Proton CT Scanner
Lessons learned 2001-2015

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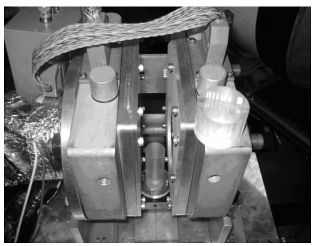
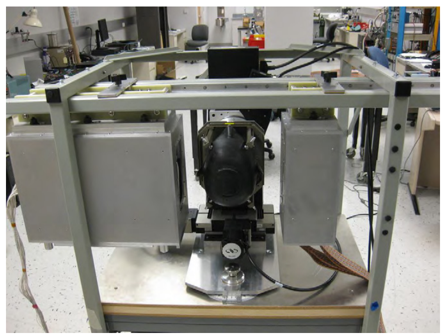
with the pCT Collaboration
(UC Santa Cruz – Loma Linda UMC – Baylor U.)
and UFSD Collaboration
(UC Santa Cruz – INFN Torino– CNM - RD50)

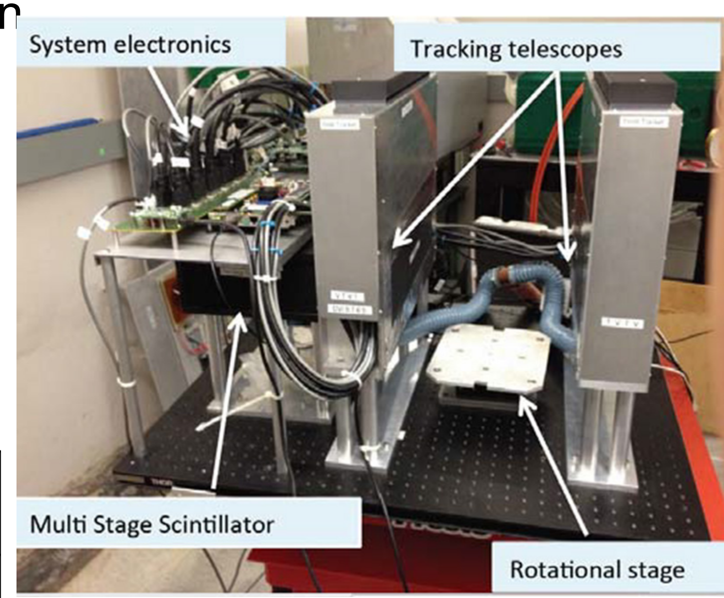
- Status of present proton CT scanner
  - Tracker
  - WEPL detector
- Requirements for a future proton CT scanner
- Options for proton tracking and WEPL detectors
- Ultra-Fast Silicon Detectors

3 Generations of pCT

Tracker Material: Silicon strips
PRO: efficient, fast, integrated, no consumables, good signal-to-noise
Improve speed with integration time of ASIC
CON: 90 deg stereo (low efficiency for multiple protons), -> add rotated plane.
WEPL detector: hodoscopic X-tals -> monolithic scintillators
PRO: uniformity of response, signal speed, resolution
CON: No multi-proton events



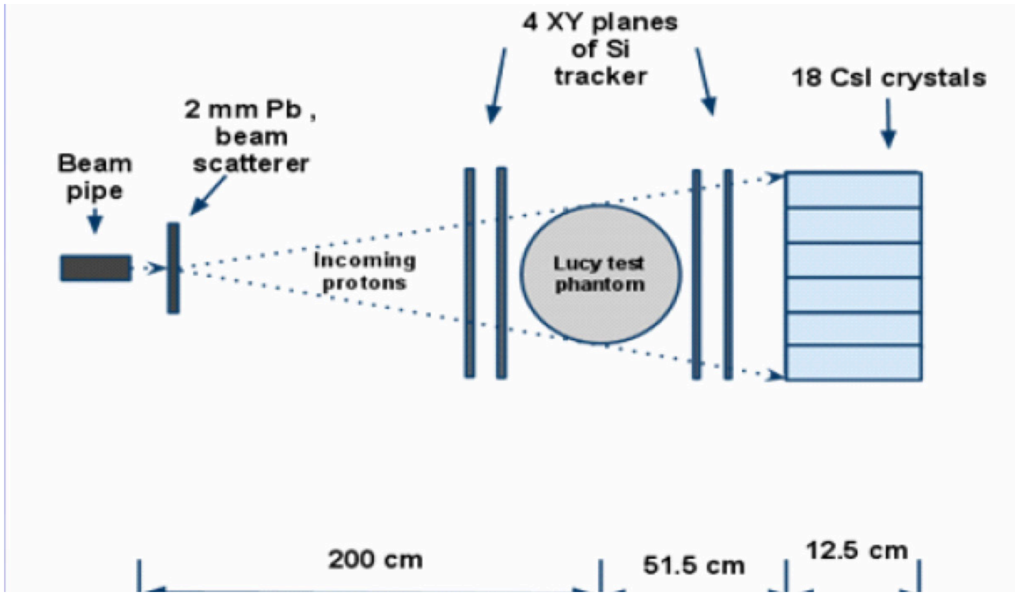


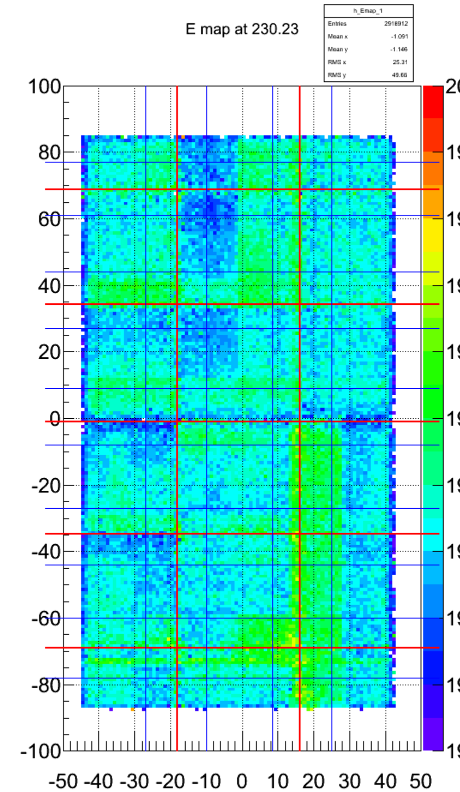


Stage 0	Stage I	Stage II (Head Scanner)
5 cm x 5cm	9 cm x 18 cm	9 cm x 36 cm
Tracker ToT & Single CsI X-tal	18 CsI X-tal Hodoscope	5 layer Multi-stage Scintillator
1 kHz	15 kHz	1 MHz
	7 hrs	9 min

Driving Force: Proton Rate -> increase speed and segmentation

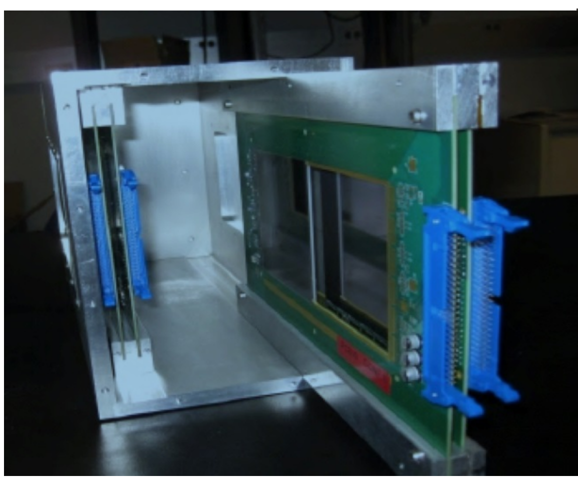
2nd Generation WEPL Detector (Phase I)

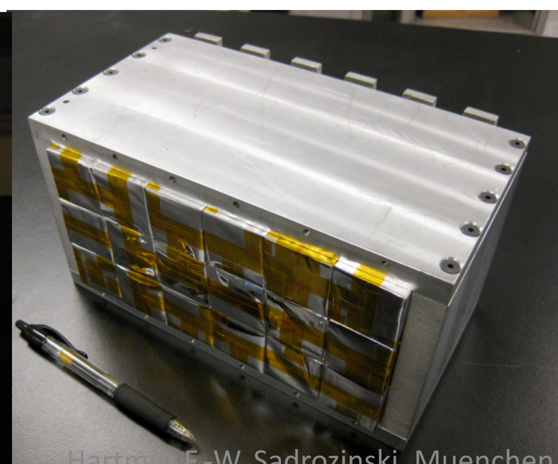




NaI x-tals are slow.

Need precise calibration (much better than 1%!)

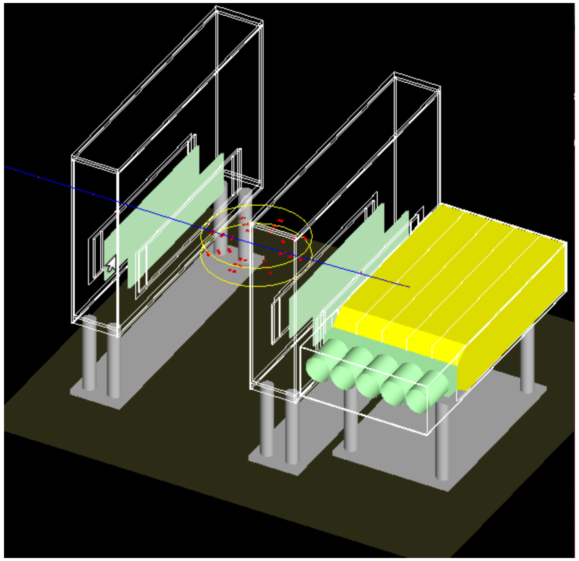




Phantom-empty data exhibit non-uniform pattern,
due to the tracker trigger and the x-tal inter-calibration

Status of 3rd Generation proton CT scanner

The UCSC-LLU-Baylor head scanner is optimized for operation at the LLU synchrotron with ~100 ns spill structure. Its active area is 9 cm high x 36 cm wide.



Tracker

Tracker uses 4 x-y planes of silicon strip sensors
("slim edges", 228 μm pitch, 90 degree stereo angle)
Custom ASIC for fast readout and extensive buffering
Depending on the position of the tracks, at most two tracks can be measured at the same time.

WEPL Detector

The WEPL detector uses 5 scintillator modules in the beam direction each covering the entire active area.
The residual energy of only one proton can be measured at a time.

Limitations of present proton CT scanner

Bunched vs. continuous beam

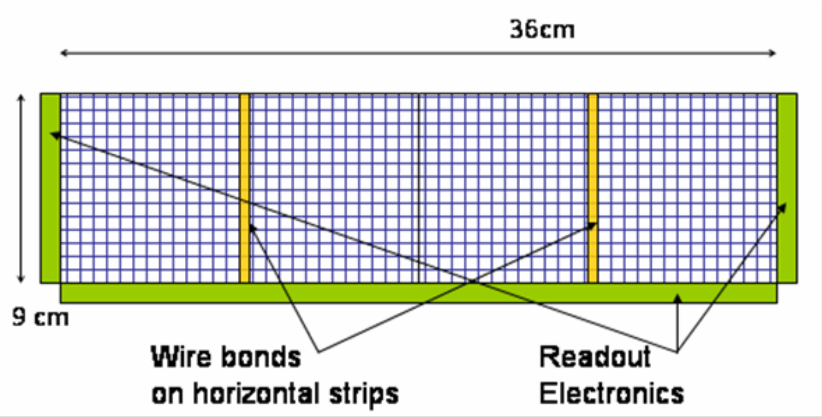
The use of the scanner in a modern quasi-continuous beam (like in a cyclotron) will require a data structure using time-stamps.

Multiple protons

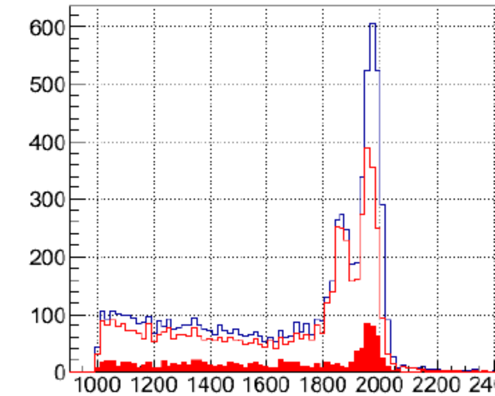
Only one proton can be measured within the present spill structure of 100 ns.

3rd Generation Large Area Si Tracker

Large area coverage requires tiling of 4 9 cm x 9 cm sensors, having ~ 1mm inactive edges which create image artifacts.

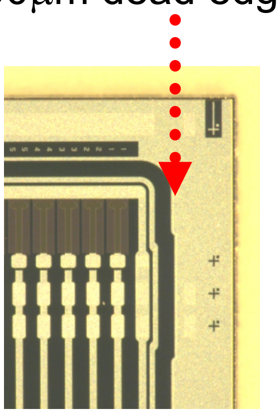


Overlapping sensors introduces artifacts requiring additional, non-uniform energy corrections



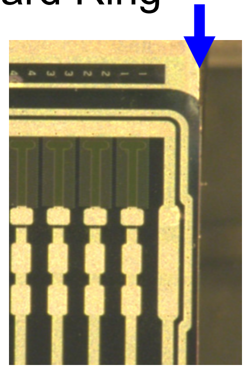
For Tiling with no Overlap: "Slim Edges"

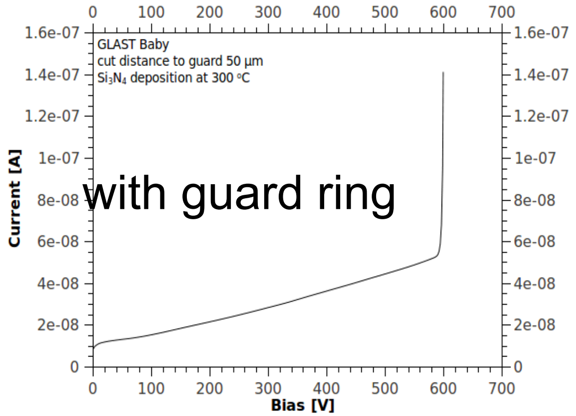
Si SSD with 900µm dead edge



S-C-P:
Scribing (XeF_2)
+ Cleaving
+ Passivating
(N_2 PECVD)

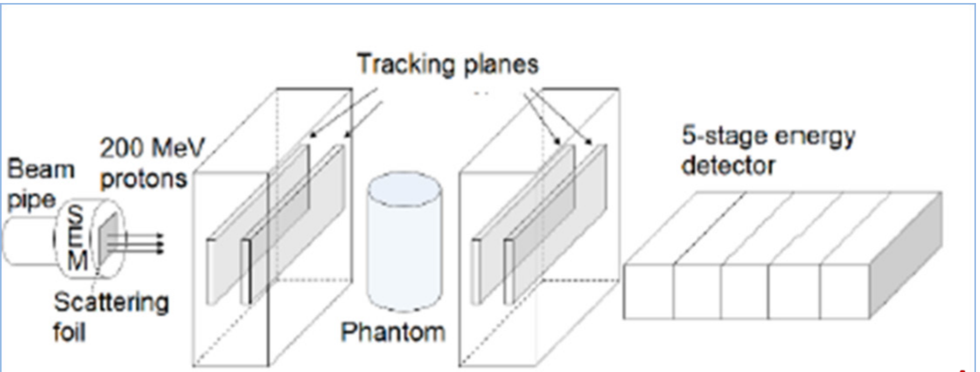
Cut within 50 µm of Guard Ring

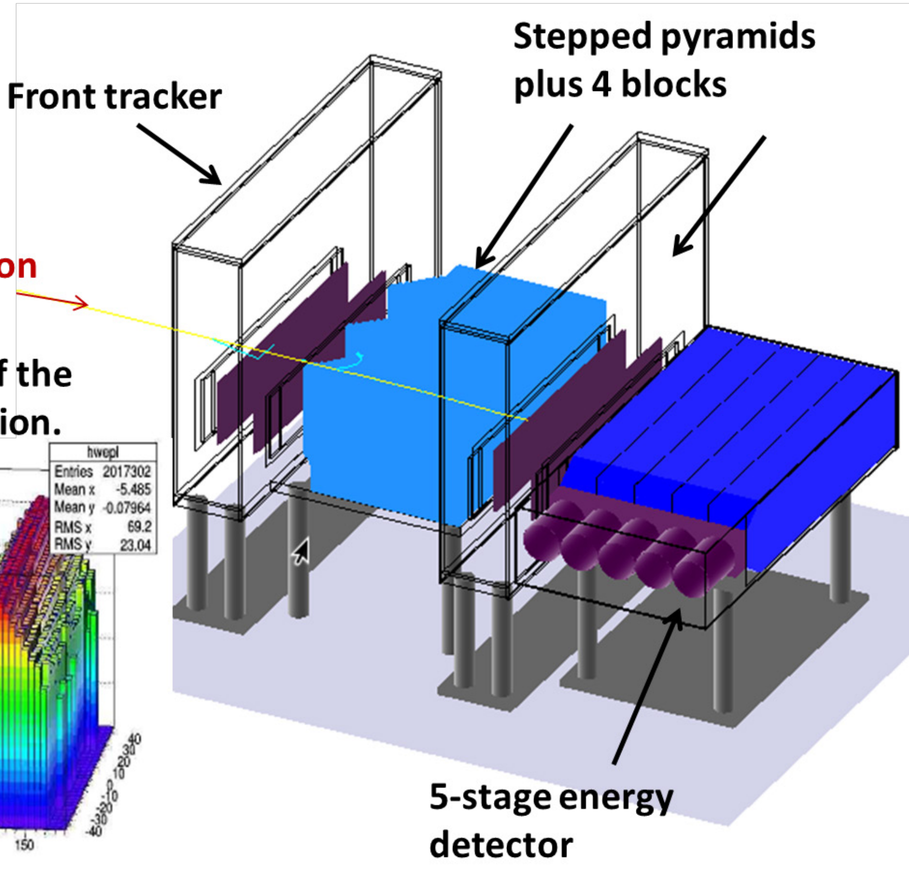


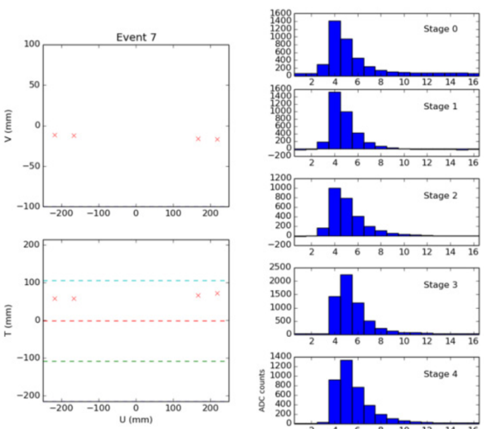


M. Christophersen et al., SSE 81, (2013) 8–12

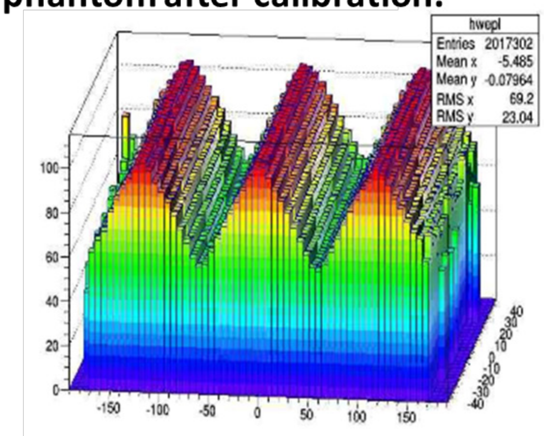
3rd Generation WEPL Detector (Phase II)







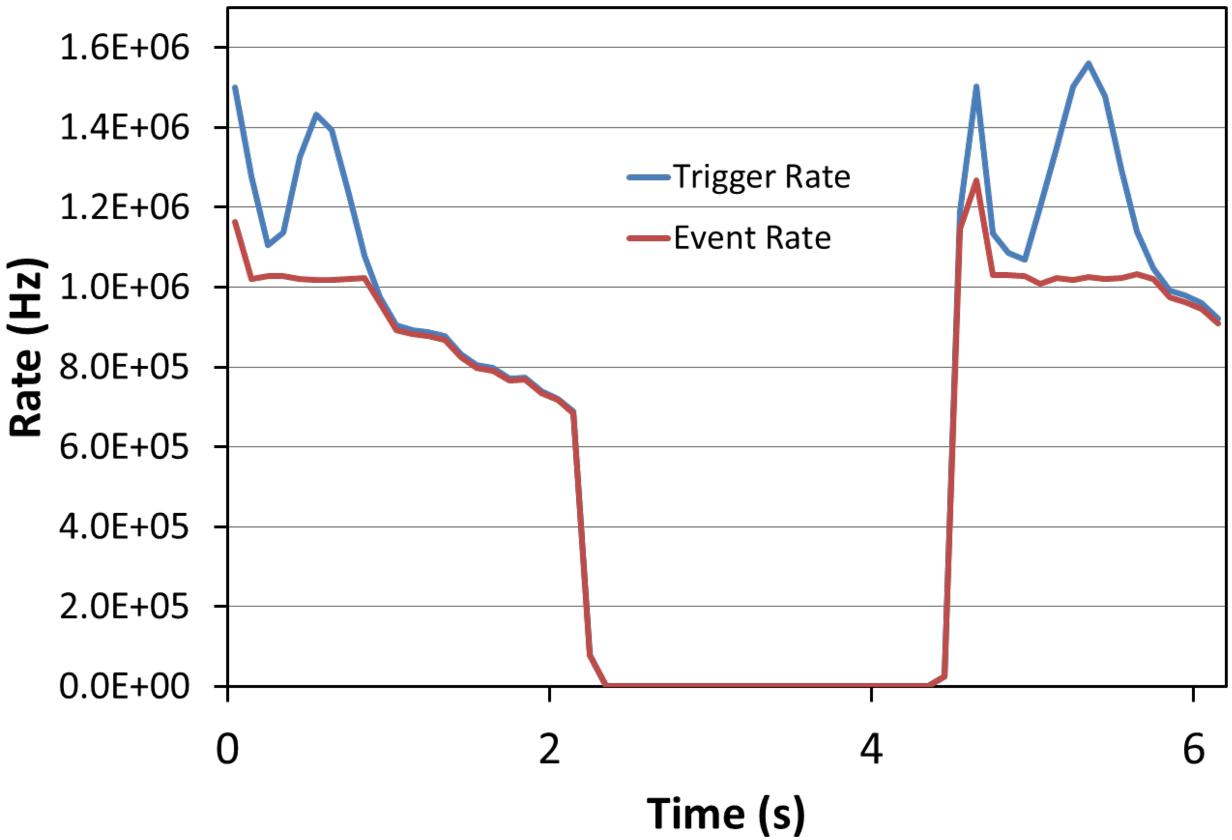
Reconstructed WEPL of the phantom after calibration.



Requires precise calibration (much better than 1%!)
Only 5 crystals, easy procedure, but still analog.

On-line Rate Record of Trigger and Data Rates

Spill –structure: 2.3 sec on / 2.3 sec off.
Data taken and partially processed during spill-on.
Rotation of gantry (now phantom) in angular steps during spill-off.
Excessive proton rate reflected in trigger rate.
Stable data rate at > 1MHz independent of excessive trigger.



Requirements for a proton CT scanner

"Position Resolution" 1 mm
(determine the relative stopping power RSP within a 1 mm^3 voxel)
"WEPL Resolution" ~ 1%
(commensurate with the straggling limit)
Measure for each proton (could this be relaxed for pencil-beams?)
- Location and direction before and after patient for determination of the MLP to1mm
- residual energy after patient to achieve water-equivalent path length (WEPL) resolution of 3 mm (straggling limit)

Raster scanning might not efficient use of detector bandwidth:
Assume cone beam operation (Pb foil) for pCT.
Assume continuous scan, divided in 180 views.

10 x 30 cm^2 scanner, 1x1x1 mm^3 voxels -> $3\cdot10^4$ 2-D voxels
100 protons/voxel -> $3\cdot10^6$ protons/view = $5.4\cdot10^8$ protons/scan

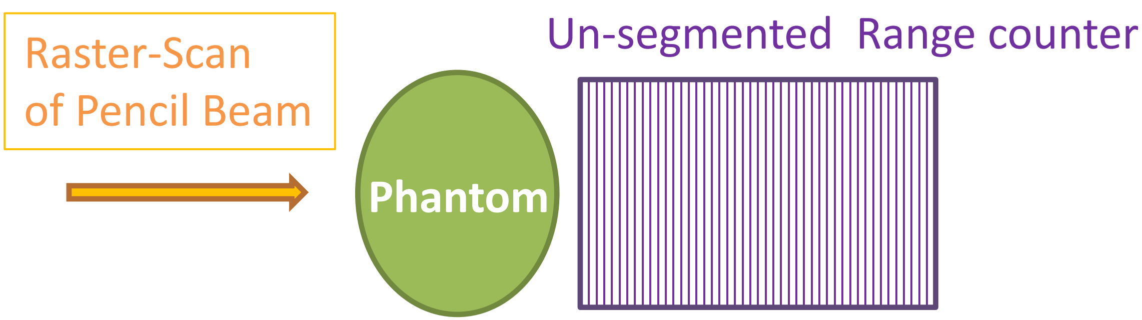
Consider **total scan time of 1 and 3 min** (what is the limit on the gantry?)

Issues:
Accidental position and time overlap in tracker and WEPL detector.
Speed of data acquisition system (DAQ)

Option #1: Low-cost Pencil Beam pCT Detector

No Tracker
WEPL Range Counter:
No longitudinal segmentation, summing-up of signal in each layer

Pencil beam determines the location and lateral size of investigated phantom volume
Proximity to phantom reduces (but does not eliminates) the effect of multiple scattering

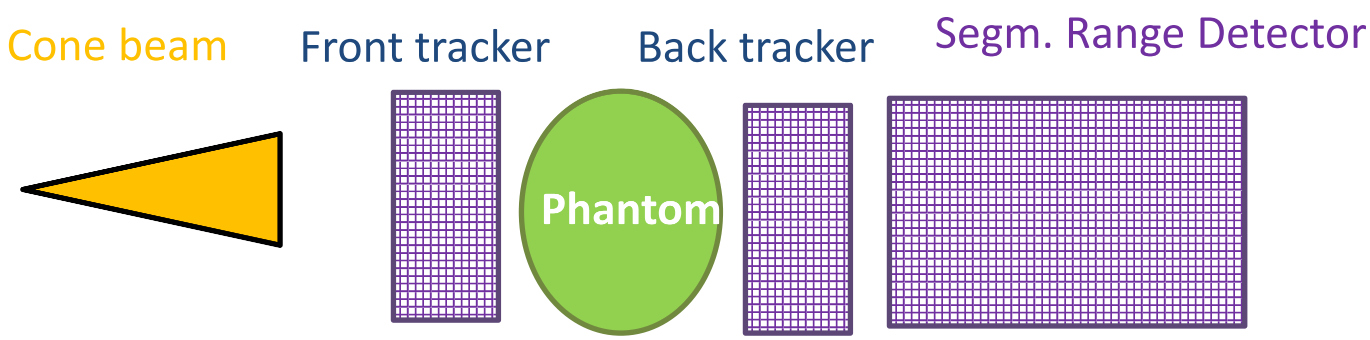


Questions:
what is the smallest beam emittance (size and angular divergence)?
how much does MCS increase the beam size?
is this size clinically interesting?

Option # 2: “Tracker-Only” Pixel/Strip pCT Detector

Same Silicon technology for tracker and WEPL detector.
High segmentation, low time resolution (50us MAPs, 150 ns strips?): integrate over many events in one readout.

For Monolithic Active Pixel (MAP) Detectors:
With 20 kHz readout rate (50usec), negligible occupancy
(3 min scan: 150 protons/event, 1 min scan: 450 protons/event)
With 1 kHz readout rate (1msec), negligible occupancy
(3 min scan: 3k protons/event, 1 min scan: 9k protons/event)
For strips: 0.45 protons/event (3 min scan), 1.45 protons/event (1 min scan)
Tracker: Front and back tracker needed for MLP?
WEPL Range Counter: 64 layers: Total cost $$?



Option #3: Time-resolved Tracking & WEPL Detector

(Extrapolation of our experience, low-cost, high performance)

Tracker: high segmentation, moderate time resolution (150ns)

Finely segmented: **200 µm** strips

Resolving ambiguity (“ghosts”) in multiple proton events with rotated plane

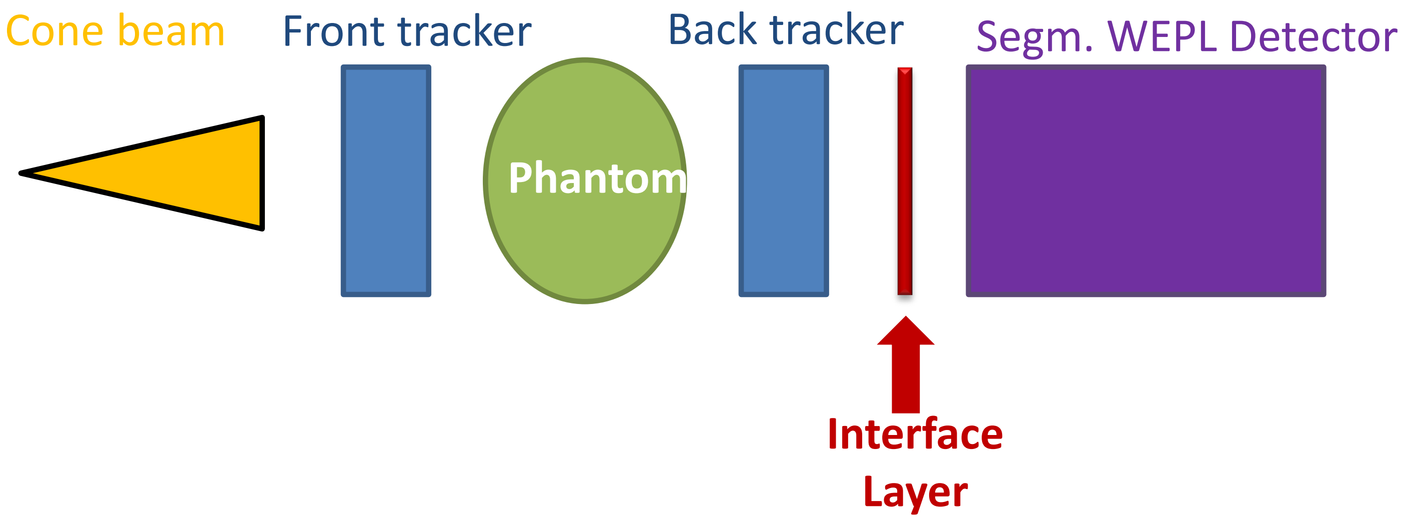
WEPL Range Counter:

Low (no) segmentation, high time resolution (5 ns) & “interface layer”

OR

High segmentation, low time resolution (Si Pixels/Strips)

Interface Layer: moderate segmentation & high time resolution



Occupancy in Space and Time

in Time-resolved Proton Tracking & WEPL Detector

Total Occupancy = Space occupancy*Time occupancy
Space Occupancy = # of “contemporary” protons / # of detector elements
# of detector elements = (area of detector elements / scanner area)
Time occupancy = Fraction of detector time stamp interval

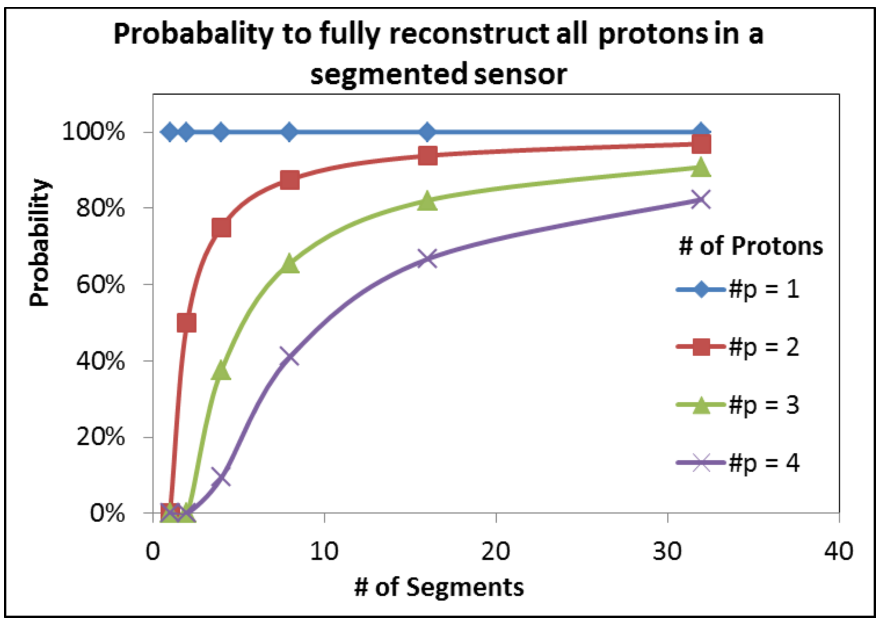
Total occupancy should be small to avoid increase of dose, goal: 5%

Scanner area: 100mm x 300mm
Total scan time 1 or 3 min, 180 views
$9 \cdot 10^6$ or $3 \cdot 10^6$ protons/sec (up to 9 MHz!)

Tracker:
200 um x 10 cm strips
WEPL (Range Counter)
One plane: 1 cm x10 cm Scintillator and 63 planes 30 cm x 10 cm Scintillator

Reconstruction Efficiency in Multi-Proton Events

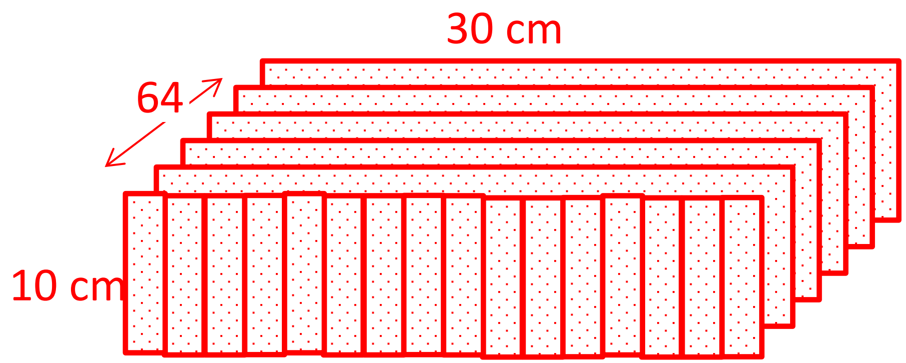
To reconstruct **multi-proton events**, need **segmentation**.
Divide the sensor area into a number (= Seg) of independent segments.
Evaluate the probability that none of the up to 4 protons in an event coincide in the same segment, as a function of segmentation.



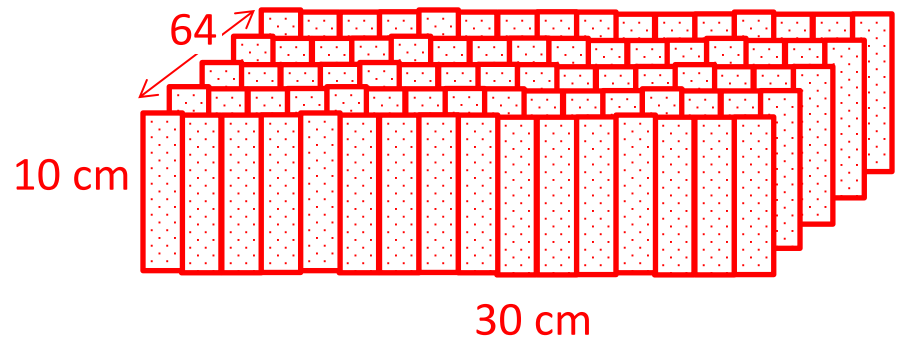
A segmentation of Seg = 16
allows fully reconstruction of
67% of the 4 proton events,
82% of the 3 proton events,
94% of the 2 proton events.
100% of the 1 proton events

Upgrade Energy (WEPL) Detector:

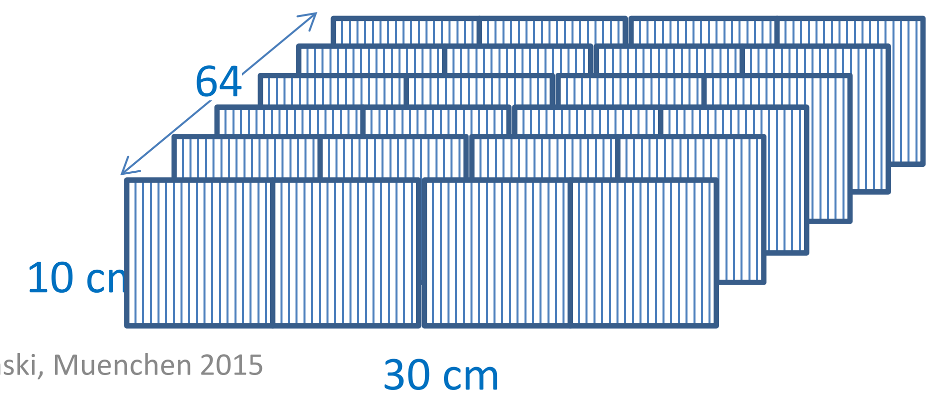
a. Range counter with segmented front
(64 plates of 5mm thick Polystyrene),
either SIPM or Multi-Anode PMT.
One layer segmented into 10 or 30 strips
to correlate time stamp with location



b. Segmented Range counter
(64 plates of 5mm thick Polystyrene),
either SIPM or Multi-Anode PMT.
all layers segmented into 10-30 strips



c. Si Range counter
64 Si sensor planes: either strips or pixels.
< 400 um thick, ~ 500 um pitch
256 6" wafers, 128 8" wafers



Occupancies in Space and Time:

Need to match protons in 4D: Space and Time

a. Silicon Strips & WEPL Range Counter with segmented front

Match silicon x-y planes: add one extra plane rotated by 10 deg.

Match WEPL counter time stamp between segmented front and un-segmented back
Match silicon tracker time stamp and WEPL counter time stamp of segmented front

WEPL Time Matching Front-Back			
Scan time	[sec]	180	60
Proton rate	[MHz]	3	9
Av. Time betw. Protons	[ns]	333	111
Time Resolution	[ns]	15	5
WEPL Occ		4.5%	4.5%
Si Tracker - WEPL Time & Space Matching			
Si Time resolution	[ns]	150	150
Si Time Occ		45%	135%
WEPL Front size	[mm]	10	10
WEPL Front Occ		3.3%	3.3%
Si-WEPL Occ		1.5%	4.5%

Lessons learned in ~ 15 years of pCT

- The requirement of tracking the path and energy loss of every proton is a challenge: Can we relax this requirement?
- Speed (i.e. rata rate) matters, generating challenges for the DAQ
- Segmentation in space and time is needed for contemporary “protons”
- Analog measurements require precision calibration: -> go binary
- Tracker: needs high segmentation
- Tracker Material: Silicon strips / Pixels with broad heritage & technological base
- WEPL detector**:** Segmented scintillator (fast) or highly-segmented Si (slower)
  - Range counter
  - ToF counter
  - Magnetic spectrometer

Looking forward encountering differing conclusions during this Symposium!

Time Resolution and Slew Rate

The time resolution depends on rise time τ_r ,
and τ_r depends on the collection time (i.e. the detector thickness).
3 terms: **time walk** due to amplitude variation, **time jitter** due to noise, **binning.**

$$\sigma_t^{\ 2} = ([\tau_r \frac{V_{th}}{S}]_{RMS})^2 + (\tau_r \frac{1}{S/N})^2 + (\frac{TDC_{bin}}{\sqrt{12}})^2$$

Introducing the **slew-rate S/ τ_r = dV/dt**

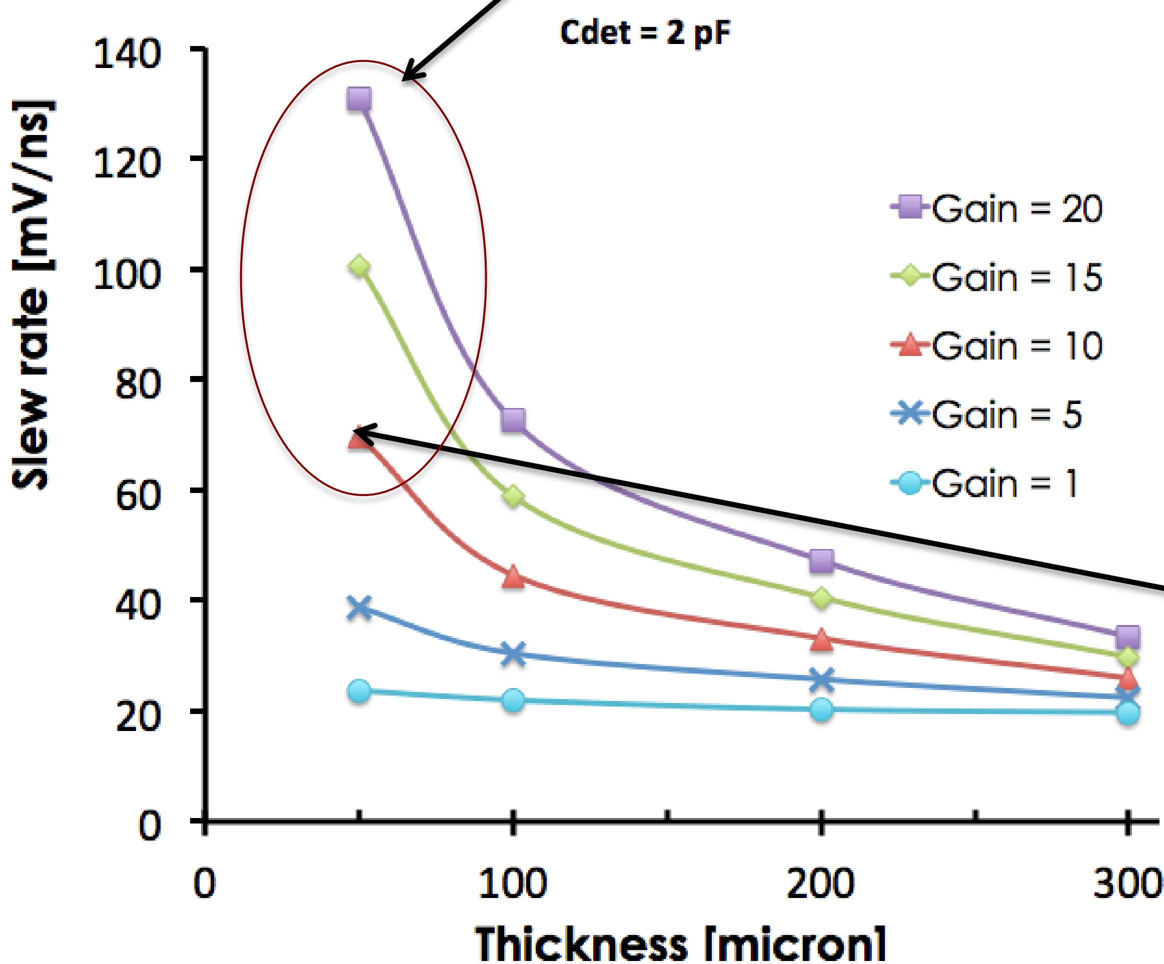
$$\sigma_t^{\ 2} = ([\frac{V_{th}}{dV/dt}]_{RMS})^2 + (\frac{N}{dV/dt})^2 + (\frac{TDC_{bin}}{\sqrt{12}})^2$$

we find that for constant noise N, to minimize the time resolution, we need to maximize the slew-rate dV/dt of the signal.

Need large and fast signals.

Slew-rate as a function of sensor thickness

Large slew rate, good time resolutions



Weightfield2 simulation

N. Cartiglia et al.

2014 IEEE NSS-MIC

50 micron:

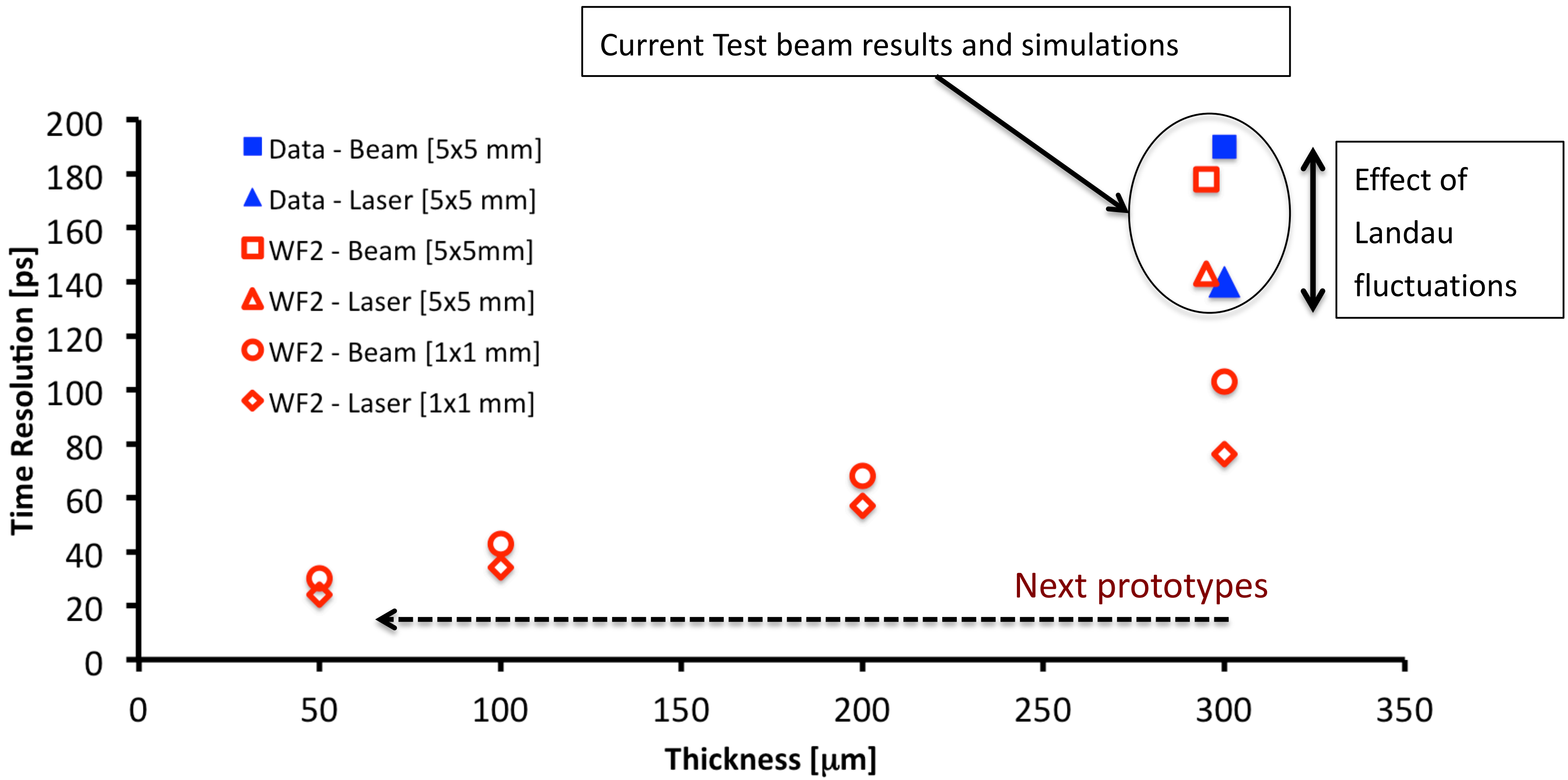
~ 3x improvement with gain = 10

Significant improvements in time resolution require thin detectors

Present results and future productions

With WF2, we can reproduce very well the laser and testbeam results.

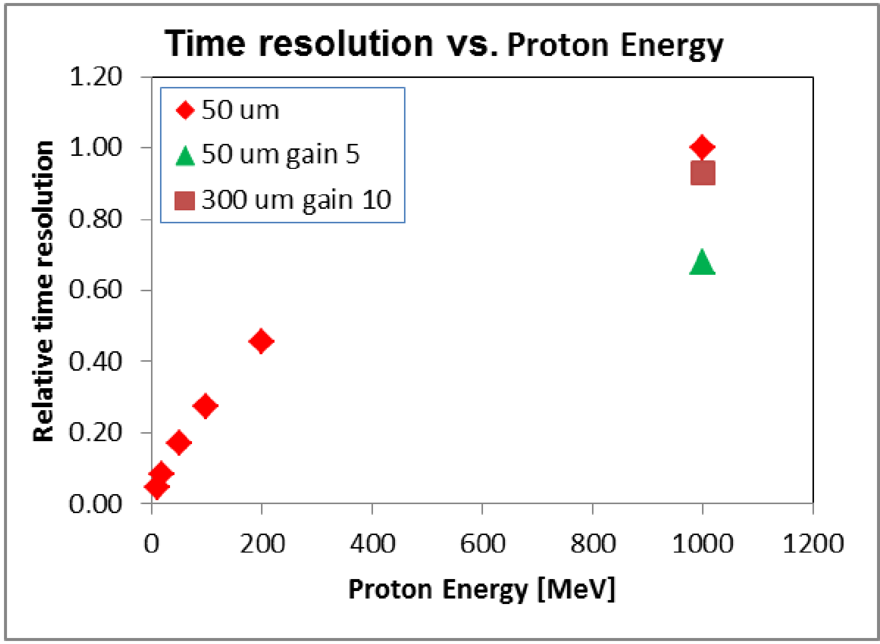
Assuming the same electronics, and 1 mm^2 LGAD pad with gain 10, we can predict the timing capabilities for MIPs of the next sets of sensors.



Weightfield study of dV/dt for large dE/dx

Time resolution ~ $(dV/dt)^{-1}$
dV/dt referred to MIPS in 50um Silicon without gain

Thickness [um]	Energy [MeV]	dV/dt [mV/ns]	Rel dV/dt
50	10	476	20.70
50	20	278	12.09
50	50	136	5.91
50	100	83.5	3.63
50	200	50.6	2.20
50	1000	23	1.00
50	MIP gain 5	34	1.48
300	MIP gain 10	24.7	1.07

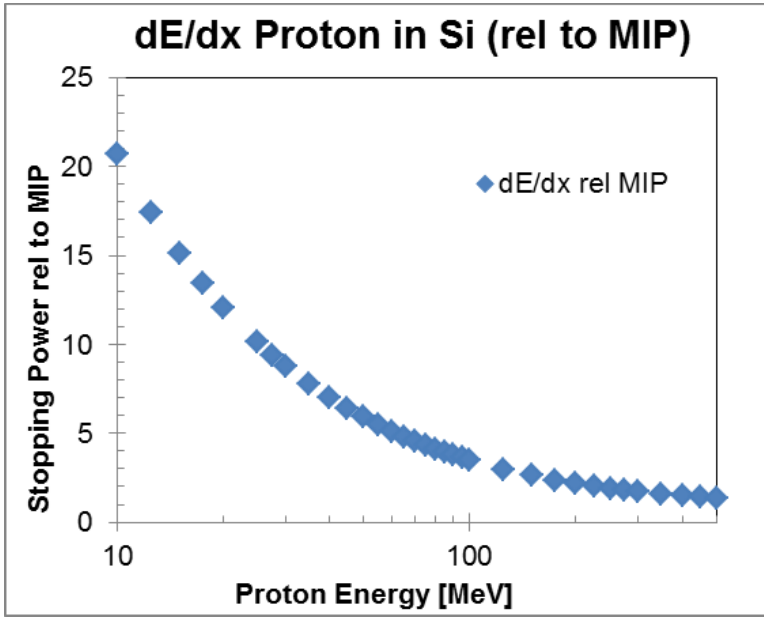


Very large improvement of slew-rate (dV/dt) for low-energy protons!

Excellent Time Resolution for low-energy Protons

Large dE/dx increases the slew-rate dV/dt

Predictions from simulations:
For MIPs in 50 um sensors
time resolution: 30 ps with gain = 10
time resolution: 84 ps without gain



Predicted time resolution for protons in Ultra-fast Silicon Detectors without gain:

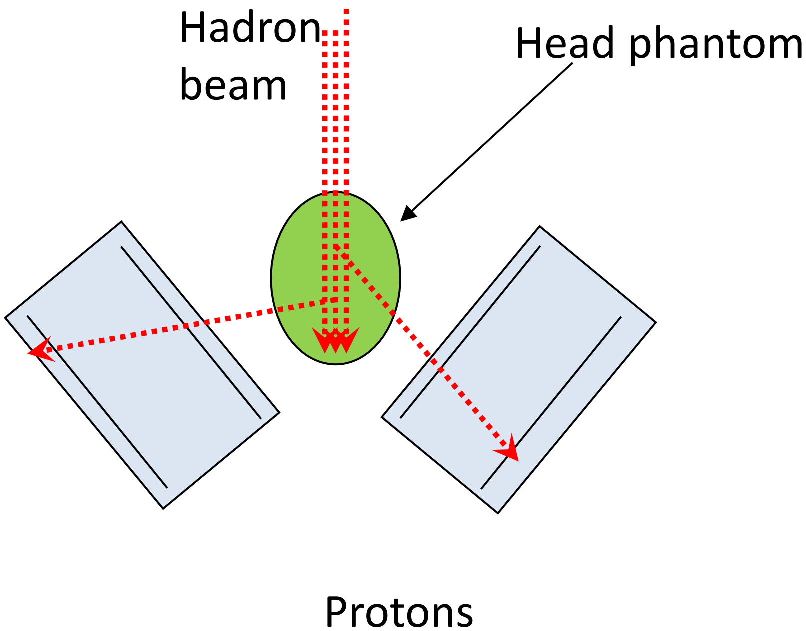
E [MeV]	rel. dE/dx	Time res. [ps]
10	20.7	4.1
20	12.1	6.9
50	5.9	14.2
100	3.6	23.3
200	2.2	38.2

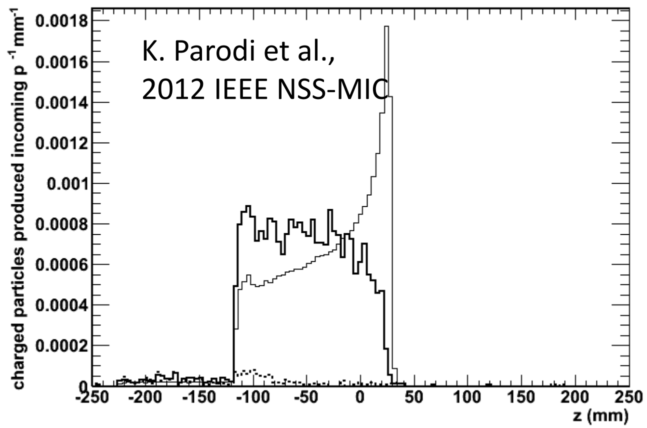
With USFD with gain = 10, the time resolution is reduced by a factor3.

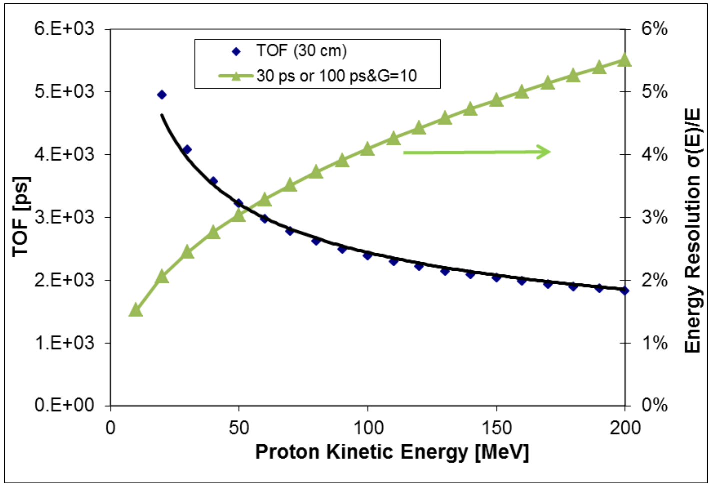
Low-energy protons afford very good time resolution, allowing the measurement of the proton energy by time-of-flight TOF.

IVI with Ultra-Fast Silicon Detectors

UFSD: 50 um thin, pixels 300um x 300 um,
Time resolution of 30 ps (goal), 100ps (measured) allows energy measurement by TOF



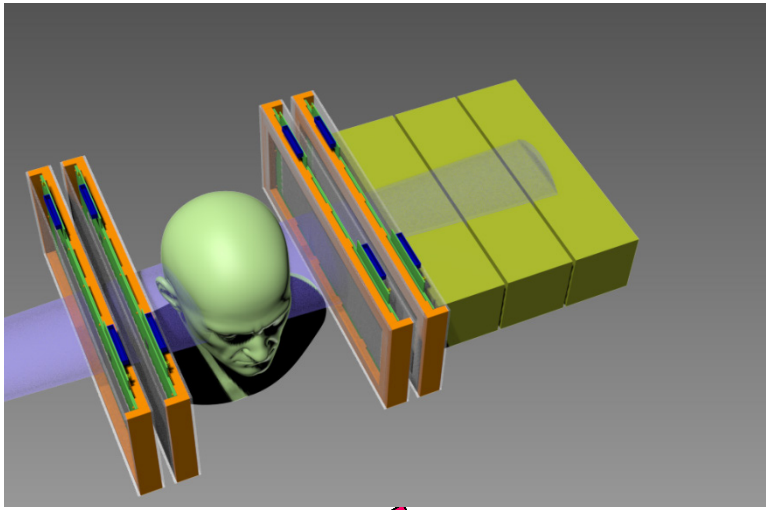


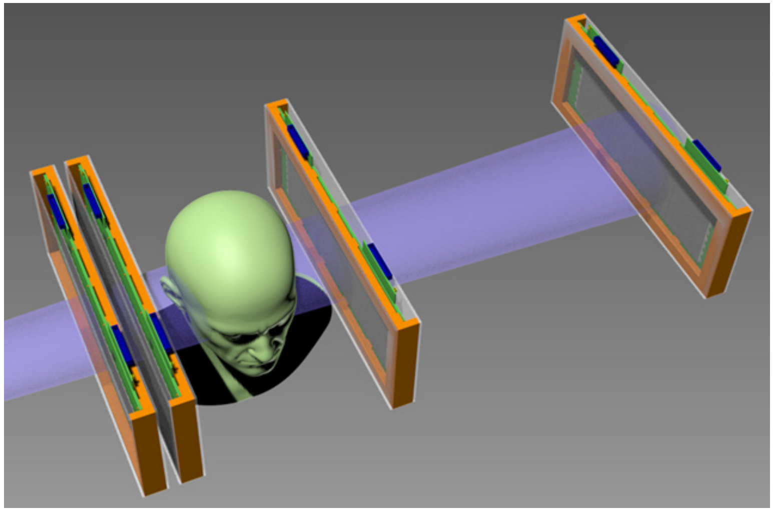


Energy resolution on secondaries:
100 MeV pions: **16%**
100 MeV protons : **4%**

Rate: Yield of secondaries depends on energy cut-off and detector area.
With 1% efficiency and 10% solid angle, a beam of 10^{10} p/sec gives a 10 MHz rate.
UFSD can operate at 10 MHz rate and provide real-time beam diagnostics.

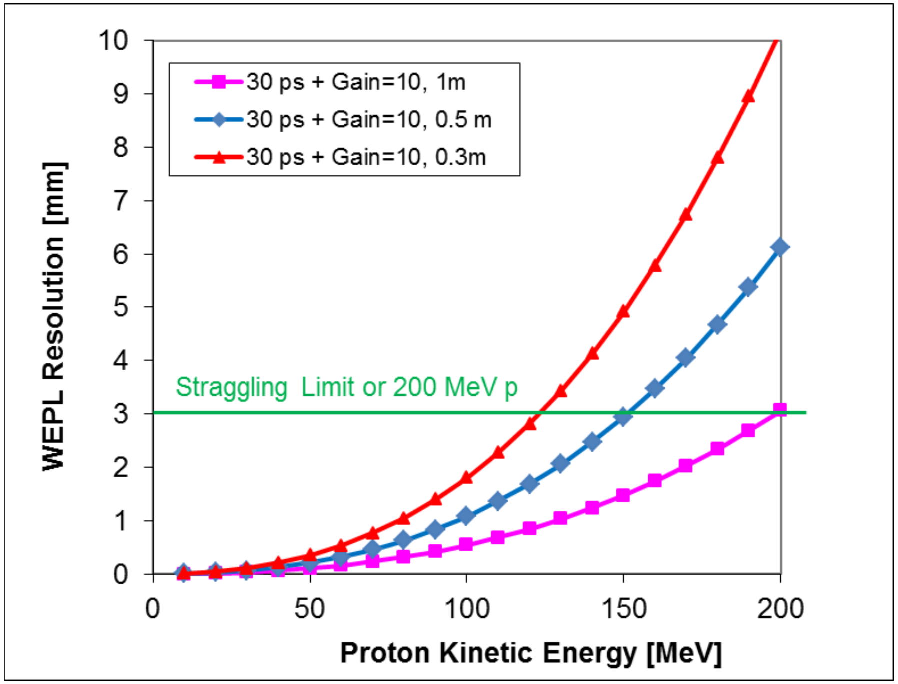
Future: 4-D Ultra-Fast Si Detectors for WEPL?





Protons of 200 MeV have a range of ~ 30 cm in plastic scintillator. The straggling limits the WEPL resolution.

Replace calorimeter/range counter by TOF:
Light-weight, combine tracking with WEPL determination



We are developing ultra-fast silicon sensors based on internal charge multiplication, investigated by RD50, with the goal of thin sensors with moderate gain.

Prospects for use of UFSD in Low-energy Protons

- Ultra-fast silicon detectors (UFSD) afford very good time resolution for low-energy proton (or ions) since they have very high slew-rare.

- The large slew rate due to the high specific energy loss of low-energy protons is enhanced by a factor 3 when a UFSD with gain = 10 is used. Timing resolution of < 10 ps for protons with E < 150 MeV are predicted.

- The fact that UFSDs have their best timing capability when the sensor is thin (< 50 um) goes hand-in-hand with the fact that tracking of low-energy protons need thin sensors to reduce MCS (Multiple coulomb scattering).

- Smaller UFSD with 200um thickness and 50um thickness (epi) will be available this Summer.

On-going Research with the pCT Head Scanner

Much of the work is done by UCSC Student Tia Plautz <tplautz@ucsc.edu>

Radiography
- Stopping Power (RSP)
- Scattering

3D Image reconstruction
- (compare to X-rays)
- Catphan® 404 for RSP validation
- Anthromorphic Head Phantom
- (Spatial Resolution)
- Edge Phantom

A step forward into Imaging History..

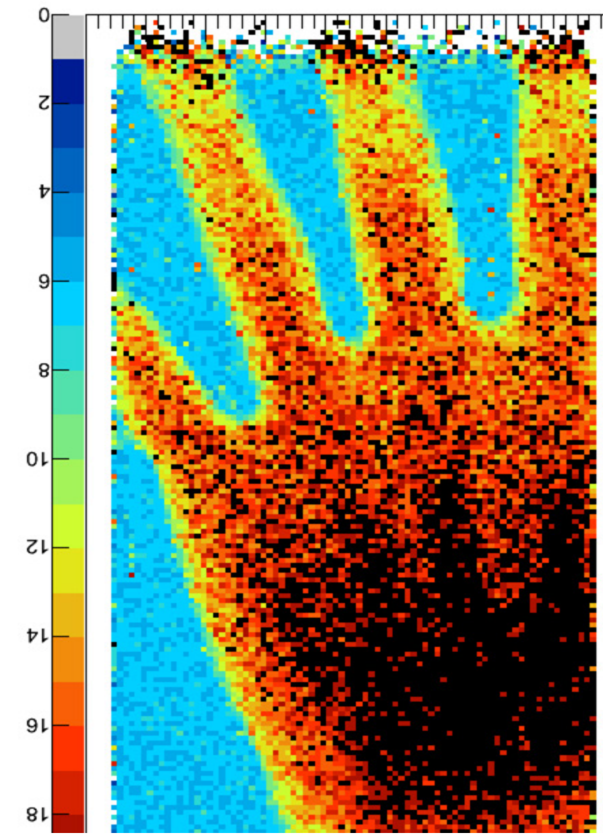
X-Rays

Wilhelm Roentgen,
Laboratory Radiology (1895)

200 MeV Protons

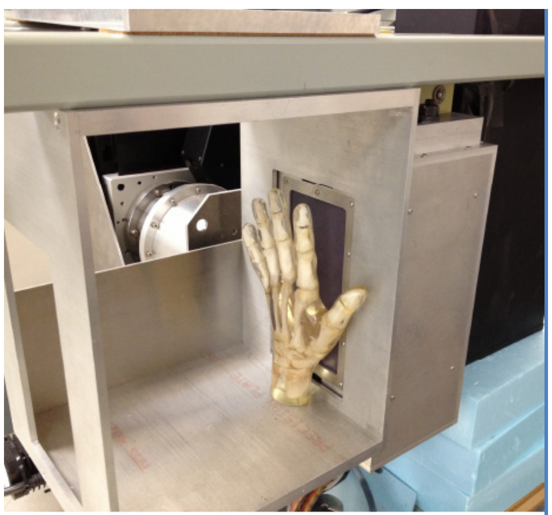
Stopping Power

Multiple Scattering

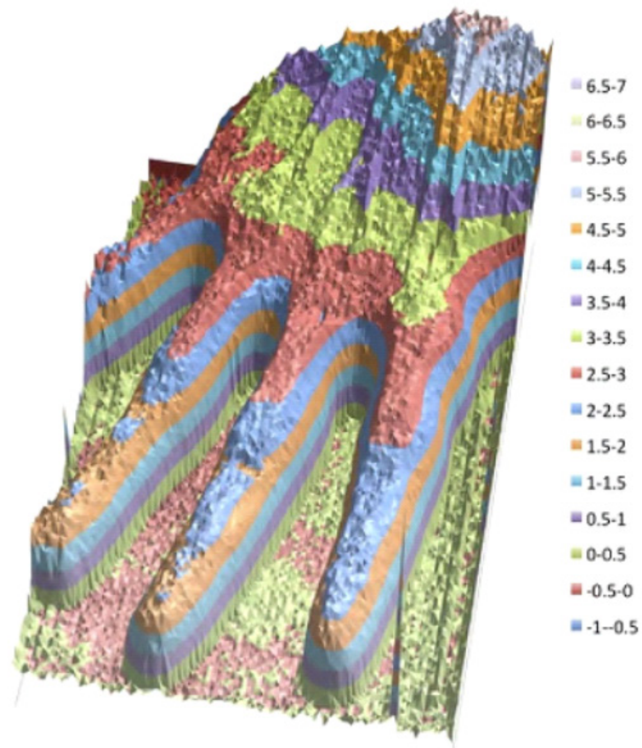


UCSC-LLU-CSUSB 2012, T. Plautz et al., 2012 IEEE NSS-MIC

Hand Radiography: Something New (?)



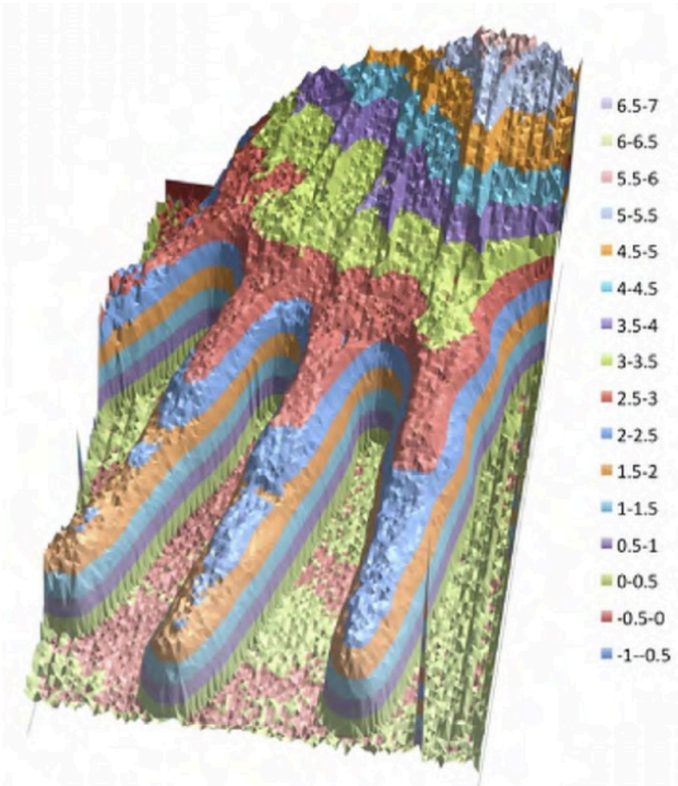
Hand Phantom imaged with 200 MeV protons at the Loma Linda Synchrotron, using the existing pCT scanner.



Color-coded image of the summed-up stopping power in terms of water-equivalent thickness [in mm].

Note the varying thickness of the hand and clear structural details.

Energy-Loss (RSP) Radiography



- The quantity of importance for proton treatment planning is relative stopping power (RSP) of protons with respect to water (Bethe - Bloch)
- RSP is practically energy independent and is determined mostly by the electron density of the material or tissue.

- We define Water Equivalent Path Length (WEPL):

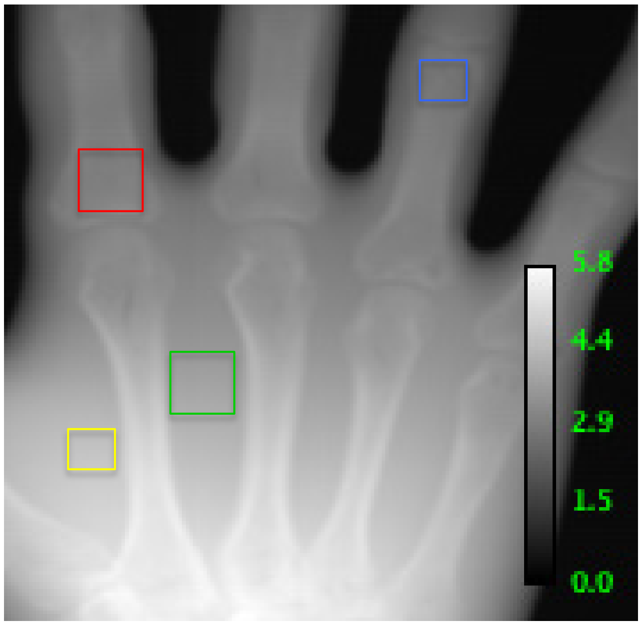
$$L = \int_{E_{out}}^{E_{in}} \frac{dE}{S(I_w, E)}$$

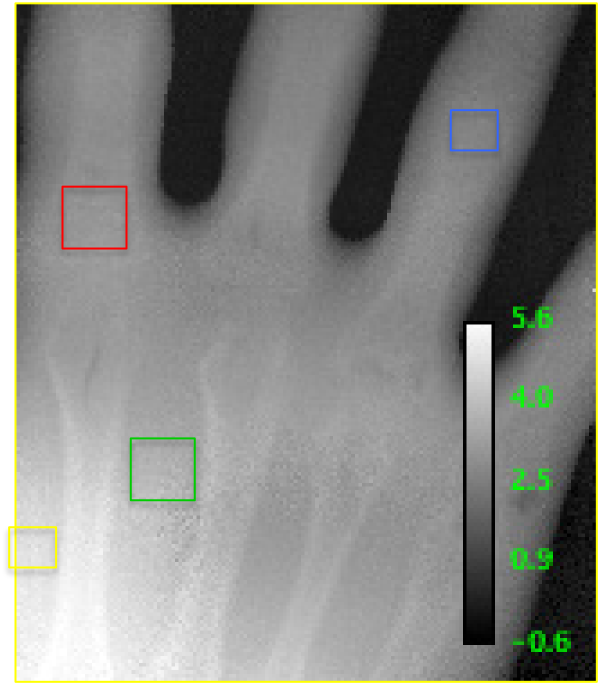
Where S is -dE/dx in the Bethe-Bloch Equation:

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2}\frac{nz^2}{\beta^2}\left(\frac{e^2}{4\pi\epsilon_o}\right)^2\left[\log\left(\frac{2m_e c^2\beta^2}{I(1-\beta^2)}\right) - \beta^2\right]$$

This can be simplified to: $L = \int_l \varrho dl$, where ρ is the ratio of the stopping powers

RSP from x-rays & protons





Left: Xray radiograph transformed from Hounsfield Units to RSP

Right: proton Radiograph with 0.5x0.5 mm pixels

ROI	RSP_{xray} (cm)	RSP_{proton} (cm)	% difference (2*diff/sum)	Relative Error
a.	3.618±0.130	3.527±0.125	2.55%	0.505σ
b.	2.892±0.070	3.015±0.076	4.16%	1.190σ
c.	4.236±0.119	4.561±0.153	7.39%	1.677σ
d.	2.548±0.082	2.539±0.041	3.54%	0.0981σ

Scattering Radiography

The amount a proton is scattered between its entry and exit from a phantom is proportional to the inverse of its energy and can be described by the Lynch-Dahl approximation for multiple scattering events:

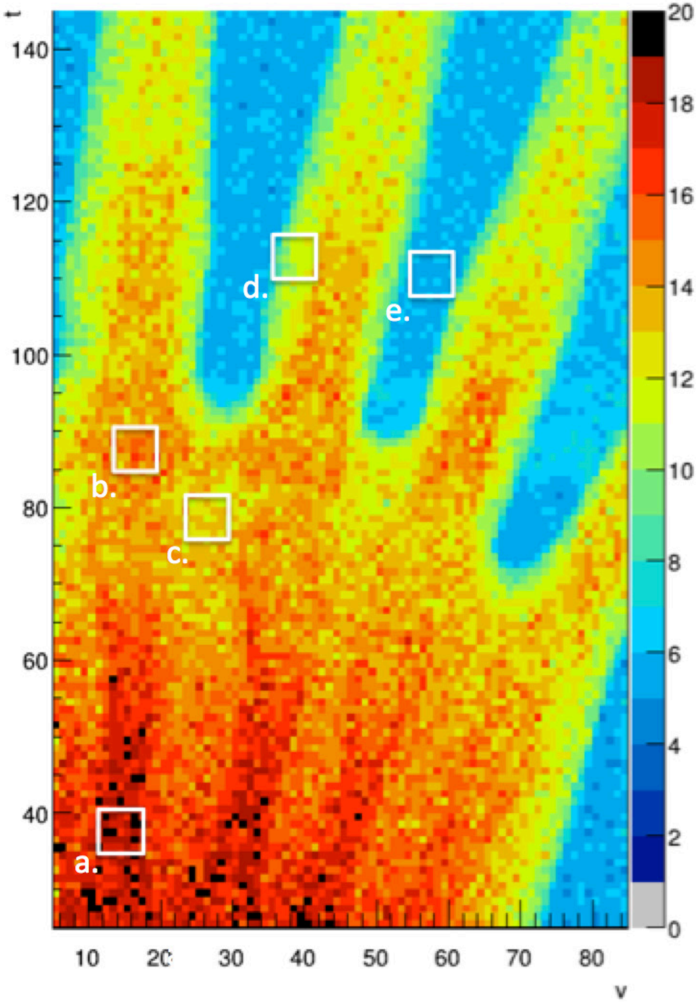
$$\theta = \frac{13.6\ \mathtt{MeV}}{\beta cp} z \sqrt{\frac{x}{X_o}} \left[1 + 0.038 \log \frac{x}{X_o} \right]$$

where β, p are the velocity and momentum of the proton, respectively, z is the charge of the proton and X_0 is the radiation length of the material and can be calculated using:

$$\frac{1}{X_o} = \sum \frac{w_j}{X_j}$$

where the w_j's are the weights of each element in a given material.

Scattering Radiography



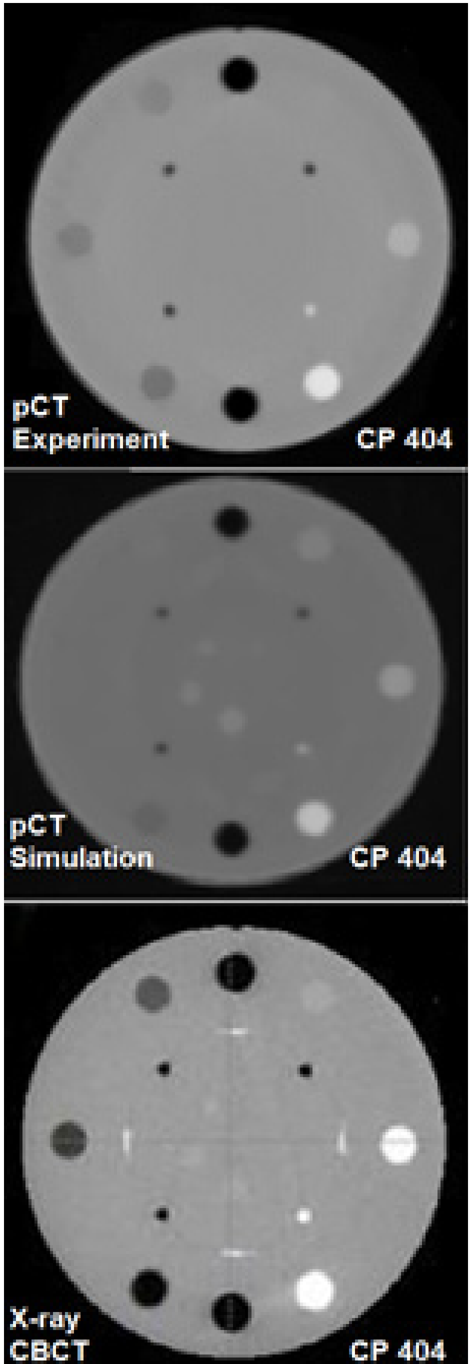
Scattering angle derived from RSP and assumption of material

TABLE I – Expected and Observed Scattering Angles for 200 MeV Protons ($\beta = .566$, $p =$ 644 MeV/c) for Selected ROIs (units in mrad)

ROI	Expected	Fig. 7	Relative Difference
(a.)	17.	$17.8. \pm 0.9$	0.9σ
(b.)	15.	$14.1. \pm 0.9$	$1.\sigma$
(c.)	11.	12.3 ± 0.7	$1.\sigma$
(d.)	10.	$10.3. \pm 1.3$	0.2σ
(e.)	5.	5.2 ± 0.4	0.5σ

TABLE II – Densities and radiation lengths of materials commonly encountered in pCT. Data for bone: [18]. Data for tissue, water and silicon: [19]

Material	Density (g/cm^3)	Radiation Length, X_o (g/cm^2)
bone	1.45	16.6
tissue	1.00	38.2
water	1.00	36.1
silicon	2.33	21.8



pCT Scan: Catphan® 404 Module

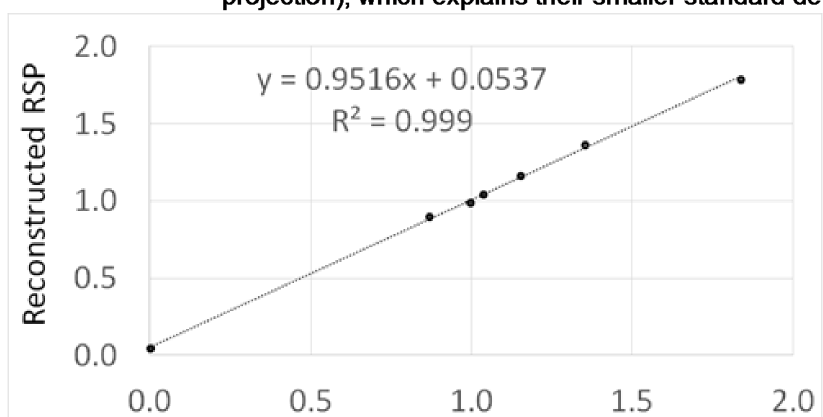
Weighted CT Dose Index (CTDI) Results

X-ray CBCT: 2.53 mGy

Proton CT (2 M histories): 0.61 mGy

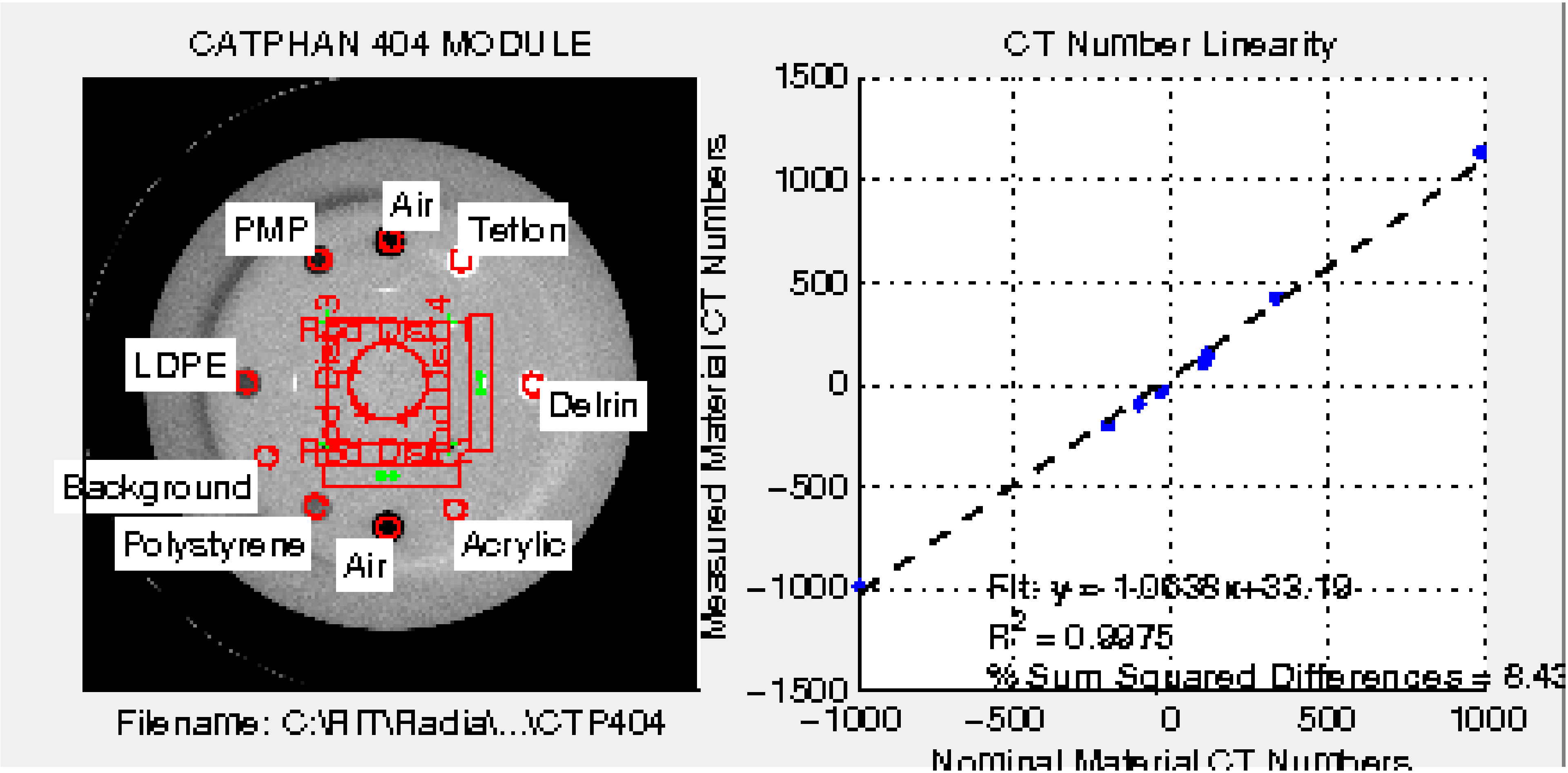
Insert	Predicted	Reconstr Exp/Sim	Stdnd dev Exp/Sim	Abs Diff |Rec-Pred| Exp/Sim
Teflon	1.84	1.78/1.82	0.002/0.02	0.06
Delrin	1.35	1.36/1.35	0.001/0.02	0.01
Acrylic	1.16	1.16/1.16	0.002/0.02	0.01
Air	0.001	0.04/0.02	0.004/0.02	0.04
PMP	0.87	0.90/0.88	0.004/0.03	0.03
Polystyrene	1.04	1.04/1.04	0.007/0.02	0.00
LDPE	1.00	0.99/1.00	0.005/0.02	0.01

Table 1. Comparison of predicted versus reconstructed mean RSP of sensitometry inserts for experimental and simulated pCT data. The experimental data had better statistics (2.5M histories per projection), which explains their smaller standard deviation.



Catphan® 404 Module

(careful: ours has different orientation!)

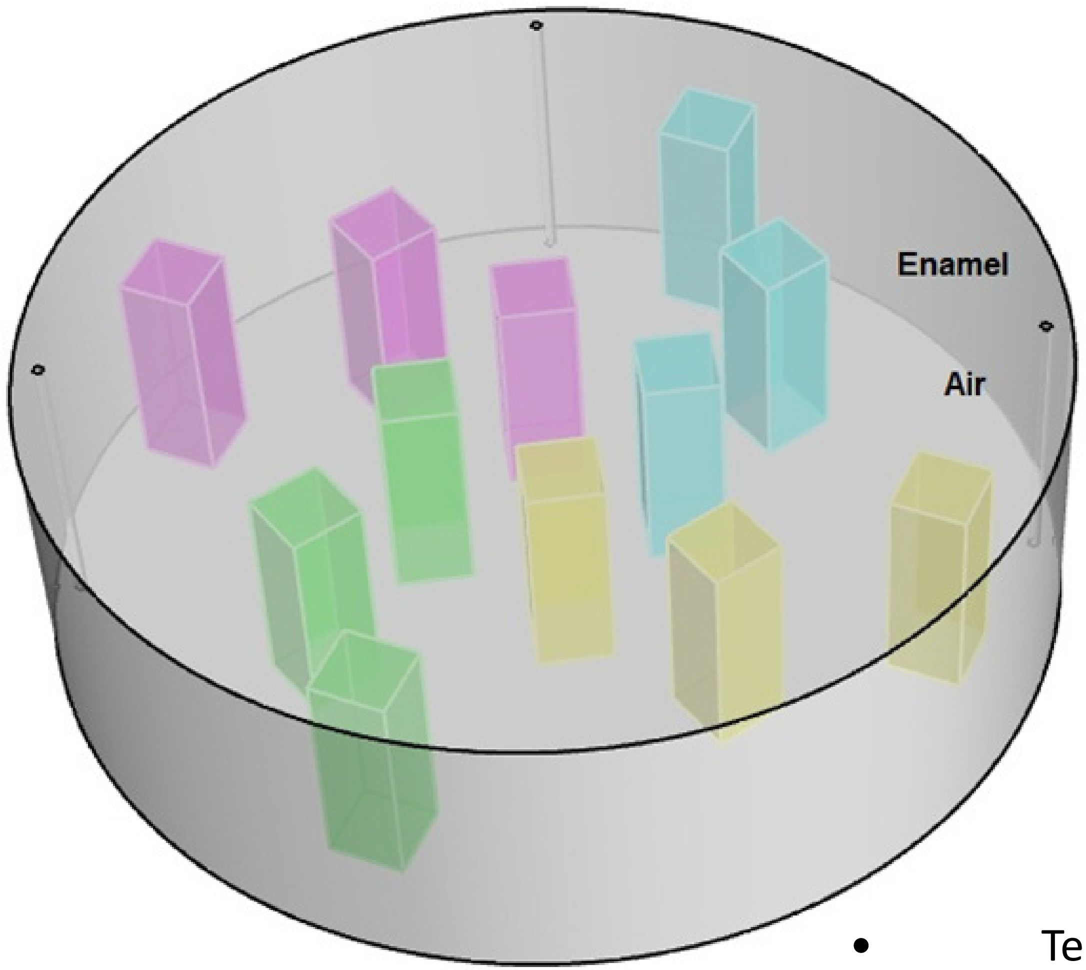


pCT Scan: Anthromorphic Head Phantom

Large contrast difference between pCT
and
X-ray CT

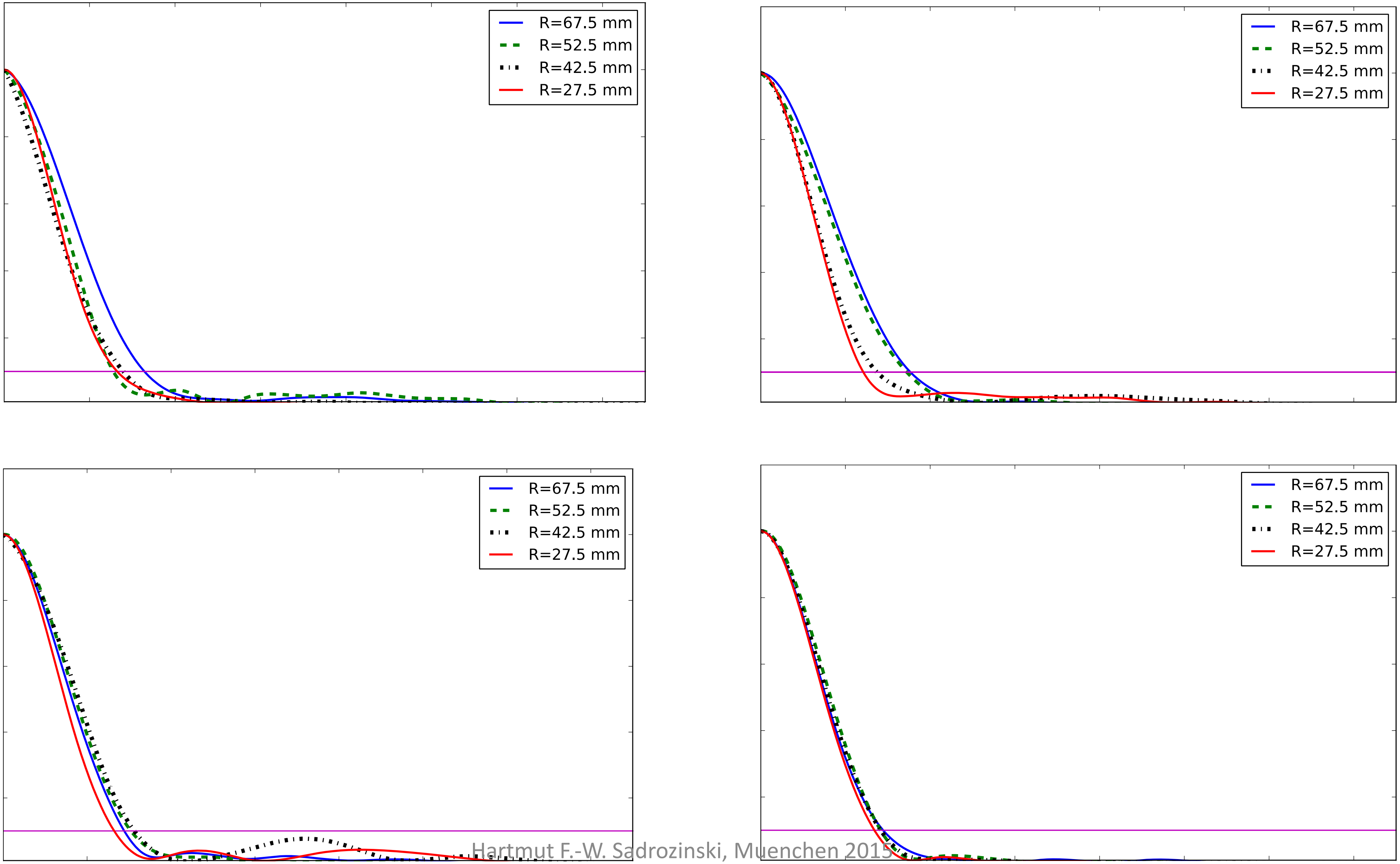
Material	Predicted	Reconstr	Stdnd dev	Rec-Pred
Sinus Cavities	0.20	0.34	0.032	0.14
Soft Tissue	1.03	1.02	0.003	0.005
Brain	1.04	1.04	0.008	0.007
Trabecular Bone	1.10	1.11	0.008	0.013

Edge Phantom to Investigate Spatial Resolution

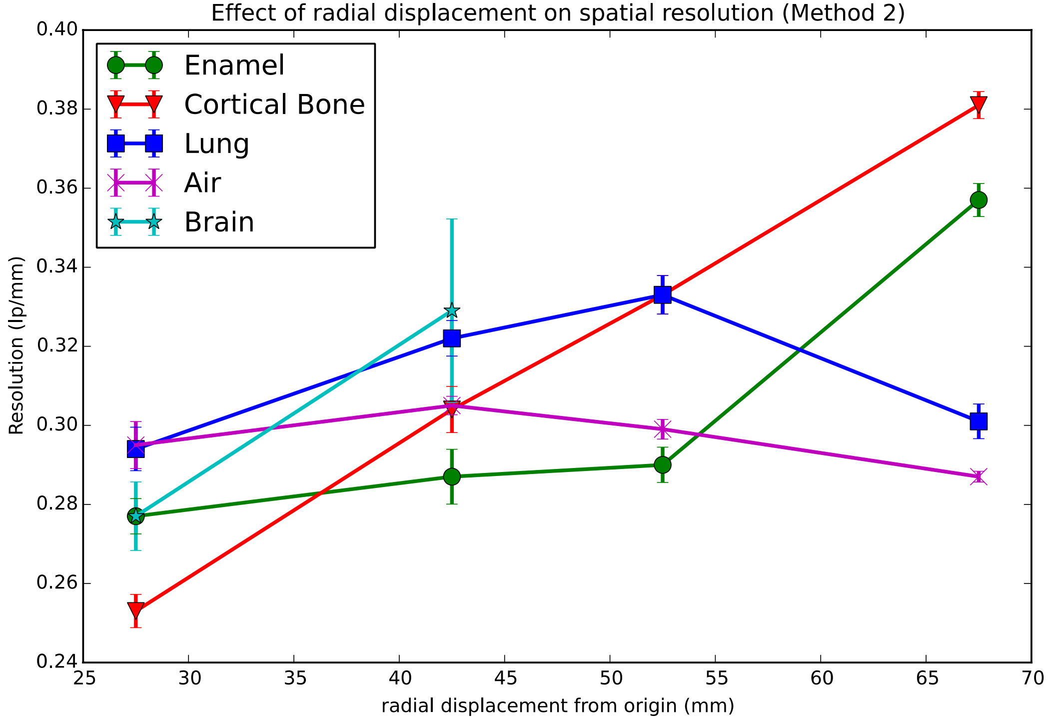


- Teeth Enamel (represent in cyan
- Cortical Bone (represent in magenta
- Lung (represent in green
- Air (represent in yellow

MTFs for High Contrast Inserts



Maximum Resolution For High Contrast Inserts



Material	27.5 mm	42.5 mm	52.5 mm	67.5 mm
Enamel	0.265	0.279	0.256	0.328
Cortical Bone	0.242	0.275	0.345	0.353
Brain	0.329	0.277	XXX	XXX
Lung	0.264	0.312	0.304	0.288
Air	0.268	0.283	0.283	0.289

As the radial displacement from the center of the phantom increases, the data indicate that for…

- Enamel: the resolution increases significantly, 3.38σ
- Cortical Bone: the resolution increases significantly, 6.07σ
- Lung: the resolution does not change significantly, 0.61σ
- Air the resolution does not change significantly -0.34σ

Explanation: For high density inserts scattering (and therefore uncertainty in the MLP increases) therefore reducing spatial resolution. For low density inserts scattering and uncertainty decrease.