# From PRaVDA to OPTIma: challenges in designing a clinical pCT system


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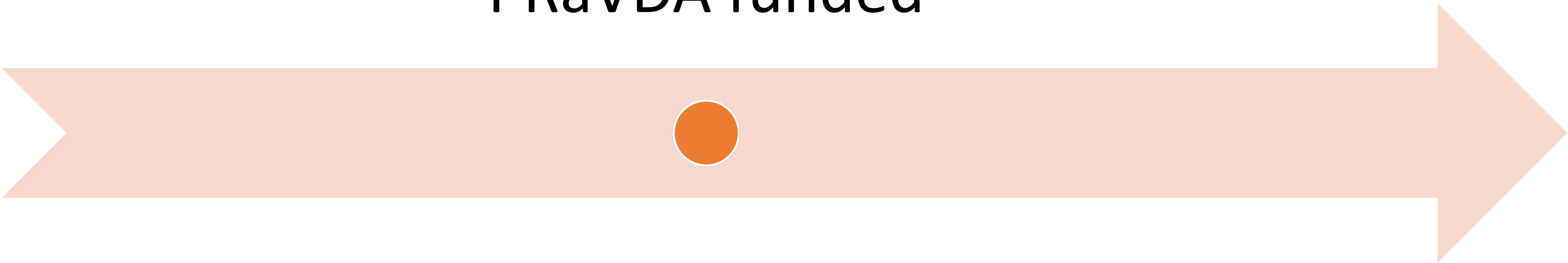
University of Lincoln


23.07.2019

**5h Annual Loma Linda workshop on Algorithms in Particle Imaging and Treatment Planning Workshop**

# 2013

# PRaVDA funded



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Nigel Allinson

**University of Birmingham**
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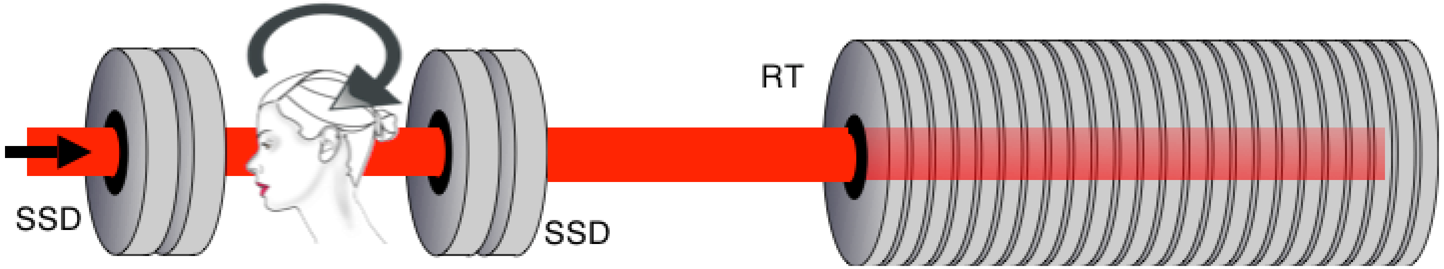
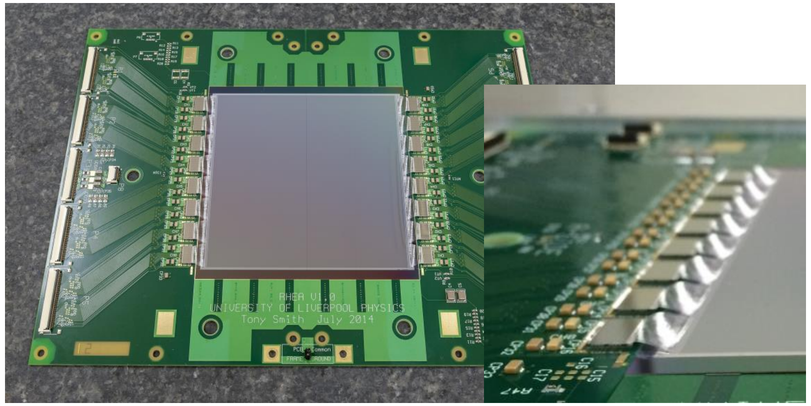
PRaVDA

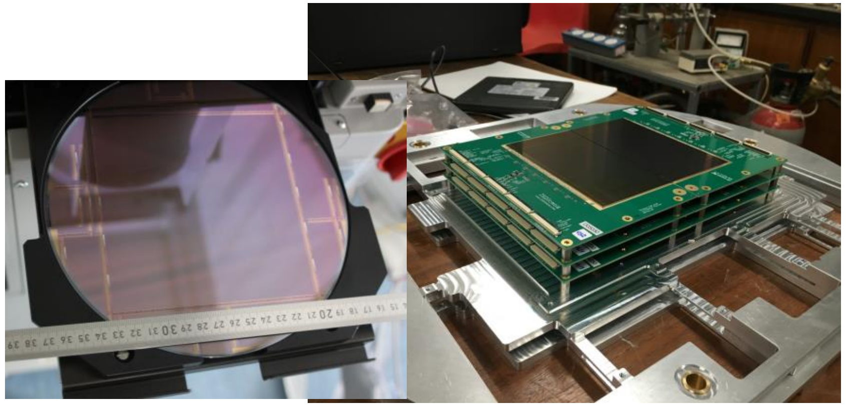

# PRaVDA: what we had in mind – system




Silicon Strip Detectors

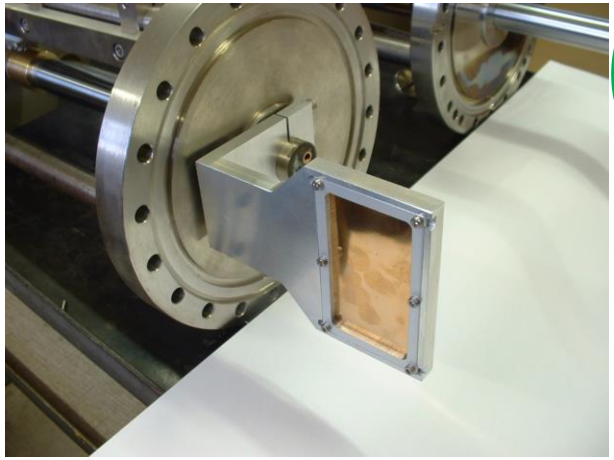


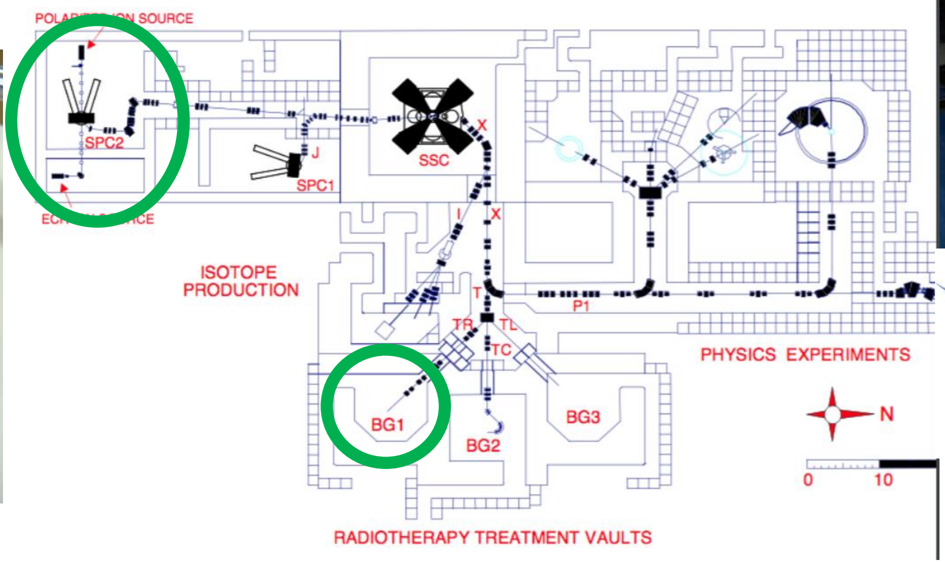
CMOS Active Pixel Sensors

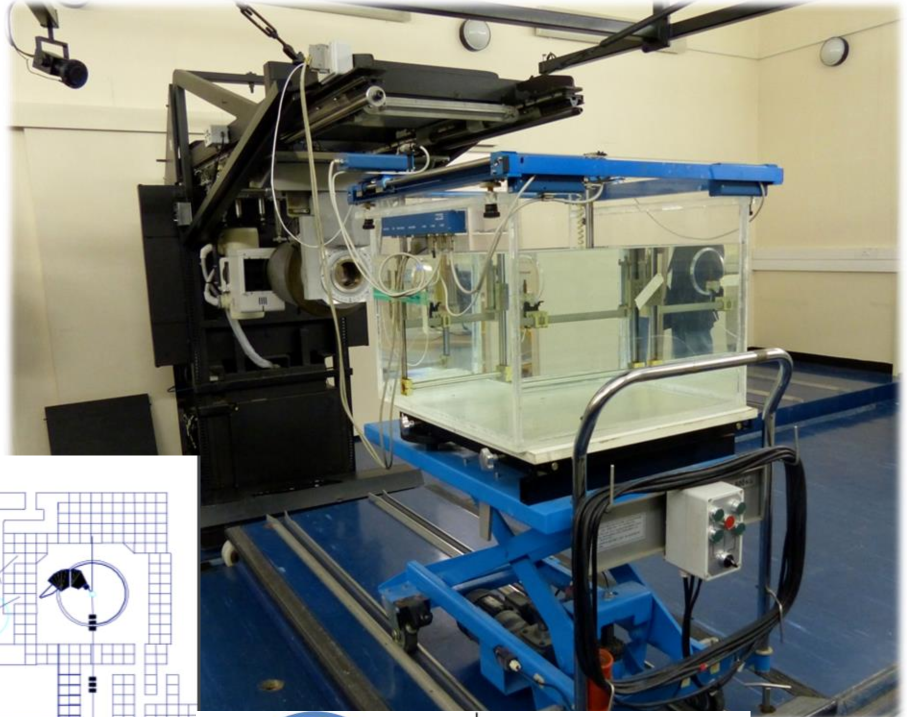


# PRaVDA: what we had in mind – facility

- Passively scattered beam
- 191 MeV – max energy
- "Research" ion source
- Mesh filters to attenuate flux ($10^{-2}$-$10^{-4}$)





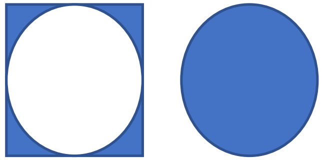



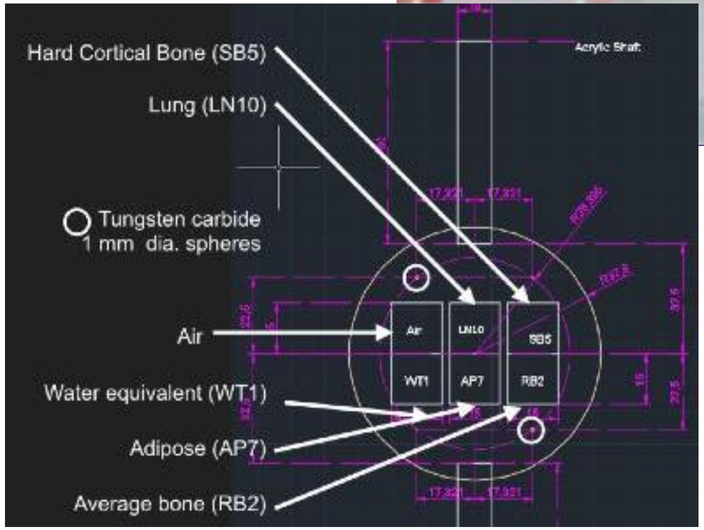
NRF National Research Foundation

iThemba LABS Laboratory for Accelerator Based Sciences

# PRaVDA: what we had in mind – pCT scan

- Size of phantom set by size of detectors
- Proof of concept demonstrator
- 75 mm ⌀ PMMA phantom
- 6×15 mm ⌀ tissue equivalent inserts
- 125 MeV p
- Range compensator






- Not aiming for a clinical usable scan time, but need to identify a clinically scalable route

2013

PRaVDA funded

2014

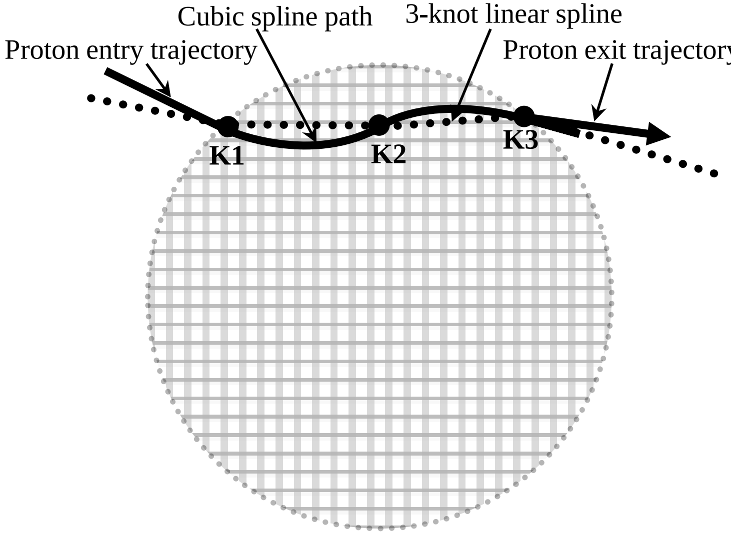
Reconstruction algorithm

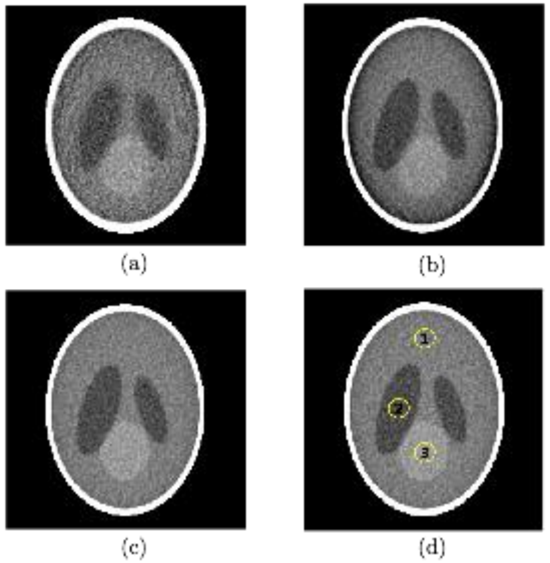
G Poludniowski, N M Allinson and P M Evans "Proton Computed Tomography reconstruction using a backprojection-then-filtering approach", Phys Med Biol. 59:7905-7918 (2014)

# Backprojection-then-filtering (BPF) algorithm

Sampling ray-projections through a 2D slice → Backprojecting the ray-projections through a 2D rec. matrix → Convolving (or filtering) this 2D matrix of data with a 2D kernel → Repetition over a set of angles

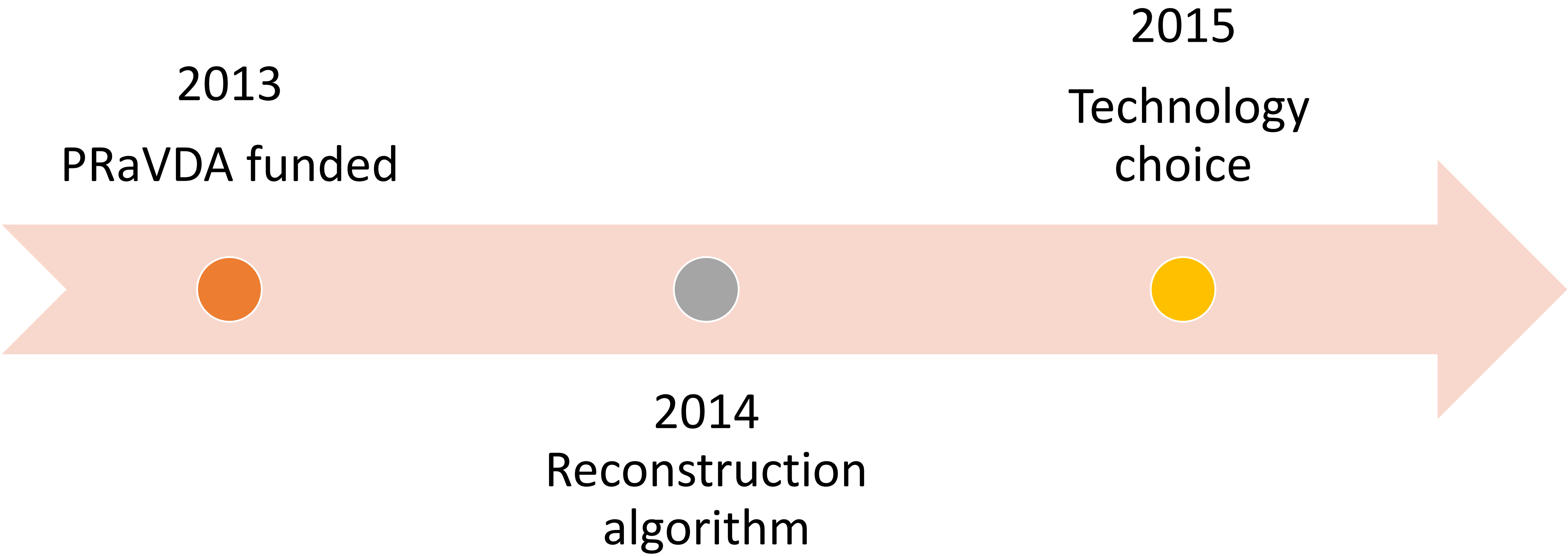
- Naturally deals with list mode data, without need for binning
- Naturally accommodates non-linear proton paths



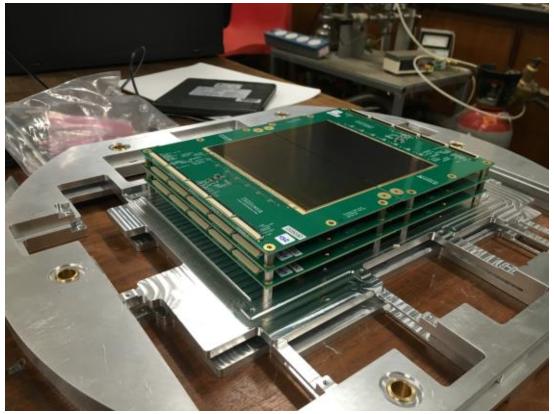

Back-Projection Filtered (BPF)
Filtered Back-Projection (FBP)

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


2013
PRaVDA funded
2014
Reconstruction algorithm
2015
Technology choice

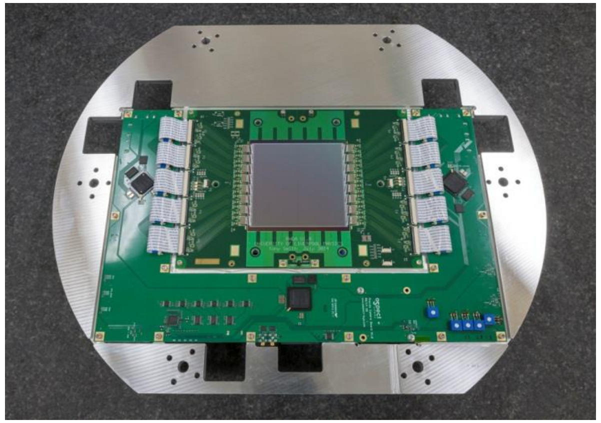
# Detector technology

**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 sensor
- High material budget

**Silicon Strip Sensors**

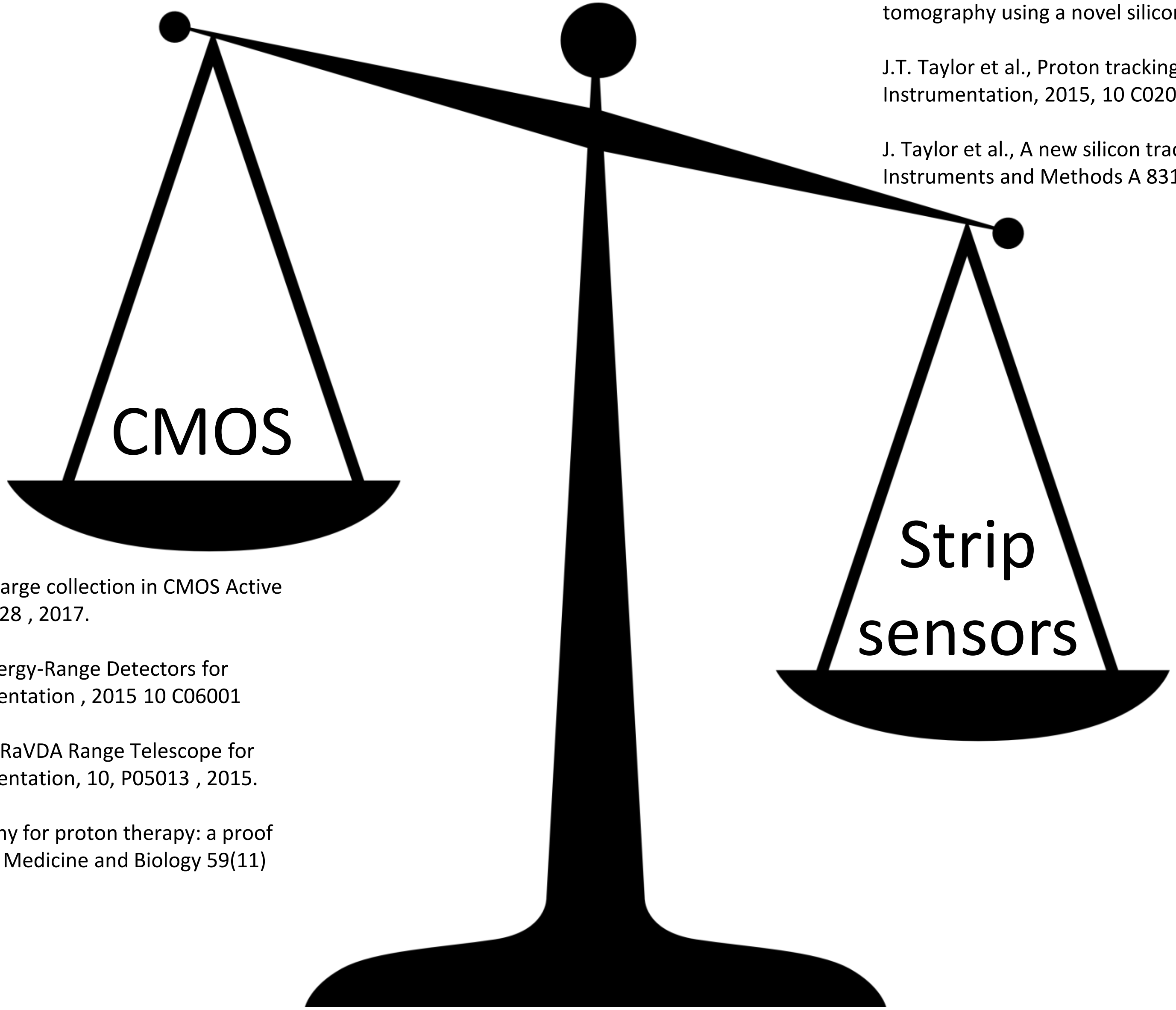


- 1D-positional detectors
- Binary readout (in our implementation)
- MHz readout (low occupancy per R/O cycle)
- Radiation tolerant to LHC doses
- Dead areas when tiling to larger areas
- Low material budget

J.T. Taylor et al., An experimental demonstration of a new type of proton computed tomography using a novel silicon tracking detector, Medical Physics. 43 (11) , 2016.

J.T. Taylor et al., Proton tracking for medical imaging and dosimetry, Journal of Instrumentation, 2015, 10 C02015

J. Taylor et al., A new silicon tracker for proton imaging and dosimetry, Nuclear Instruments and Methods A 831, 362 (2016).



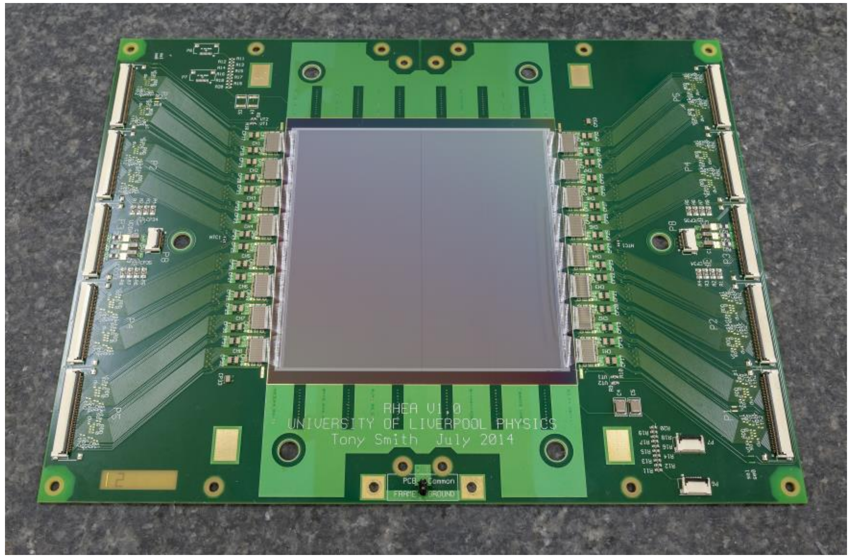

M. Esposito at al. , Geant4-based simulations of charge collection in CMOS Active Pixel Sensors, Journal of Instrumentation, 12, P03028 , 2017.

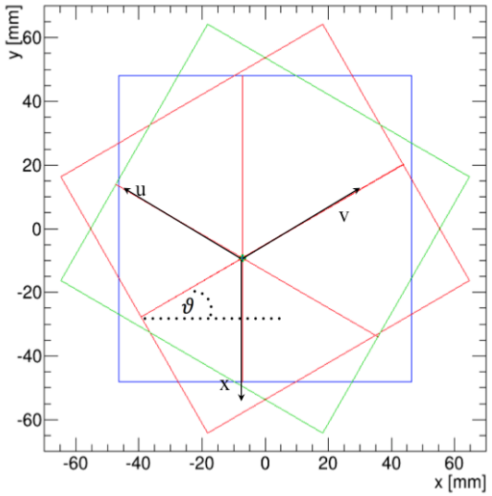
M. Esposito et al, CMOS Active Pixel Sensors as Energy-Range Detectors for Proton Computed Tomography, Journal of Instrumentation , 2015 10 C06001

T. Price et al,. Expected proton signal sizes in the PRaVDA Range Telescope for proton Computed Tomography, Journal of Instrumentation, 10, P05013 , 2015.

G. Poludniowski, et al.. Proton-counting radiography for proton therapy: a proof of principle using CMOS APS technology, Physics in Medicine and Biology 59(11) :2569,2014.

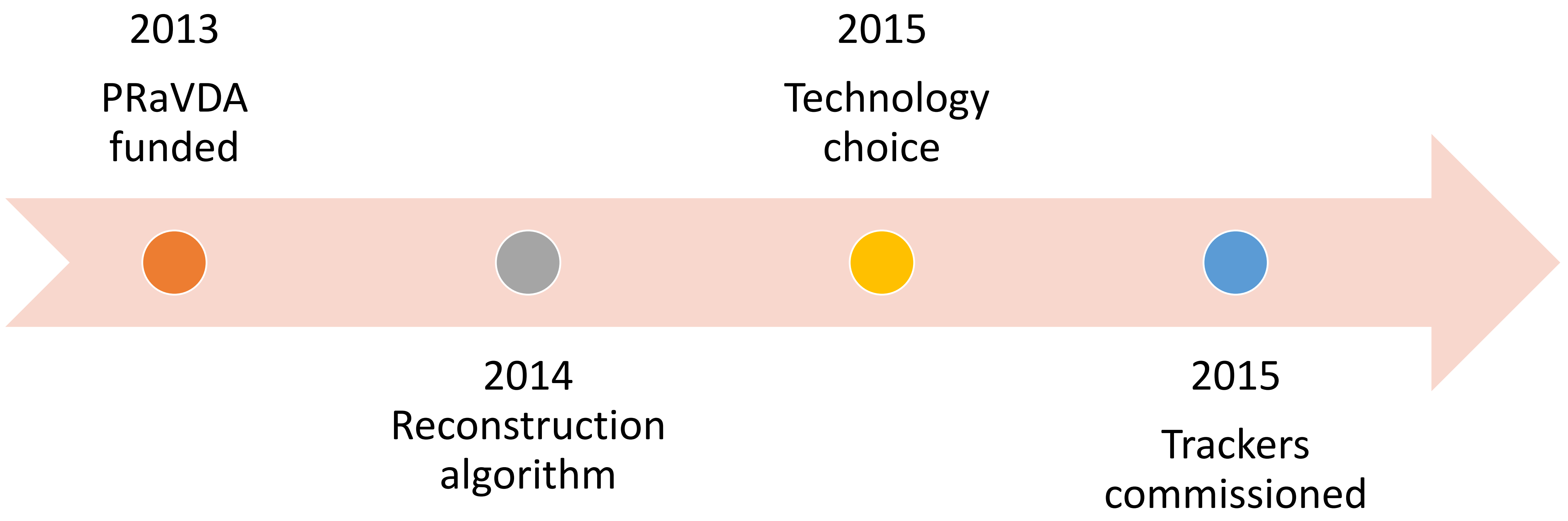
# Silicon strip sensors




- 150 mm thick *n-in-p* Si
- 93×96 mm$^2$
- 90.8 mm pitch
- 2048 strips readout by 16 custom ASICs (128 channels per ASIC)
- 2 tunable thresholds:
- 26 MHz readout

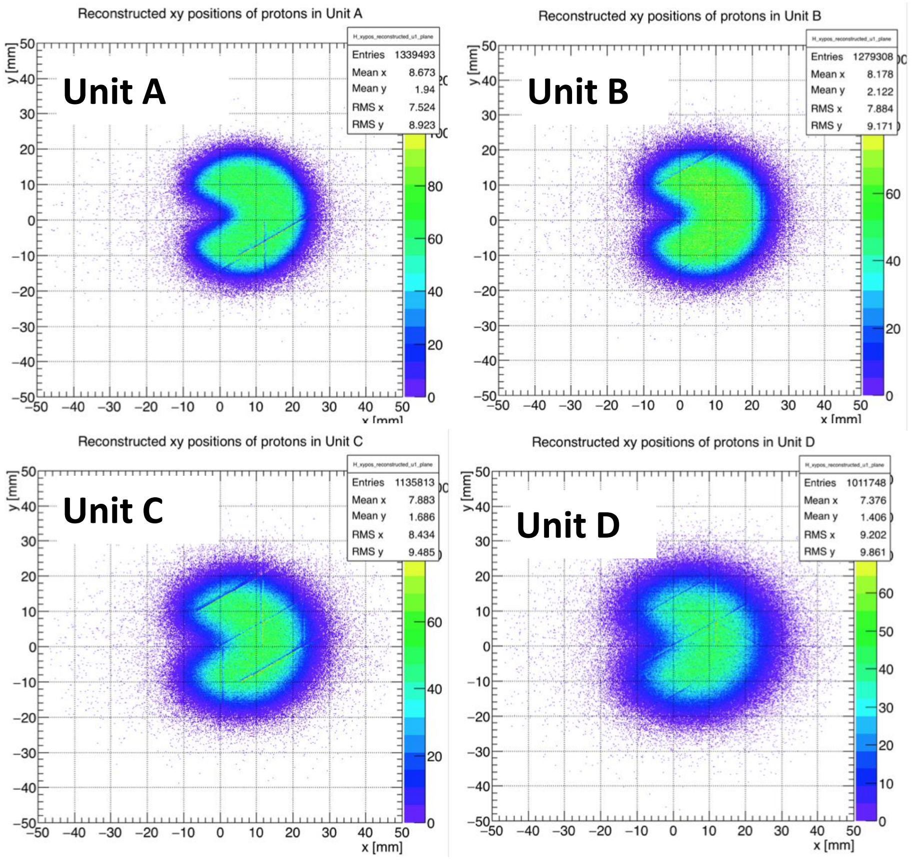
- Maximum fluence = 2×10$^8$ protons/s over full imaging area


2013
PRaVDA funded
2014
Reconstruction algorithm
2015
Technology choice
2015
Trackers commissioned

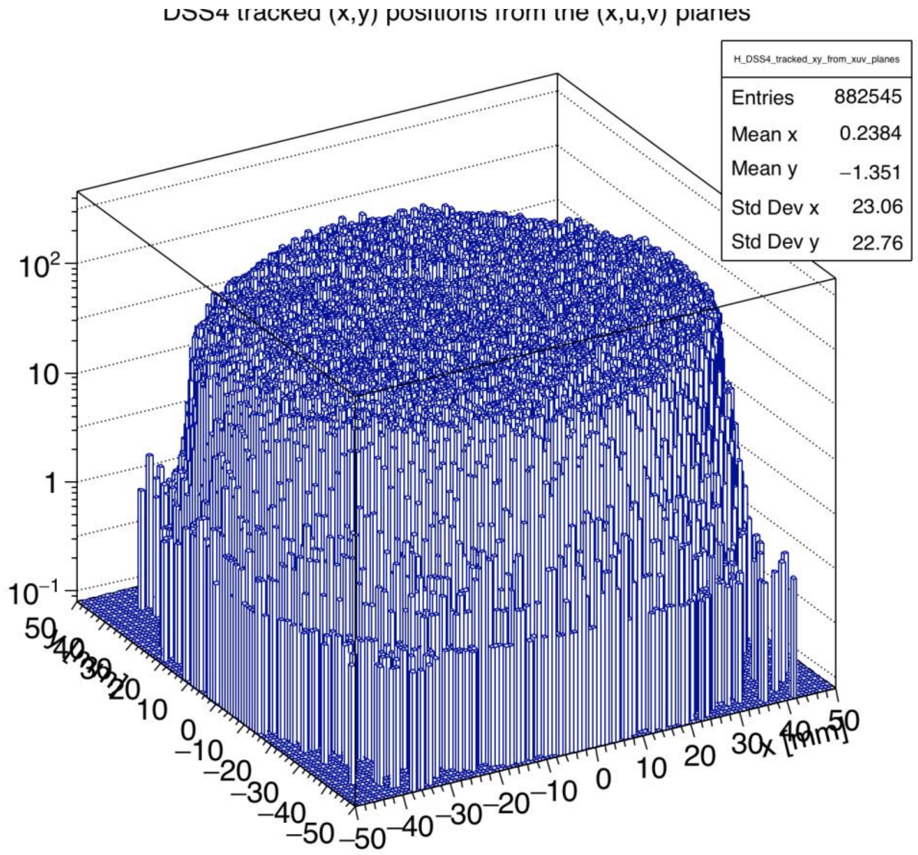
Data and analysis by Jon Taylor, University of Liverpool

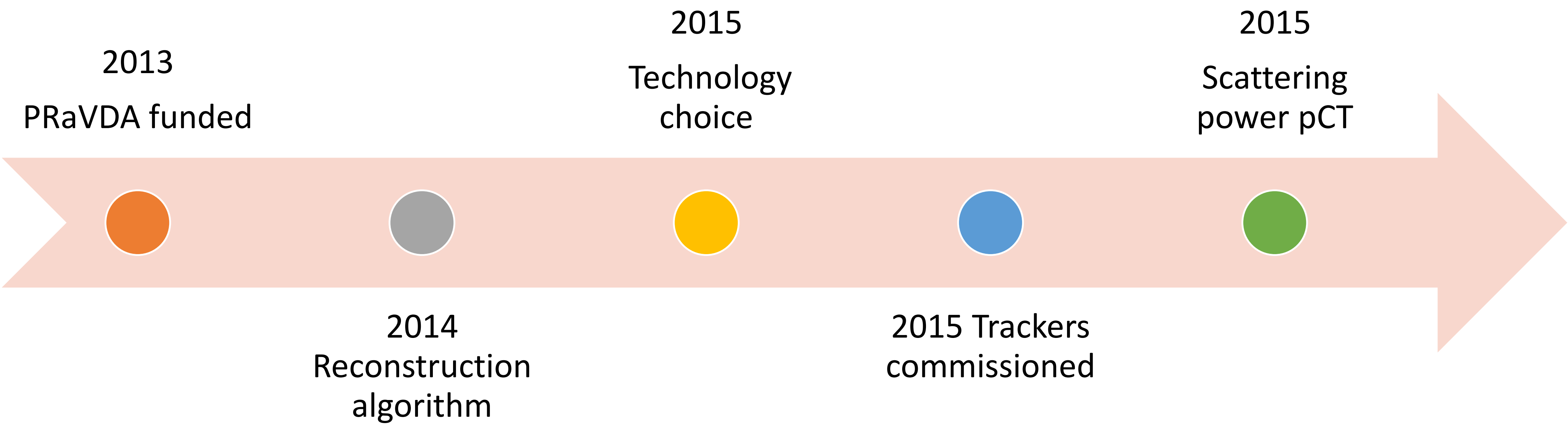
# Trackers commissioning

36 MeV protons, MC40 cyclotron, University of Birmingham




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




2013
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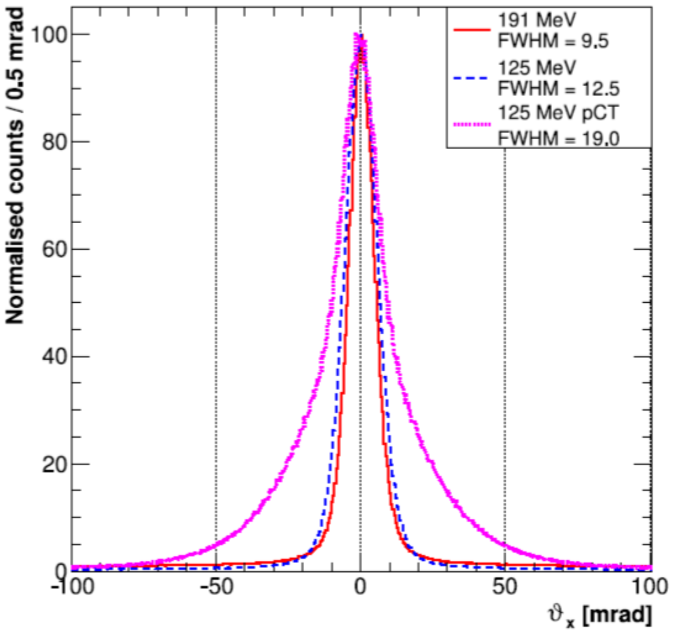
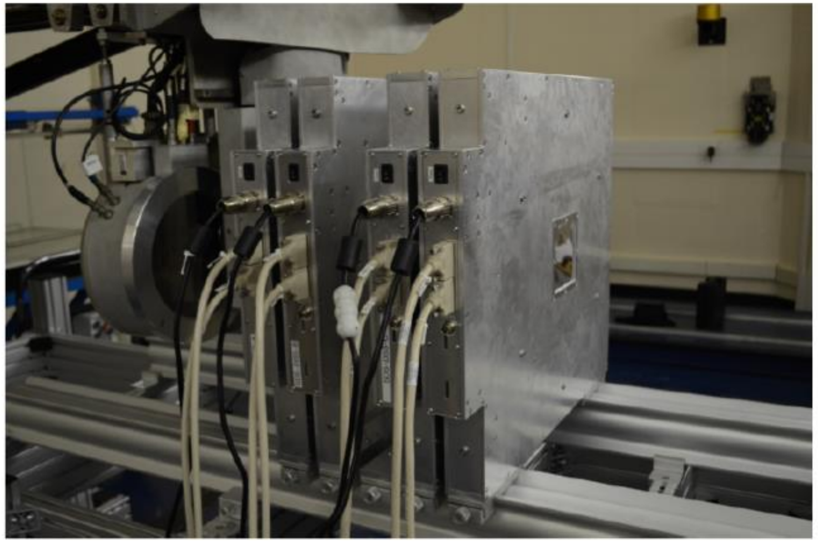
Technology choice
2015 Trackers commissioned
2015
Scattering power pCT

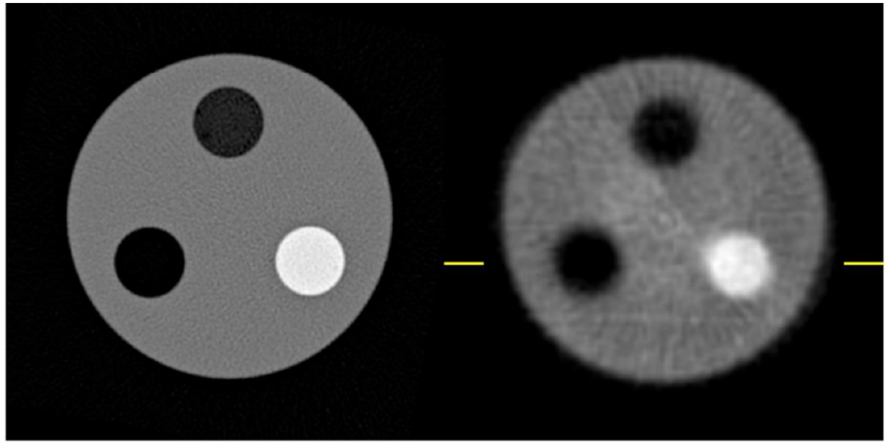
Taylor et al., An experimental demonstration of a new type of proton computed tomography using a novel silicon tracking detector, Med. Phys. 43 (11) 2016

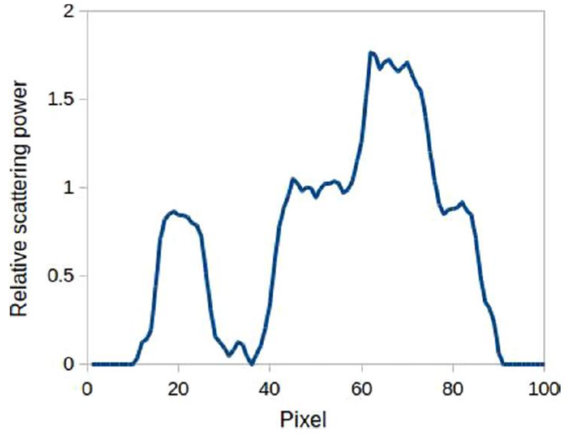
# Scattering power pCT

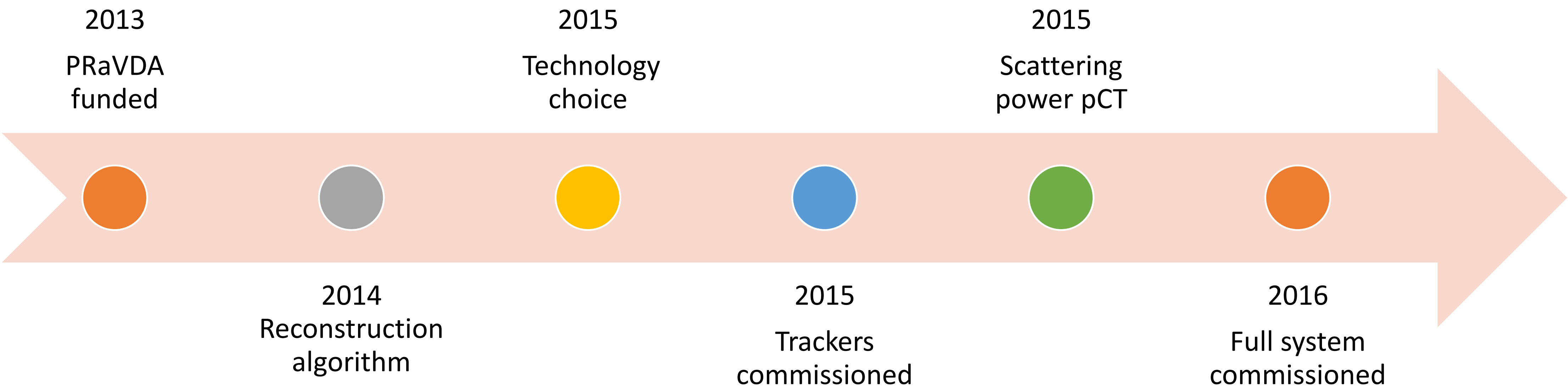
Estimates path length of water that would give an equivalent mean-square scattering angle.



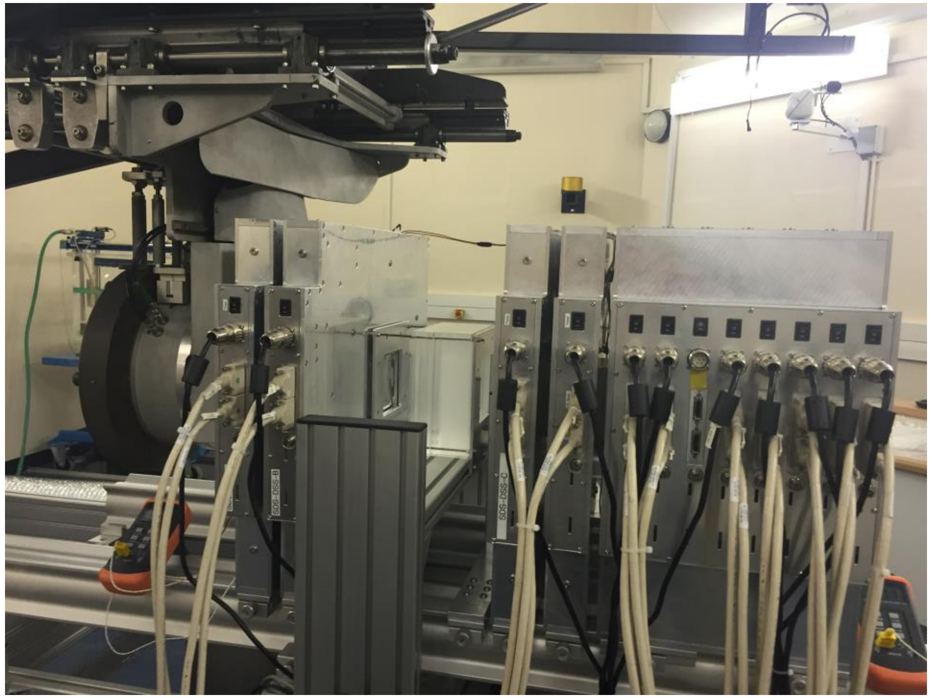



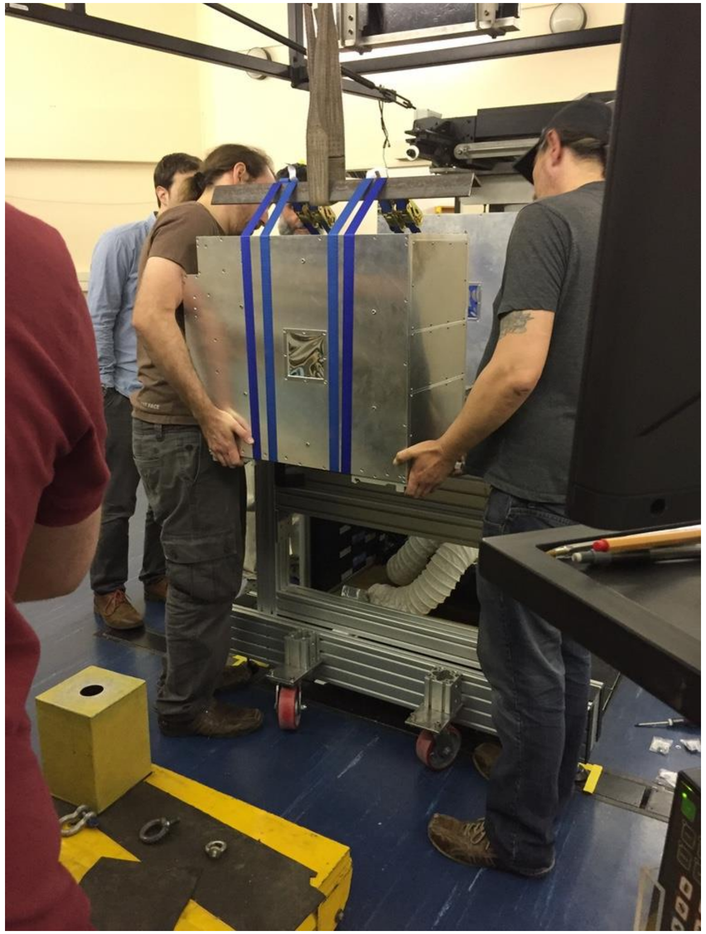





2013
PRaVDA funded
2014
Reconstruction algorithm
2015
Technology choice
2015
Trackers commissioned
2015
Scattering power pCT
2016
Full system commissioned

# Full system commissioned at iThemba LABS

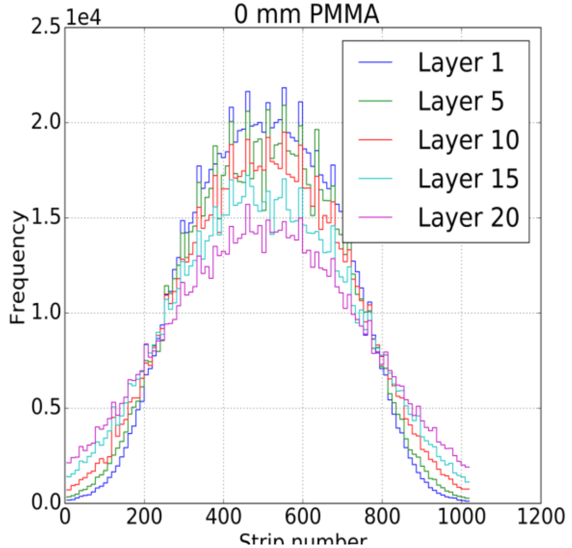




# Range Telescope

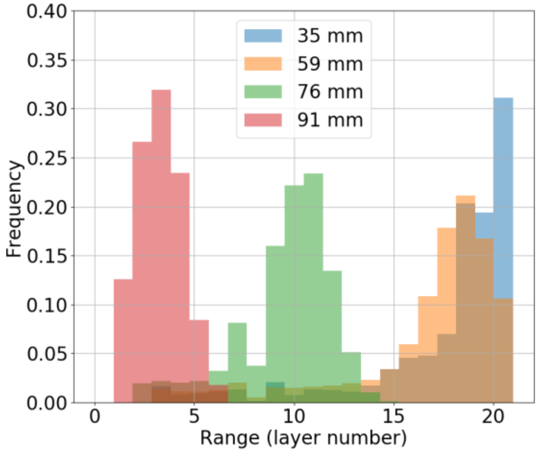
- 21 Si layers
- Each layer includes a 2-mm thick PMMA absorber
- WET of a single layer = 2.8 mm

MC40 cyclotron,
University of Birmingham

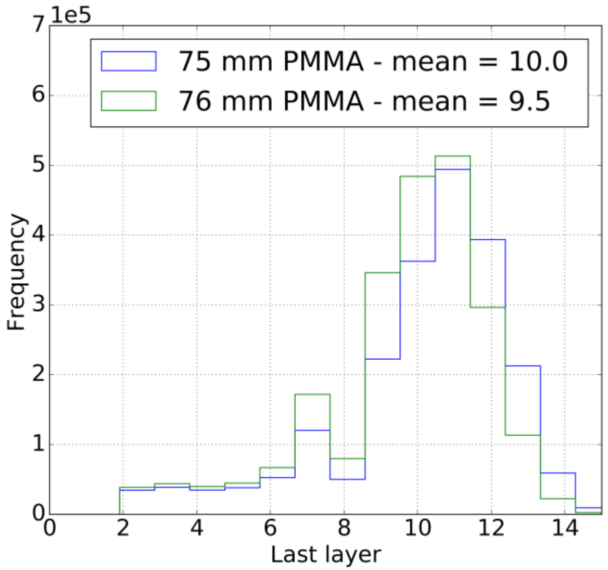


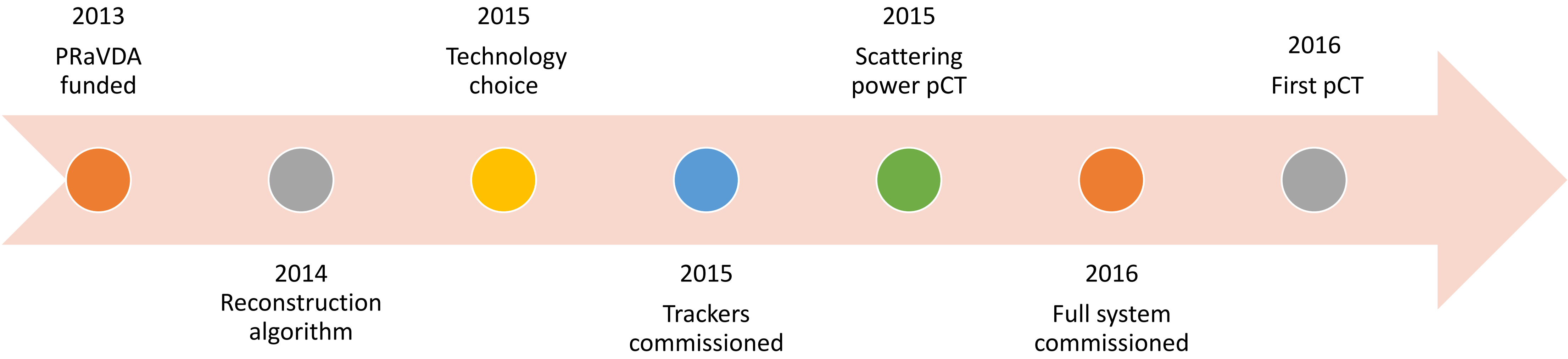

1D beam profile of 36 MeV p through the RT

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




Range distributions

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Technology choice
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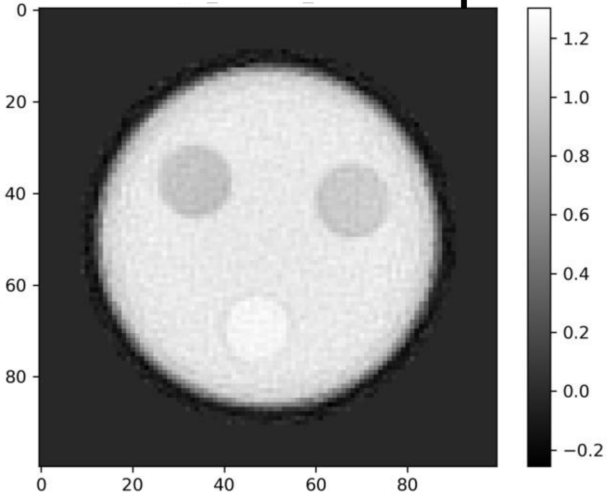
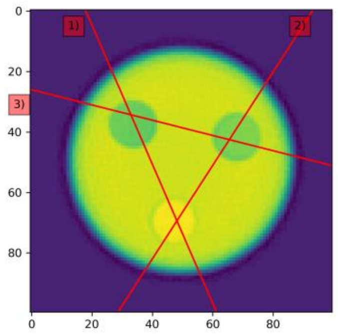
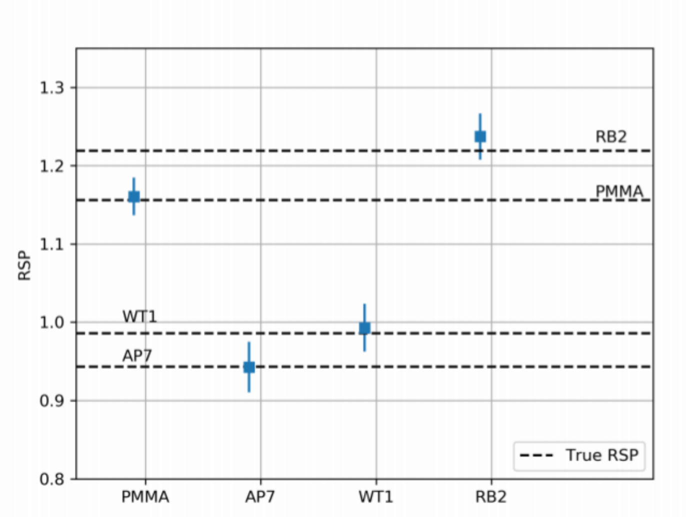
Trackers commissioned
2015
Scattering power pCT
2016
Full system commissioned
2016
First pCT

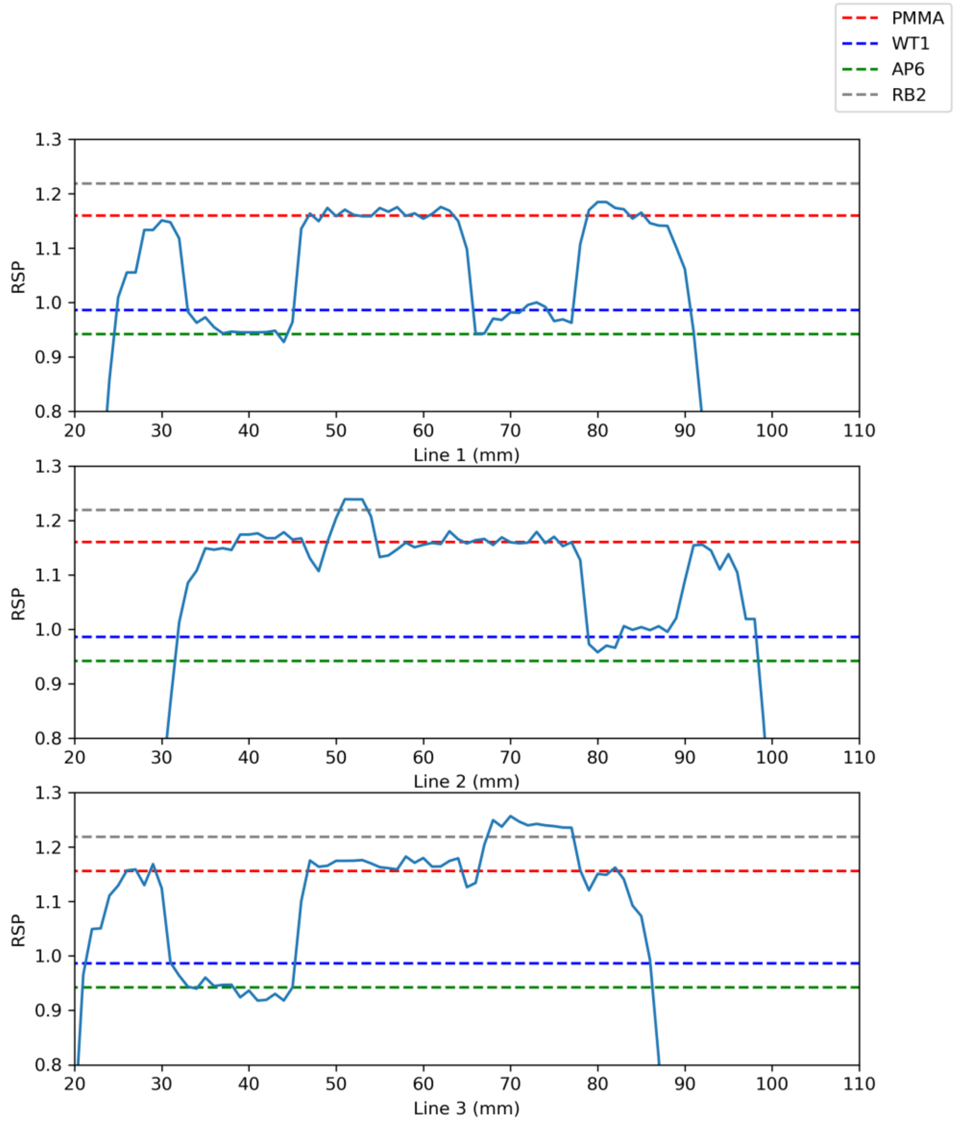
# Proton CT

## Low contrast hemisphere

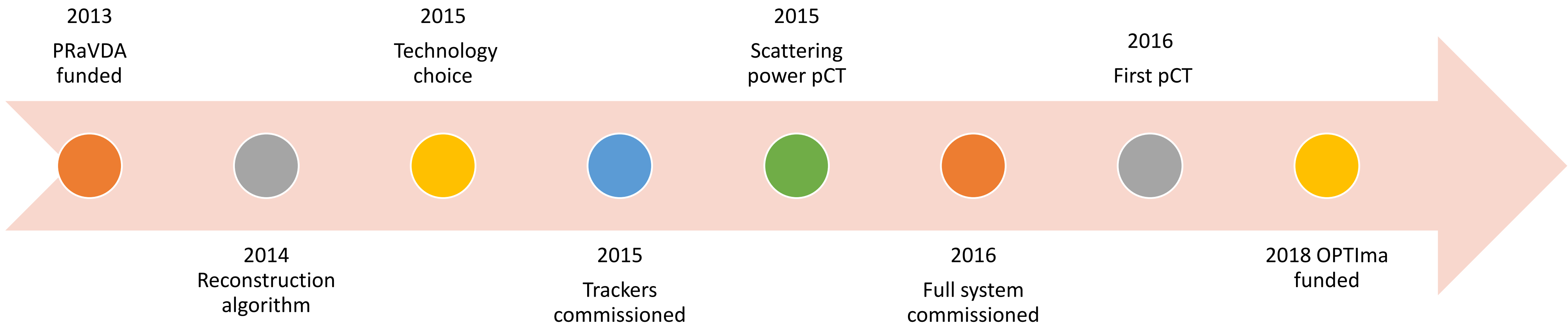



| Material | Expected RSP | pCT RSP | RSP Accuracy (%) |
|---|---|---|---|
| Adipose (AP7) | 0.943 | 0.943 | -0.02 |
| Average bone (RB2) | 1.219 | 1.237 | 1.5 |
| Water (WT1) | 0.986 | 0.983 | 0.7 |
| PMMA | 1.156 | 1.161 | 0.4 |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2016
First pCT
2018 OPTIma funded

OPTIma

Optimising Proton Therapy through Imaging

EPSRC Healthcare Technology
Investigator-led initiative

1 September 2018 – 30 May 2022


**University of Lincoln**
Grainne Riley
Chris Waltham
Michela Esposito
Nigel Allinson

**University of Manchester**
Karen Kirby
Michael Merchant
Hywel Owen
Michael Taylor
Carla Winterhalter

**The Christie NHS Foundation Trust**
Ranald Mackay
Adam Aitkenhead

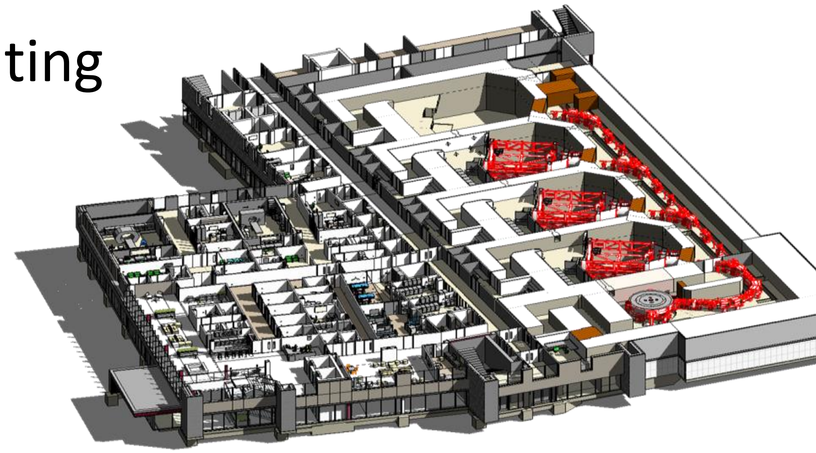
**University of Birmingham**
Phil Allport
Tony Price
John Cotterill
Alasdair Winter

**NHS University Hospital Birmingham NHS Foundation Trust**
Stuart Green

**NHS University Hospital Coventry and Warwickshire NHS Foundation Trust**
Jane Rogers

# OPTIMA: what are we designing for?

- Research room at the Christie NHS Foundation Trust
- A clinical system:
  a) System has to operate close to or within normal operating envelope
  b) System has to cope with multiple protons per bunch
  c) Pencil scanning delivery system
  d) Minimum imaging area 20x20 $cm^2$ but ideally larger
  e) Range (energy) measuring detector to stop full beam - resolution comparable with range straggling
  f) Fast!



# OPTIMA: what are we designing for?

a) System has to operate close to or within normal operating envelope
   - ❑ Difficult for operational clinics to operate far outside the normal treatment conditions. It takes time to stabilise the system back to normal operating conditions

b) System has to cope with multiple protons per bunch
   - ❑ Though average current is low enough such that less that one proton per bunch is possible, in practice protons may not randomly spread and multi-proton bunches do occur

c) Pencil scanning delivery system

d) Minimum imaging area 20x20 $cm^2$ but ideally up to 40x40 $cm^2$

e) Range (energy) measuring detector to stop full beam energy with resolution comparable with range straggling

f) Fast!

# OPTIMA: what are we designing for?

a) System has to operate close to or within normal operating envelope
   - ❑ Difficult for operation clinics to operate far outside the normal treatment conditions. It takes time to stabilise the system back to normal operating conditions
   - ❑ Working with very low currents can be challenging. About 10 pA is the minimum current

b) System has to cope with multiple protons per bunch
   - ❑ Though average current is low enough such that less that one proton per bunch is possible, in practice protons are not randomly spread and multi-proton bunches do occur

c) Spot scanning delivery system
   - ❑ Practical issues in scanning an unfocused beam (nozzle size)

d) Minimum imaging area 20x20 $cm^2$ but ideally up to 40x40 $cm^2$

e) Range (energy) measuring detector to stop full beam energy with resolution comparable with range straggling

f) Fast!

# OPTIMA: what are we designing for?

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d) Minimum imaging area 20x20 $cm^2$ but ideally up to 40x40 $cm^2$
   - ❑ Modular system

e) Range (energy) measuring detector to stop full beam energy with resolution comparable with range straggling
   - ❑ Calorimeter

f) Fast!

# OPTIMA: what are we designing for?

a) System has to operate close to or within normal operating envelope
   - Difficult for operation clinics to operate far outside the normal treatment conditions. It takes time to stabilise the system back to normal operating conditions
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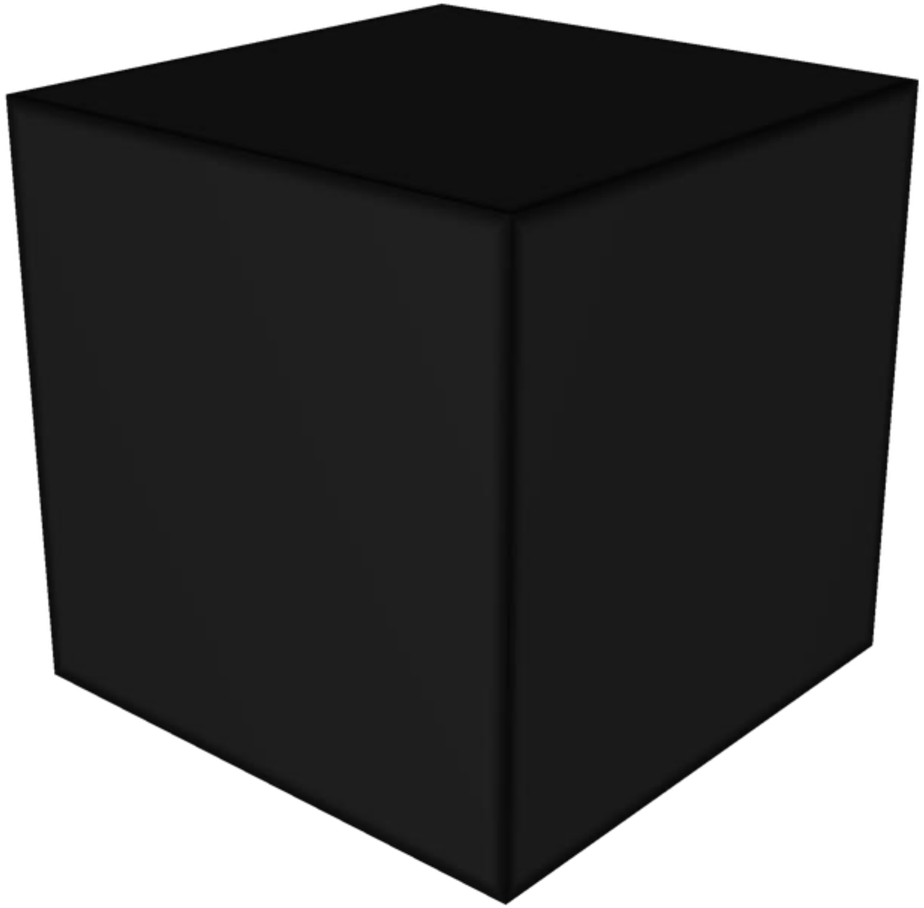
   - Modular system

e) Range (energy) measuring detector to stop full beam energy with resolution comparable with range straggling
   - Calorimeter

f) Fast!
   - $\leq$ 5 min

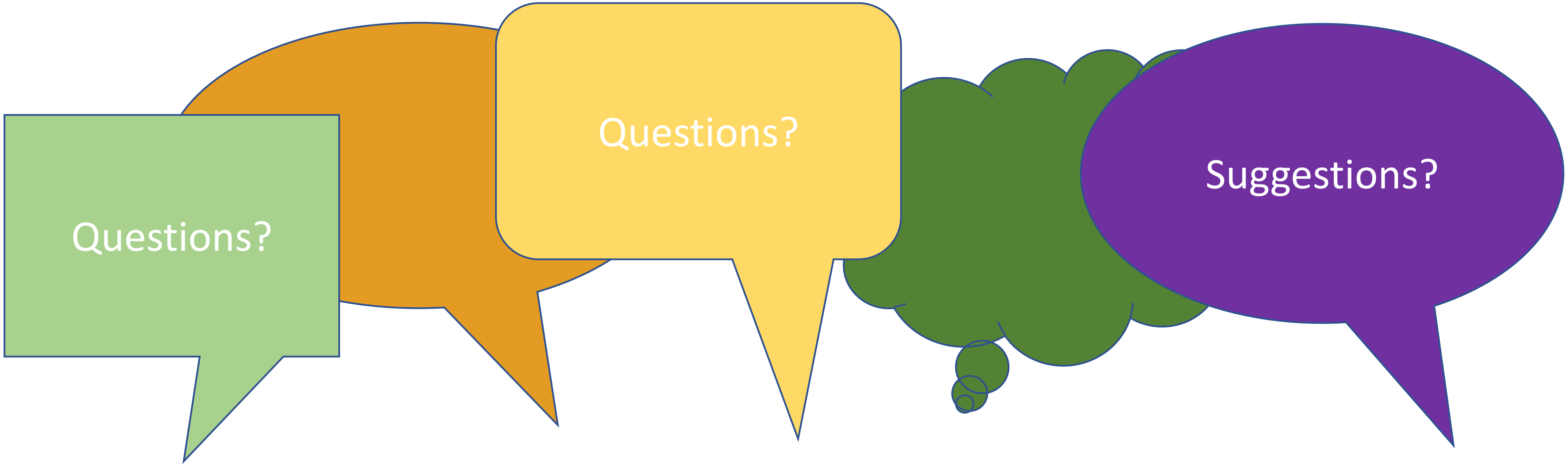
# How OPTIma will look like



1. System must operate close to or within normal operating envelope
2. Cope with multiple protons per bunch
3. Use calorimeter to measure residual energy directly
4. Large area and clear upgrade path

5. Modular system – range probe is a single module
6. Interface easily with different manufacturers
7. Use robust technology with as many COTS elements as possible
8. Provide upgrade path for gantry installation

# Thank you!




mesposito@lincoln.ac.uk