Proton CT reconstruction

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Bergen pCT workshop, november 2016

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pCT requirements

Table 1. Requirements for a practical (proton-tracking) CT scanner for proton therapy

Category	Parameter	Value
Proton beam	Energy	$\geq$200 MeV (head)
		$\geq$250 MeV (body)
	Flux[a]	$\geq$3000 protons cm^{-2} s^{-2}
Imaging dose	Maximum absorbed dose[b]	<20 mGy
Image quality	Spatial resolution, σ	$\approx$1 mm
	Relative stopping-power accuracy	<1%
Time	Data acquisition time	<10 min
	Reconstruction time	<10 min

[a] Quoted figure based on the scenario of 1-mm voxels and 180 projections, a target of 100 protons passing through a voxel per projection[6] and a 10-min acquisition.
[b] Quoted figure based on a crude calculation of comparable stochastic risk to typical X-ray CT head scans ($\approx$40 mGy[7,8]), assuming a proton radiation weighting factor twice that of photons.[9]

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«Track reconstruction»

Three different meanings:

1. **Track reconstruction inside calorimeter to find range**
   - Implemented in our code

2. **Track reconstruction inside patient / phantom**
   - Not yet implemented, no experimental data

3. **Image reconstruction**
   - Use external software (some available)

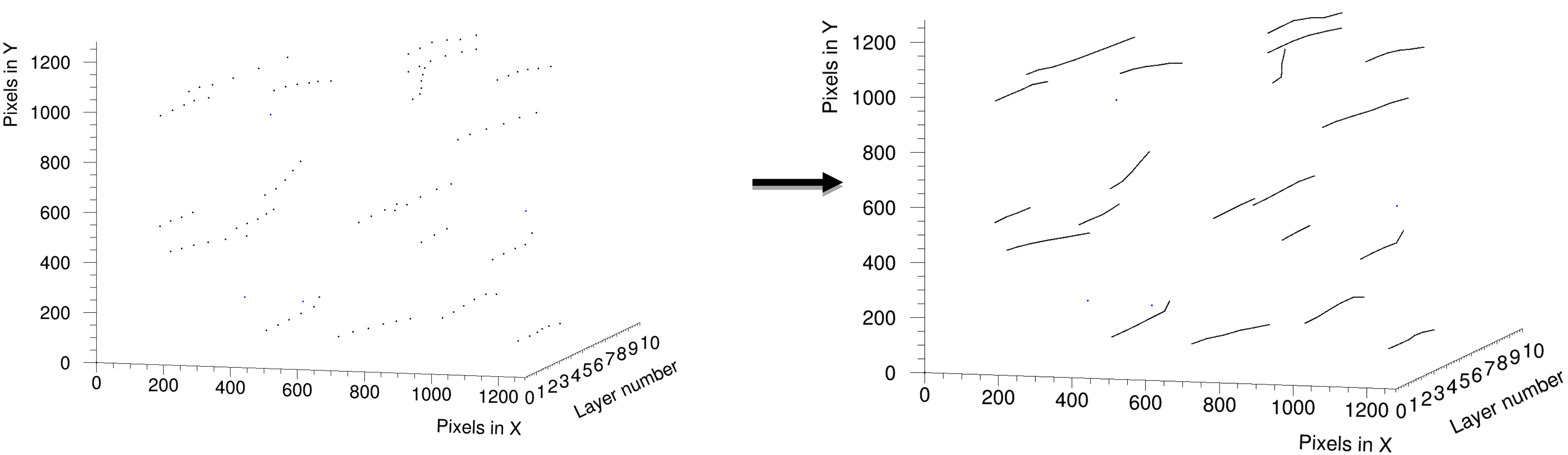
Track reconstruction in detector

Input:

1. Hits with (x,y) in each layer, clustered together

Output:

2. A set of track objects representing the proton tracks



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Track reconstruction in detector

Follow scheme called «Track Following» as specified in Strandlie, my implementation and interpretation

REVIEWS OF MODERN PHYSICS, VOLUME 82, APRIL–JUNE 2010

Track and vertex reconstruction: From classical to adaptive methods

Are Strandlie*
Gjøvik University College, P.O. Box 191, N-2802 Gjøvik, Norway

Rudolf Frühwirth†
Institute of High Energy Physics of the Austrian Academy of Sciences, Nikolsdorfer Gasse 18, A-1050 Wien, Austria

(Published 7 May 2010)

- Most litterature deal with vertex finding, fitting track parameters, perfectly curved electron tracks in magnetic field etc.,
    - Here: «Perfect» measurements dominated by MCS deflection of straight path

Track following

1. Find seed hits from first layer
2. Find nearby hits in 2nd layer
   - Use calculated MCS straggling angle in current layer
3. Use all initial vectors from (1,2) to find expected position in 3rd layer
   - Locate all possible next hits in next layer, choose the one with lowest angular deflection
4. Use best track from (3) as track candidate from seeds (1,2)
   - Best track: Based on length, edep shape, straggling, …

Track scoring

- Many initial vectors from first seed: Follow all possibilities within search cone
  - Many track candidates with different incoming angles
- Use track scoring scheme to find best candidate:
  - Up to 25 points for track range: 25 points * range / max range
  - Up to 10 points for small total angular deflection (sum slope angle difference in terms of expeced in each layer, linear increasing score with falling sum)
  - 10 points if a Bragg Peak is detected within detector

Proton tracking – seach cone

- Speed optimized
  - Search list is a Cluster object array (x,y,layer,edep,…)
  - Sorted as descending pixel column
  - Use index list to only search through Clusters with *y* values in search cone radius
  - Search cone:
    - Find individual proton energy at current layer depth
    - MCS angle ,

Proton tracking – Corrections

Several corrections are performed in order to increase

- efficiency (# reconstructed tracks / # primaries)
- accuracy (% of reconstructed tracks have identical MC tagged primary)

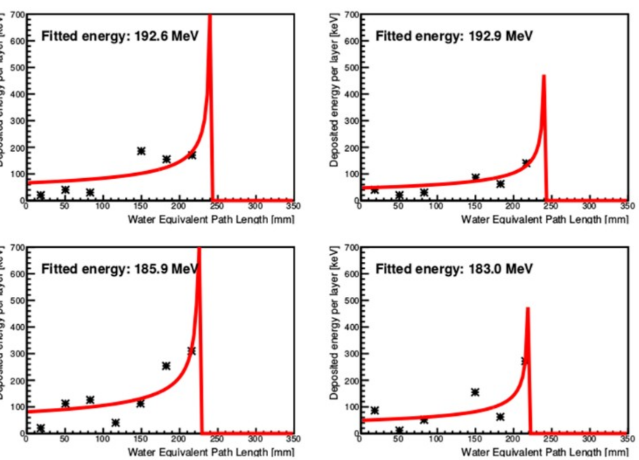
1. Splitting of merged clusters
2. Removal of tracks leaving detector laterally
3. Removal of tracks ending in dead chips
4. Allowing tracks to be followed «through» dead chips
5. Tried forward-backwards tracking, which reduced the reconstruction accuracy

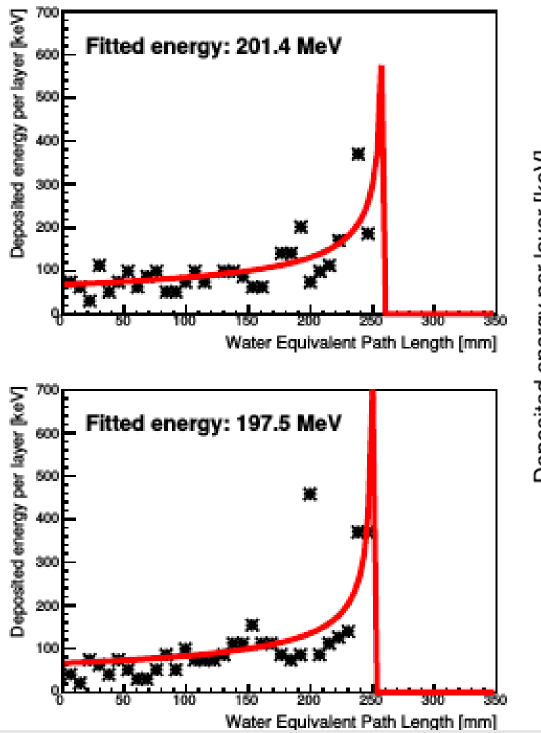
Proton tracking – Sparse sampling

- Focal: 32 mm water equivalent material between each sensor layer (3.3 mm W)

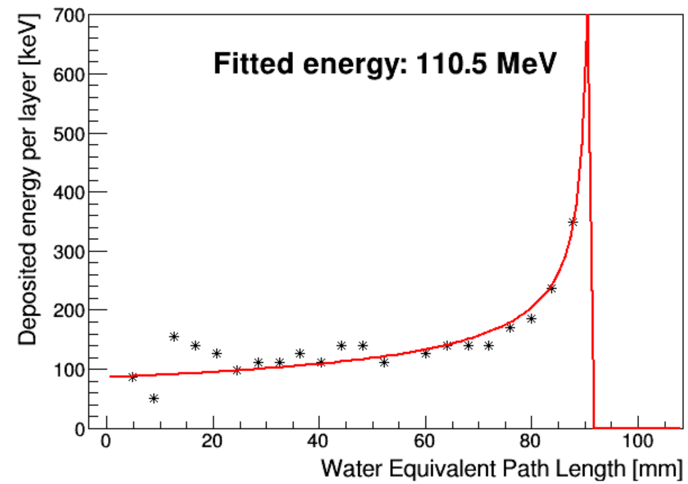
Aluminium absorbator @ 200 MeV MC

Plots of individual protons
188 MeV experimental data





PMMA absorbator @ 200 MeV MC



Proton tracking – Efficiency

In experimental data:

- 15% of tracks leave the detector laterally
- 35% of the tracks stop abrubtly (18% expected from nuclear interactions)
- And only 60% of frames have proton data! (2 kHz readout, 1.2 kHz proton beam)

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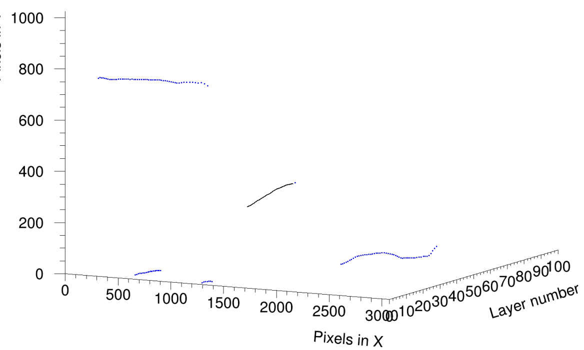
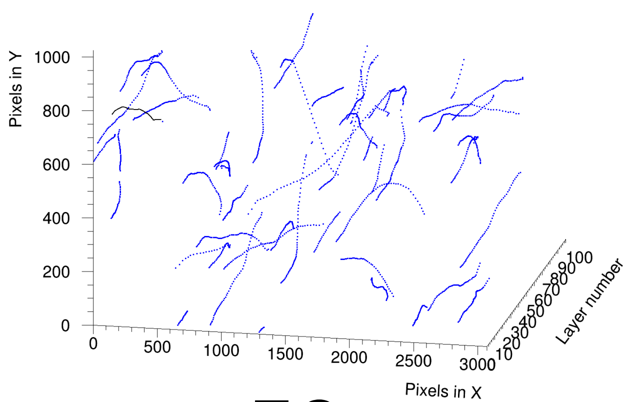
Proton tracking – Accuracy

The more protons to be reconstructed at the same, the smaller the probability of finding the correct track

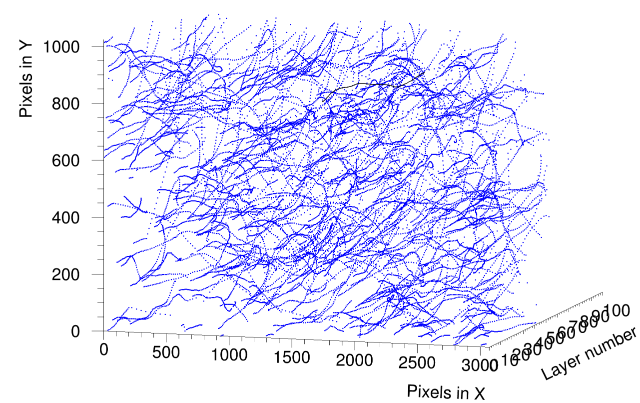


5

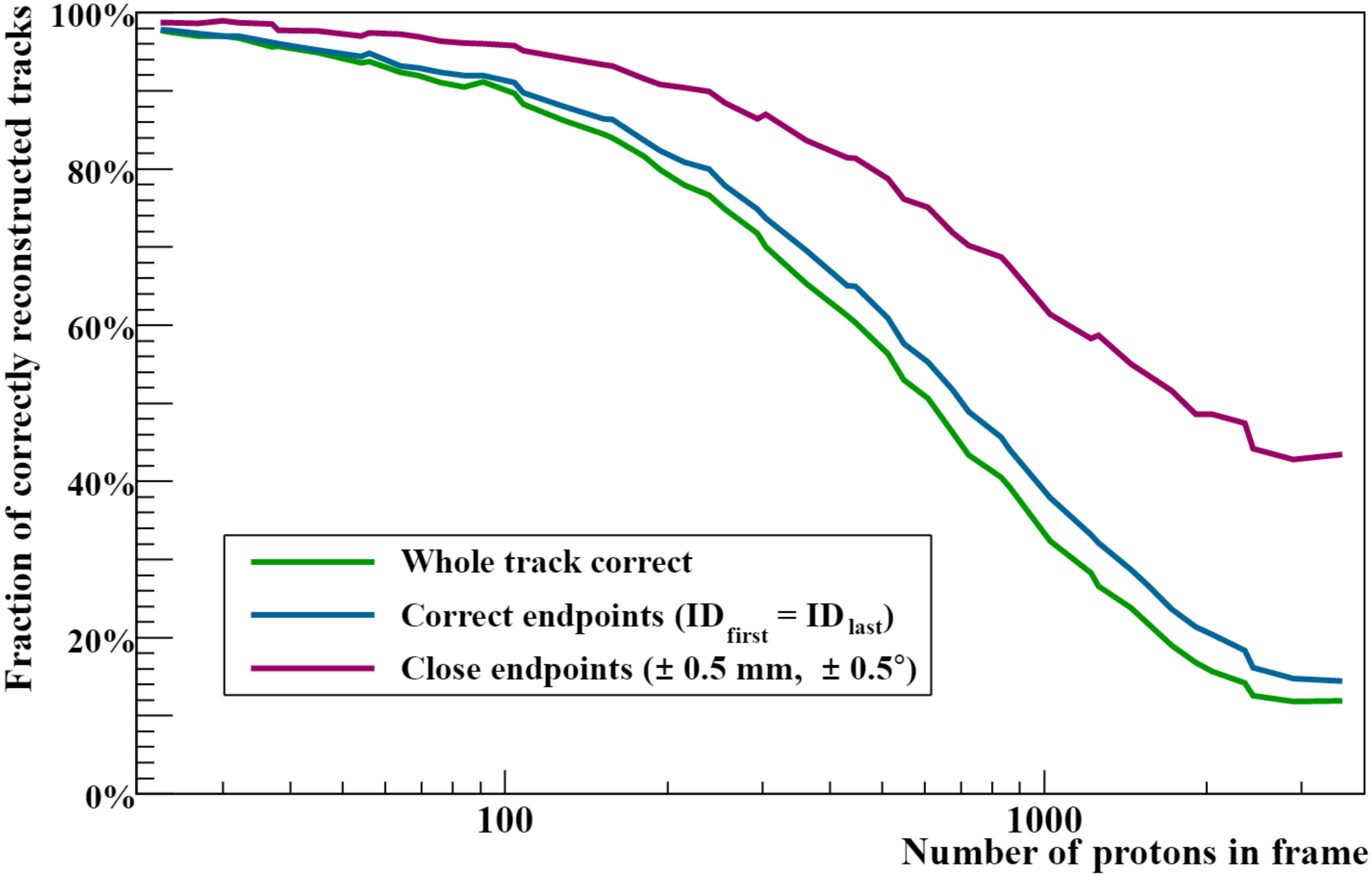


50

500



Tracking accuracy – FOCAL



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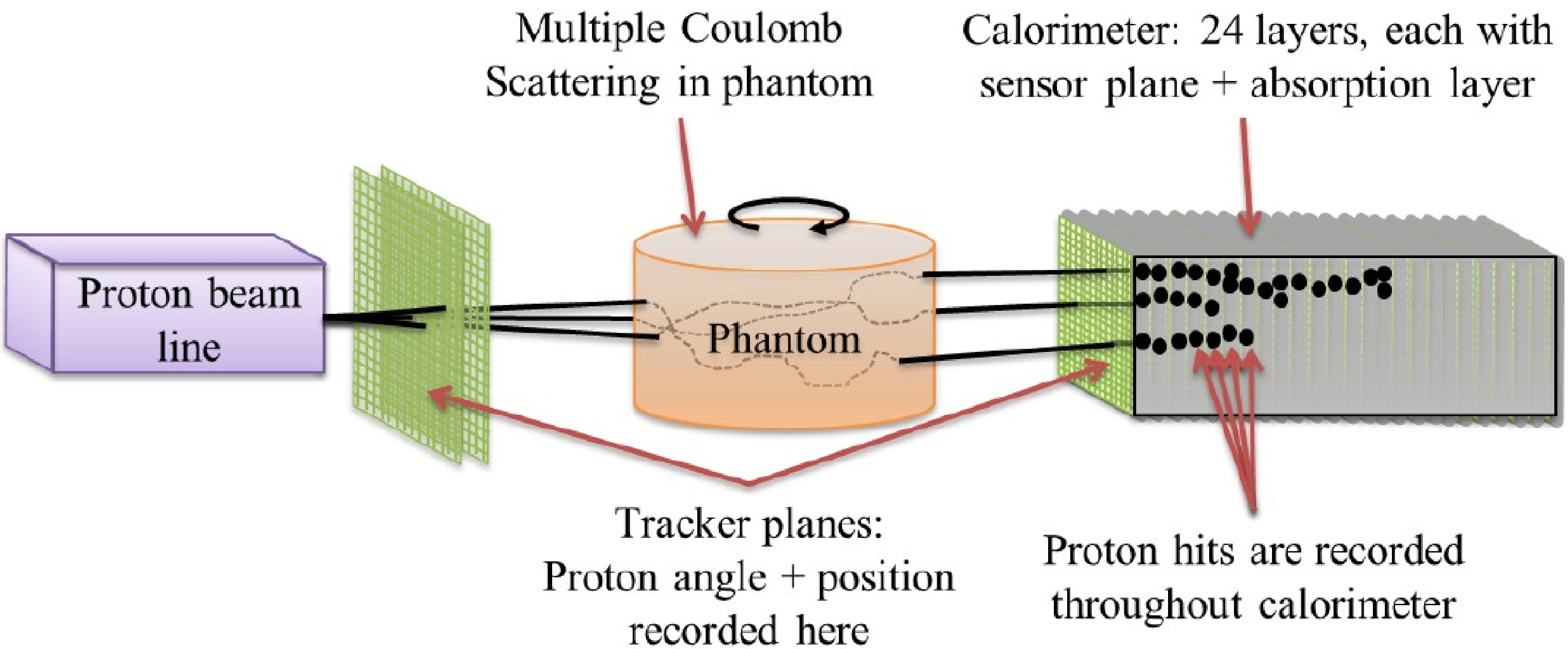
Patient track reconstruction

The proton track between the two tracker planes must be assumed



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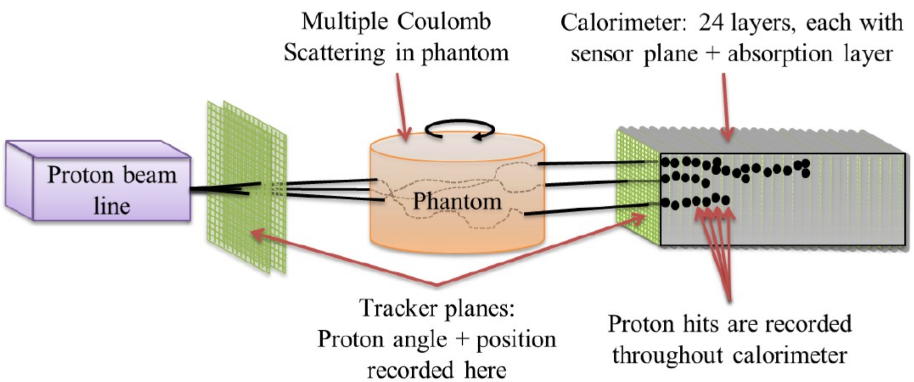
Patient track reconstruction

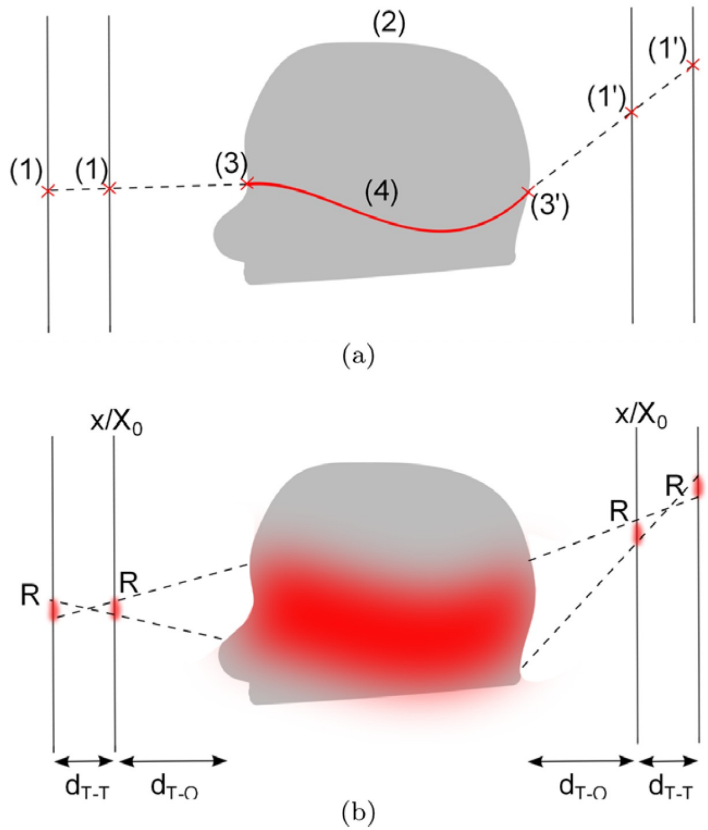
Problems:

- Need to identify which tracker hits belong to which proton (very, very sparse sampling if many protons in readout frame)
- With >> 100 protons/frame: Well, Padua's problem
- Then, assume proton track the spline from the two vectors
  - Better track model: Higher image resolution



Patient track reconstruction

Resolution of voxel's stopping power determined from the goodness of the track in patient



The impact of tracking system properties on the most likely path estimation in proton CT

C Bopp, R Rescigno, M Rousseau and D Brasse

Proton CT image reconstruction

Reconstruction of proton CT images:

- Find proton vectors before / after patient
- Find proton energy before / after patient
- Calculate energy loss
- Calculate proton's path
- Repeat for a number of angles (phantom can be rotated, patient can NOT)
- 4 degree steps usual
- Result: A number of swiggly sinograms

Sinogram reconstruction

First…. How to do this with regular CT?

In the simple case of parallel-beam x-ray CT, the image can be reconstructed via the formula

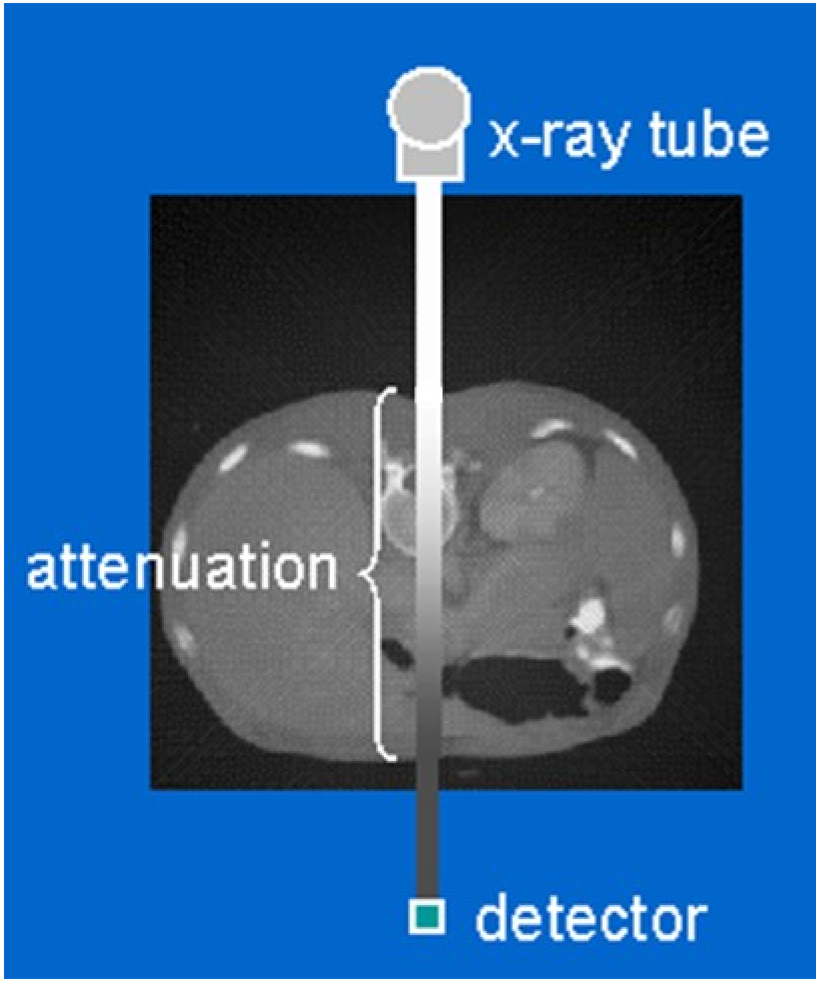
$$\mathbf{u} = \mathcal{R}^{-1}(\mathbf{p}) = \mathcal{R}^{\dagger}(\mathbf{k}_{1\mathrm{D}} * \mathbf{p}) \tag{31}$$

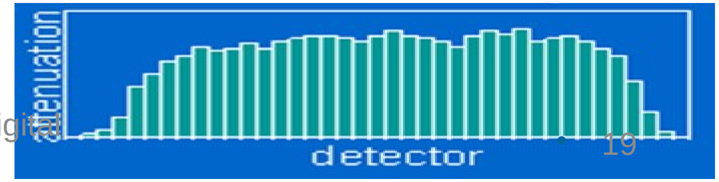
where $\mathcal{R}^{\dagger}$ is the adjoint of the Radon transform, more commonly known as the back-projection. $\mathbf{k}_{1\mathrm{D}} * \mathbf{p}$ represents the convolution of the projection data $\mathbf{p}$ with the 1D kernel $\mathbf{k}_{1\mathrm{D}}$. For the exact reconstruction, $\mathbf{k}_{1\mathrm{D}}$ is the so called ramp-filter, defined in Fourier space as simply the absolute value of the frequency. The combined method is generally known as the filtered back-projection. This has been exten-

X-ray CT reconstruction

We do we measure?

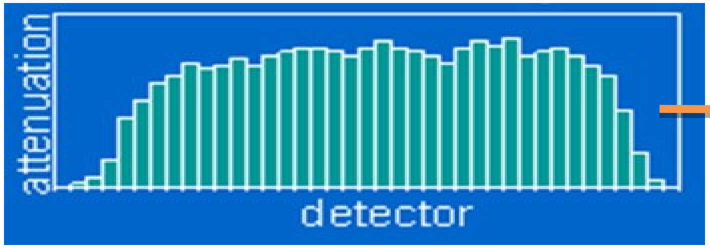
- The linear attenuation coefficient **μ** between the x-ray
  tube and the detectors
- μ is a measure of how fast the x-ray are absorbed in the material
- By using many parallel detectors, we get an attenuation map lateral across the patient

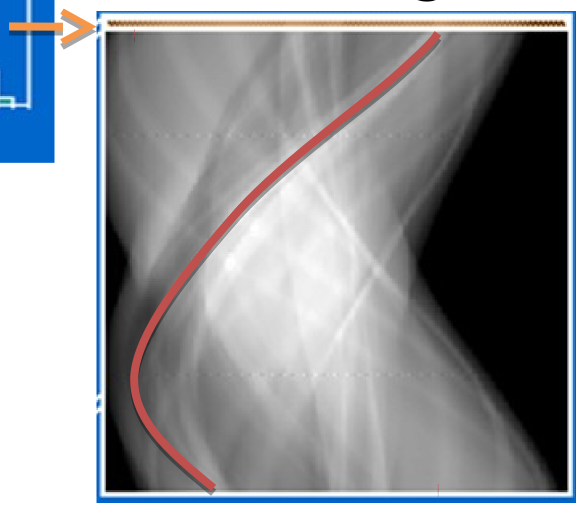




X-ray CT reconstruction

This attenuation map equals one row in the CT raw data (called the **sinogram**)



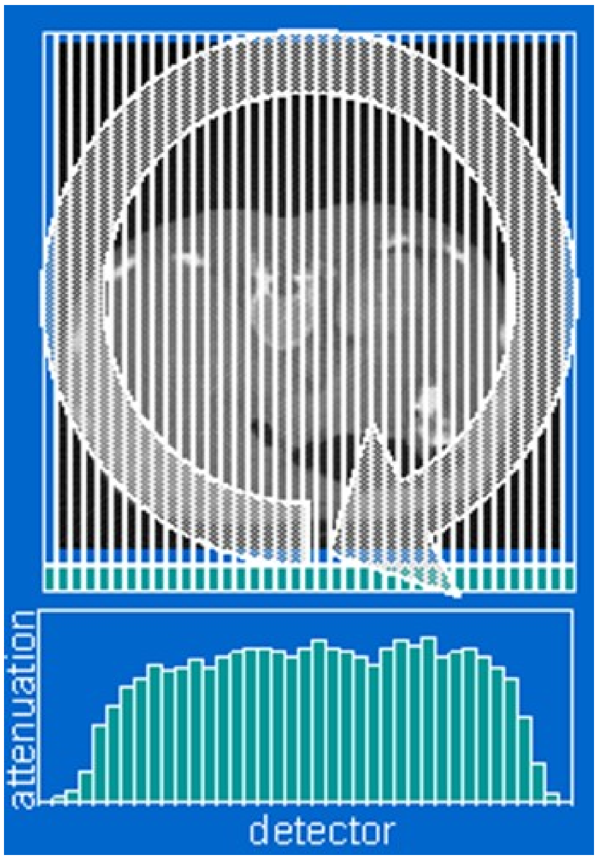


By rotating the gantry one step, the next attenuation map equals the next row in the sinogram

So: A small object in the CT gets a sine shaped representation in the sinogram due to the rotational geometry

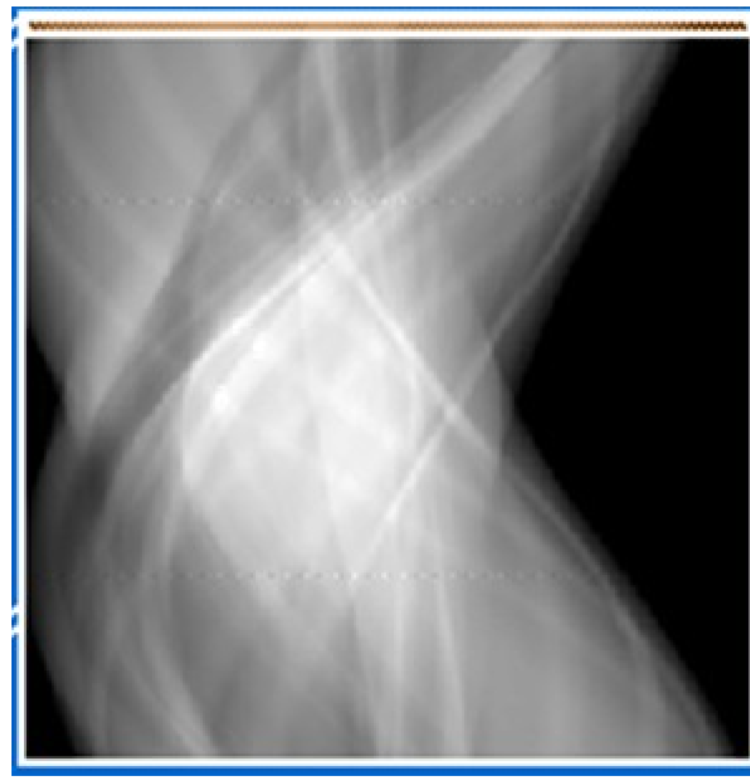
X-ray CT reconstruction

The sinogram



- Radial detectors at same φ →

Radial detectors at same



- Gantry angle φ →

Gantry angle

X-ray CT reconstruction

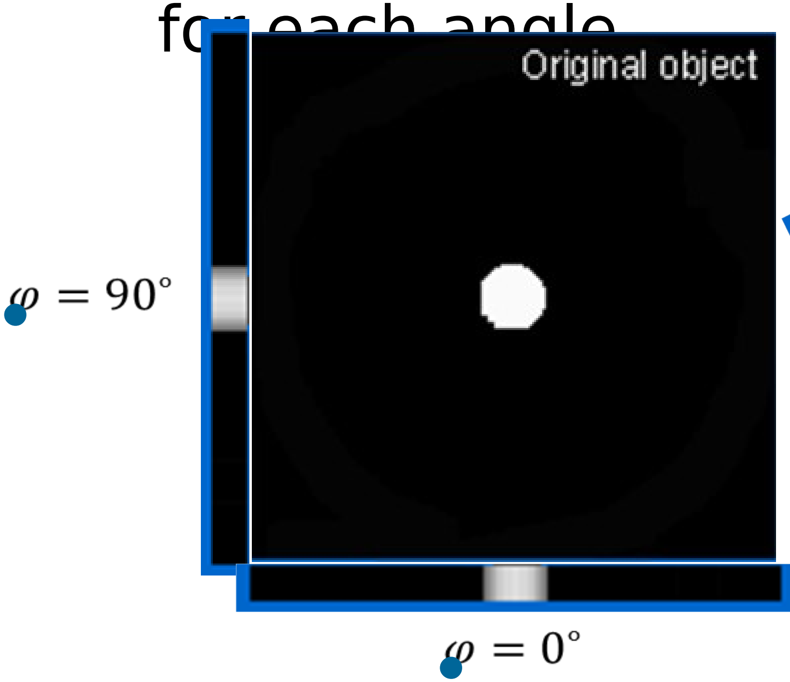
The reconstruction problem: How to create image from sinogram?

?

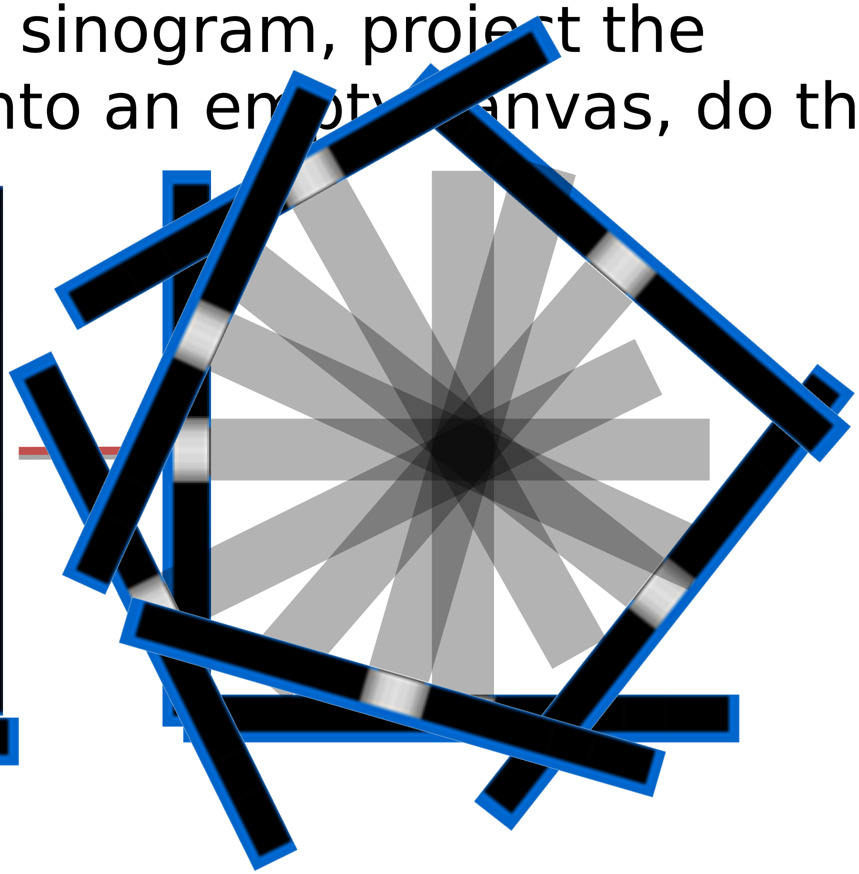
Back projection

The simple solution:

- For each row in the sinogram, project the attenuation map onto an empty canvas, do this for each angle



Object



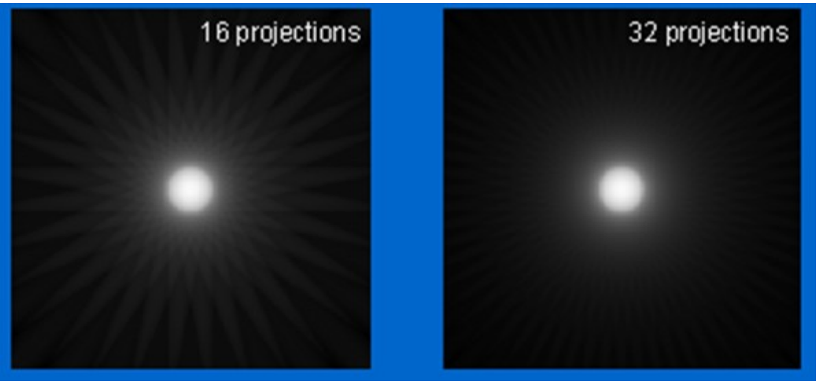
Back projection

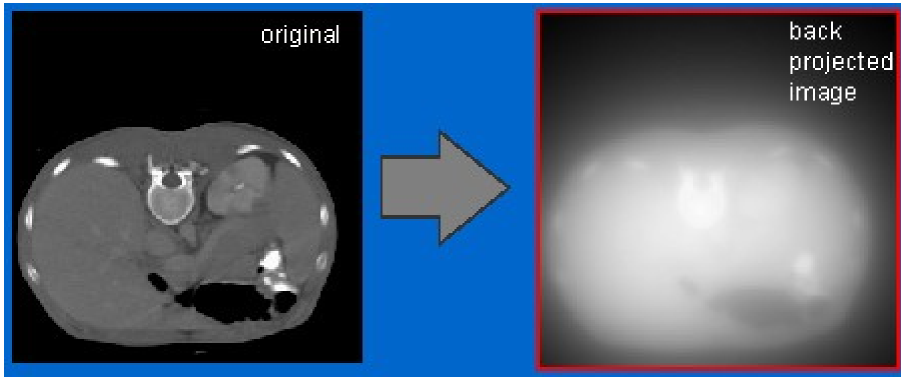
Back projection

Using this methodology, the result is OK for simple objects (with some ghosting)

For complex objects, very very blurry

- Need to deconvolute the blurriness





…We can filter the raw data

1. Horizontal blurring

$$\begin{matrix} 0 & 0 & 0 \\ 1 & 1 & 1 \\ 0 & 0 & 0 \end{matrix}$$

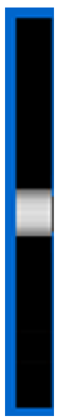
2. Edge enhancing

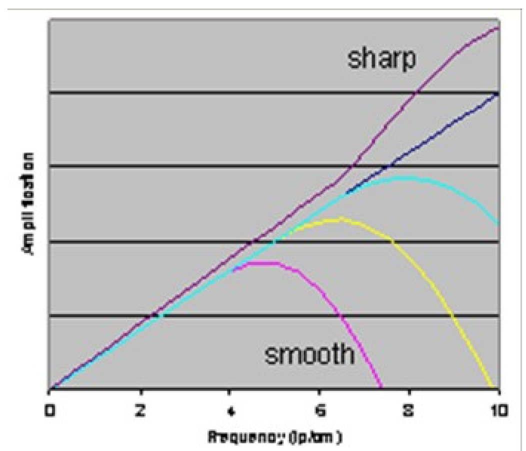
$$\begin{matrix} -1 & -1 & -1 \\ -1 & 9 & -1 \\ -1 & -1 & -1 \end{matrix}$$

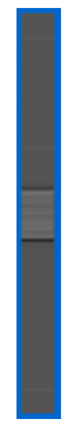
Filtered back projection (FBP)

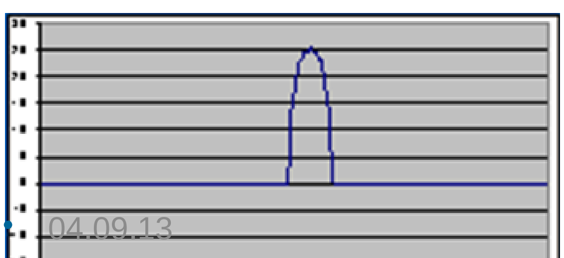
Use an edge enhancing filter on each row of the sinogram

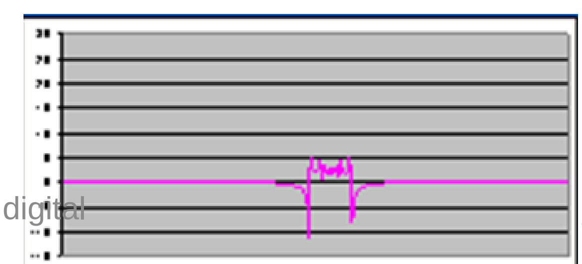
- Filter shape and size affects the clinical target of the image (smooth soft tissue filter, sharp bone filter)





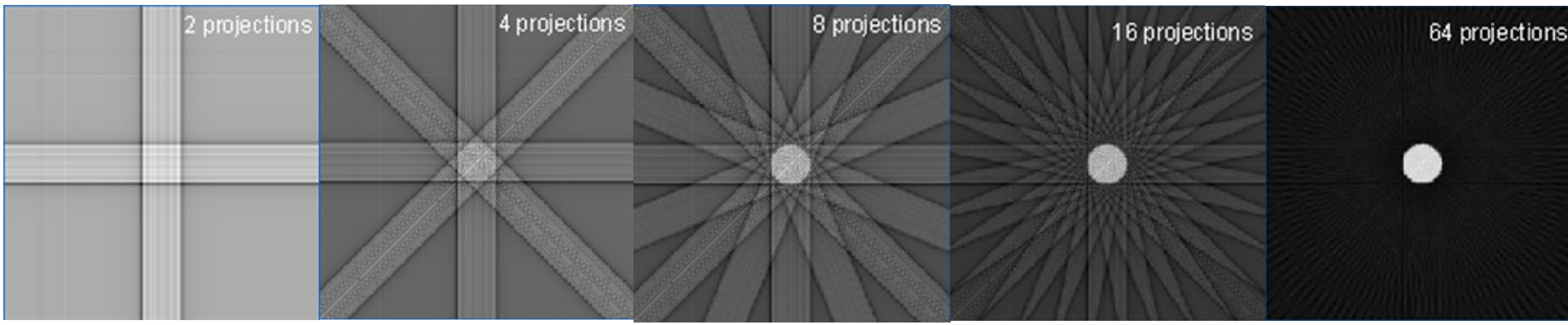


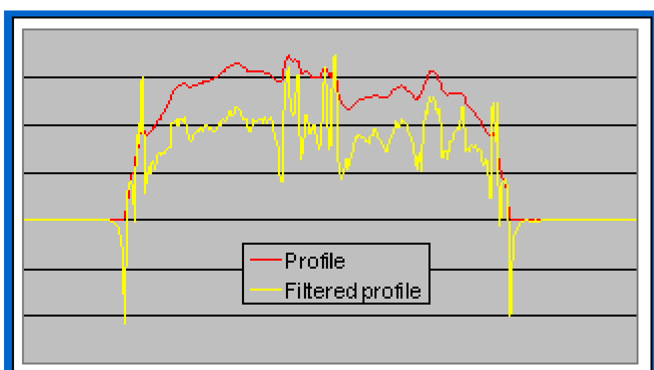


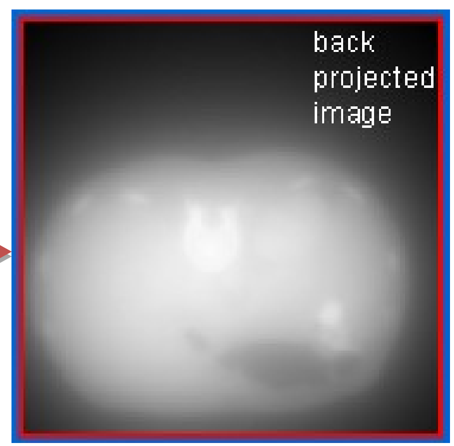


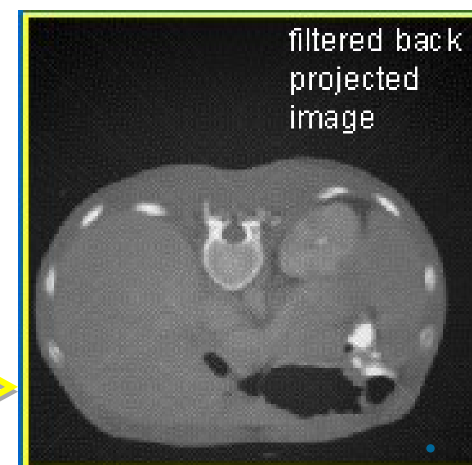
Filtered back projection

The image ghosting then disappears



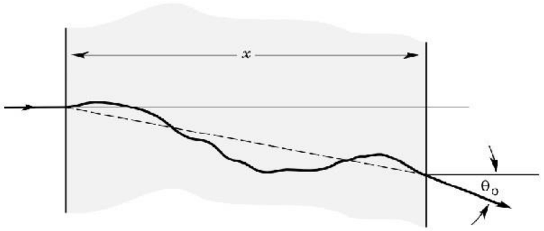


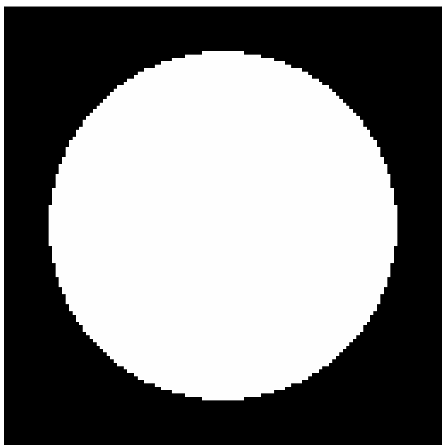




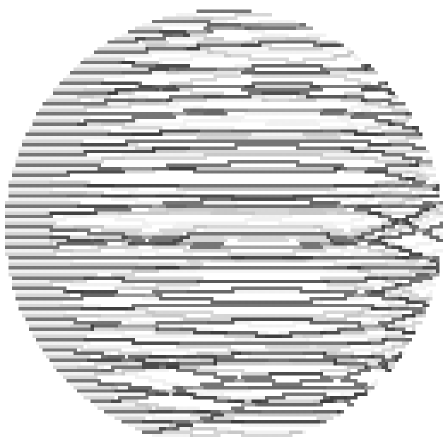
Proton CT filtered backprojection

The proton's path is not a straight line!!

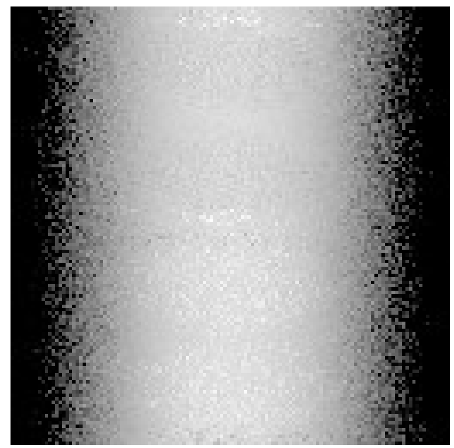




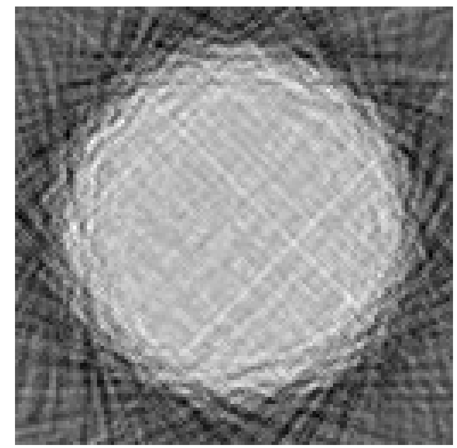
Object (O)



The proton tracks through O



Raw data projection (sinogram)



FBP reconstruction using straight path approach

Li, T. and J.Z. Liang. *Reconstruction with most likely trajectory for proton computed tomography*. SPIE proceedings, 2004

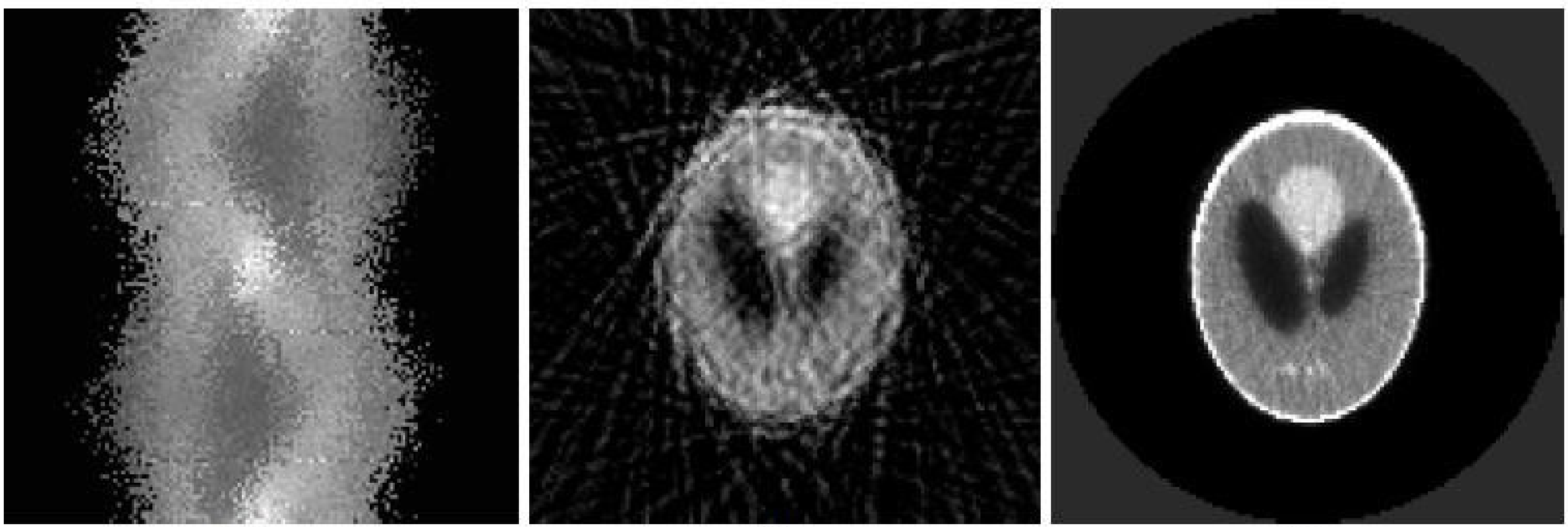
Going from straight lines to curved paths

Several possible steps to improve image quality

- Curved reconstruction using iterative reconstruction with priors such as noise models, constraints on stopping power, help from x-ray CT, etc…
- Perform filtering step after linear reconstruction

Reconstruction with most likely trajectory for proton computed tomography

Tianfang Li* and Jerome Liang
Department of Radiology, State University of New York, Stony Brook, NY 11794, USA



(a) (b) (c)

Fig. 10. (a) Analytical simulation of pCT sinogram using the Shepp-Logan phantom. (b) FBP reconstruction from sinogram (a). (c) Simultaneous ART reconstruction using MLTs from data (a).

Proton computed tomography reconstruction using a backprojection-then-filtering approach

G Poludniowski[1,3], N M Allinson[2] and P M Evans[1]

[1] Centre for Vision Speech and Signal Processing, University of Surrey, Guildford, GU2 7XH, UK
[2] Laboratory of Vision Engineering, School of Computer Science, University of Lincoln, Brayford Pool, Lincoln, LN6 7TS, UK

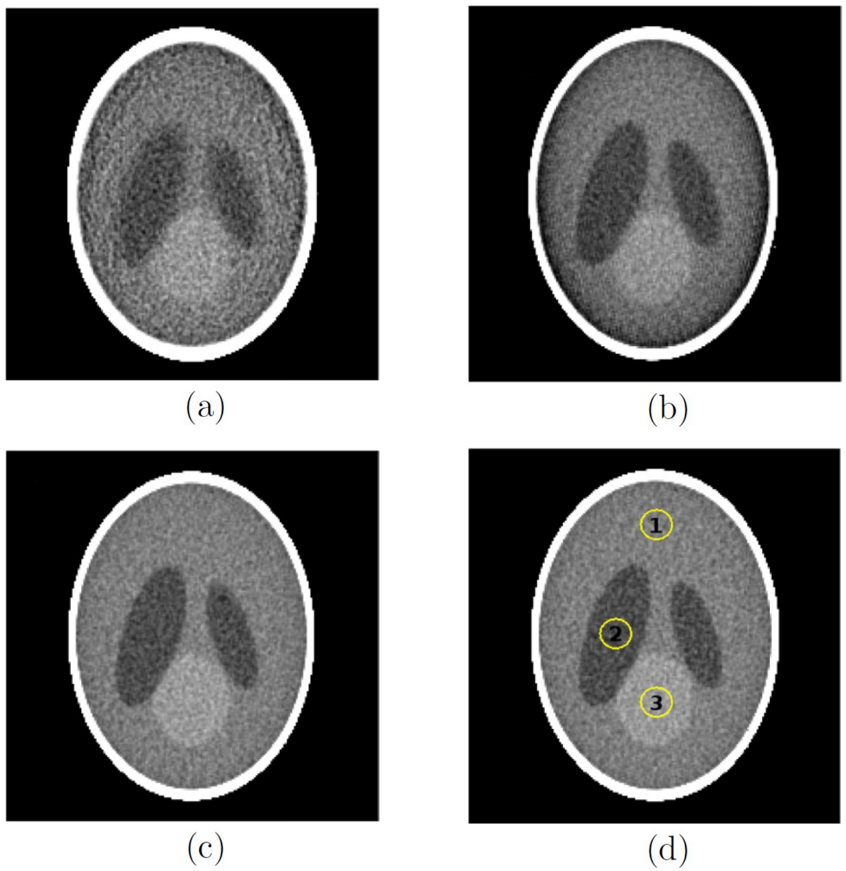


Figure 4. A transverse slice ($z = 2.0$ cm, 1.0 mm voxels, Gaussian filter) reconstructed by (*a*) SFBP, (*b*) BPF (0-knot), (*c*) BPF (2-knot) and (*d*) BPF (9-knot) methods.

Improved proton computed tomography by dual modality image reconstruction

David C. Hansen[a)]
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Jørgen Breede Baltzer Petersen
Medical Physics, Aarhus University Hospital, 8000 Aarhus C, Denmark

Niels Bassler
Experimental Clinical Oncology, Aarhus University, 8000 Aarhus C, Denmark

Thomas Sangild Sørensen
Computer Science, Aarhus University, 8000 Aarhus C, Denmark and Clinical Medicine, Aarhus University, 8200 Aarhus N, Denmark

$$\min_{\mathbf{u}} \alpha \left(\| W(\mathbf{u} - \mathbf{u}_p) \|_2^2 + \| \mathrm{TV}(\mathbf{u}) \|_1 \right) + \| A\mathbf{u} - \mathbf{f} \|_2^2,$$

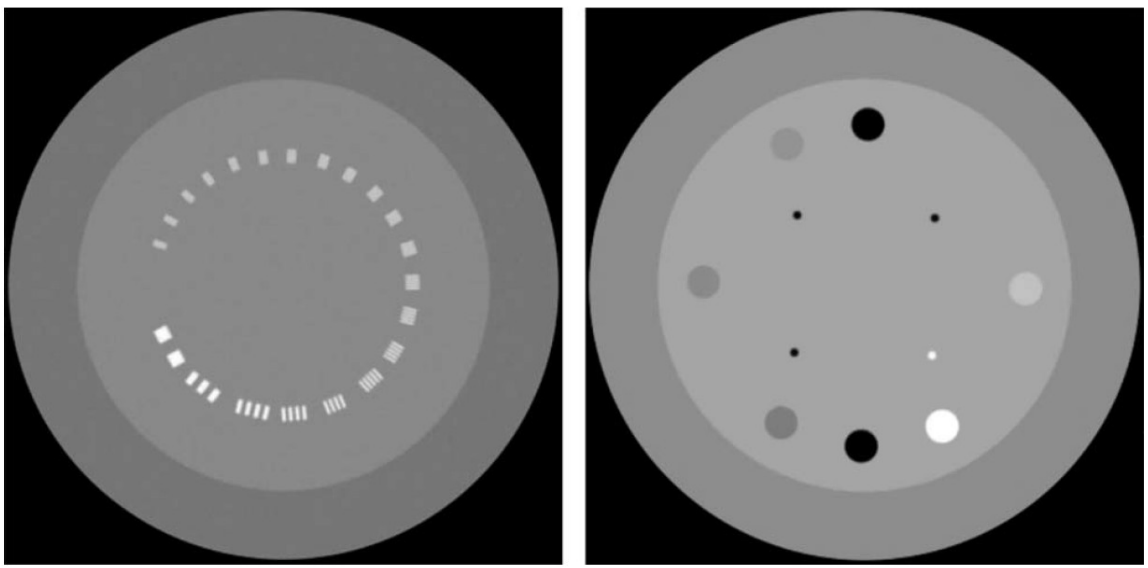

FIG. 2. Fully sampled DMR image of the CPT528 resolution section (left) and CPT404) density section (right).

$$\min_{\mathbf{u}} \alpha \left(\| W(\mathbf{u} - \mathbf{u}_p)\|_2^2 + \|\mathrm{TV}(\mathbf{u})\|_1 \right) + \| A\mathbf{u} - \mathbf{f}\|_2^2,$$

Minimize distance between error-weighed x-ray CT and reconstructed image u

Reconstruction term: f is projection data, u is reconstructed image and A is the linear transform between them

Noise term: Ensure that solution is stable in (x,y) and iteration number

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2010

Image reconstruction and Monte Carlo simulations in the development of proton computed tomography for applications in proton radiation therapy

Scott Nicholas Penfold
University of Wollongong

Software for proton CT image reconstruction

To perform the reconstructions listed above:

1. Implement the mathematics outlined in a number of publications
2. Use reconstruction software
    1. ART-based C++ from CREATIS / Lyon (Available to us now)
    2. GPU-accelerated iterative reconstruction from Aarhus
    3. Loma Linda code (available if we ask)

Status today – image reconstruction

1. In FOCAL and its next optimized MC based versions, we are able to estimate the vectors at the calorimeter face and the remaining proton energies
2. We need to add a front tracker, as well as a method for connecting proton paths
   - To first order this can be done easily using MC truth
3. Then add phantom before calorimeter and perform simulations at different angles (both easy using GATE)
4. Extract pre- and post-phantom vectors and energy loss
5. Install any of the available ready-made reconstruction packages
6. Give ROOT file to the software: Images