Imaging with Protons

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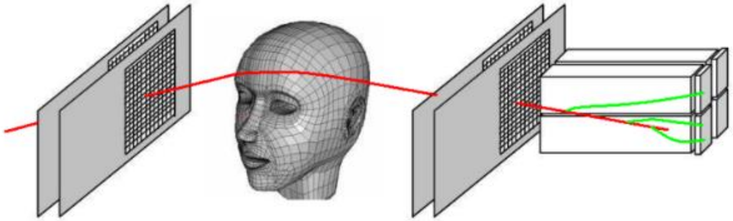
On behalf of the Proton CT Collaboration



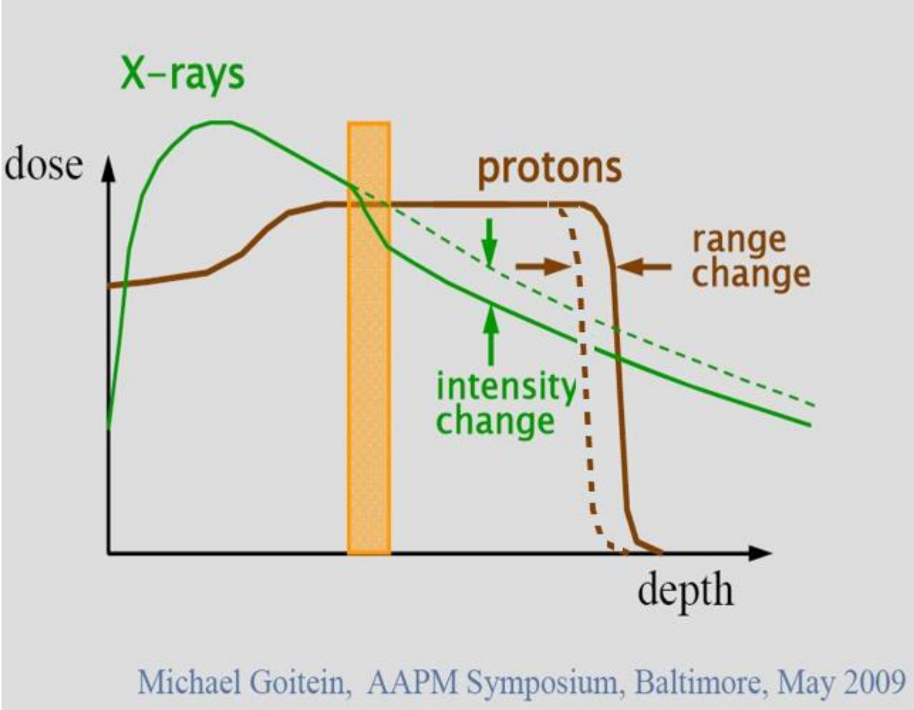
Outline

- Hadron therapy: the need for imaging
- Efforts in particle imaging world-wide
- Proton CT Collaboration: a status update
- Accelerators for particle imaging: challenges & opportunities
- Summary and Outlook

HADRON THERAPY – WE NEED IMAGING!

Proton therapy – The need for accurate imaging

- Proton therapy, because of its high sensitivity to tissue distribution and much more than photon therapy, relies on accurate imaging
- Treatment planning requires good knowledge of the stopping power ratio (w.r.t.) water of tissues
- For OARs in close proximity to high-dose GTVs, hypo-fractionation, and rapidly changing tumors (head & neck), require daily imaging +/- replanning

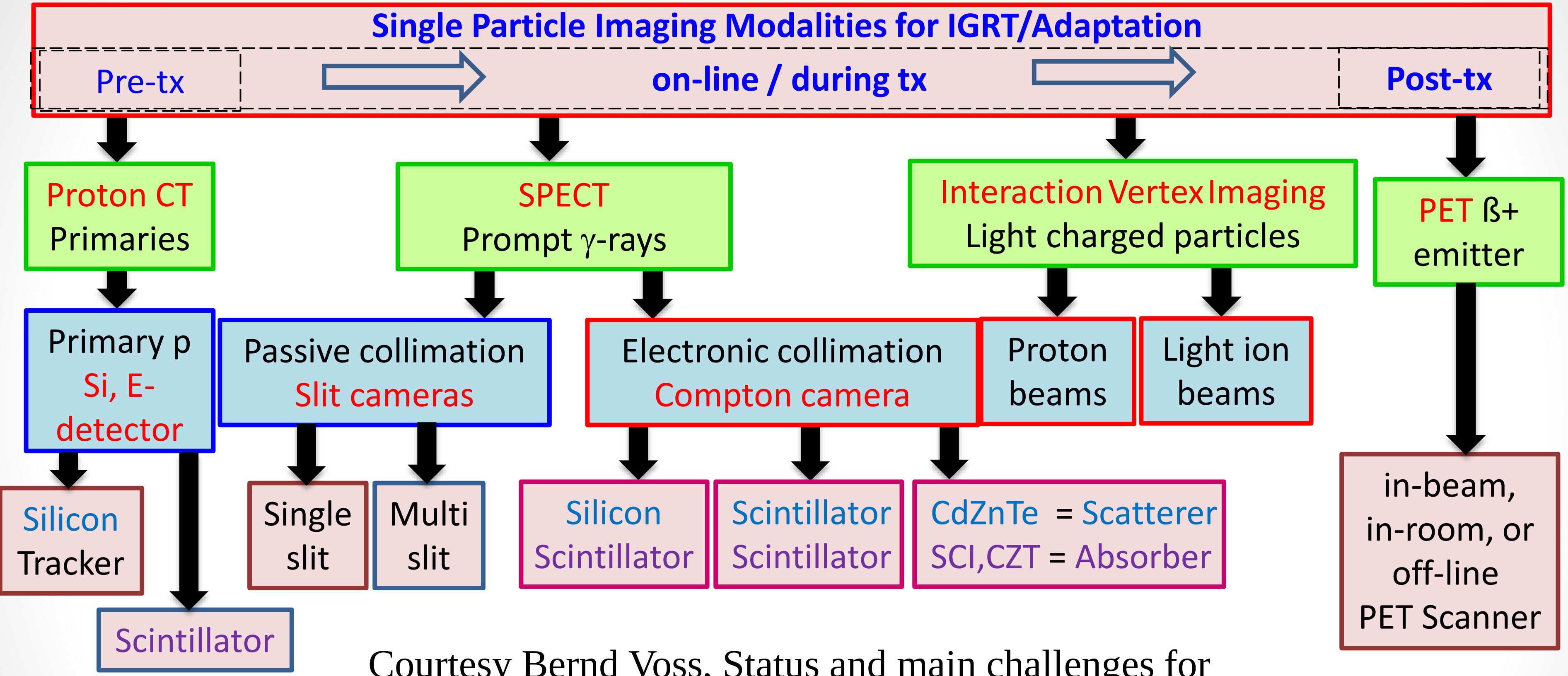


Michael Goitein, AAPM Symposium, Baltimore, May 2009

Current & Emerging Imaging Techniques in the Hadron Therapy Workflow

- Imaging target definition (MRI, PET, MSCT)
- Imaging for treatment planning (MSCT, DECT p-CT)
- Imaging for pre-treatment plan verification & adaptation = IGRT, ART (CBCT, MSCT, DECT, p-CT, p-radiography, MRI?)
- Imaging for intra-treatment range verification (prompt γ, thermoacoustic, IVI)
- Imaging for post-treatment verification (PET)

Single-Particle Imaging in the Tx Room



Single Particle Imaging Modalities for IGRT/Adaptation

Pre-tx

on-line / during tx

Post-tx

Proton CT
Primaries

SPECT
Prompt γ-rays

Interaction Vertex Imaging
Light charged particles

PET ß+
emitter

Primary p
Si, E-detector

Passive collimation
Slit cameras

Electronic collimation
Compton camera

Proton
beams

Light ion
beams

Silicon
Tracker

Scintillator

Single
slit

Multi
slit

Silicon
Scintillator

Scintillator
Scintillator

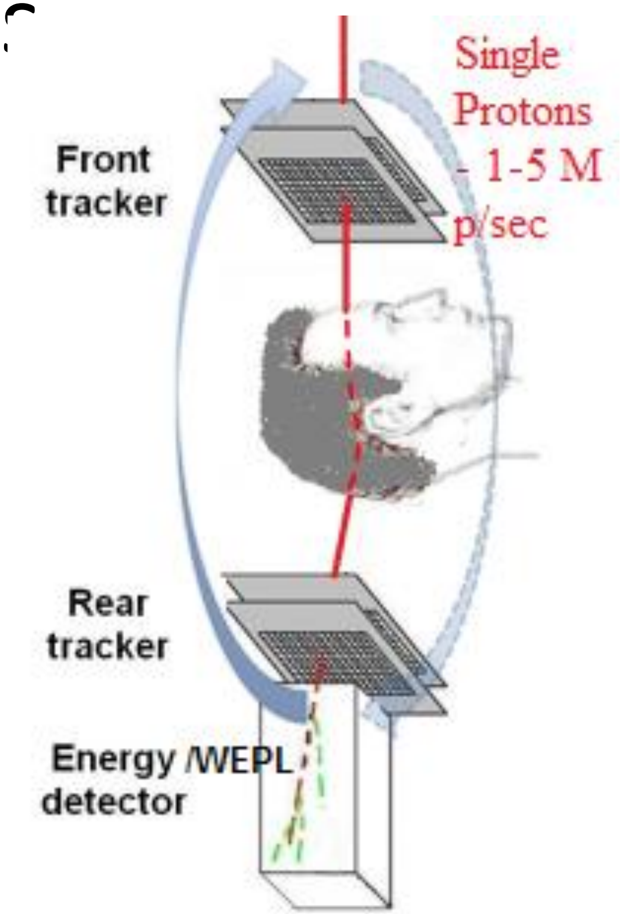
CdZnTe = Scatterer
SCI,CZT = Absorber

in-beam,
in-room, or
off-line
PET Scanner

Courtesy Bernd Voss, Status and main challenges for detectors in Hadron Therapy Hadron Therapy Technology Workshop, IEEE NSS-MIC, Seoul, Korea, 2013, modified

Particle Imaging for Planning & Image Guidance– One solution that fits all? needs

- BEV imaging, no change of patient position
- Most accurate for proton treatment planning (accurate RSP maps)
- Useful for image guidance & tx plan adaptation – low dose, accurate RSP maps, less artifacts
- Radiographic range verification during tx also, in principle, possible



Proton imaging (radiography & CT) concep
Bashkirov et al. NIM-A, 2015

SECTION I

EFFORTS IN PARTICLE IMAGING WORLD-WIDE

Currently funded Proton CT Developments

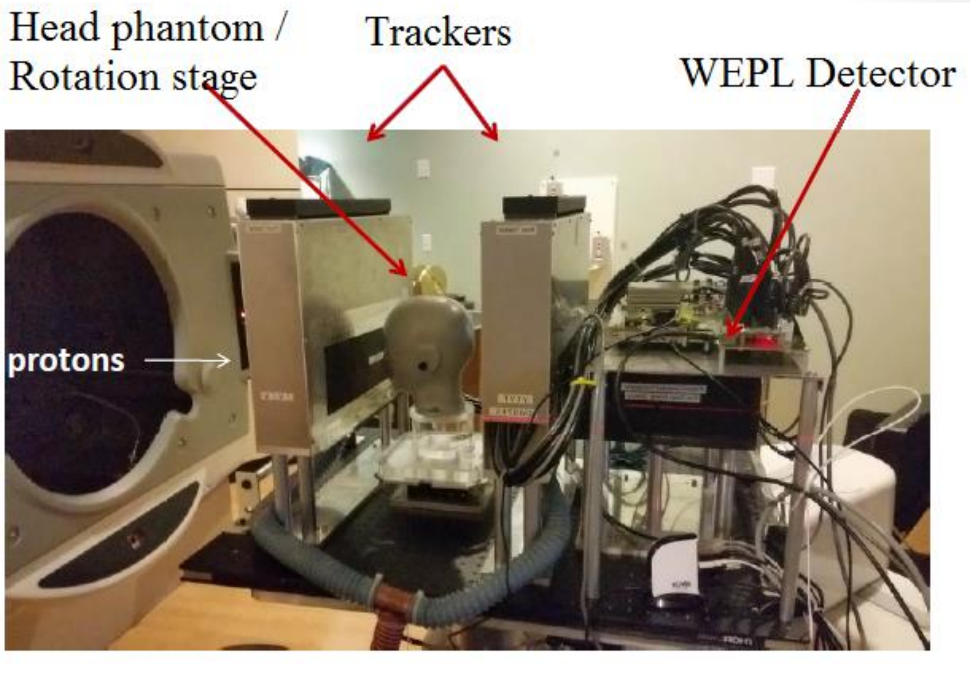
- Proton CT collaboration (U.S. based, currently LLU, UCSC, Baylor University): Phase 0, I, II, … scanner towards clinical application, funded by NIH, BSF
- INFN, Padua (P Giubilato, PI): 5 year European Research Council (ERC) grant to develop monolithic pixel sensor for proton CT

SECTION I

WORK OF THE PROTON CT COLLABORATION: A STATUS UPDATE

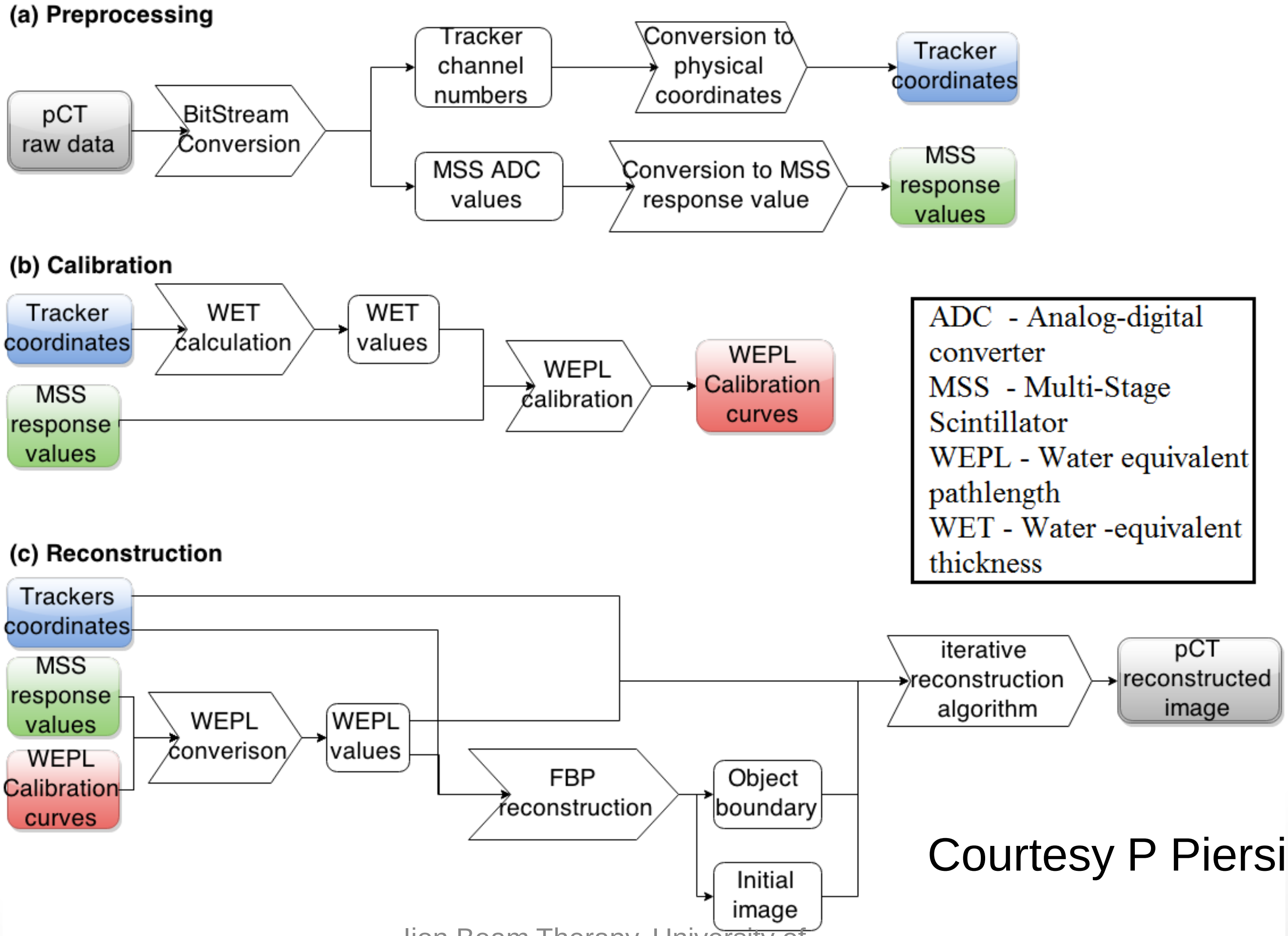
An Experimental Proton CT Imaging System (Phase II pCT Scanner)

- The proton CT scanner prototype is a compact proton imaging system that can be mounted on any horizontal proton beam line for testing
- The system is currently at the Northwestern Medicine Chicago Proton Therapy Center, a facility operating a 235 MeV IBA cyclotron for extensive testing using their horizontal uniform scanning beam line
- The scanner area is 36 cm x 9 cm allowing to image standard QA and head phantoms
- I single continuous scan of high quality takes about 6 minutes at a data rate of ~1 million protons/sec (0.1% of therapeutic beam intensity)



The proton CT scanner on the Chicago Proton Treatment Center beam line

Proton Imaging Data Flow



(a) Preprocessing

pCT raw data → BitStream Conversion → Tracker channel numbers → Conversion to physical coordinates → Tracker coordinates

BitStream Conversion → MSS ADC values → Conversion to MSS response value → MSS response values

(b) Calibration

Tracker coordinates → WET calculation → WET values → WEPL calibration

MSS response values → WEPL calibration → WEPL Calibration curves

(c) Reconstruction

Trackers coordinates

MSS response values

WEPL Calibration curves

WEPL converison

WEPL values

FBP reconstruction

Object boundary

Initial image

iterative reconstruction algorithm

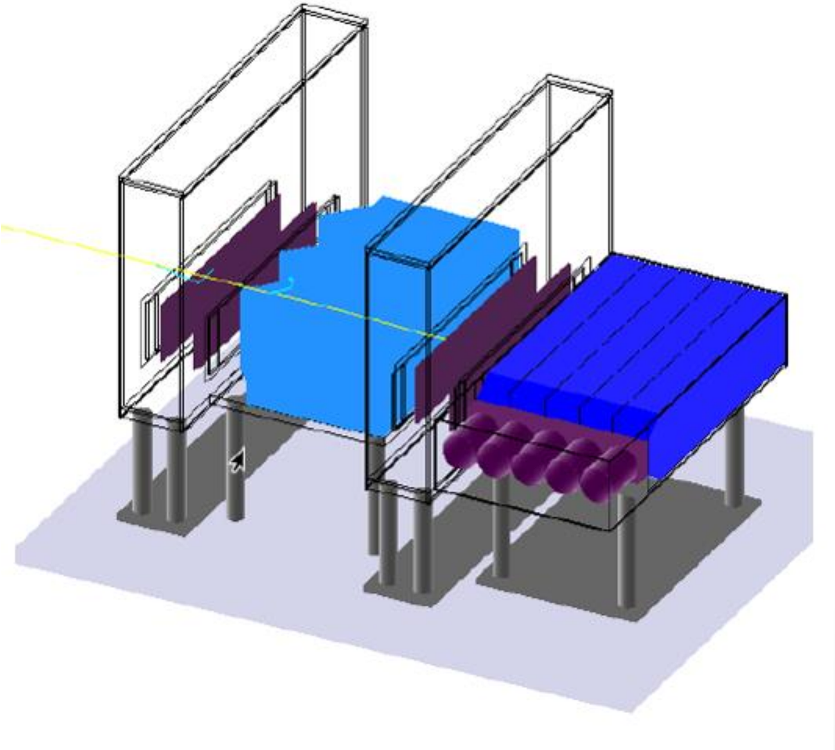
pCT reconstructed image

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

Courtesy P Piersimoni

Monte Carlo Simulation Platform

- To better understand scanner performance (and improve it), a simulation platform was built in Geant4 (also available in TOPAS)
- Beam line and phantom geometries are included
- Platform is being validated by comparing simulation and experimental results
- Also useful as virtual test bed for new ideas (larger scanner, moving phantoms etc.)



Geant4 proton CT simulation platform (calibration setup). Courtesy V. Giacometti

Proton Imaging Reconstruction Principles

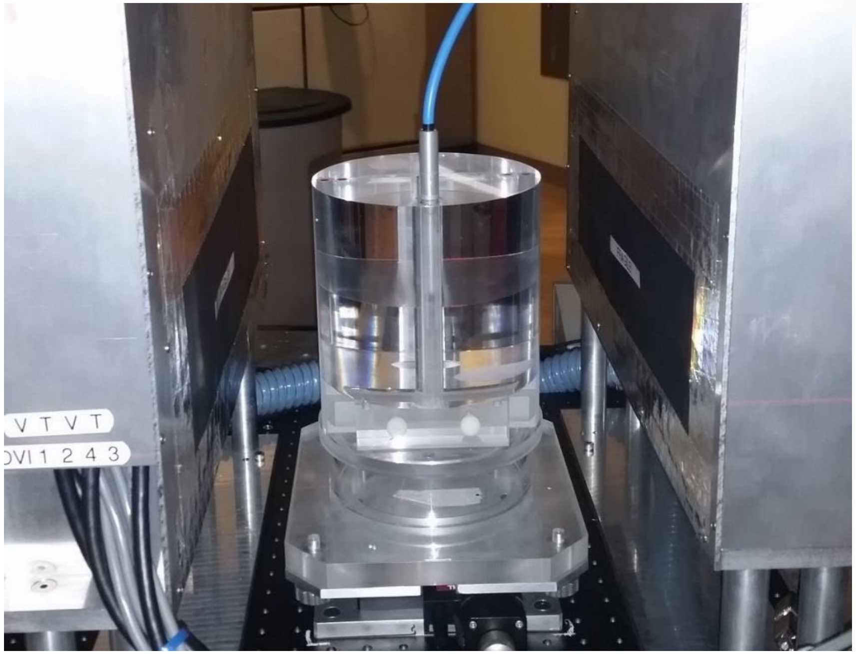
- Input data into reconstruction consist of proton coordinates and direction vectors & WEPL values
- Protons data are binned spatially and w.r.t. to direction and outliers of due to large scattering or energy loss are removed
- For each proton an estimated (most likely) path is calculated that establishes a system matrix A, while WEPL values form a vector b
- Iterative solution of the algebraic linear system Ax=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)
- “Superiorization” finds a solution that has superior quality (smaller TV) compared to feasible solution without superiorization

Proton Imaging – Pre-Clinical Evaluation

- Proton CT dose
- Random noise and systematic errors – WET calibration
- CT RSP# accuracy
- Spatial resolution, MLP accuracy
- End-to-end testing with head phantom -> small animal model: 3D alignment error, range error, comparison to DECT

Proton Imaging Dose

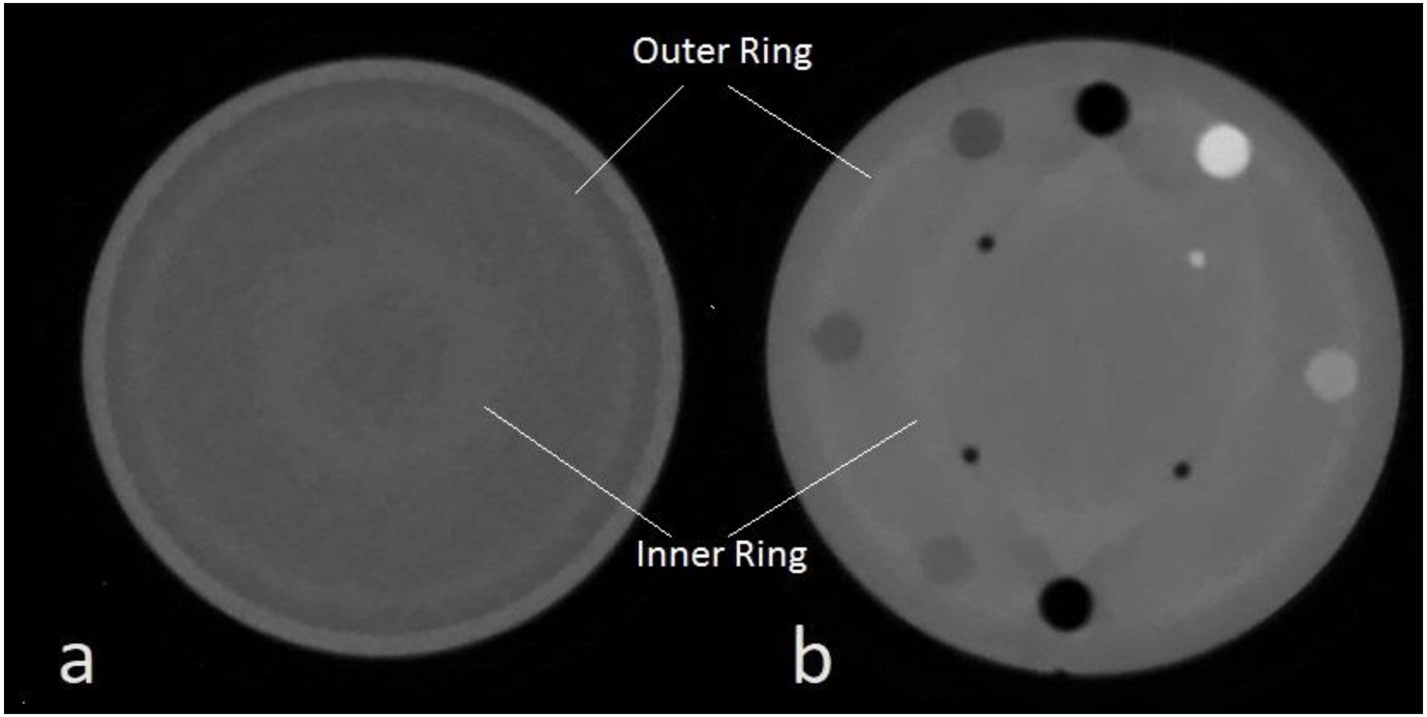
- Ideally, proton imaging should be very dose efficient due to high detection efficiency of protons
- We measured the dose as a function of entrance fluence and found the dose to be **1 mGy for a fluence of 10^6 p/cm^2** both at the center and the periphery of the acrylic CTP554 dose phantom



Catphan CTP554 acrylic dose phantom (Ø 16 cm) with Farmer ionization chamber mounted on the proton CT imager

Proton Imaging – Ring Artifacts

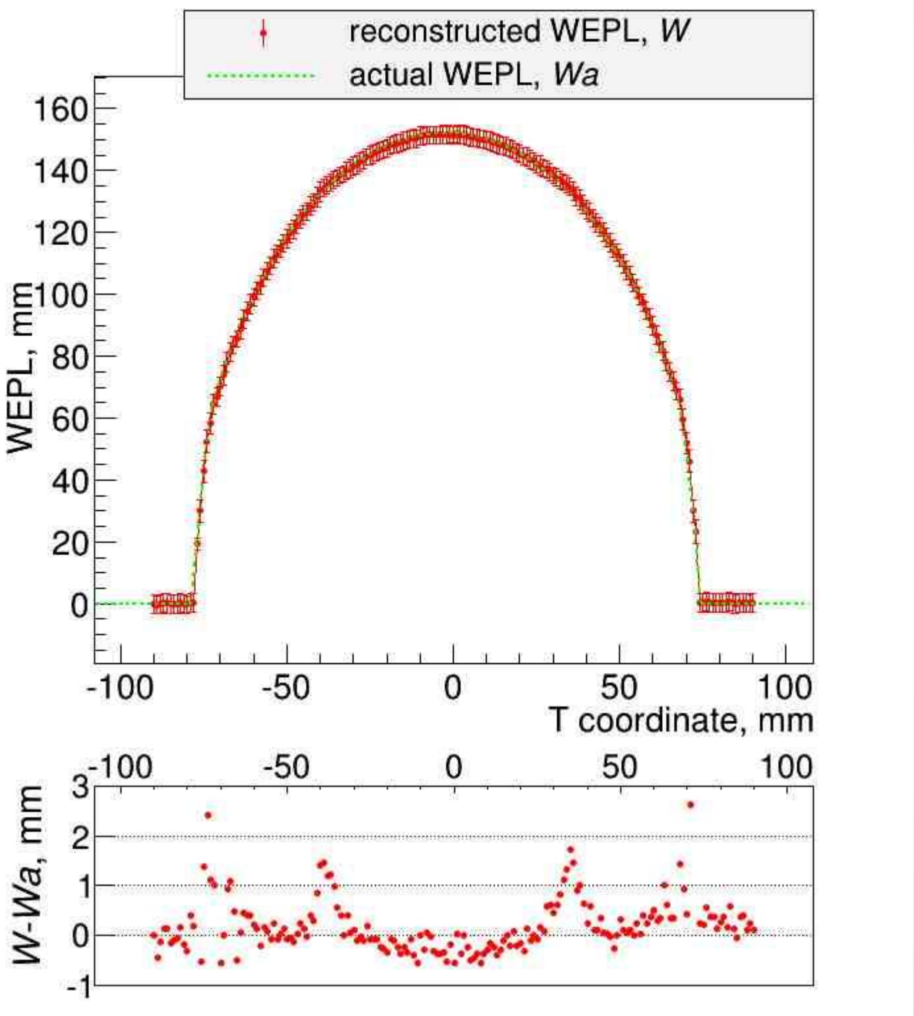
a) Water Phantom b) CTP404



Ring artifacts arise from WEPL calibration errors, i.e., wrong conversion of the proton response in the WEPL detector into WEPL; these errors occur at the interfaces between stages of the multi-stage scintillator

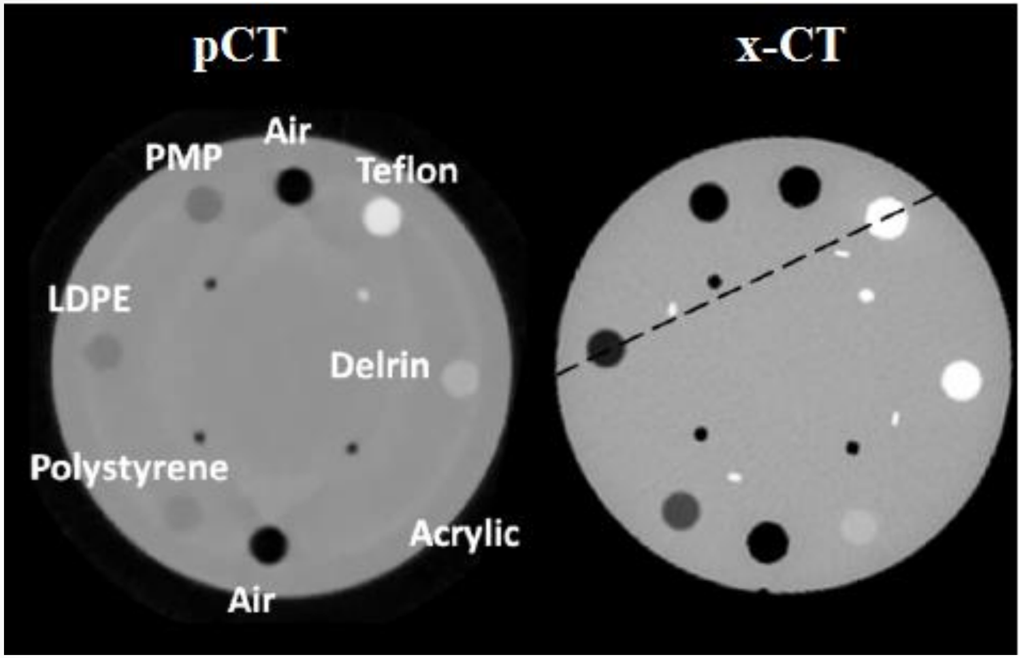
Noise and Systematic Reconstruction Errors

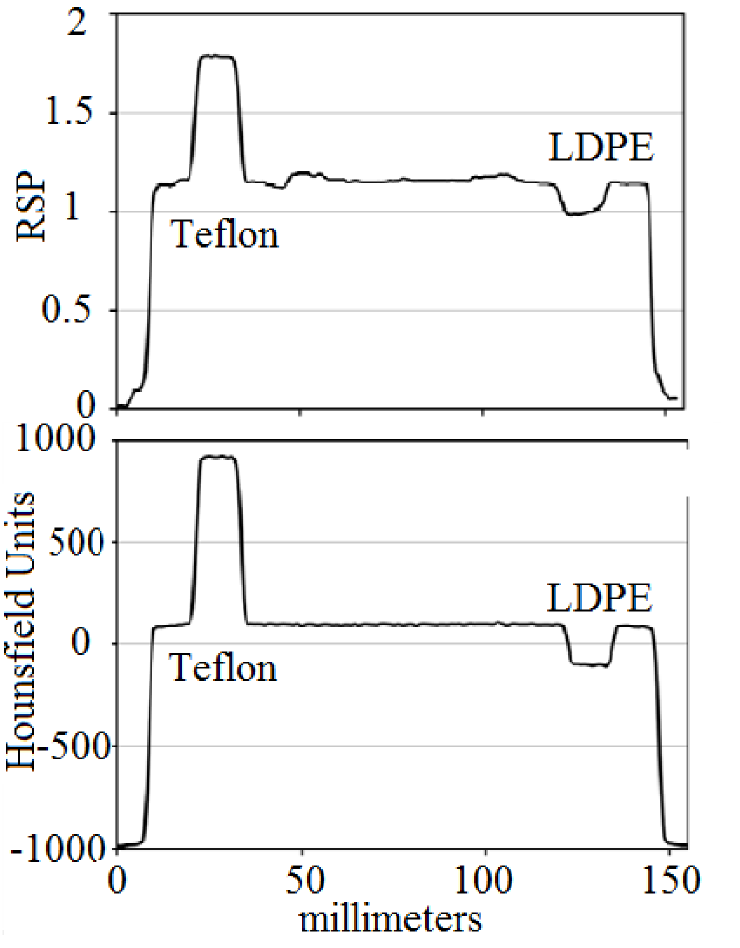
- The WEPL detector has been calibrated with a polystyrene stair phantom and systematic WEPL errors have been minimized with support from MC simulations
- The WEPL noise per 200 MeV proton is ~+/-3 mm, thus 0.3 mm for a 1 mm^2 image voxel for a fluence of 100 p/ mm^2
- For a full CT scan with 100 projections this corresponds to a dose of ~1 mGy, resulting in a CT noise of < 1%
- Systematic errors occur when the Bragg peak is located at multi-stage WEPL detector interfaces



WEPL profile & error of a 15-cm Ø water phantom with acrylic

CT RSP Reconstruction CPT404





Proton CT and x-ray CT reconstructions of the CPT404 phantom

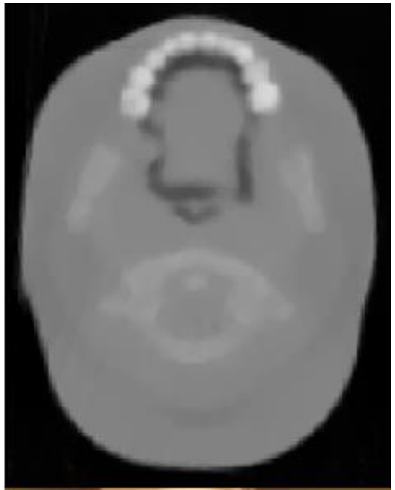
pCT RSP # Accuracy – Comparison with Peakfinder (PF) Measurements

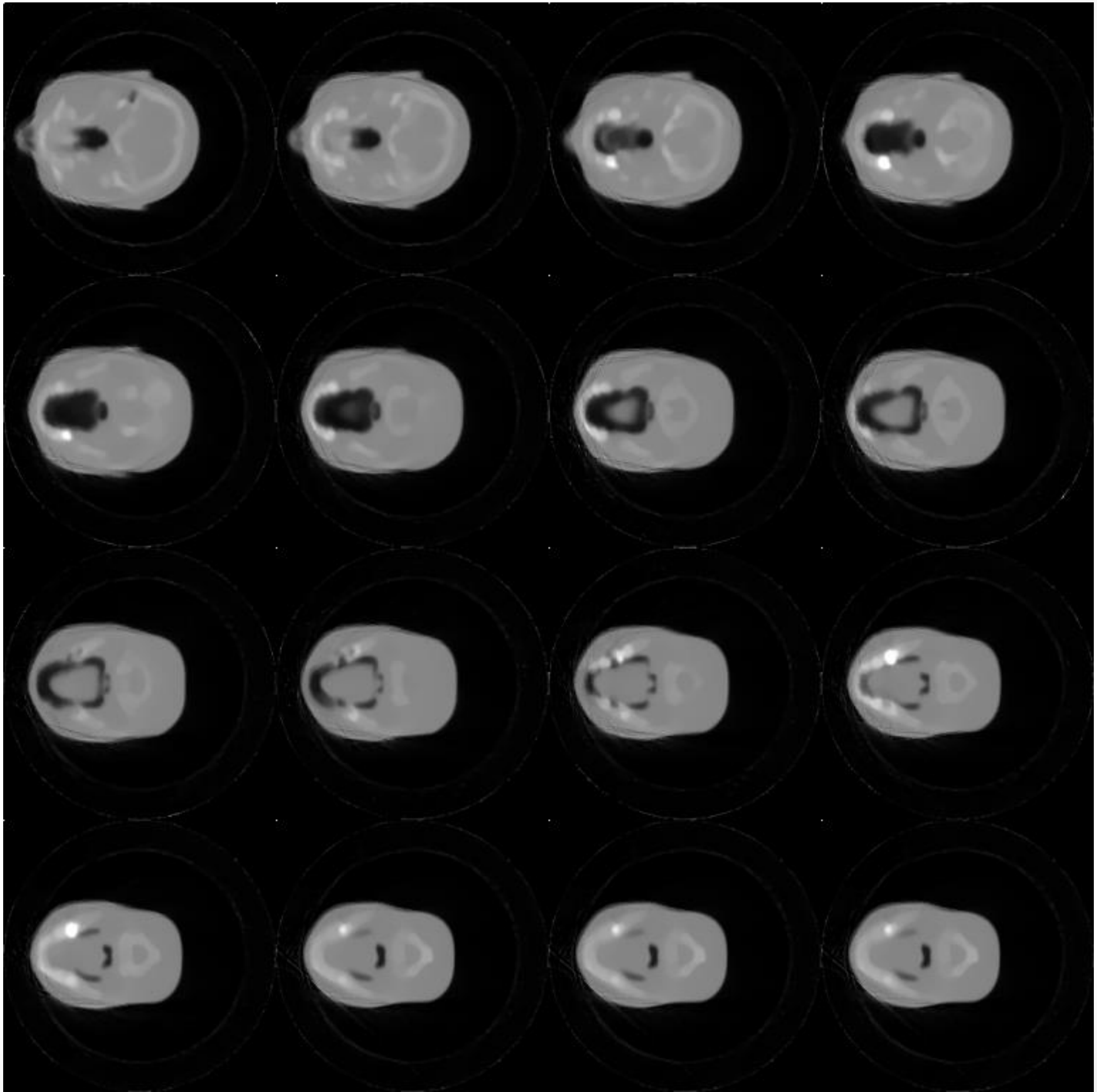
Material	RSP (PF) *	RSP (pCT)	RSP (Bethe Bloch)
Body (clear epoxy)	1.14 +/- 0.001	1.14 +/- 0.01	NA (proprietary composition)
LDPE	0.98 + 0.01	0.99 +/- 0.01	0.98
Polystyrene	1.03 + 0.01	1.04 +/- 0.01	1.03
PMMA (Acrylic)	1.16 + 0.01	1.16 +/- 0.01	1.16
Delrin	1.36 + 0.01	1.36 +/- 0.01	1.36
Teflon	1.79 + 0.01	1.78 +/- 0.01	1.79
PMP	0.88 +0.005	0.90 +/- 0.01	0.88

*Courtesy Thomas Tessonnier, HIT

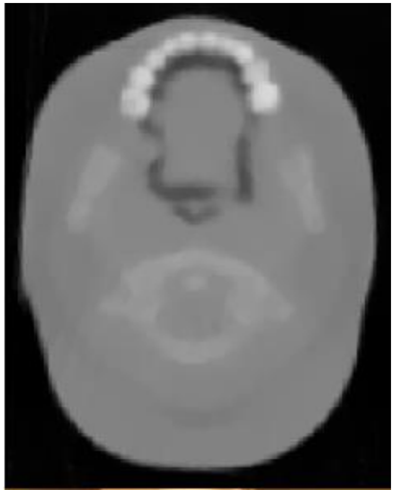
1^{st} complete head scan (CIRS model 715) Loma Linda –UCSC Phase II scanner

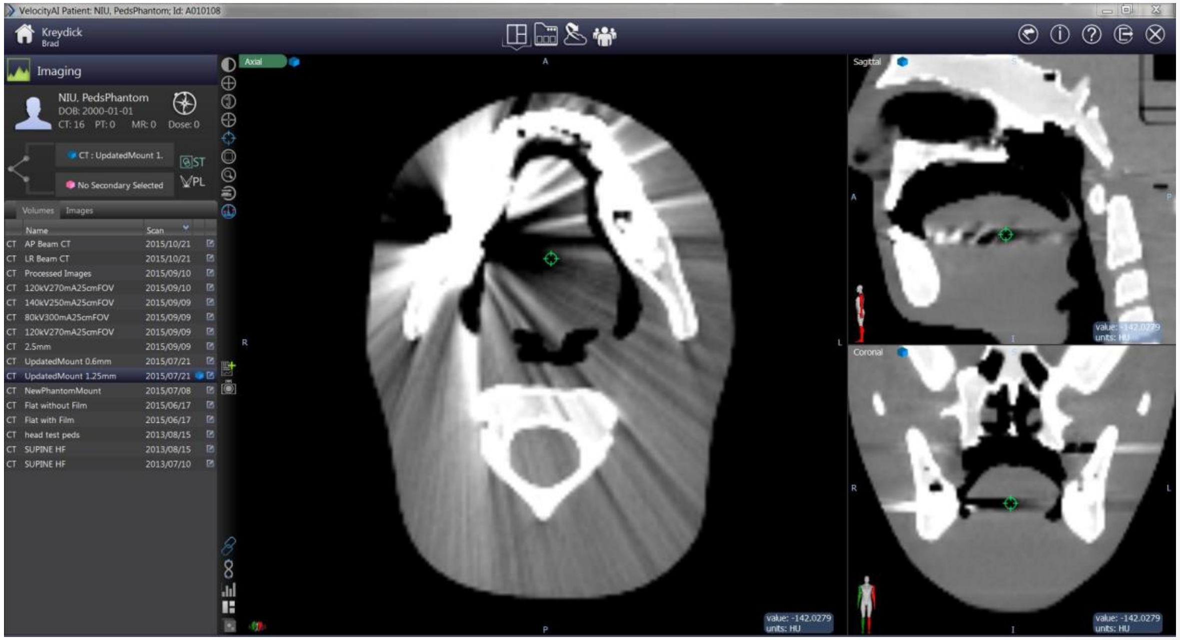
- Pediatric (5 yr. old, CIRS) head phantom used for imaging
- Single reconstructed proton CT slice through lower mandible and teeth
- Data acquired at 1 million events per second using a 200 MeV proton beam and continuous rotation
- Total scan time < 6 min





PCT slice (left) and x-CT slice (right) through the dental filling of CIRS HN 715 phantom





VelocityAI Patient: NIU, PedsPhantom; Id: A010108

Kreydick
Brad

NIU, PedsPhantom
DOB: 2000-01-01
CT: 16 PT: 0 MR: 0 Dose: 0

CT : UpdatedMount 1.
No Secondary Selected

	Name	Scan
CT	AP Beam CT	2015/10/21
CT	LR Beam CT	2015/10/21
CT	Processed Images	2015/09/10
CT	120kV270mA25cmFOV	2015/09/10
CT	140kV250mA25cmFOV	2015/09/09
CT	80kV300mA25cmFOV	2015/09/09
CT	120kV270mA25cmFOV	2015/09/09
CT	2.5mm	2015/09/09
CT	UpdatedMount 0.6mm	2015/07/21
CT	UpdatedMount 1.25mm	2015/07/21
CT	NewPhantomMount	2015/07/08
CT	Flat without Film	2015/06/17
CT	Flat with Film	2015/06/17
CT	head test peds	2013/08/15
CT	SUPINE HF	2013/08/15
CT	SUPINE HF	2013/07/10

value: -142.0279
units: HU

SECTION I

ACCELERATORS & BEAM DELIVERY TECHNOLOGY FOR PARTICLE IMAGING

Challenge 1: Particle imaging and therapy require very different intensities

- Particle imaging, if based on single-particle registration, requires a low-intensity beam, of the order of $10^6 – 10^7$ p/s compared to 10^{11} p/s (ideally) for therapeutic beams
- Current experience tells us that tuning a particle accelerator to very low intensities is difficult, not always reproducible, and time-consuming
- Current beam line monitors are not sensitive enough for low-intensity imaging beams

Challenge 2: Protons may not be the ideal particle for imaging

- Experience tells that multiple Coulomb scattering limits spatial resolution of particle imaging
- Heavier ions, e.g., deuterium or helium, may result in better image quality, and straight-line image reconstruction may be become possible
- However, multi-particle accelerators with fast switching between particle species and particle energies are not available

Challenge 3: Current particle imaging systems use a single particle energy, which is not higher than 250 MeV for protons

- There is a wide range of thicknesses particles encounter when traversing the patient
- In order to image all anatomical regions in all patients, we will need a proton energy of up to 330 MeV
- Ideally one should adjust the energy according to the thickness traversed in order to optimize image quality and minimize size of energy detector

Specifications for Future Hadron Therapy Systems Suitable for Imaging

- Challenge 1:
  - Separate high-intensity therapy from low-intensity imaging (e.g., separate ion source, separate accelerator, separate beam port)
- Challenge 2:
  - Develop accelerators that can provide multiple particle species for both imaging and therapy beams, with fast switching between them (seconds or less)
- Challenge 3:
  - Develop light ions (p-He) accelerators that provide energies suitable imaging all anatomical parts in all patients
  - Develop fast pencil beam scanning systems for imaging that allow millisecond change of energy during scanning

Summary & Outlook

- Range accuracy and verification are important goals in proton therapy
- Better RSP determination will allow dose escalation and hypofractionation
- Particle imaging will offer many advantages if available, but technical challenges have to be addressed, especially on the accelerator and beam delivery side

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