Proton Computed Tomography

Sam Manger

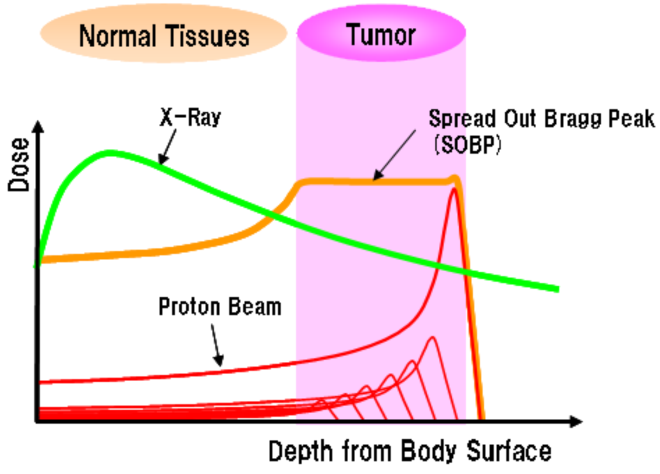
On Behalf of PRaVDA

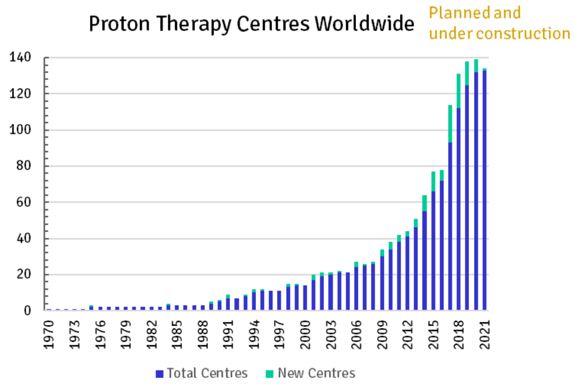
Aim of Talk

- Introduce proton therapy
- Introduce proton computed tomography (pCT)
- The need for pCT
- PRaVDA and the story so far
- My own work developing a phantom for use with PRaVDA

Proton Therapy

- Type of radiotherapy using protons
- Energy loss of protons described by Bethe-Bloch formula
- Leads to characteristic Bragg peak, where range is determined by beam energy
- Lots of dose deposited at target, minimal entry dose, no exit dose
- In theory, lower integral dose to patient
- Beam of 230 MeV has range of around 41 cm in water





Data taken from http://www.ptcog.ch, updated March 2017

Limitations of Proton Therapy

- Uncertainty in the delivered proton range in-vivo is ~ 3%
- Biggest source is from conversion of x-ray HU to proton stopping powers
- Stopping powers are calculated using tabulated I-values, which are also subject to uncertainty

IOP Publishing — Physics in Medicine and Biology
Phys. Med. Biol. 57 (2012) R99–R117 — doi:10.1088/0031-9155/57/11/R99

TOPICAL REVIEW

Range uncertainties in proton therapy and the role of Monte Carlo simulations

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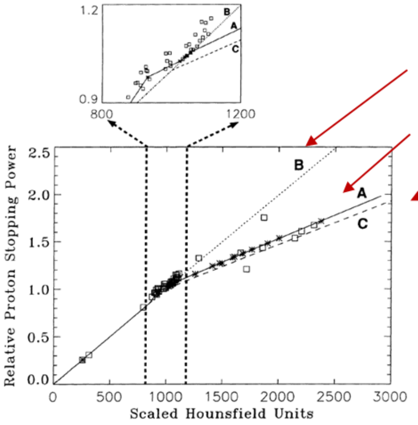
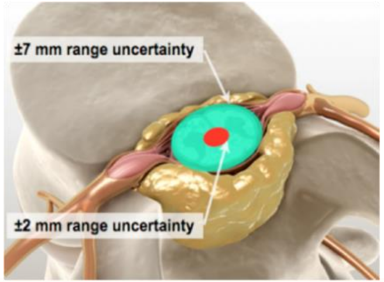
Source of range uncertainty in the patient	Range uncertainty without Monte Carlo	Range uncertainty with Monte Carlo
Independent of dose calculation		
Measurement uncertainty in water for commissioning	±0.3 mm	±0.3 mm
Compensator design	±0.2 mm	±0.2 mm
Beam reproducibility	±0.2 mm	±0.2 mm
Patient setup	±0.7 mm	±0.7 mm
Dose calculation		
Biology (always positive) ˆ	+~0.8%	+~0.8%
CT imaging and calibration	±0.5% [a]	±0.5% [a]
CT conversion to tissue (excluding I-values)	±0.5% [b]	±0.2% [g]
CT grid size	±0.3% [c]	±0.3% [c]
Mean excitation energy (I-values) in tissues	±1.5% [d]	±1.5% [d]
Range degradation; complex inhomogeneities	−0.7% [e]	±0.1%
Range degradation; local lateral inhomogeneities *	±2.5% [f]	±0.1%
Total (excluding *, ˆ)	2.7% + 1.2 mm	2.4% + 1.2 mm
Total (excluding ˆ)	4.6% + 1.2 mm	2.4% + 1.2 mm

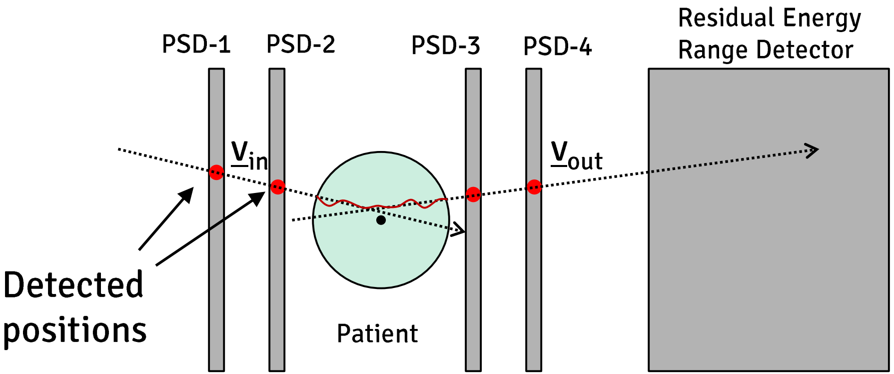


Choice of materials leads to different conversion curves being produced



A solution - Proton CT

- Proton CT directly measures stopping power in-vivo
- Trackers count each proton entering an exiting the patient
- “Range Telescope” (or RERD) measures residual energy
- Require 200 protons per voxel per projection
- 10^6 protons per projection for 10 cm^3 area



Schematic of ideal proton-tracking proton CT system

Redrawn from G Poludniowski, N M Allinson, and P M Evans The British Journal of Radiology 2015 88:1053

Who are PRaVDA?

PRaVDA

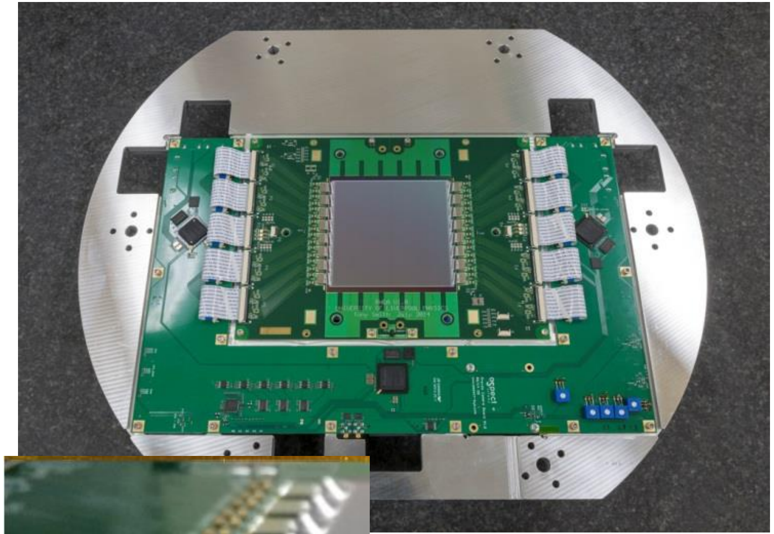
- PRaVDA – Proton RAdiotherapy Verification and Dosimetry Applications
- Team of researchers from 12 institutions and 2 industrial partners aiming to build the world's first solid-state proton CT device
- Supported by Wellcome Trust Translation Award Scheme, Grant 098285

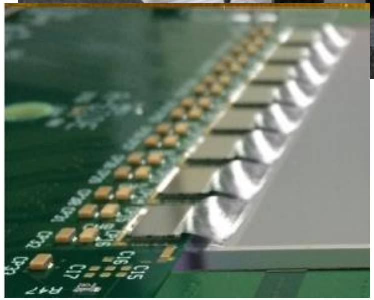
University of Lincoln
University of Birmingham
Warwick – The University of Warwick
University of Cape Town
aspect systems
Karolinska Institutet
University of Surrey
University of Liverpool
isdi – Image Sensor Design & Innovation
NRF – National Research Foundation
iThemba LABS – Laboratory for Accelerator Based Sciences
University Hospitals Birmingham NHS Foundation Trust
University Hospitals Coventry and Warwickshire NHS Trust
United Lincolnshire Hospitals NHS Trust
The Christie NHS Foundation Trust
wellcome

PRaVDA Technology – Strip Trackers

- Developed by University of Liverpool HEP group
- Manufactured by Micron Semiconductor
- Used to calculate input and output vectors of protons entering and exiting phantom
- 26 MHz readout cycle, triggered from cyclotron beam clock

  - Active area of 93x96 mm^2
  - 150 um thick n-in-p silicon
  - Strip pitch of 90.8 um
  - Strip length of 48 mm
  - 2048 strips, 1024 read out from each side
  - 16 ASICs (8 for each strip half)
  - Double threshold binary readout

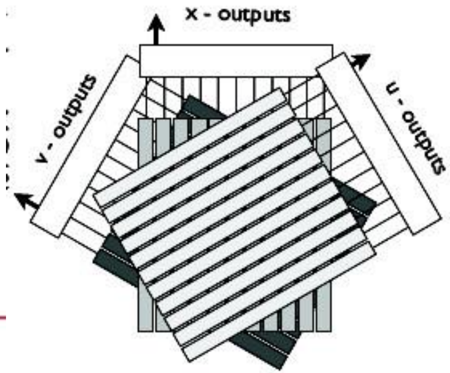


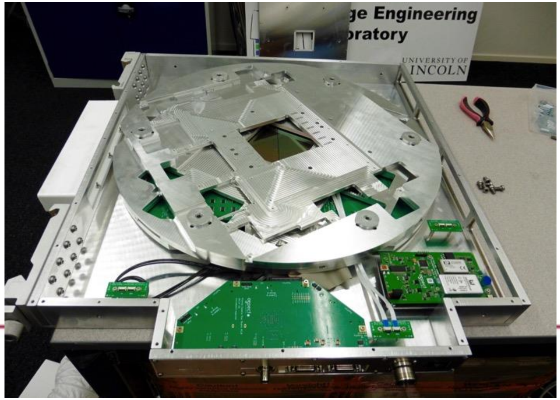


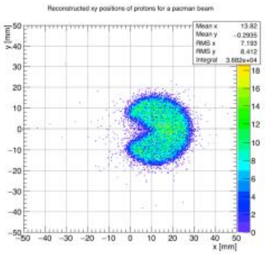
Module construction and wire bonding joint effort between Liverpool and new University of Birmingham BILPA lab

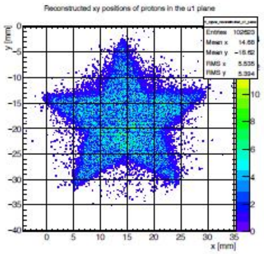
x-u-v Orientation

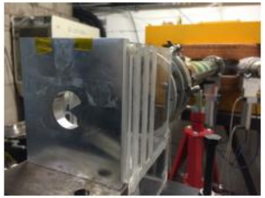
- Each tracking unit consists of 3 strip sensors, rotated at 60 degrees to each other
- The x-u-v orientation reduces ambiguities and allows for higher occupancies in the trackers
- Published Patent WO2015/189601







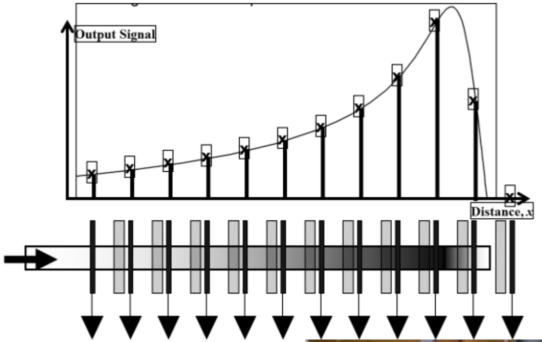




PRaVDA Technology – Range Telescope

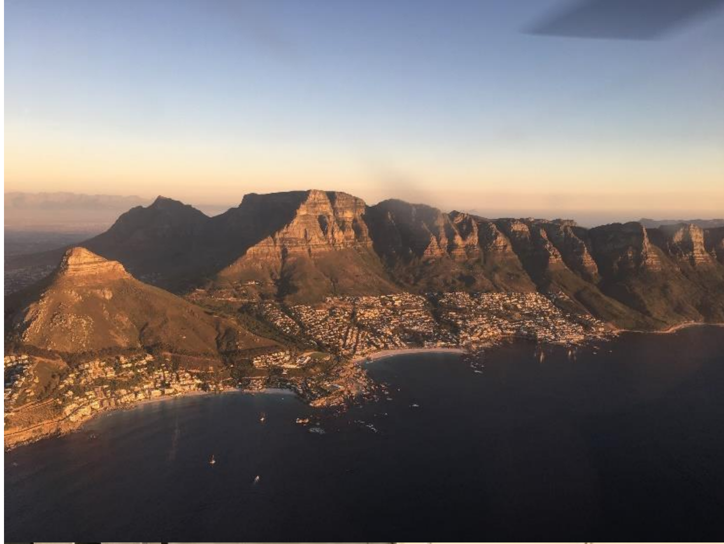
- Range telescope uses silicon strips interleaved with Perspex absorbers to measure residual range of protons

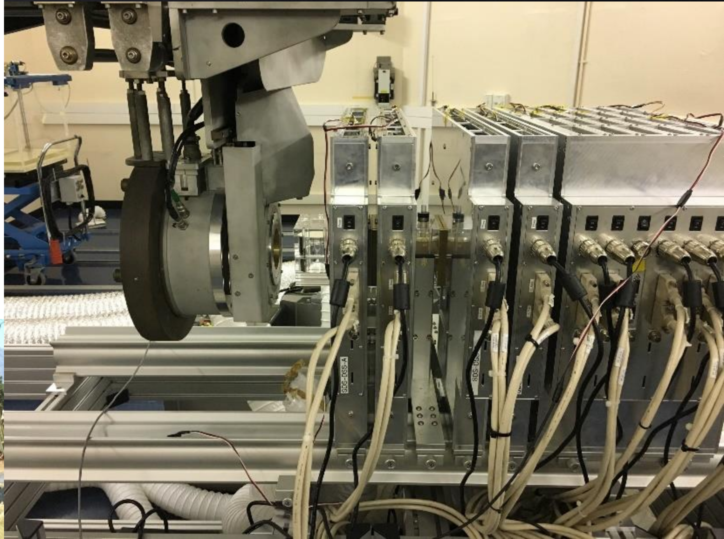
- Proton track length in RT is the matched with hits in trackers to allow backprojection and image reconstruction



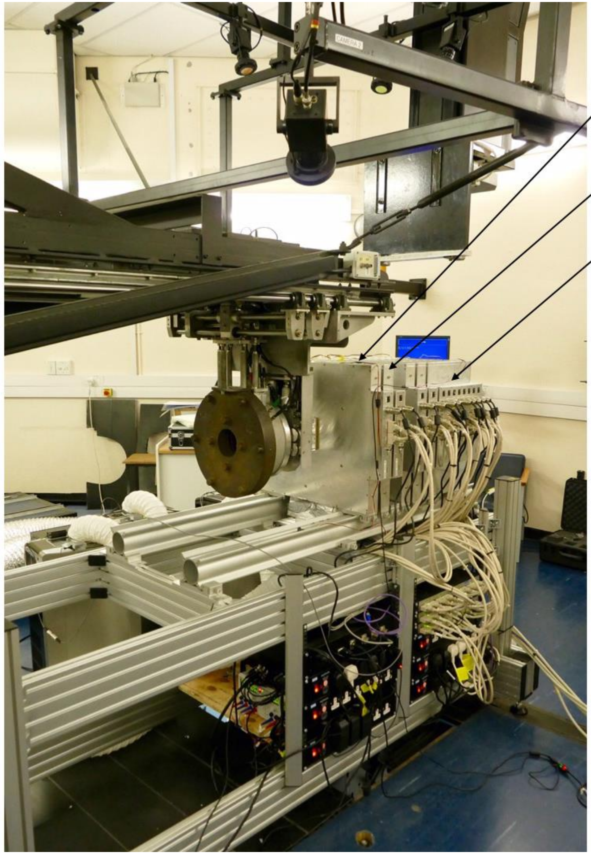
iThemba LABS November 2016

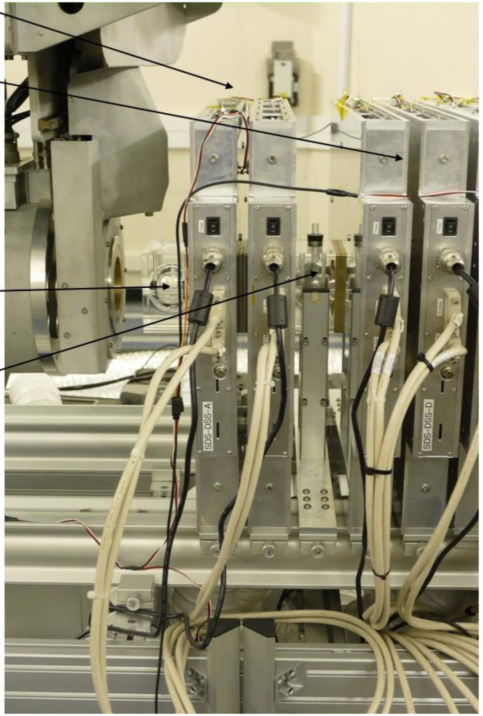
- No suitable test beams in the UK (yet)
- We were hosted by iThemba LABS, South Africa
- Cyclotron providing 192 MeV clinical proton beam
- Performed calibration of instrument and took several pCT scans
- 2 weekends of testing, 72 hour shifts
- Returned with ~10 Tb of data!





Installation in SA





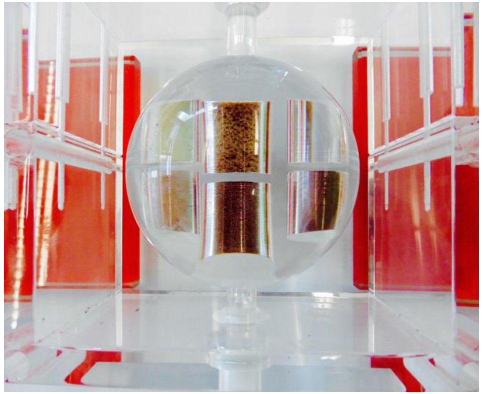
PRaVDA

@

NRF
National Research Foundation

iThemba LABS
Laboratory for Accelerator Based Sciences

Imaging Objects



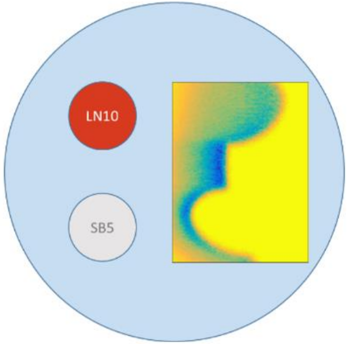
Perspex Phantom
High energy pCT (191 MeV)
Low energy pCT (125 MeV)

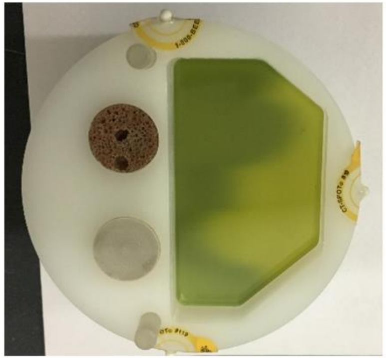
Film Phantom
High energy pCT (191 MeV)
Low energy pCT (125 MeV)
Treatment dose to film

Tissue/"Meat" Phantom
Low energy pCT (125 MeV)

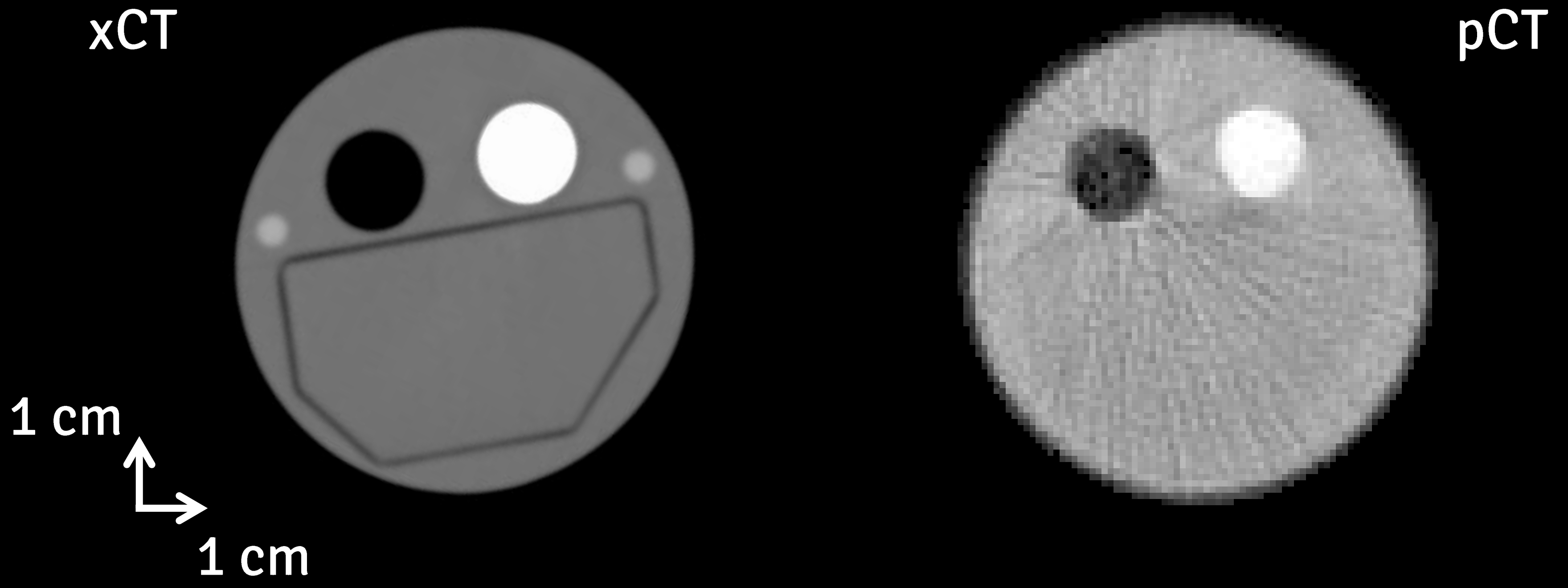
Film Phantom

- Designed and evaluated for use using GATE, a Geant4-based simulation framework
- Designed to be imaged with x-ray CT and proton CT
- Also “treated” with a proton beam
- Monte Carlo simulation to be performed on results from pCT and xCT images to evaluate stopping power measurements and compare to “real” experiment



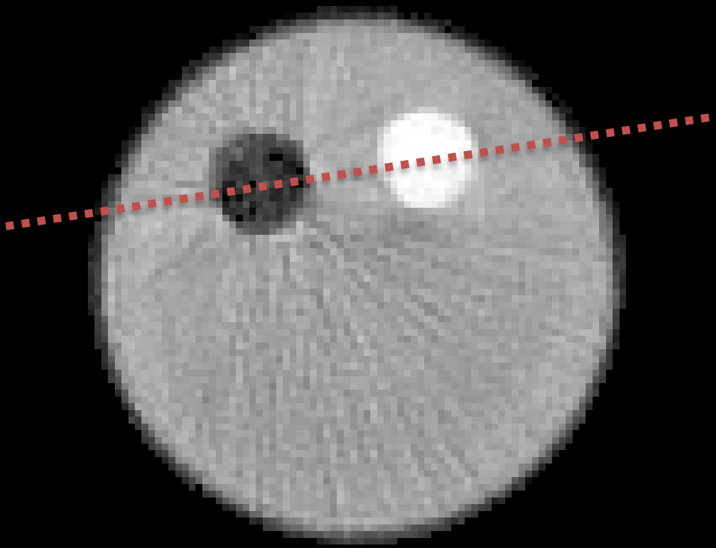


PRELIMINARY RESULTS

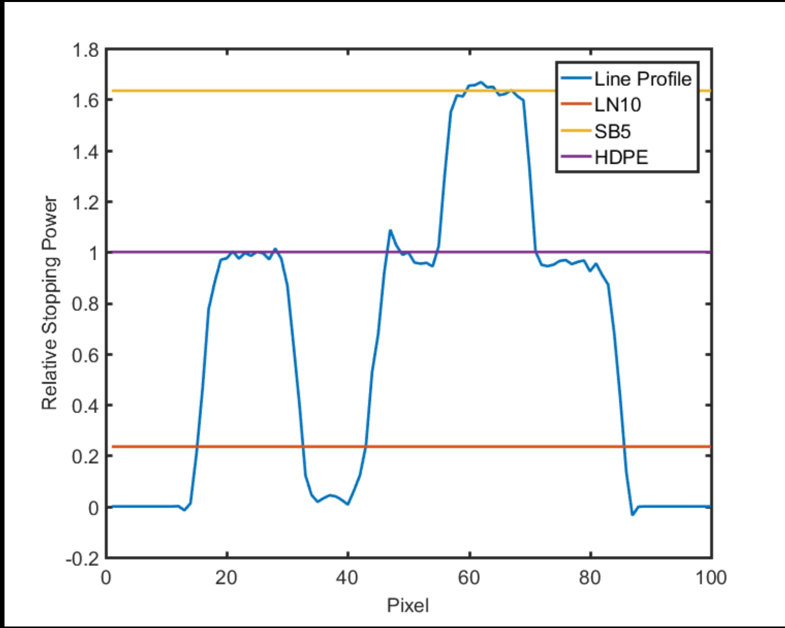


- First reconstruction completed, using 2m protons per angle
- A few streaky artefacts originating from the “lung” insert
- Air gap around the film insert is less visible – this is good as should be negligible

PRELIMINARY RESULTS



pCT



- Line profile through inserts shows good reconstruction of stopping powers through polyethylene body and “bone” insert
- “Lung” insert reconstruction is below expected value – under investigation

Future work (myself)

- Import voxelised geometries from xCT and pCT into simulation to perform Monte Carlo dose delivery
- Repeat experiment in silico with virtual anatomical phantom using validated pCT and xCT simulations

Future work (PRaVDA)

- Produce a spot-scanning proton CT scan
- Complete analysis of existing data from iThemba
  - Still a lot to make sense of and finalize!

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aSpect
Marcus Verhoeven
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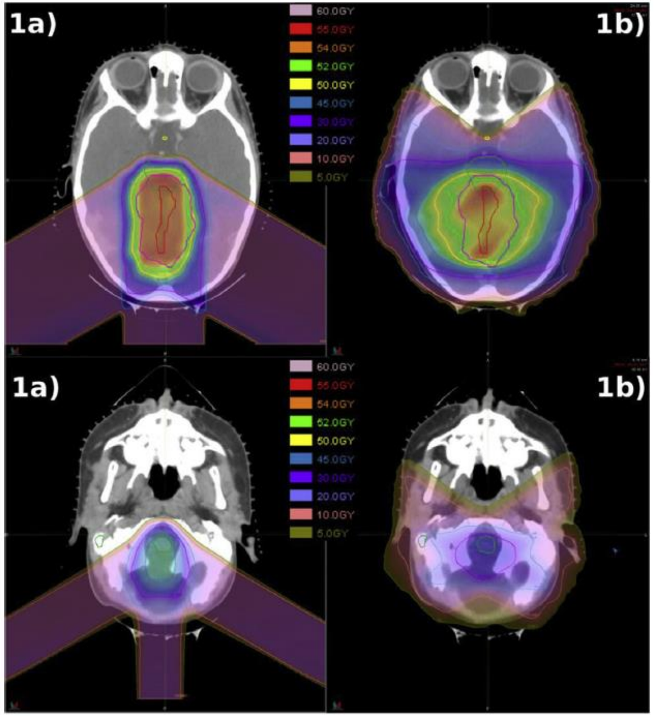
Questions?

Patient Benefits

- Finite range of proton beam promises lower integral dose delivered to patient
- Reduce damage to healthy tissues
- Particularly important for paediatric cancers
- Reduces late effects, second cancers
- Better quality of life



Dose distributions for a) 3-dimensional proton beam treatment and b) intensity-modulated x-ray radiotherapy. Target volume shown in purple. Proton beam plans demonstrate superior sparing of normal structures.

Jimenez, R. B. et al. *International Journal of Radiation Oncology Biology Physics, 87*(1), 120–126.

X-ray HU to SP Conversion

- X-ray CT scanner uses Hounsfield Units
- Hounsfield Units measure x-ray absorption relative to water, scaled such that HU_{water} = 1000 HU
- Stoichiometric conversion method parameterises the response of the x-ray CT scanner
- For material with known chemical compositions, theoretical HU and stopping powers are then calculated
- Piecewise fit used as conversion curve

$$HU \propto \rho_e(K^{ph}\tilde{Z}^{3.62} + K^{coh}\hat{Z}^{1.86} + K^{KN})$$

$$\hat{Z}^{1.86} = \sum \lambda_i Z_i^{1.86} \qquad \tilde{Z}^{3.62} = \sum \lambda_i Z^{3.62}$$

X-ray Absorption

$$RSP = \rho_{e,rel} \times \frac{\ln \frac{2m_ec^2\beta^2}{(1-\beta^2)I_{m,x}} - \beta^2}{\ln \frac{2m_ec^2\beta^2}{(1-\beta^2)I_{w,x}} - \beta^2}$$

Proton Stopping Power