MCMA
15-18 October 2017

Monte Carlo simulations for imaging in proton therapy

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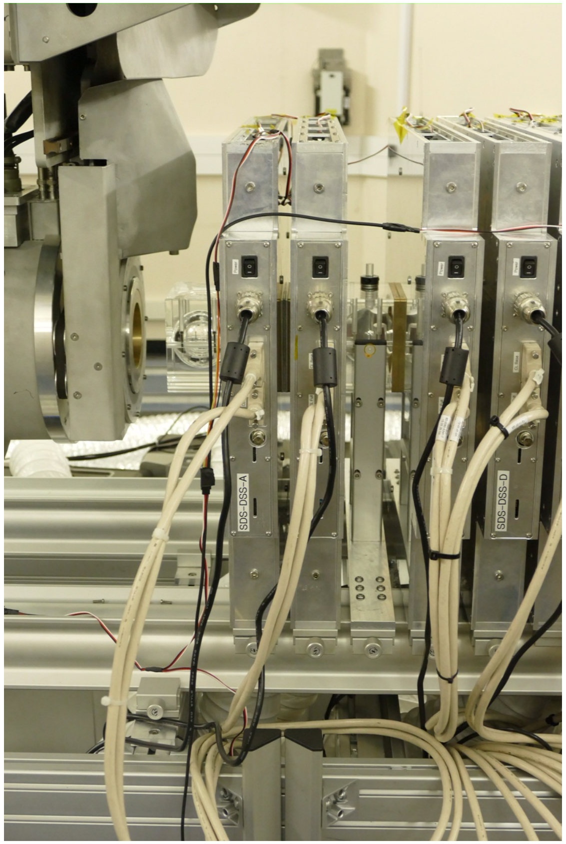
Philip P. Allport, Spyros Manolopoulos, Jaime Nieto-Camero and Nigel M. Allinson

Proton Radiotherapy Verification and Dosimetry Applications

– integrated platform for proton therapy imaging and dosimetry



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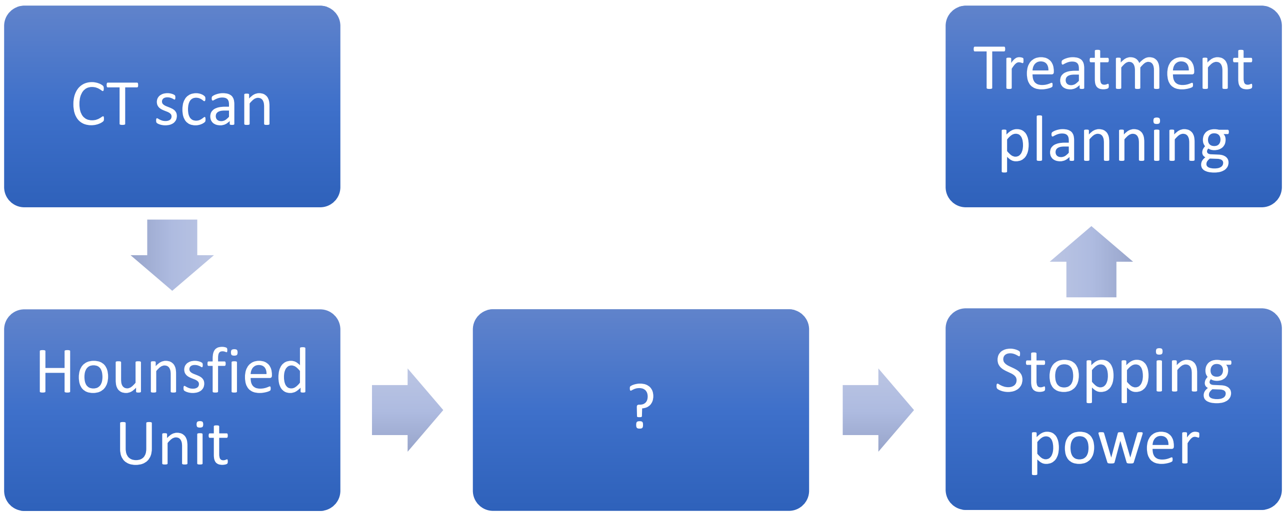
- University Hospital Coventry and Warwickshire NHS Trust
- National Research Foundation (NRF) - iThemba LABS, SA
- United Lincolnshire Hospitals NHS Trust
- The Christie NHS Foundation Trust

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

Funded by wellcome trust

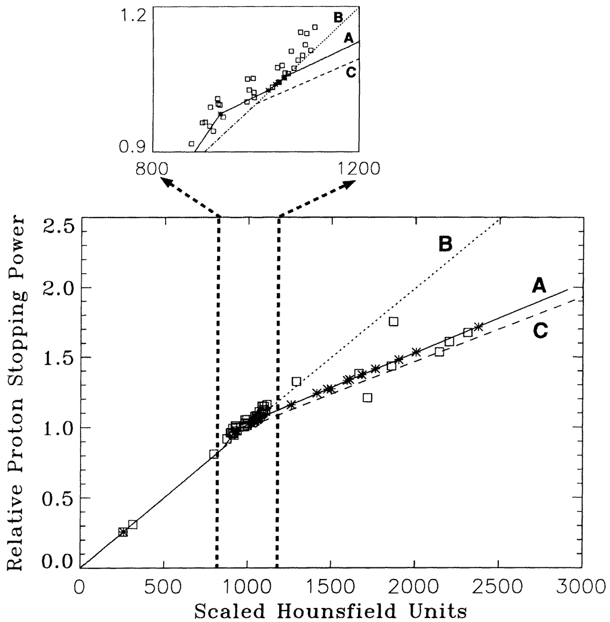
Grant Number 098285

Why do we need proton CT?



Why do we need proton CT?

Stoichiometric calibration



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

IOP PUBLISHING PHYSICS IN MEDICINE AND BIOLOGY

Phys. Med. Biol. **57** (2012) R99–R117 doi:10.1088/0031-9155/57/11/R99

TOPICAL REVIEW

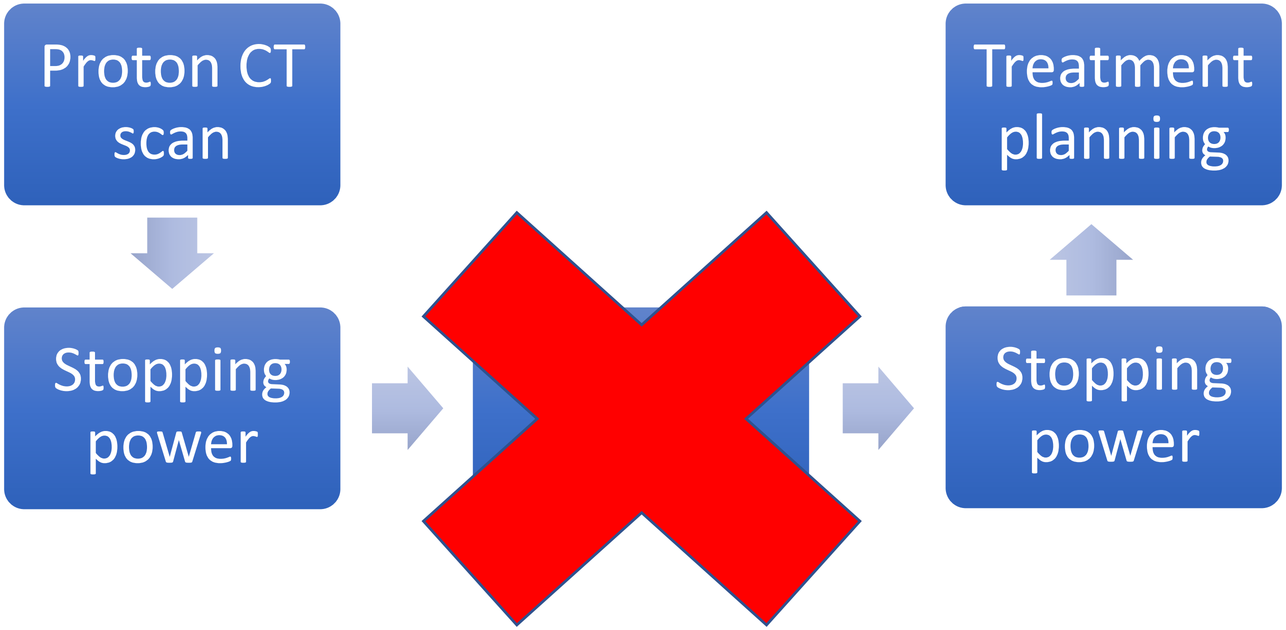
Range uncertainties in proton therapy and the role of Monte Carlo simulations

Harald Paganetti

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) ^	+~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 *, ^)	2.7% + 1.2 mm	2.4% + 1.2 mm
Total (excluding ^)	4.6% + 1.2 mm	2.4% + 1.2 mm

Uncertainty in proton stopping power leads to uncertainty in where protons stop

Why do we need proton CT?

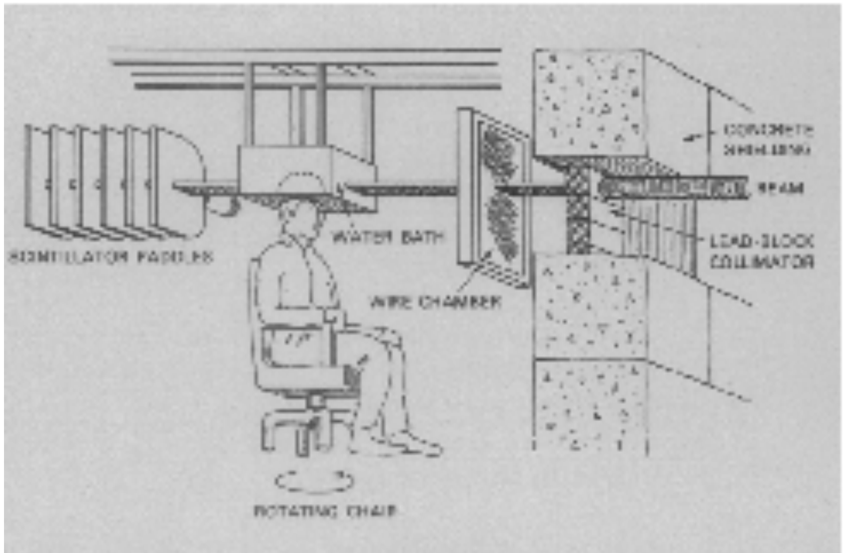


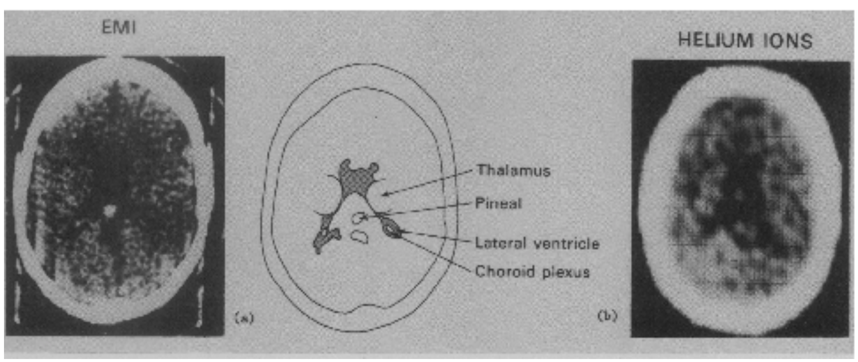
Aim to reduce stopping power uncertainty to 1%

HADRON COMPUTED TOMOGRAPHY

A 40 years old idea

The first alpha scanner ever trialled on humans





The next application of the solution [for Computed Tomography]... concerns the recent use of the peak in the Bragg curve for the ionisation caused by protons, to produce small regions of high ionisation in tissue. The radiotherapist is confronted with the problem of determining the energy of the incident protons necessary to produce the high ionisation at just the right place, and this requires knowing the variable specific ionisation of the tissue through which the protons must pass.

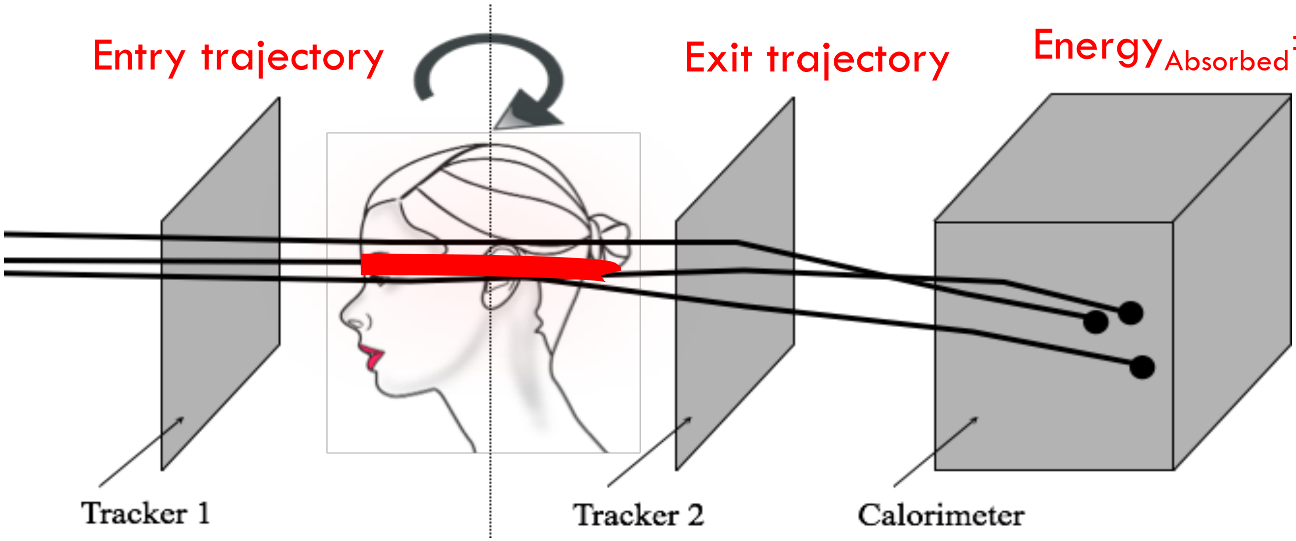
A. M. Cormack. Representation of a Function by Its Line Integrals, with Some Radiological Applications. Journal of Applied Physics, 34(9), 1963.

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

Basics of proton CT

Entry trajectory
Exit trajectory
$\text{Energy}_{\text{Absorbed}}$

} Repeat millions of times!



$\text{Energy}_{\text{Absorbed}} = \text{Energy}_{\text{Beam}} - \text{Energy}_{\text{Residual}}$

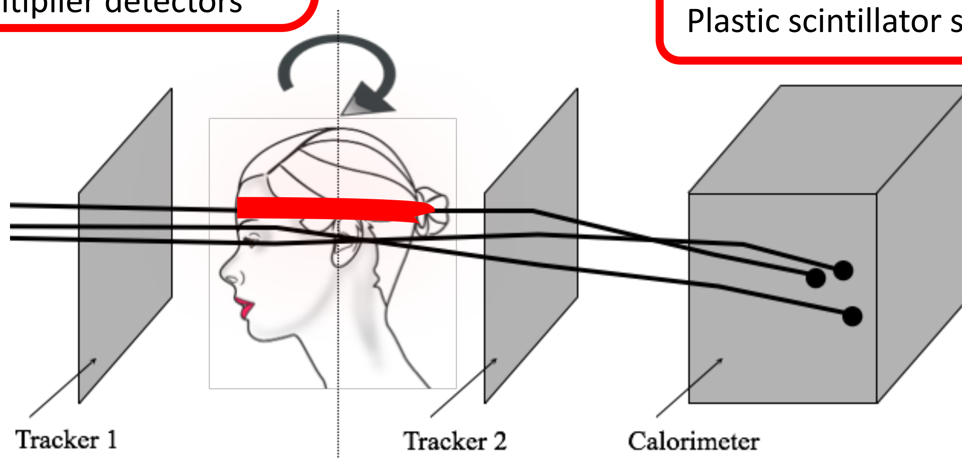
G. Poludniowski et al., Br J Radiol 2015; 88: 20150134.

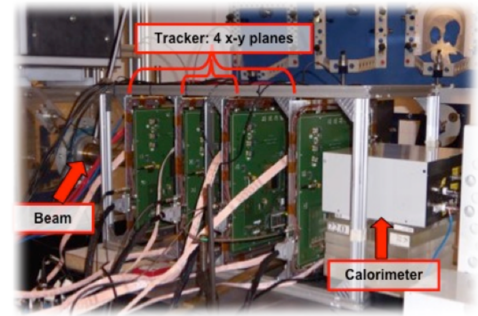
Category	Parameter	Value
Proton beam	Energy	≥200 MeV (head)
		≥250 MeV (body)
	Flux[a]	≥3000 protons $cm^{-2}s^{-2}$
Imaging dose	Maximum absorbed dose[b]	<20 mGy
Image quality	Spatial resolution, σ	≈1 mm
	Relative stopping-power accuracy	<1%
Time	Data acquisition time	<10 min
	Reconstruction time	<10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

Basics of proton CT

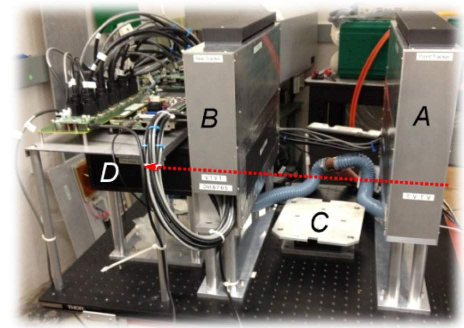
Multi-wire Proportional Chambers
Double-Sided Strip Detectors
Scintillating Fibres Hodoscopes
Gas Electron Multiplier detectors

Scintillator-based calorimeter
Plastic scintillator stack

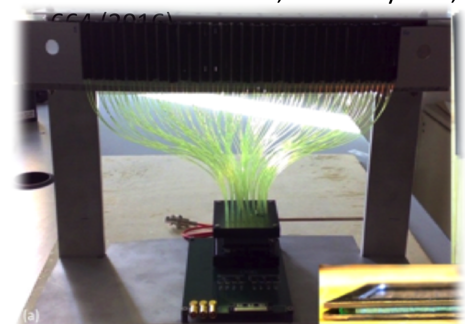




V. Sipala et al., POS (RD11) 013, 2011

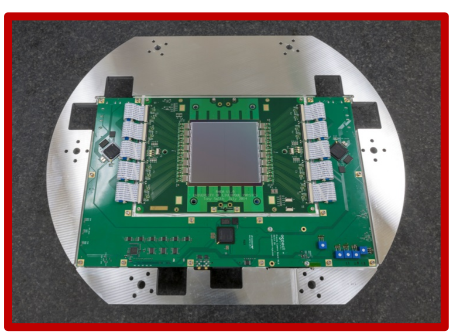


V.A. Bashkirov et al., Med. Phys. **43**,



D. Lo Presti et al., J. Inst. 9, C06012, 2014

PRaVDA

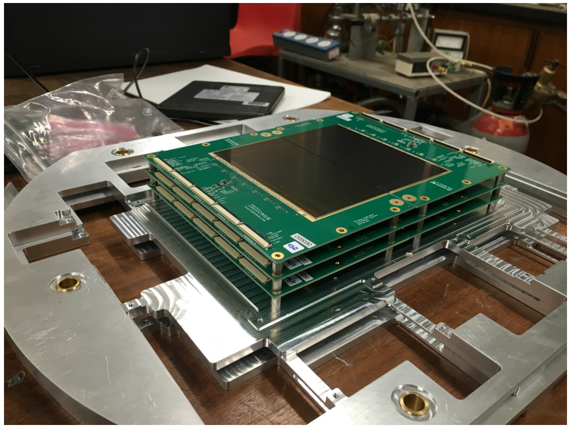


The first solid-state energy-range detector for proton CT.

Unlike calorimeters, position sensitive detectors allow for multiple proton tracks to be detected in a single readout cycle potentially reducing CT scan times.

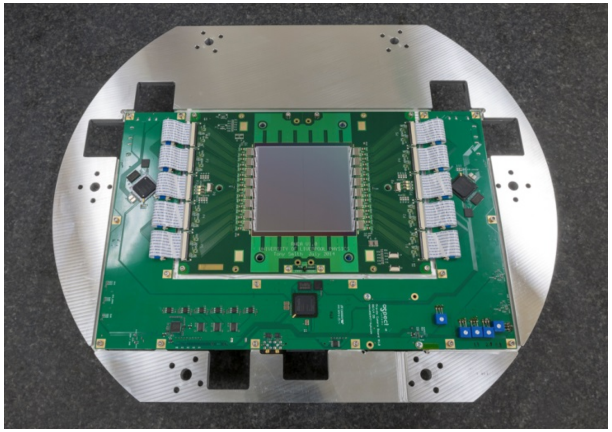
Detector technology

CMOS Active Pixel Sensors



- 2D-positional detectors
- Analog readout
- kHz readout (high occupancy per R/O cycle)
- Moderately radiation tolerant
- Mosaic tiling of edge-less sensors to cover larger areas
- High material budget

Silicon Strip Sensors



- 1D-positional detectors
- Binary readout (in our implementation)
- MHz readout (low occupancy per R/O cycle)
- Radiation tolerant to LHC doses
- Dead areas when tiling to larger areas
- Low material budget

The PRaVDA proton CT system

2 tracking units

- 4 sets of 3 layers of Silicon Strip Detectors (SSD)
- Crossed at 60°

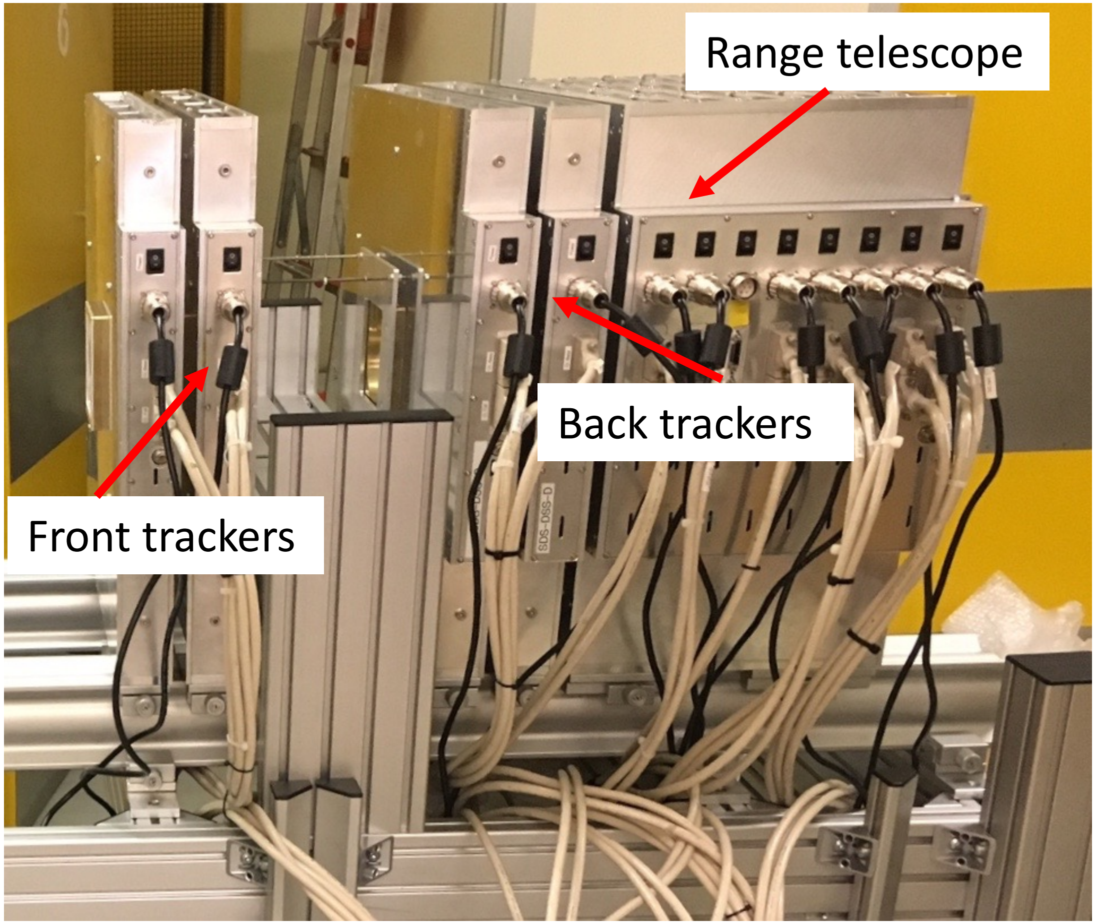
Range Telescope

- 21 layers (SSD)
- 1D tracking

Readout frequency = 26 MHz

Max hit rate = 2×10^8 hits/second (uniform field)

Total data throughput = 66 Gb/s



Why do we need a Monte Carlo simulation?

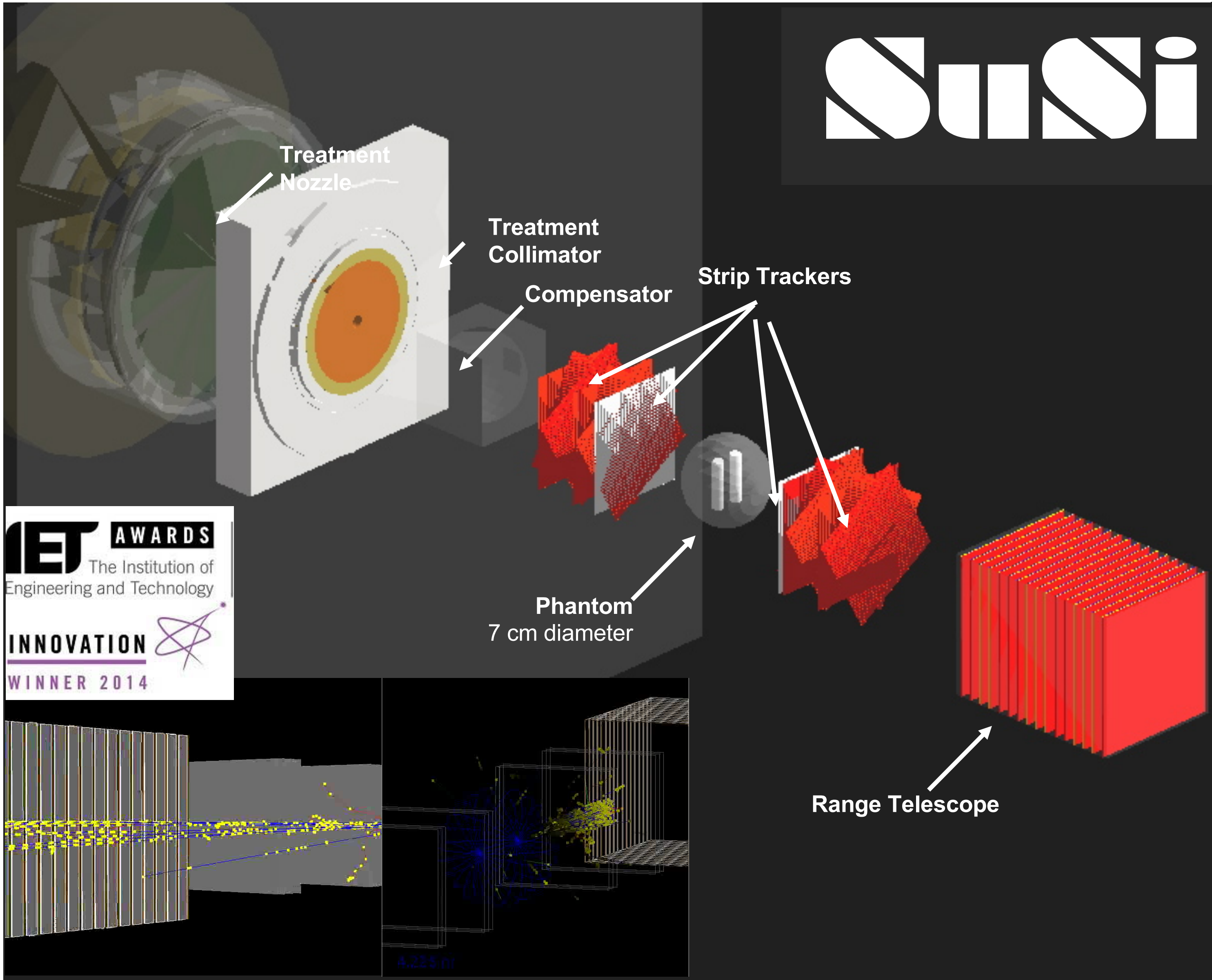
Detector design

- 2 different technologies
- SSD derived from HEP
- CMOS sensors derived from medical imaging

Radiation tolerance and shielding

Tracking algorithms (trackers and range telescope)

CT reconstruction algorithms



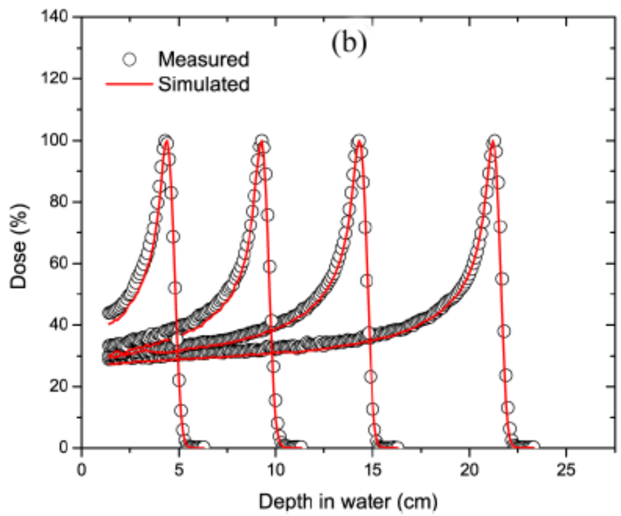
Geant 4.10.1
Standard opt_3
QGSP_BIC

University of Birmingham BlueBEAR HPC cluster and GridPP

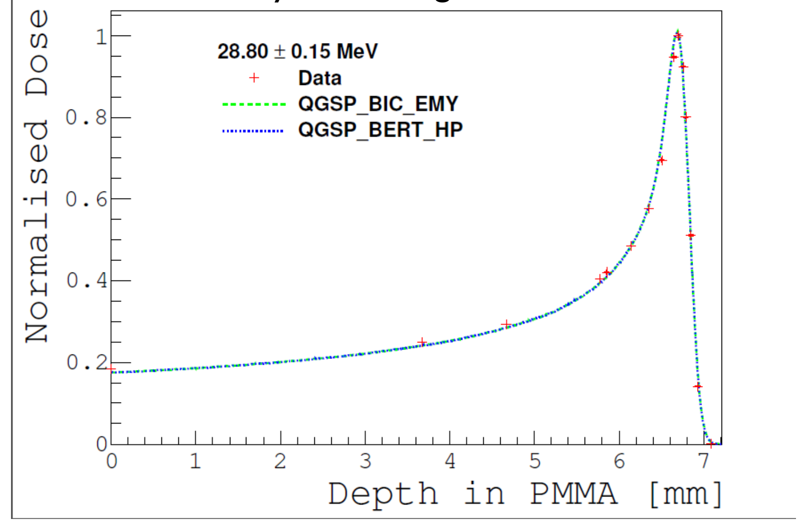
More details on beam line models in **Tony Price**'s talk yesterday: "Code sharing of MC beam models for advanced radiotherapy" (ID: 201) and poster "A validated model of the University of Birmingham Medical Beamline (ID:248)

SuSi – validation results

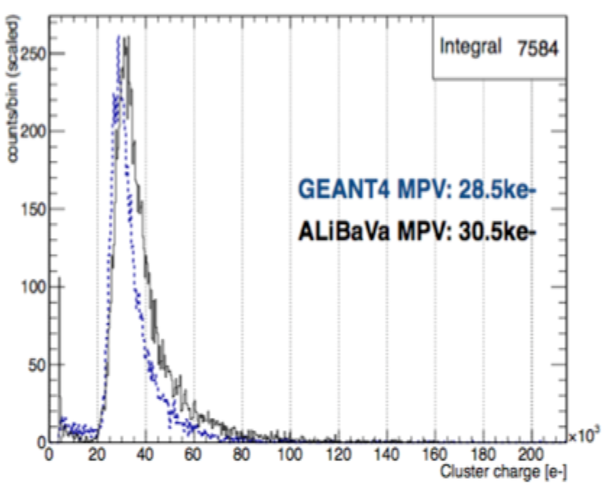
iThemba beamline



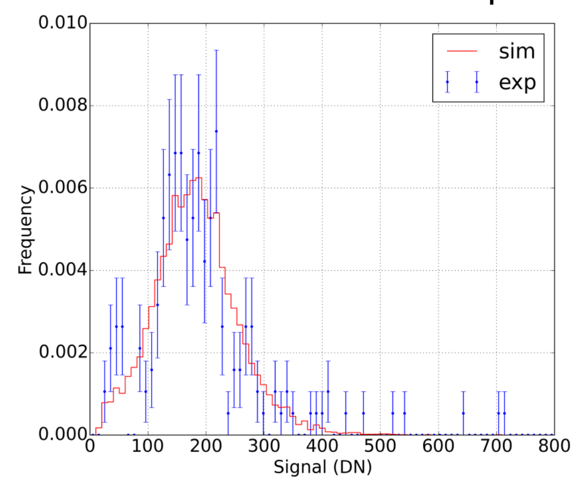
University of Birmingham beamline



SDS – 191 MeV p

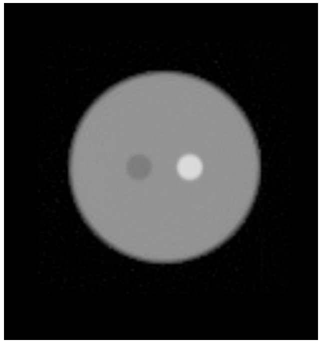


CMOS sensor – 29 MeV p

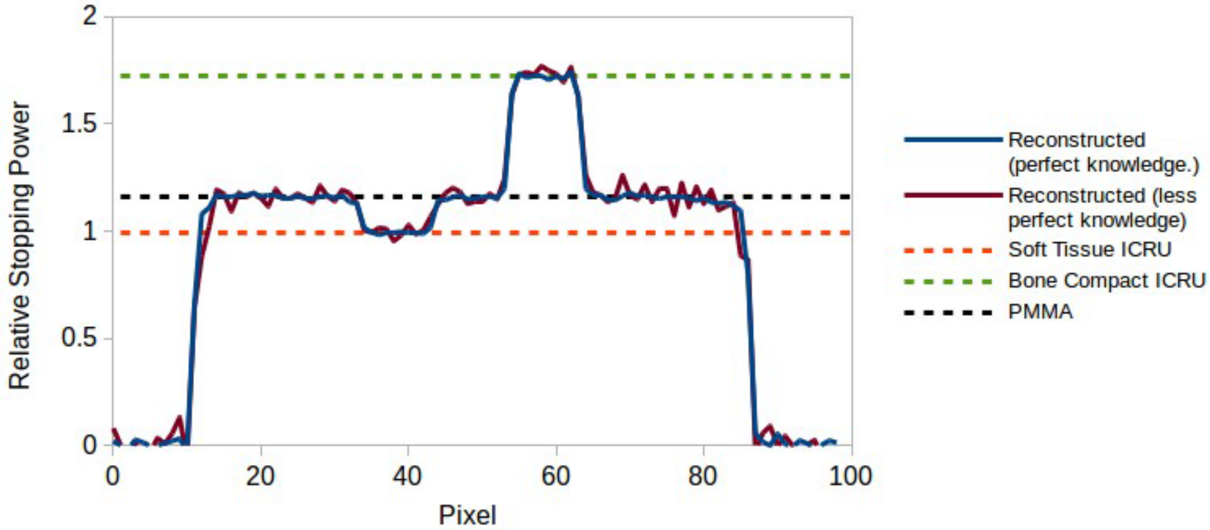


Proton CT reconstruction algorithm

Novel algorithm for CT reconstruction:
Back projection-then-filtering



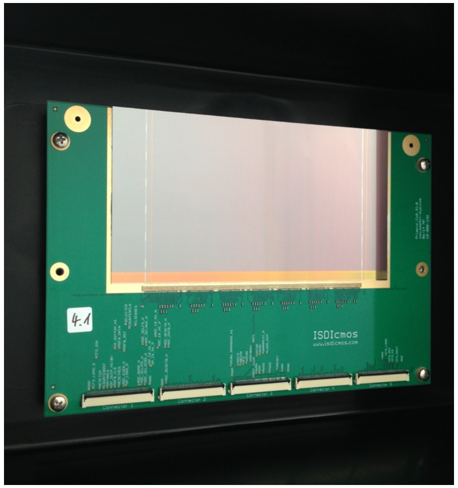
Stopping power uncertainty <0.2%



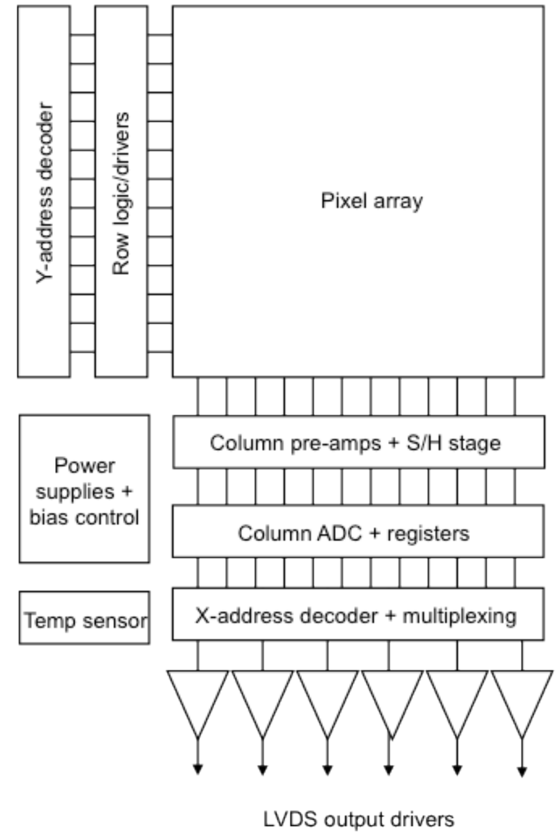
Poludniowski, G., Allinson, N.M. and Evans, P.M., 2014. Proton computed tomography reconstruction using a backprojection-then-filtering approach. *Physics in medicine and biology*, *59*(24), p.7905.

PRaVDA

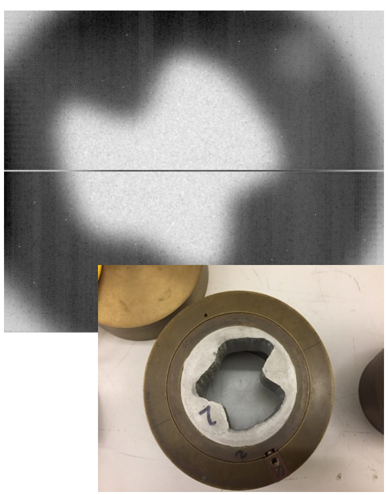
The PRaVDA CMOS imager



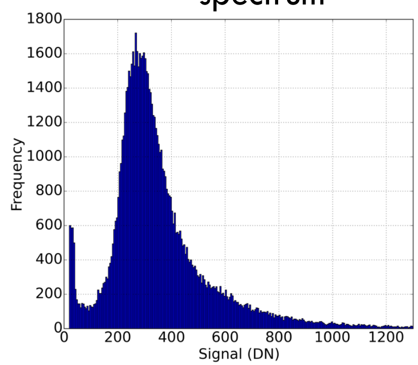
Design specifications:
- 0.35 μm technology
- 5 cm ×10 cm imaging area
- 3-side buttable
- 194 μm pixel
- 150 e- noise floor
- 1kHz frame rate (11 bits)



Patient collimator



29 MeV protons signal spectrum



Further readings:
M. Esposito et al, J. Inst 2015; 10 (06), C06001
T. Price et al., J. Inst. 2015;10 (05), P05013
G. Poludniowski et al., Phys. Med. Biol. **59** (2014) 2569–2581

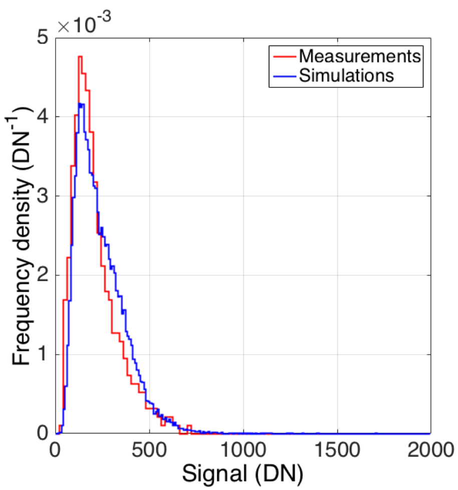
PRaVDA

Charge sharing model

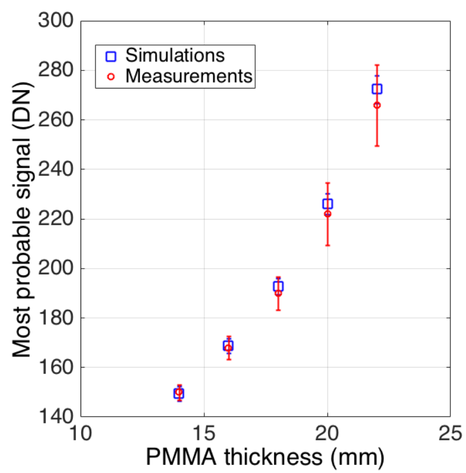
Charge generation → Charge diffusion → Charge collection → Parametric charge sharing → Digitisation

Geant4-based simulations of charge collection in CMOS Active Pixel Sensors, M. Esposito et al., Jinst 12 P03028, 2017

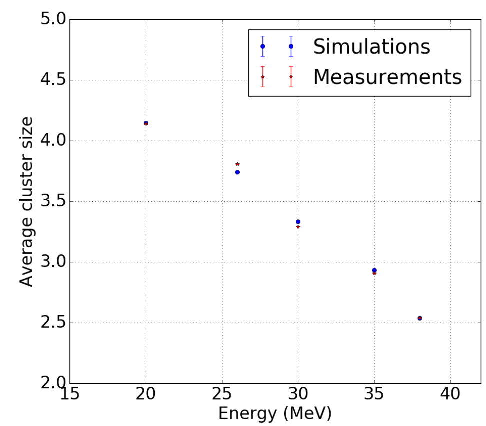
Validation results



Signal spectrum(38 MeV p)

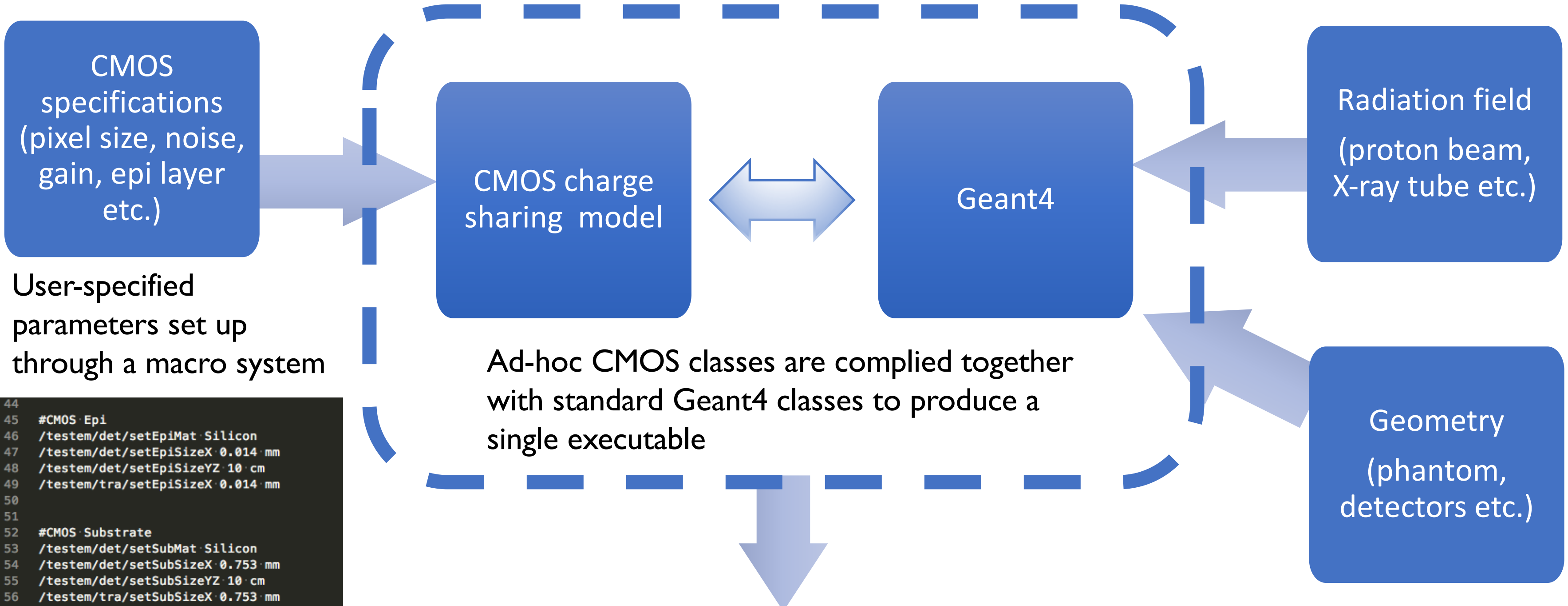


Most probable signal (20-38 MeV p)



Average cluster size (20-38 MeV p)

Integration into the Geant4 toolkit



User-specified parameters set up through a macro system

```

#CMOS Epi
/testem/det/setEpiMat Silicon
/testem/det/setEpiSizeX 0.014 mm
/testem/det/setEpiSizeYZ 10 cm
/testem/tra/setEpiSizeX 0.014 mm


#CMOS Substrate
/testem/det/setSubMat Silicon
/testem/det/setSubSizeX 0.753 mm
/testem/det/setSubSizeYZ 10 cm
/testem/tra/setSubSizeX 0.753 mm

```

Ad-hoc CMOS classes are complied together with standard Geant4 classes to produce a single executable

Flexible tool which can simulate commercial CMOS sensors for any medical application (radiography, portal imaging etc.)

A CMOS image
Each pixel value corresponding to the expected DN, given the experimental parameters and the detector specifications

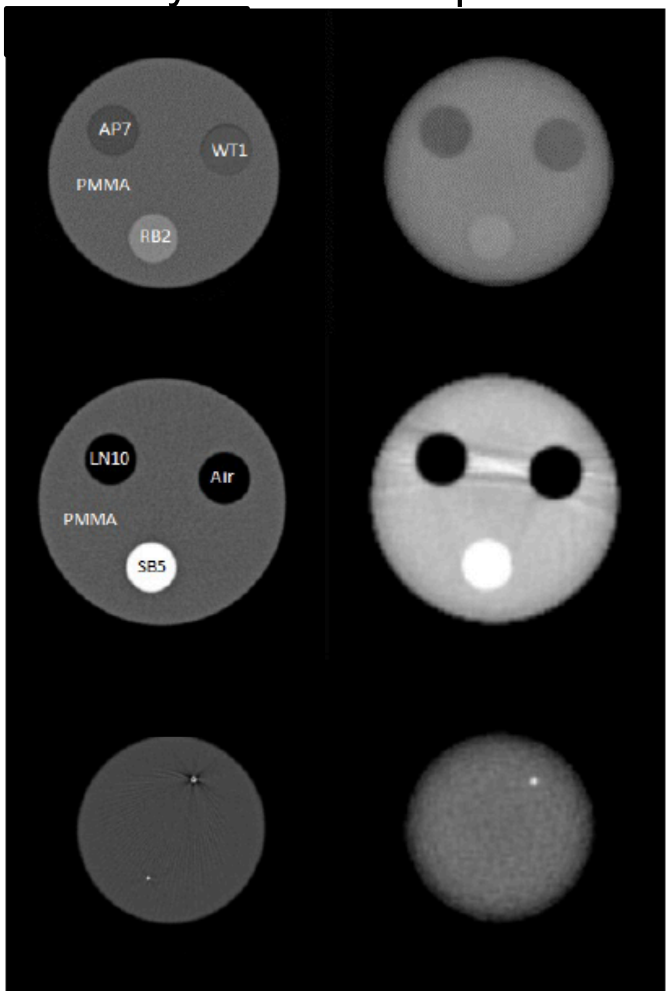
PRaVDA proton CT

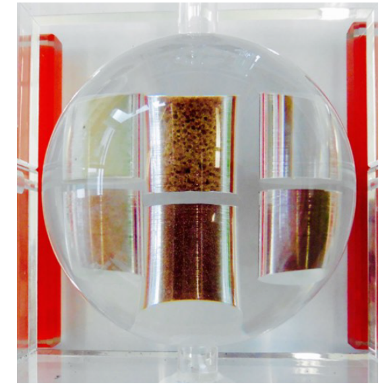
X-ray CT pCT

Low contrast

High contrast

W beads





Material	Density [g/cm^3]	Expected RSP	pCT RSP	Percent error
PMMA	~1.16	1.15	1.15	0.0
AP7	0.92	0.95	0.94	-0.7
WT1	1.00	1.00	0.98	-1.6
RB2	1.40	1.21	1.22	1.2
SB5	1.84	1.63	1.62	-0.4
LN10	0.25-0.35	0.25	0.29*	-
AIR	0.00	0.00	0.09*	-

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

Conclusions

- PRaVDA has developed 2 solid-state technologies for proton CT
- Design heavily relied on MC simulations
- Simulation of charge sharing in CMOS Active Pixel Sensors
- Model of a multi-step process from e/h pair generation to digitalisation
- Flexible tool to be integrated into Geant4
- Developed for proton CT but can be seamlessly extend to:
  - Different commercial CMOS sensors (just setting sensor specs)
  - Different radiation field/geometry
  - E.g. radiography, mammography, portal imaging, fluoroscopy etc.
- Happy to share the code for different applications/experiments

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- On our first proton CT stopping power uncertainty equal or lower of 1.6% - preliminary analysis

Acknowledgments

University of Lincoln
Grainne Riley
Chris Waltham
Nigel Allinson

University of Birmingham
David Parker
Tony Price
Ben Phoenix
Phil Allport

University of Liverpool
Jon Taylor
Gianluigi Casse,
Tony Smith,
Ilya Tsurin

University of Surrey
Phil Evans

University of Warwick
Sam Manager
Jon Duffy

Karolinska University Hospital, Sweden
Gavin Poludniowski

University Hospital Birmingham NHS Foundation Trust
Stuart Green

University Hospital Coventry and Warwickshire NHS Trust
Spyros Manolopoulos

iThemba LABS, SA
Jaime Nieto-Camero
Julian Symons

ISDI
Thalis Anaxagoras
Andre Fant
Przemyslaw Gasiorek
Michael Koeberle

aSpect
Marcus Verhoeven
Daniel Welzig
Daniel Schöne
Frank Lauba

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