Software development for Proton Computed Tomography

VALENTINA GIACOMETTI
UNIVERSITY OF BERGEN

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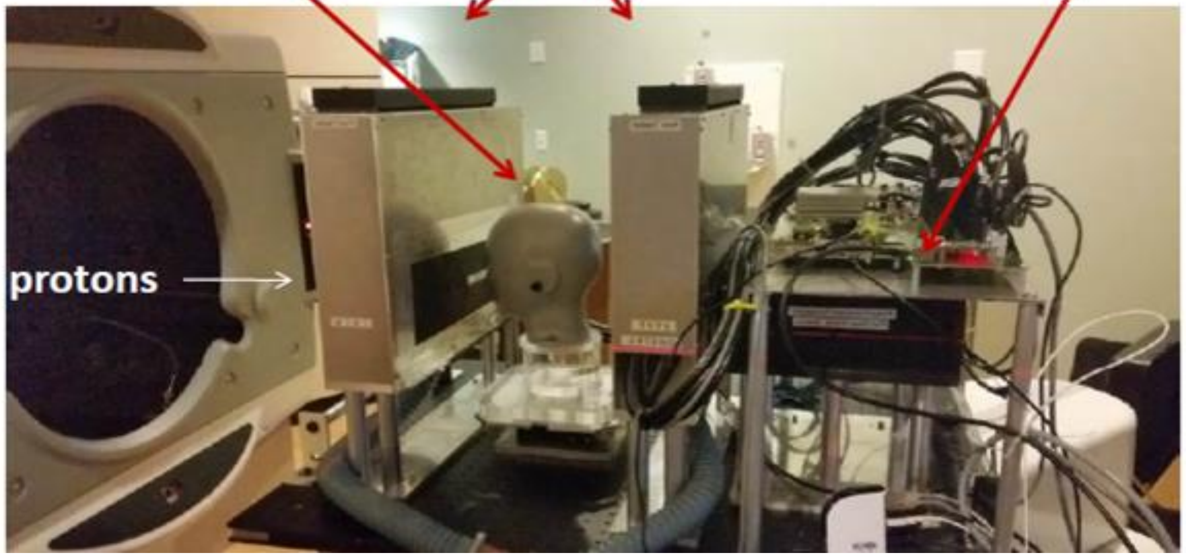
PhD project: modelling and improvement of proton computed tomography

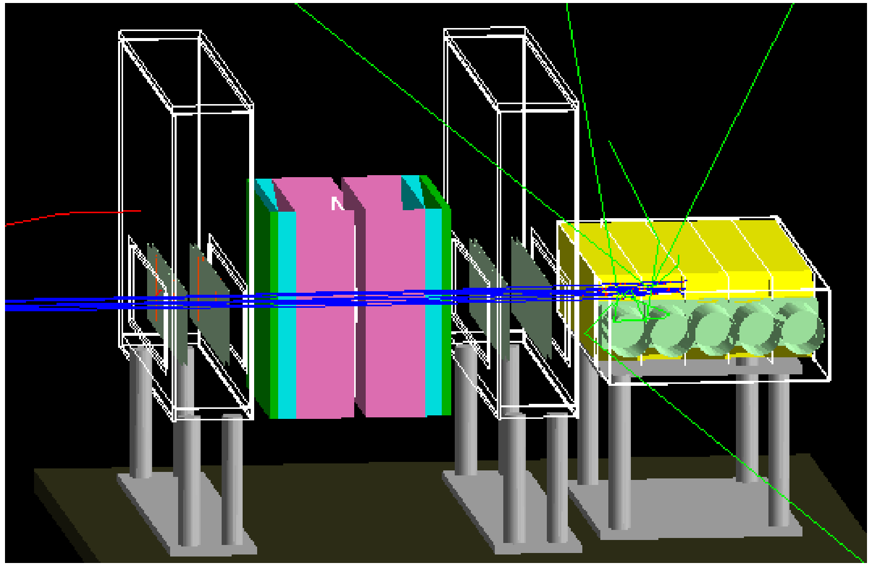
PCT scanner prototype: experimental & simulated pCT images - analysis, interpretation & use

- Proton Computed Tomography (pCT): imaging technique in which protons substitute x-rays to product tomographic images of the anatomy of the patient. Its goal is to calculate and reconstruct the distribution of the relative stopping power (RSP) with respect to water of a 3D object.
- pCT scanner prototype realized at Loma Linda University in collaboration with Santa Cruz University. Experimental measurements were conducted at the Loma Linda University (California, USA) and the Northwestern Medicine Chicago Proton Center (Warrenville, Illinois, USA).
- pCT scanner modelled with Geant4: beam line --› data acquisition --› image reconstruction
    - *V. Giacometti, et al., "Software Platform for Simulation of a Prototype Proton CT Scanner", Medical Physics, 2017*

Platform for Simulation of a Prototype pCT scanner



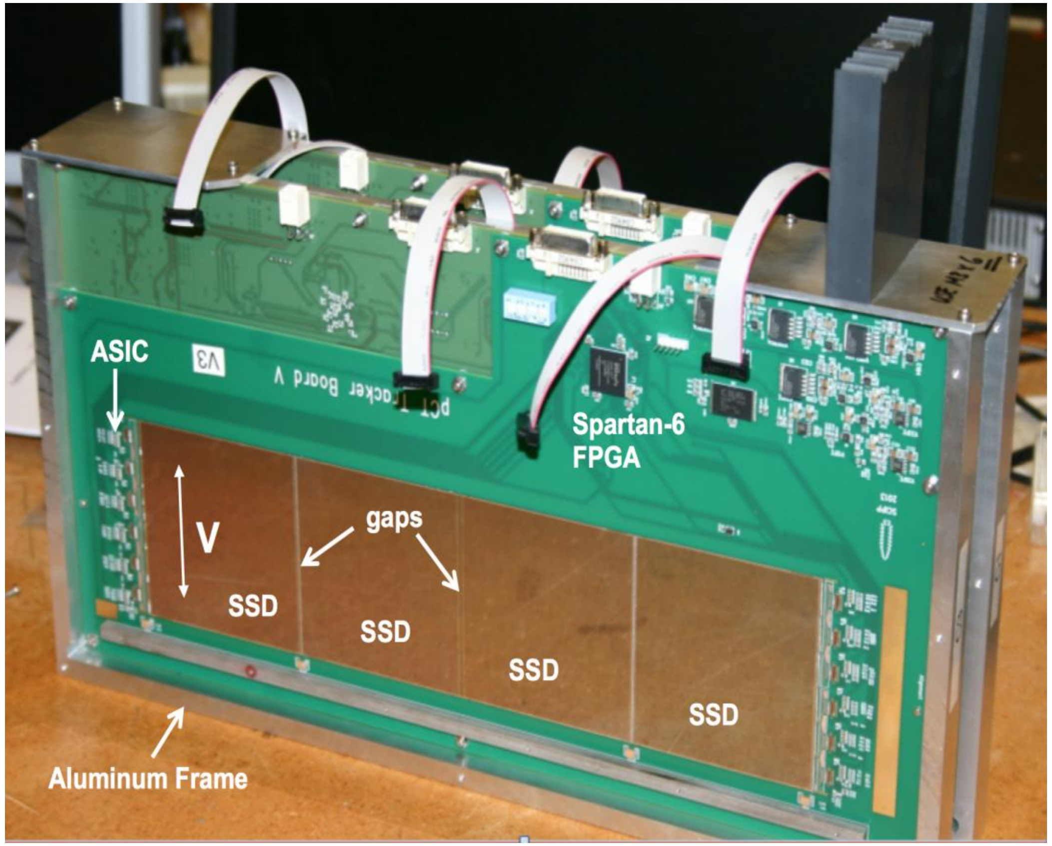
pCT scanner prototype



Geant4 model of the pCT scanner prototype

V. Giacometti, et al., "Software Platform for Simulation of a Prototype Proton CT Scanner", Medical Physics, 2017

LLU/UCSC pCT scanner prototype: tracking planes



- Front and rear trackers are **positioned symmetrically with respect to the scanner isocenter**
- The trackers and associated electronics are housed in an **aluminium cassette**.
- 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**.
- Protons tracks can be reconstructed both using 8 hits (complete track reconstruction) or using 7 hits recovering the missing hit

A. Zatserklyaniy et al., Track reconstruction with the silicon strip tracker of the proton CT phase 2 scanner, IEEE NSS/MIC Conf.Record., 2014

LLU/UCSC pCT scanner prototype: energy detector

- Multi-stage detector is composed of five UPS-923A **polystyrene scintillators** with a **sensitive area of 36 × 10 cm^2** and a **thickness of 5.1 cm.**
- The total **water equivalent thickness** of the detector is **26.4 cm** (sufficient to stop 200 MeV protons).
- The scintillating light of protons stopping or traversing a stage is registered by an R3318 Hamamatsu **photomultiplier** (PMT) attached to the top of the stage and converted to a digital value by custom readout electronics.
- A layer of VikuitiTM ESR film, 65 µm thick, was used to wrap the each scintillator-PMT. VikuitiTM ESR is a **reflective material** with greater than 98% reflectance.
- The five stages are enclosed in an **steel housing**.

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

Platform for Simulation of a Prototype pCT scanner

WHAT I HAD

- PCT scanner prototype (2014)
- Reconstruction code (ready in 2010, still people working on modifying it)
- Very preliminary Geant4 simulation of the system (but the beam line was well modelled)
- Several "physical" phantoms (Catphan 600 series, The Phantom Laboratory)

WHAT I NEEDED

- Exact geometry of the scanner
- Exact geometry of the phantoms to be scanned
- Good understanding of the calibration process in order to reproduce it
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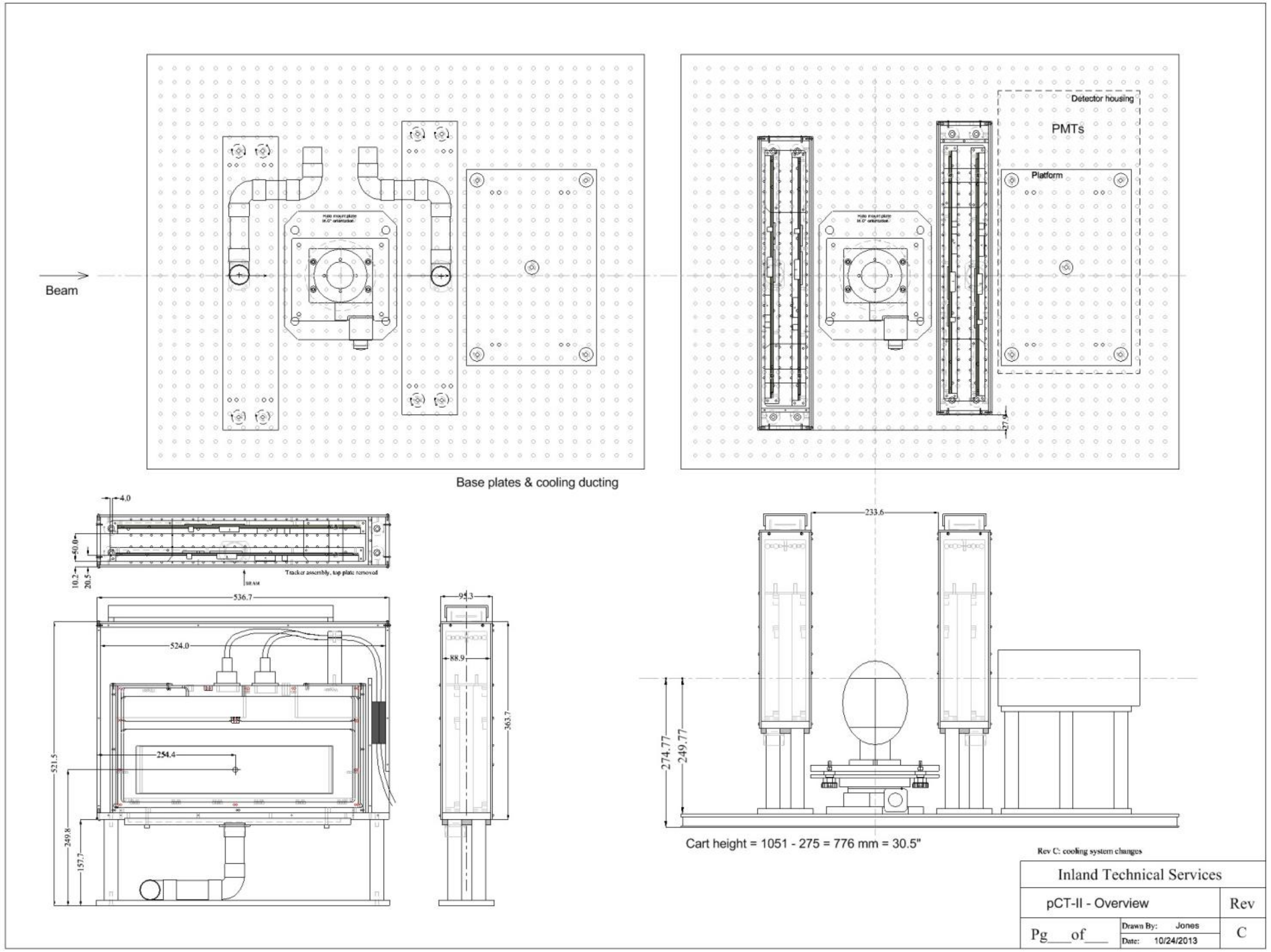
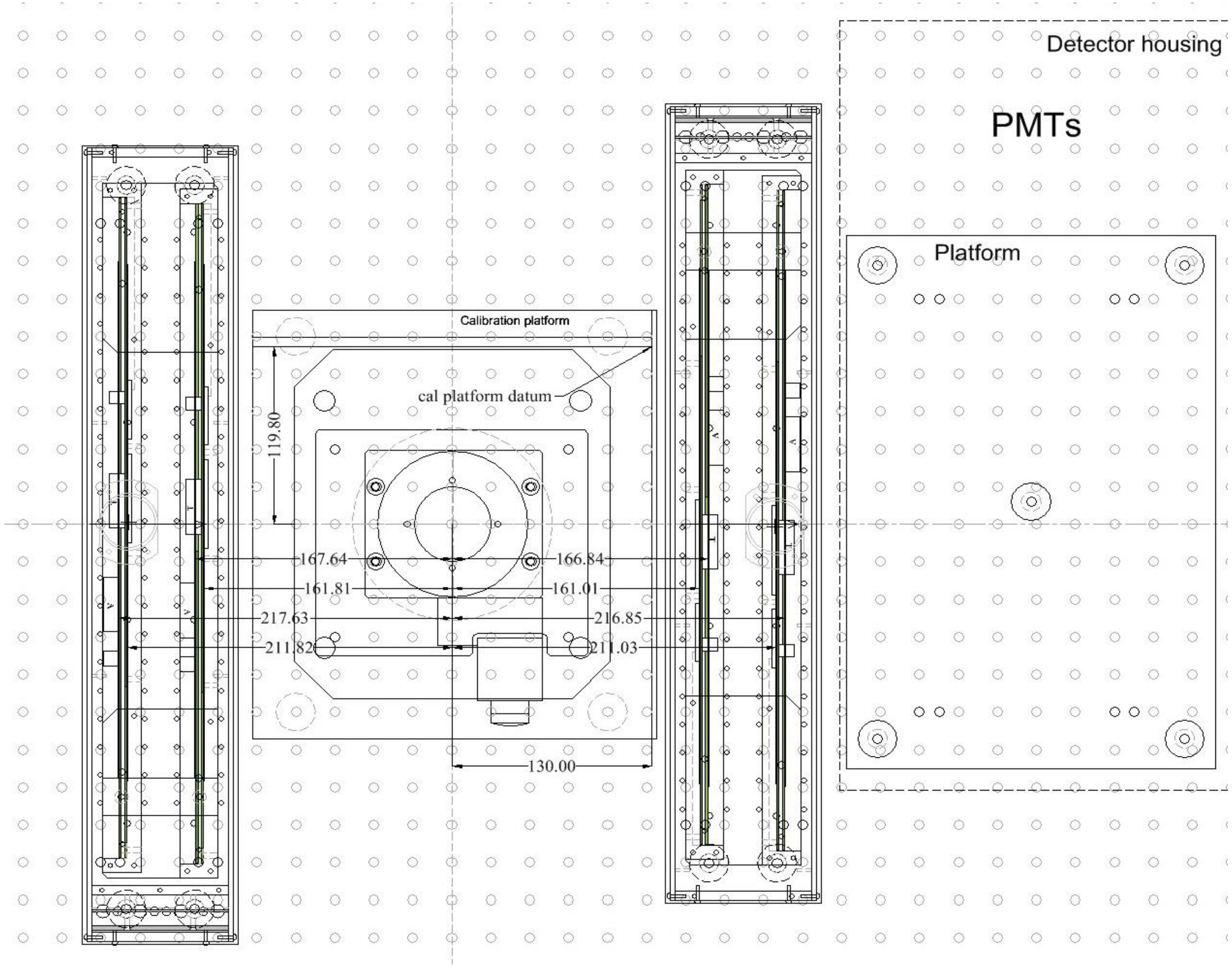


Exact Geometry of the scanner



KEEP A RECORD OF EVERYTHING

- Exact measurements
  - Scanner
  - Table
  - Platforms
  - Positions
  - Etc…
- Changes to the original plan
  - Reason of the choice
  - When it is implemented
  - Effects on the rest of the system
- Communication among different groups working on the pCT project
  - Group meeting
  - Record of the group meeting to keep track of the discussion

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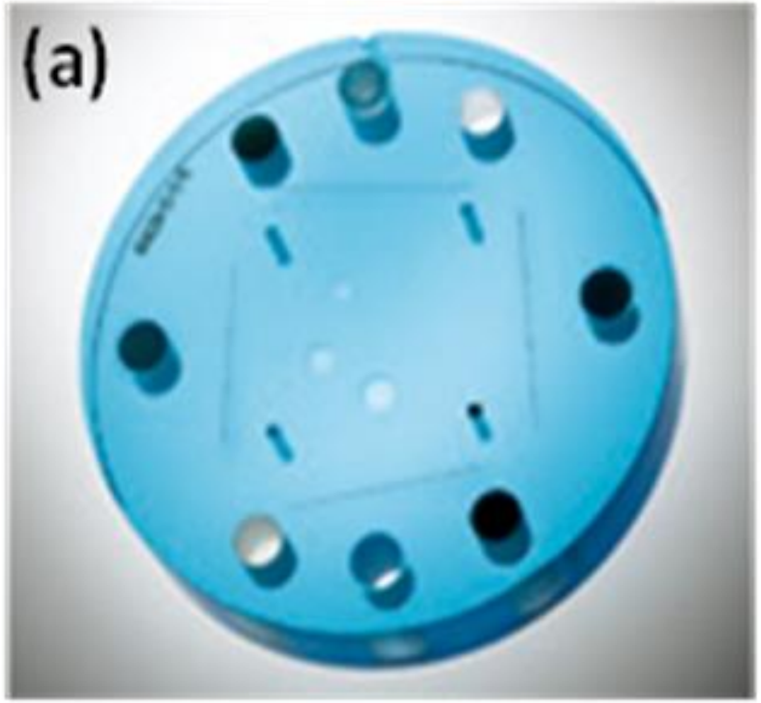
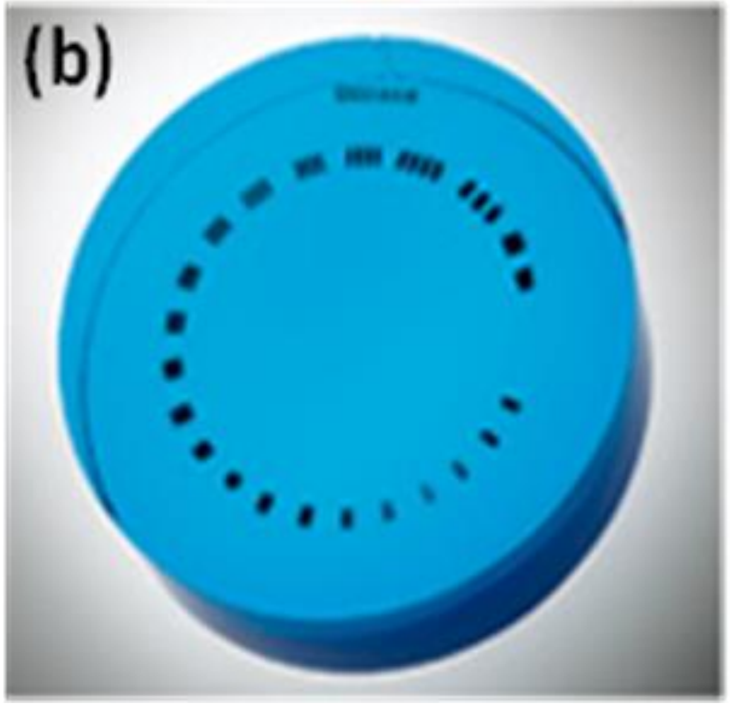
Exact geometry of the phantom to be scanned

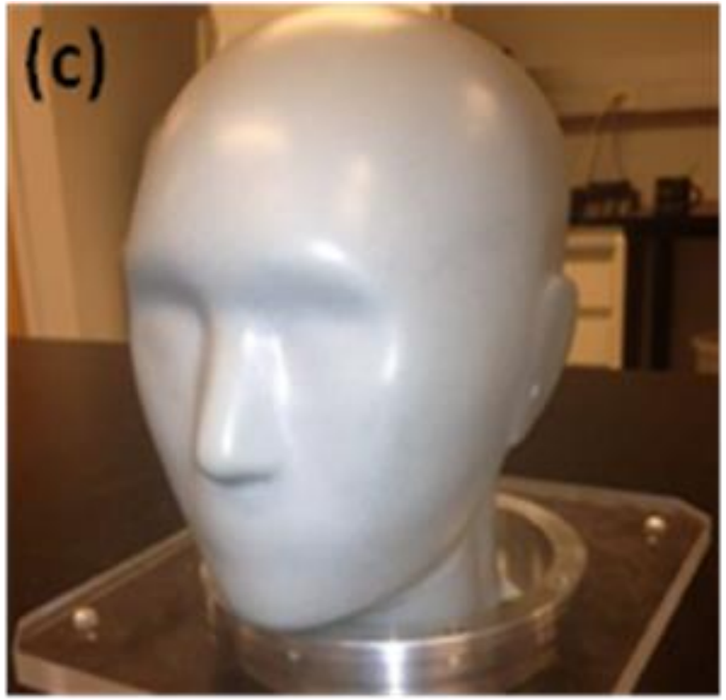
Sensitometry



Linepair

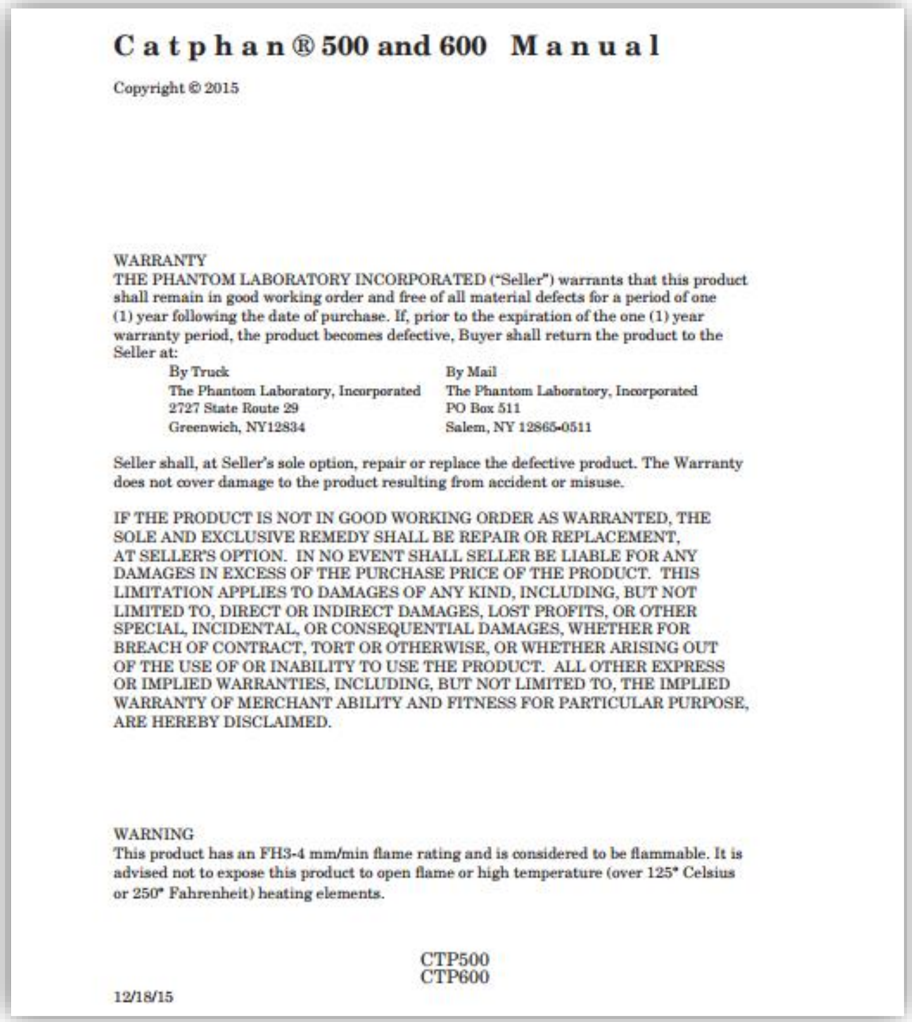


Head Phantom



(a) Sensitometry and linepair module of the Catphan® 600 serie.
(c) Realistic anthropomorphic pediatric head phantom, model HN715 (CIRS).

Exact Geometry of the scanner



Catphan® 500 and 600 Manual

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WARRANTY
THE PHANTOM LABORATORY INCORPORATED ("Seller") warrants that this product shall remain in good working order and free of all material defects for a period of one (1) year following the date of purchase. If, prior to the expiration of the one (1) year warranty period, the product becomes defective, Buyer shall return the product to the Seller at:

By Truck	By Mail
The Phantom Laboratory, Incorporated	The Phantom Laboratory, Incorporated
2727 State Route 29	PO Box 511
Greenwich, NY12834	Salem, NY 12865-0511

Seller shall, at Seller's sole option, repair or replace the defective product. The Warranty does not cover damage to the product resulting from accident or misuse.

IF THE PRODUCT IS NOT IN GOOD WORKING ORDER AS WARRANTED, THE SOLE AND EXCLUSIVE REMEDY SHALL BE REPAIR OR REPLACEMENT, AT SELLER'S OPTION. IN NO EVENT SHALL SELLER BE LIABLE FOR ANY DAMAGES IN EXCESS OF THE PURCHASE PRICE OF THE PRODUCT. THIS LIMITATION APPLIES TO DAMAGES OF ANY KIND, INCLUDING, BUT NOT LIMITED TO, DIRECT OR INDIRECT DAMAGES, LOST PROFITS, OR OTHER SPECIAL, INCIDENTAL, OR CONSEQUENTIAL DAMAGES, WHETHER FOR BREACH OF CONTRACT, TORT OR OTHERWISE, OR WHETHER ARISING OUT OF THE USE OF OR INABILITY TO USE THE PRODUCT. ALL OTHER EXPRESS OR IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTY OF MERCHANT ABILITY AND FITNESS FOR PARTICULAR PURPOSE, ARE HEREBY DISCLAIMED.

WARNING
This product has an FH3-4 mm/min flame rating and is considered to be flammable. It is advised not to expose this product to open flame or high temperature (over 125° Celsius or 250° Fahrenheit) heating elements.

CTP500
CTP600

12/18/15

FROM SIMPLE OBJECTS TO MORE COMPLEX ONES

- Start from simple objects (i.e. water phantom) to test the scanner
- Get as many information as you can from the phantom producer (manual)
  - If not all the info are provided, try to find them out
  - In case something is cryptic or not clear, contact the provider directly
  - The company is NOT always right so.. Investigate meticulously your outcome
- Decide with the group which phantoms to study first and in which order
- For the anthropomorphic head phantom model, ask me ☺

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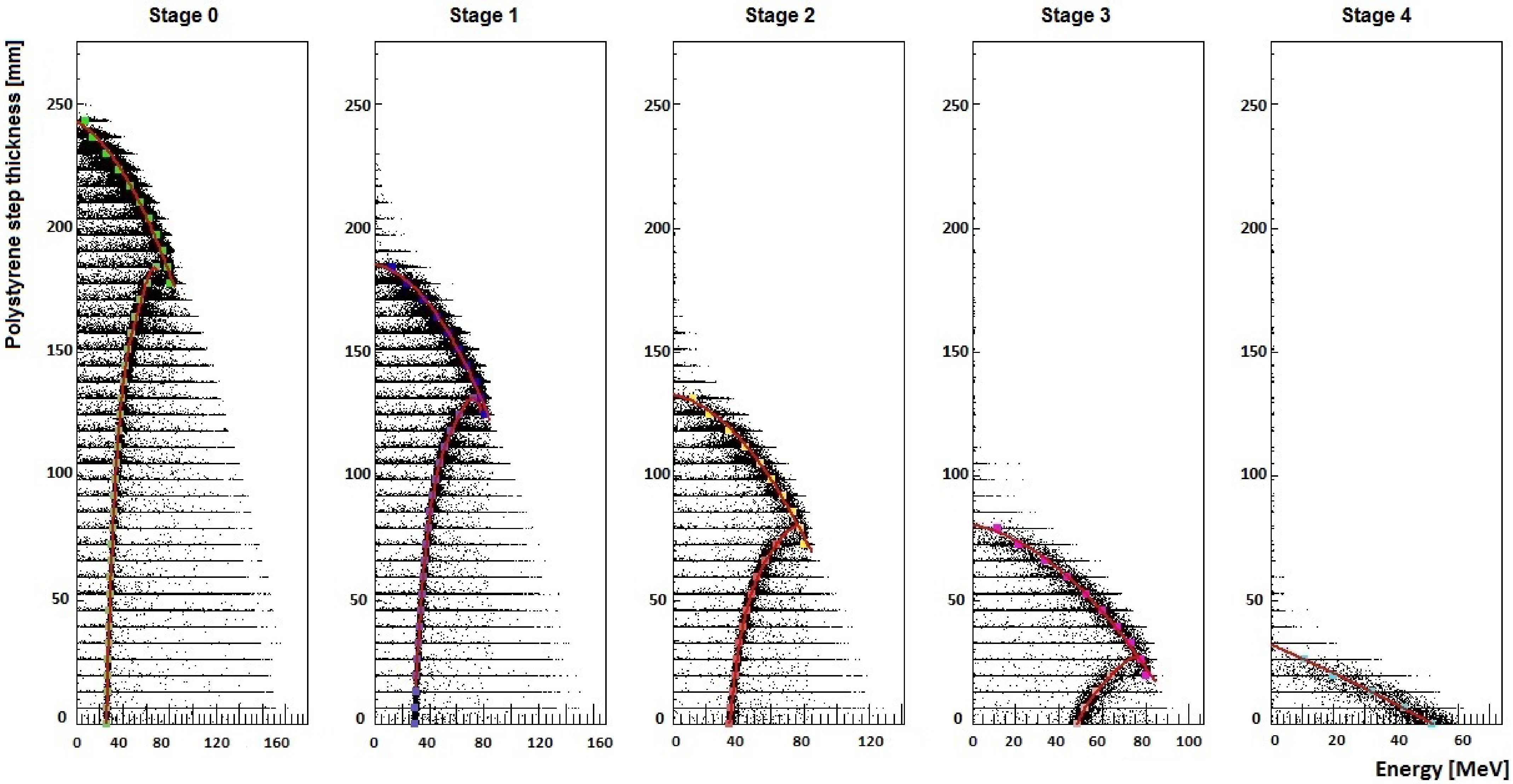
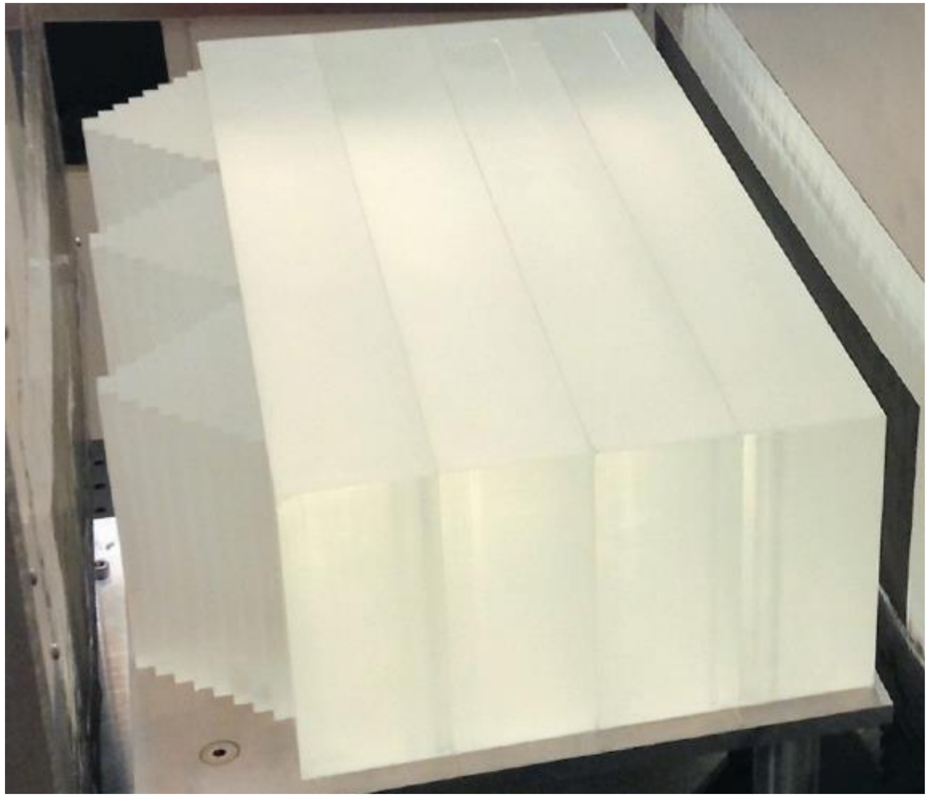
Good understanding of the calibration process



Good understanding of the calibration process



Calibration phantom

HAVE A CLEAR CALIBRATION PROCEDURE

- The calibration has to be understood by everybody, particularly by the people responsible of the data flow structure and the image reconstruction.
- If you need degraders, use polystyrene slabs (homogeneous, RSP known)
- Collect data at several energies, the more points you have the better, the calibration look like.
- Calibration done in Loma Linda:
  - Custom calibration phantom , 8 steps of 6.35 mm steps
  - RSP traversed material known

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

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  1. Input data and format
  2. computational requirements
- Knowledge of the format of the data stream output of the scanner

1. Knowledge of the input necessary for the reconstruction code

For the Loma Linda reconstruction code, the necessary information are:

i. **Entry and exit coordinates** (in mm) of the protons traversing the scanned object.

ii. **Conversion of the residual energy** deposited by the protons in the multistage energy detector into **water equivalent path length (WEPL).**

These information have to be imported in cthe orrect format for the **image reconstruction algorithm**.

HAVE CLEAR IN MIND WHICH INFORMATION YOU NEED FROM YOUR SYSTEM (REAL OR SIMULATED)

- Important for the data flow structure
- Fundamental to set up a correct simulation
- Contact the code creator if necessary!!!

2. Knowledge of the computational requirements necessary to run the reconstruction code

The Loma Linda reconstruction code **main characteristics**:

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

ii. Iterative solution of the algebraic linear system A*x* = b for the unknown RSP vector *x* is displayed as a 3D voxel image (stack of slices) with isotropic voxel size (1 x 1 x 1 mm^3)

The Loma Linda reconstruction code **main requirements**:

i. GPU with CUDA 5.5 installed

ii. 15 minutes to process the files (1 million particle per projection, 90 projections)

iii. Output size was not bigger than a gigabyte BUT the processed file could use up to20 Gb – computer with a decent hard drive and RAM.

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

2. Knowledge of the computational requirements necessary to run the reconstruction code

HAVE CLEAR IN MIND WHICH CODE YOU HAVE AND WHERE/HOW TO RUN IT

- Computational requirements of the code (GPU? CUDA?)
- Memory necessary to run the code (RAM - indicative)
- Size of the data you are handling – this is difficult to do it upfront but simulations could help
- Contact the code creator if necessary!!!

Contacting both Simon Rit (for the code output) and Reinhard Schulte (to know if I can use the Loma Linda code)

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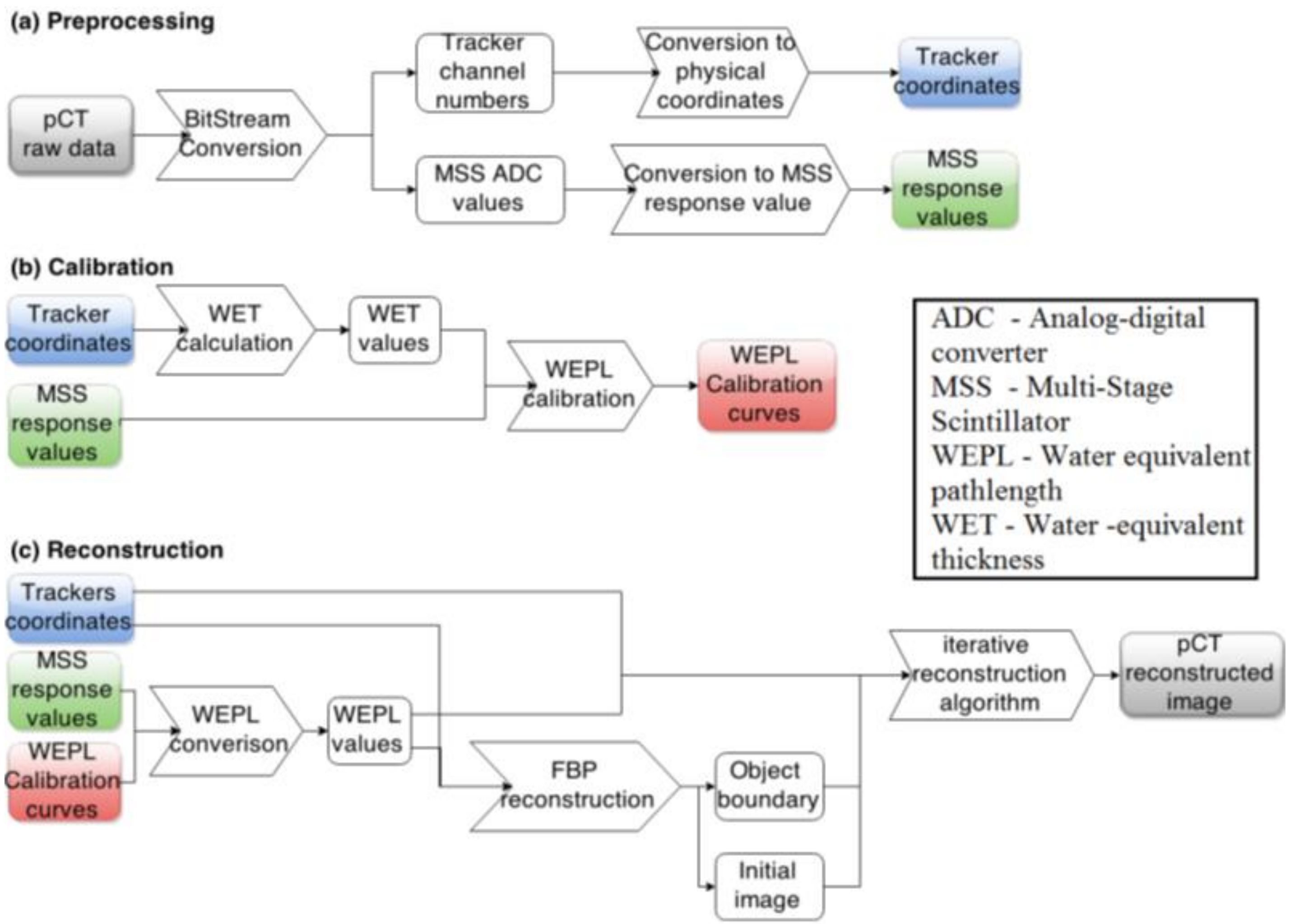
Knowledge of the format of the data stream output of the scanner



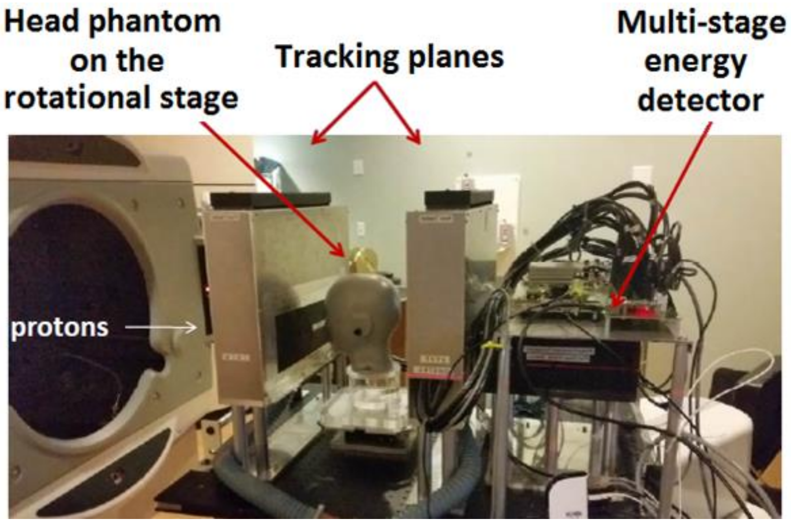
HAVE A DATA FLOW STRUCTURE IN MIND

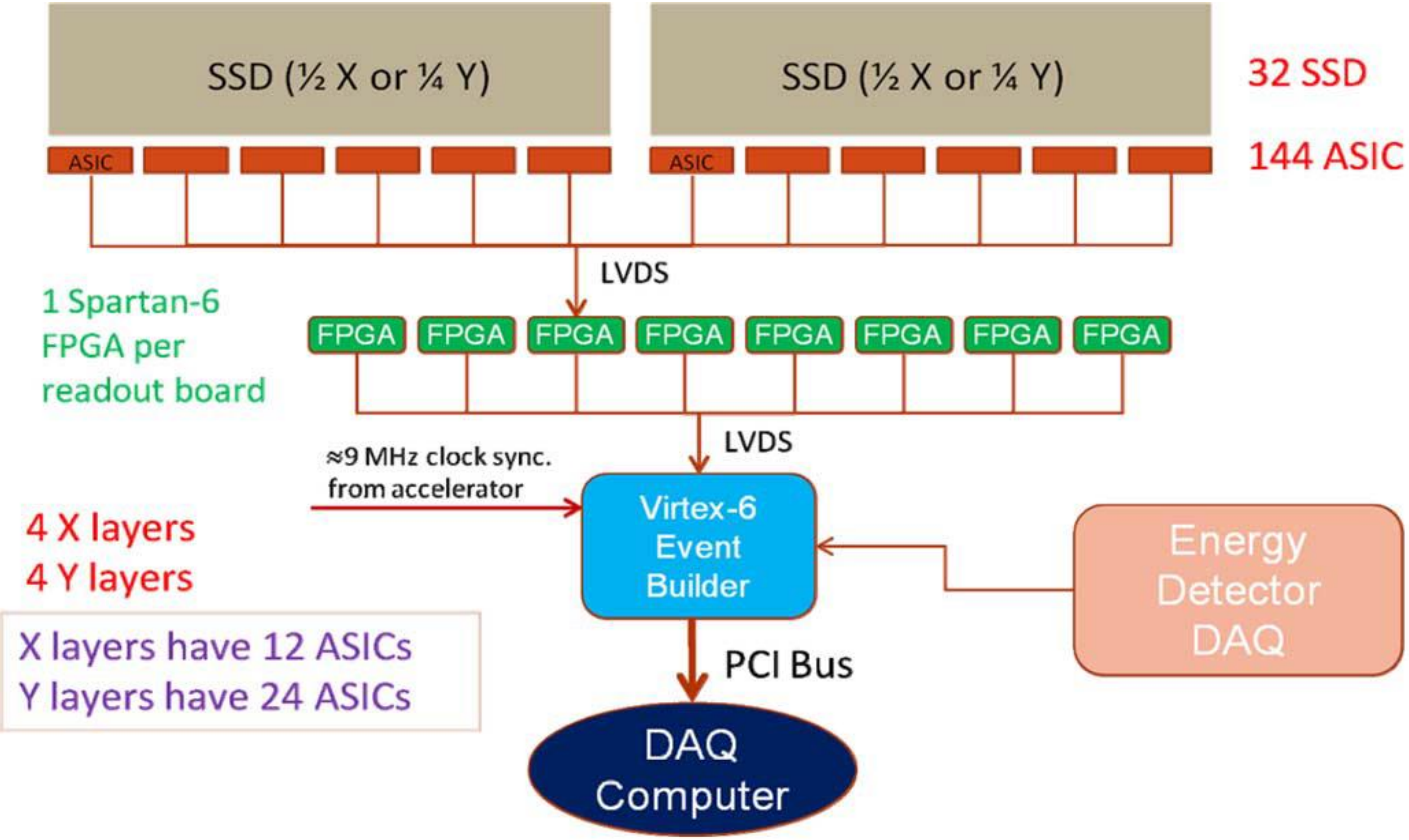
Experimental&simulated data MUST include:

- Tracker readout
- Energy response
- WEPL calibration to be used to have WEPL data from the system
- Input for the reconstruction code

Knowledge of the format of the data stream output of the scanner

Experimental readout LLU scanner prototype: collecting data with the scanner in the picture below following the read out data structure shown in the diagram on the right.





R. P. Johnson, et al., *Tracker readout ASIC for proton computed tomography data acquisition*, IEEE Trans. Nulcl. Sci., 2013

Knowledge of the format of the data stream output of the scanner

OPTION 1 - simplify the modelling and the simulation

- Simulation & experimental data have different format
- The input for the reconstruction code MUST be the same – data processed differently
- The calibration procedure used MUST be the same for both
- ✓ ADVANTAGES: the simulation should be quicker and more efficient
- x DISADVANTAGES: different preprocessing code might be necessary & calibration might result more complicated

OPTION 2 - this can be done from the beginning or later, it depends on you

- Simulation & experimental data have the same format
- Same way to process the data and run the calibration
- ✓ ADVANTAGES: the data are processed exactly in the same way = only 1 processing code
- x DISADVANTAGES: the simulation might become very complex
- x **Simulation must be validated no matter which option is chosen!**

Knowledge of the format of the data stream output of the scanner

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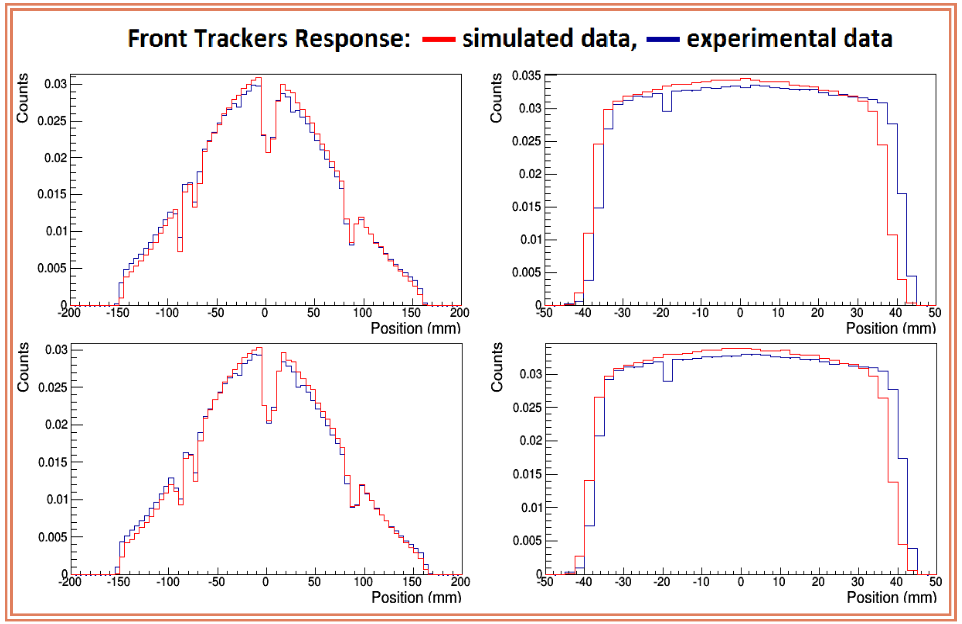

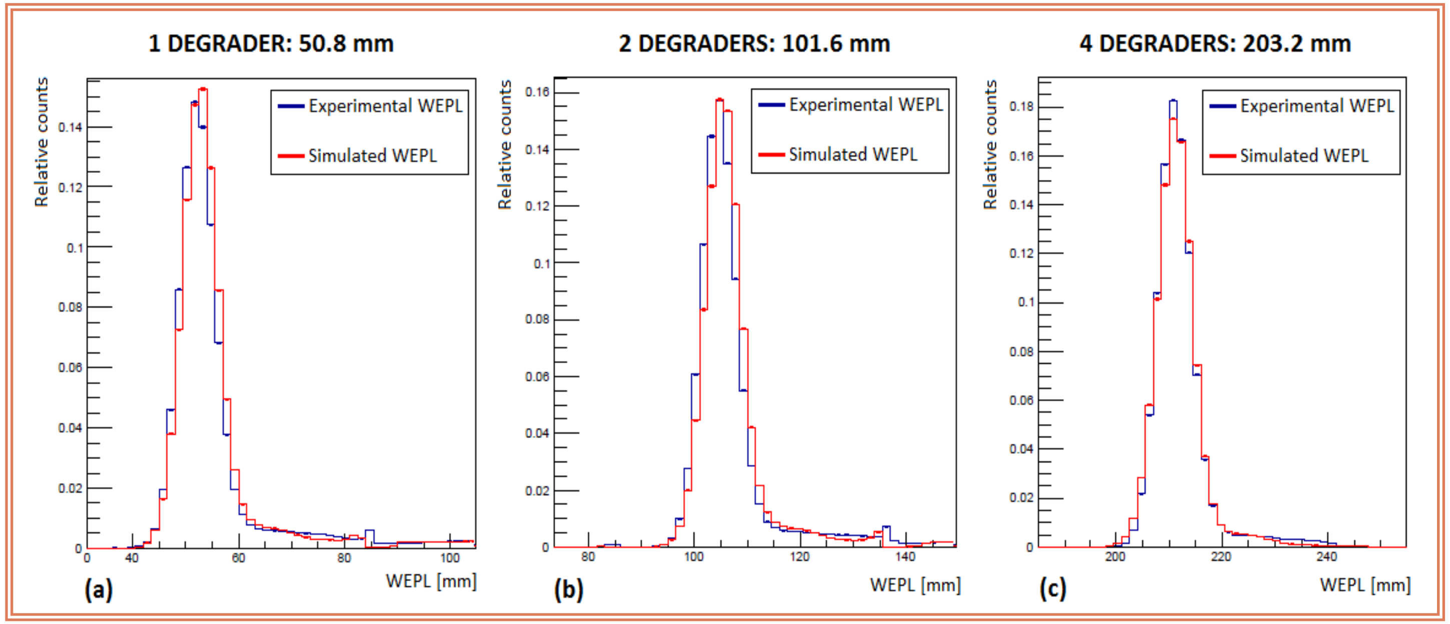

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Knowledge of the format of the data stream output of the scanner

OPTION 2 - this can be done from the beginning or later, it depends on you

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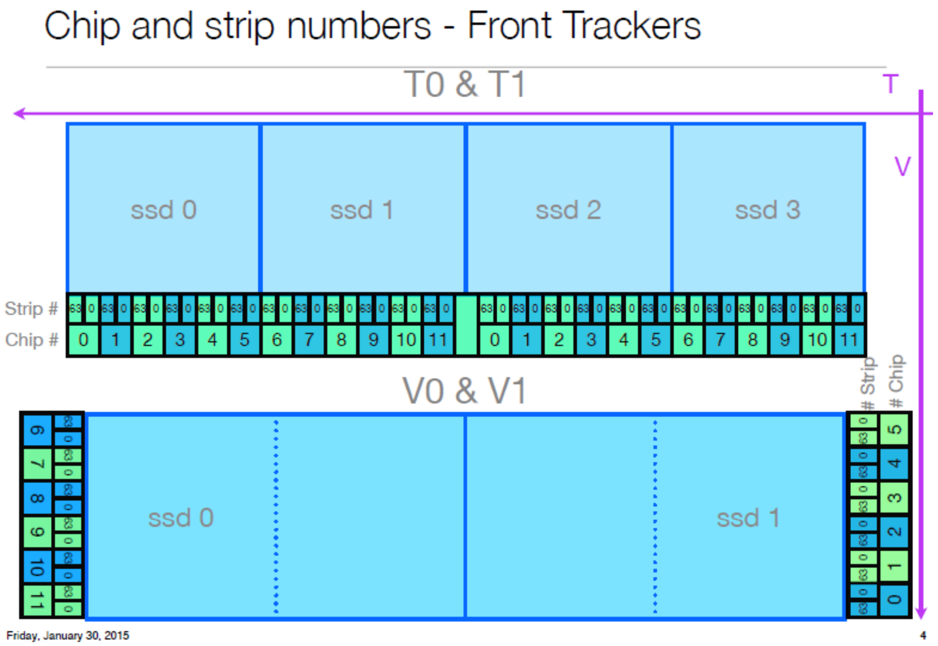

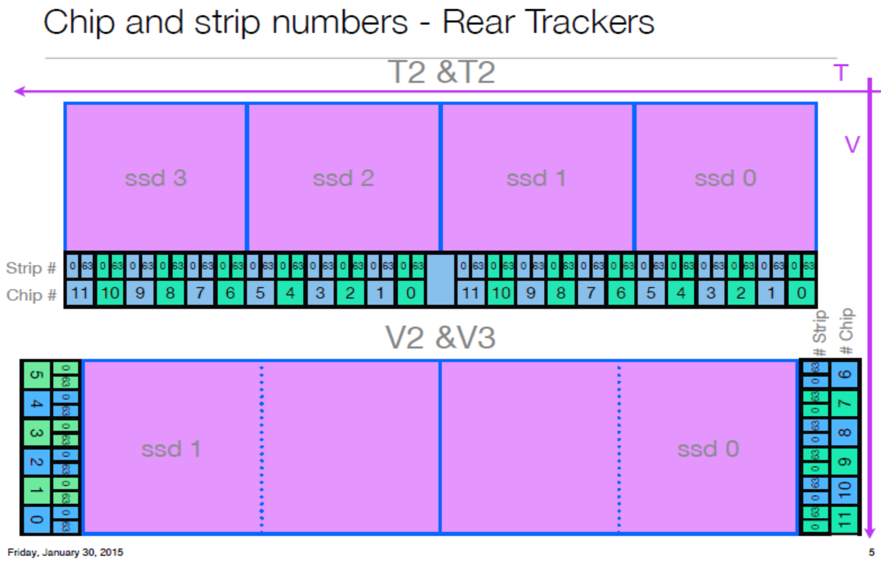

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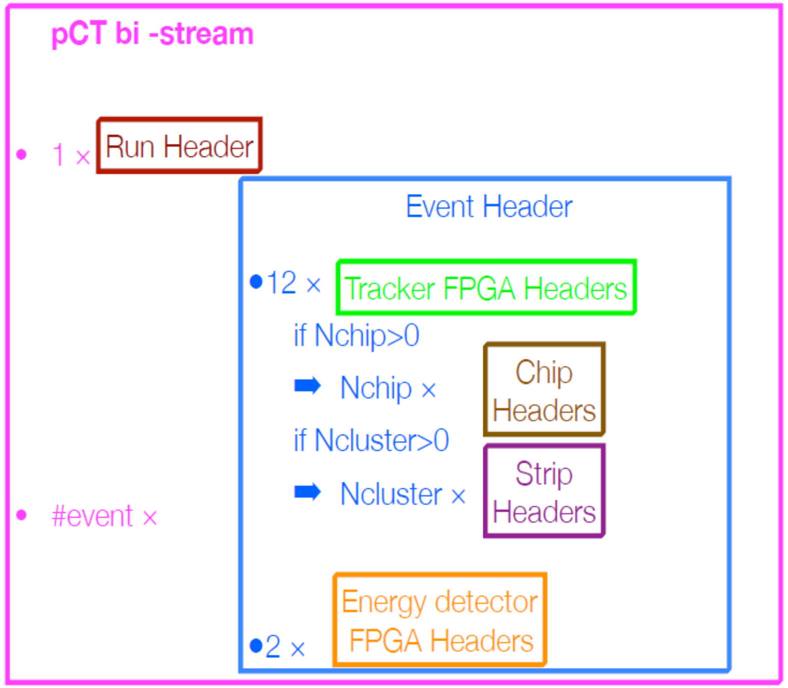


Energy Deposition FPGA headers (12 bit)

- ★ 2-bit trigger tag
  - 1-bit pedestal flag (**PedFlag**): 1 = included 0 = not included
  - 1-bit additional trigger tag
- ★ 3-bit tag for the front-end buffer
- ★ 1-bit data type flag: 1 = samples 0 = reduced (in the latest beam tests is 0)
- ★ 1-bit error flag
- ★ 2-bits number of channel (**Nch**) per FPGA: 3 for FPGA #12 (connected to 3 calorimeter stage) 2 for FPGA #13

Nch times the following:

- ★ (16) 24-bit energy deposition data (16 if PedFlag=0)
  - if PedFlag =1 -> 8-bit pedestal (**PedValue**) [signed integer]
  - 16-bit calorimeter response (sample sum) (**EnergyValue**) [signed integer]
- ★ if reduced data AND no pedestal AND Nch=2-> 4 unused 0 bits

Strip headers (12 bits)

- 6-bit number of hit strips (**Nstrips**)
- 6-bit first hit strip address (**AddStrip**)

CHIP (ASIC) headers (12 bits)

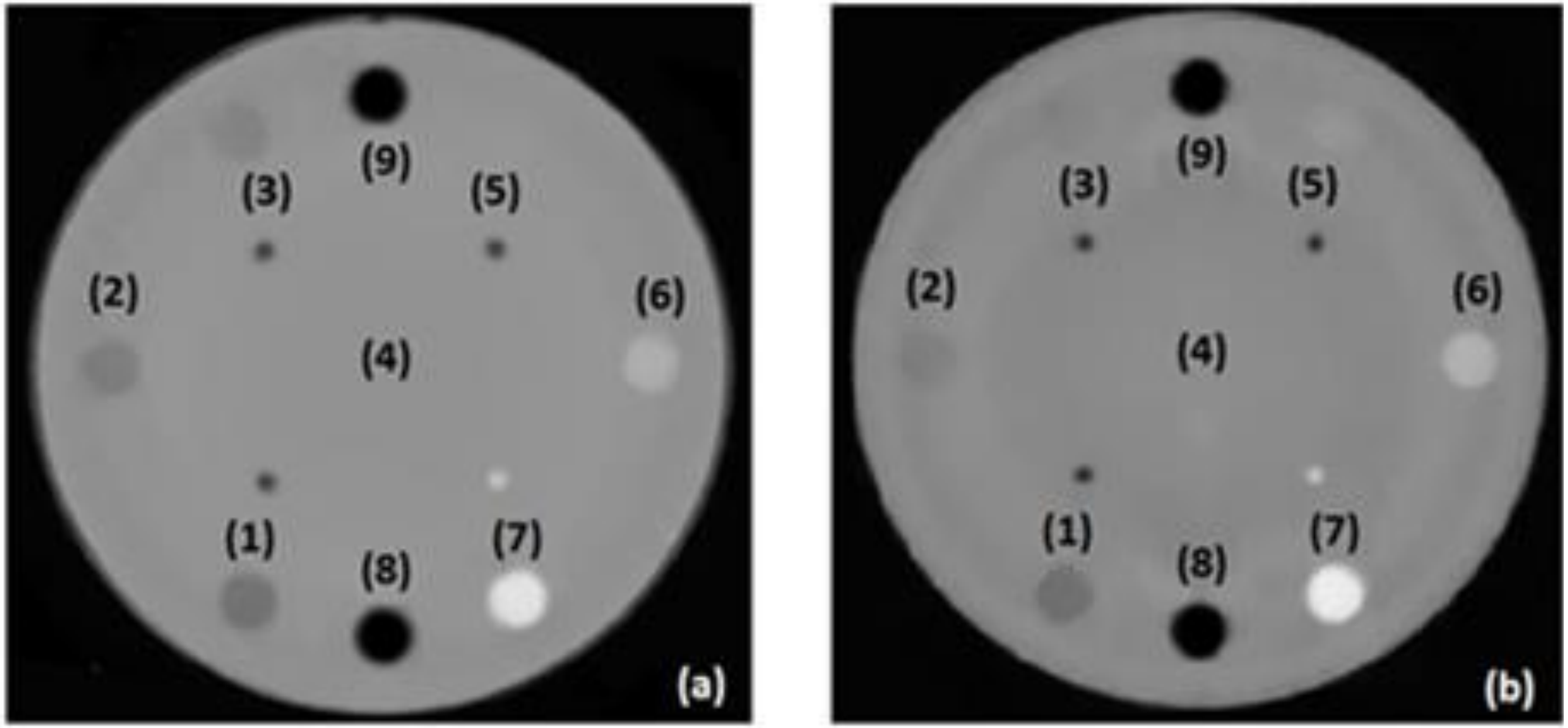
- 1-bit cluster overflow
- 1 unused 0 bit
- 4-bit number of hit strips cluster (**Ncluster**)
- chip error bit
- parity error bit
- 4-bit CHIP address (**AddChip**)

Tracker FPGA headers (12 bits)

- For each event at least a header for each Tracker FPGA is registered
  - 4-bit FPGA address :
    from 0000 (**FPGA #0**) to 1011 (**FPGA#11**)
  - 3-bit event tag: 1-bit tag clock counter + 2-bit ASIC trigger
  - 1-bit error flag (trigger tag mismatch)
  - 4-bit number of chips (**Nchip**) reporting cluster (strip) data, i.e. number of CHIP containing one or more hit strings.
- if Nchip is ≠ 0, #Nchip × CHIP headers are registered in the bit stream.

Software development for PCT: some results

Experimental *Simulated*



Catphan 600 sensitometry module pCT reconstruction. The insertions are: PMP (1), LDPE (2), Polystyrene (3), Epoxy (4), PMMA (5), Delrin (6), Teflon (7), Air (8, 9).

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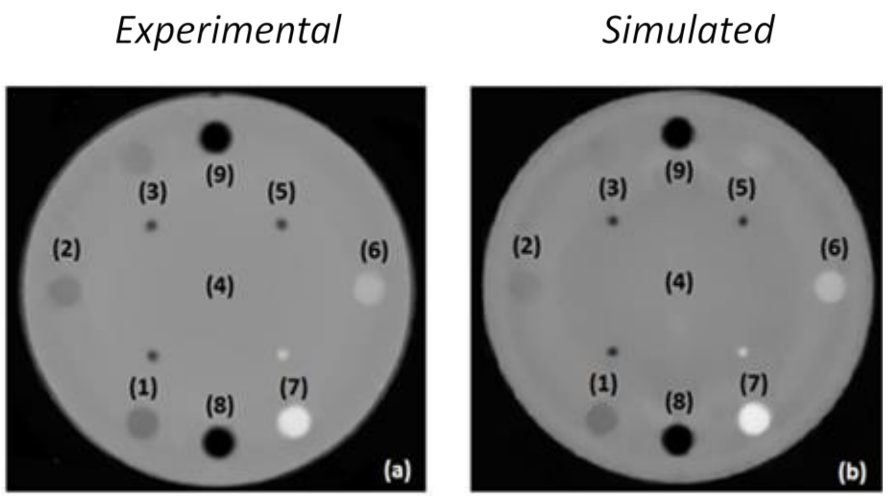

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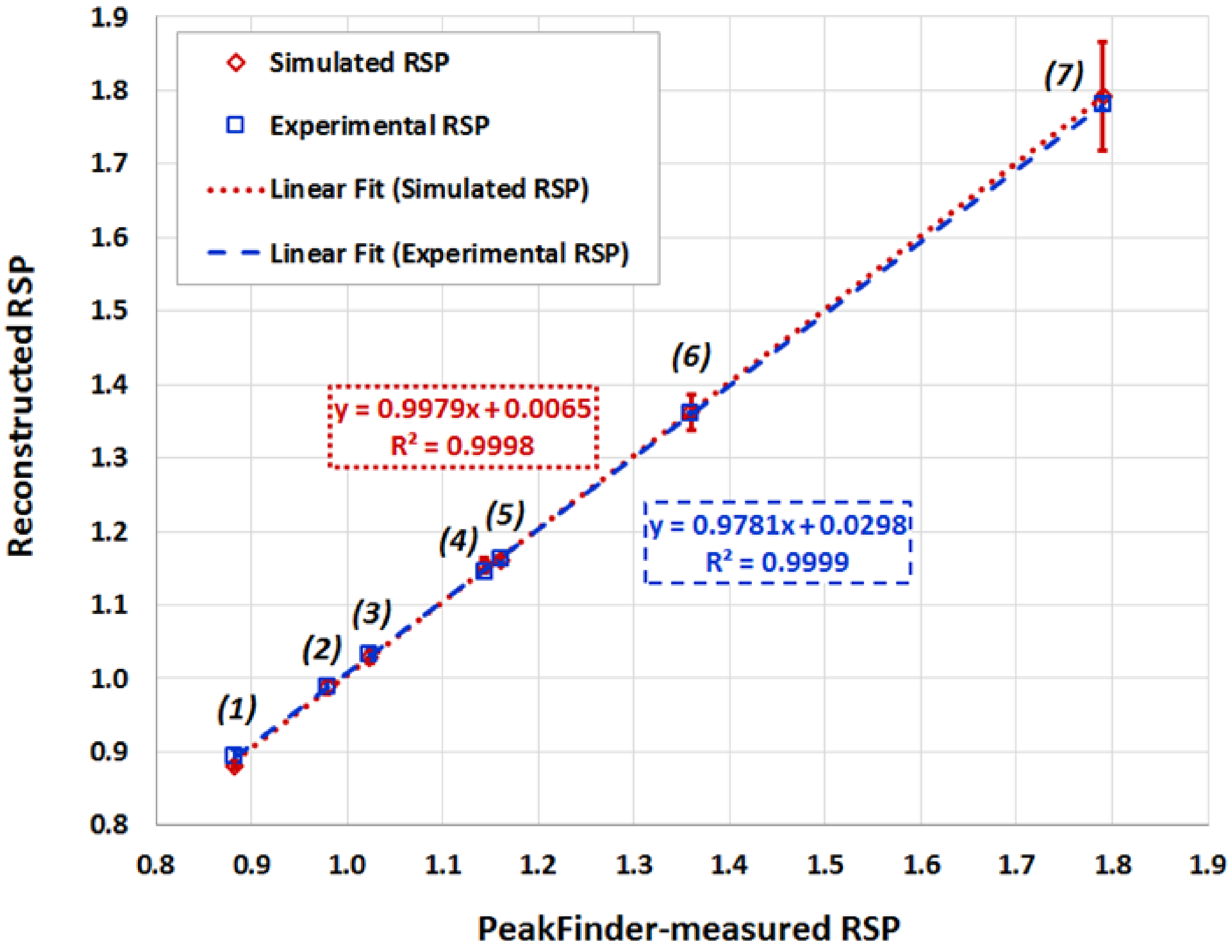

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Software development for PCT: summary & conclusions

- List of what I have and what I need clear in mind in order to go step by step
- Geometry – phantoms and scanner – keep track of everything
- Importance of having a unique, tested and simple calibration process
- Reconstruction code MUST be understood at least in terms of input, output and possible parameters that can be changed
- The data format scheme (both for simulation and experimental data) should be established as soon as there are data.

Thank you!