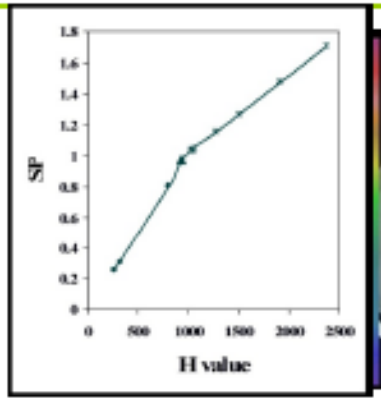
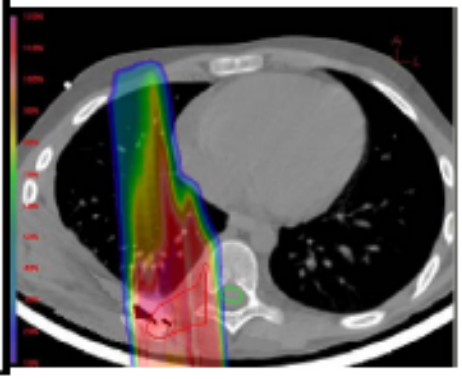
The Proton CT project at NMCPC

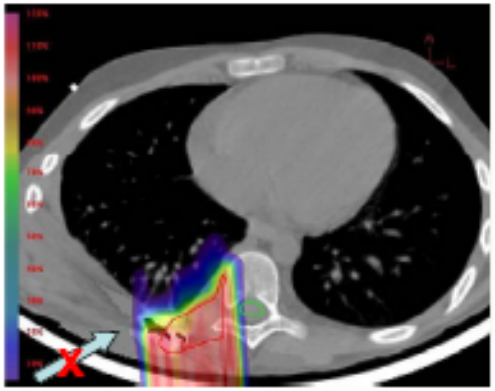
Loma Linda University
Dr. Reinhard Schulte, MD, V. Bashkirov
and
Santa Cruz Institute for Particle Physics, UCSC
H. Sadrozinski, R. Johnson, A. Zatserklyyaniy
And
Northwestern Medicine Chicago Proton Center
M. Pankuch, Brad Kreydick
And
Northern Illinois Univ. (image reconstruction)
G. Coutrakon, N. Karonis, C. Ordonez, K. Duffin
And
Baylor University (image reconstruction)
K. Schubert, B. Schultze
And
Univ. of Cal. San Francisco
B. Faddegan, J. Ramos-Mendez, P.Piersimoni

The Range Uncertainty Problem in Proton Beam Therapy

- Proton range depends on the initial proton energy and the distribution of stopping power on the beam path
- The distribution of stopping power (rel to water) is presently determined from X-ray CT
- CT Hounsfield units need to be converted to rel. stopping power
- Uncertainty in calibration curve leads to range uncertainties of about 3.5% of proton range
- This problem needs to be solved before protons can be used to the fullest extent

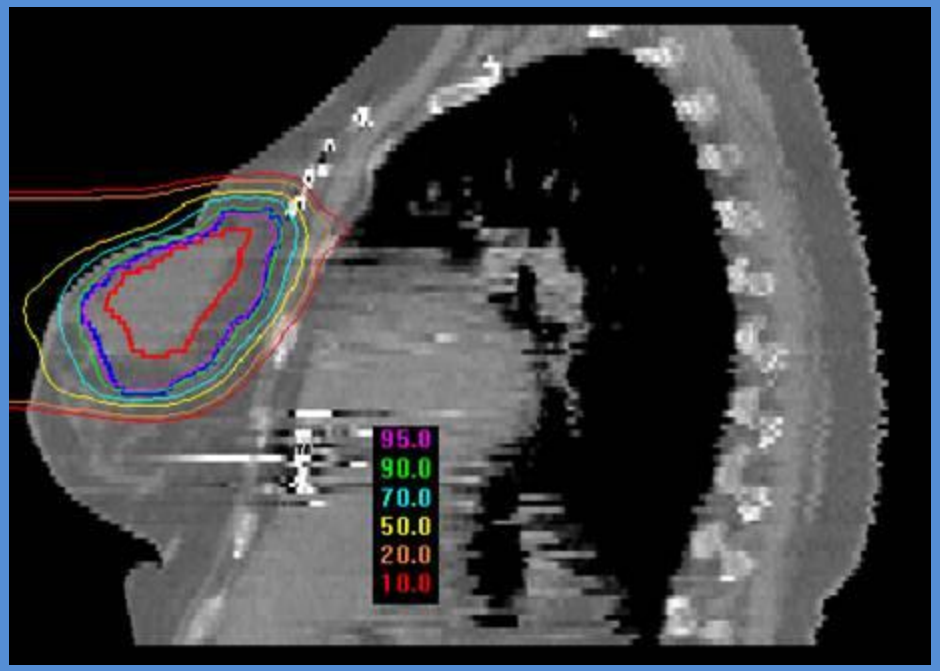






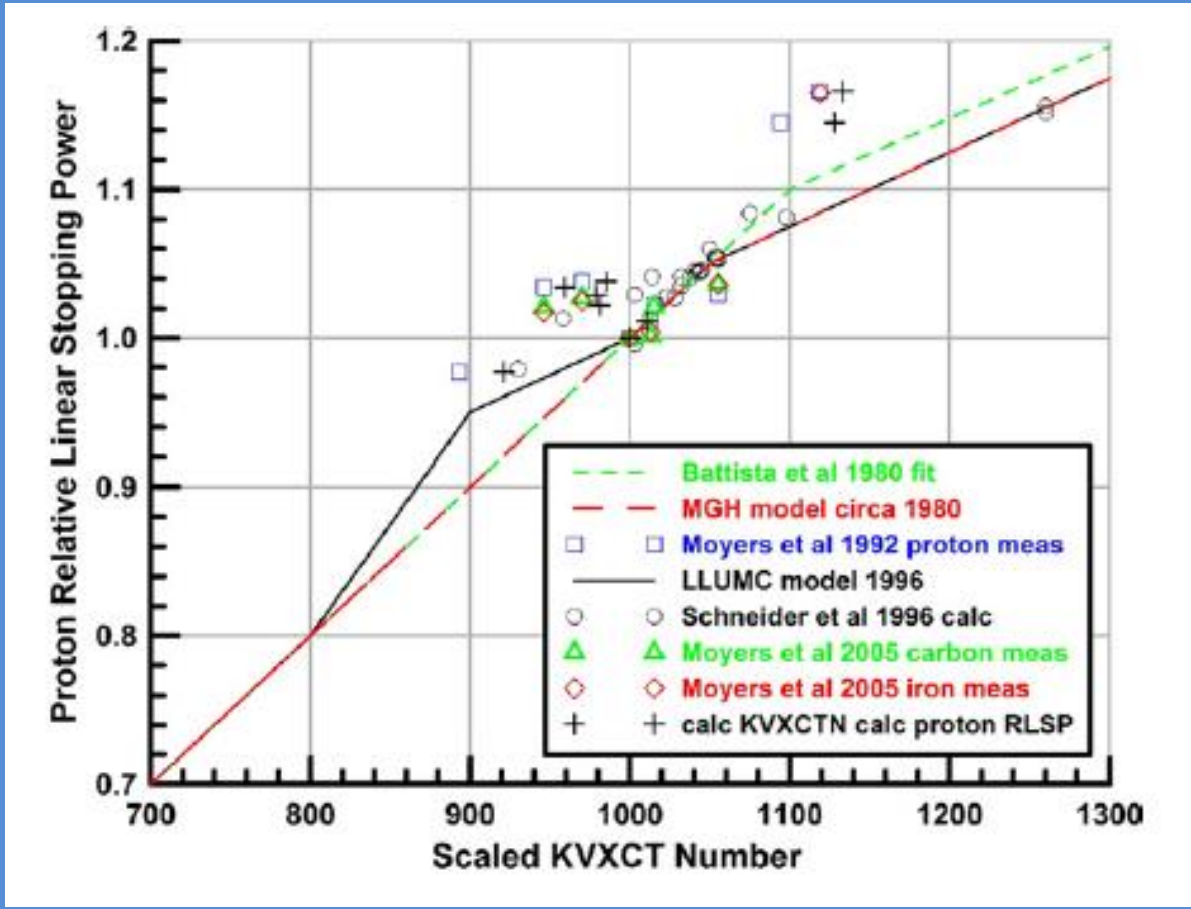
Slide courtesy of Reinhard Schulte, Loma Linda University

Proton treatment plan for breast tumor.
Errors in proton stopping powers can lead to heart and lung dose beyond the target due to proton range errors



Proton Treatment Plans currently use X-ray CT for proton RSP values. These produce range errors of 3.5%

Proton RSP's are derived from x-ray linear attenuation coefficient (μ) in tissue substitutes with "reasonable" success.



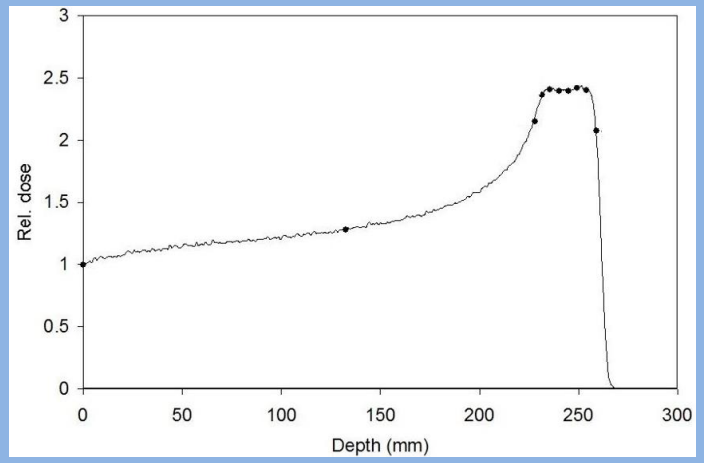
(Moyers, Medical Dosimetry, Oct 2010)

Better Dose accuracy means better RSP values

Depth in Patient → WEPL → Relative Dose

$$WEPL = \sum_{l=1}^{n} RSP(l)dl$$

$$RSP = \frac{\frac{dE}{dx}(medium)}{\frac{dE}{dx}(water)} = \frac{\rho_m}{\rho_w}\frac{S_m}{S_w} \approx \frac{\rho_m}{\rho_w} \quad within\ 3\%$$



To calculate dose in each voxel we need water equivalent depth of each voxel along the proton path

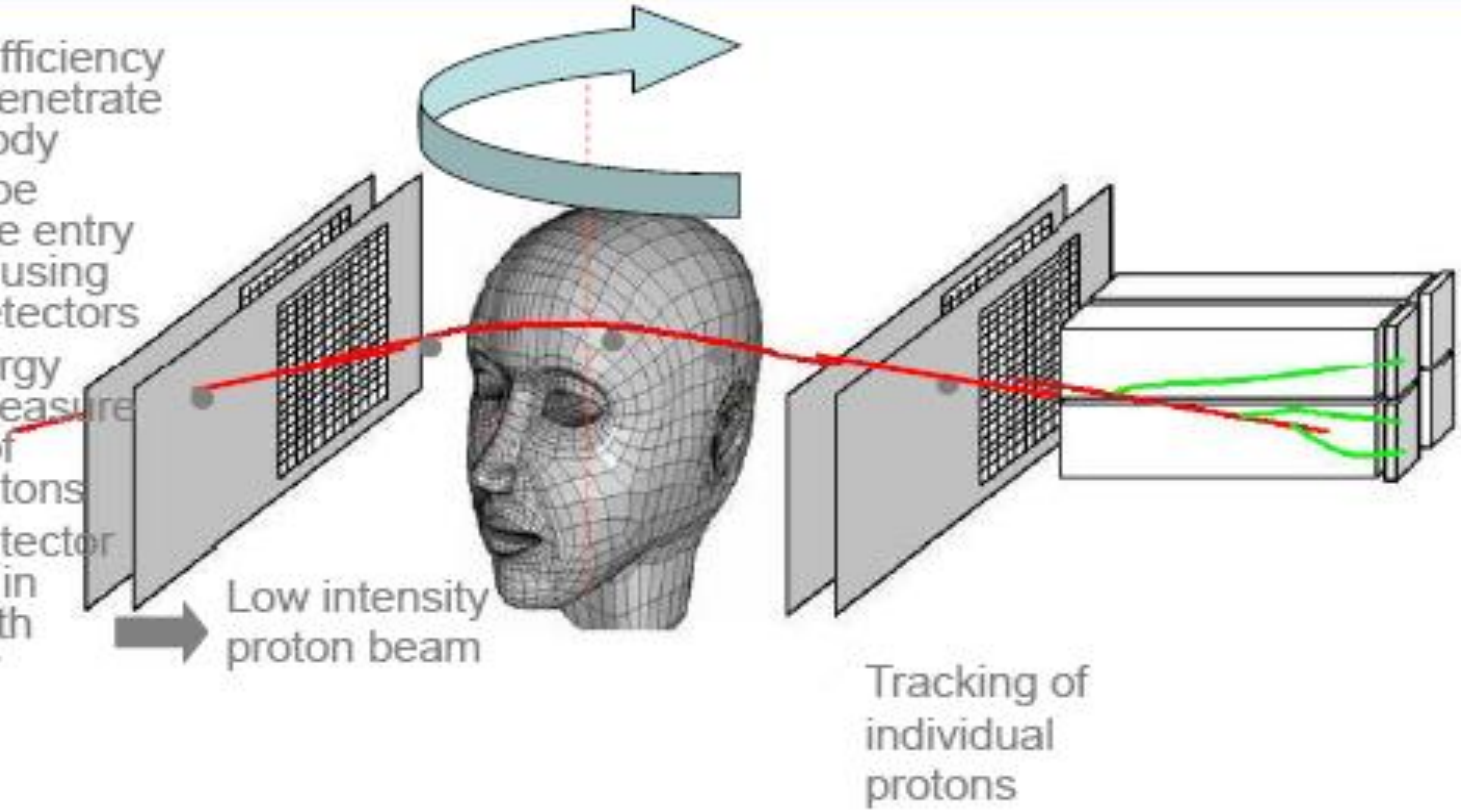
Alan Cormack- Nobel Laureate for X-ray CT

- Cormack (1924-1998) published 1st paper on 3D image reconstruction based on X-ray absorption. (J. Appl. Phys. 34, 2722, 1963).
- Images are made using x-ray attenuation coefficients in each 3D voxel of the patient.
- He was also the 1st to propose using 200-300 MeV protons on a gantry to image a patient with protons.

Alan M. Cormack, Physicist, 1979 Nobel Laureate

Protons can be used for CT imaging very dose-efficiently

- Protons of sufficiency energy can penetrate the human body
- Protons can be tracked on the entry and exit side using modern Si detectors
- Residual energy detector to measure energy loss of individual protons
- Rotational detector arrangement in synchrony with proton gantry



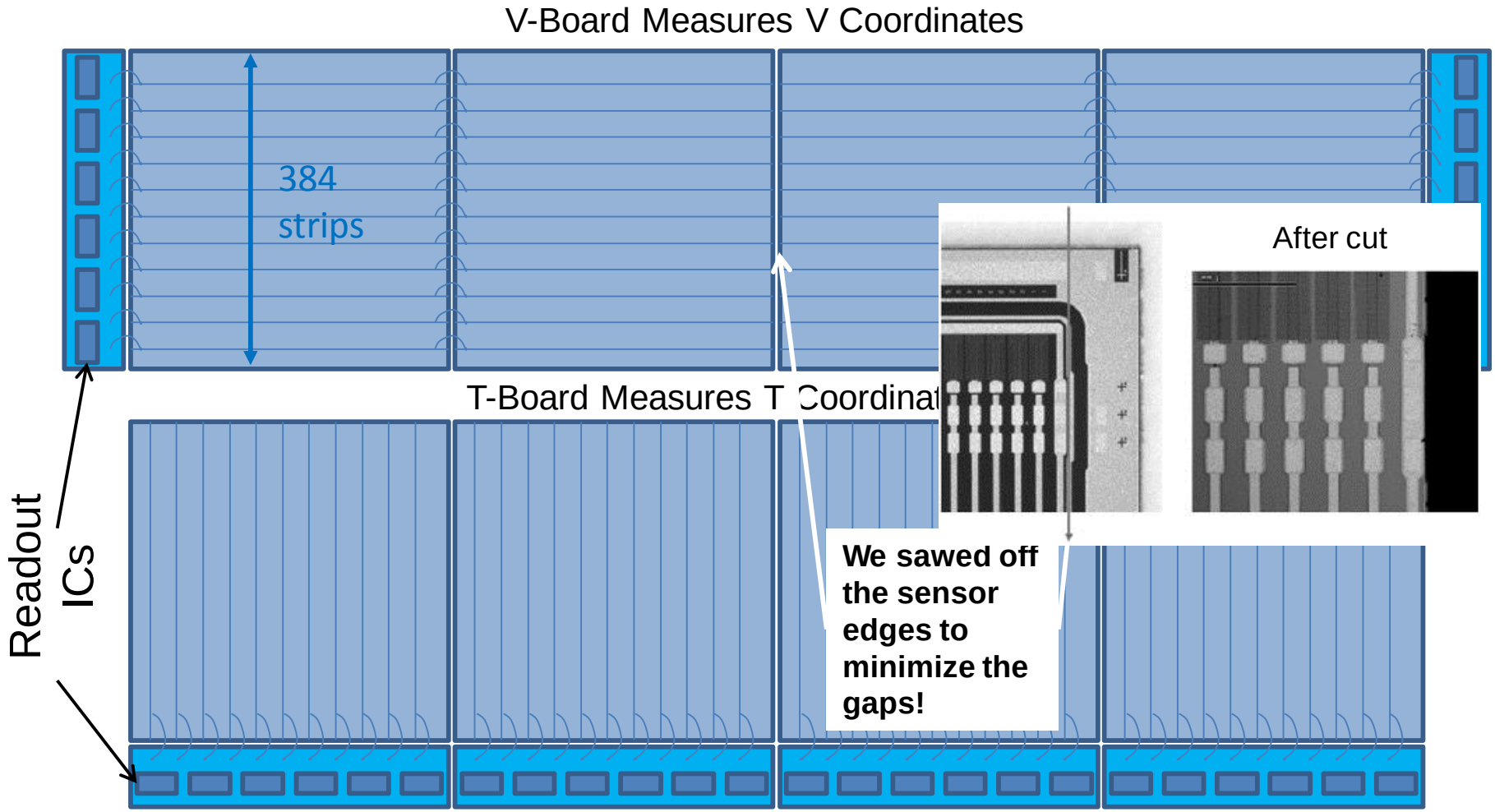
Slide courtesy of Reinhard Schulte, Loma Linda Univ.

How it works; solving for RSP(x,y,z)

- The head is partitioned into 1 mm^3 voxels; want to find RSPs
- Fire 360 million protons through phantom from 0^0 to 360^0
- Each proton has its path reconstructed through a set of voxels
- Each proton has its residual energy recorded to calculate a WEPL through the phantom
- Linearize RSP(x,y,z) → RSP(i) , I = 1, n ; n ≅ 10^7
- A set of m equations is generated for m tracks
- $WEPL_i = \sum_{j=1}^{N} (\Delta L)_{ij} RSP_j$
- $(\Delta L)_{ij}$ is a sparse matrix of chord lengths for traversed voxels
- Solve this m x n matrix of linear equations for RSP_j ; j=1- 10^7 using methods of iterative solvers for sparse matrices.

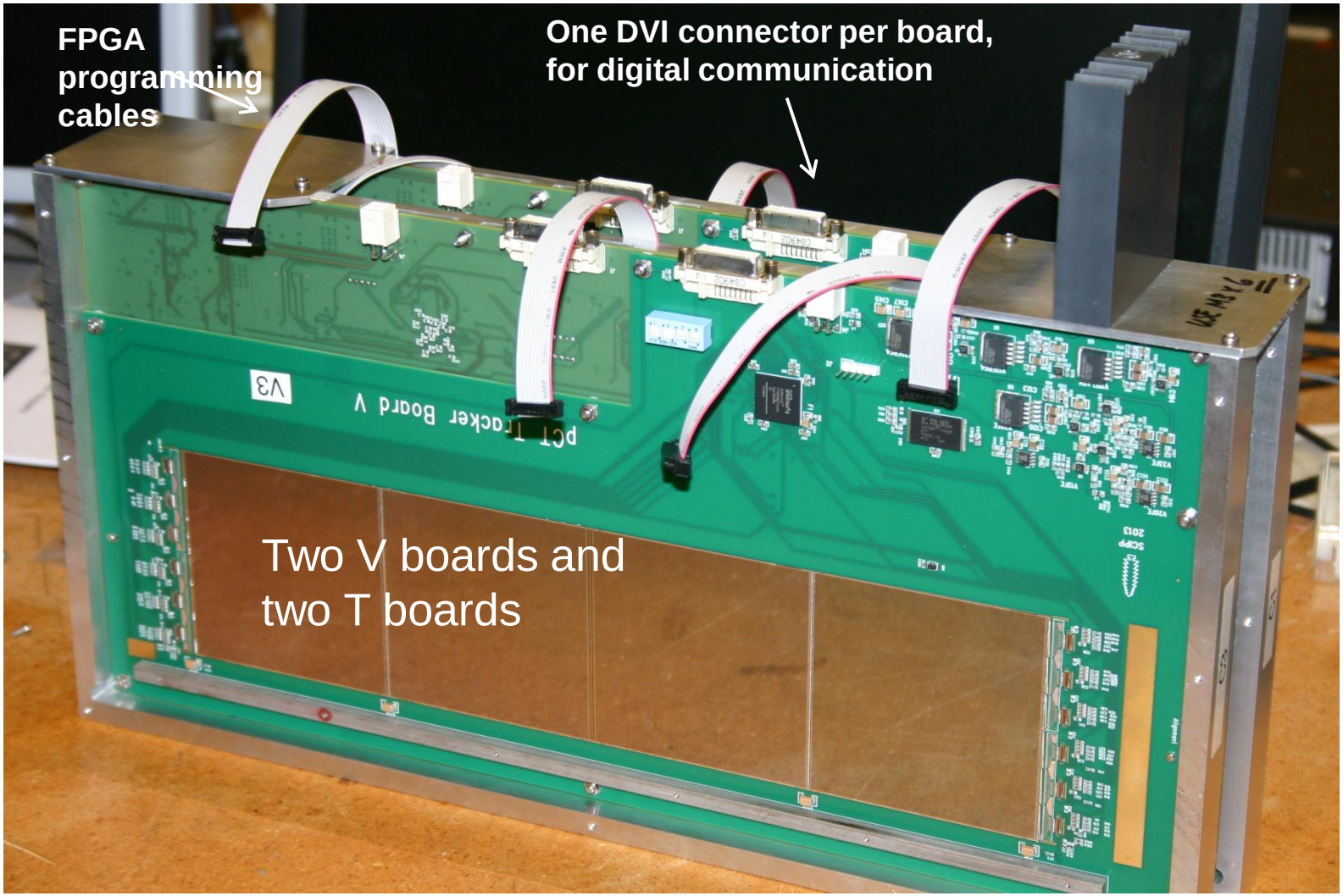
Silicon-Strip Tracking Plane

Two layers of single-sided detectors are needed to measure a 3-D space point.



Complete Tracker Module at UCSC

Measures two 3-D space points, to give a track vector



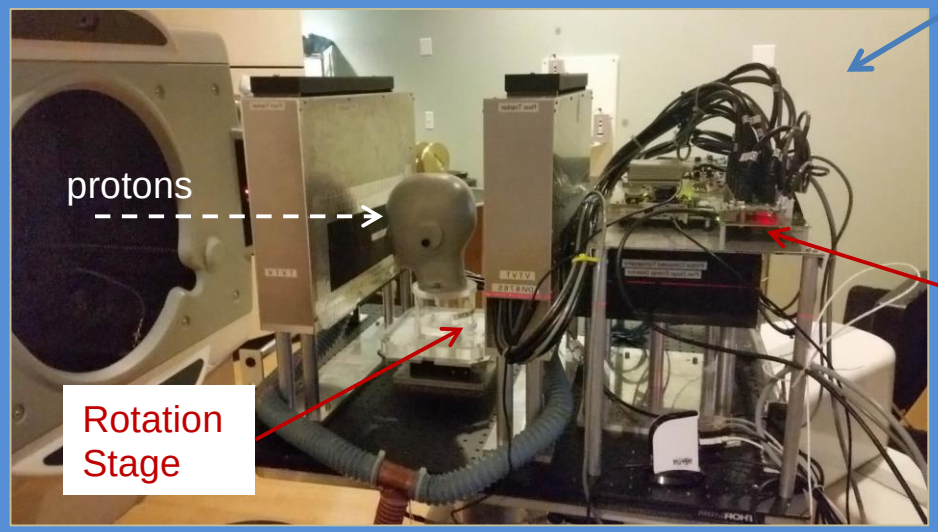
Loma Linda's 5 Stage Scintillator – Energy detector

V.A. Bashkirov, R.P. Johnson, et al., *Novel Scintillation Detector Design and Performance for Proton Radiography and Computed Tomography*, Med. Phys. 43, 664 (2016).

At 1 MHz rate the PMT currents are very high in the last 3 dynodes, so active bias is needed.

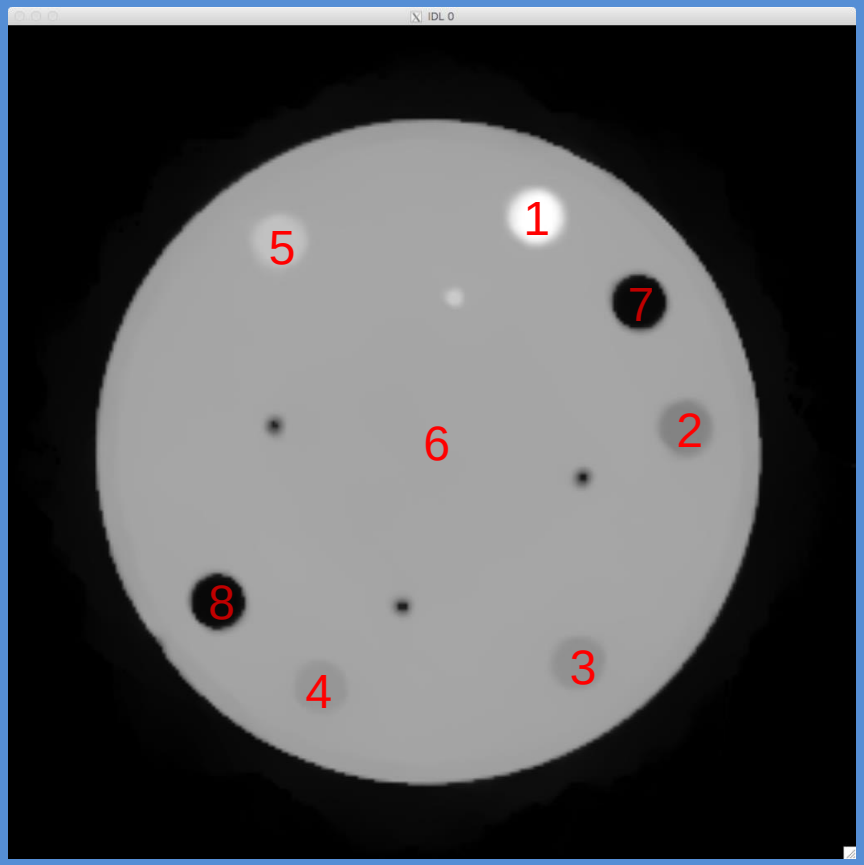
UCSC + LLUMC + CSSB/Baylor

UCSC Scanner



- 9 cm by 36 cm aperture
- Silicon strips for the tracking detectors; 228um spacing
- Plastic scintillator measures proton energy E(out) after phantom
- E(in)-E(out)=Energy loss→ WEPL through the phantom
- See R.P. Johnson et.al., IEEE Trans. Nucl. Sci. 63-1 , p52 (Feb. 2016)

PCT image of sensitom phantom for RSP accuracy test 350 M protons, 1.4 mGy dose



- Region of Interest
  - Cylinder
    - Diameter: 7 pixels
    - Length: 21 slices

ID	Material	RSP[a]
1	Teflon	1.790
2	PMP	0.883
3	LDPE	0.979
4	Polystyrene	1.024
5	Delrin	1.359
6	PMMA/Acrylic	1.160
7	Air	0.00113
8	Air	0.00113

[a]Measured with PeakFinder; calculated for Air

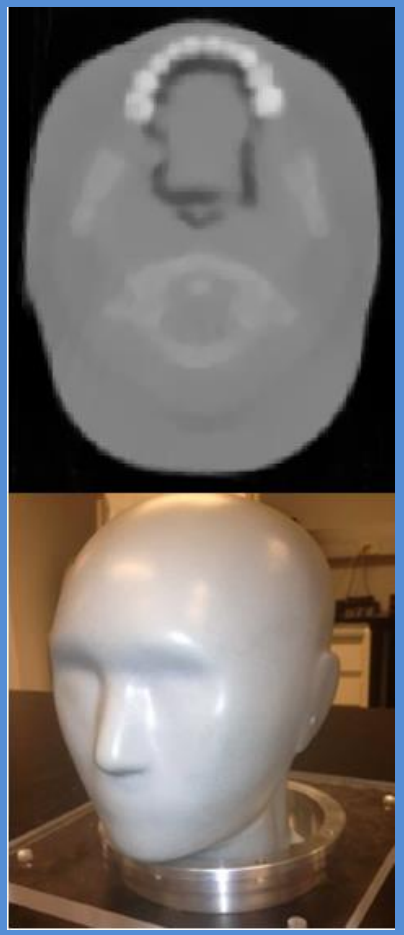
Reconstructed RSP[1]: % Error

Material	True RSP[2]	Reconstructed	% error
Teflon	1.790	1.782 +/- 0.019	-0.44
PMP	0.883	0.882 +/- 0.161	-0.11
LDPE	0.979	0.971 +/- 0.018	-0.82
Polystyrene	1.024	1.017 +/- 0.018	-0.68
Delrin	1.359	1.353 +/- 0.015	-0.44
PMMA/Acrylic	1.160	1.137 +/- 0.019	-1.98

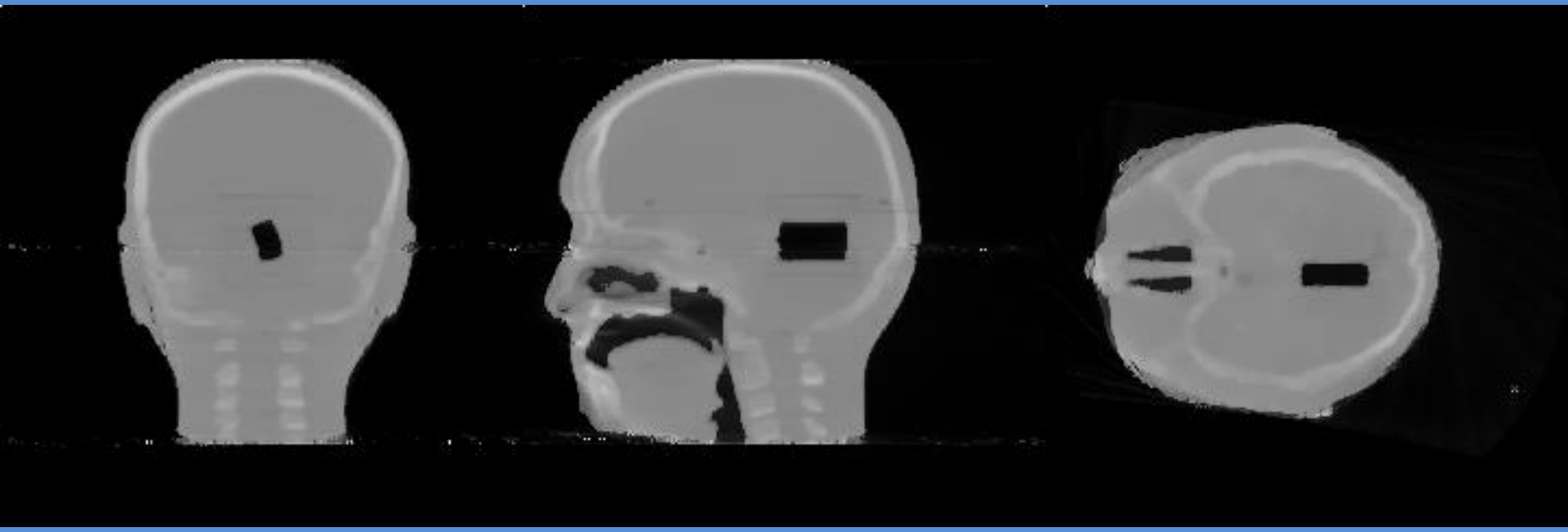
[1]Using 60 CPU cores and 60 GPUs
[2]Measured with PeakFinder

1st complete head scan (CIRS model 715). Taken with Loma Linda –UCSC Phase II scanner

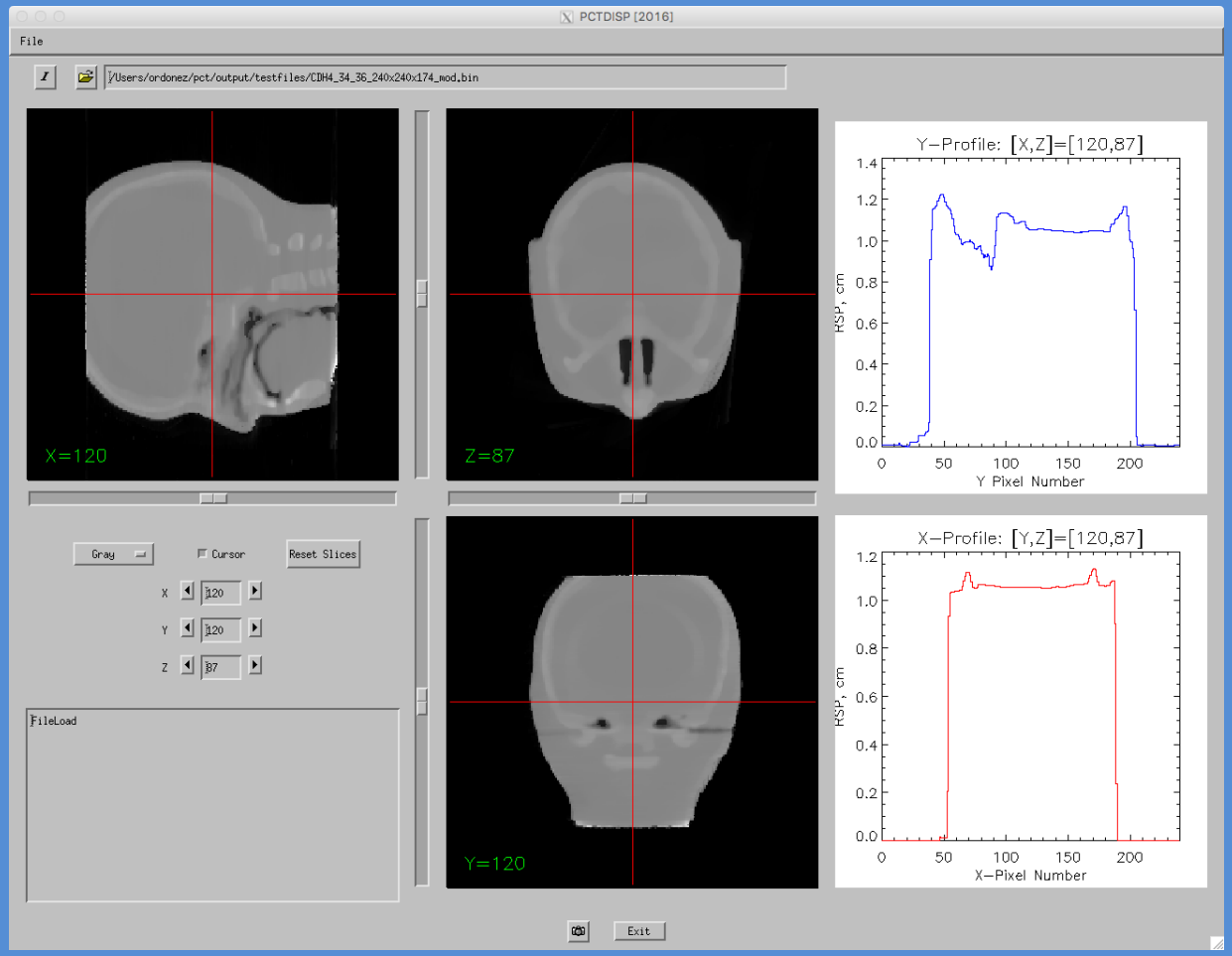
- Pediatric (5 yr. old, CIRS) head phantom used for imaging
- Single reconstructed proton CT slice through lower mandible and teeth
- Data acquired at 1 million events per second using a 200 MeV proton beam and 90 beam entry angles (4 deg intervals)
- Total scan time = 12 min.



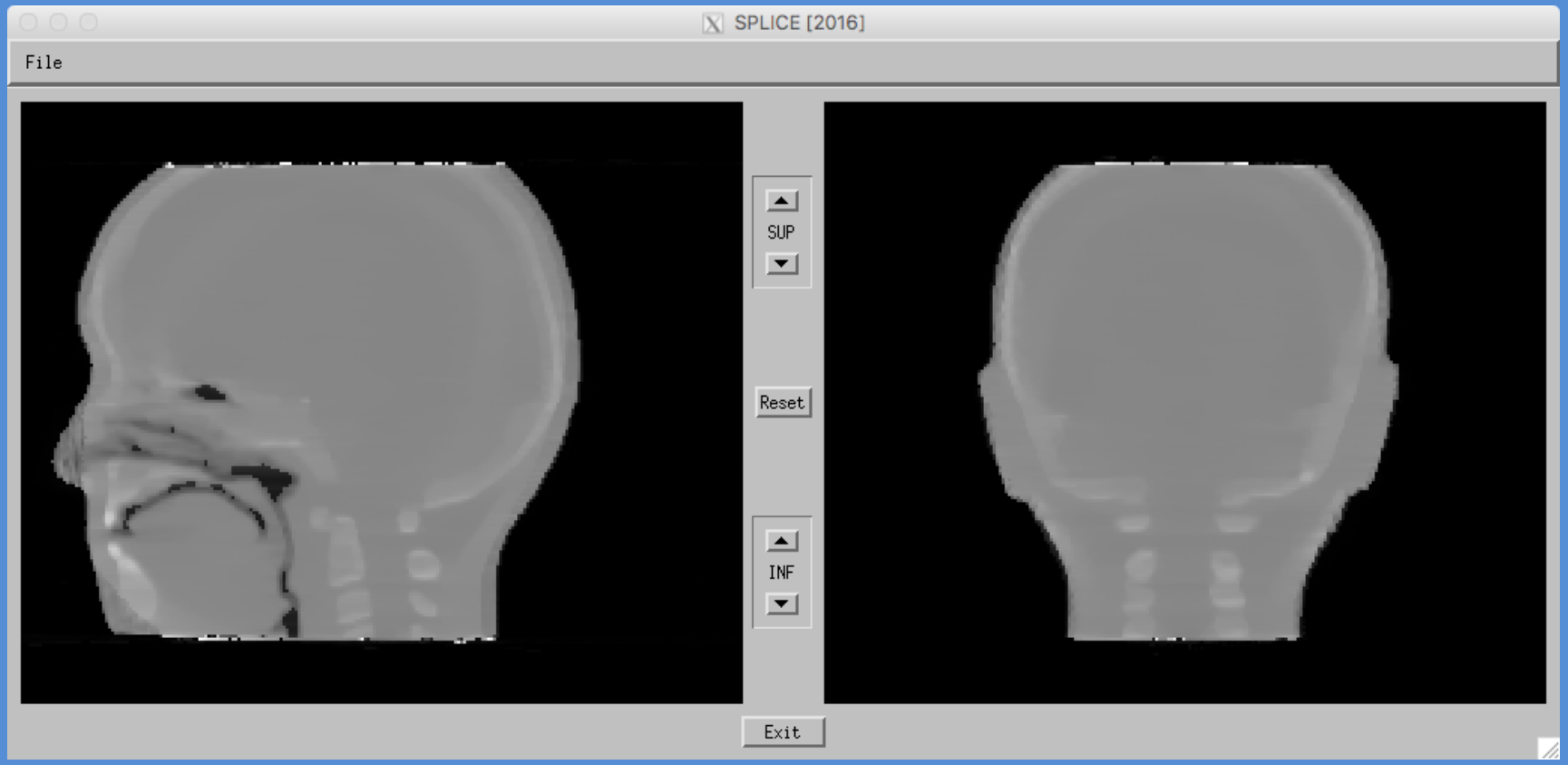
Proton CT reconstructed images of pediatric head phantom using 350 million proton trajectories distributed 0 to 360^0 about vertical axis



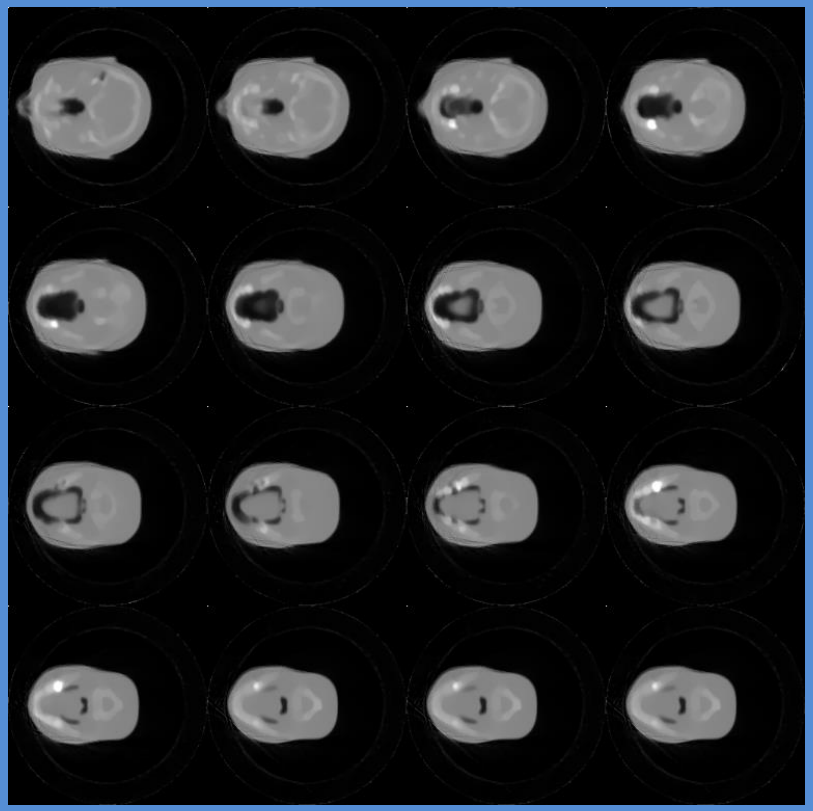
Proton CT reconstructed images of pediatric head phantom using 350 million proton trajectories distributed 0 to 360^0 about vertical axis



1st He CT images from Heidelberg HIT Facility

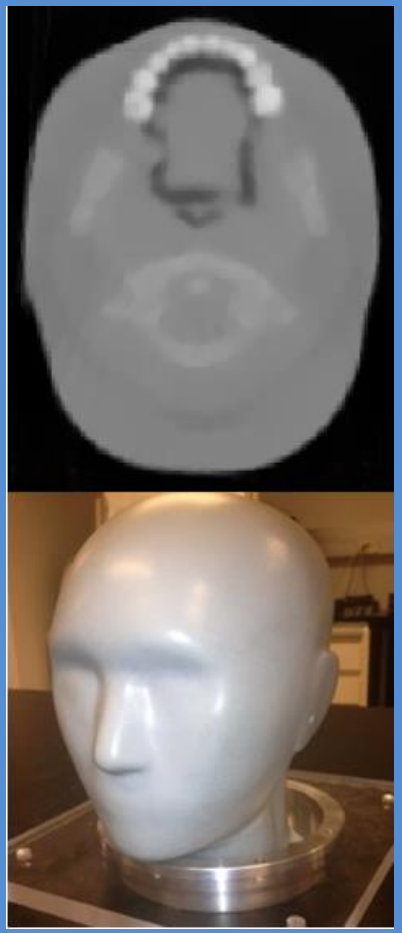


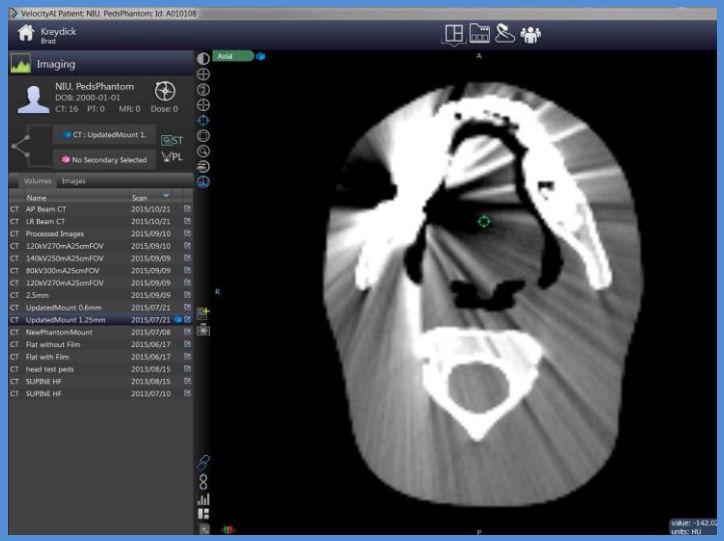
16 Proton CT slices of pediatric head phantom
Each slice is 2.5 mm thick, resolution in each slice: 0.6 x 0.6 mm



Note: There is a amalgam dental filling (upper right image) and a Gold crown (lower left image)

Absence of streaking artifacts by dental fillings
PCT image (left) and X-CT image (right) through the head phantom

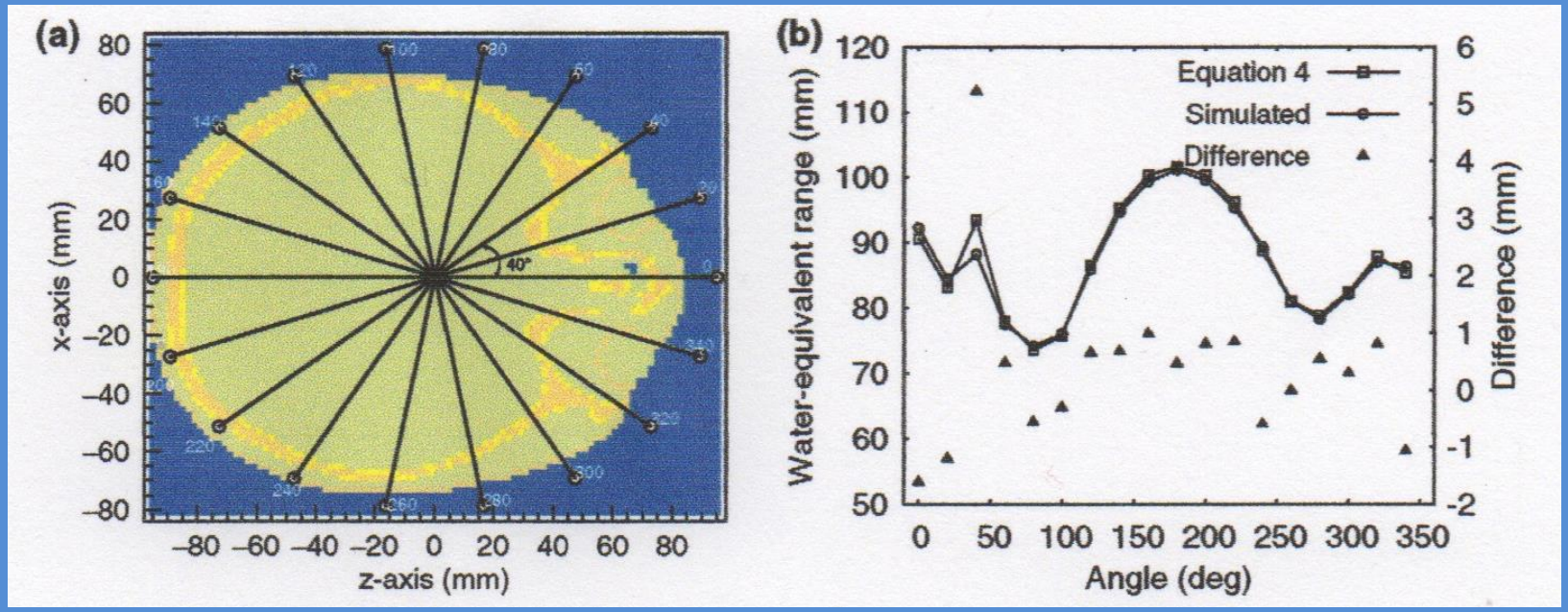




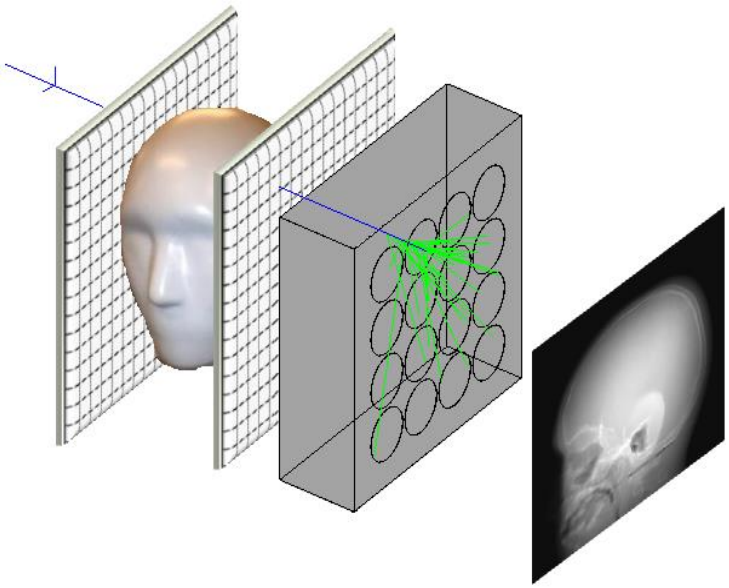
Proton range errors from G4 simulation of NMCPC beam, UCSC detector, and head phantom using image reconstruction software

Piersimoni et. al., Med. Phys, 44, Jan. 2017

- 5 materials of head phantom analyzed; brain, bone and teeth
- True RSPs are calculated from Bethe-Bloch equation in G4
- Reconstructed RSP errors are less than 1% for most materials
- Range errors for 17 rays shown below are less than 1mm



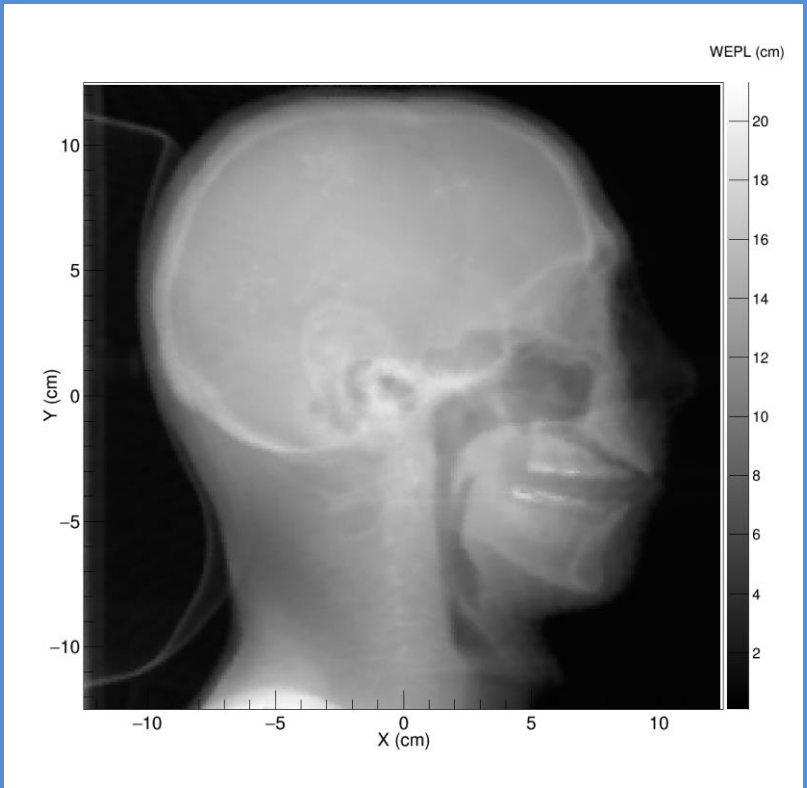
Proton VDA- A Chicago company building a commercially viable proton radiography system for adaption in a proton therapy room



(Left) – 2 (X,Y) optical fiber tracking planes and a plastic scintillator for measuring energy loss, or WEPL.

(Right) – C-arm for holding upstream and downstream detectors

Proton Radiograph simulated in Geant4 using an X-ray CT and Proton VDA proton detectors



Proton radiographs measure water equivalent thicknesses in beam's eye view. They can be used to see anatomic changes before patient treatment and replace x-ray alignment

Summary & Conclusion

- Proton CT can reduce target volume in proton therapy → less dose to healthy tissue.
- Important when treating tumors close to critical structures like brain stem, optic chiasm, and spinal cord.
- New proton CT head scanner has shown high quality images at a fraction of an X-ray CT dose

End of presentation

Thank you for your attention