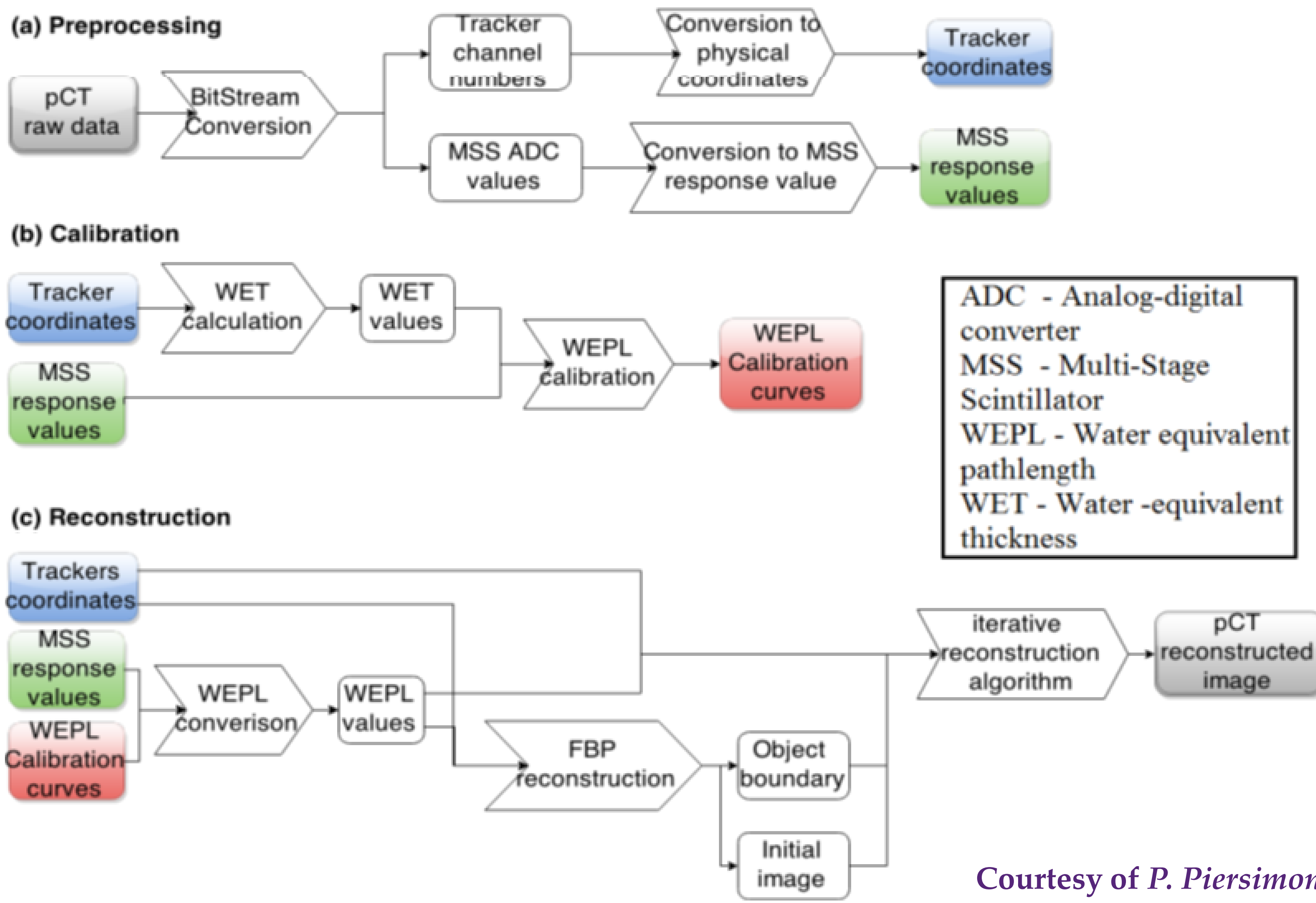
- Multi-stage detector composed of five UPS-923A **polystyrene scintillators** with a **sensitive area of 36 × 10 cm^2** and a **thickness of 5.1 cm.**
- Total **water equivalent thickness** of the detector is **26.4 cm** (sufficient to stop 200 MeV protons).
- Scintillating light of protons registered by a **photomultiplier** (PMT, model R3318 Hamamatsu) and **converted to a digital value** by custom readout.



Assembly of the multi-stage energy detector of the pCT scanner prototype.

V. A. Bashkirov, et al., ***Novel scintillation detector design and performance for proton radiography and computed tomography*****, Med. Phys., 2016.**

pCT scanner prototype: data flow

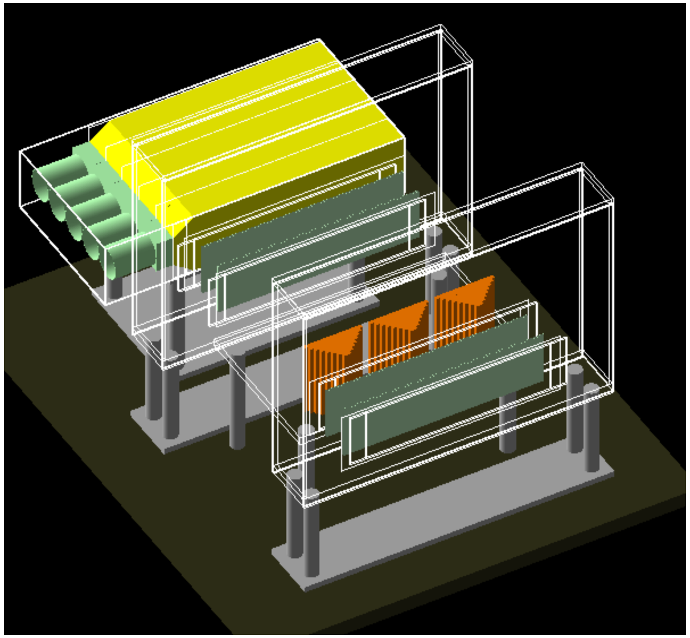


ADC - Analog-digital converter
MSS - Multi-Stage Scintillator
WEPL - Water equivalent pathlength
WET - Water -equivalent thickness

Courtesy of *P. Piersimoni*

pCT scanner prototype: software simulation platform

- Software simulation platform created to reproduce the entire pCT system: data acquisition --› calibration --› image reconstruction.
- pCT scanner modelled with **Geant4** (beam line, scanner geometry, phantoms).
- Simulation platform **validated** by means of **experimental results** (tracking planes response, energy detector response and image reconstruction)
- Simulation platform can be used for **virtual tests** (larger objects scanned, moving phantoms, etc.)



Geant4 presentation of the pCT scanner prototype with the step calibration phantom (orange).

V. Giacometti, et al. *Software Platform for Simulation of a Prototype Proton CT Scanner*, Med. Phys. (submitted and accepted), 2016.

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pCT scanner prototype: image reconstruction

Algebraic Reconstruction Technique (ART) is a method that takes into account the non-linear particle paths involved in the tomographic acquisition due to MCS of protons in the patient.

- Input: proton coordinates and directions (front and rear trackers) & WEPL
- Proton path estimated (most likely path) --› **A** (matrix)
- WEPL values --› **b** (vector)
- Iterative solution of the **algebraic linear system** $\mathbf{A}x = \mathbf{b}$ --› x is the unknown RSP vector
- RSP displayed as a 3D voxel image (stack of slices) with isotropic voxel size (1 x 1 x 1 mm^3)

S. N. Penfold, et al., *Characteristics of proton CT images reconstructed with filtered backprojection and iterative projection algorithms*, IEEE Trans. Nucl. Sci., 2009.

F. Feldt, et al., *Prototype tracking studies for proton CT*, IEEE Trans. Nucl. Sci., 2005.

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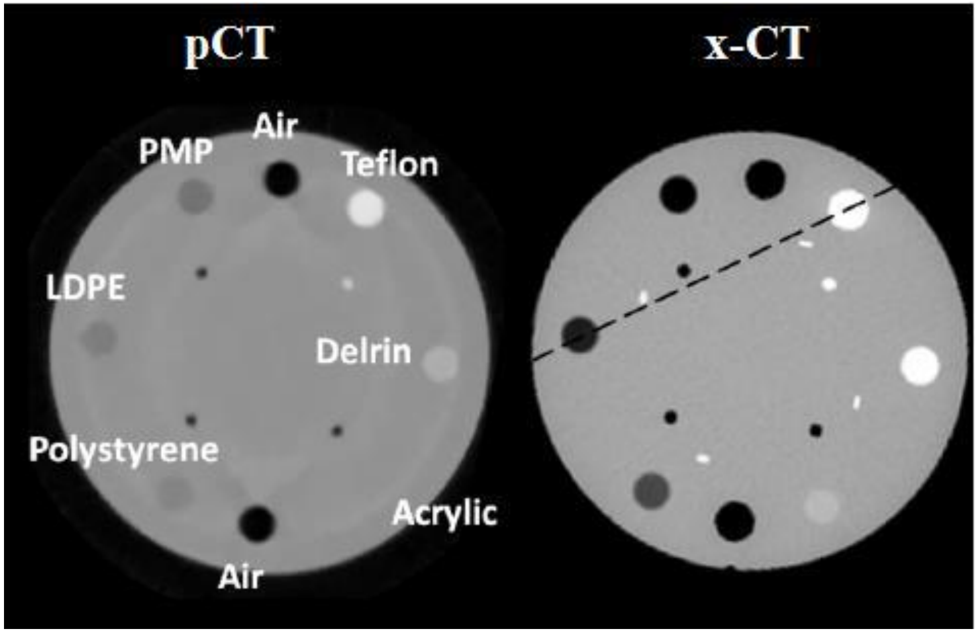
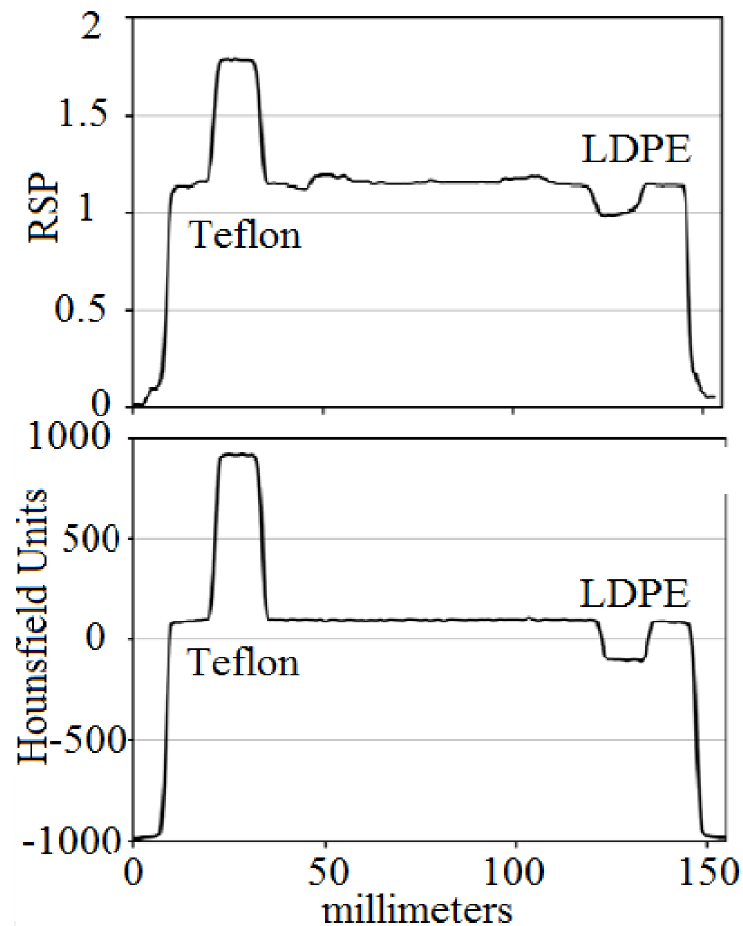
pCT Image Reconstruction: sensitometry module (CTP404)



Proton CT and x-ray CT reconstruction of the CTP404 phantom

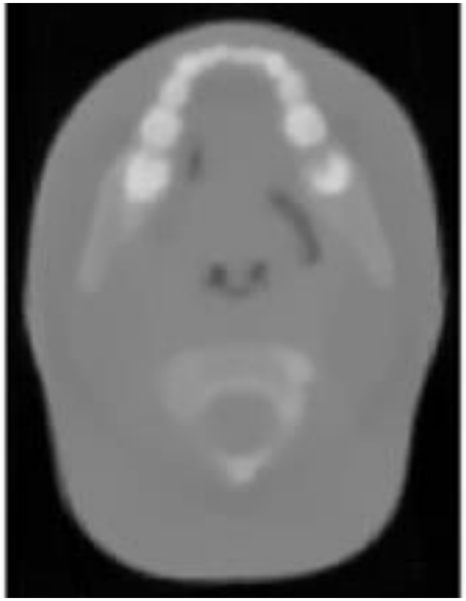


R. P. Johnson, et al., *A fast experimental scanner for proton CT: technical performance and first experience with phantom scans*, IEEE Trans. Nucl. Sci., 2016.

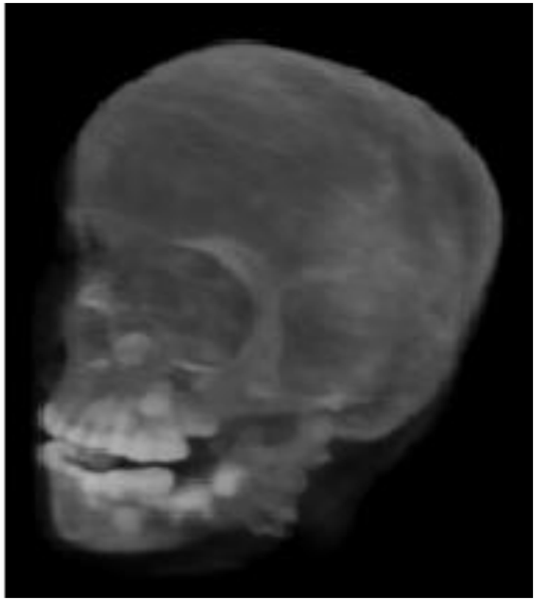
pCT Image Reconstruction: Pediatric head phantom

Paediatric head phantom

pCT reconstruction (slice)



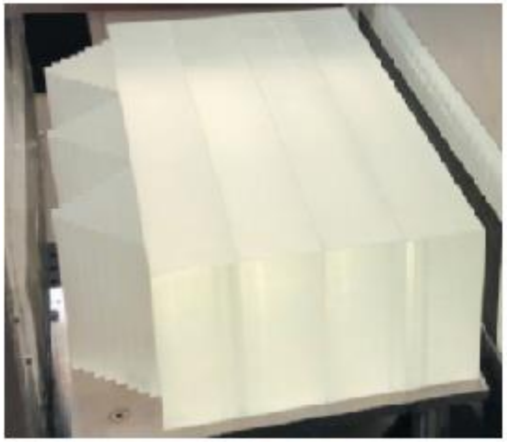
pCT reconstruction (volume)



Courtesy of *R. Cassetta*

pCT Image Reconstruction: Water phantom

Step phantom calibration



Wedge phantom calibration

Courtesy of *C. Ordonez*

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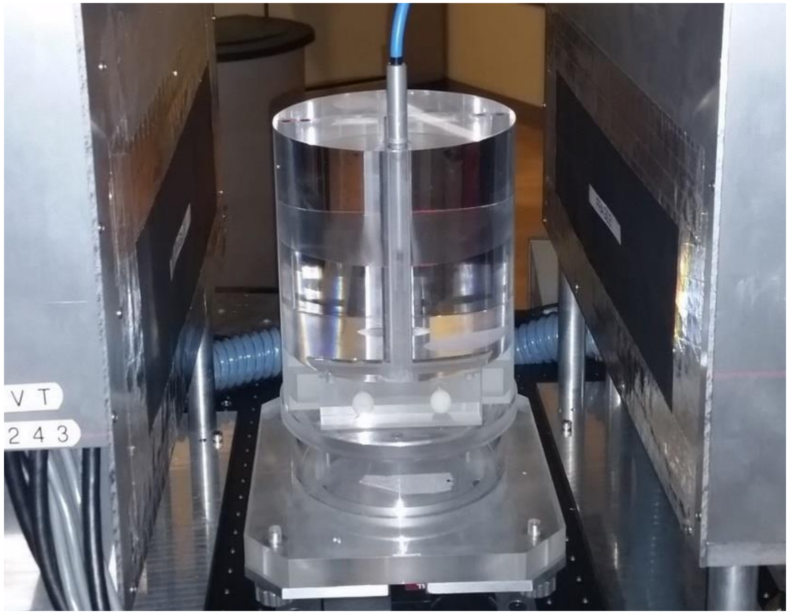
pCT scanner prototype: dosimetric evaluation

- Proton energy of **200 MeV** at nozzle exit (Northwestern Medicine Chicago Proton Center).
- Dose phantom installed on the rotation platform.
- **Farmer ionization chamber (model 30013, PTW, Freiburg, Germany)** installed:
  - in the central hole --› phantom kept motion less during the pCT exposure;
  - in one of the peripheral holes of the dose phantom --› phantom continuously rotated at a speed of 1 rpm.



Catphan CTP554 acrylic dose phantom (Ø 16 cm) with Farmer ionization chamber mounted in the central hole.

V. Giacometti, et al., *Dosimetric Evaluation of Proton CT using a Prototype Proton CT scanner*, 2016 IEEE NSS/MIC Conference Record, Strasbourg, (FR).

pCT scanner prototype: dosimetric evaluation

- Accumulated charge measured with the 35040 Advanced Therapy Dosimeter (Fluke Biomedical, Solon, OH, USA).

- Dose phantom exposed for **7 minutes** for both locations --› proton fluence at the level of upstream inner tracker planes estimated to be 1.4 M protons/cm^2.

- Dose to water, after the background correction:
  - **1.46 mGy** in the peripheral location.
  - **1.48 mGy** in the central location.

- Uniform dose across the phantom.

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Conclusions & future work

- pCT promising imaging technique for:
  - **RSP accuracy** - important for treatment planning and verification;
  - **Low dose** - important for repeated imaging in treatment room.
- pCT scanner prototype **modelled** using **Monte Carlo methods** (validated results);
- Important: **comparison against other method** (e.g. in room CT, DECT).
- **Further improvements** for the next pCT scanner generation (phase III):
  - Faster data acquisition;
  - Faster image reconstruction;
  - Continuous data stream.
- **Clinical translation (clinical pCT)**: small animals, large animals (PET patients), human pilot studies.

Thank you

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- Tia Plautz, PhD (UCSC)
- Keith E. Schubert, PhD (BU)
- B. Schultze cand PhD (BU)
- Scott Penfold, PhD
- Andriy Zatserklyaniy, PhD (UCSC)
- Pierluigi Piersimoni, PhD
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- Jose Ramos, PhD (UCSF)

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- Nicholas Karonis, PhD
- Caesar Ordonez, PhD
- Mark Pankuch, PhD
- Brad Kreydick PhD
- Fritz DeJong, PhD
- Victor Rykalin, PhD
- Katia Parodi PhD
- Guillaume Landry, PhD
- George Dedes, PhD
- Thomas Tessionner, cand PhD
- Howard Heaton, cand PhD