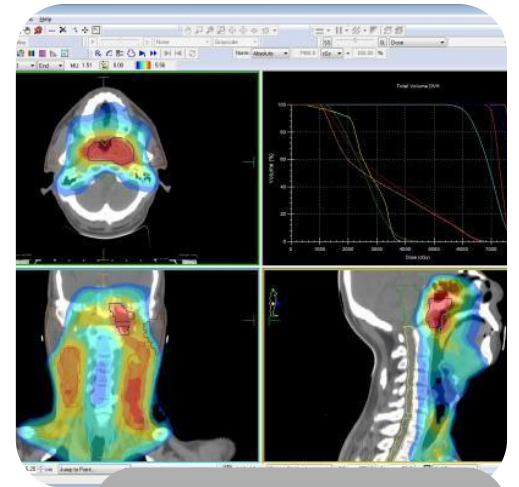
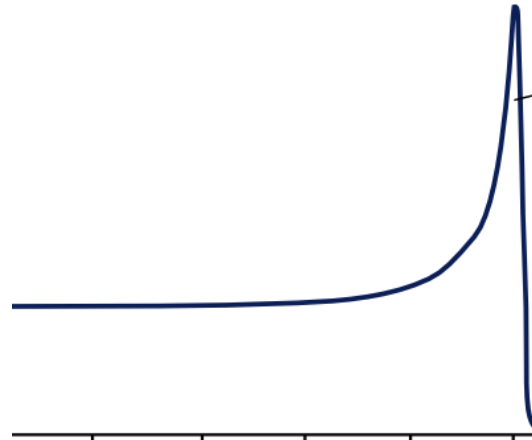
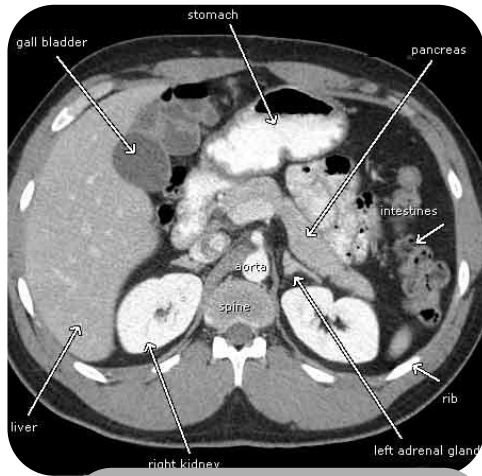


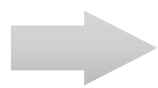
PRaVDA and OPTima: Solid-state proton CT systems

Michela Esposito
University of Lincoln

Why do we need proton CT?



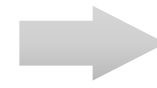
CT scan



Hounsfield units



Stopping power



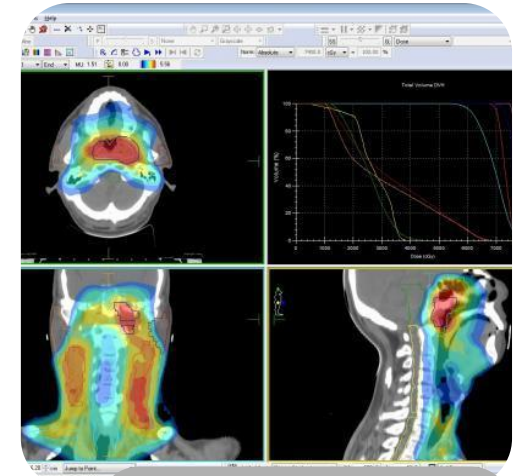
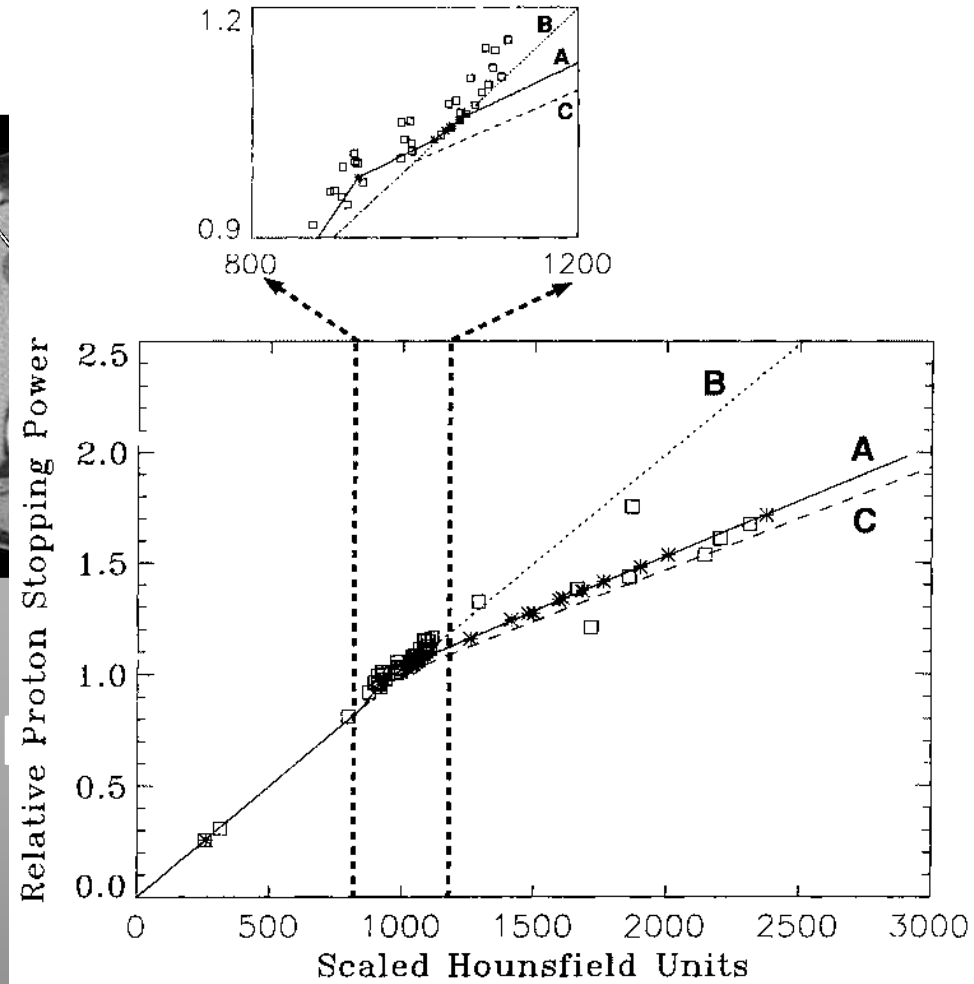
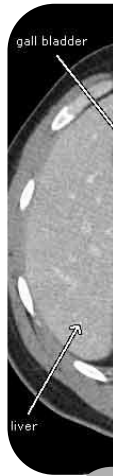
Treatment planning

Why do we need proton CT?

Stoichiometric calibration



CT scan

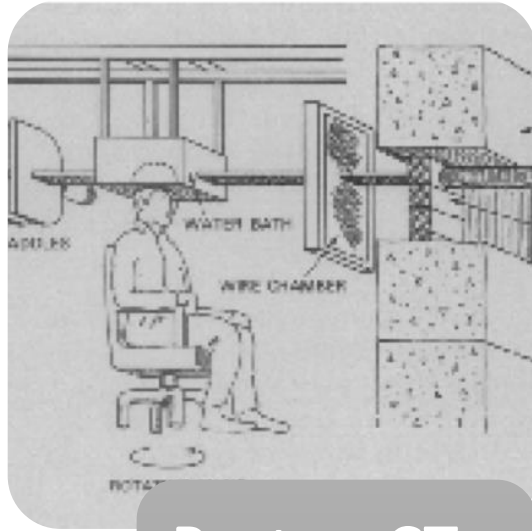


Treatment planning

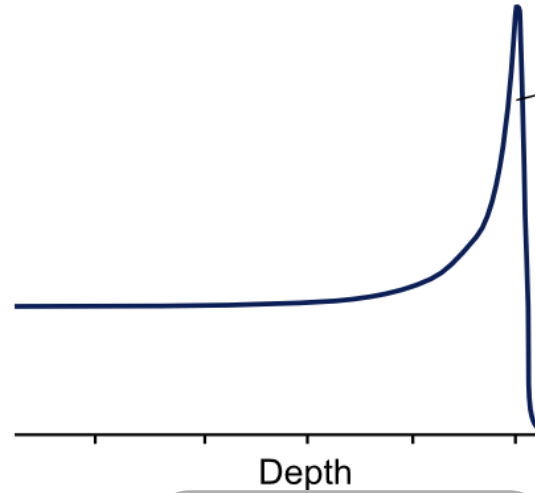
U. Schneider, Phys. Med. Biol. **41**
(1996) 111–124

Why do we need proton CT?

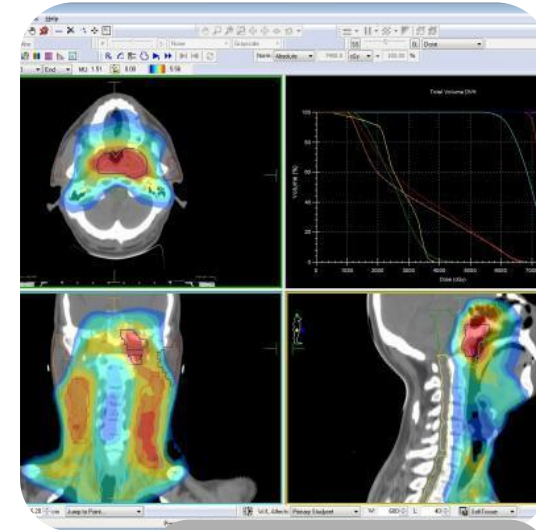
K.M. Crowe et al.. Axial Scanning with 900 MeV Alpha Particles.
Nuclear Science, IEEE Transactions on, 22(3):1752–1754, June 1975.



Proton CT scan

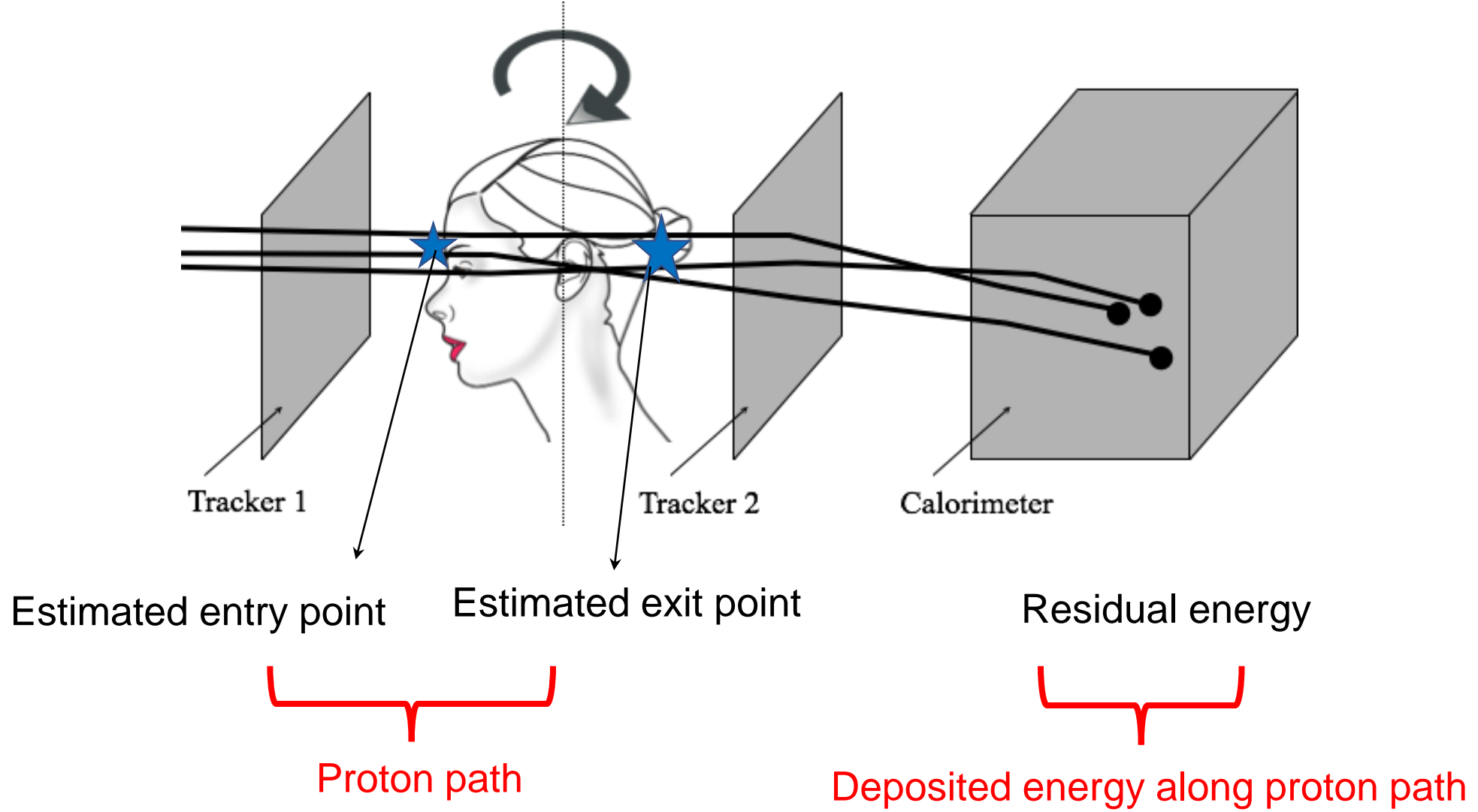


Stopping power

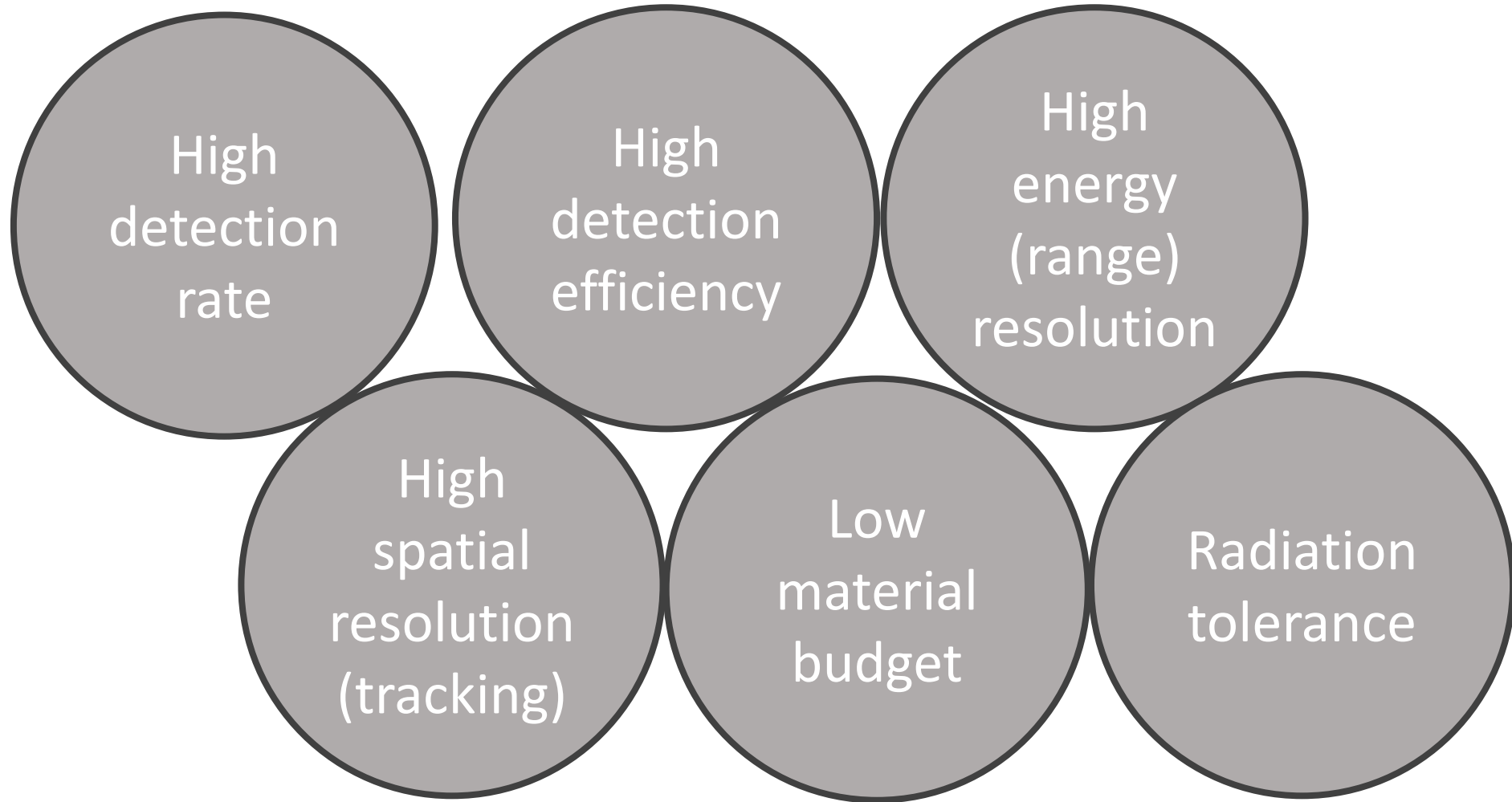


Treatment planning

How does proton CT work?



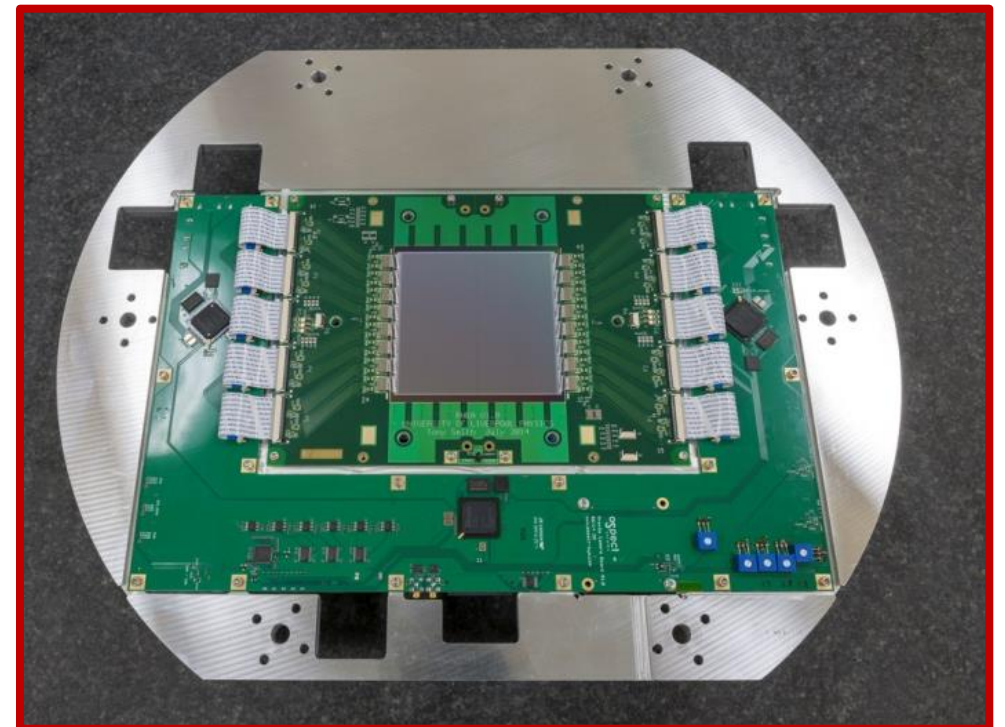
Detector requirements



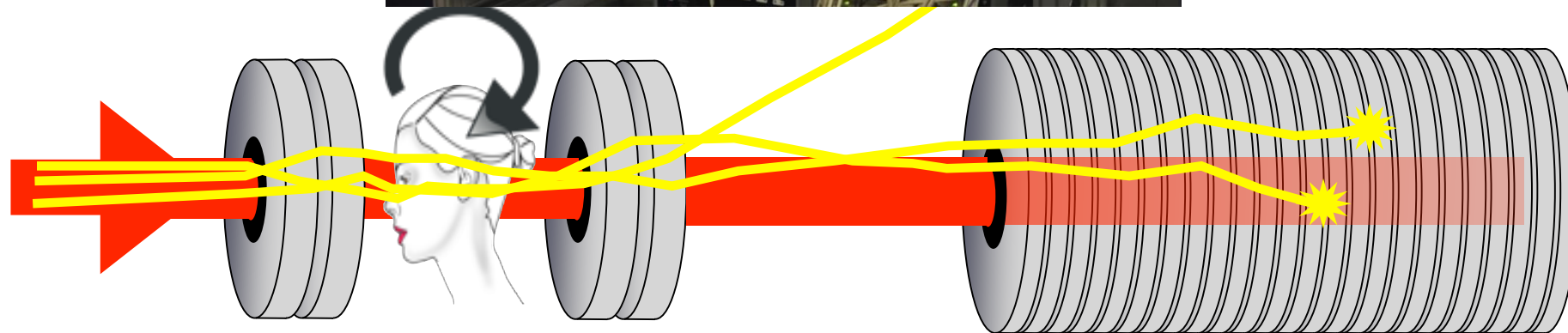
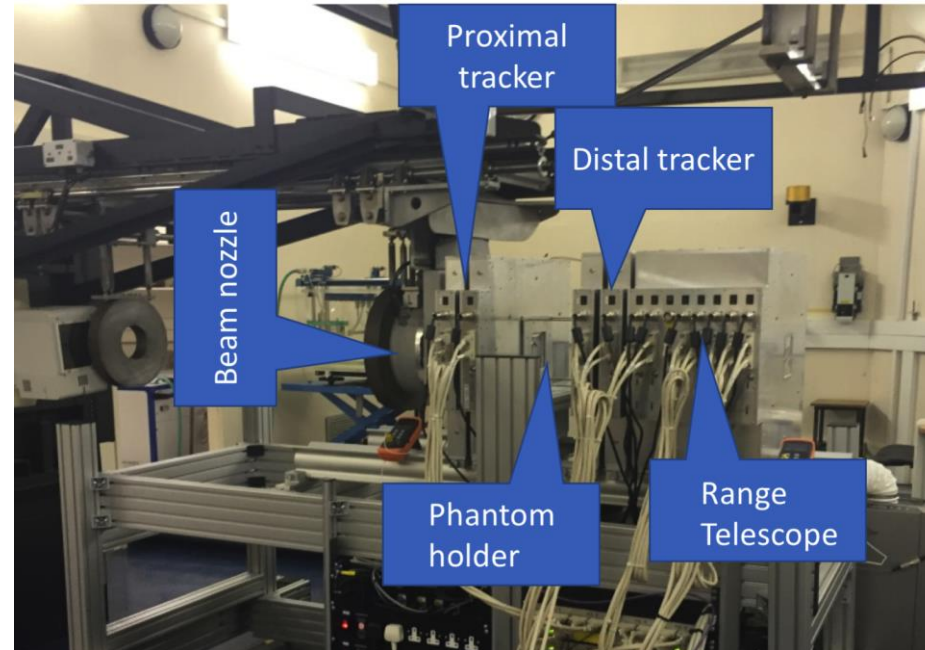
Proton Radiotherapy Verification and Dosimetry Applications

University of Lincoln
University of Birmingham
University of Liverpool
University of Surrey
University of Cape Town
University of Warwick
Karolinska University Hospital, Sweden
University Hospital Birmingham NHS Foundation Trust
University Hospital Coventry and Warwickshire NHS Trust
National Research Foundation (NRF) - iThemba LABS, SA
United Lincolnshire Hospitals NHS Trust
The Christie NHS Foundation Trust

ISDI: Image Sensor Design and Innovation Ltd
aSpect Systems GmbH
Elekta AB (Publ)
Advanced Oncotherapy Plc

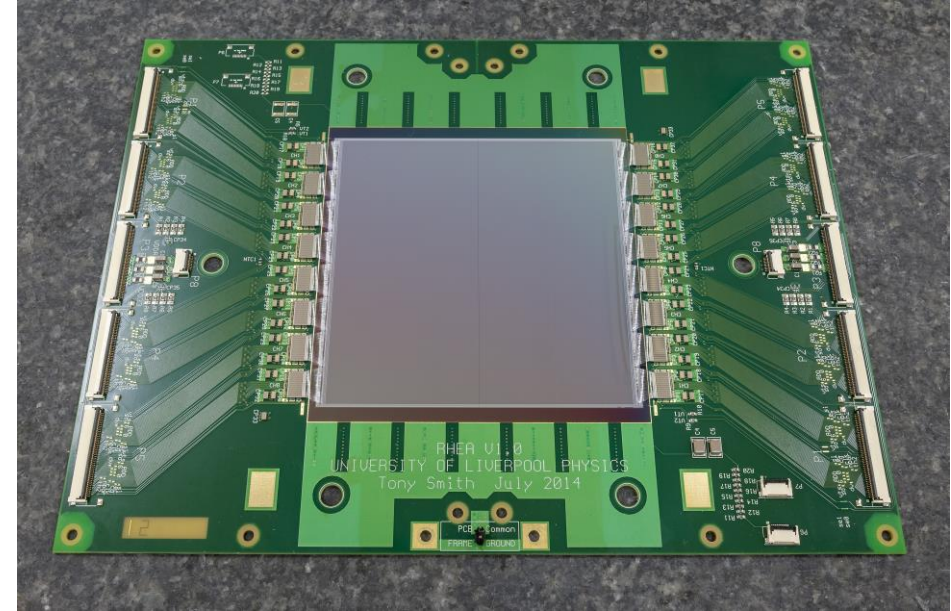


The PRaVDA proton CT imaging system



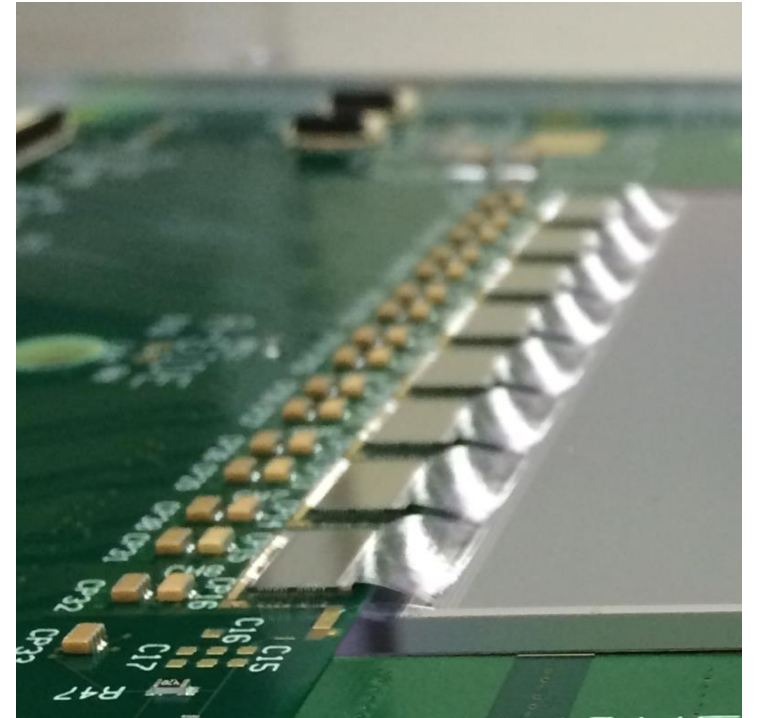
Silicon Strip Sensors

- 150 μm thick *n-in-p* Si
- 93×96 mm²
- 90.8 mm pitch
- 2048 strips
- Developed for the ATLAS experiment at High Luminosity LHC
- Designed by the University of Liverpool and fabricated by Micron Semiconductor Ltd
- Sensor QA carried out in Liverpool Semiconductor Detector Centre
- Wire-bonding and hybrid assembly carried out at Liverpool and Birmingham



RHEA (Rapid High-speed Extended ASIC)

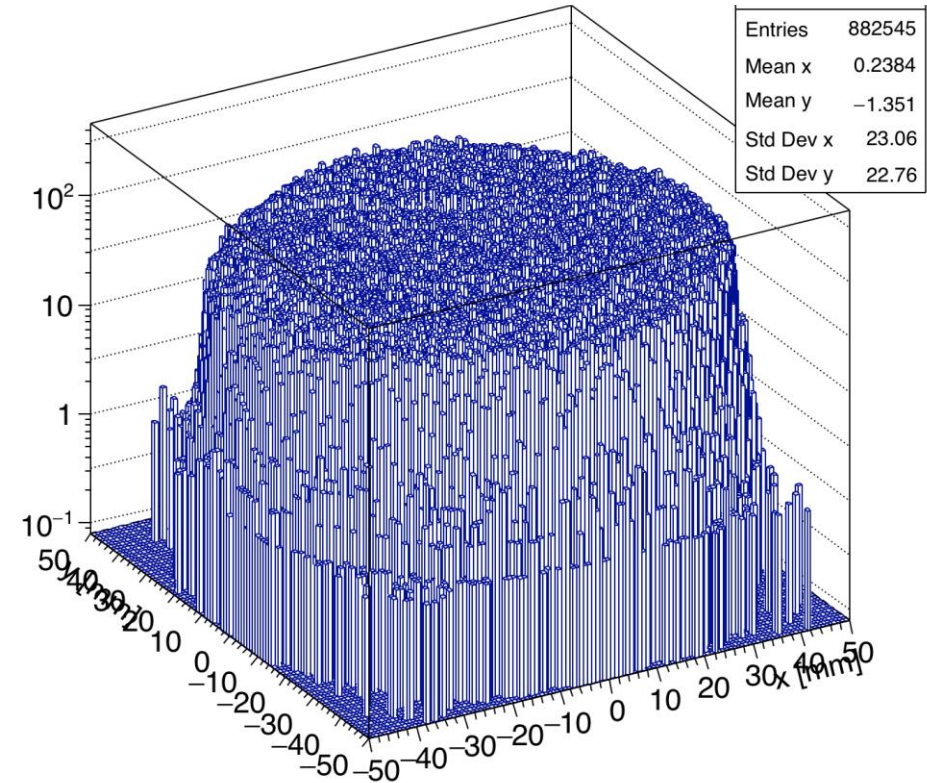
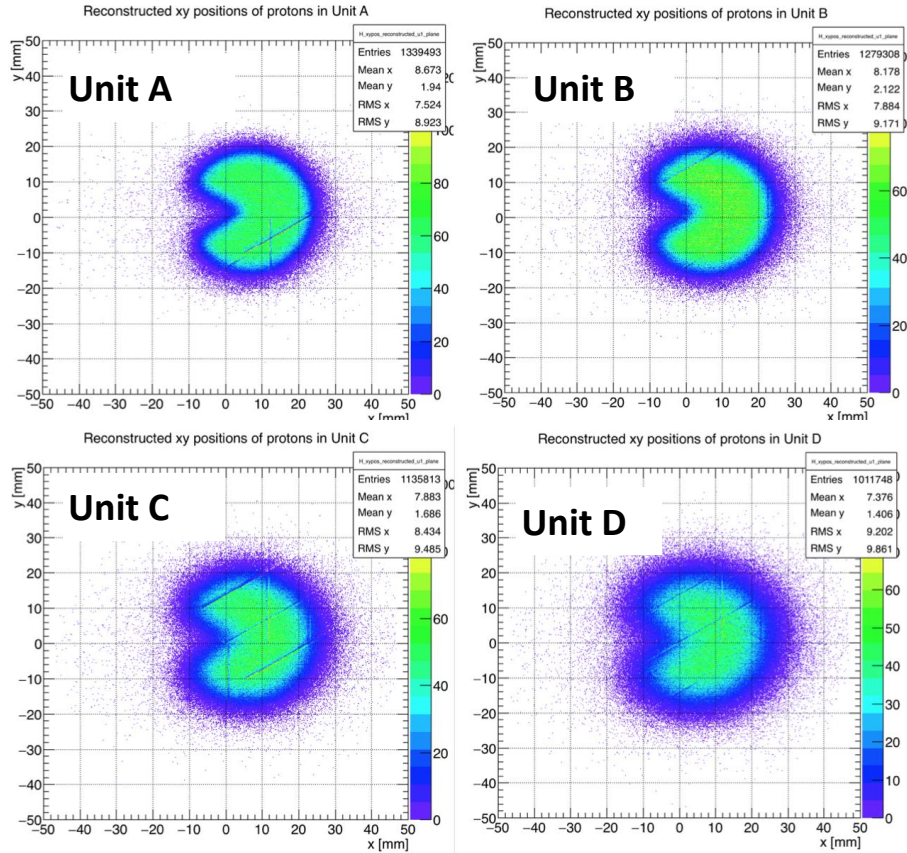
- 2048 channels readout by 16 custom ASICs (128 channels per ASIC)
- Designed by ISDI Ltd
- 0.18 μm CMOS process
- Binary chip
- 2 tunable thresholds:
 - Low threshold \rightarrow noise rejection
 - High threshold \rightarrow multiple hits
- 26 MHz readout
- Up to 8 channel readout per R/O cycle per ASIC
- Maximum fluence = 2×10^8 protons/s over full imaging area



Trackers commissioning

36 MeV protons, MC40 cyclotron,
University of Birmingham

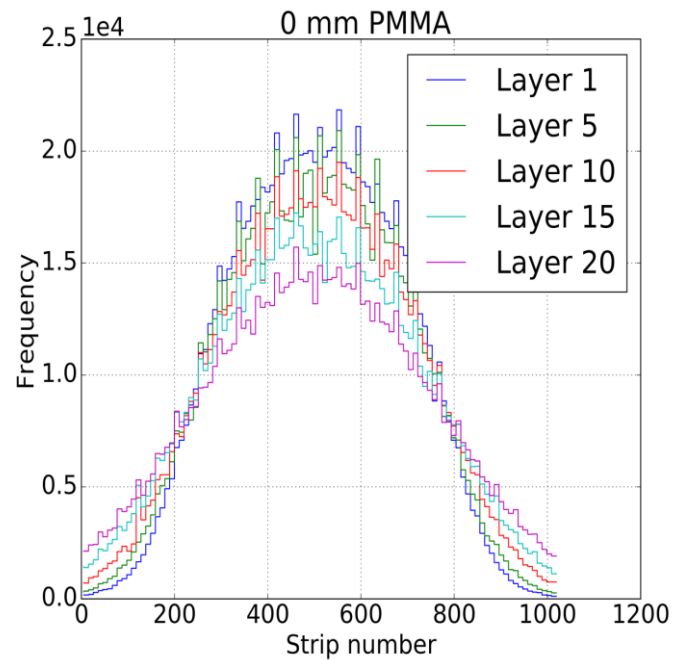
85 mm passively scattered beam, 125 MeV
protons, iThemba LABS



Data and analysis by Jon Taylor, University of Liverpool

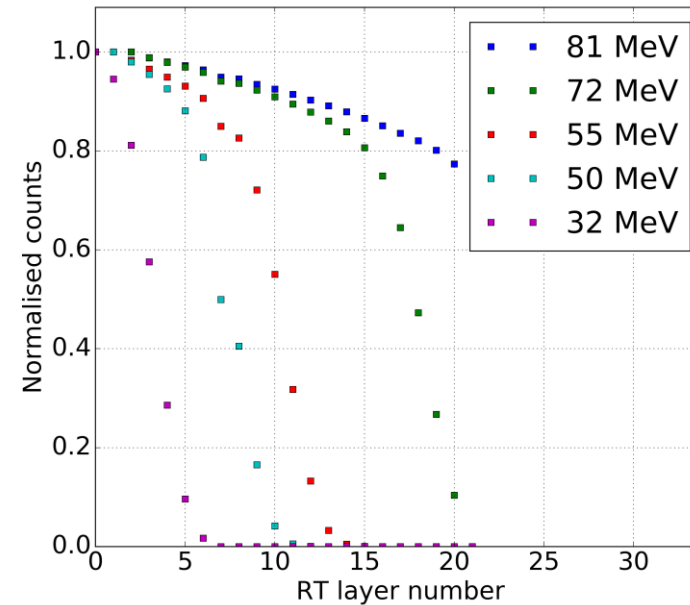
Range telescope commissioning

MC40 cyclotron,
University of Birmingham



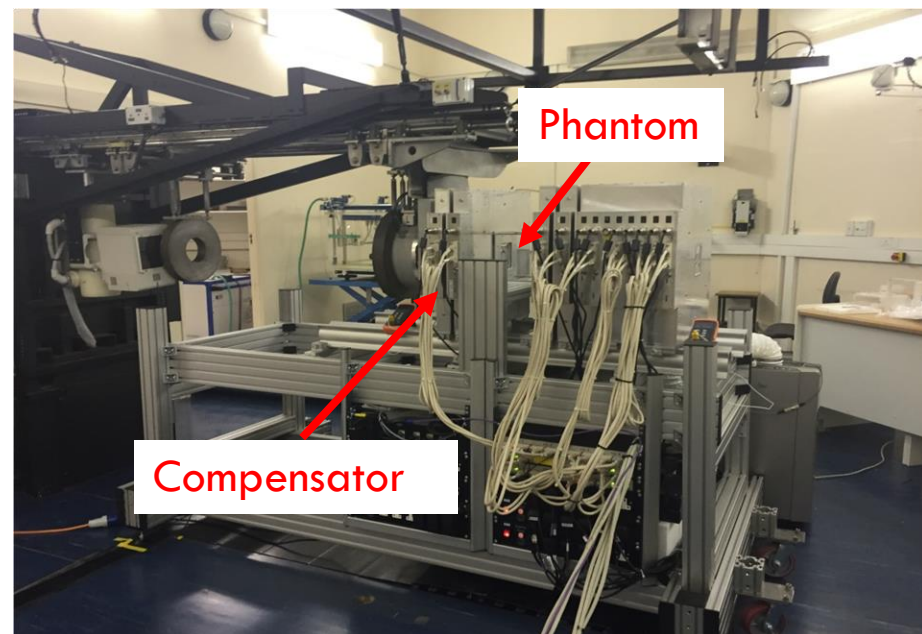
1D beam profile of 36 MeV p
through the RT

125 MeV protons degraded to 81-32 MeV
by PMMA absorbers, iThemba LABS



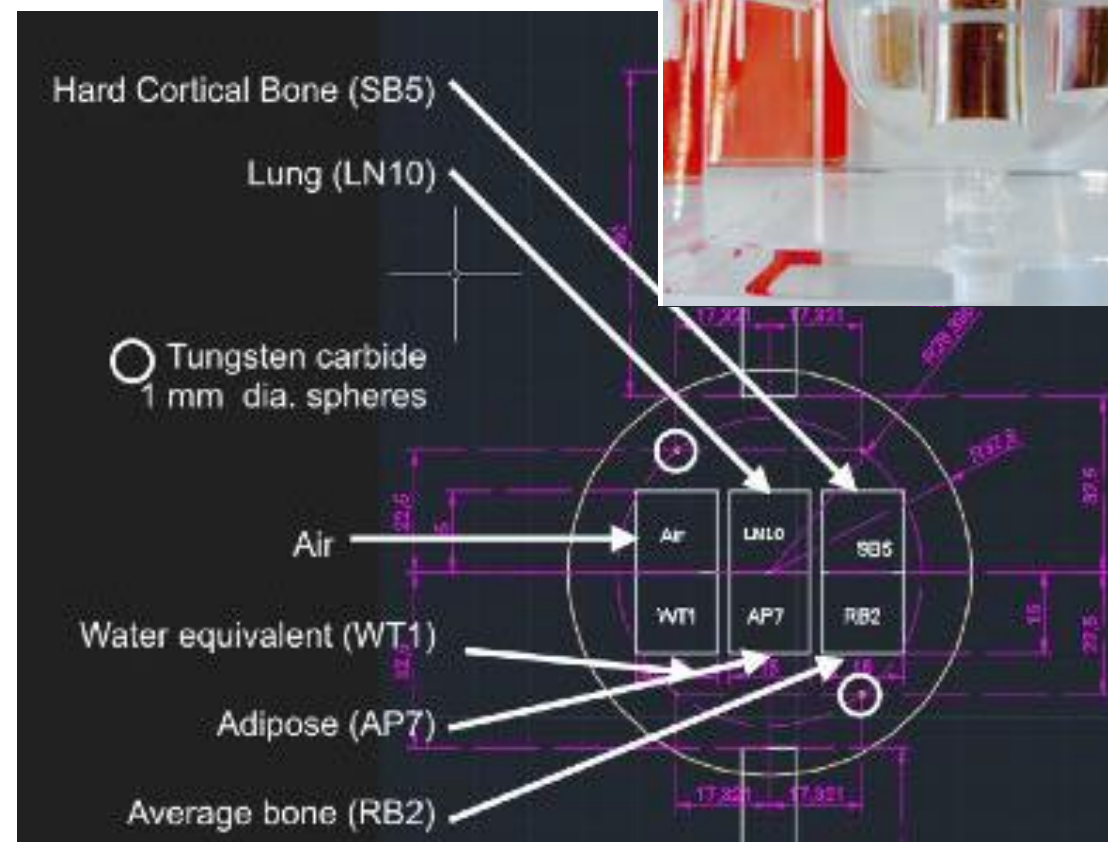
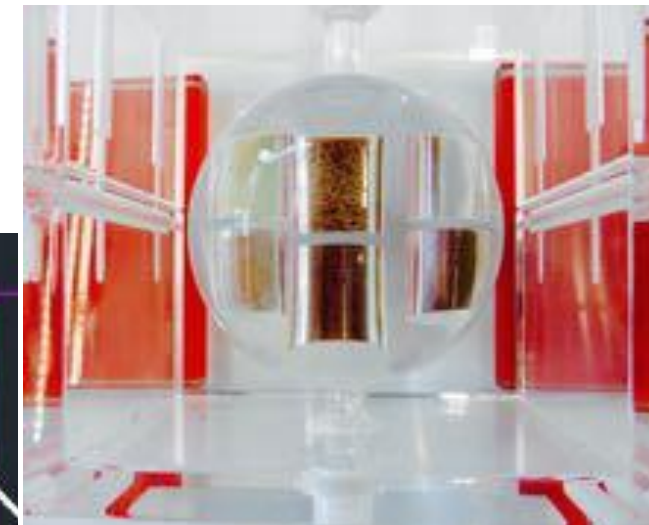
Fluence-depth curves

Proton CT: set up

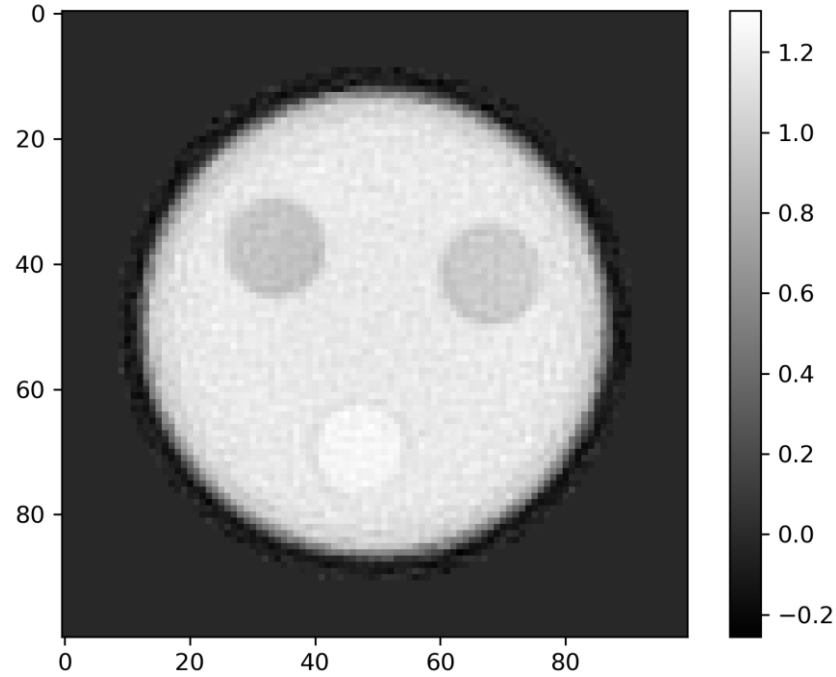


- iThemba LABS cyclotron
- $E_{MLFC} = 198.741$ MeV
- $R_{50} = 117.7$ mm (graphite wedges)
- 8.5 \varnothing cm collimator
- 500pA
- 180 projections over 360 deg
- $\sim 2.8 \times 10^8$ proton tracks

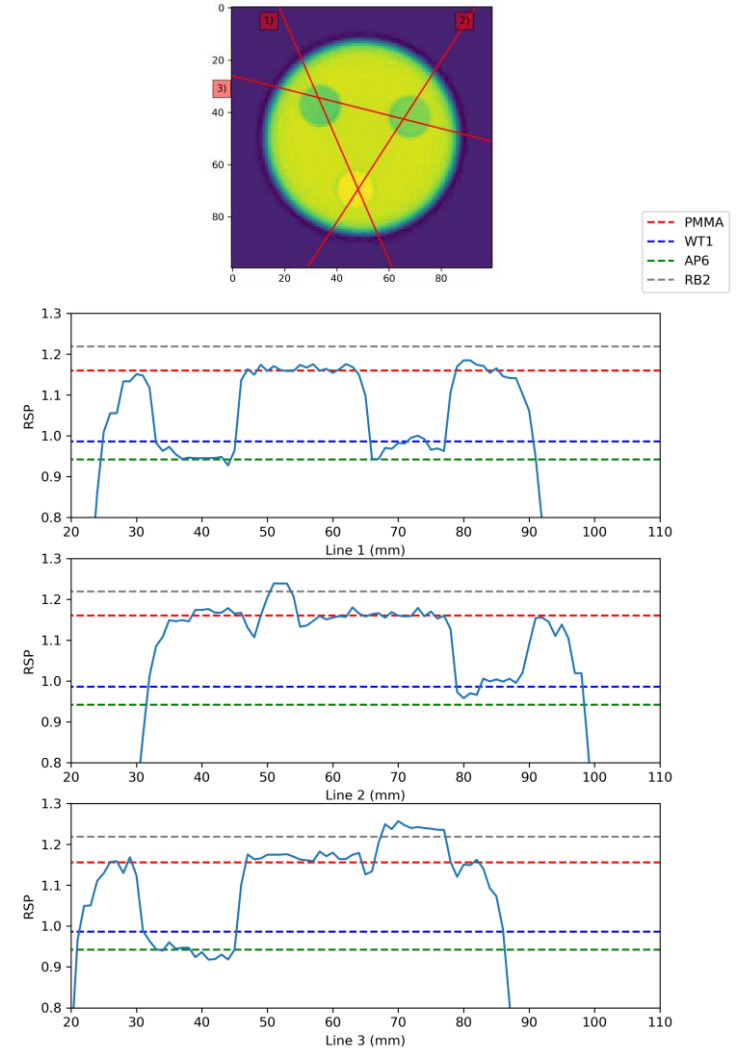
Phantom 75 mm \varnothing
Inserts 15 mm \varnothing



Proton CT: results

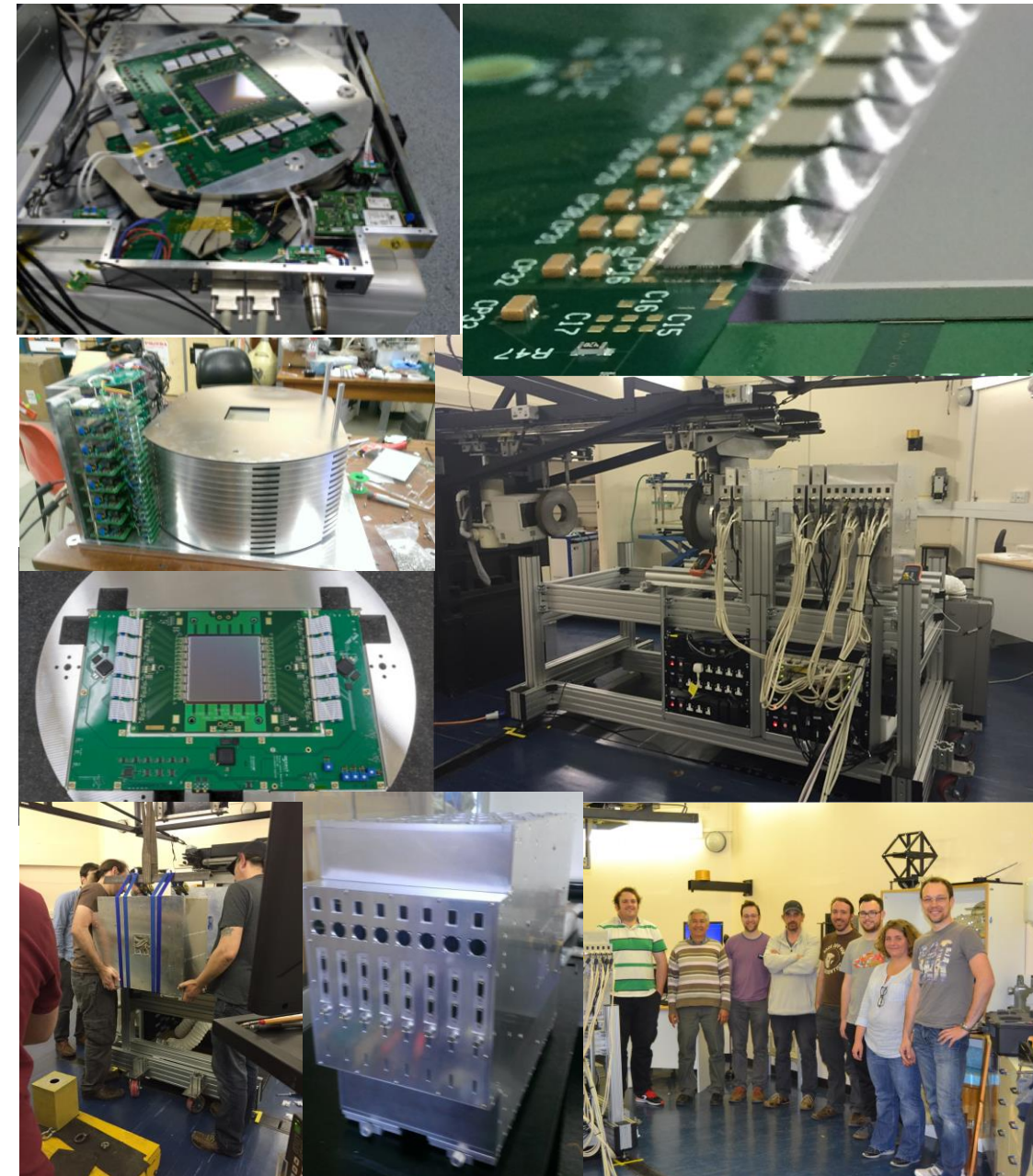


Material	Expected RSP	pCT RSP	RSP Accuracy (%)
Adipose (AP7)	0.943	0.943	-0.02
Average bone (RB2)	1.219	1.237	1.5
Water (WT1)	0.986	0.983	0.7
PMMA	1.156	1.161	0.4



Summary

- First solid state system for proton CT
- 33 layers of Silicon Strip Sensors
- 67584 channels
- 26 MHz readout
- 66 Gb/s max data rate
- Capability to detect up to 2×10^8 protons/s over the full imaging area
- Ability to track multiple protons per readout cycle
- Early pCT results: RSP uncertainty $< 1.5\%$



OPTiⁱma

Optimising Proton Therapy through Imaging

4 years to:

- Develop a pCT for spot scanning systems
- Combine different imaging modalities (x-ray CT, PET, etc)
- Provide a facility for phantom calibration
- Integrate pCT in the clinical workflow
- Develop proton imaging for gantry systems

University of Lincoln

University of Manchester

Christie NHS Foundation Trust

University of Birmingham

University Hospitals Birmingham

Univ Hosp Coventry & Warwick NHS Trust

University of Surrey

EPSRC

Spot scanning beams

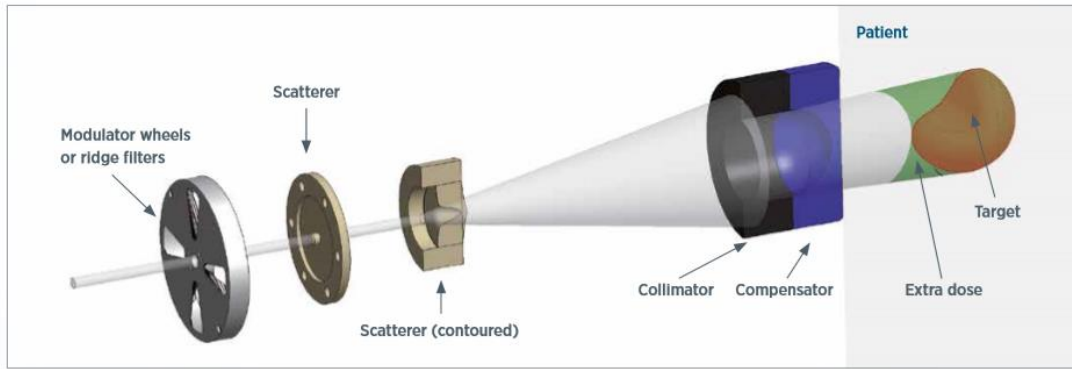


Figure 1: Scattering diagram

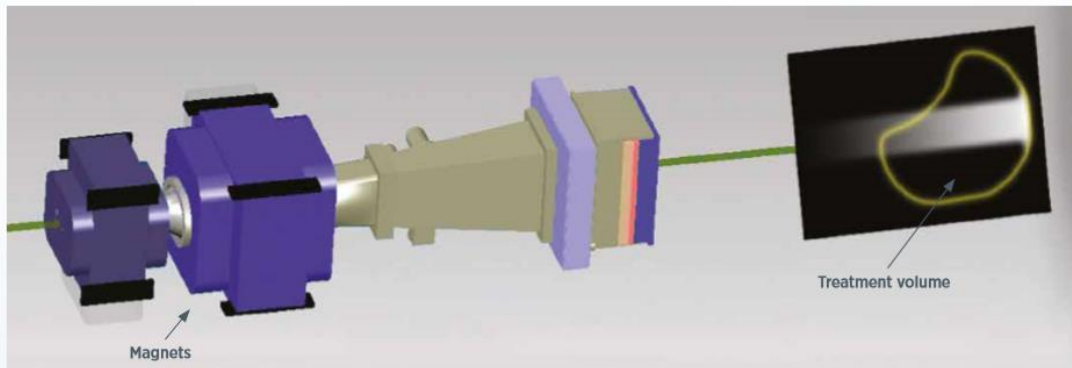
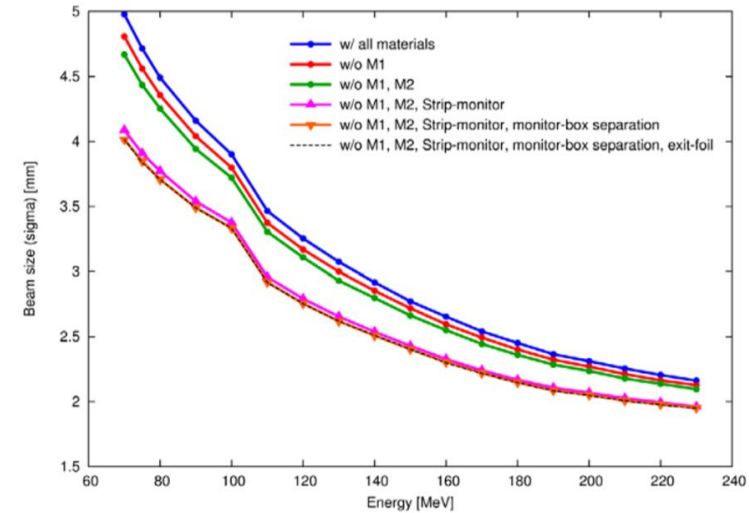


Figure 2: Scanning diagram

Image courtesy of Varian



E. Pedroni et. al., *Eur. Phys. J. Plus* (2011) 126: 66

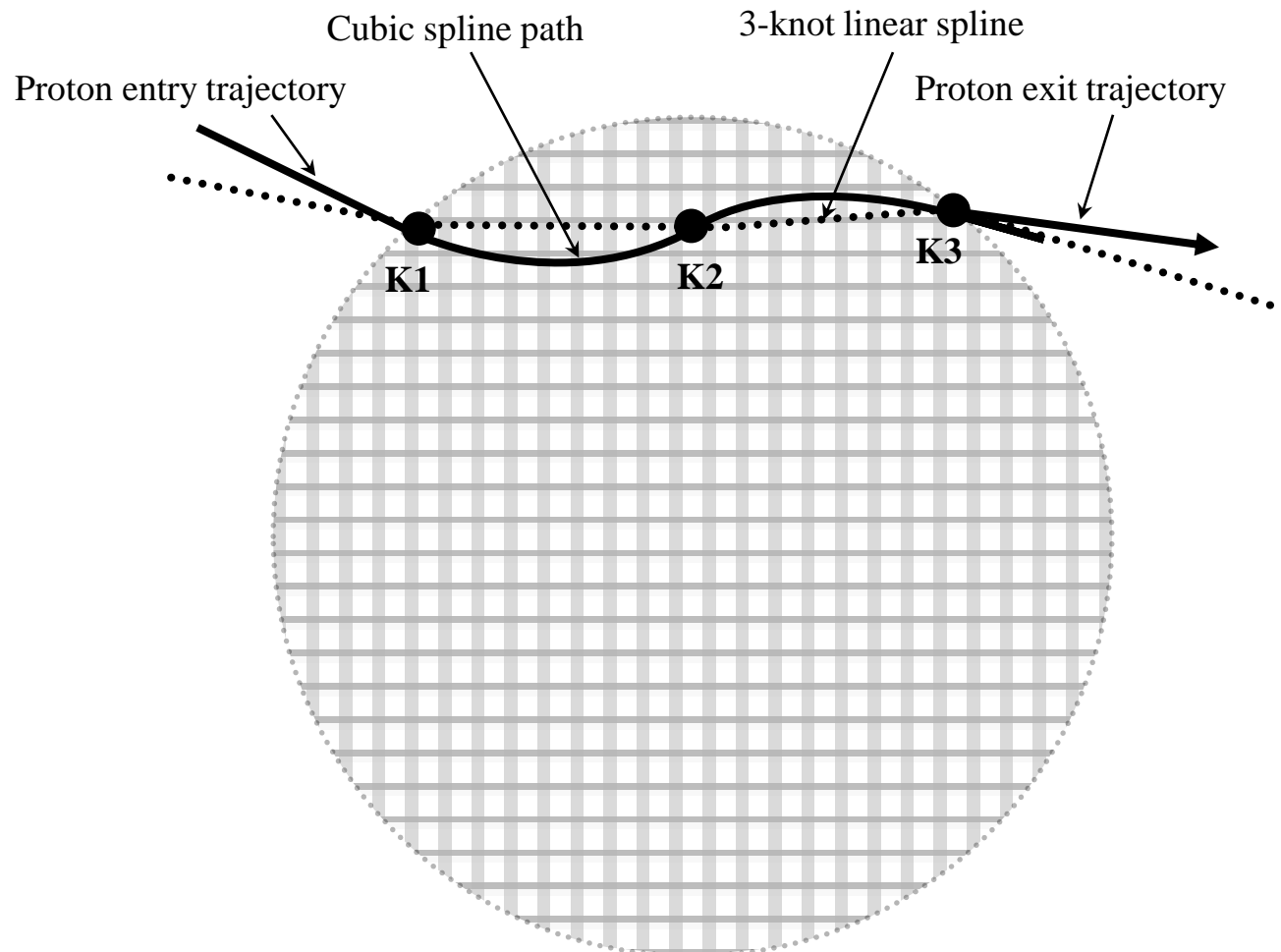
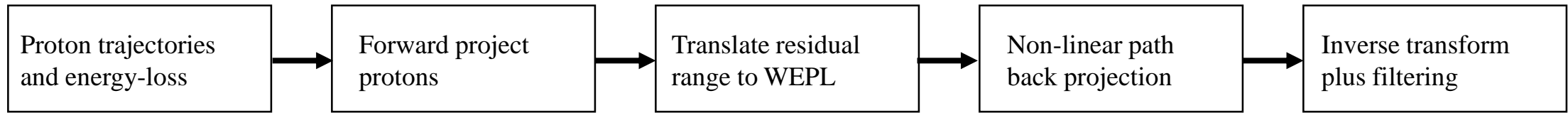
Backup slides

SSD -> DMAPS

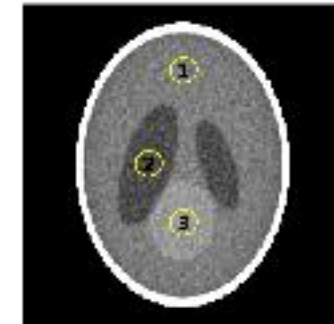
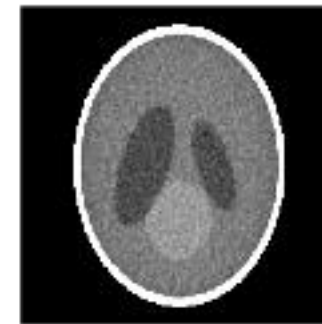
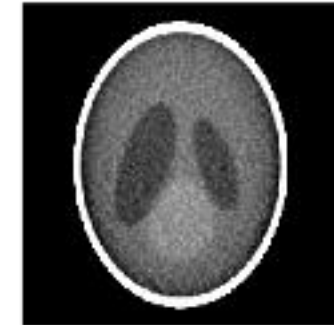
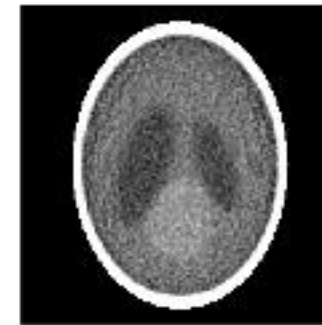
Criteria	PRaVDA - SSD	DMAPS	Gain SSD ⇒ DMAPS
Sustainable proton flux ∝ to scan time	2×10^6 proton/s/cm ²	$< 2 \times 10^8$ proton/s/cm ²	100 times faster: shorter pCT scans
Manufacturing process	Non-standard	Standard	Fast volume production
Ease to run and maintain	3 sensors required for inferring x-y coordinates	A single pixelated sensor provides x-y coordinates	Reduction in complexity: 3 times less sensors
Readout	Dedicated ASIC needed	Direct DAQ interface	Cost and maintenance
Charge information	No	Yes	Improved range resolution
Sensor thickness ∝ MCS*	150 mm	75-100 mm	Improved tracking resolution
Radiation tolerance	10^{15} n _{eq} /cm ²	$>10^{15}$ n _{eq} /cm ²	Several years life-time
Area	10x10 cm ²	?	

PROTON CT RECONSTRUCTION

G Poludniowski, N M Allinson and P M Evans "Proton Computed Tomography reconstruction using a backprojection-then-filtering approach", Phys Med Biol. 59:7905-7918 (2014)

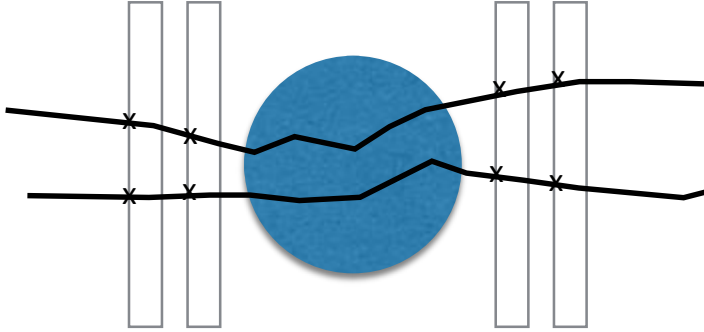


Back-Projection Filtered (BPF)
Filtered Back-Projection (FBP)



- (a) FBP
- (b) BPF - 0-knot
- (c) BPF - 2-knot
- (d) BPF - 9-knot

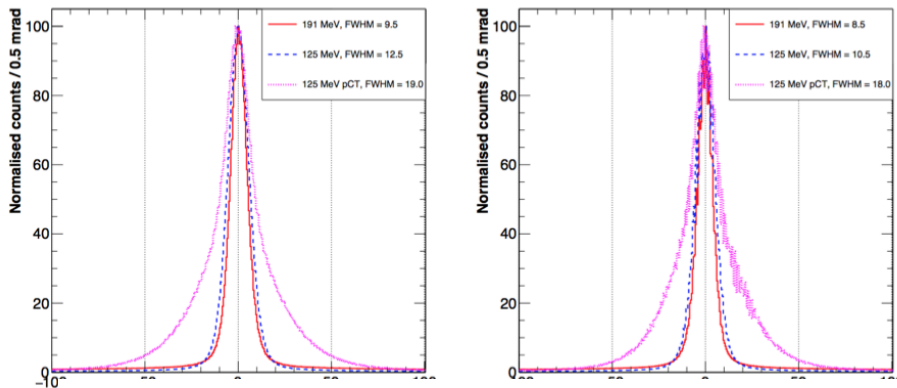
Trackers only CT



Traditional proton CT estimates path length of water that would give an equivalent energy-loss to that lost by protons passing through the patient.

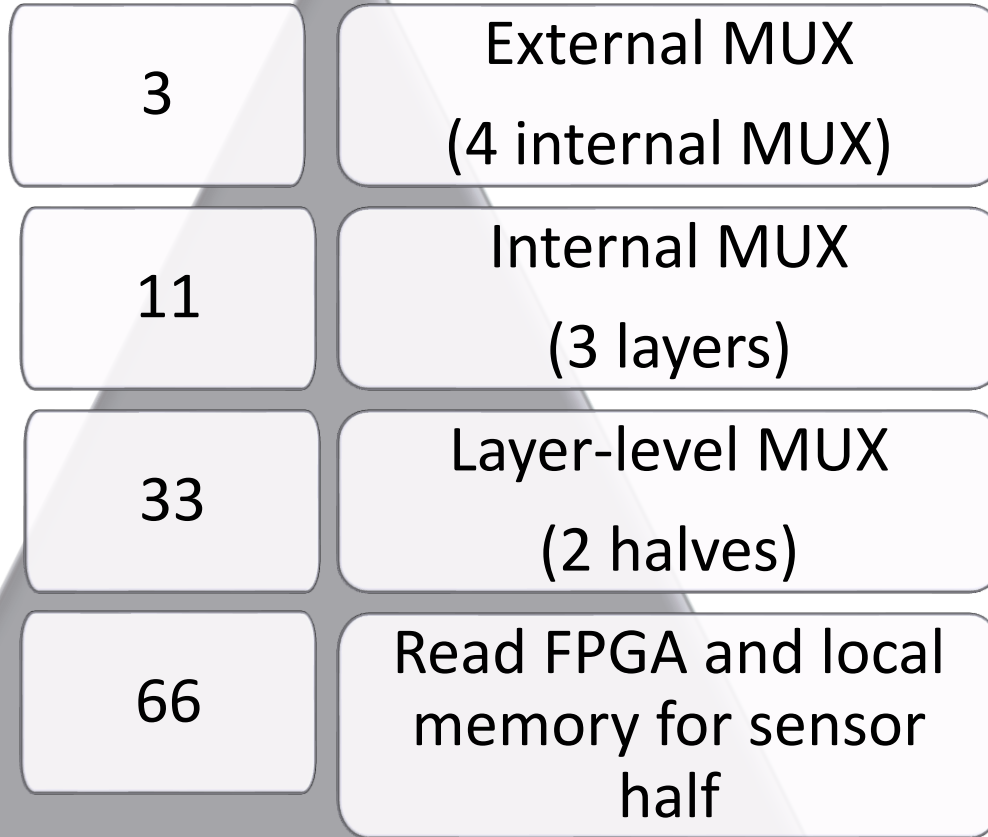
Proposed tracker-only CT estimates path length of water that would give an equivalent mean-square scattering angle.

Former reconstructs stopping-power, latter scattering-power, which is related to material properties such as density and atomic number in different ways.

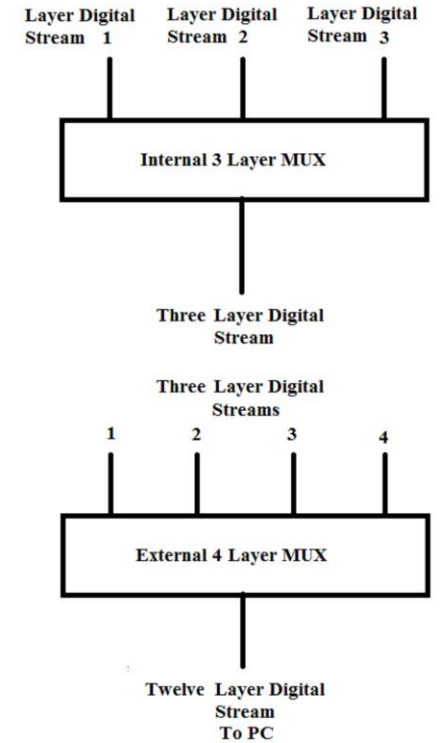
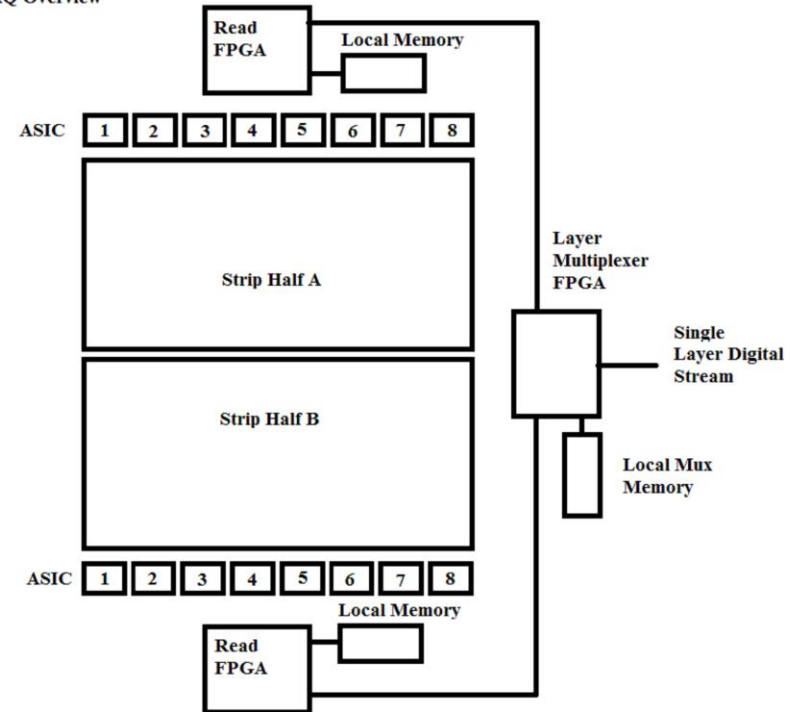


Scattering angles measured in tracker

DAQ

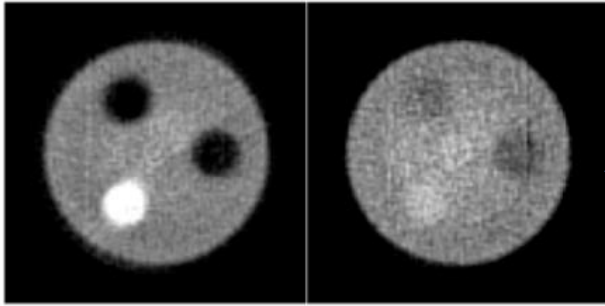


DAQ Overview

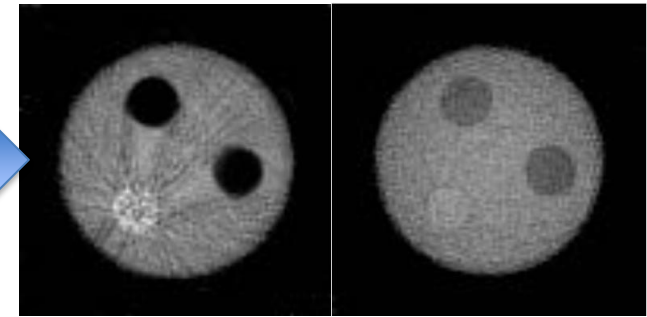


Data rate ~ 66 Gb/s

Trackers only CT



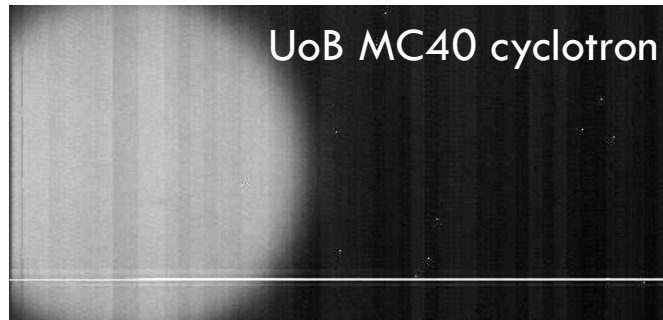
Tracking only - MCS
(Scattering power)



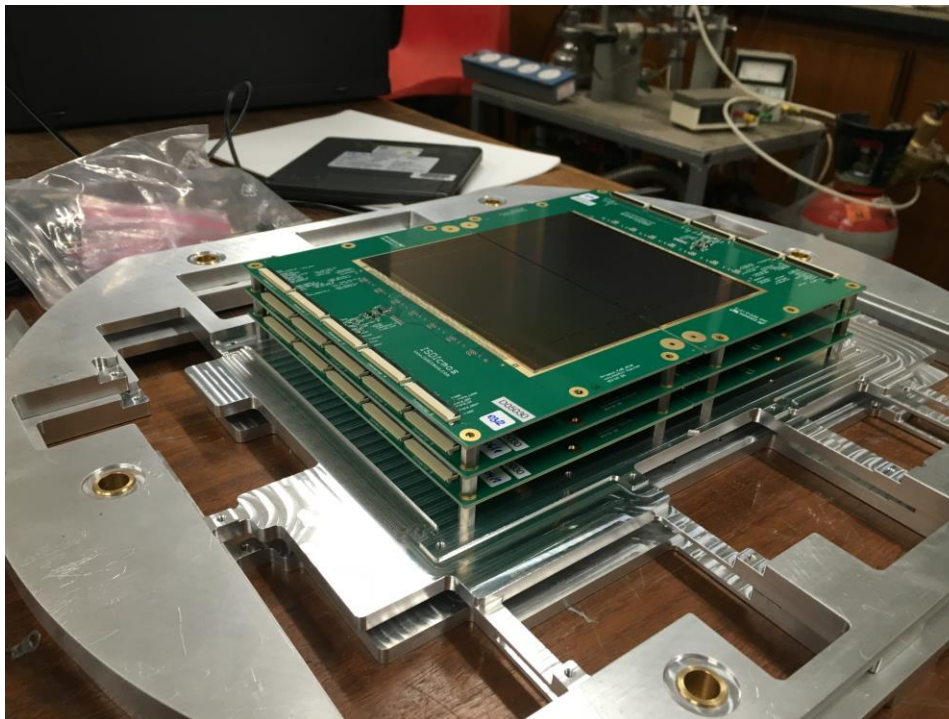
Tracking and energy (stopping power)

Tracker Paper: J. T. Taylor et al, Med. Phys. Vol. 43, Issue 11 (2016), Reconstruction Paper: G.Poludniowski et al, Phys. Med. Biol. 59 (2014)

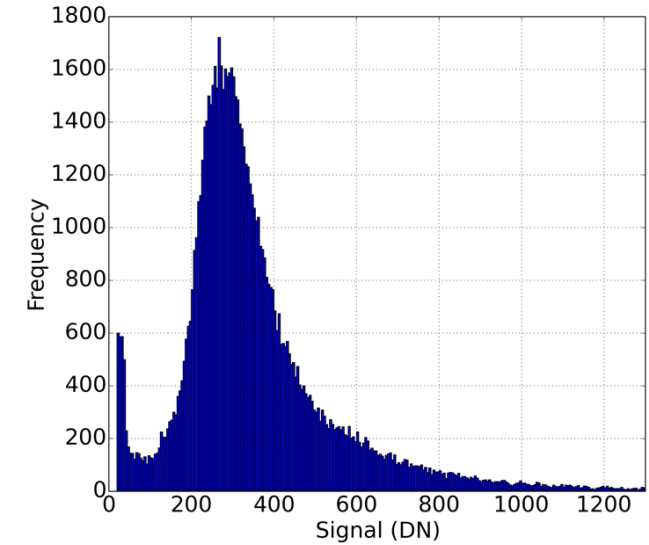
CMOS IMAGERS



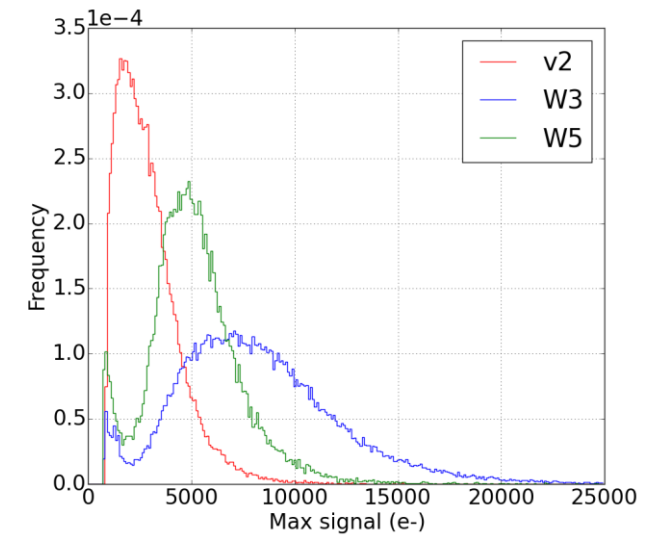
- 0.35 μm technology
- Radiation hard by design
- 5×10 cm imaging area
- 3-side buttable
- 194 μm pixel
- 150 e- noise floor
- 1kHz frame rate (11 bits)



29 MeV protons

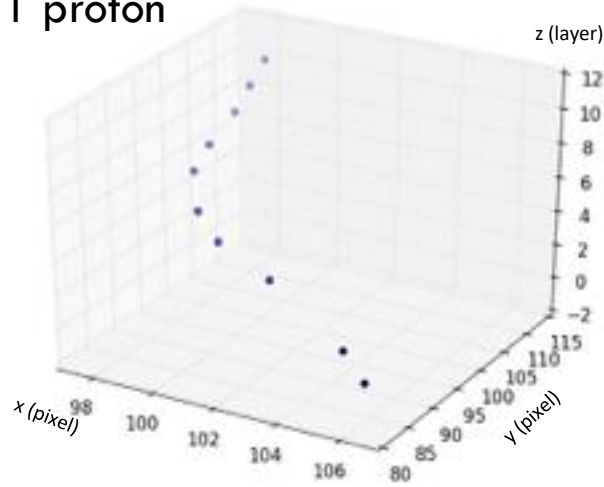


Optimisation of epitaxial resistivity

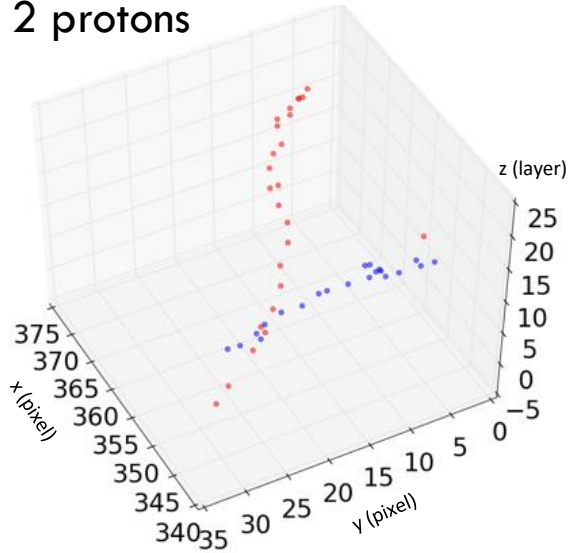


CMOS IMAGERS

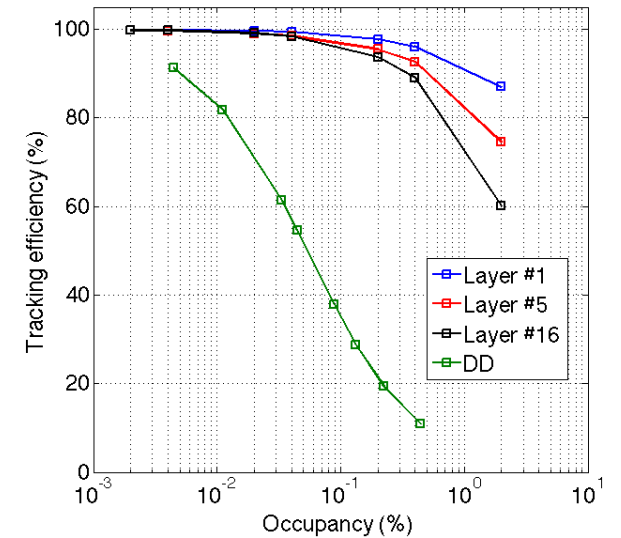
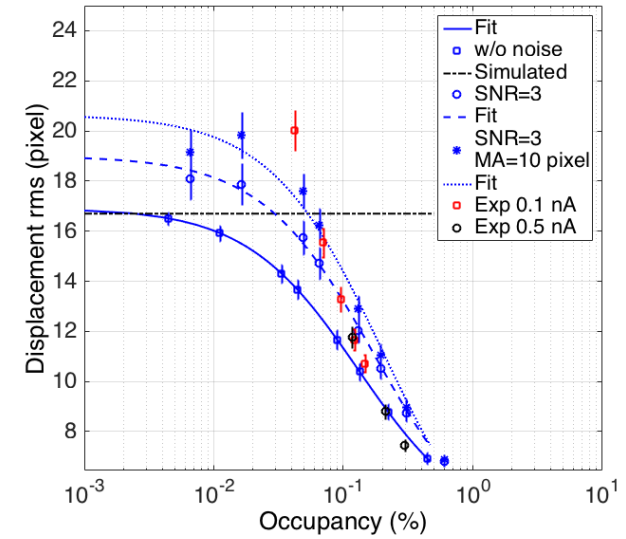
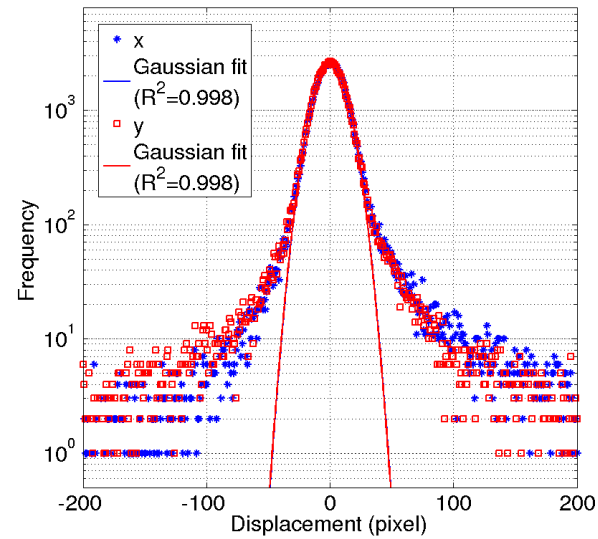
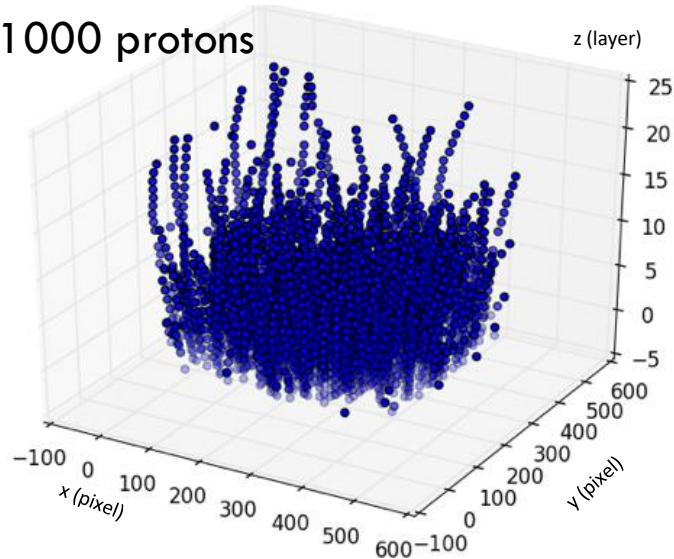
1 proton



2 protons



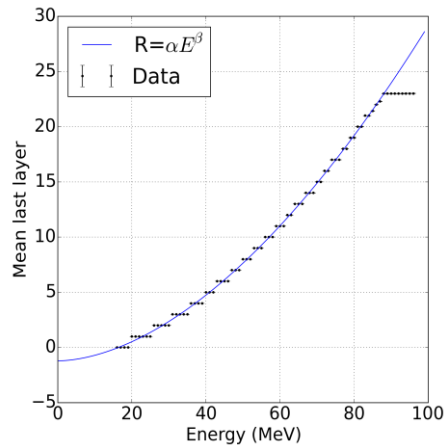
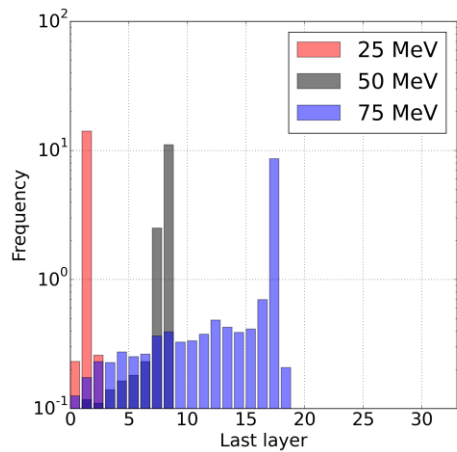
1000 protons



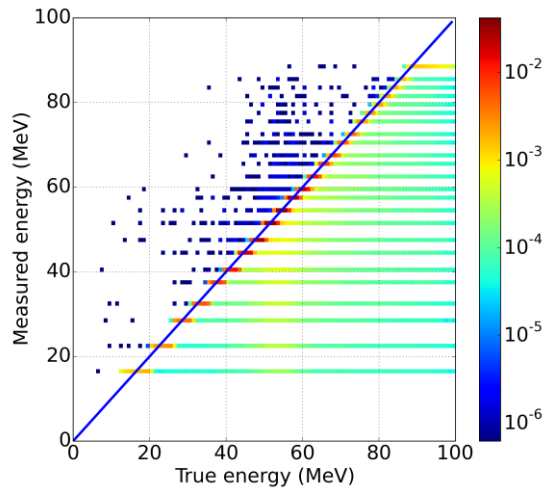
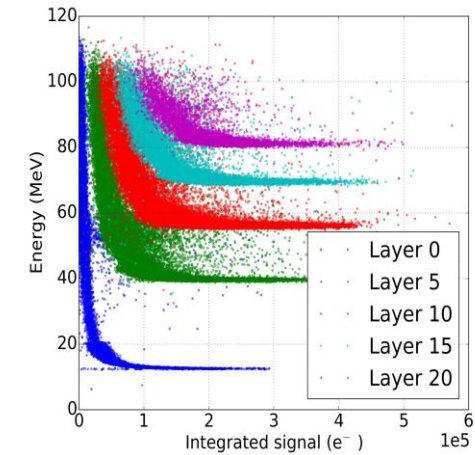
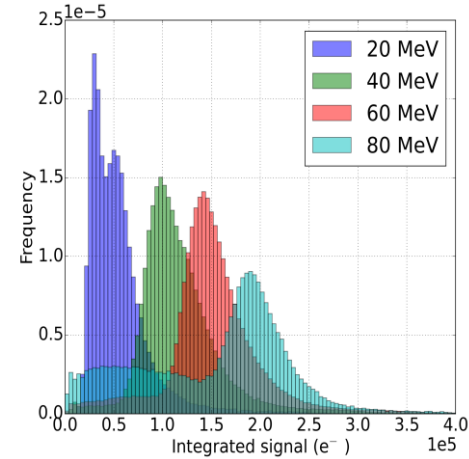
- CMOS readout speed \sim kHz
- Strip readout speed \sim MHz
- Need to reconstruct proton tracks in the CMOS Range Telescope
- Track following algorithm, based on adaptive velocity calculation and minimisation of layer-to-layer displacement

CMOS RT: energy calibration

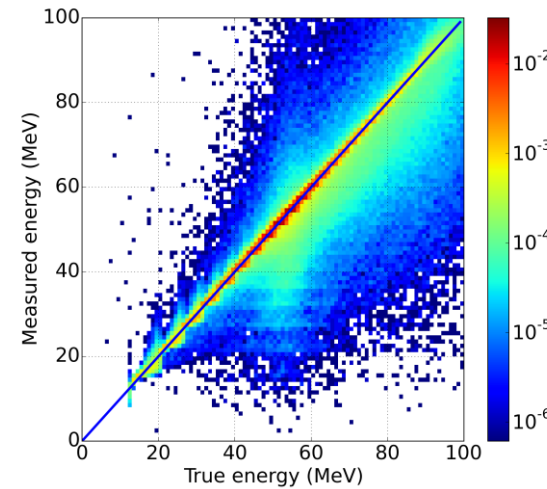
Range counter



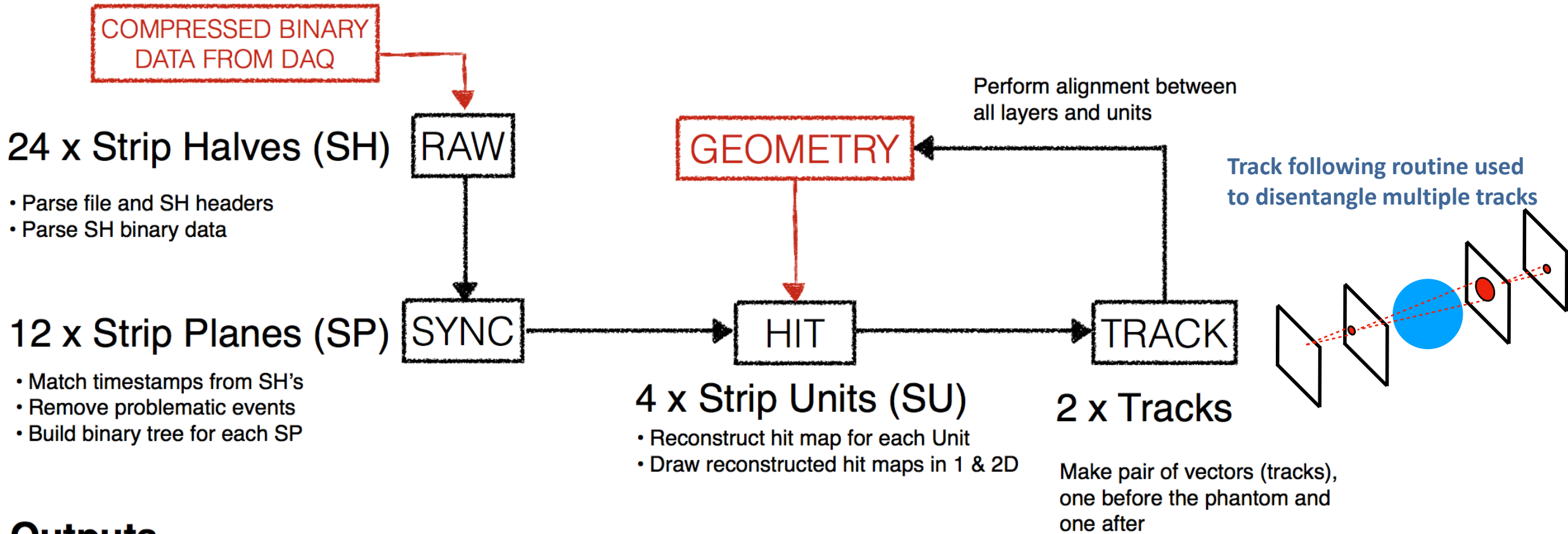
Range and signal



Energy resolution
@60 MeV: 4.4%



Energy resolution
@60 MeV: 2.8%



Outputs

- ◆ All levels can output histograms in the CERN based ROOT format for analysis
- ◆ TRACK level produces a binary file with a timestamp of each hit and four synchronised positions from the tracker
- ◆ Binary outputs also possible at SYNC level for DAQ debug and RT data format

Proton tracking in the Range Telescope

- Suppression of noisy channels by beam profile fit
- Cluster reconstruction (multiple-strip hits)
- Layer-by-layer **track-following** algorithm based on:
 - ❖ Track projection from tracker detectors
 - ❖ Minimum layer-to-layer displacement of projected tracks
 - ❖ Handling of multiple tracks per R/O
 - ❖ Angular cuts
 - ❖ Range cuts

