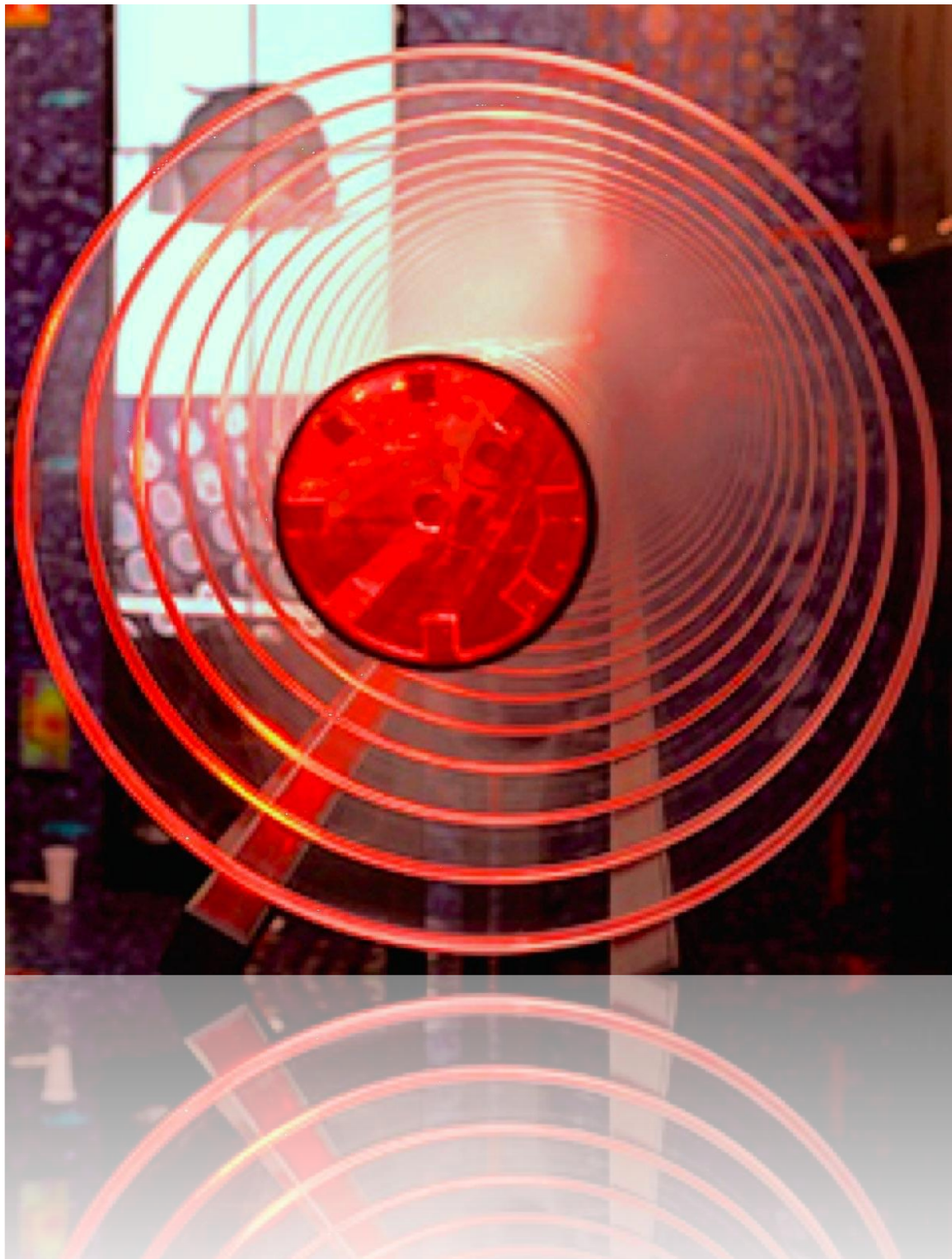
Silicon Sensors for Proton Therapy

Thoughts from the PRaVDA consortium

Nigel M Allinson

University of Lincoln

On behalf of the PRaVDA Consortium



University of Lincoln

University of Birmingham

University of Liverpool

University of Surrey

University of Warwick

Karolinska University Hospital, Sweden

University of Cape Town

University Hospital Birmingham NHS Foundation Trust

The Christie NHS Foundation Trust

University Hospital Coventry and Warwickshire NHS Trust

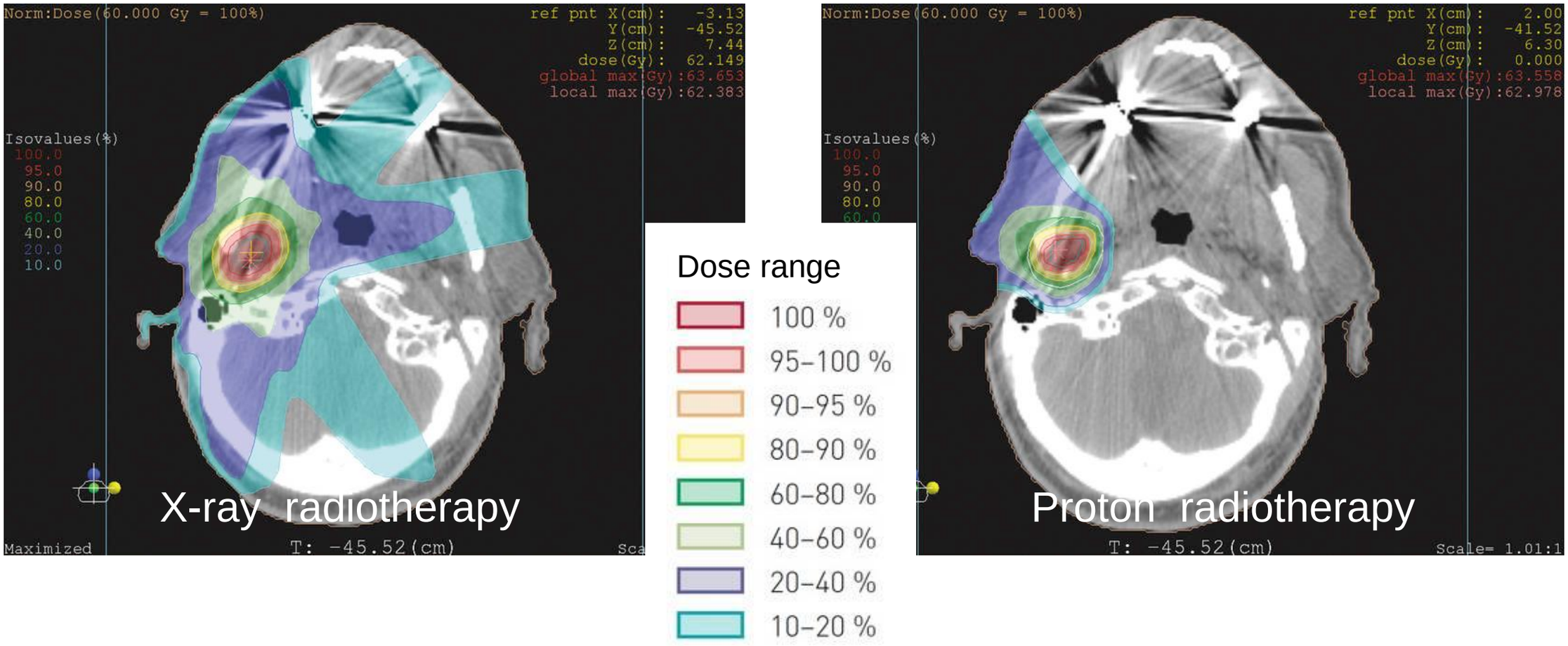
iThemba LABS, SA

ISDI Ltd

aSpect Systems GmbH

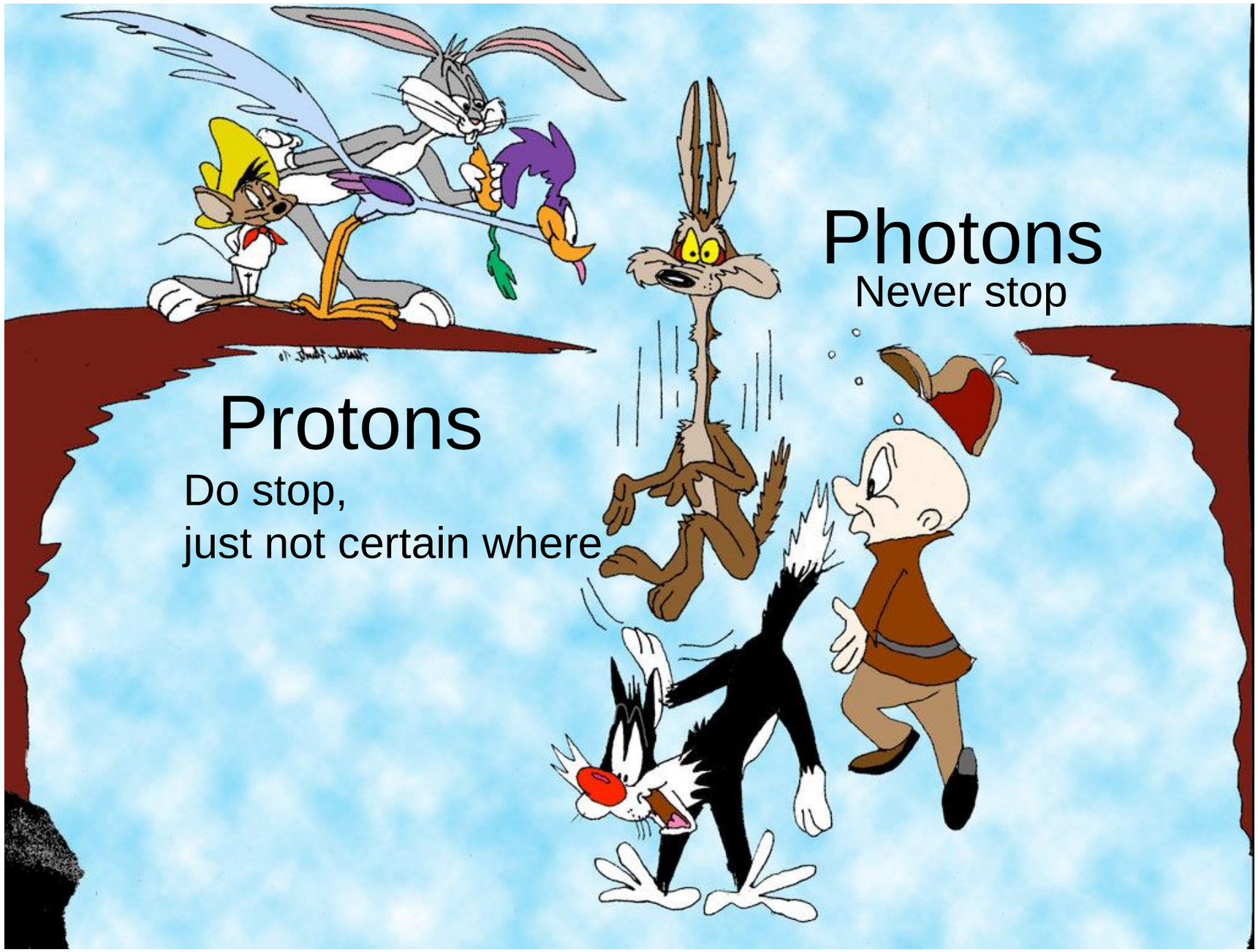
Funded by wellcome trust

Advantages of PBT (as promised)



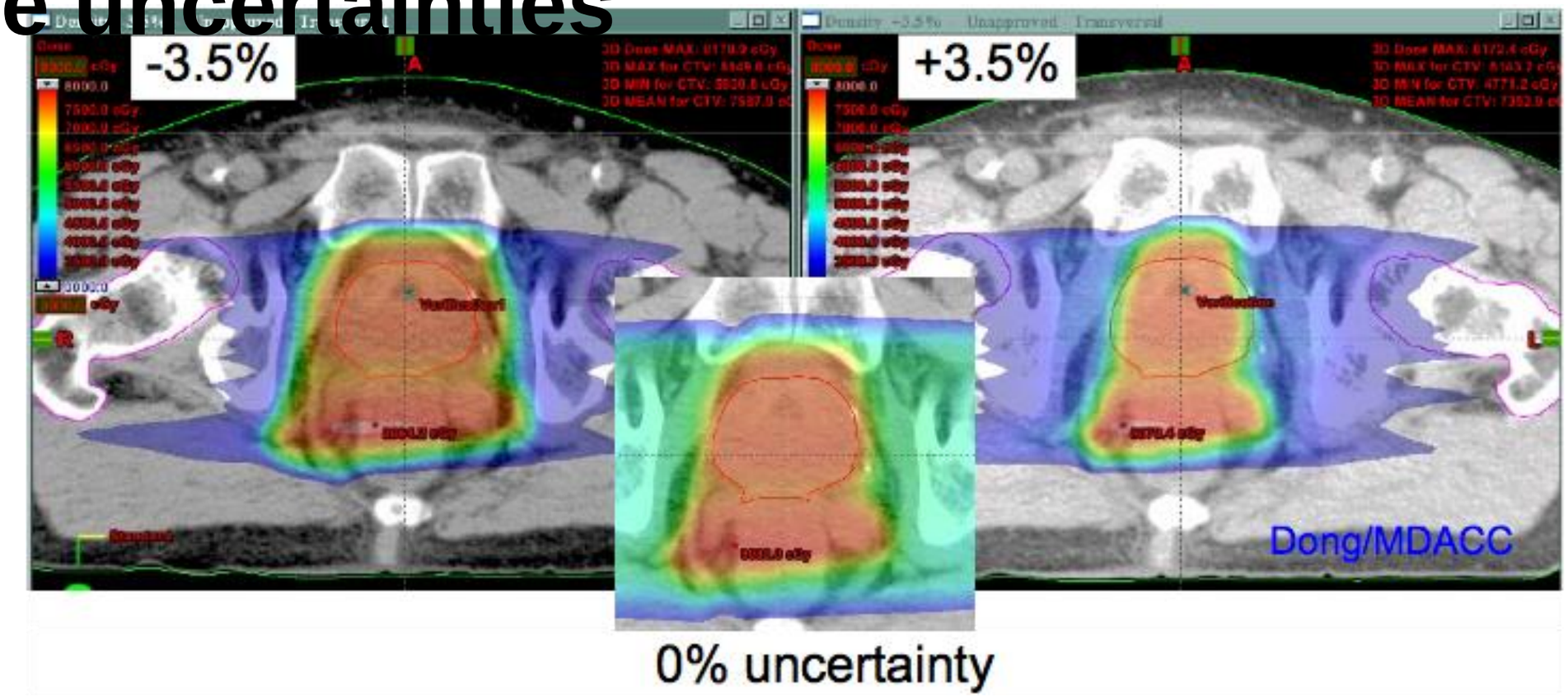
Better targeting of tumour, reduced dose to healthy tissue

- Tumours in the head and neck region
- Tumours near the spine or other critical organs
- Some types of brain tumours
- Most childhood cancers



The advantage is the disadvantage

Range uncertainties

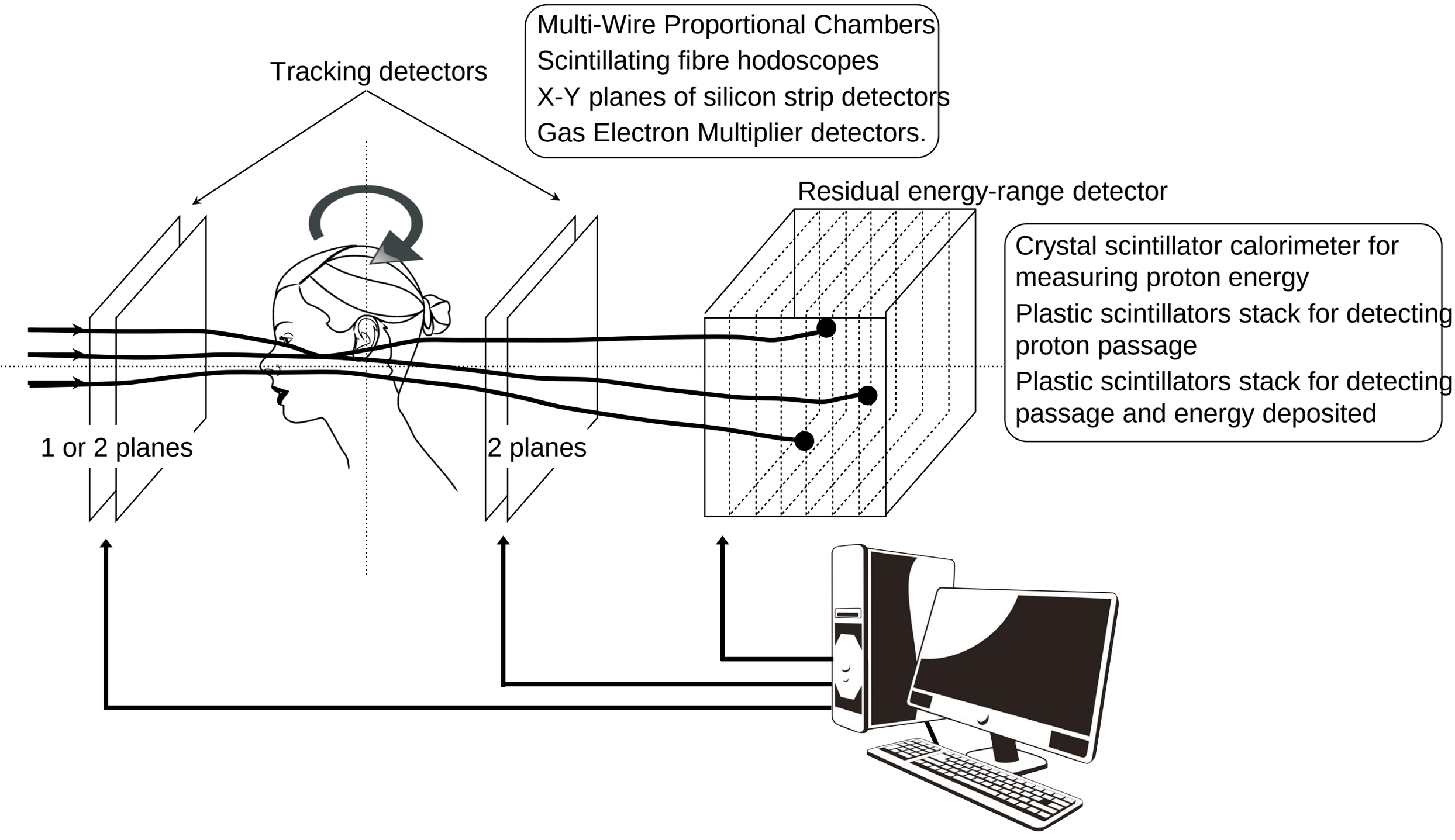


Not present in proton CT

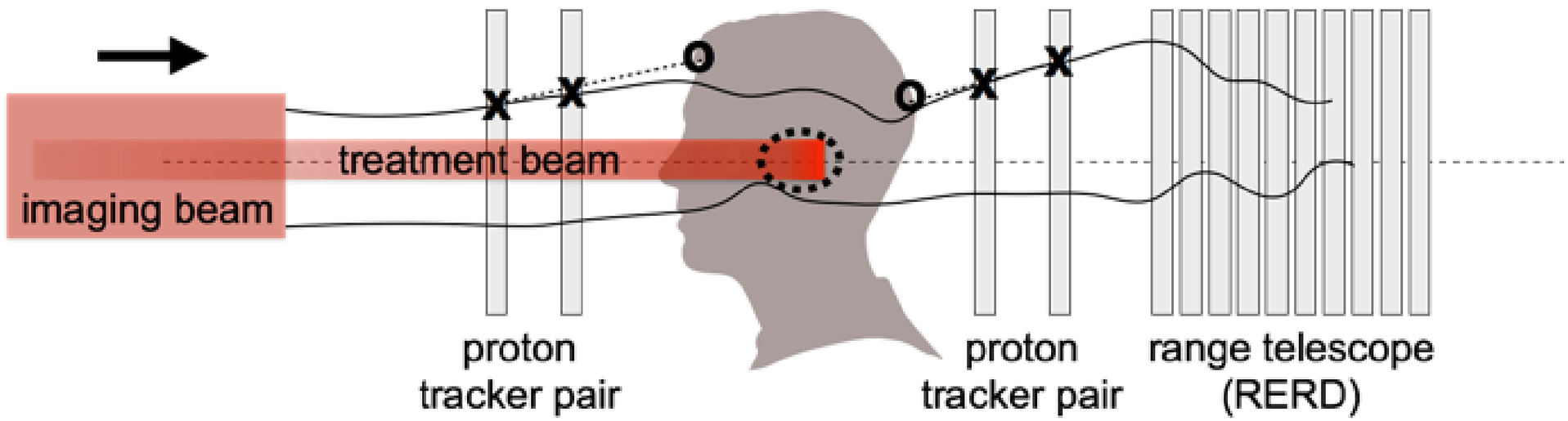
Uncertainty source	Uncertainties in SPR estimation (1σ)		
	Lung (%)	Soft (%)	Bone (%)
Uncertainties in patient CT imaging	3.3	0.6	1.5
Uncertainties in the parameterized stoichiometric formula to calculate theoretical CT numbers	3.8	0.8	0.5
Uncertainties due to deviation of actual human body tissue from ICRU standard tissue	0.2	1.2	1.6
Uncertainties in mean excitation energies	0.2	0.2	0.6
Uncertainties due to energy dependence of SPR not accounted by dose algorithm	0.2	0.2	0.4
Total (root-sum-square)	5.0	1.6	2.4

Yang, M., Zhu, X.R., Park, P.C., Titt, U., Mohan, R., Virshup, G., Clayton, J.E. and Dong, L., 2012. *Comprehensive analysis of proton range uncertainties related to patient stopping-power-ratio estimation using the stoichiometric calibration*. *Physics in medicine and biology*, *57*, p.4095.

Proton CT Technology



Instrument Principles

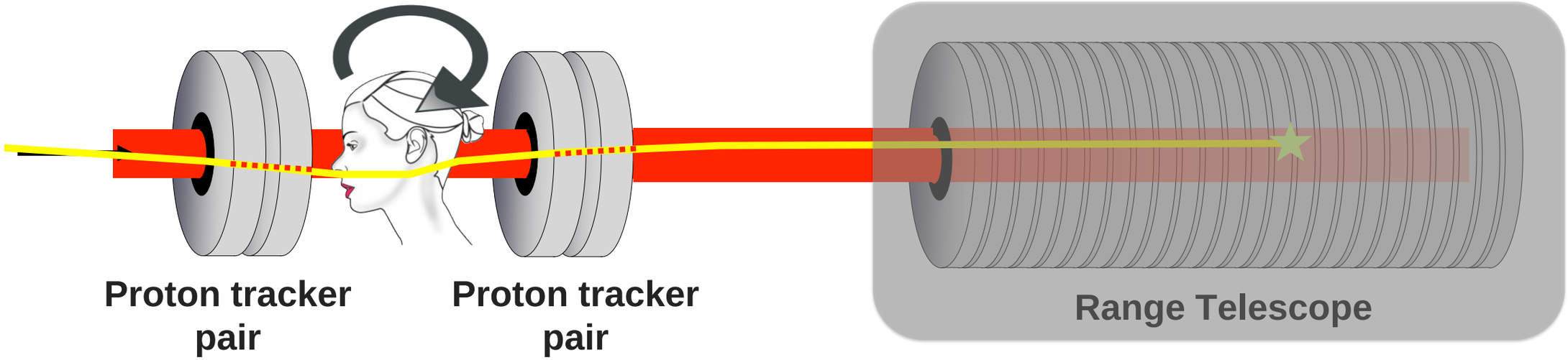


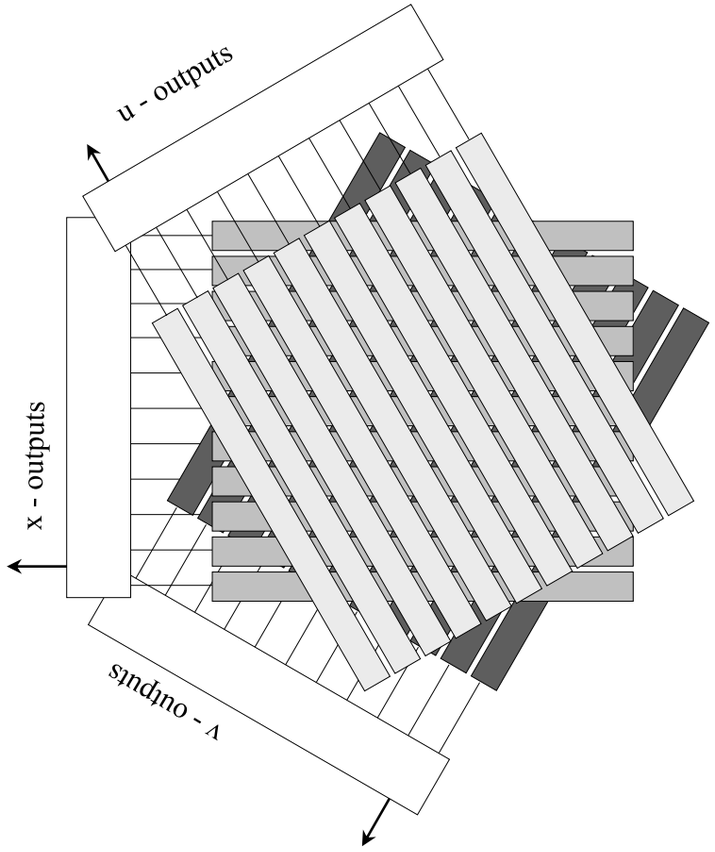
- Increase proton energy and reduce intensity of beam by a factor of ~10,000
- Pair of proximal position-sensitive trackers records trajectory of each incident proton and identical pair of distal trackers records corresponding exit trajectory
- Residual Energy Resolving Detector (RERD) logs the residual energy of each proton
- Following information for each proton: entry position, exit position and energy absorbed
- To produce a clinical-quality CT, require ~$10^{7\text{-}8}$ such triplets.

Some design parameters

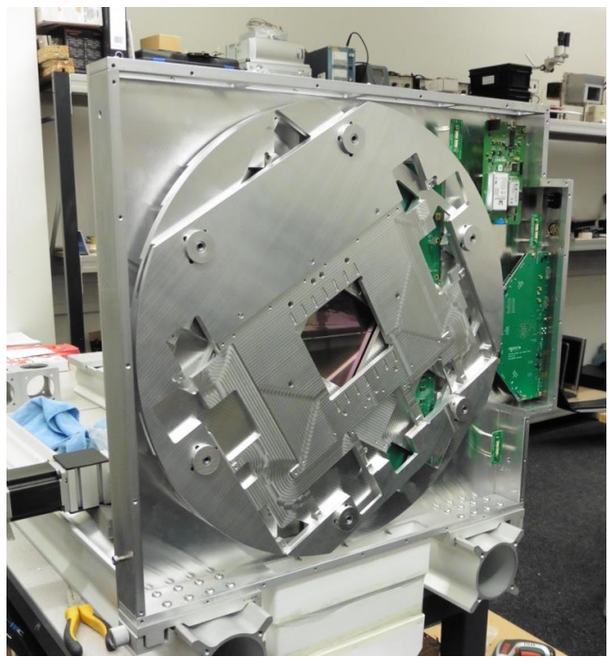
Category	Parameter	Value
Proton beam	Energy	≥ 200 MeV (head) ≥ 250 MeV (body)
	Flux	≥ 3,000 protons·cm^{-2}· s^{-1}
Imaging dose	Maximum absorbed dose	< 20 mGy
Image quality	Spatial resolution, σ	≈ 1 mm
	Relative stopping-power inaccuracy	< 1%
Time	Data acquisition time	< 10 min
	Reconstruction time	< 10 min

PRaVDA instrument

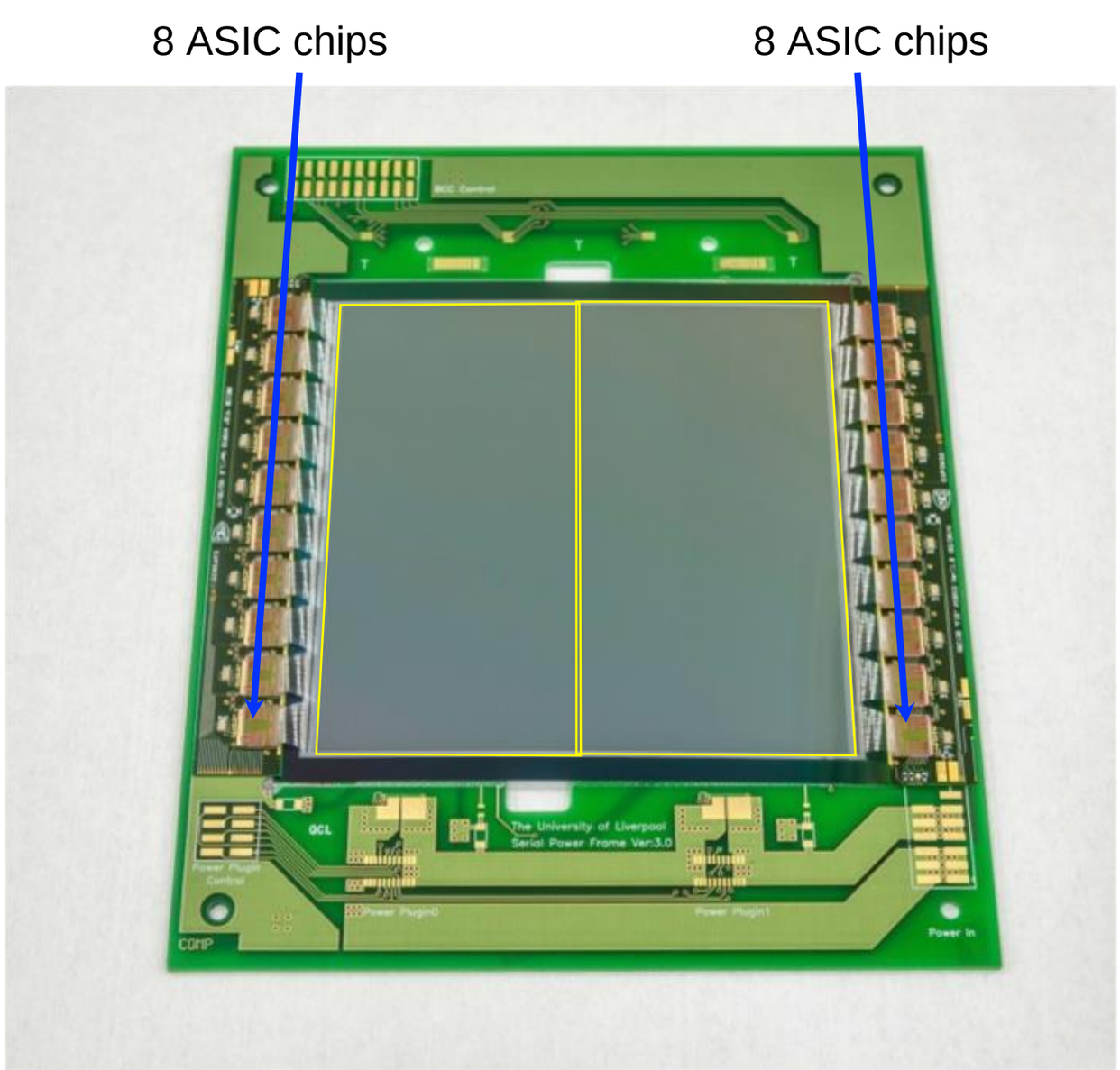




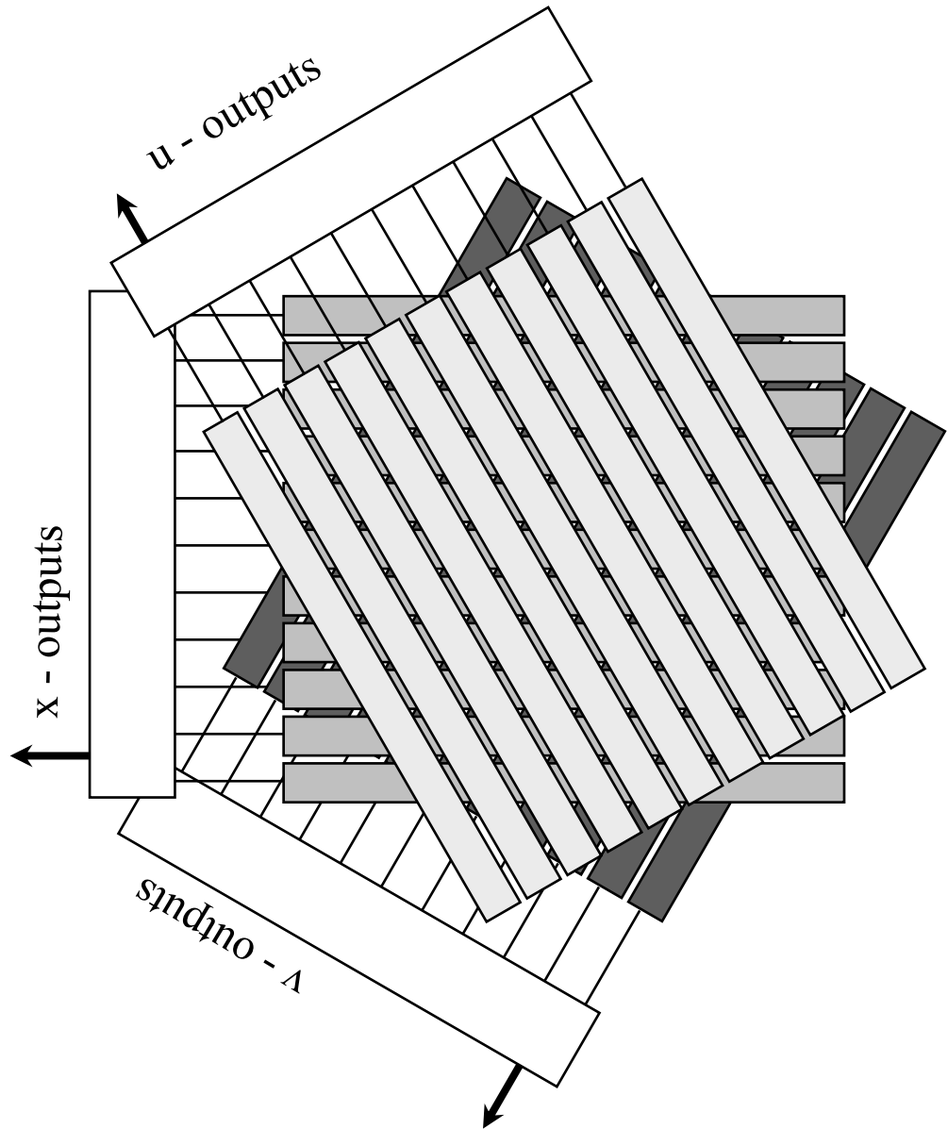
- Three equi-rotated custom silicon strip sensors – greatly reduces anomalous events
- Copes with high flux levels (treatment beam)
- High count rate, in excess of 25 million/sec
- Extremely radiation hard (developed for HL-LHC)



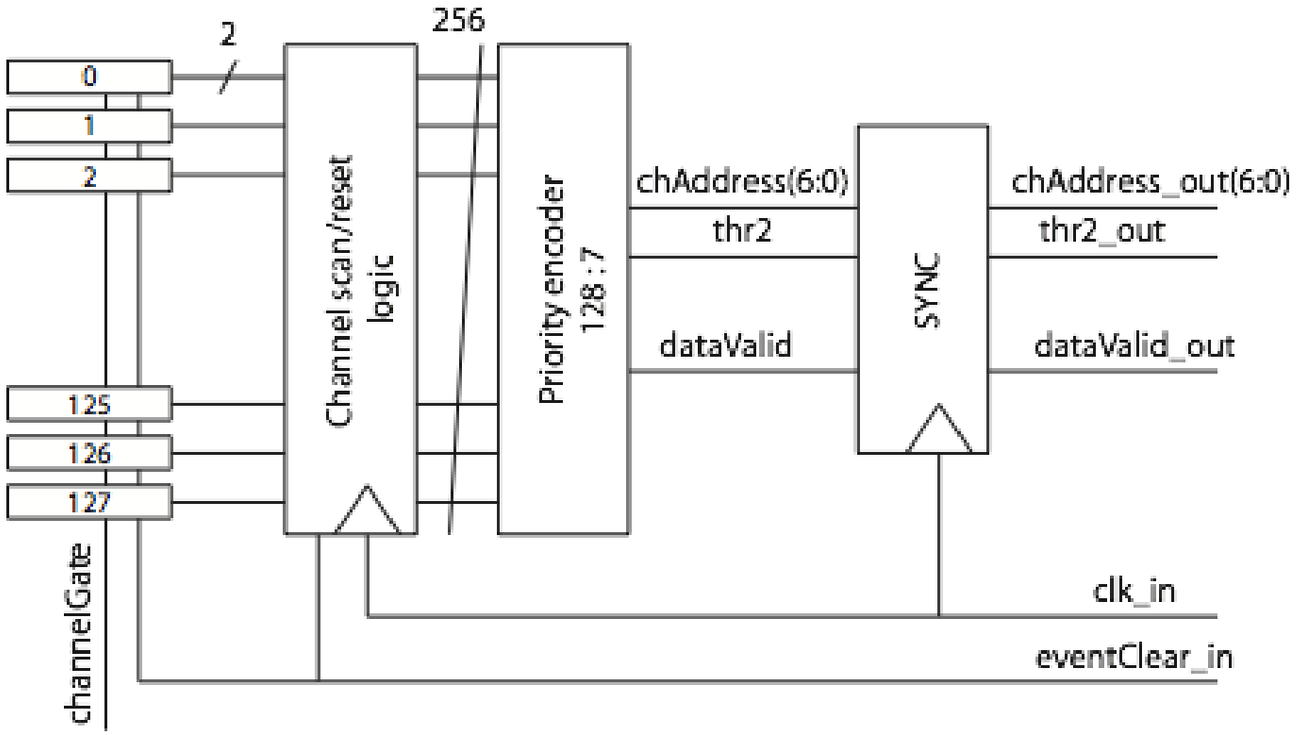
Strip Detectors



Double-ended 150µm thick n-in-p technology
– 1024 strips at 90.8 um pitch



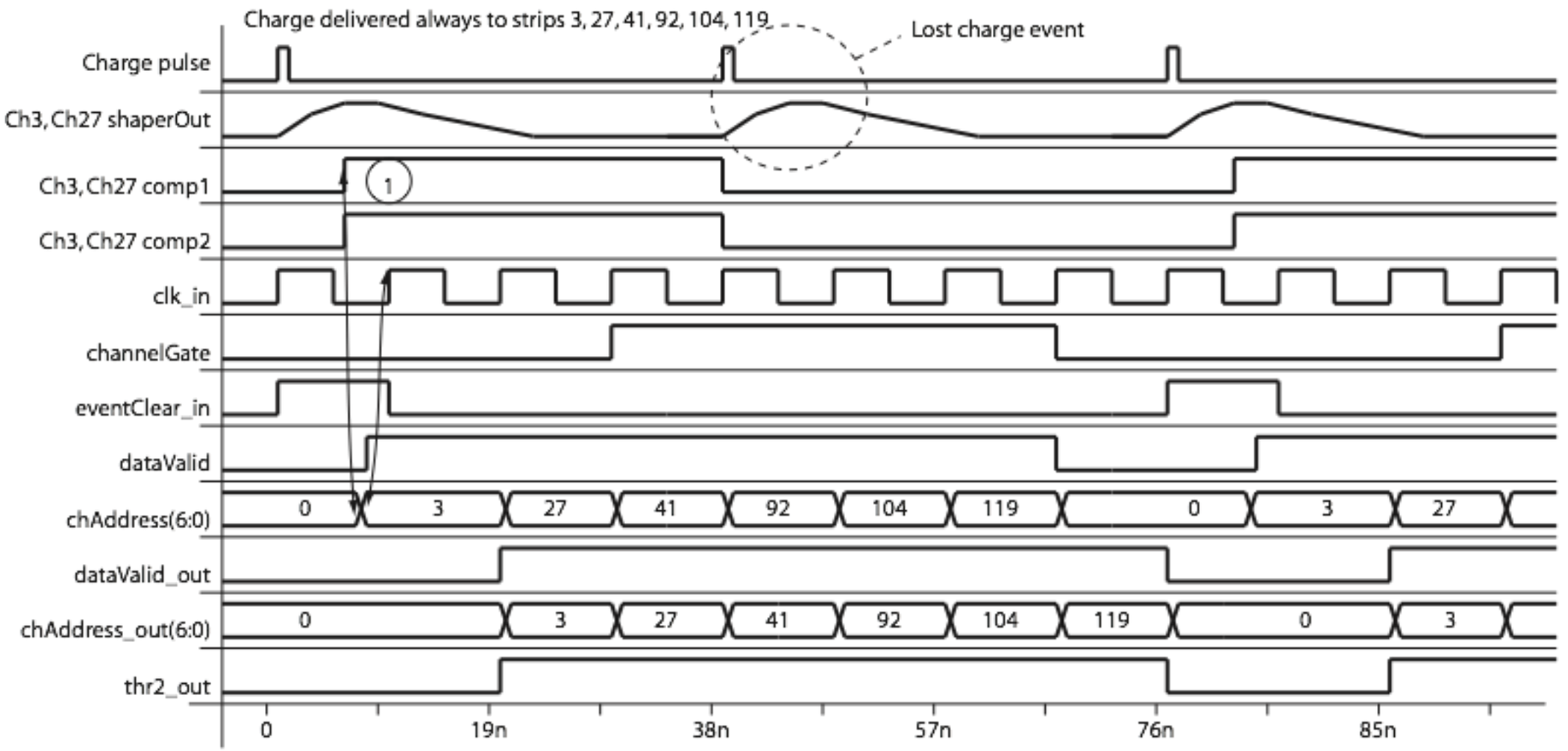
3 equi-rotated strip assemblies per tracker
Greatly reduces ambiguities



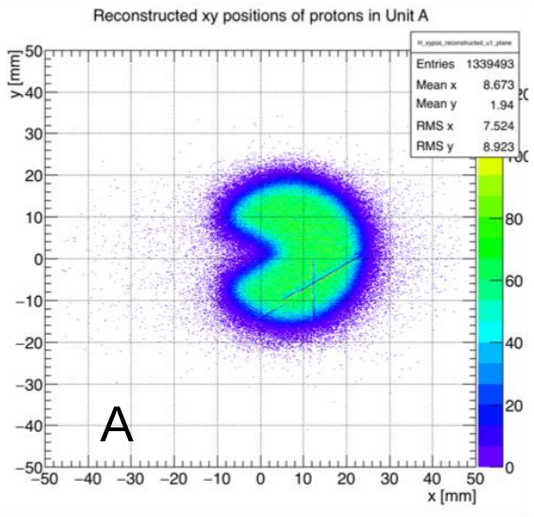
ASIC – Rhea

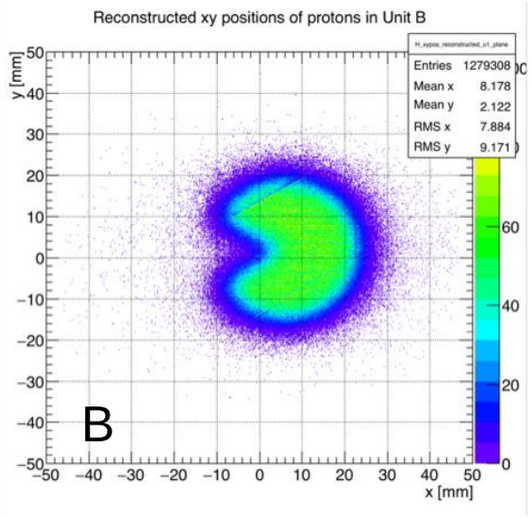
Imaging mode
Every proton detected

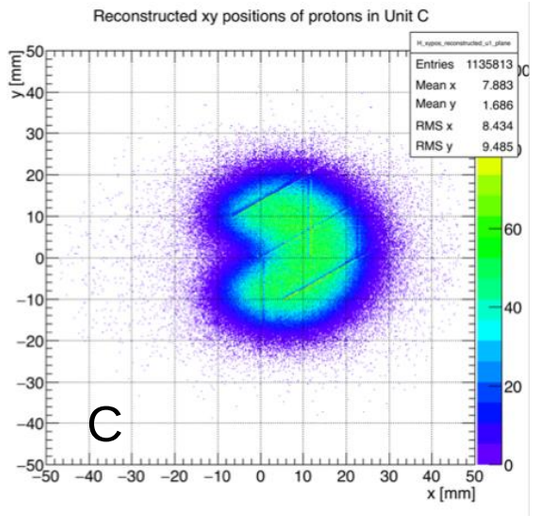
Treatment mode
Specified fraction of protons detected



Proton tracker results







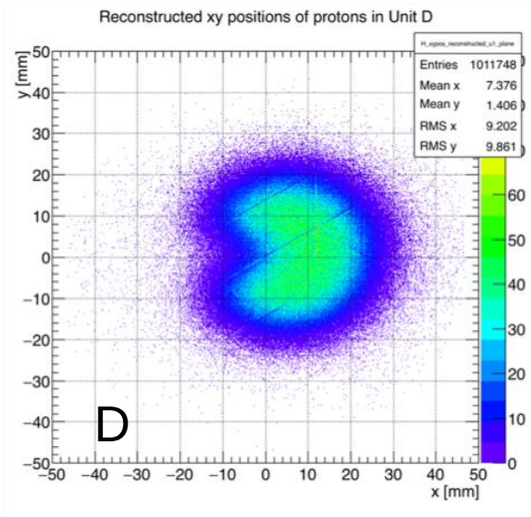
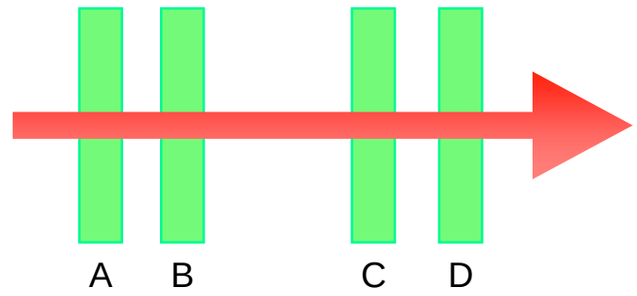
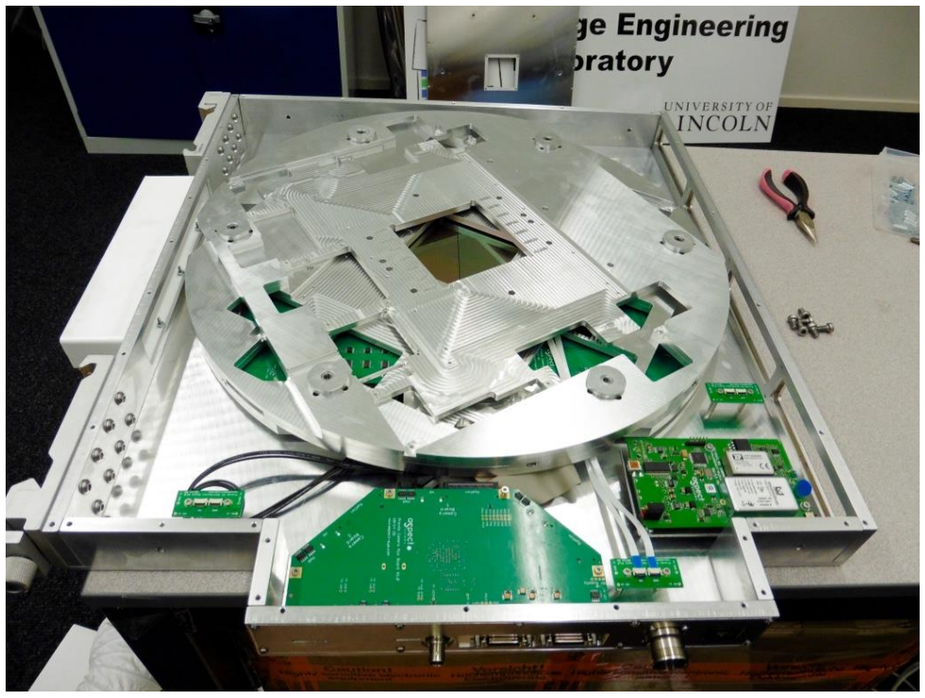
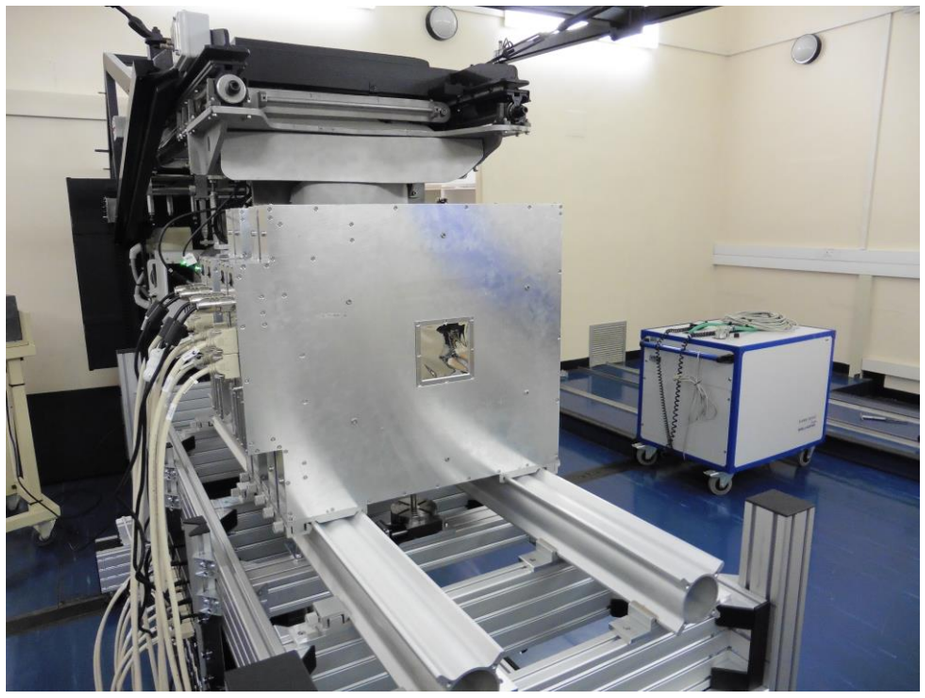


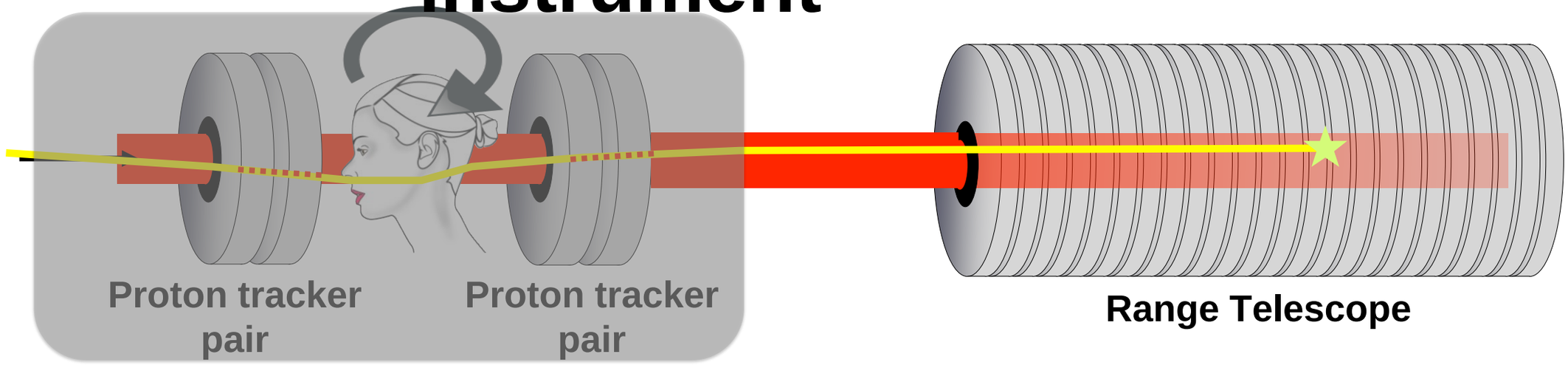
Image reconstructions – Pac-man collimator (29 MeV)

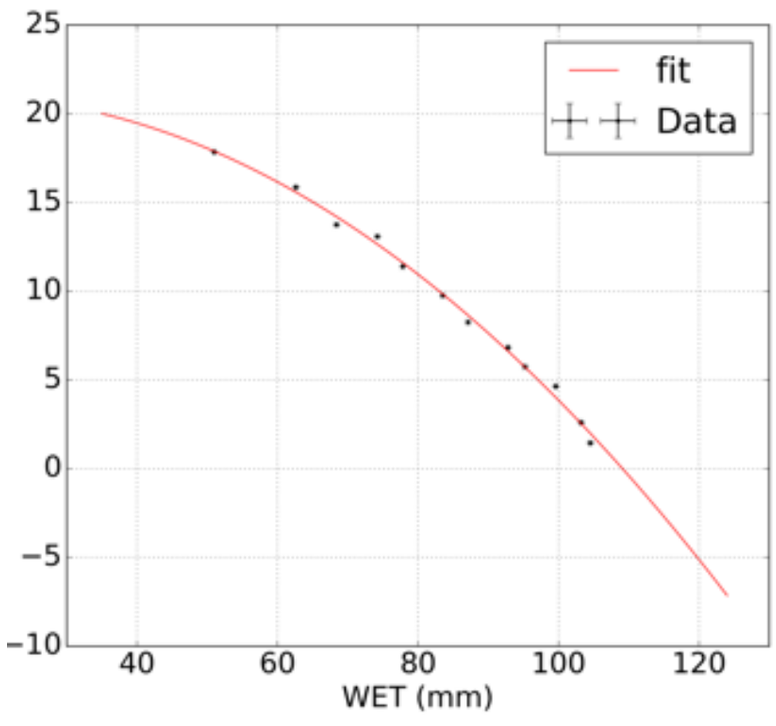




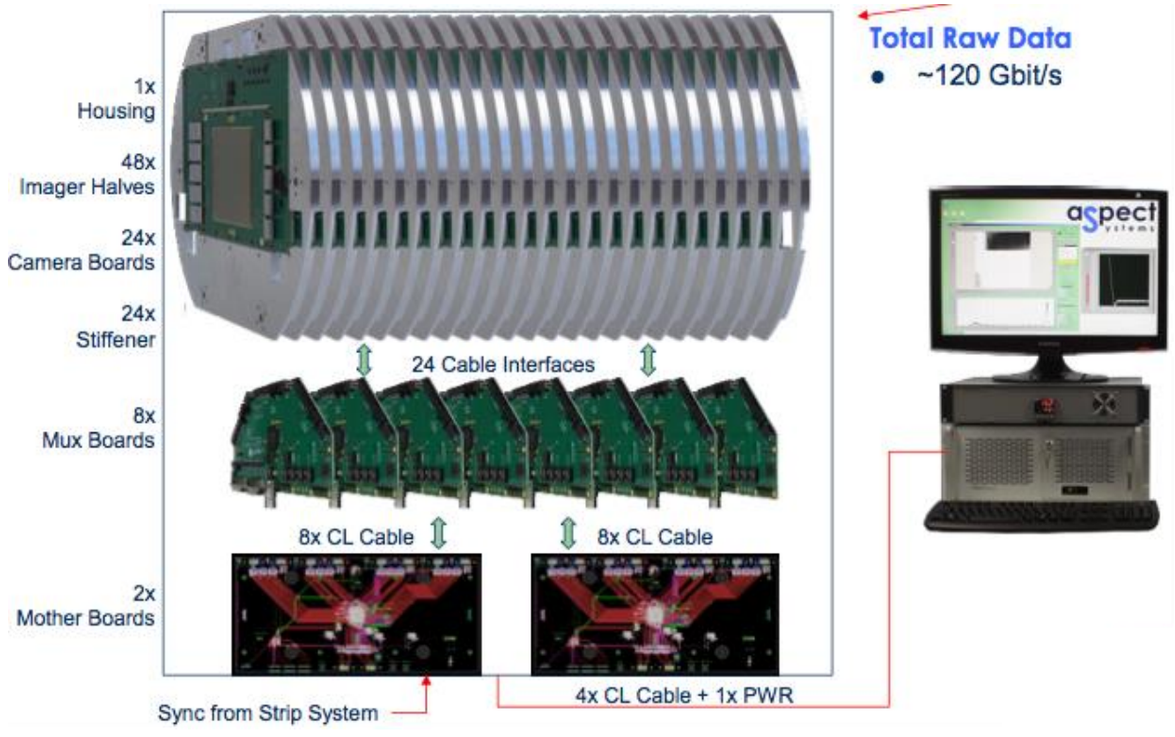


instrument



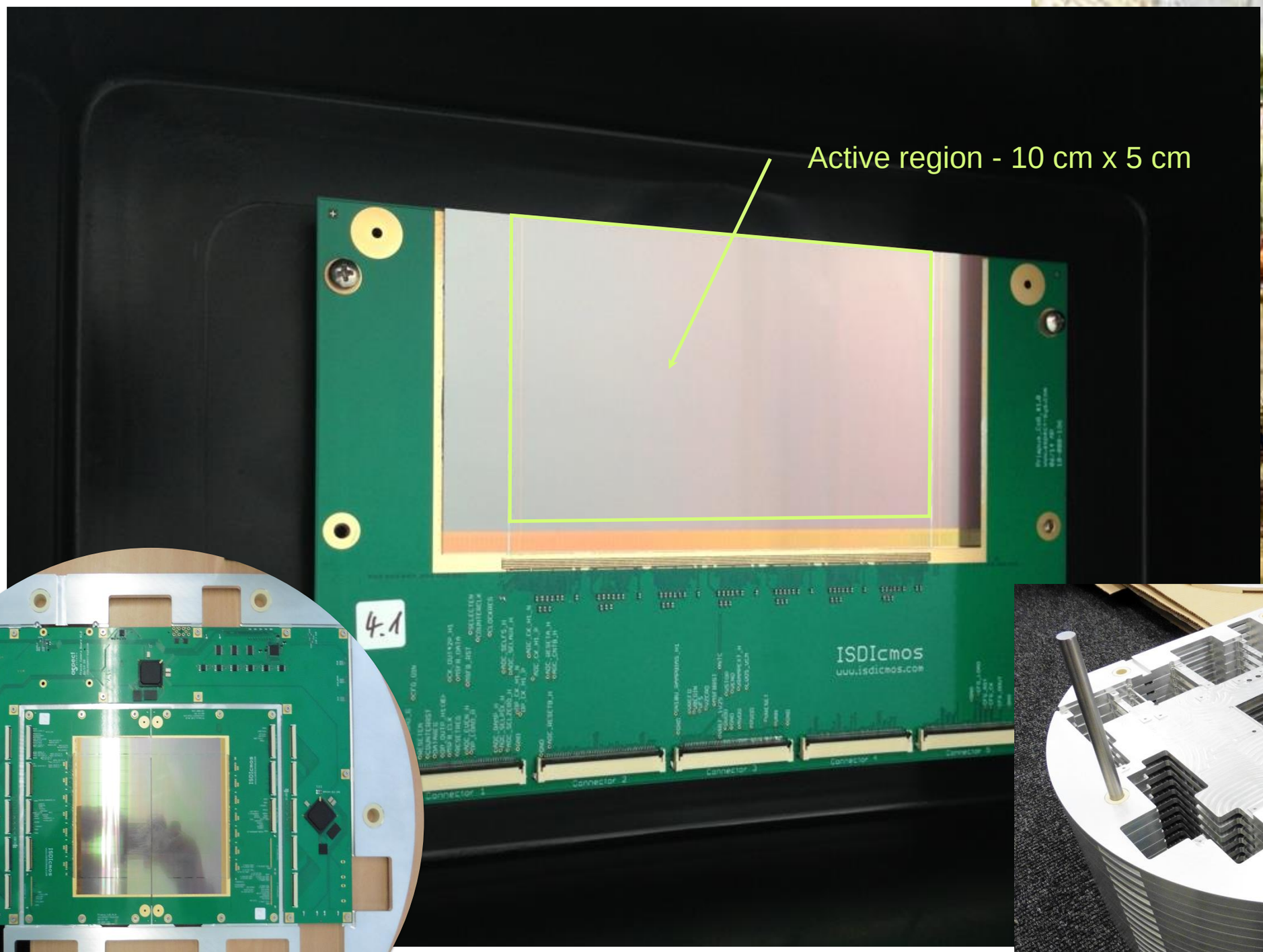


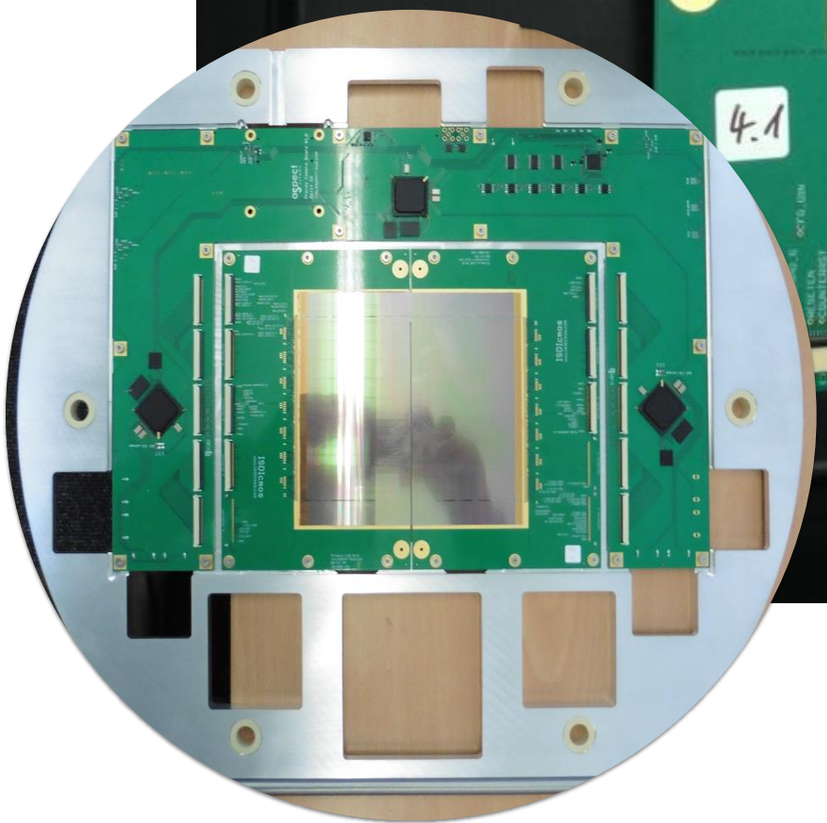
Calibration curve

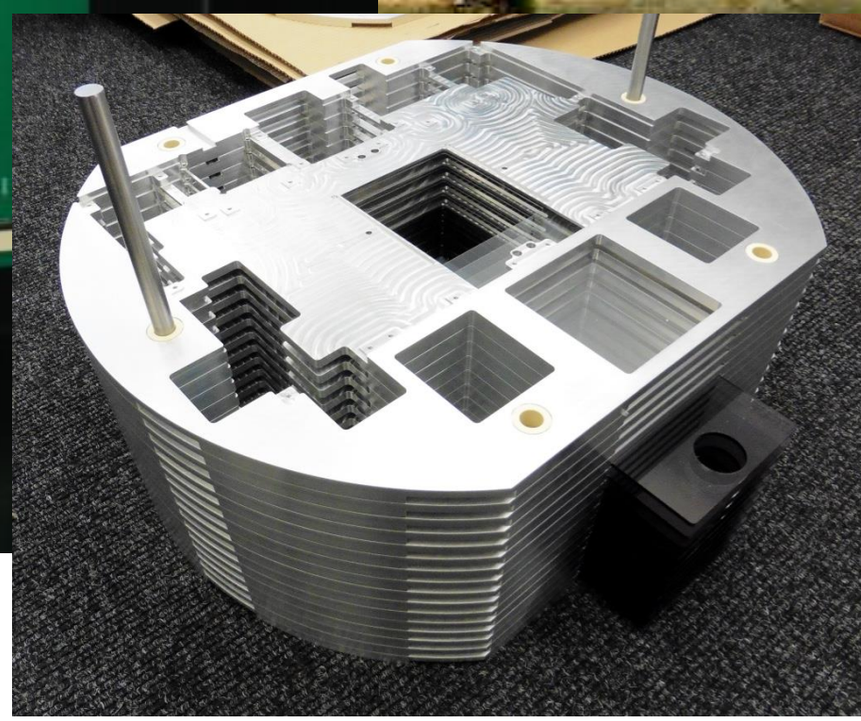


- Currently 22 layers of silicon strip sensors
- Can replace with high-speed CMOS imagers

RT CMOS imager – Priapus

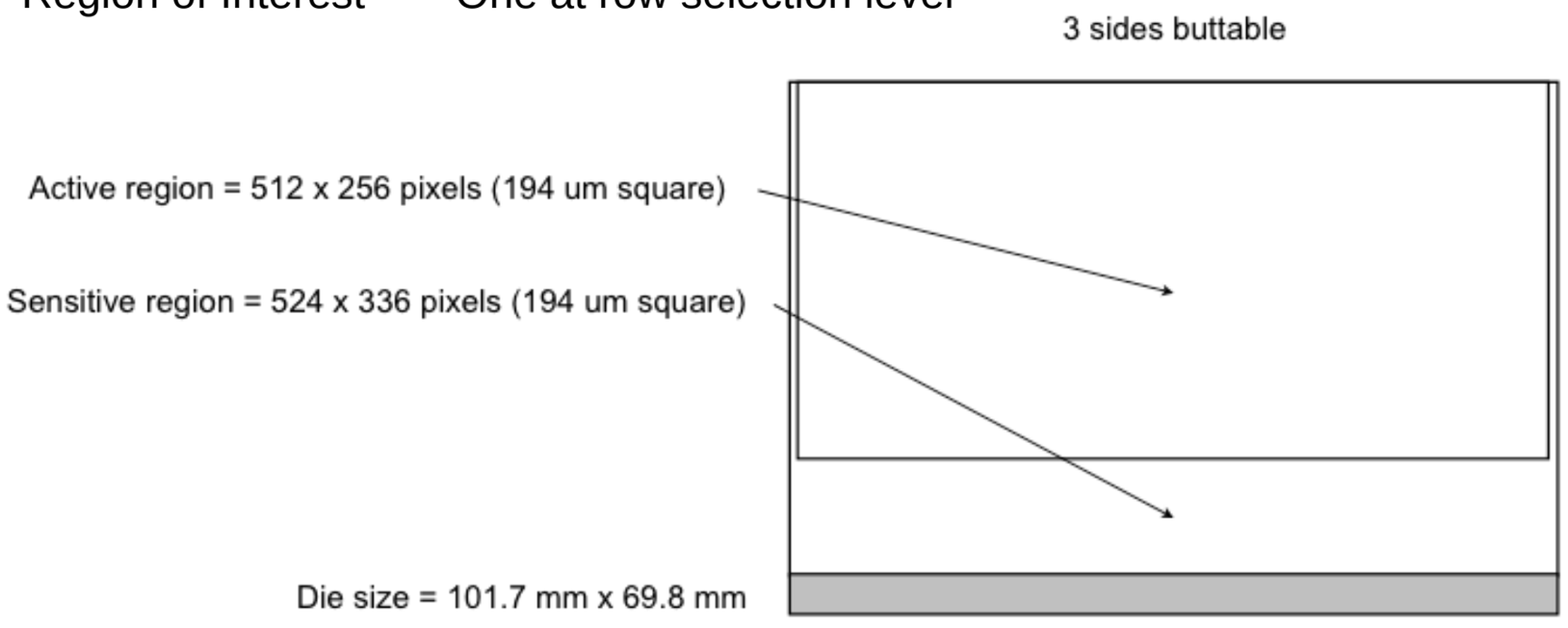


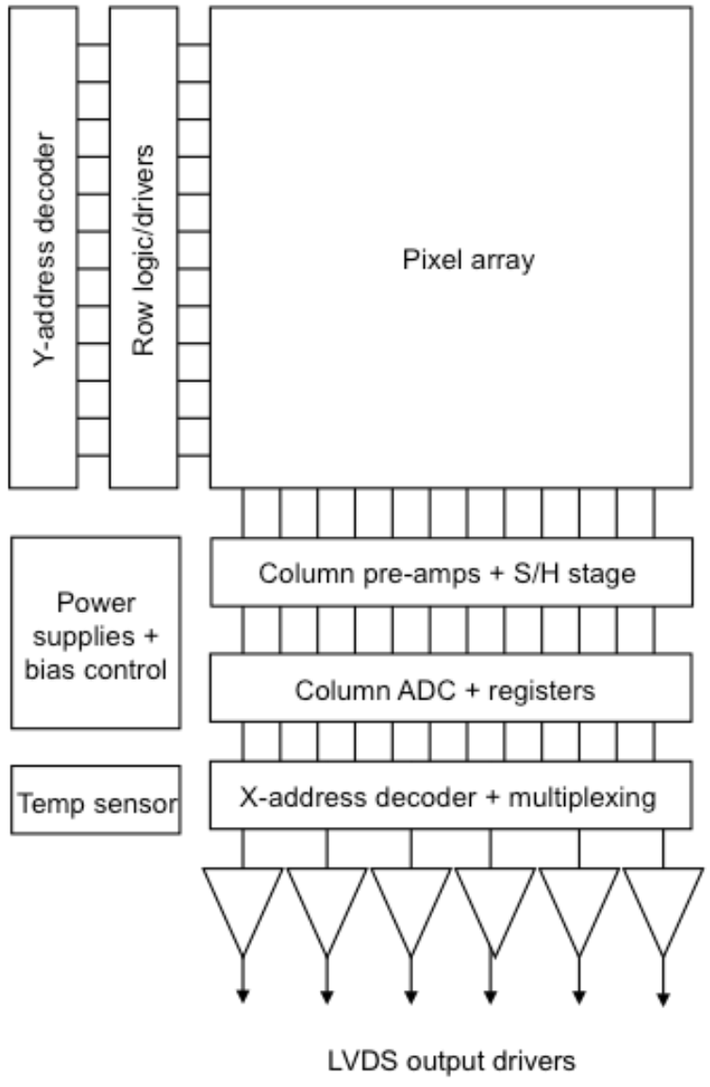


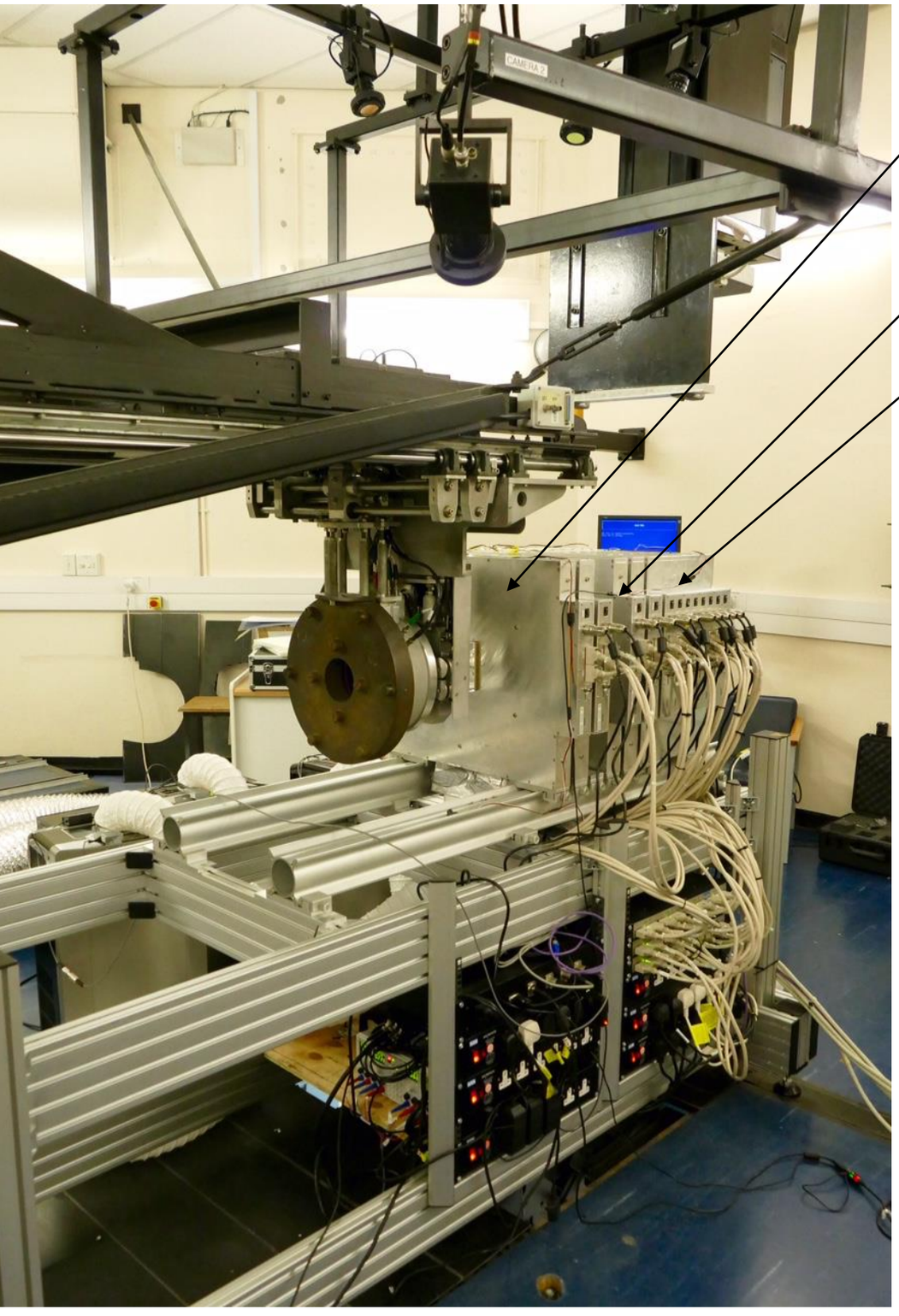


Priapus specification

Parameter	Value
Technology chains	0.35 um CMOS Active Pixel Sensor. Rad-hard pixels and on-chip analogue
Pixel pitch (um)	194
Active area (cm^2)	5 cm × 10 cm - three sides buttable (< 1 pixel loss)
Epitaxial thickness (um)	18
Noise floor (e^-)	~120
Saturation charge (e^-)	< 5×10^5 at <5% non-linearity
ADC Resolution (bit)	8 – 14 programmable step/offset
Frame rate (fps)	>1,000 (expect 1,600)
Readout	Rolling shutter
Region of Interest	One at row selection level







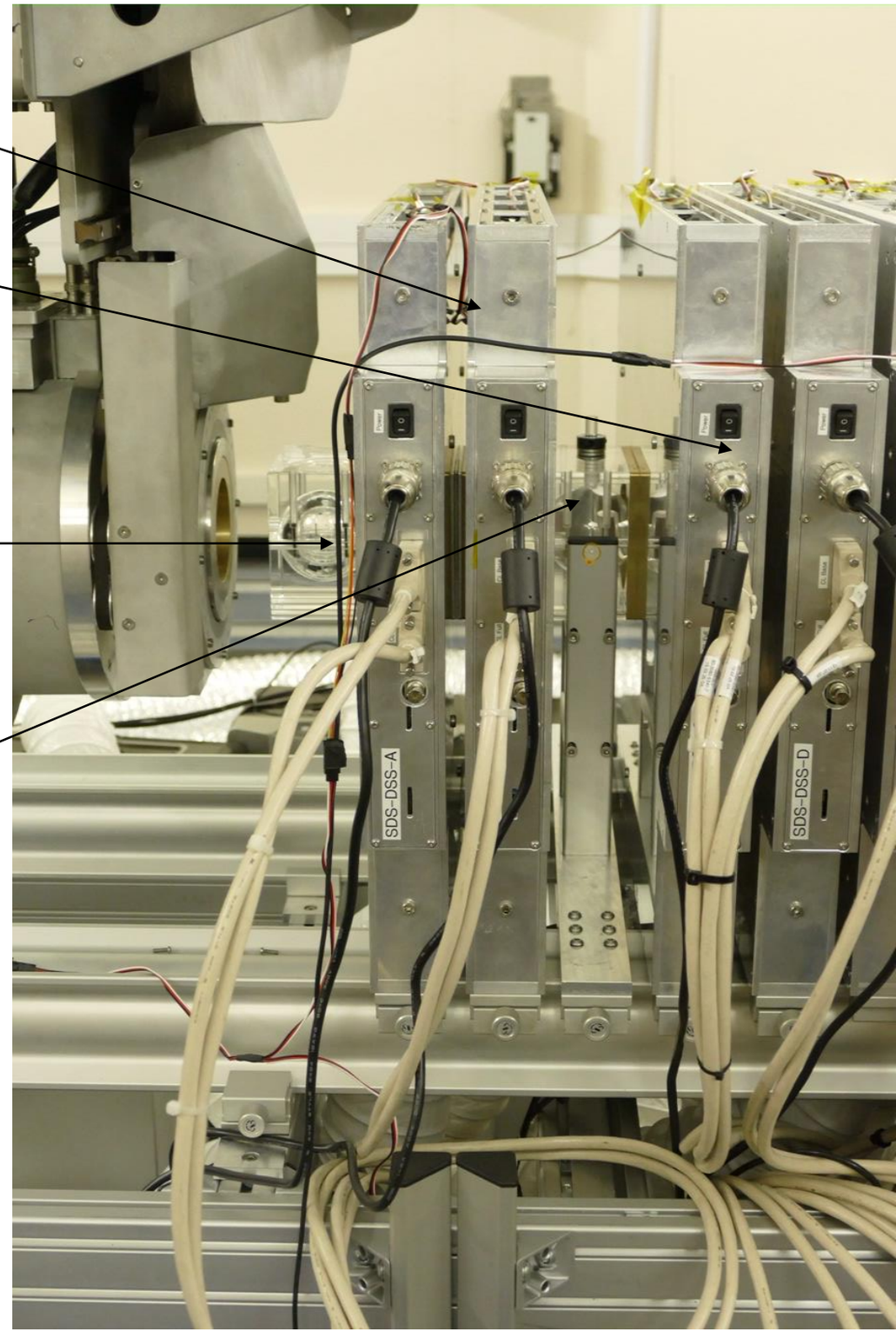
Proximal trackers

Distal trackers

Range telescope

Compensator

Phantom

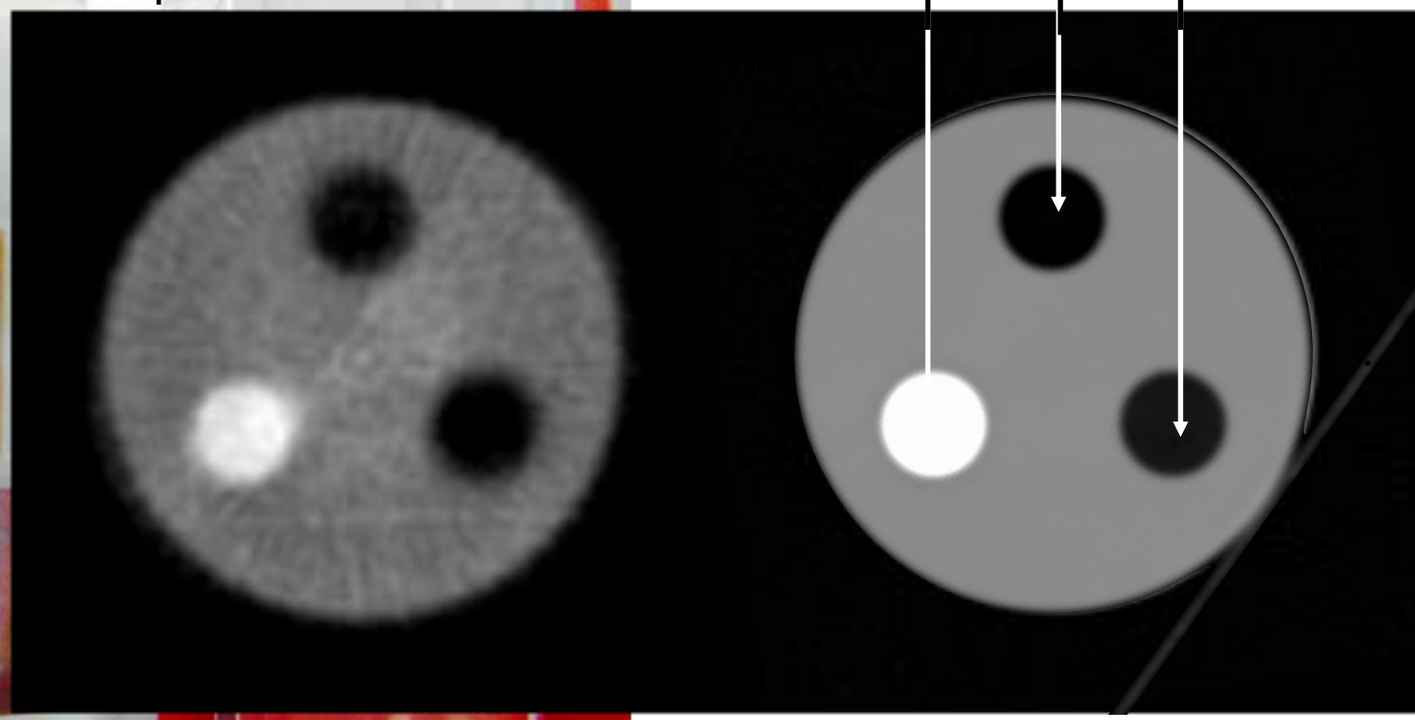


PRaVDA

Relative scattering-power pCT

Only trackers needed

Experimental Result

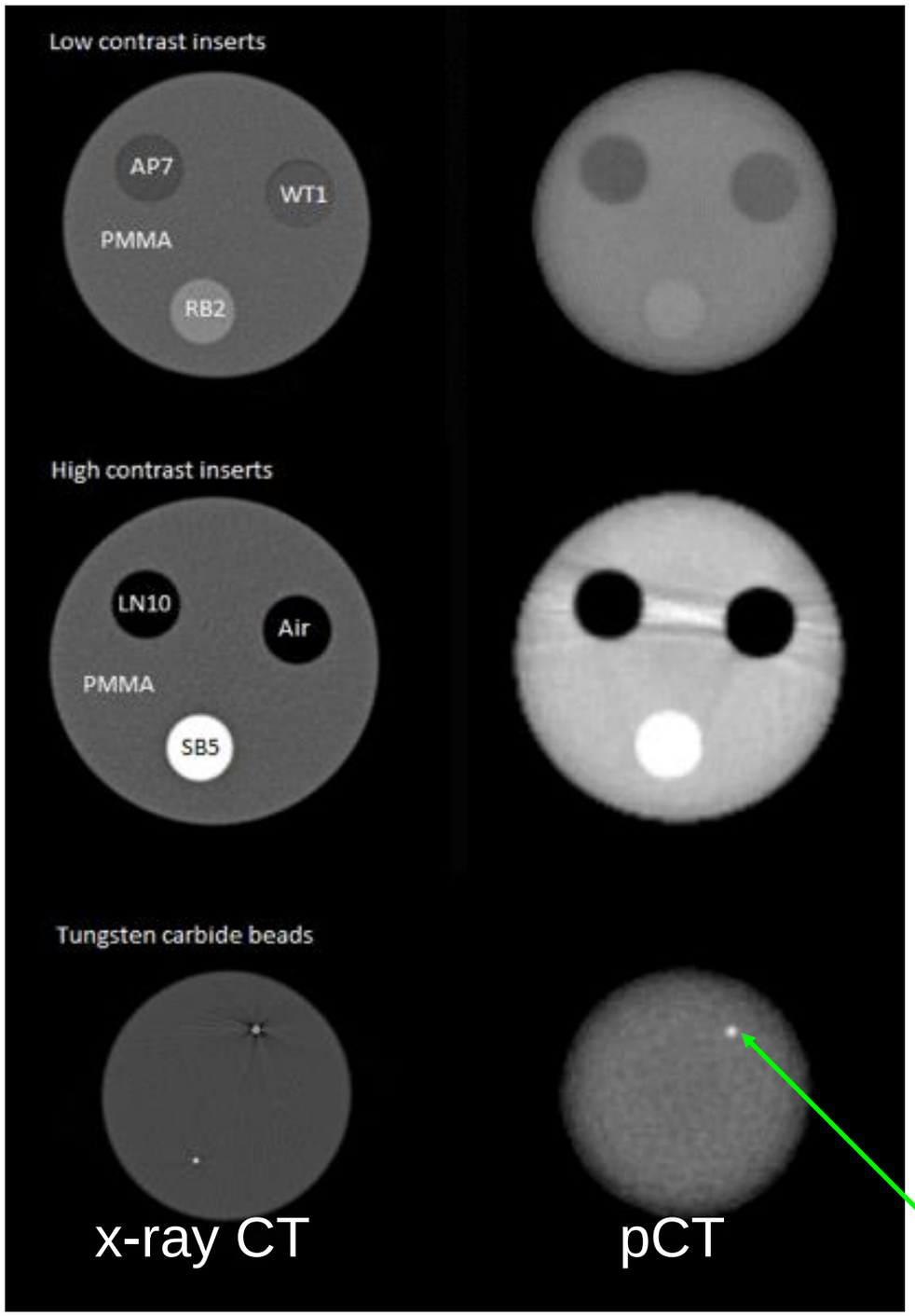


pCT

x-ray CT

Taylor, J. T., et al., (2016), *An experimental demonstration of a new type of proton computed tomography using a novel silicon tracking detector*. Med. Phys., 43: 6129–6136.

Relative stopping-power pCT



Preliminary

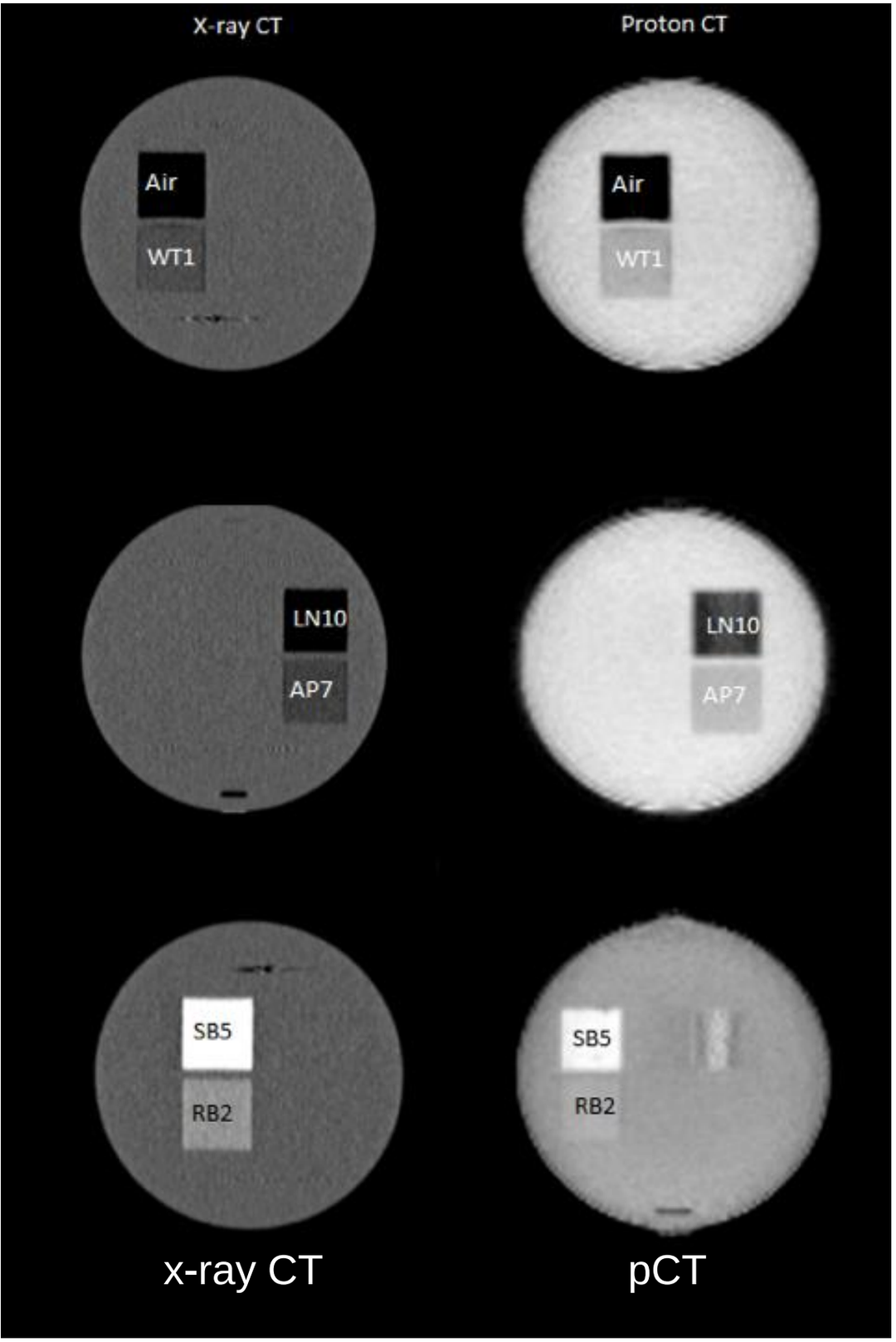
Material	Density [g/cc]	Expected RSP	pCT RSP	Percent error
PMMA	*~1.16*	*1.15*	*1.15*	*0.0*
AP7(adipose)	*0.92*	*0.95*	*0.94*	*-0.7*
WT1(water equivalent)	*1.00*	*1.00*	*0.98*	*-1.6*
RB2 rib/average bone	*1.40*	*1.21*	*1.22*	*1.2*
SB5 hard cortical bone	*1.84*	*1.63*	*1.62*	*-0.4*
LN10 *lung*	0.25-0.35	0.25	0.29*	-*
AIR	0.00	0.00	0.09*	-*

Comparison of known residual stopping power for Leeds Test Objects and as measured using proton CT

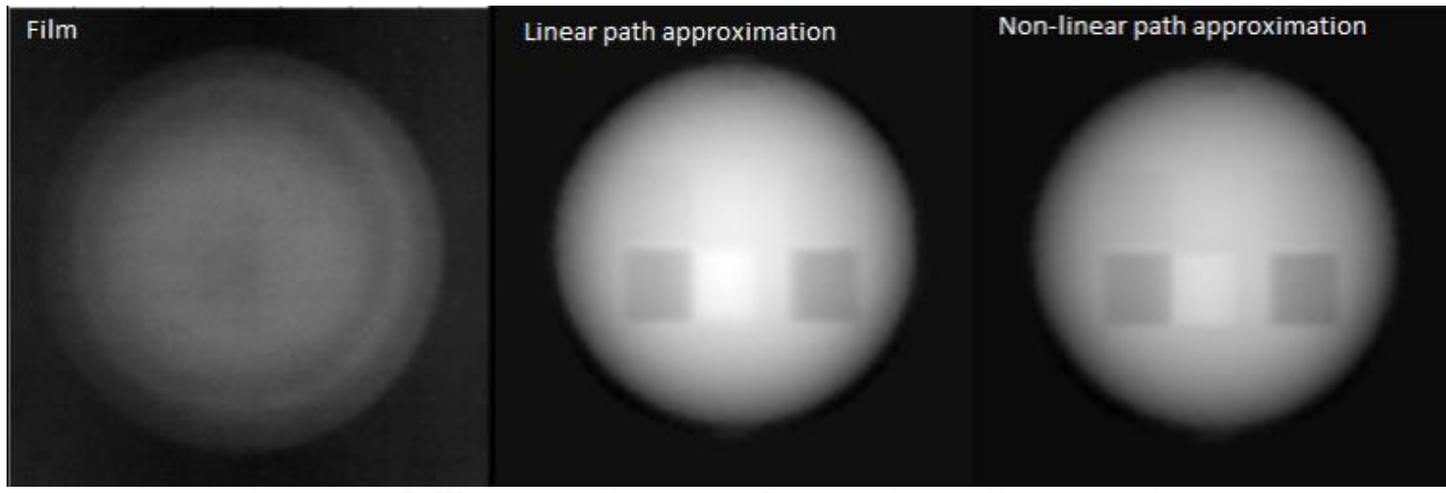
* Image slices containing LN10 insert and air cavity show streak artefacts that compromise quantitative accuracy. For that reason, percentages error is not shown for these two materials.

1 mm diameter sphere

Proton CT slices of 6-insert phantom



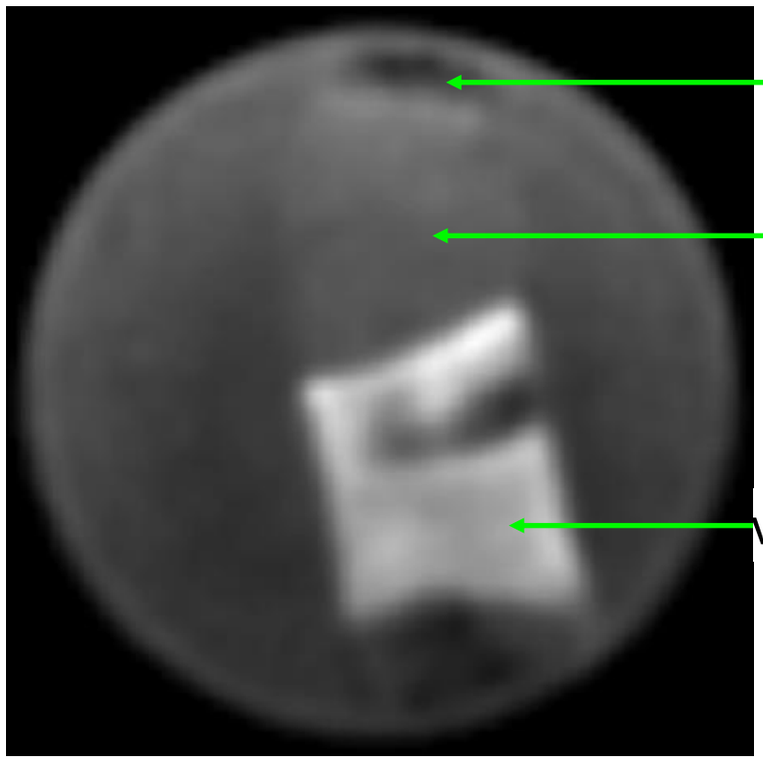
Reconstructed CT image coronal slices of the imaging phant



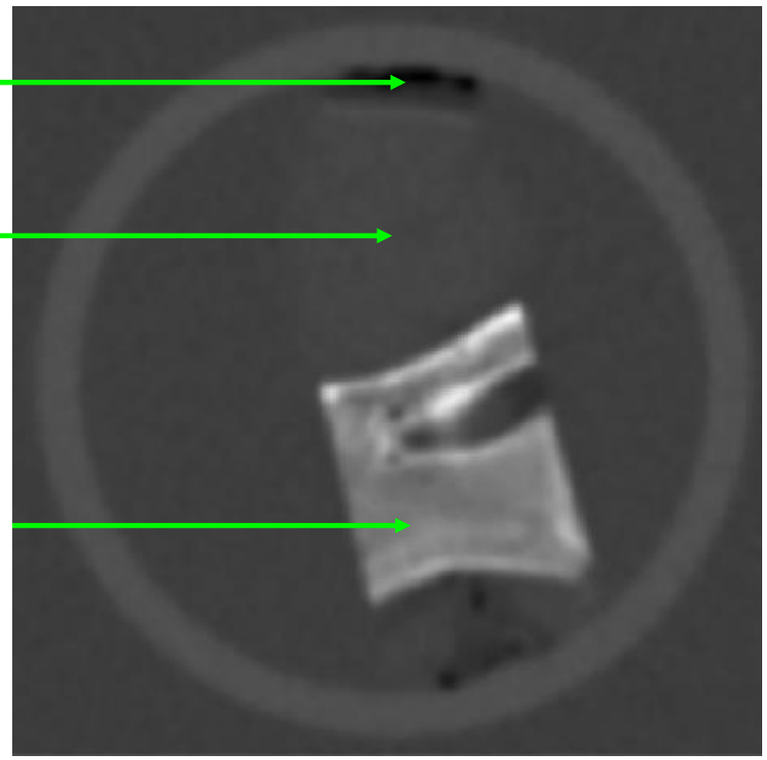
Comparison of film radiograph and radiographs from the PRaVDA system

Preliminary

Proton CT biological sample



Proton CT

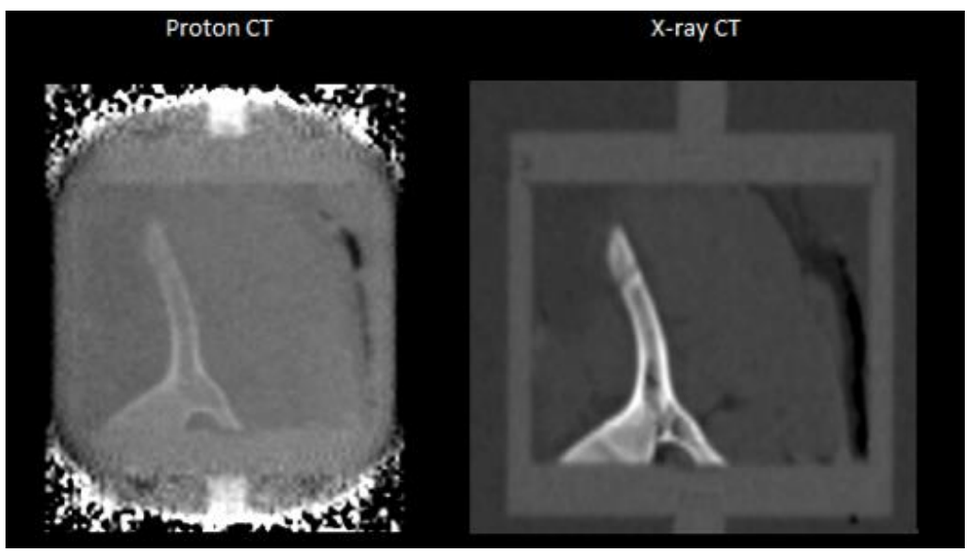


X-ray CT

Lamb chop in agar

Preliminary

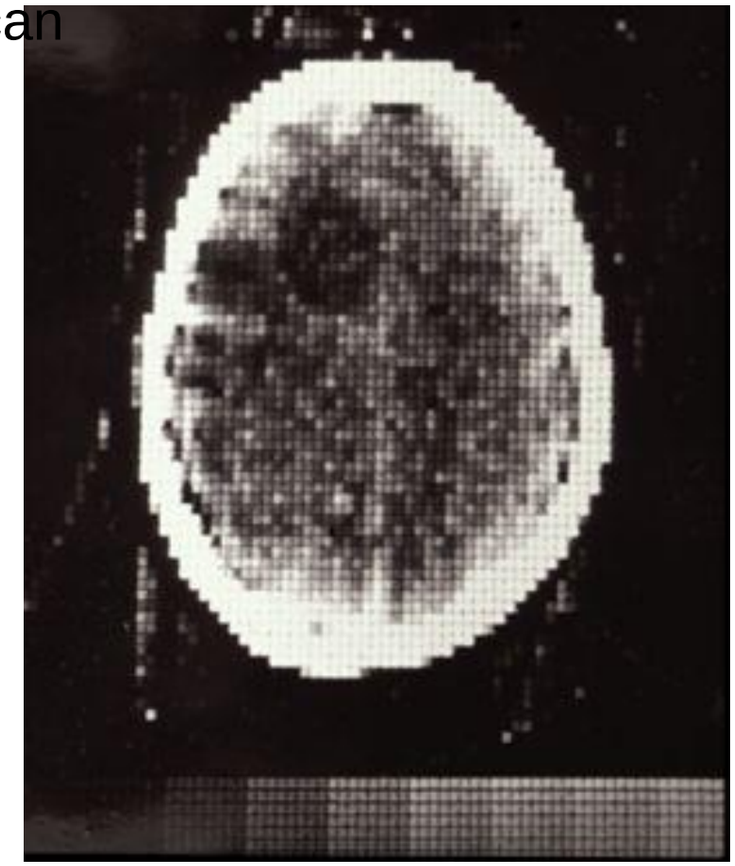
Coronal pCT and 120kV X-ray CT image slices. Fine bone structure is visible in both images. No smoothing has been applied to the pCT image



Conclusions

First clinical CT scan - 1st October 1971 at Atkinson Morley Hospital, London

80 x 80 image, about 5 mins for each scan



Getting there!

Thank you

nallinson@lincoln.ac.uk