The 3D Medical Imaging using Proton Computed Tomography

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Robert Wilson

In: Radiological use of fast protons. Wilson R. R., Radiology 45, 487-91, (1946)

- Described the advantages of proton and ion beams for radiation therapy.
- Suggested several techniques that are still in use today.

Radiological Use of Fast Protons

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Except for electrons, the particles which have been accelerated to high energies by machines such as cyclotrons or Van de Graaff generators have not been directly used therapeutically. Rather, the neutrons, gamma rays, or artificial radioactivities produced in various reactions of the primary particles have been applied to medical problems. This has, in large part, been due to the very short penetration in tissue of protons, deuterons, and alpha particles from present accelerators. Higher-energy machines are now under construction, however, and the ions from them will in general be energetic enough to have a range in tissue comparable to body dimensions. It must have occurred to many people that the particles themselves now become of considerable therapeutic interest. The object of this paper is to acquaint medical and biological workers with some of the physical properties and possibilities of such rays.

To be as simple as possible, let us consider only high-energy protons: later we can generalize to other particles. The accelerators now being constructed or planned will yield protons of energies above 125 Mev (million electron volts) and perhaps as high as 400 Mev. The range of a 125 Mev proton in tissue is 12 cm., while that of a 200 Mev proton is 27 cm. It is clear that such protons can penetrate to any part of the body.

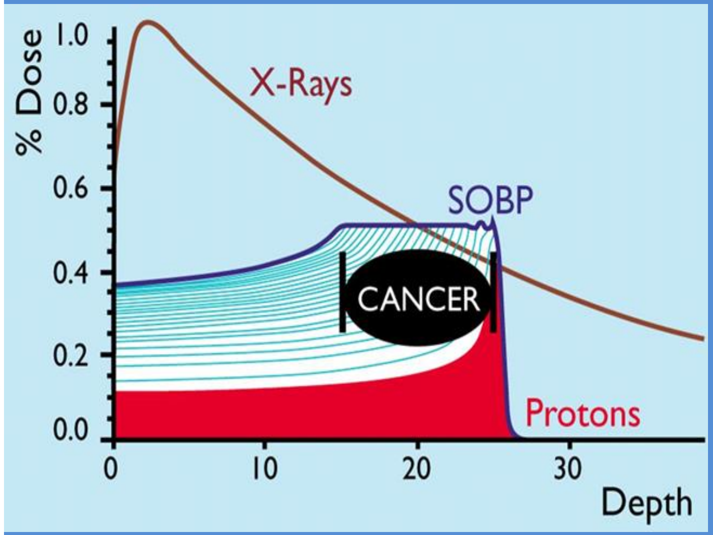
The proton proceeds through the tissue in very nearly a straight line, and the tissue is ionized at the expense of the energy of the proton until the proton is stopped. The dosage is proportional to the ionization per centimeter of path, or specific ionization, and this varies almost inversely with the energy of the proton. Thus the specific ionization or dose is many times less where the proton enters the tissue at high energy than it is in the last centimeter of the path where the ion is brought to rest.

These properties make it possible to irradiate intensely a strictly localized region within the body, with but little skin dose. It will be easy to produce well collimated narrow beams of fast protons, and since the range of the beam is easily controllable, precision exposure of well defined small volumes within the body will soon be feasible.

Let us examine the properties of fast protons somewhat more quantitatively. Perhaps the most important biological quantity is the specific ionization, or number of ions per centimeter of track. This quantity is not difficult to calculate. The results of such calculations are shown in Figure 1, where the range of protons in tissue is plotted for protons of various energies. In the same figure, the specific ionization is plotted as a function of the range in tissue. For purposes of calculation, tissue has been assumed to have the molecular formula (1): $C_{5}H_{40}O_{18}N_{0.14}$, and to be of unit density, *i.e.*, 15 per cent protein and 85 per cent water. The calculations can be easily extended to other materials and densities.[2] The accuracy is perhaps 5 per cent. However, exact values for various tissues can be quickly measured as soon as the fast protons are available.

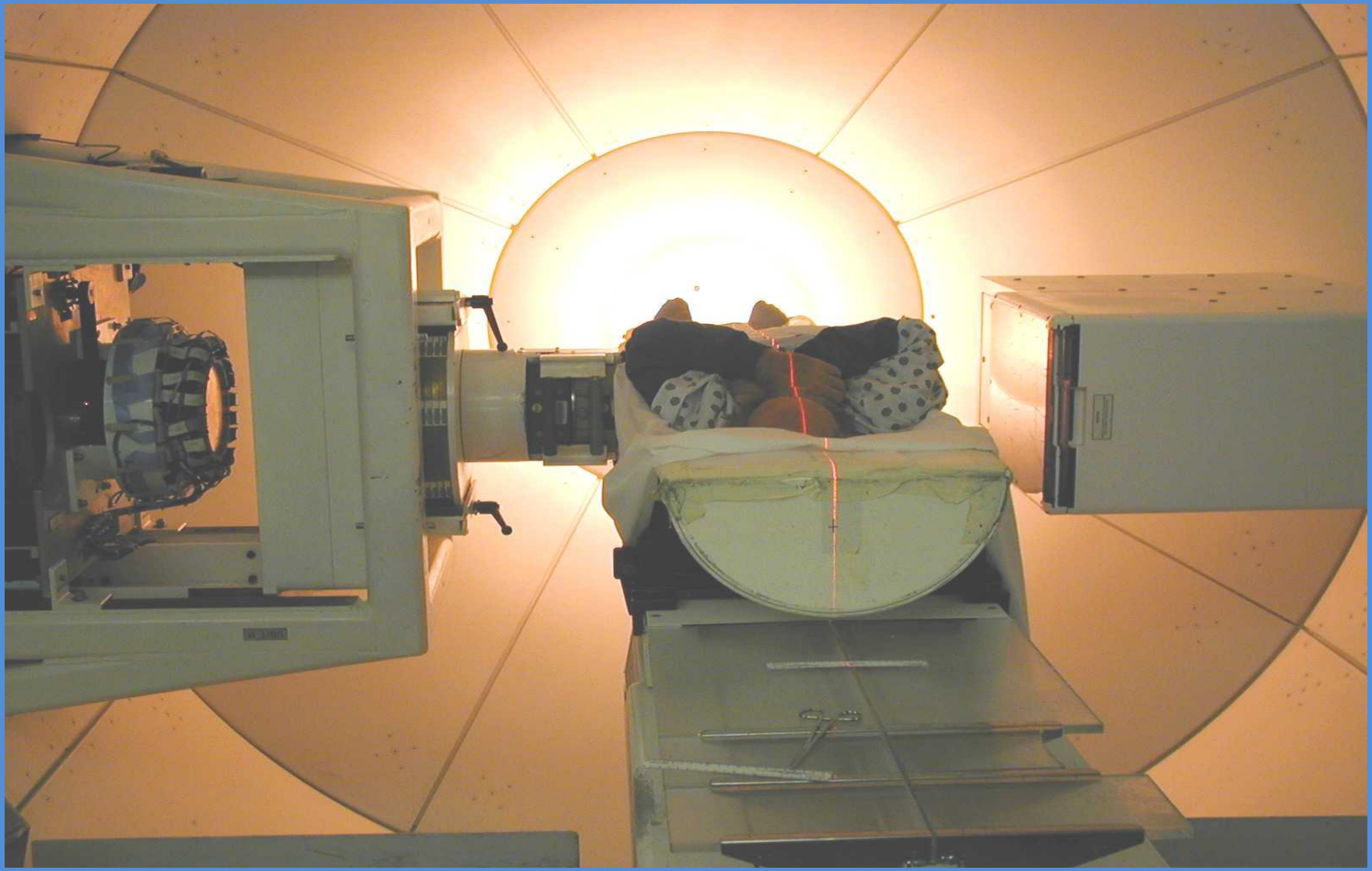
Figure 1 shows, for example, that if we want to expose a region located 10 cm. be-

[1] Accepted for publication in July 1946.
[2] The range of a proton in air in meters is given by the convenient formula $R = (E/9.29)^{1.8}$ where the energy is expressed in Mev. The range in tissue is 1.11×10^{-3} times the range in air. The stopping power of other substances may be found in Livingston and Bethe: Rev. Mod. Physics 9: 246, 1937. The physical calculations of this paper will be submitted to the *Physical Review* for publication.

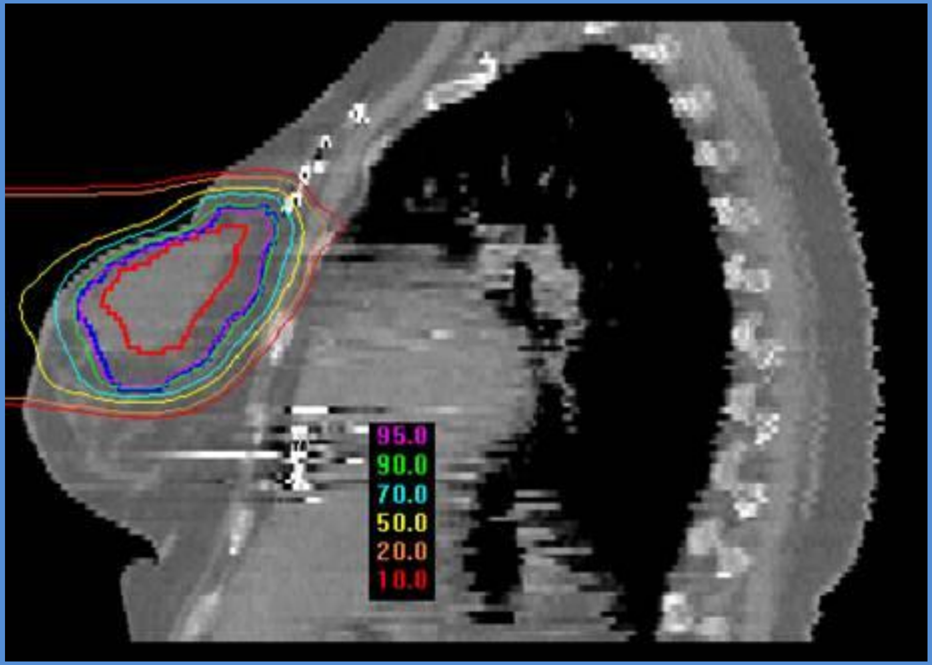


Proton beams can be delivered throughout 360 degrees around the patient using a Gantry

Proton Gantry is also needed for Proton CT



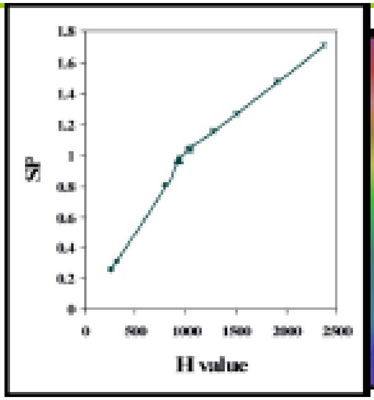
Proton treatment plan for breast tumor.
Errors in proton stopping powers can lead to heart and lung dose beyond the target due to proton range errors

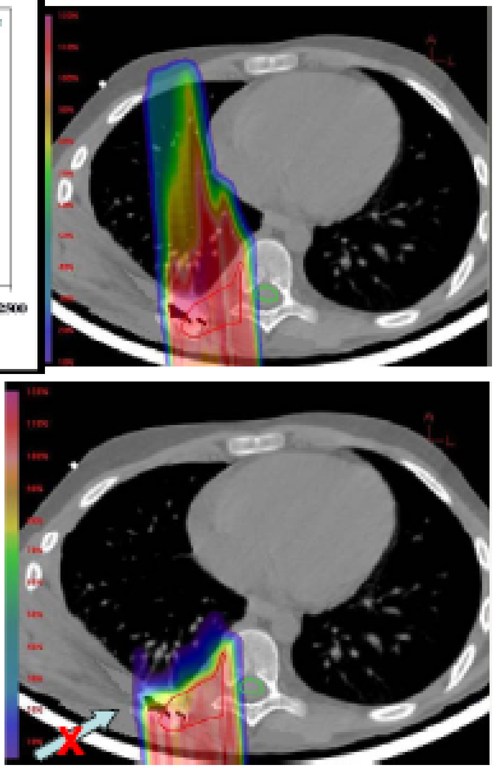


Proton Treatment Plans currently use X-ray CT for proton RSP values. These produce range errors of 3.5%

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



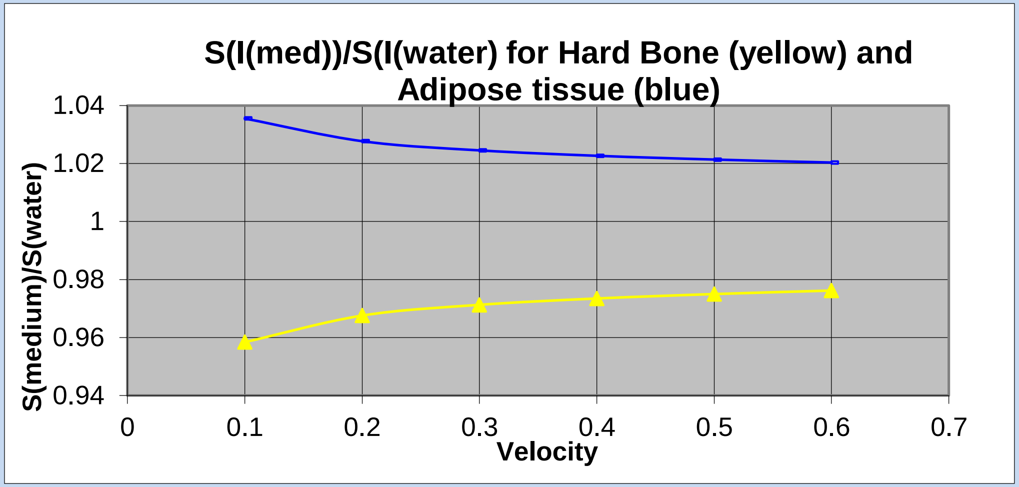


Slide courtesy of Reinhard Schulte, Loma Linda University

Relative stopping power and electron density

$$\frac{dE}{dx} = \frac{k\rho_e}{\beta^2}\left[\ln\left(\frac{2m_e\beta^2}{I\,(1-\beta^2)}\right) - \beta^2\right] = \rho_e\, S(I,\beta)$$

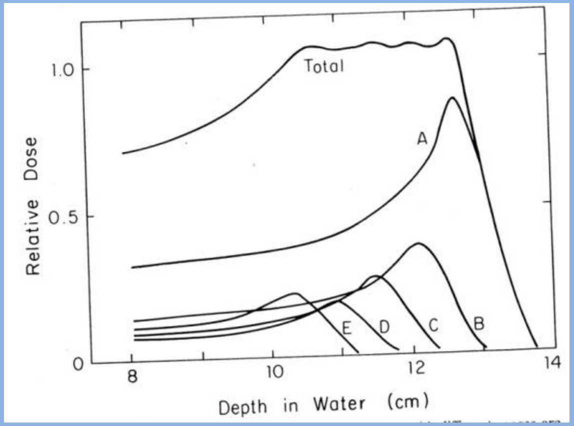
$$RSP = \frac{\rho_e\,(med)}{\rho_e(water)}\,\frac{S(I_{med},\beta)}{S(I_{water},\beta)}$$



RSP → WEPL → Relative Dose

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

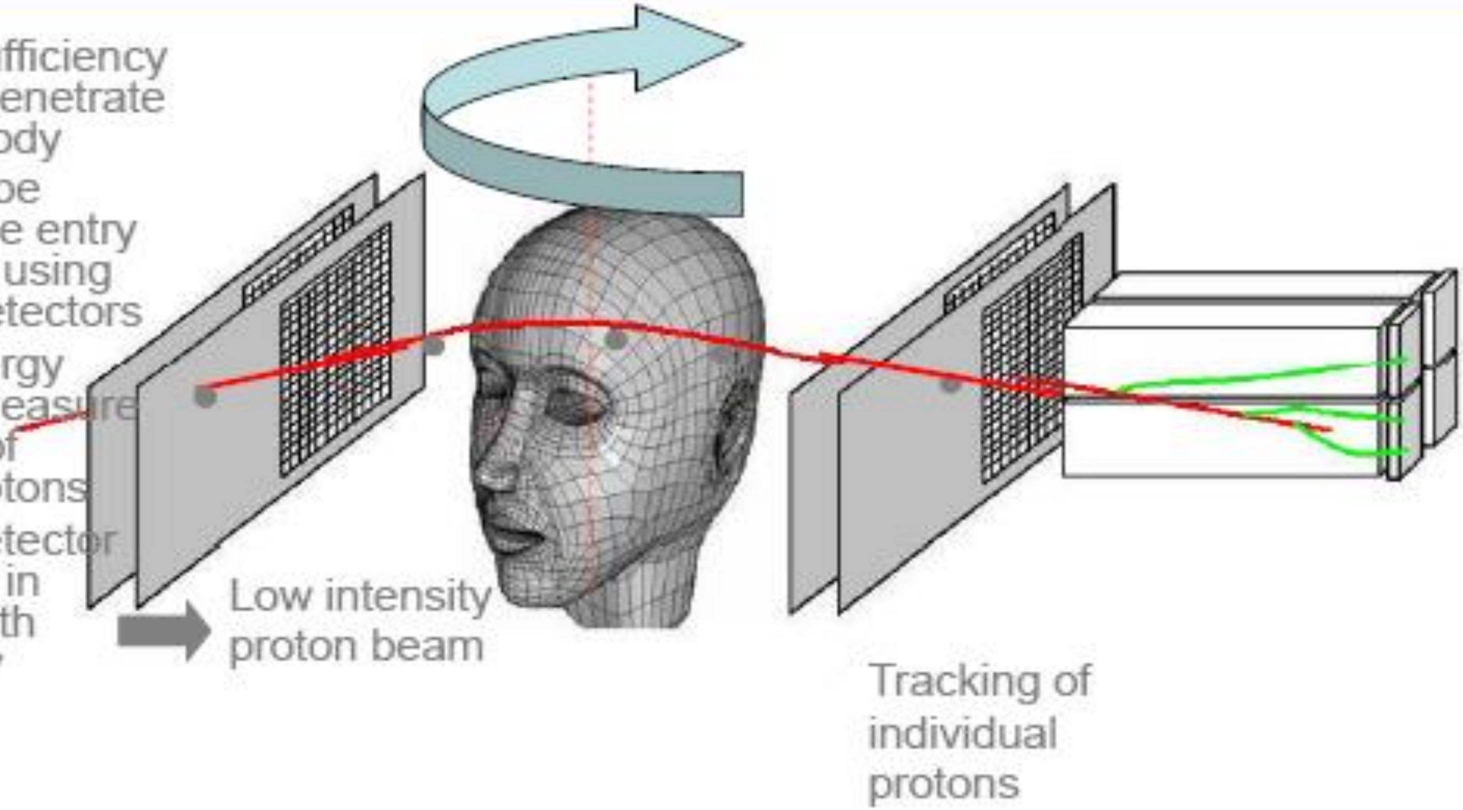
$$RSP = \frac{\frac{dE}{dx}(medium)}{\frac{dE}{dx}(water)} = \frac{\rho_m}{\rho_w}\frac{S_m}{S_w} \approx \frac{\rho_m}{\rho_w} \quad within\ 3\%$$



To calculate dose and P^+ range we need relative stopping power (RSP) in each 3D voxel of the patient along the proton path

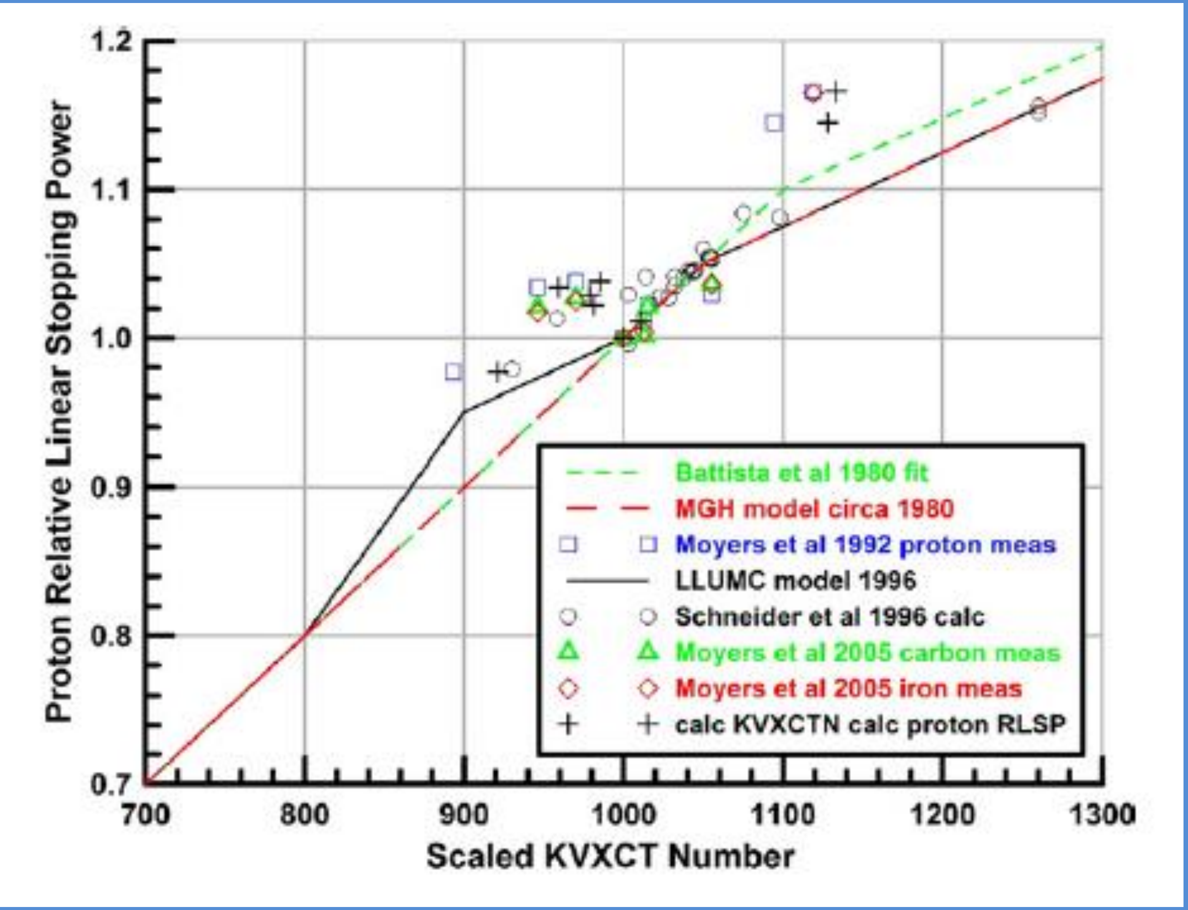
Protons can be used for CT imaging very dose-efficiently

- 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.

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



(Moyers, Medical Dosimetry, Oct 2010)

Advantages of proton CT over X-ray CT

- Decrease the range error from 3% to 1% for better electron density map for proton T_x Planning => better dose accuracy to target volume. Range error is caused by RSP error
- Reduce or eliminate CT artifacts due to metal/dental implants with high Z materials
- Lower dose (factor 3) to patient relative to X-ray CT
- pCT head dose = 1.4 mS = 140 mrem; X-ray CT dose=500mrem
- pCT imaging could replace all other x-ray imaging for patient alignment verification before Treatment
- Spatial resolution will be worse than x-ray CT, but density resolution will be better.

High Level Proton CT Detector requirements

- Head Imaging Volume– 20 cm diam. Cylinder; 20 cm long
- Need 100 proton tracks per voxel for a head size phantom with 4 million voxels to get 1% density or RSP resolution
- Need 400 million protons fired from 0 to 360^0 of rotation with **scan time less than 10 min**.
- Data acquisition rate = 1 MHz for tracker + Calorimeter
- Compact size→ upstream detector < 20 cm ”thick” and retractable
- Spatial resolution of track < 1mm (rms)
- Thin tracking detectors < 1 mm water equivalence thickness per plane. Exiting proton energy as low as 50 MeV→ multiple coulomb scattering.
- Energy resolution of scintillator; dE/E < 2 % (i.e., not limited by energy straggling of phantom plus energy detector)
- Angular resolution pointing to head < 5 mrad to get 0.5 mm

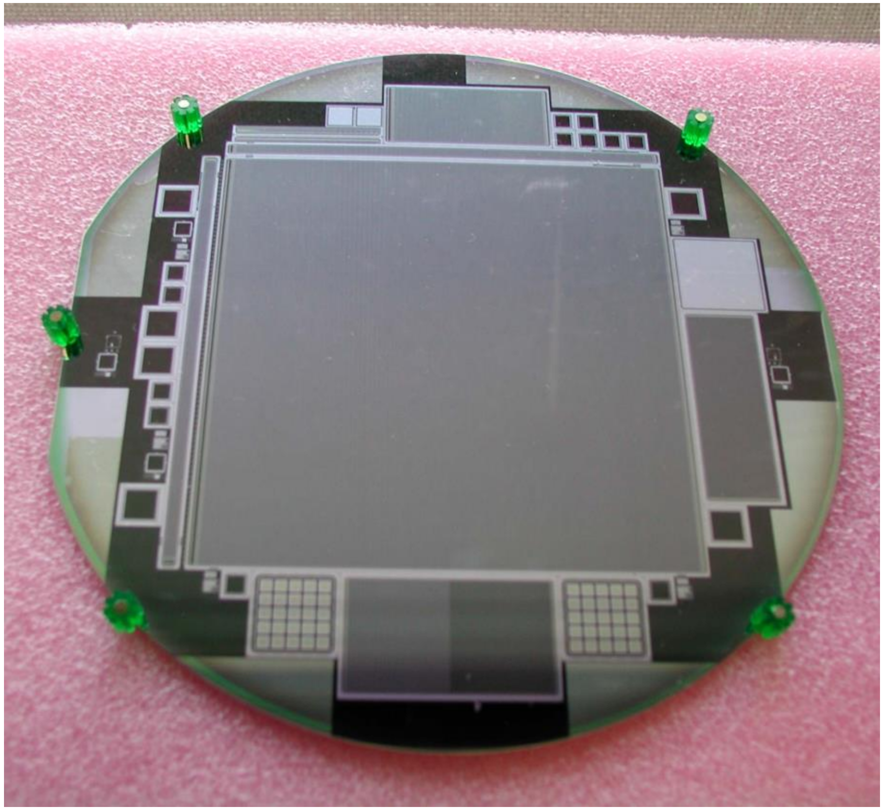
UC Santa Cruz Silicon Strip Detector

PIN Diode sensors:

- P type implants on top, in the form of long, narrow strips
- n-type Instrinsic (ultra high purity) silicon bulk
- N type implants on the bottom plane

The diodes are reverse biased with +100 V applied to the back plane, and each strip is connected to ground by an integrated resistor. As a result, the bulk silicon is fully depleted.

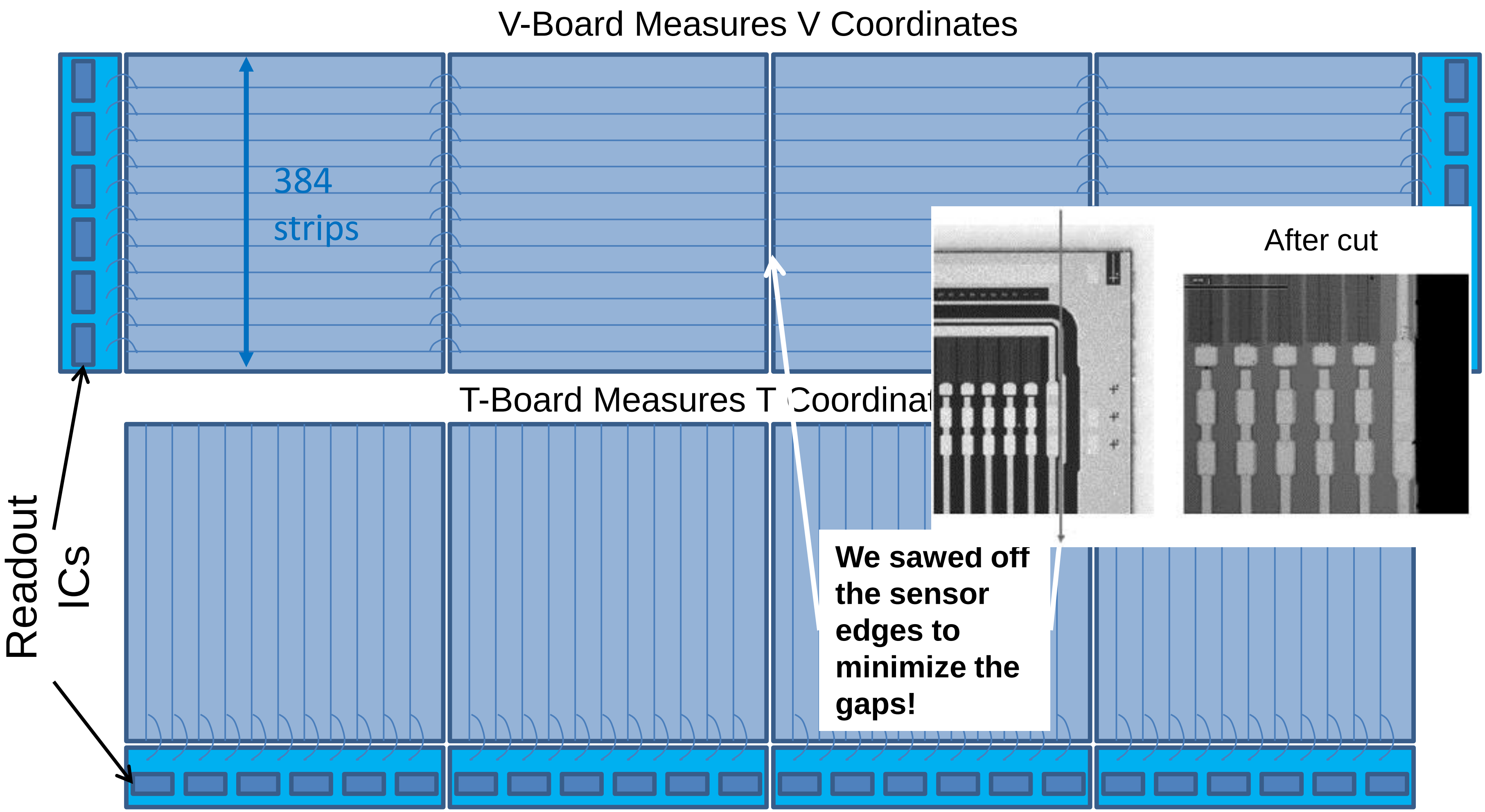
Each strip is covered by a thin oxide layer with an aluminum strip on top, forming integrated capacitors between the p strips and the aluminum pads to which we connect the amplifiers.



8.95 cm square Hamamatsu-Photonics SSD before cutting from the 6-inch wafer. The thickness is 400 microns, and the strip pitch is 228 microns.

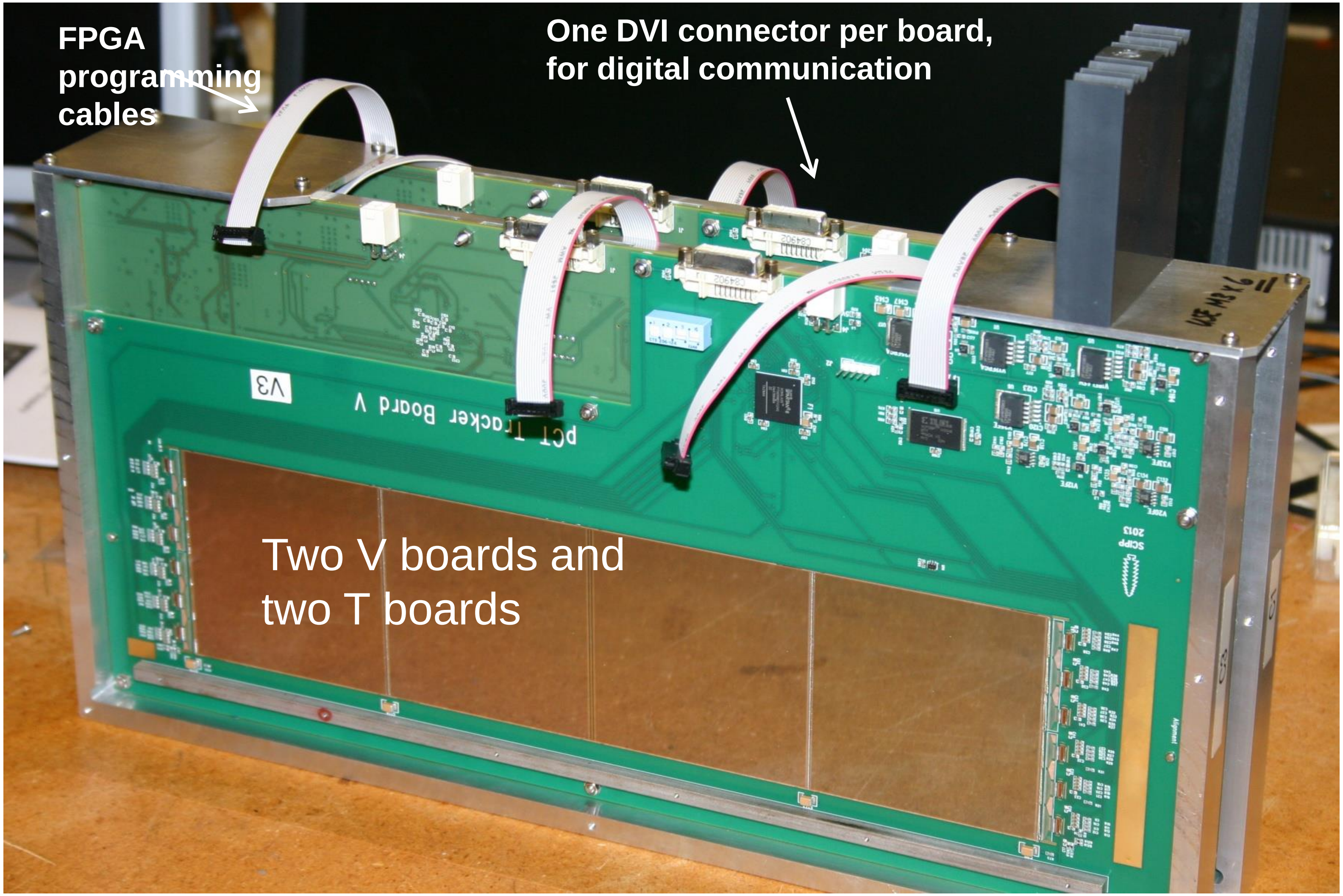
Silicon-Strip Tracking Plane

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



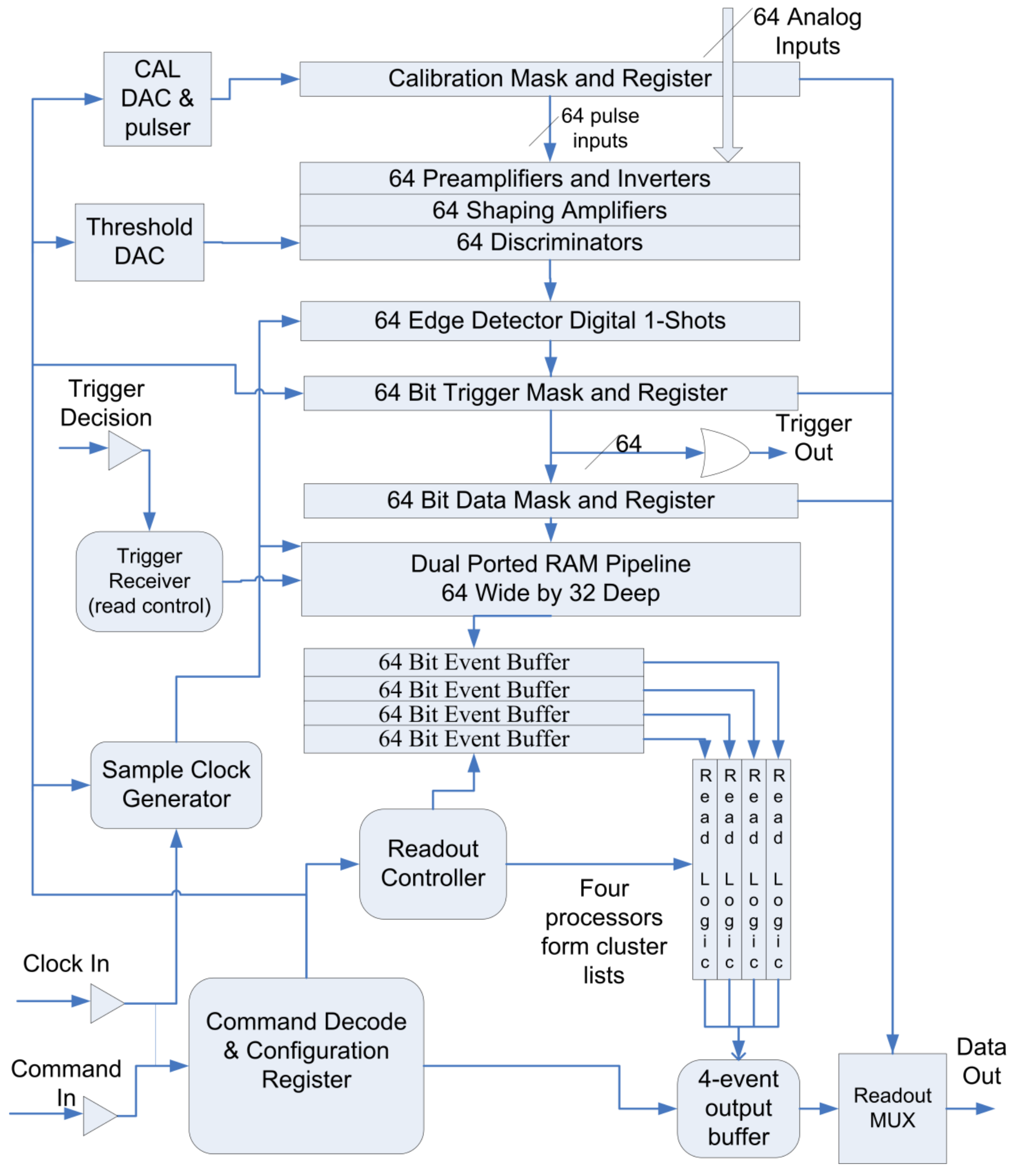
Complete Tracker Module at UCSC

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

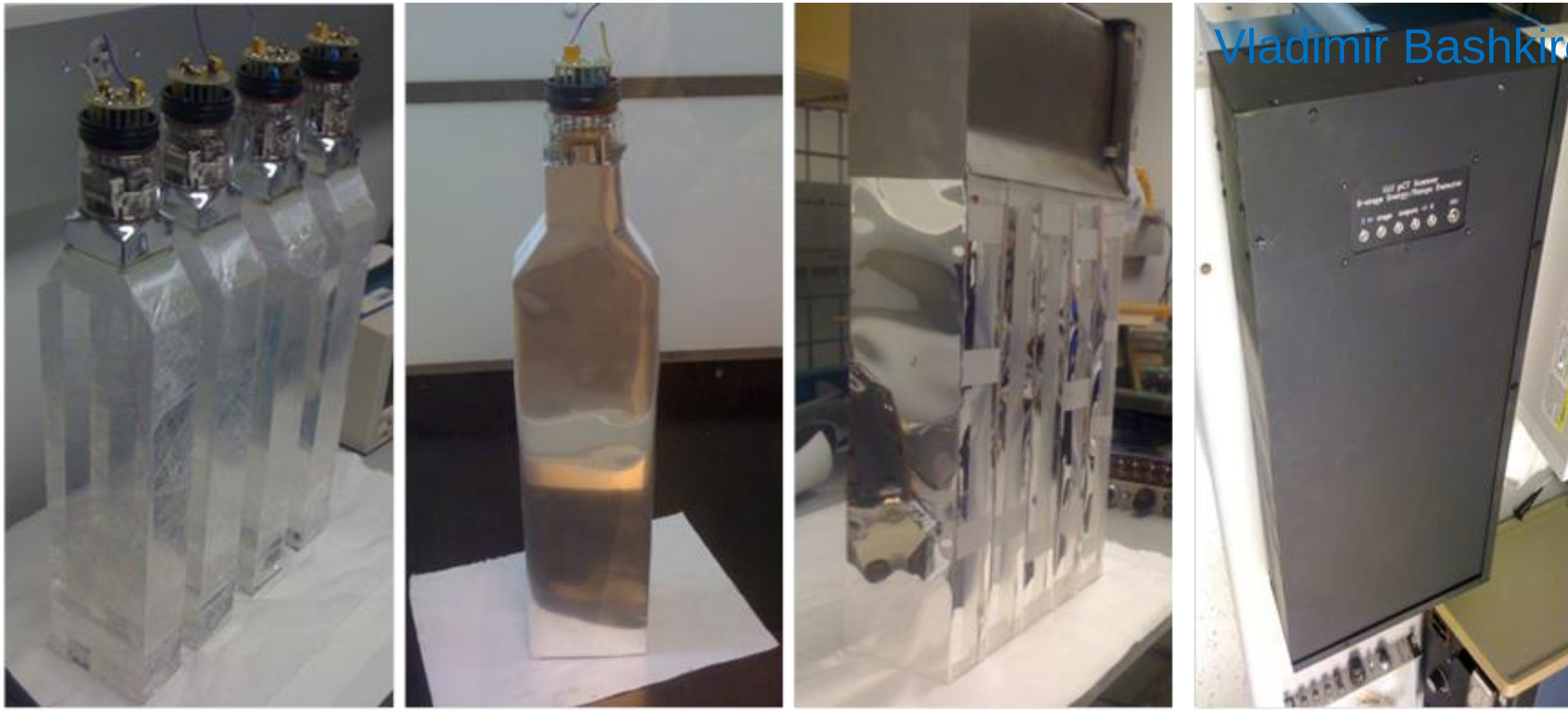


The UCSC Tracker Readout Custom IC ("ASIC")

Includes a lot of digital buffering and processing for the data acquisition, in addition to the 64 amplifiers and discriminators.



Loma Linda’s 5 Stage Scintillator – Energy detector

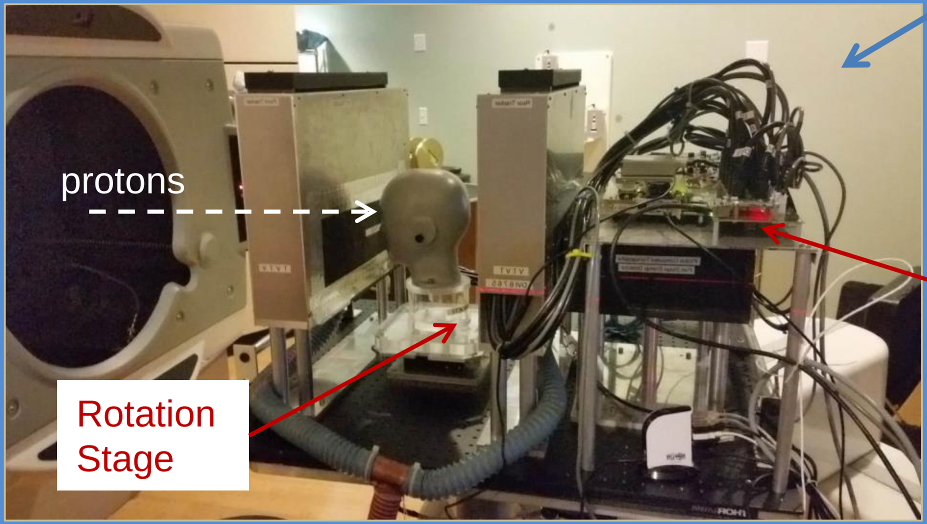


V.A. Bashkirov, R.P. Johnson, et al., *Novel Scintillation Detector Design and Performance for Proton Radiography and Computed Tomography*, Med. Phys. 43, 664 (2016).

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 (2015)

R.P. Johnson, et al.,, IEEE Trans. Nucl. Sci. 63-1 (2015).

1st 3D images of an object scanned by proton CT (2010)

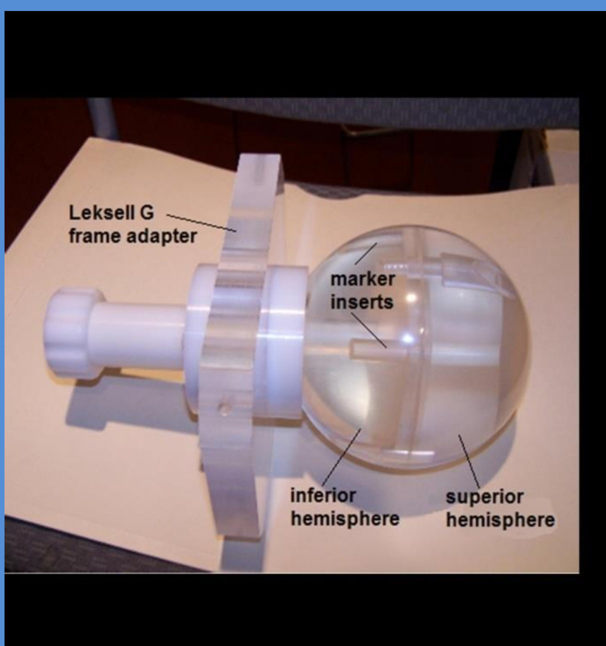
130 million protons at 200 MeV, 90 angles

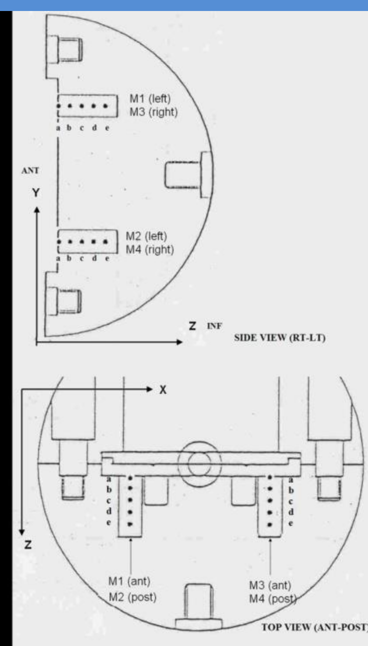
14 cm polystyrene sphere with 3 inserts

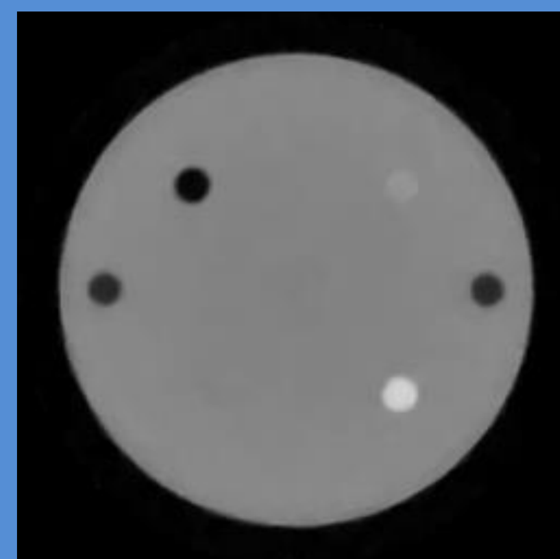
CT slice (2.5 mm) is through the diameter

Image is gray scale of RSP values in 0.6 mm x 0.6 mm

RSP range: 0(air)→1.7 (bone)





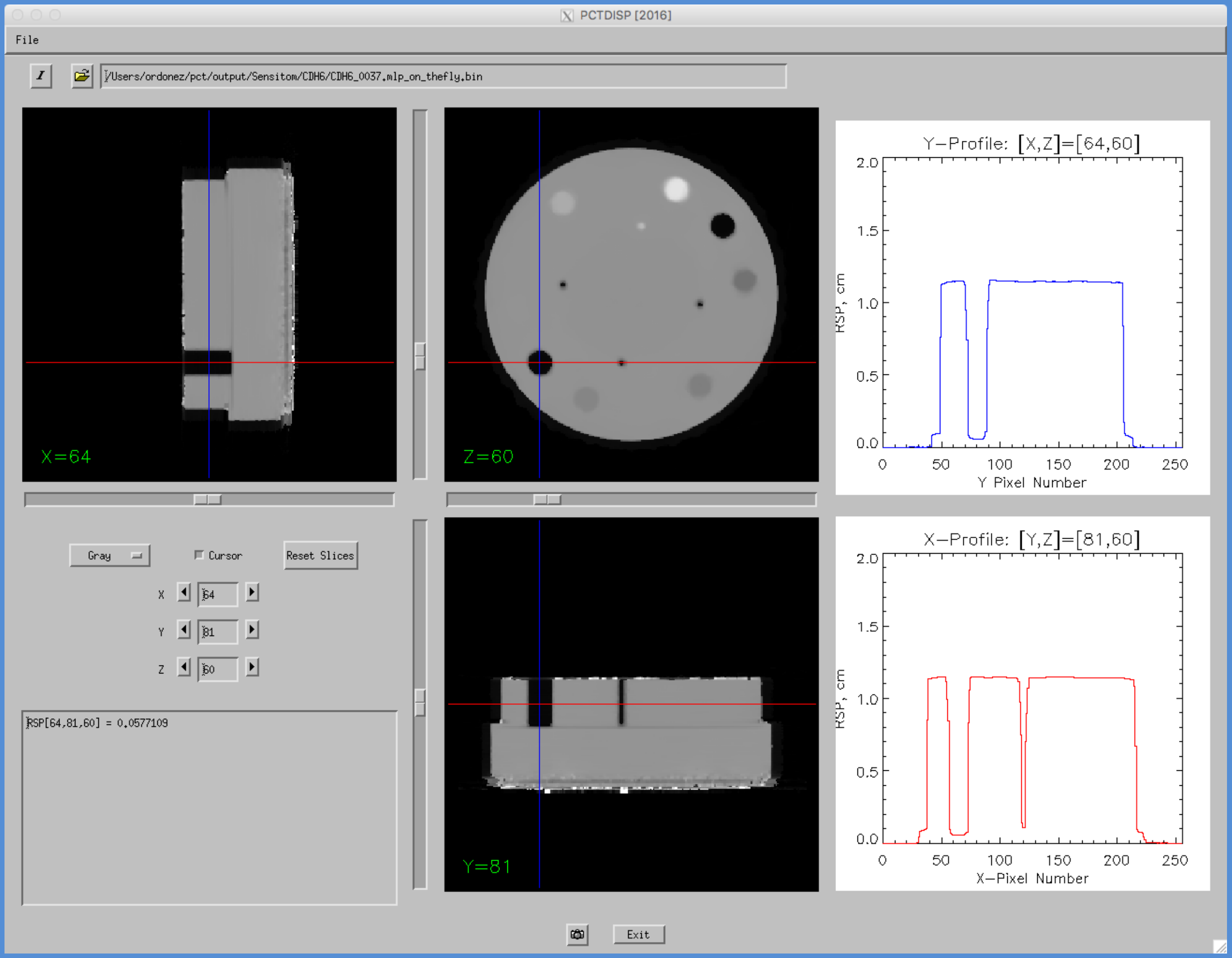


Reconstructed relative stopping powers (RSP) from 3D image reconstruction of LUCY phantom

	Averege RSP (measured)	**RSP (calculated)**
Polystyrene	1.037	1.035
Bone	1.62	1.65
Lucite	1.15	1.15
Air	0.05	0.001

UC Santa Cruz PCT Scan of Sensitom Phantom

[DROP, 45 blocks, 10 iterations, λ=0.1, pixel=0.75mm, slice=0.75mm]



UC Santa Cruz PCT Scan of Sensitom Phantom

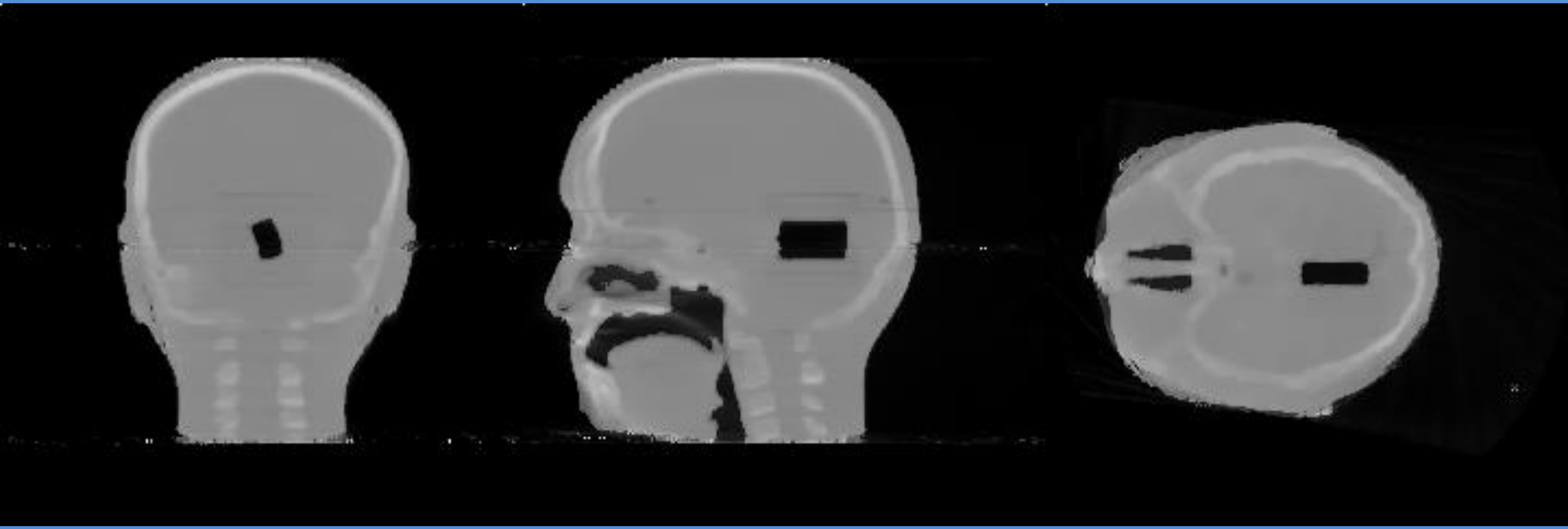
[pixel size =0.75mm, slice thickness=0.75mm]

Material	RSP (from pCT)	RSP(true/meas.)	% error
Teflon	1.776	1.754	- 0.8 %
LDPE	1.000	0.980	2 %
Polystyrene	1.041	1.024	1.7%
Delrin	1.340	1.360	- 1.4 %
PMP	0.890	0.883	0.85 %

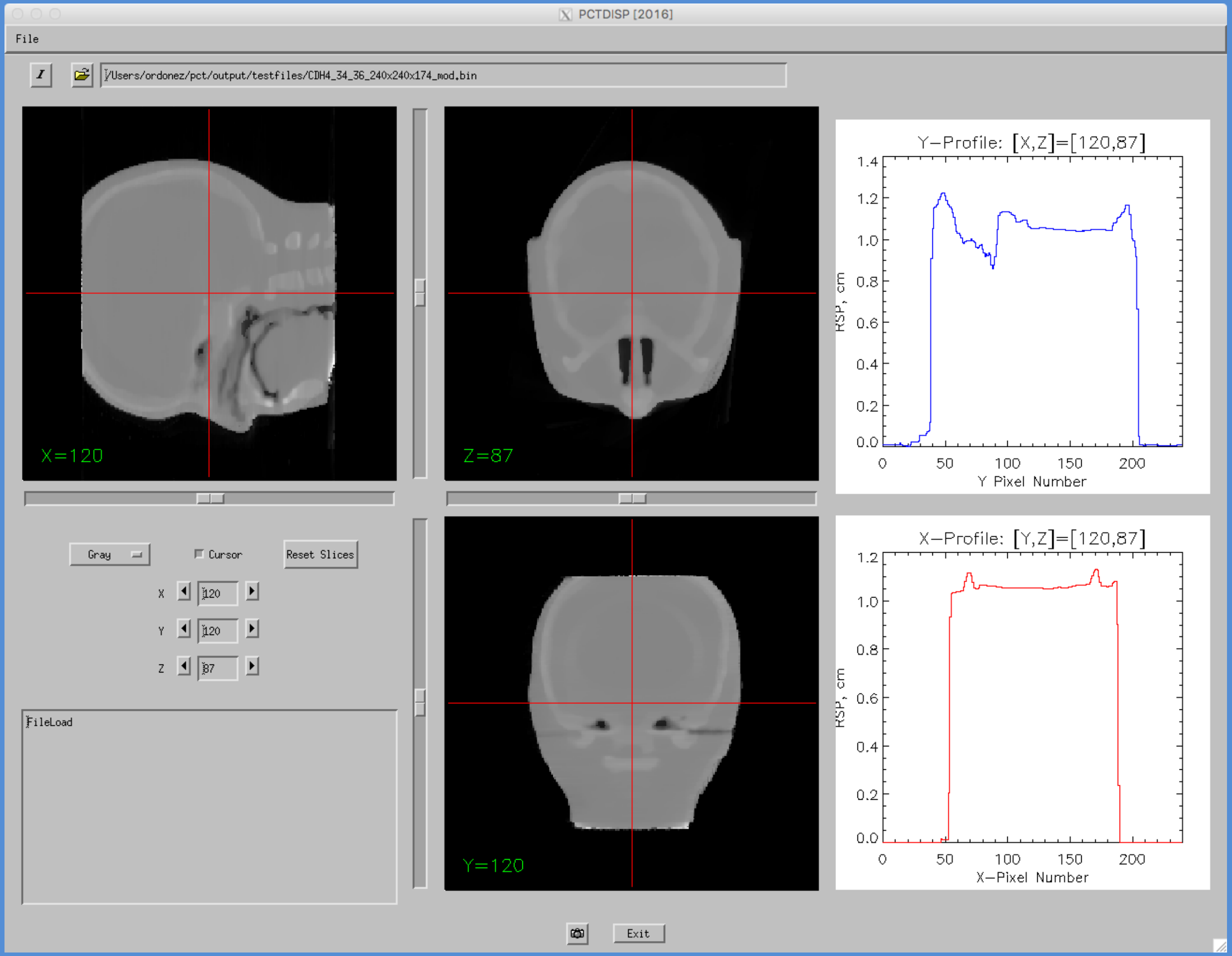
1st complete head scan (CIRS model 715). Taken with Loma Linda –UCSC Phase II scanner

- 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 < 20 min.

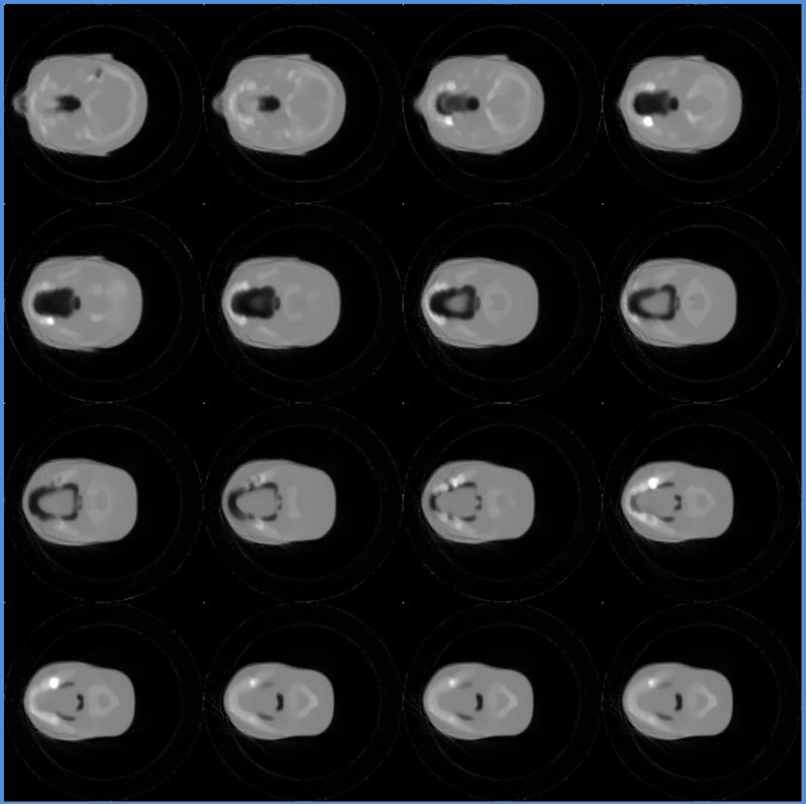
Proton CT reconstructed images of pediatric head phantom using 350 million proton trajectories distributed 0 to 360^0 about vertical axis



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

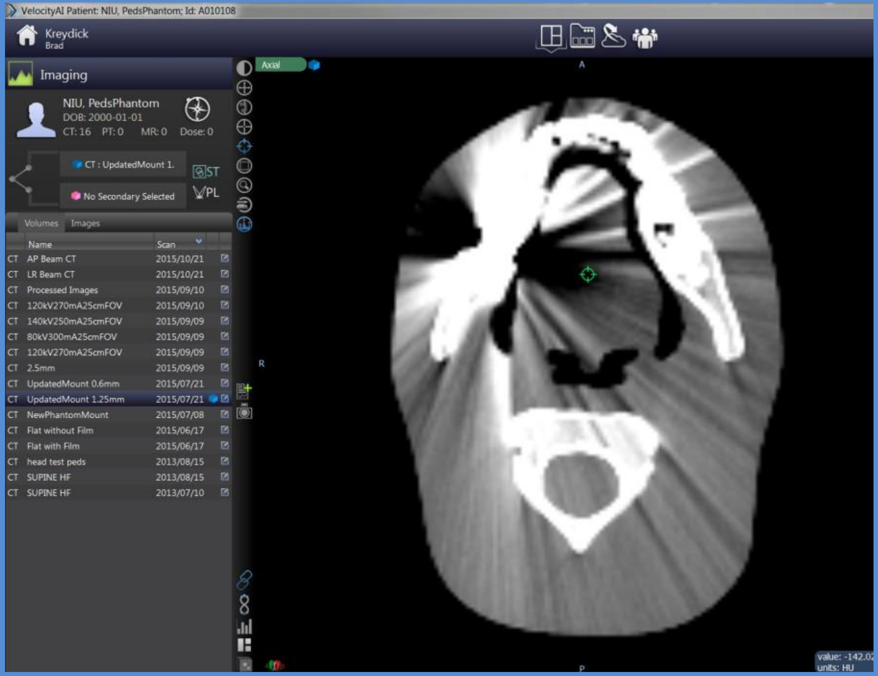


16 Proton CT slices of pediatric head phantom
Each slice is 2.5 mm thick, resolution in each slice: 0.6 x 0.6 mm



Note: There is a amalgam dental filling (upper right image) and a Gold crown on another tooth

X-ray CT slice (center image) of same phantom with Gold dental crown
High density inserts produce large streaking in X-ray CT



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.
- Proton CT also offers a several-fold dose advantage compared to x-ray CT
- No streaking artifacts from high density implants or calcification.
- New proton CT head scanner has been developed and is generating new images regularly with more improvements at the Chicago Proton Center.

End of presentation

Thank you for your attention