NPL PPRIG Proton Therapy Physics Workshop 2016

CMOS Active Pixel Sensors for imaging in proton radiotherapy

M. Esposito, T. Price, J. Taylor,
C. Waltham, B. Phoenix, S. Manger,
G. Poludniowski, P. Evans, S. Green,
D. Parker, P. Allport, S. Manolopoulos,
J. Nieto-Camero and N. Allinson[1].

PRaVDA

Proton Radiotherapy Verification and Dosimetry Applications

PRaVDA

Proton Radiotherapy Verification and Dosimetry Applications

– integrated platform for proton therapy imaging and dosimetry

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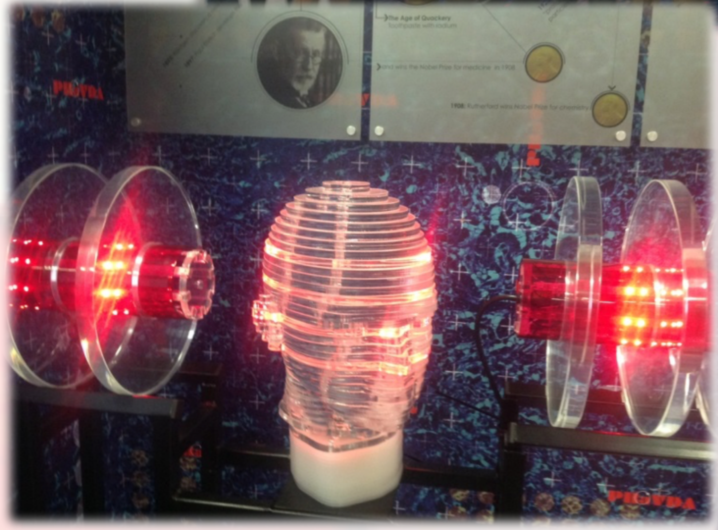
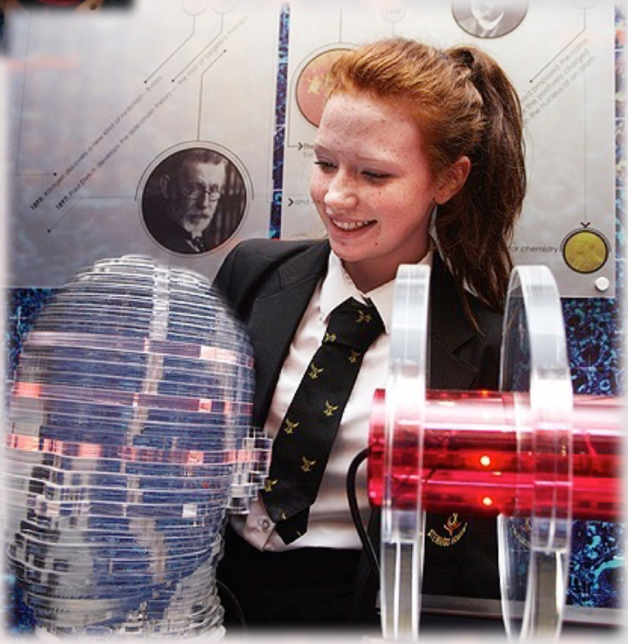
National Research Foundation (NRF) - iThemba LABS, SA
United Lincolnshire Hospitals NHS Trust
The Christie NHS Foundation Trust

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

Royal Society Summer Science Exhibition, July 2014





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PRaVDA

Proton Radiotherapy Verification and Dosimetry Applications

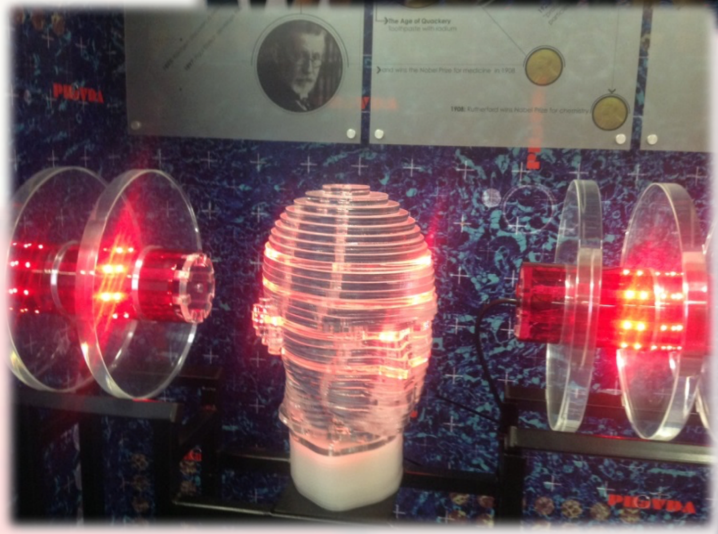
– integrated platform for proton therapy imaging and dosimetry

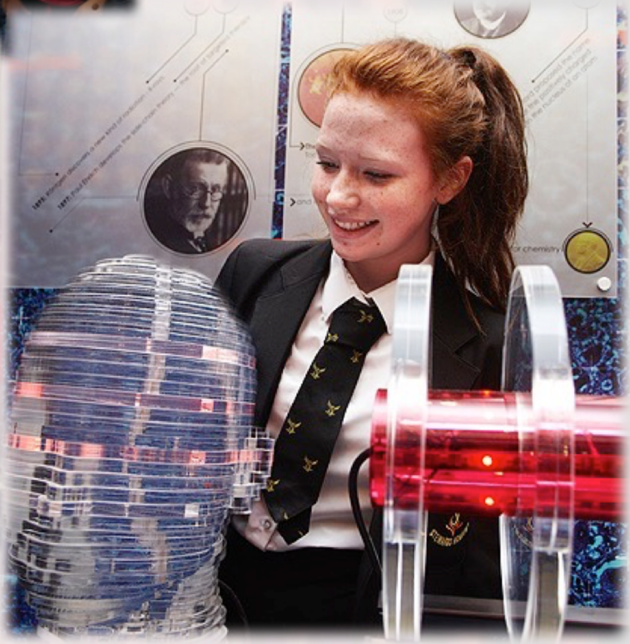
Royal Society
Summer Science
Exhibition, July 2014

More on PRaVDA:

Today at 2:35 pm, N. Allinson
"Update: Pravda project imaging update"

Poster session, S. Manger
"Development of a phantom for the evaluation of proton CT in proton therapy treatment planning"





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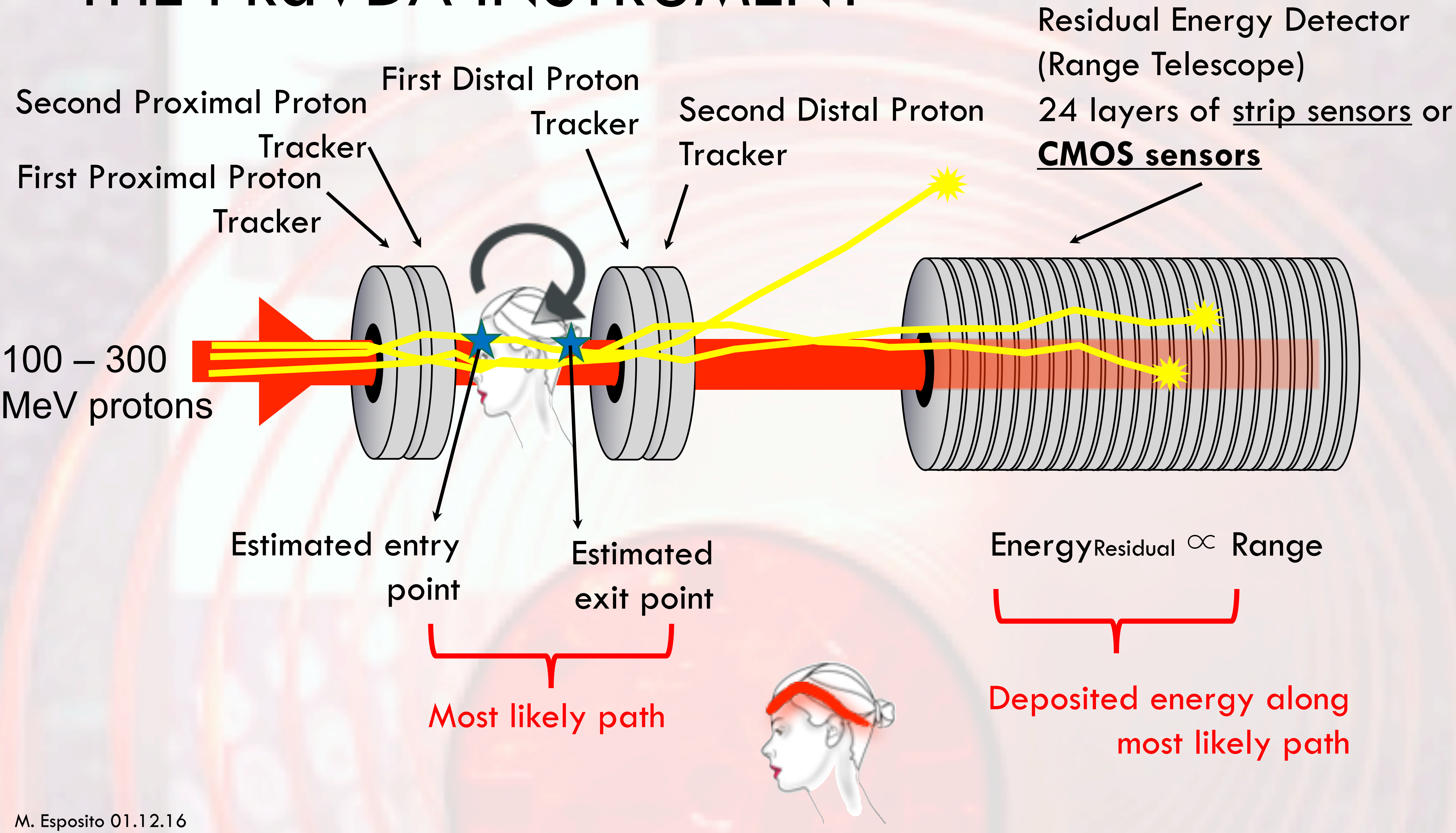
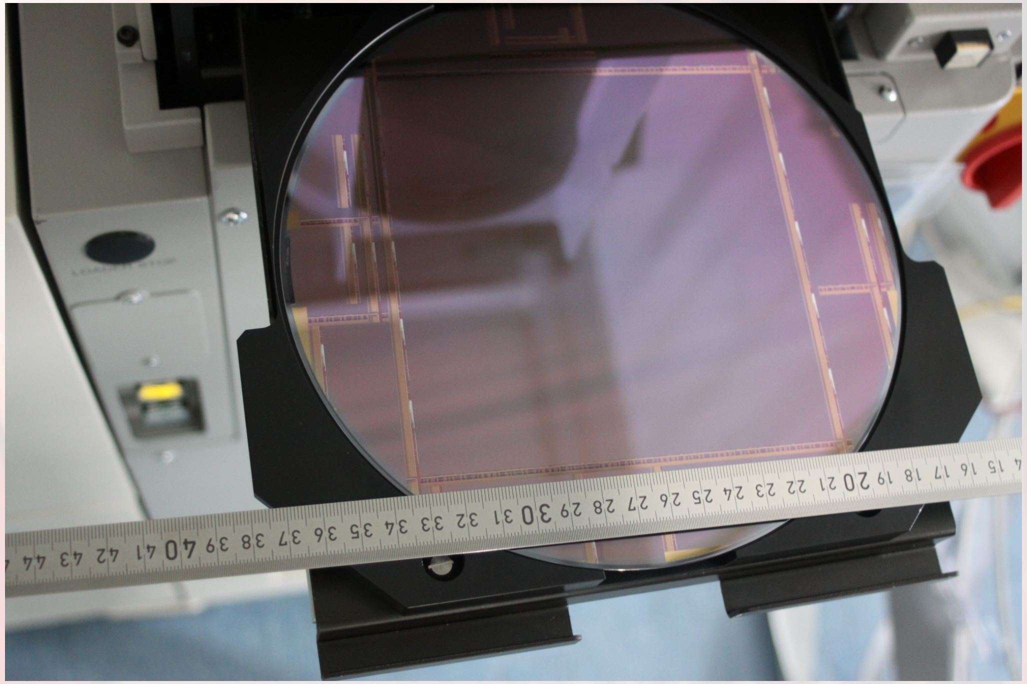
THE PRaVDA INSTRUMENT



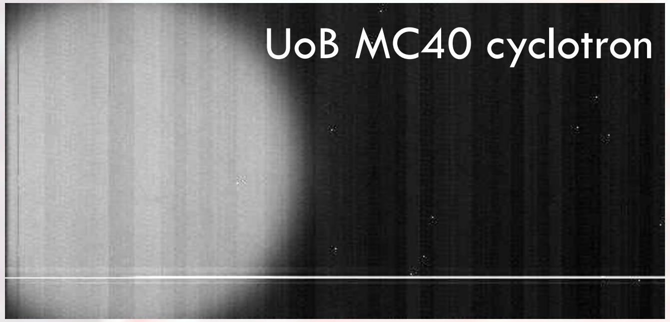
Published patent: WO2015/189603

WHY CMOS IMAGERS?

- Position sensitive detectors
  - allow for many protons to be located per R/O cycle, unlike calorimeters or scintillator stack designs
- From moderately radiation tolerant (standard CMOS processes for medical applications) to radiation hard (HEP experiments)
- Large imaging area (12” wafers)
  - Reticle stitching
  - Edge-less sensors – 4-side mosaic tiling
- Pixel detectors - x-y hit position
- Analog readout – dE/dx measurements

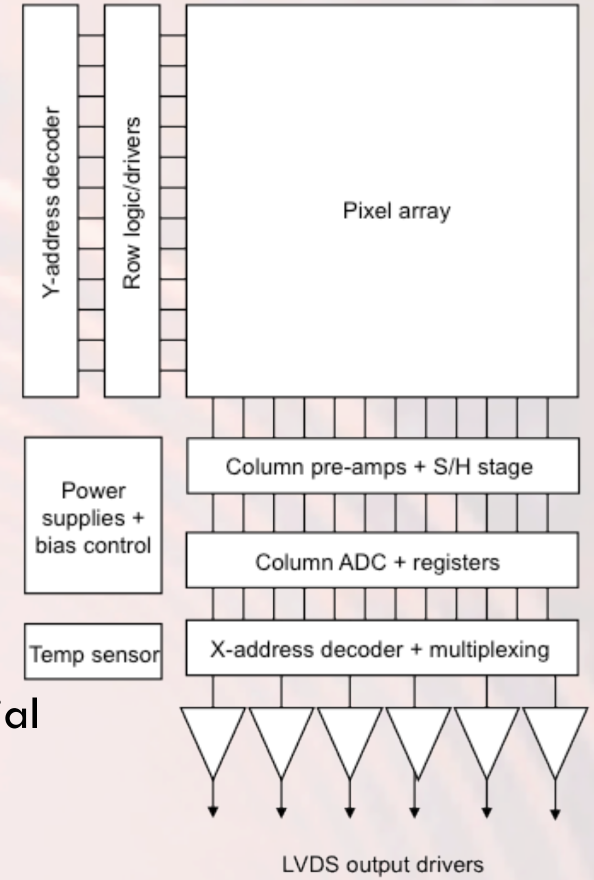


THE PRaVDA CMOS IMAGERS

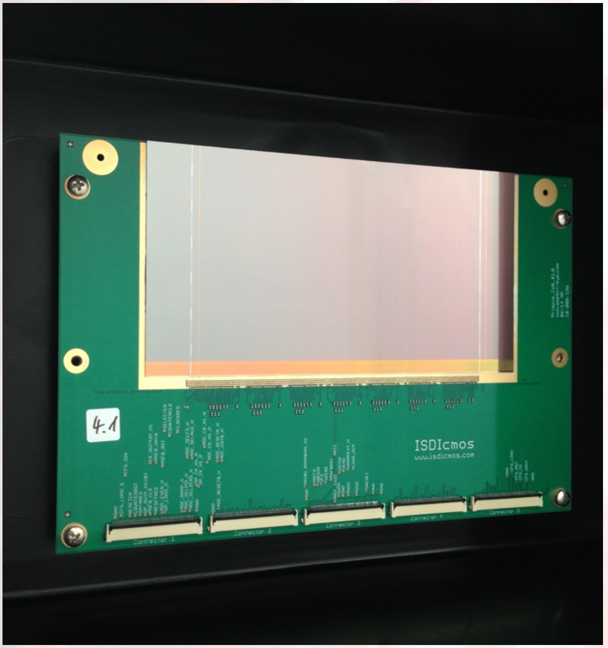


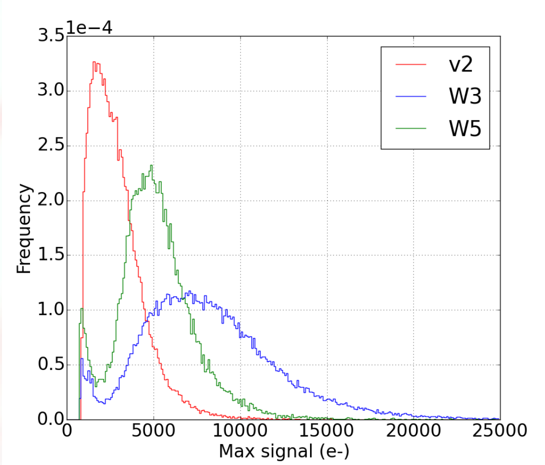
Design specifications:

- 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)

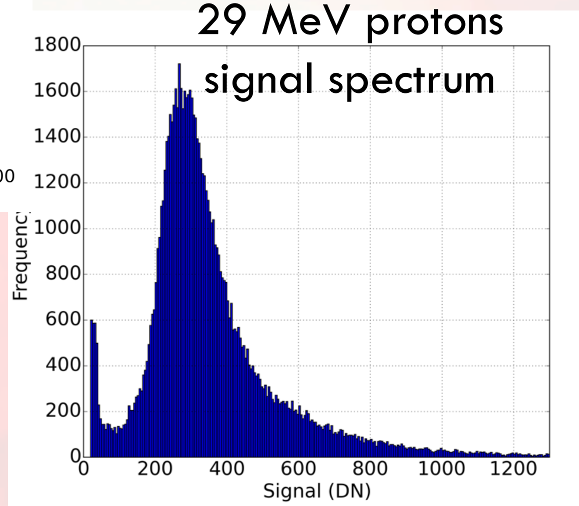


Published patent: WO2015/189602





3 iterations to optimise epitaxial resistivity (charge collection)



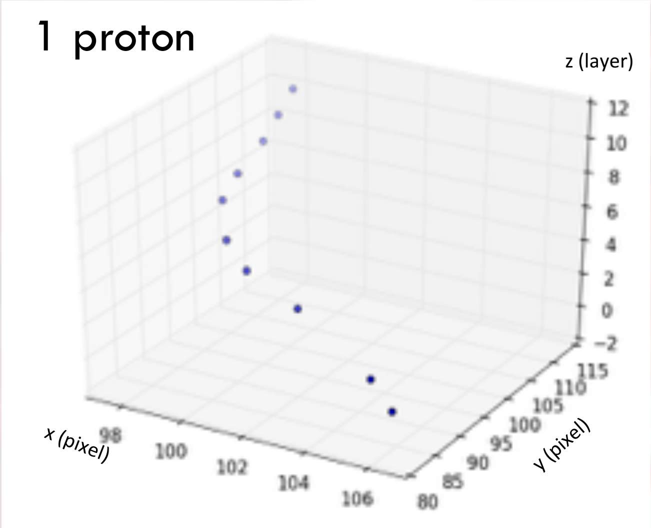
Further readings:

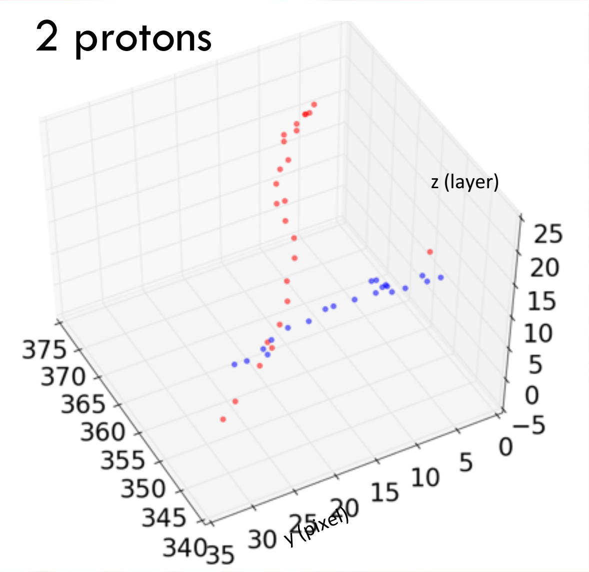
M. Esposito et al, J. Inst 2015; 10 (06), C06001

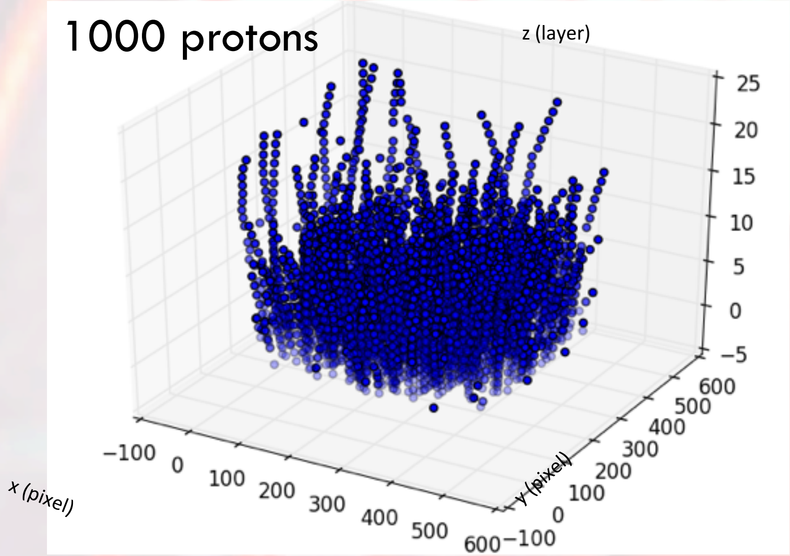
T. Price et al., J. Inst. 2015;10 (05), P05013

G. Poludniowski et al., Phys. Med. Biol. **59** (2014) 2569–2581

CMOS RT: proton tracking



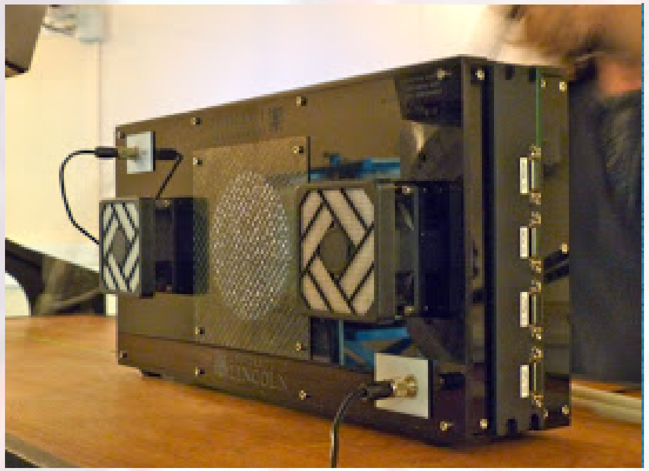


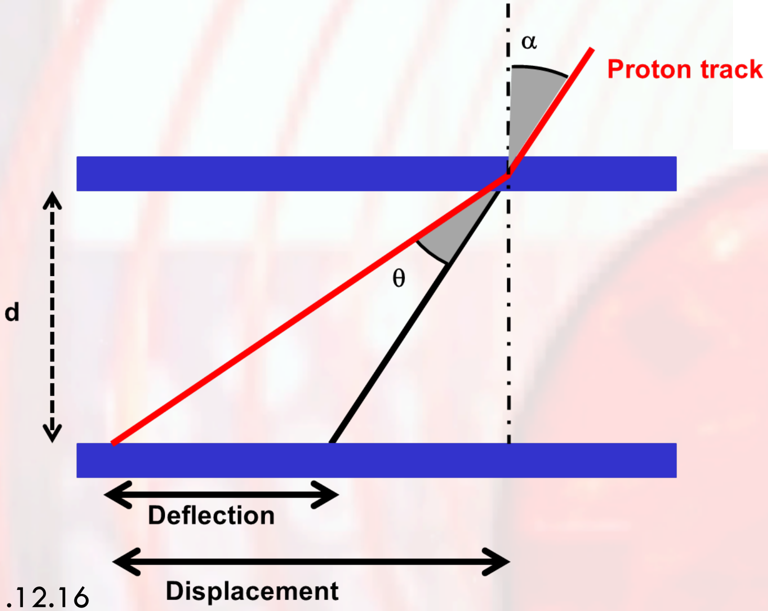


- CMOS readout speed ~kHz
- Strip readout speed ~MHz
- Need to reconstruct proton tracks in the CMOS RT
- Track following algorithm, based on adaptive velocity calculation and minimisation of layer-to-layer displacement

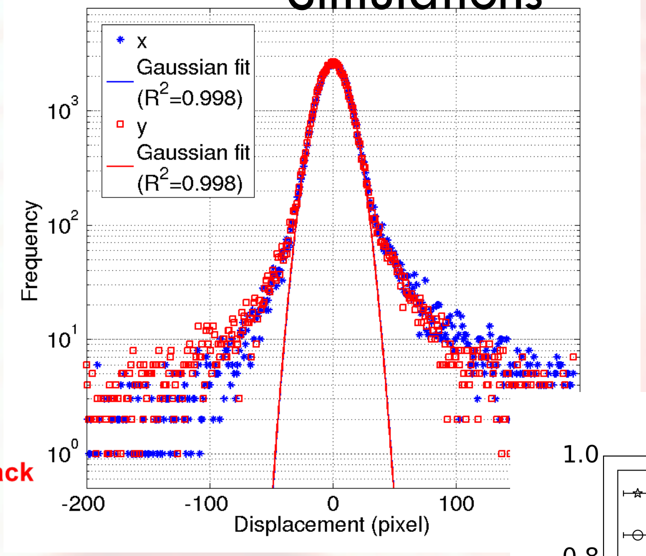
CMOS RT: proton tracking

Two-layer RT using a 55um pitch CMOS detector
And proton tracking based on minimum displacement

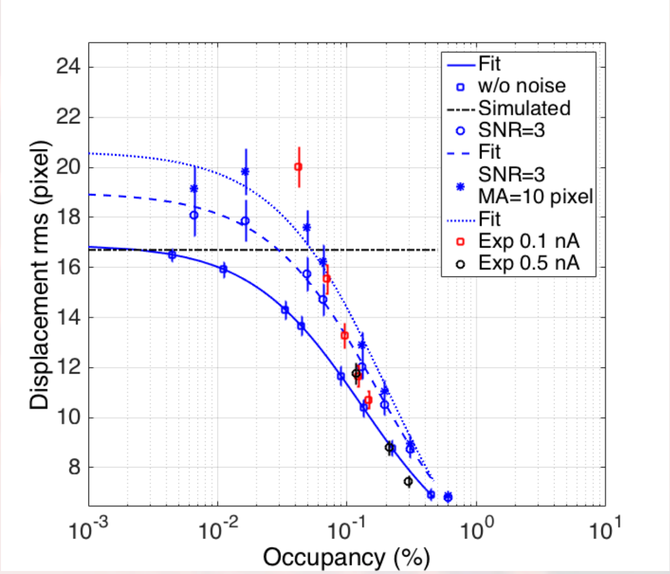




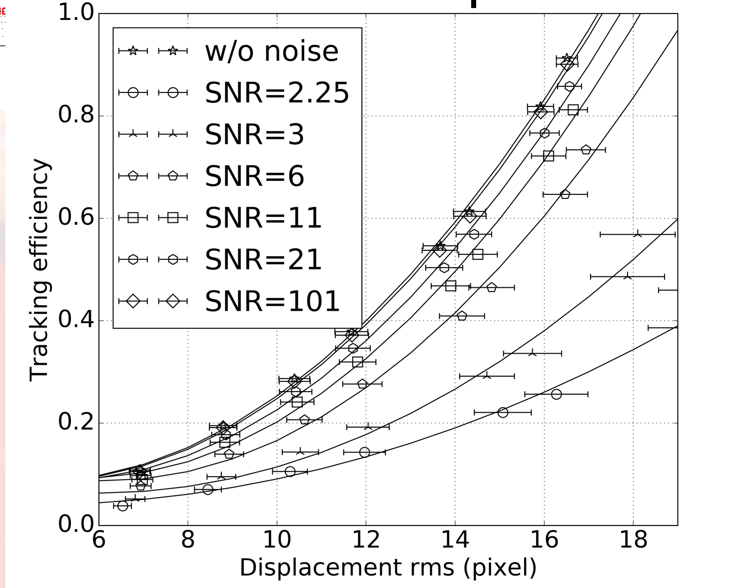
Simulations



Agreement between simulations and measurements



Model Tracking efficiency as a function observed displacement



M. Esposito 01.12.16

CMOS RT: proton tracking

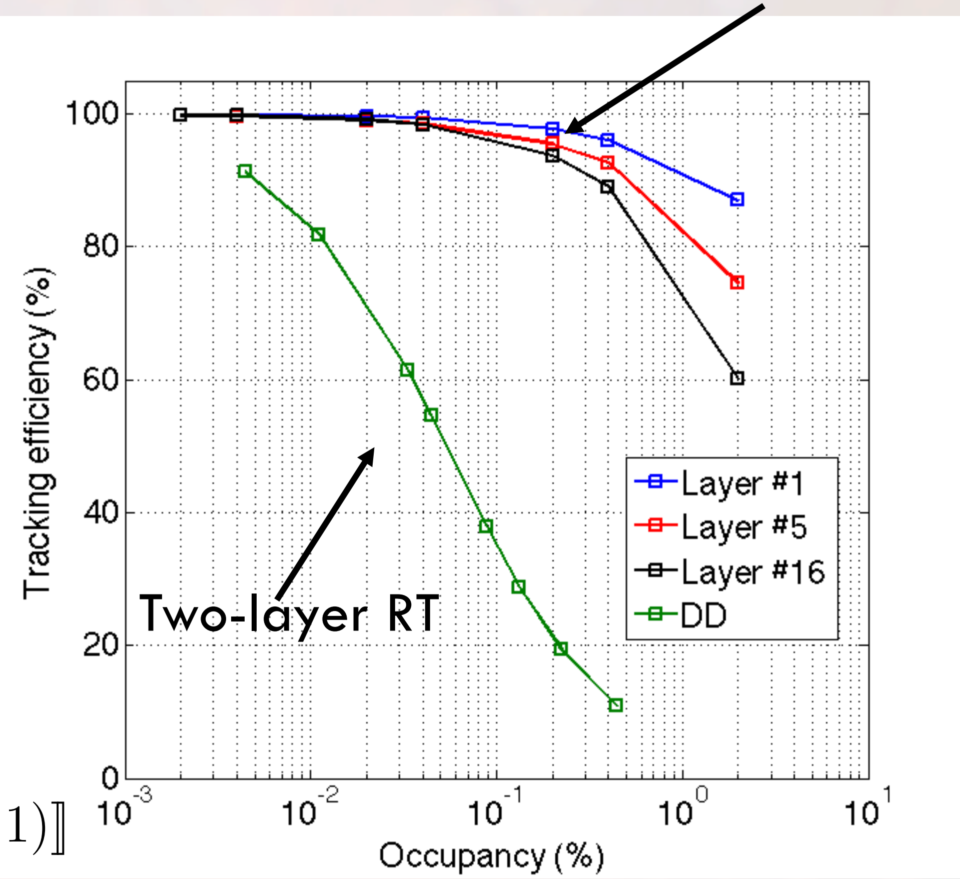
PRaVDA CMOS RT – simulated data:
16 layers, ~1mm Si each + 1mm PMMA

Expected position at layer n+1

$$\begin{cases} \boldsymbol{r}^{exp}(i, n+1) = \boldsymbol{r}^{meas}(i, n) + \hat{\boldsymbol{v}}^{meas}(i, n) \cdot t \\ r_x^{exp}(i, n+1) = d \end{cases}$$

Measured position at layer n+1

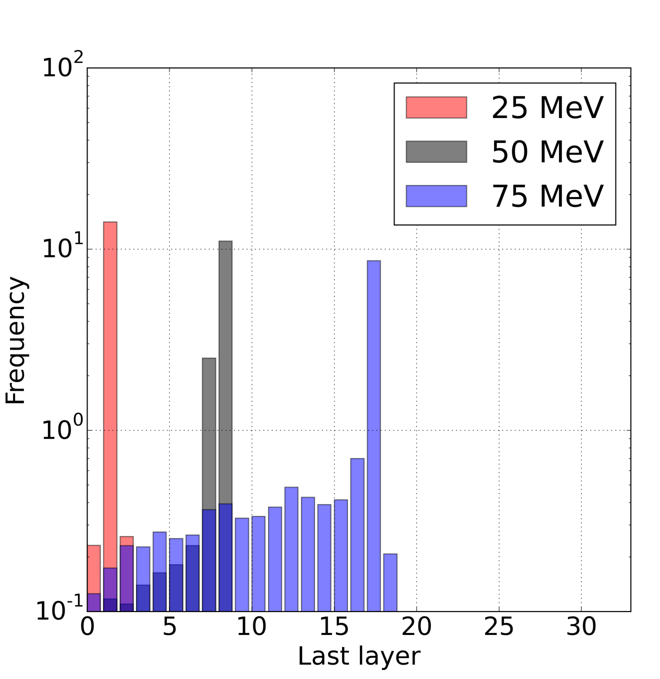
$$\tilde{j} : \boldsymbol{r}^{exp}(i, n+1) - \boldsymbol{r}^{meas}(\tilde{j}, n+1) = \min_{1 \leq j \leq N} [\![\boldsymbol{r}^{exp}(i, n+1) - \boldsymbol{r}^{meas}(j, n+1)]\!]$$

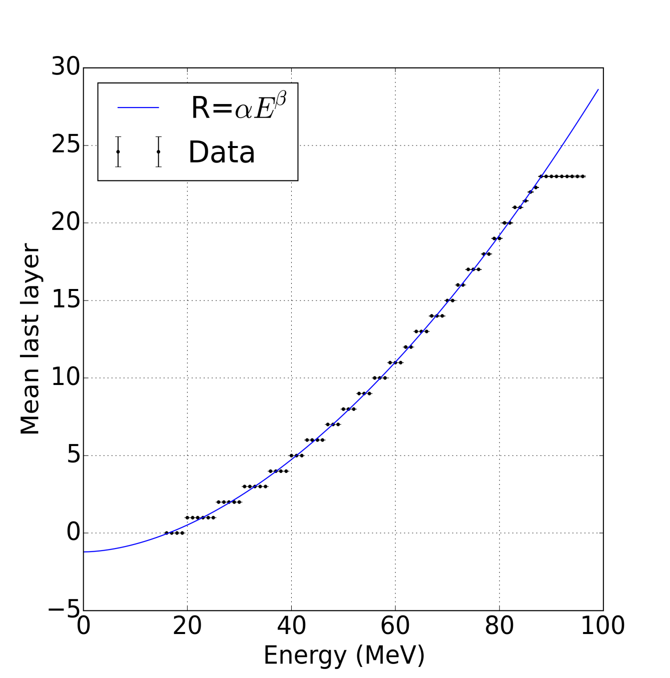


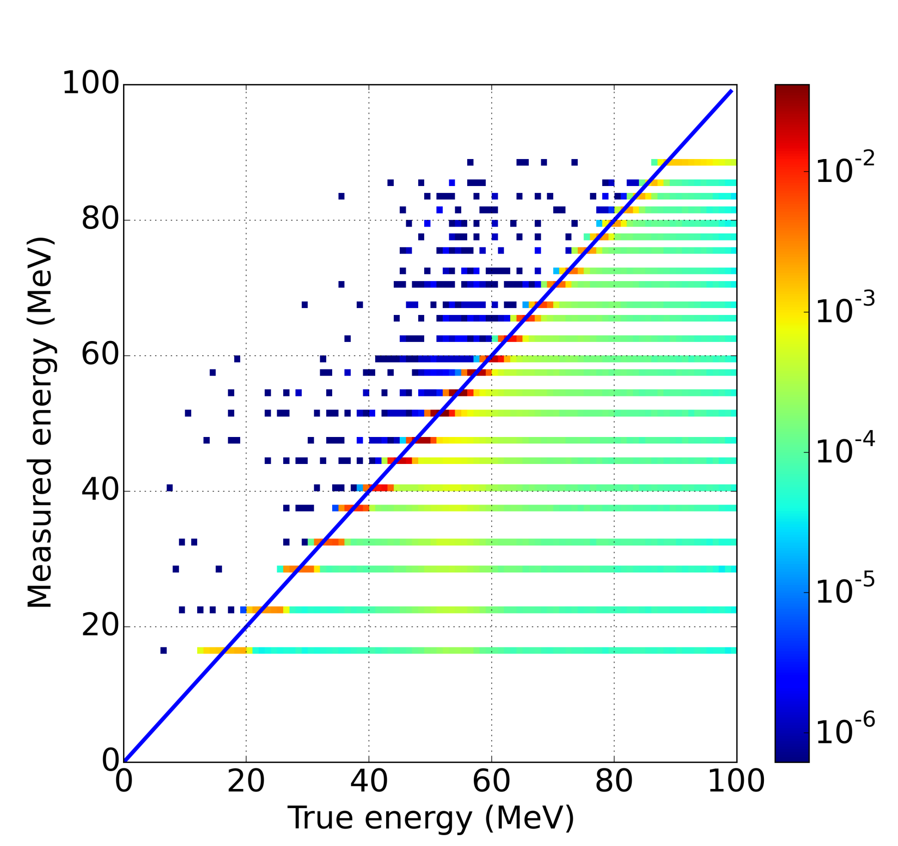
- Need an occupancy of ~0.4% (~90% tracking efficiency)
- With ~10^9 protons required over 180 projections (100 protons/voxel/projection – 1mm^3 voxels)
- ~830 Hz CMOS readout for a 5 min pCT scan

CMOS RT: energy calibration

Range counter





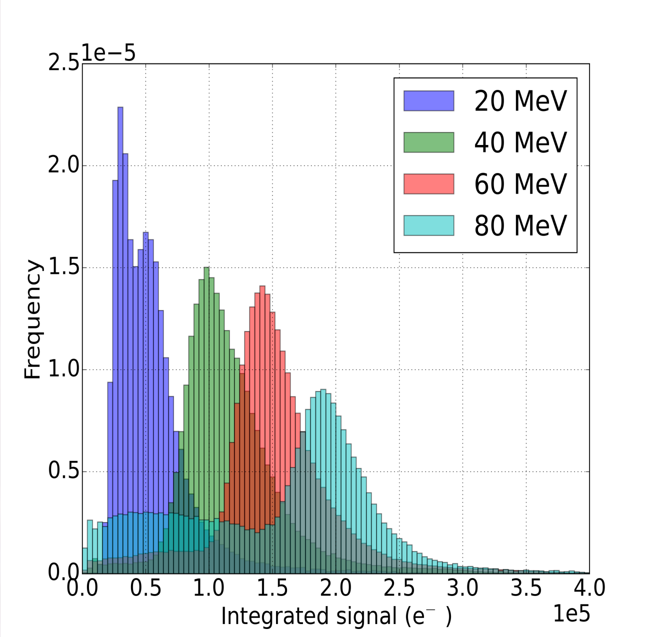


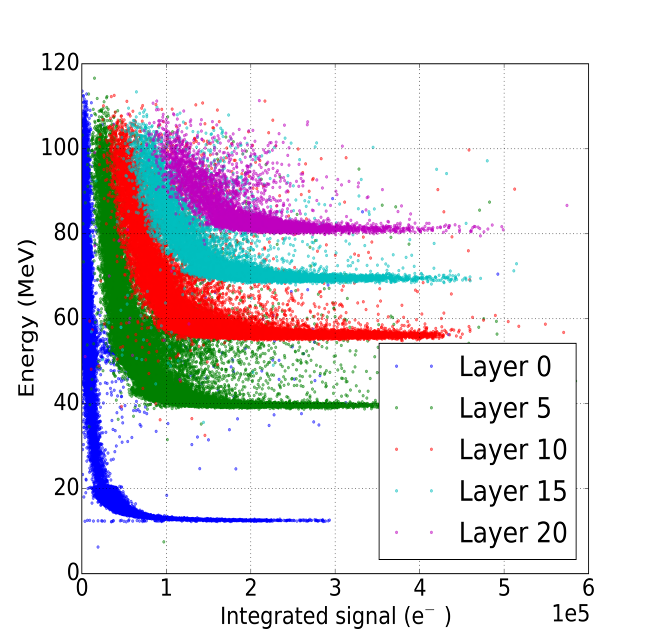
Range distribution (last layer) for mono-energetic protons ***(left).*** Calibration curve: mean last layer as function of incident proton energy. Power law fit (Bragg-Kleeman law) is also shown ***(right).***

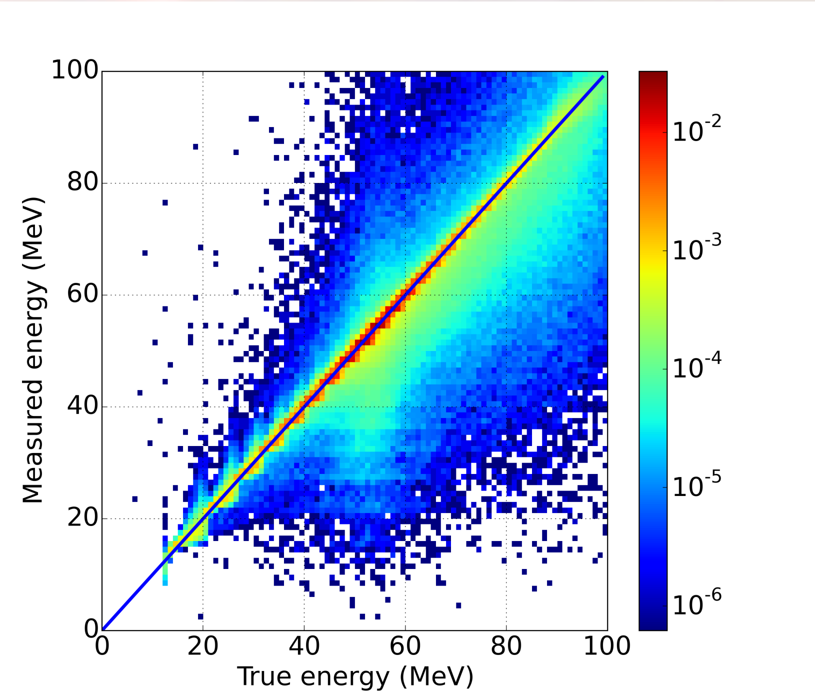
Energy resolution @60 MeV: 4.4%

CMOS RT: energy calibration

Range and deposited energy







Total signal in the RT (sum over layers) for mono-energetic protons. Due to the thickness of the CMOS epitaxial layer (18 µm), spectra are broadened and energy measurements carry large uncertainties ***(left)***. However, when total energy deposition is analysed for a given last layer, there is a monotonic relation between signal and energy ***(right)***.

Energy resolution @60 MeV: 2.8%

CONCLUSIONS

- Several iterations to optimise charge collection in PRaVDA CMOS
- Protons can be tracked through the RT with good efficiency
- kHz readout ensures pCT scan time ≤ 5 min
- Increased energy resolution using combining range and energy deposition measurements (2.8% @60 MeV)

Acknowledgements

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