Monitoring pencil beam scanned proton radiotherapy using a large format CMOS detector

Sam Flynn
The 8th Annual Loma Linda Workshop
18/07/2022

NPL National Physical Laboratory

Monitoring pencil beam scanned proton radiotherapy using a large format CMOS detector

(Commissioning a CMOS detector in scanned pencil beams for enhanced primary standard calorimetry)

Sam Flynn

The 8th Annual Loma Linda Workshop

18/07/2022

Contents

- About me
- Calorimetry
  - Context
  - Heat Flow Concerns
- CMOS detectors
  - vM2428 detector
  - Proton Studies
- Conclusion

Contents

NPL National Physical Laboratory

- About me
- Calorimetry
  - Context
  - Heat Flow Concerns
- CMOS detectors
  - vM2428 detector
  - Proton Studies
- Conclusion


UK weather

Extreme UK weather live: Met Office shows temperatures exceed 37C in parts of England and Wales amid red warning

LIVE Updated 8m ago

Government insists Boris Johnson is 'engaged' in heatwave management as 37.5C recorded in Cavendish, Suffolk

What 40C in the UK will look like

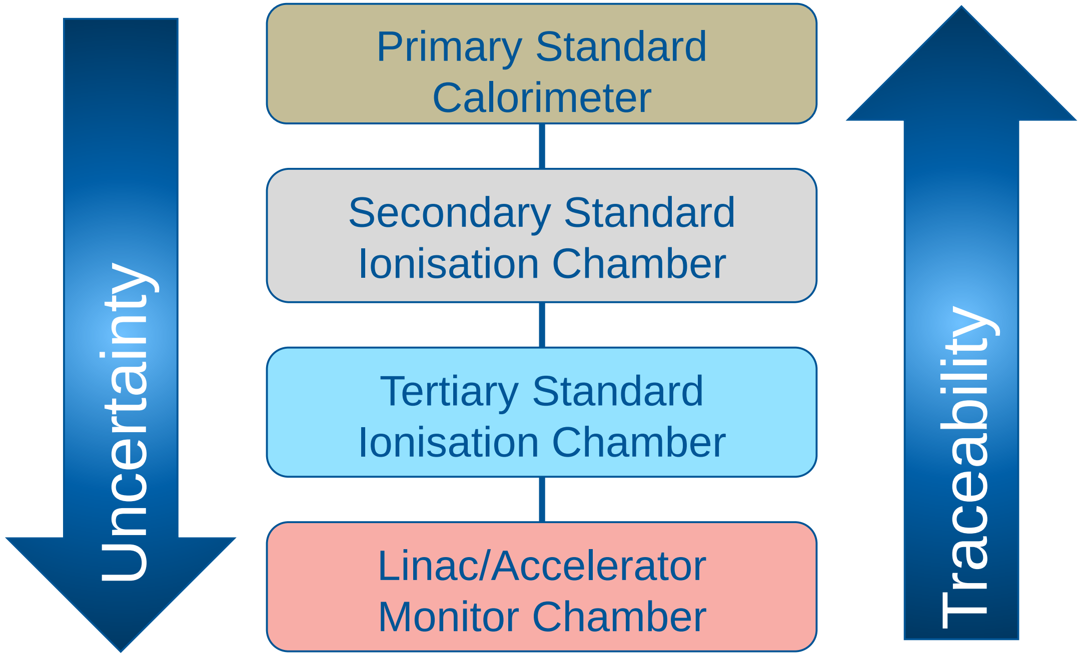
Please excuse me if I seem unable to concentrate!

About me

- Higher Research Scientist at the National Physical Laboratory, the UK’s NMI
- Responsible for the measurement and dissemination of primary standards
- Work in the radiation dosimetry team, main role is the determination of Monte Carlo corrections for proton radiotherapy

Primary Standard Calorimetry Context

- Within radiotherapy, calorimetry is used to define the primary standard of a Gray
- Using procedures such as TRS-398, this definition is distributed to the medical physics community
- Any systematic or random uncertainties in the primary standard are inherited



Primary Standard Calorimetry
NPL Primary Standard for Proton Radiotherapy

National Physical Laboratory

Nested graphite construction

- 16 mm diameter, 2 mm thick core (matched to Roos chamber)
- Two jackets to isolate environment

Portable!

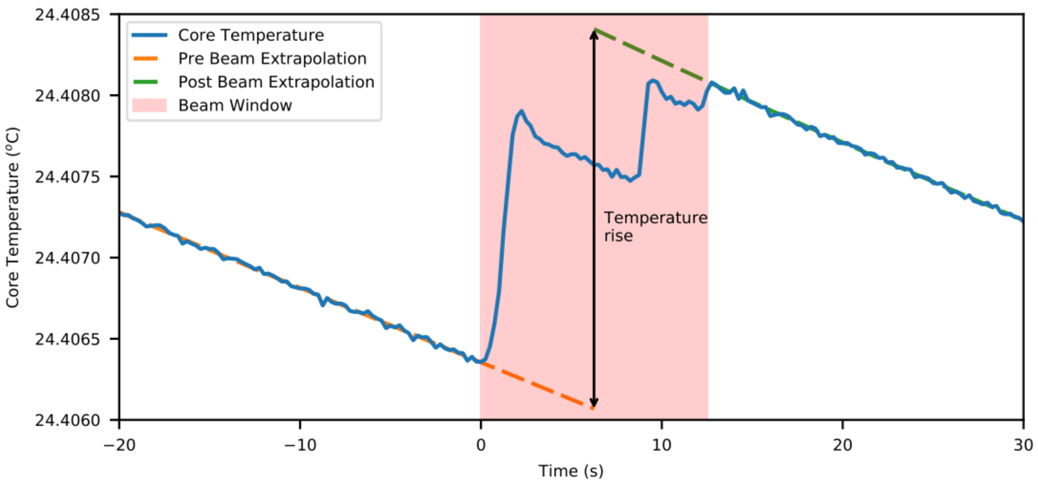
- Has travelled to USA, Japan, France, Spain…

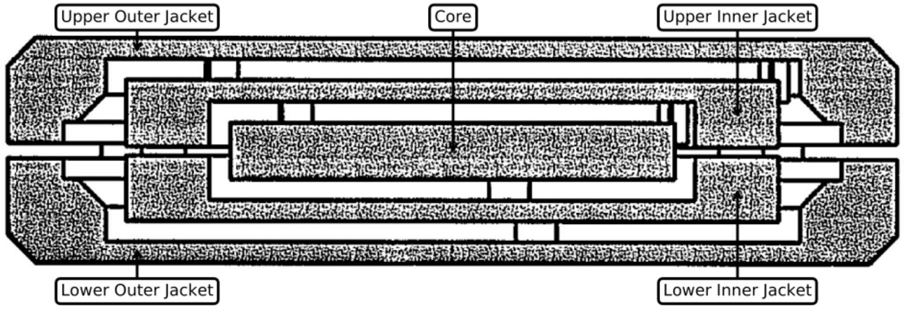
Very sensitive

- 2 Gy dose will cause temperature rise of ~2 mK

Primary Standard Calorimetry
Calorimeter Basics

- $Dose_{Graphite} = c(T)\ \Delta T_{core}\ \Pi k_i$
- Want to measure the radiation induced temperature change
- 1 Gy ~ 1 mK, extremely small!
- Several corrections required to account for impurities, air gaps, material....

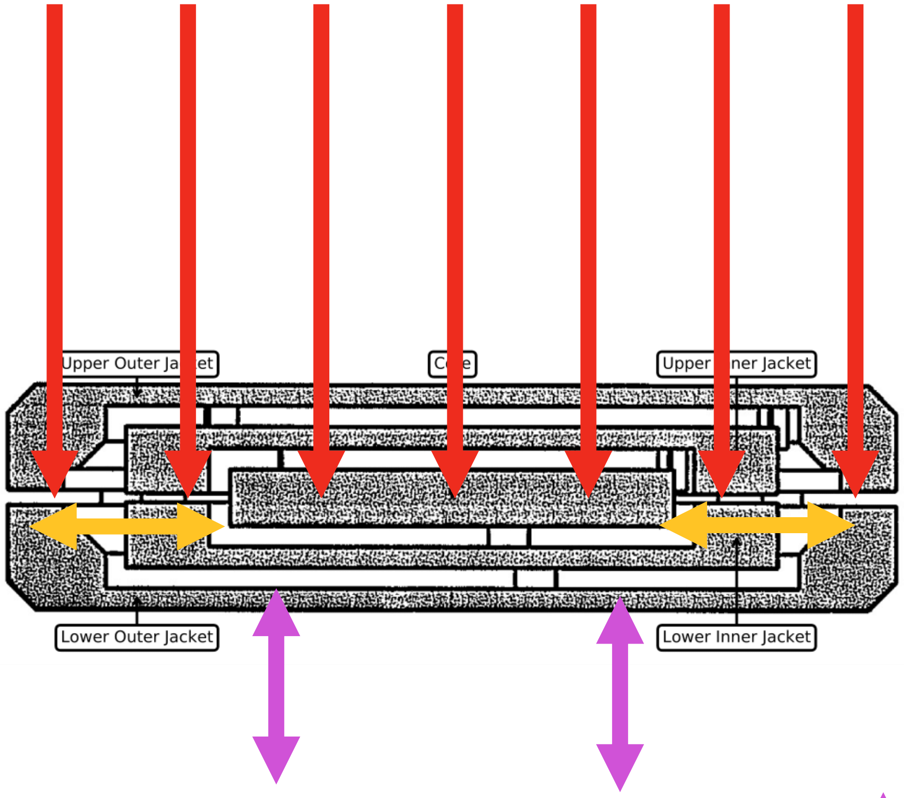




Primary Standard Calorimetry
Heat Flow Concerns

NPL
National Physical Laboratory

- Concern that in non-uniform deliveries (such as scanned pencil beams) temperature rise in the core is influenced by radiation deposited in the jackets
- In a beam delivered non-uniformly, how do you separate the radiation induced temperature increase in the core from internal heat flow?
- Uncertainty from internal heat flow is ~0.1%, but this is inherited by every ionisation chamber, and every patient



Radiation

Internal Heat Transfer

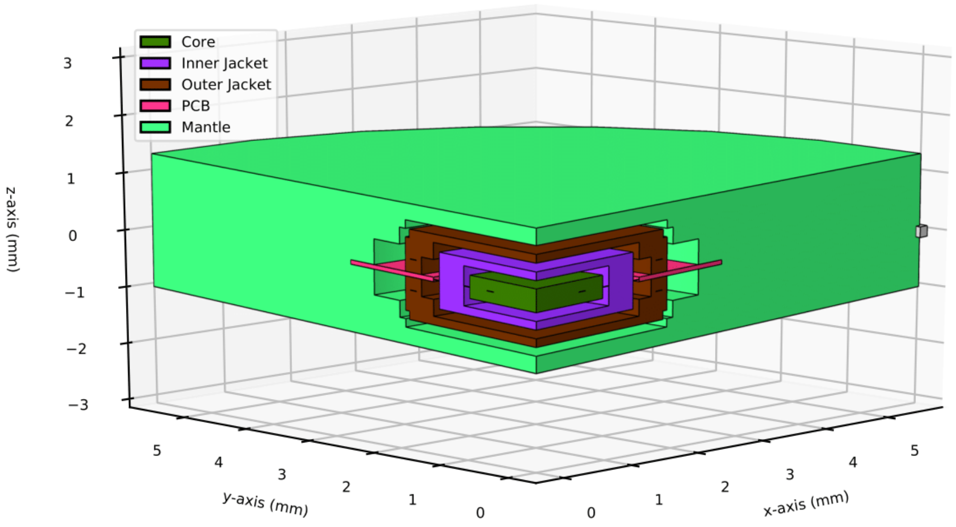
External Heat Transfer

Primary Standard Calorimetry Detector Requirements

- Internal heat flow can be modelled using COMSOL, but requires detailed *independent* information on the radiation beam

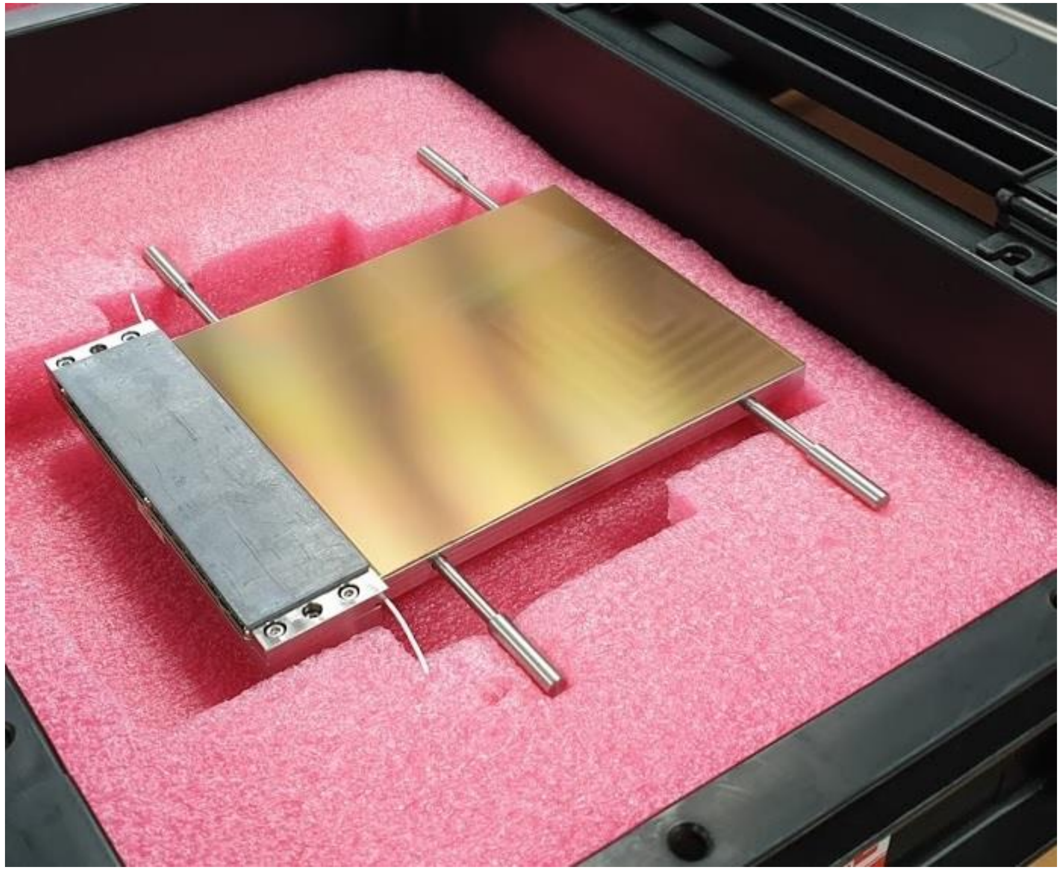
- To enable heat flow simulations:
  - Need high resolution 2D dose measurement
  - Need high temporal resolution

- To measure the beam:
  - Need minimal perturbation of incident beam
  - Need large area (proton reference field 10x10x10 cm3)



CMOS Detectors, vM2428 (LASSENA)

- Originally designed for X-ray imaging
- 2D pixelated detector
- 50 um resolution
- 34 Hz full frame refresh rate
- 12 x 14 cm^2 active area, capable of 2xN tiling



My PhD was to investigate incorporating this with the NPL Calorimeter to determine if per-beam heat loss correction factors be determined

Also useful for microbeam detection!

CMOS Detectors, Proton Concerns

NPL National Physical Laboratory

Possible issues on radiation tolerance:

- Protons damage differently to X-rays
- What is the total lifetime of the device?

Possible saturation issues:

- Maximum ~800,000 e- per pixel per frame before saturation
- A small tightly focused beam has a very high instantaneous dose rate

Possible energy response

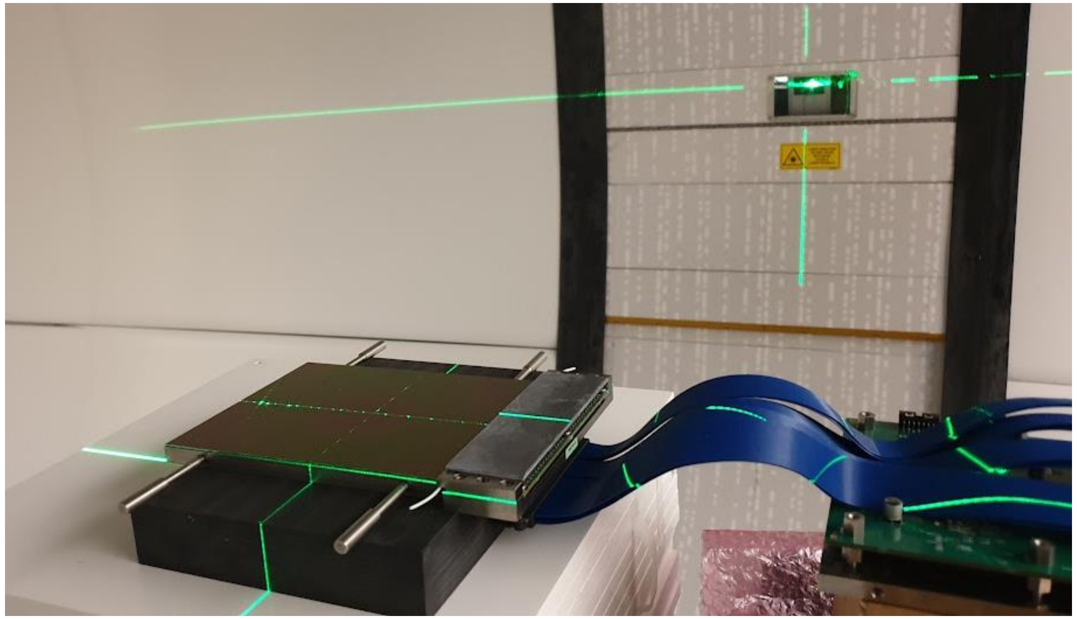
- Is it usable across the entire clinical energy range?

CMOS Detector,
UCLH Proton Therapy Centre

- (Sadly) no proton accelerator at NPL
- Worked in collaboration with colleagues at UCLH, UK
- 70-245 MeV Varian Probeam
- Was in commissioning phase, now in use clinically!

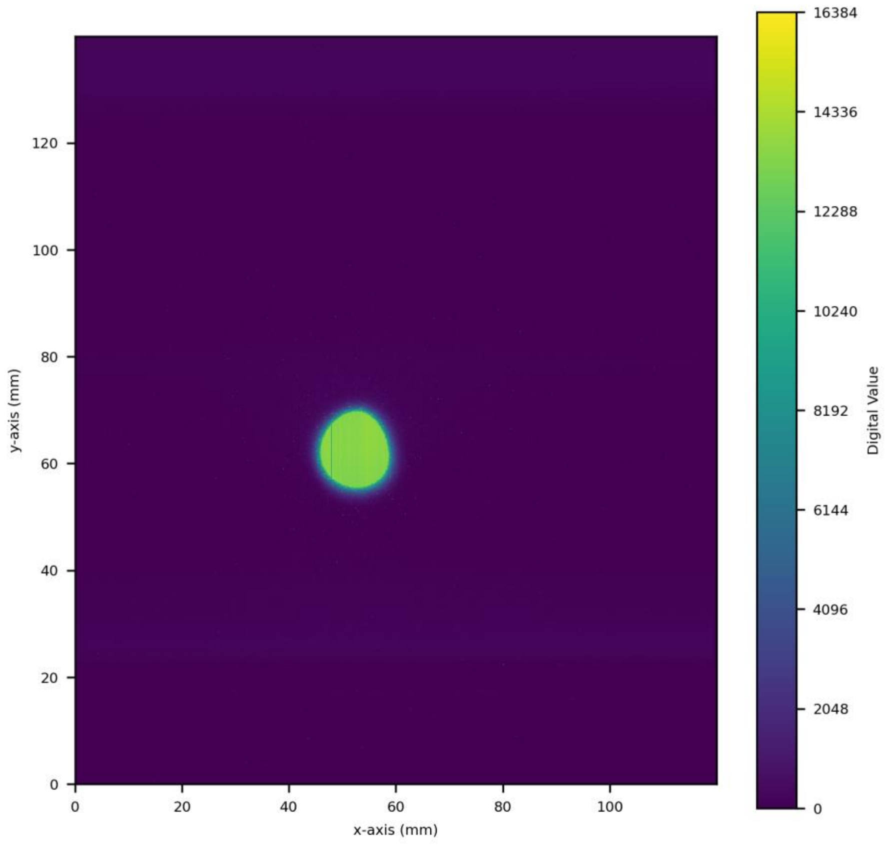
CMOS Detector, Setup

- Due to time limitations only used 220 MeV for studies
- CMOS placed on treatment couch in vertical beam
- RW3 used as beam dump
- Positioned at isocentre, before moving couch close to nozzle



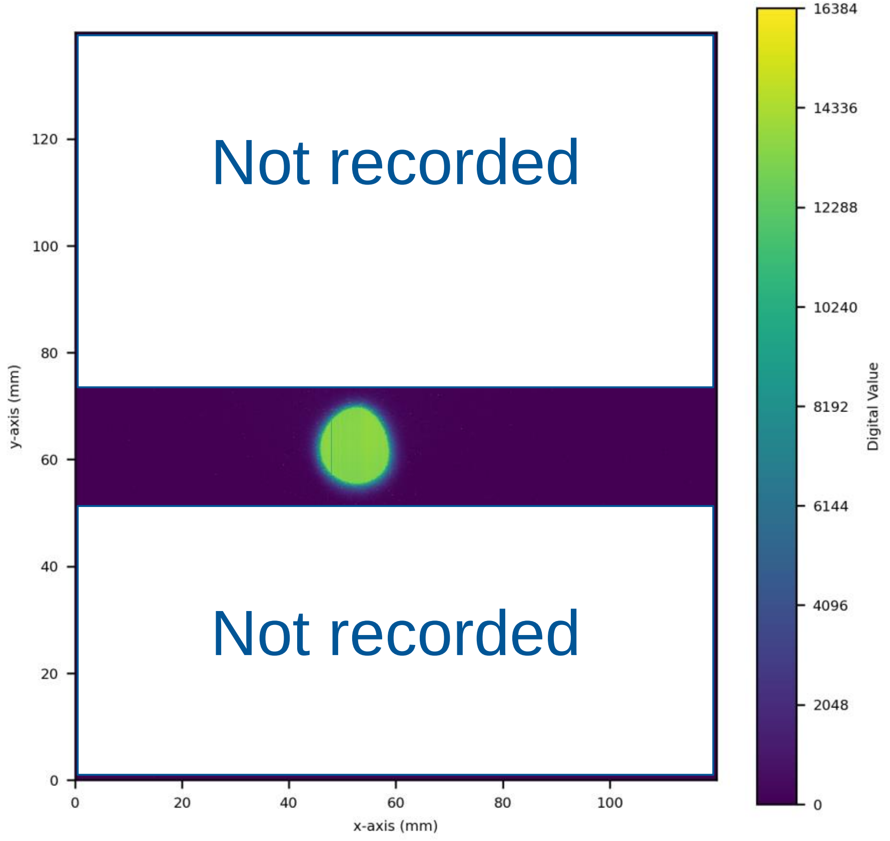
CMOS Detector Results
Full Frame Saturation

- At clinical beam current, incredibly high localised saturation
- Lack of beam halo
- Can reduce saturation by changing region of interest (ROI)



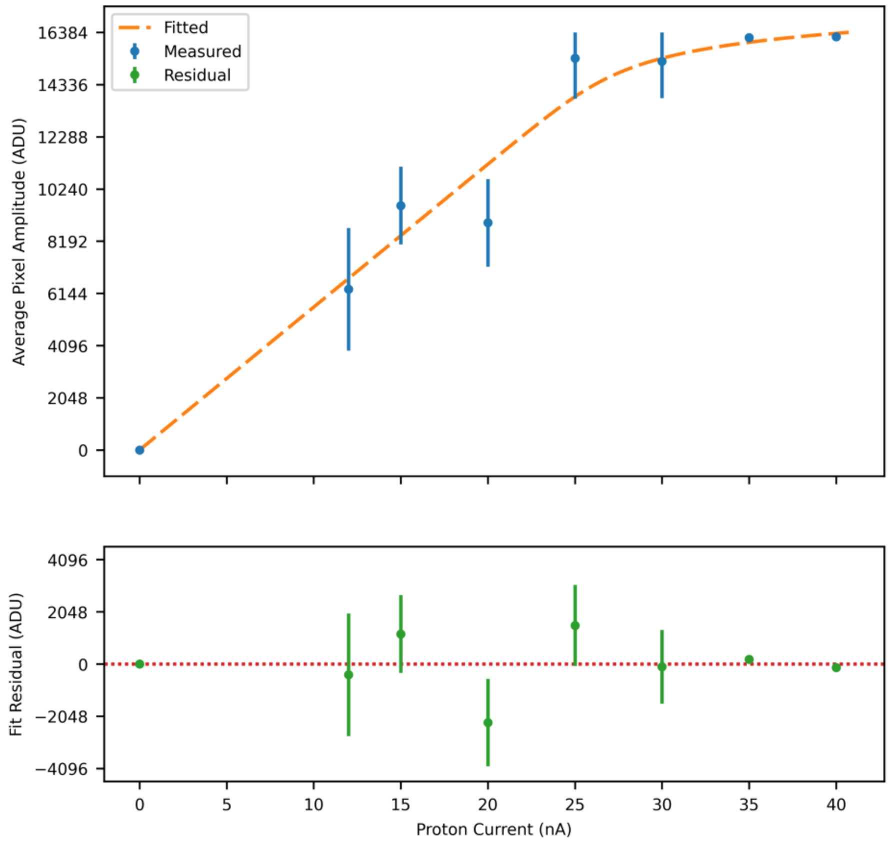
CMOS Detector Results
Full Frame Saturation

- At clinical beam current, incredibly high localised saturation
- Lack of beam halo
- Can reduce saturation by changing region of interest (ROI)



CMOS Detector Results
Linearity

- Region of interest reduced to stop saturation
  - Before:
    - ROI: 2800 rows/frame (12 x 14 cm2)
    - Integration time: 28.3 ms /frame
  - After:
    - ROI: 400 rows/frame (12 x 2 cm2)
    - Integration time: 4.0 ms /frame
- Detector was calibrated against prescribed beam current in service mode

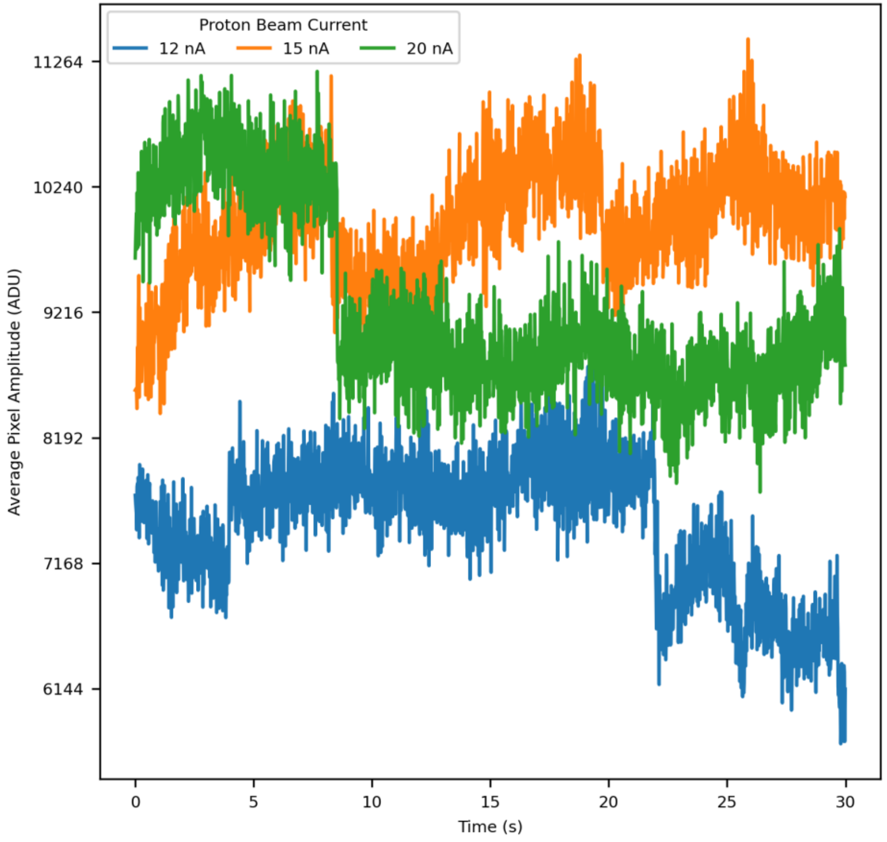


CMOS Detector Results
Instability

- Huge variation observed in pixel response

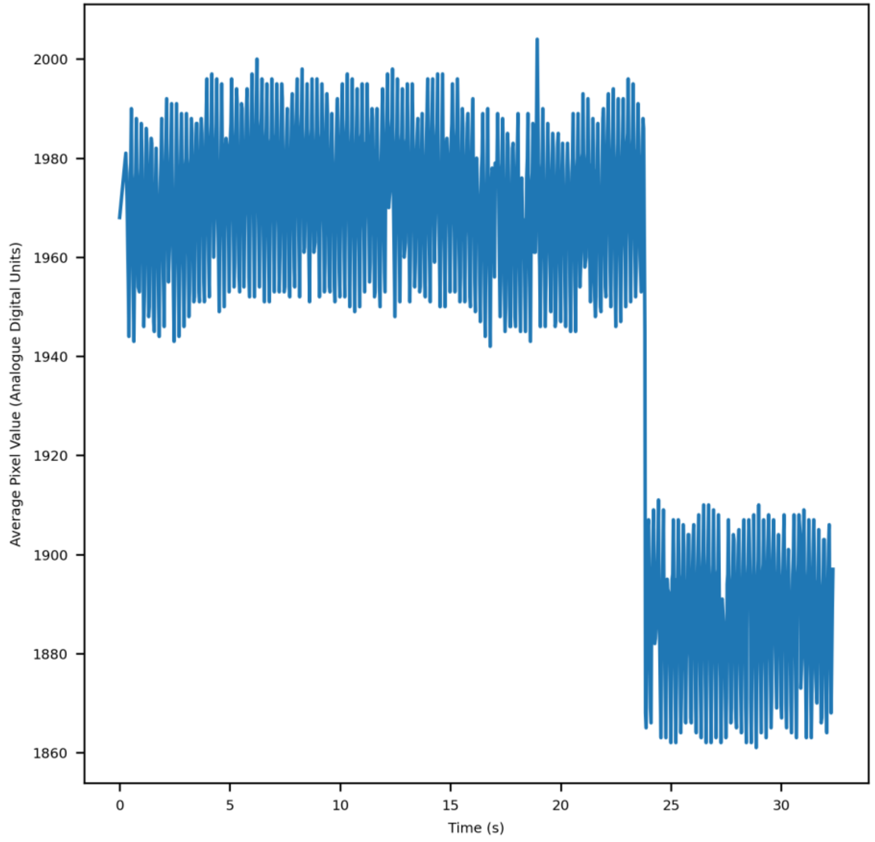
- Attributed to instability in beam current
  - Unable to deliver any beam currents below 12 nA without interlock failures

- Recommendation to the community: Independently measure with an ionisation chamber!



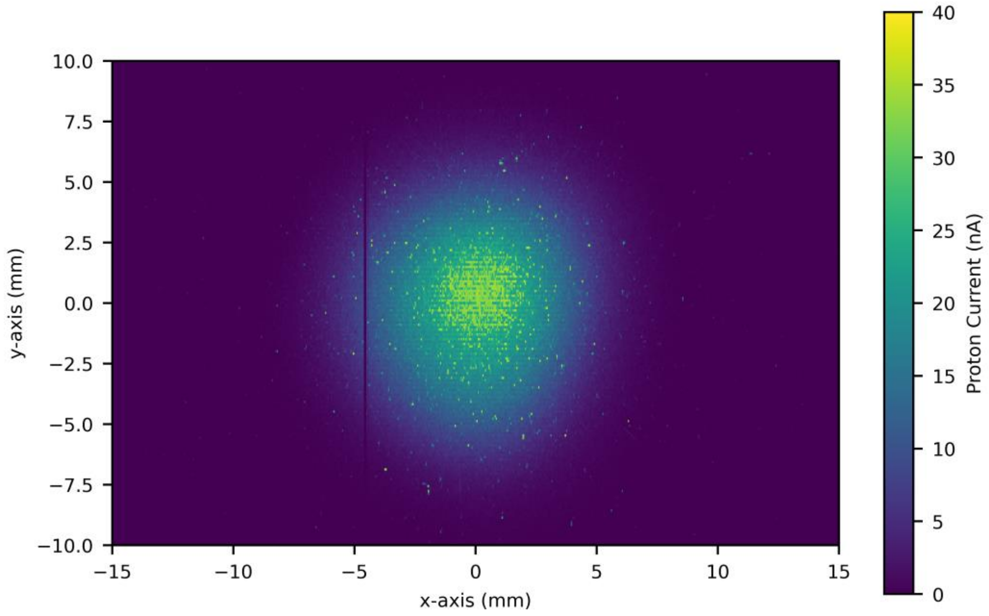
CMOS Detector Results
LED Impact

- An odd pattern was observed in the average frame value
- Eventually traced back to a single flashing LED in the beam nozzle
  - Fixed with tape ☺



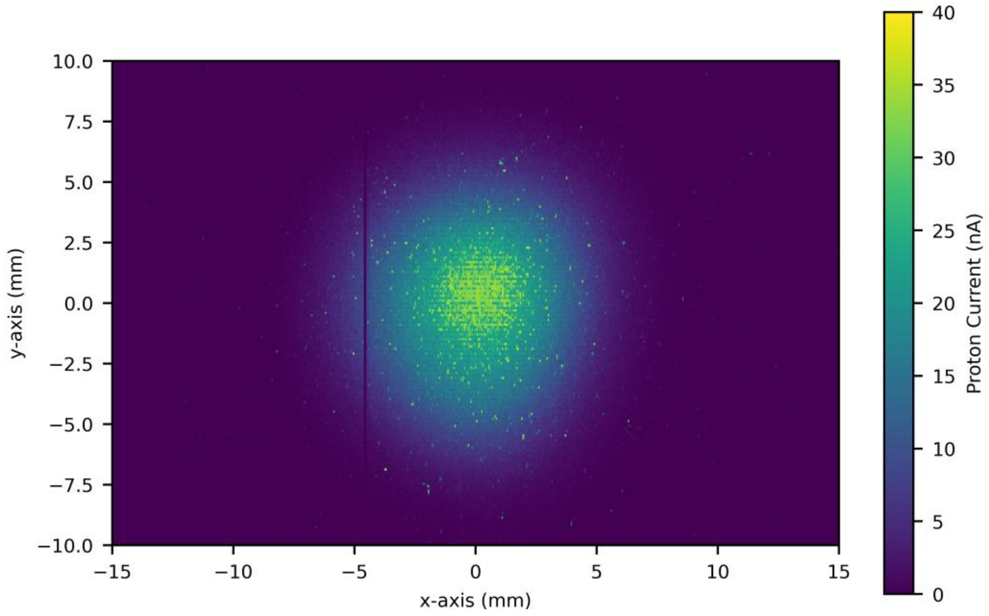
CMOS Detector Results
Spot Results

- Asked for 20 nA, linear region
- Analysis of a single frame to avoid cyclotron feedback
- Calibrated response in terms of beam current
- Able to compare symmetrical spots, and intentionally distorted spots



CMOS Detector Results
Spot Results

- Asked for 20 nA, linear region
- Analysis of a single frame to avoid cyclotron feedback
- Calibrated response in terms of beam current
- Able to compare symmetrical spots, and intentionally distorted spots

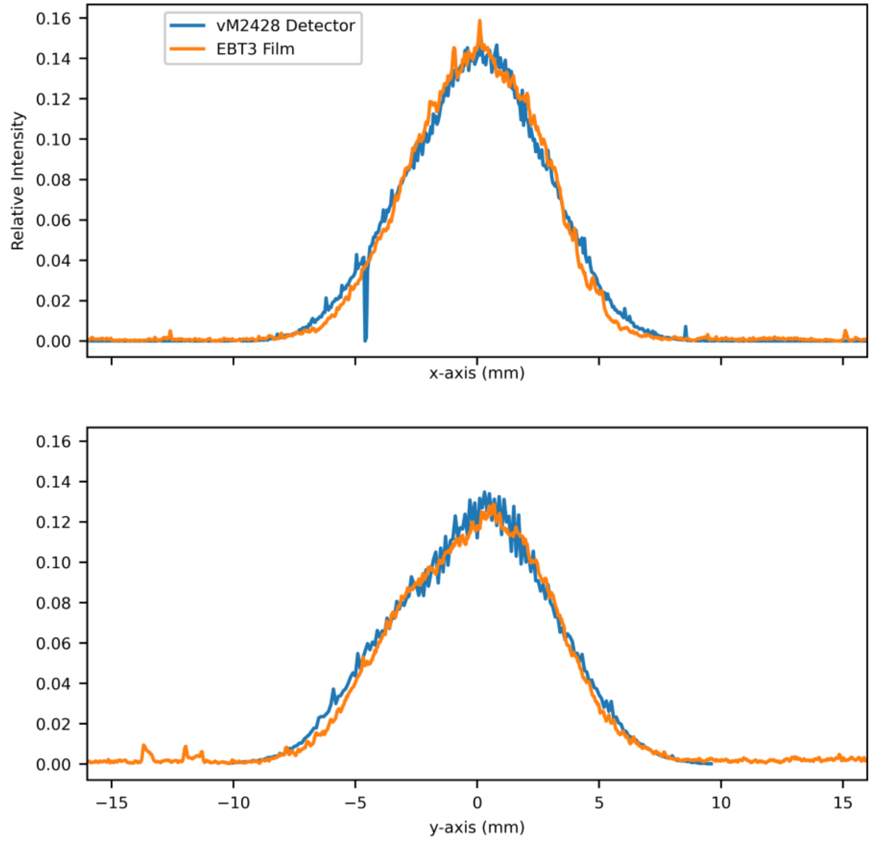


Important for calorimetry simulations!

CMOS Detector Results
Spot Profiles

- CMOS response compared to EBT3 film placed on top of detector
- Due to differing units (Dose/ Beam Current), profiles were compared by normalising with area under spot
- Comparable FWHM measurements

Axis	vM2428 Detector	EBT3 Film
x	6.93 ± 0.05 mm	6.72 ± 0.04 mm
y	7.93 ± 0.18 mm	7.80 ± 0.11 mm

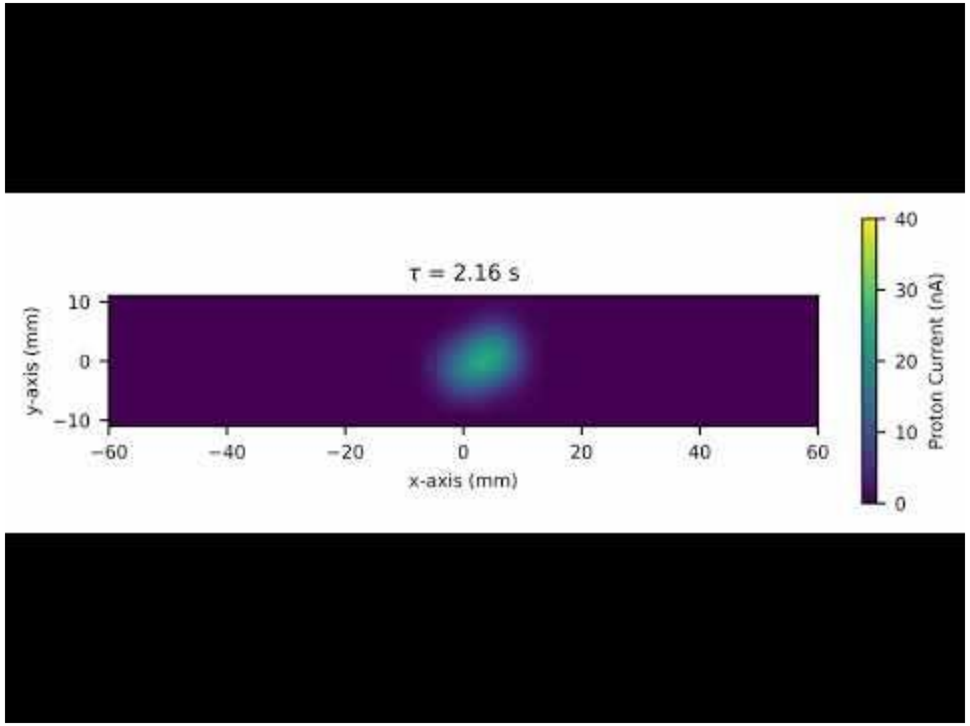


CMOS Detector Results
Moving Spots

NPL National Physical Laboratory

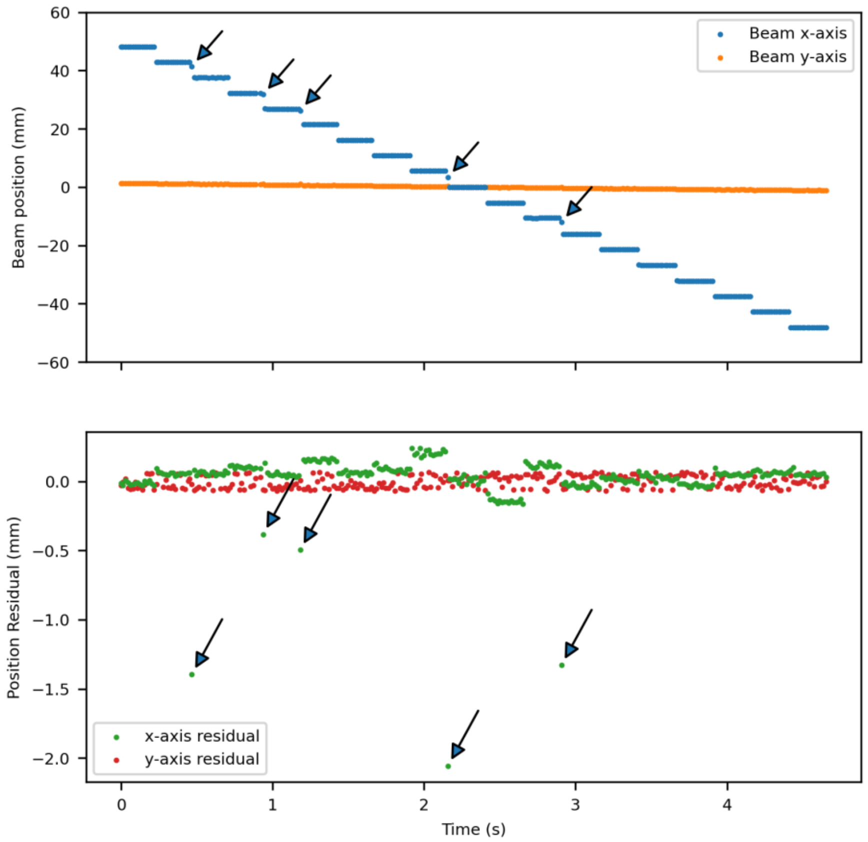
- Created a simple plan to move the beam along ROI
- Ran in clinical mode, defaulted to 40 nA
- Able to calculate beam position using centre of mass

Source	Spot Separation
vM2428 Detector	5.35 ± 0.03 mm
Treatment Planning System	5.356 mm



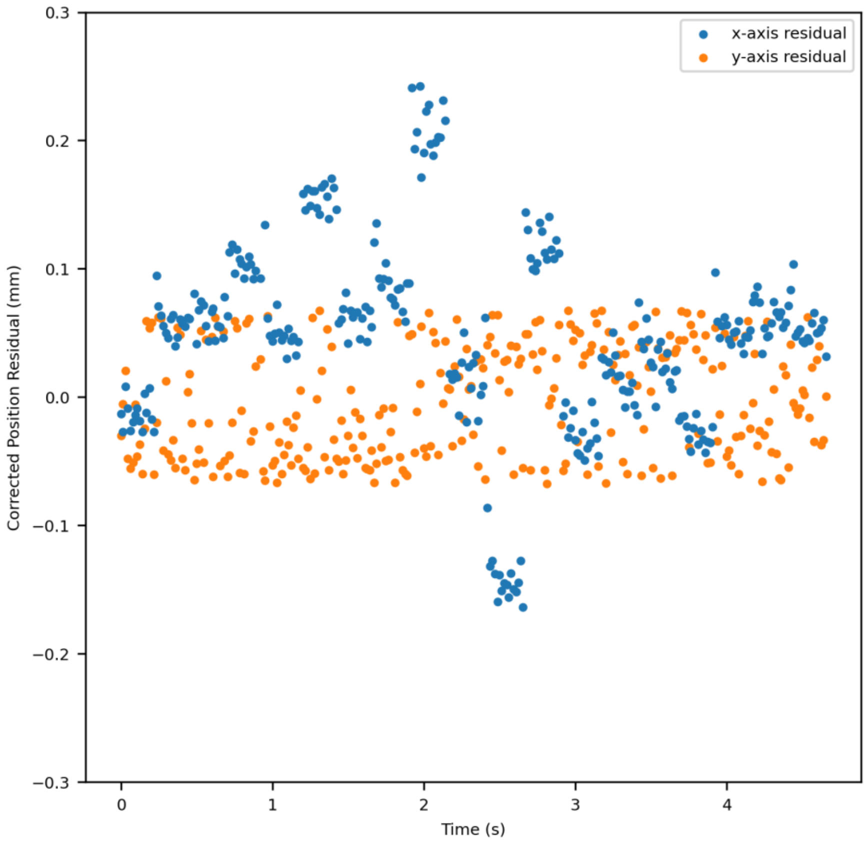
CMOS Detector Results
Moving Spots Analysis 1

- All beam positions within 0.5 mm of expected (omitting rolling shutter artefacts)
- Slight slope in y-axis indicated that detector was slightly misaligned
- No step change in y-axis position



CMOS Detector Results
Moving Spots Analysis 2

- All beam positions within 0.5 mm of expected (omitting rolling shutter artefacts)
- Slight slope in y-axis indicated that detector was slightly misaligned
- No step change in y-axis position



CMOS Detector Results
Future Outlook and objectives

- Energy Characterisation and radiation hardness studies of vM2428 detector

- Incorporation with the NPL Graphite Calorimeter for simultaneous measurements of proton beams

- Moving ROI implementation for 2D position studies

- Work with detector manufacturer to develop modification of detector with higher full well capacity
  - Need approx ~5x current full well to prevent saturation, unlikely to need significant changes to accommodate this

Conclusion/ Key Points

NPL National Physical Laboratory

- Calorimetry requires the measurement of very small temperatures (approximately1 mK/Gy)

- To reduce the uncertainty, need to understand internal heat flow.
  - Need to measure spatial and temporal portions of the beam

- Want an independent method of measuring the beam

- CMOS detectors satisfy the criteria, and whilst the technology is close to viability but work still needs to be done

Huge thanks to the team at UCLH!

NIMA: 166703 Model 5G pp. 1–9 (col. figs: 10)

ARTICLE IN PRESS

Nuclear Inst. and Methods in Physics Research, A xxx (xxxx) xxx

ELSEVIER

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Monitoring pencil beam scanned proton radiotherapy using a large format CMOS detector

Samuel Flynn [a,b,*], Spyros Manolopoulos [c], Vasilis Rompokos [d], Andrew Poynter [c,d], Allison Toltz [d], Lana Beck [f], Laura Ballisat [f], Jaap Velthuis [f,g,h], Philip Allport [b], Stuart Green [e,b], Russell Thomas [a], Tony Price [b,a]

[a] Medical Radiation Physics, National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, United Kingdom
[b] School of Physics and Astronomy, University of Birmingham, Edgbaston Campus, Birmingham, B15 2TT, United Kingdom
[c] Department of Medical Physics & Biomedical Engineering, University College London, Gower Street, London, WC1E 6BT, United Kingdom
[d] Proton Physics Group, Radiotherapy Physics, University College London Hospitals NHS Foundation Trust, Euston Road, London, NW1 2BU, United Kingdom
[e] Medical Physics, University Hospital Birmingham NHS Trust, Mindelsohn Way, Birmingham, B15 2TH, United Kingdom
[f] School of Physics, University of Bristol, H.H. Wills Physics Laboratory, Tyndall Avenue, Bristol, BS8 1TL, United Kingdom
[g] Swansea University Medical School, Singleton Park, Swansea, SA2 8QA, United Kingdom
[h] School of Nuclear Science and Technology, University of South China, West Changsheng Road, Hengyang, 421001, China

ARTICLE INFO

MSC:
0000
1111

Keywords:
CMOS
Dosimetry
Proton beam therapy
Beam monitor
Diagnostics

ABSTRACT

Pencil beam scanning is an effective form of proton radiotherapy for cancer treatment. Small beams of protons are magnetically deflected in order to conform to a tumour shape, and exploiting the Bragg peak in order to minimise dose deposited in healthy tissues. Compared to other therapy modalities, it presents many dosimetric challenges requiring new methods of quality-assurance to ensure the best patient outcome possible. Position Sensitive Detectors (PSD) made from Complementary Metal–Oxide–Semiconductor (CMOS) technology offer one such solution for in-situ and in-vivo dosimetry, with ongoing developments towards high resolution imaging panels that are tolerant to high levels of ionising radiation.

After confirming the linearity of the detector using a pulsed laser system, the suitability of CMOS technology, the vM2428 detector, a large-format CMOS device with 50 μm pixel pitch, was investigated at the University College Hospitals London NHS Foundation Trust (UCLH) proton beam centre using a 220 MeV proton beam at clinical beam currents. The shape of the proton beam was intentionally distorted, enabling the comparison of the vM2428 detector and EBT3 film spot shapes in a fault-finding scenario for QA purposes. For stationary beams, it was found that the vM2428 detector was capable of acquiring 1D and 2D beam profiles comparable to EBT3 film within a single frame (≈4 ms). The detector was then exposed to laterally displaced beams of the same spot size ("spot scanning") that emulates a clinical beam delivery and was found able to record the beam displacement in real time. The spot-to-spot separation was measured to be 5.35 ± 0.03 mm, in agreement with the planned 5.356 mm. These results highlight the versatility and potential of large-format CMOS detectors to proton beam therapy.

1. Introduction

Proton beam therapy is a modern cancer treatment modality in which the Bragg peak is used to preferentially irradiate the tumour volume, minimising dose deposited in healthy tissue [1]. Whilst in the past passive scattering was used, an increasing number of therapy centres are installing nozzles capable of delivering scanned beams [2]. In this therapeutic modality, a beam of Full Width at Half Maximum (FWHM) 4–10 mm is magnetically scanned laterally across a cross-sectional area (ideally inside the tumour volume), whilst the energy of the beam is altered in order to vary the dose with depth of the Bragg peak and thus deliver a homogeneous dose to the target volume.

Regular quality assurance and validation of the beam shape and position are vital to ensure the expected treatment is delivered as planned. Uncertainties in the delivered spot position cause errors in the delivered dose, with misaligned spots resulting in unexpected regions of high and low dose [3,4]. To mitigate this, monitoring of the beam profile is essential and can be performed within the beam delivery system with the use of silicon strip detectors [5], or arrays of ionisation chambers [6]. These instruments are not necessarily independent of the beam delivery system and may be susceptible to bias when performing quality assurance.

* Corresponding author at: Medical Radiation Physics, National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, United Kingdom.
E-mail address: sam.flynn@npl.co.uk (S. Flynn).

https://doi.org/10.1016/j.nima.2022.166703
Received 19 September 2021; Received in revised form 6 March 2022; Accepted 16 March 2022
Available online xxxx

Please cite this article as: S. Flynn, S. Manolopoulos, V. Rompokos et al., Monitoring pencil beam scanned proton radiotherapy using a large format CMOS detector, Nuclear Inst. and Methods in Physics Research, A (2022) 166703, https://doi.org/10.1016/j.nima.2022.166703.

National Physical Laboratory

Department for Business, Energy & Industrial Strategy

FUNDED BY BEIS

The National Physical Laboratory is operated by NPL Management Ltd, a wholly-owned company of the Department for Business, Energy and Industrial Strategy (BEIS).