The QuADProBe: A Comprehensive Quality Assurance System for Machine and Patient Specific Quality Assurance

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Disclosures

- I’m a high energy physicist.
- I’m socially awkward.
- I haven’t had a COVID vaccine.
- I’m difficult to work with.

- Research funded in part by UK STFC and EPSRC research councils; EU Marie Curie network “Optimisation of Medical Accelerators”.
- UCL research collaboration with Nuvia CZ for scintillator development.

- No conflicts of interest to disclose.

Abstract

Background

The clinical pressure to maximise patient throughput and increase efficiency in PBT means an increased focus on methods of decreasing the setup and measurement time for beam-based Quality Assurance (QA). This includes not only machine QA - where the focus is on making beam QA measurements both faster and more comprehensive - but also Patient Specific QA, which can be a significant load on staff and machine time better utilised elsewhere.

Methods

The Quality Assurance Detector for Proton Beam Therapy - the QuADProBe - is currently under development to integrate the various beam QA measurements into a single combined detector capable of making simultaneous measurements of absolute dose, beam position, spot size and shape and range in water across the full range of clinical energies at both clinical and FLASH dose rates. The transmission calorimeter developed at NPL offers dose measurements with consistent repeatability with less than 2% (k=1) SEOM. A Monolithic Active Pixel Sensor (MAPS) developed at the University of Birmingham measures beam spot size and position with sub-millimetre accuracy. Finally, the UCL plastic scintillator-based Quality Assurance Range Calorimeter (QuARC) allows sub-millimetre measurements of Water Equivalent Path Length up to 250 MeV.

Results

These are combined into a single nozzle-mounted enclosure with single onboard PC-based data acquisition (DAQ) system providing full detector monitoring and control through a simple web interface. The nozzle-mounted enclosure greatly simplifies setup and enables measurements at all gantry angles without adjustment to the detector setup. The web-based DAQ user interface enables detector control with any computer, tablet or mobile device connected to the same network as the QuADProBe.

Conclusions

We present QuADProBe measurements carried out at the UCLH PBT centre, covering both single energy pristine Bragg curves at a range of energies and positions, and a series of box fields, including treatment plans with multiple gantry angles. These demonstrate the feasibility of making all beam QA measurements simultaneously. Since measurements are made in real time, the QuADProBe reduces single PSQA measurements to the time taken for treatment delivery - on the order of a few minutes - since rescanning and detector adjustment is not required.

PBT Beam & Patient Quality Assurance

- Beam QA verifies 4 properties:
  - Absolute dose
  - Spot size (X & Y)
  - Spot position (X & Y)
  - Range (to water)
- Measurement frequency determines how fast/comprehensive it is:
  - Ideally measure all properties at all positions/energies
  - Too much for daily QA!
  - Limit to verification of a few properties
  - Make compromises *eg.* spot size after known absorber
- Patient QA less frequent but more comprehensive:
  - Need to verify volumetric dose to water for full treatment plan
  - Includes multiple gantry angles
- Need to compromise for speed:
  - Sample only at specific locations
  - Single gantry angle

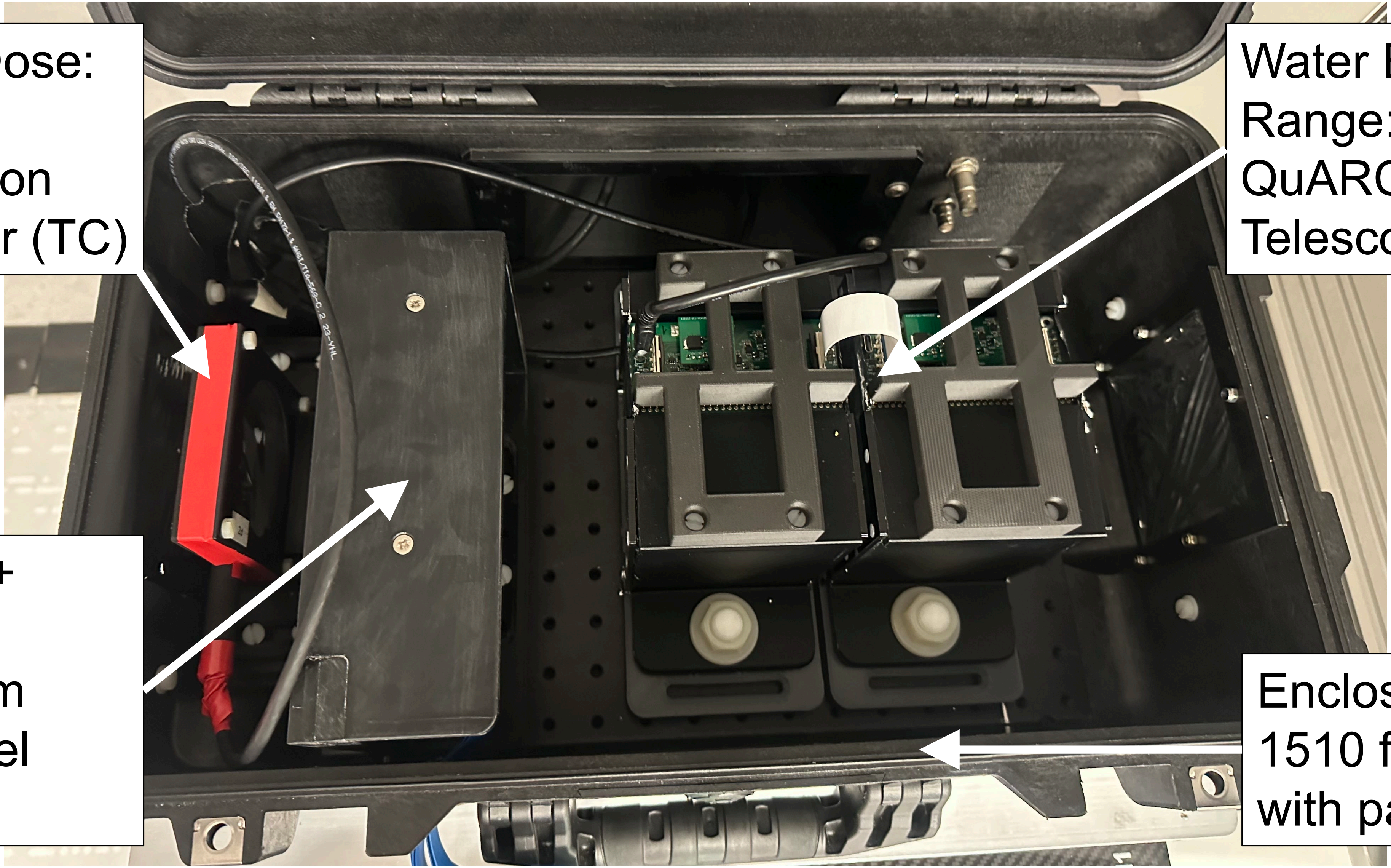
- If we can measure all properties at all positions/energies and all gantry angles, we can do better
- Measure all properties simultaneously with separate detectors
- Reconstruct in simulation

Enter: The QuADProBe

Absolute Dose: NPL Transmission Calorimeter (TC)

Water Equivalent Range: UCL QuARC Range Telescope

Protons

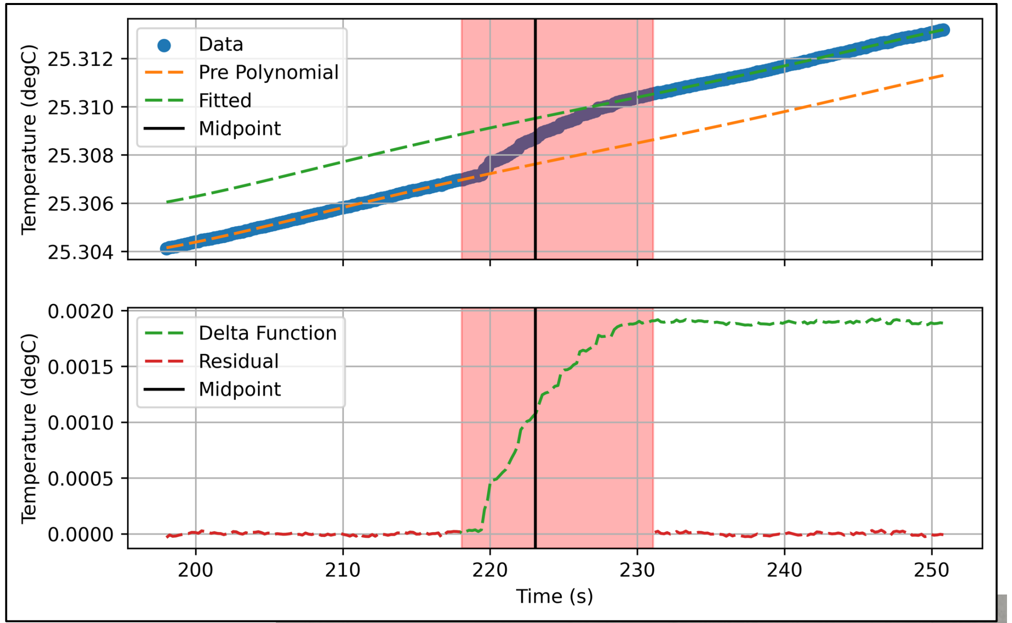


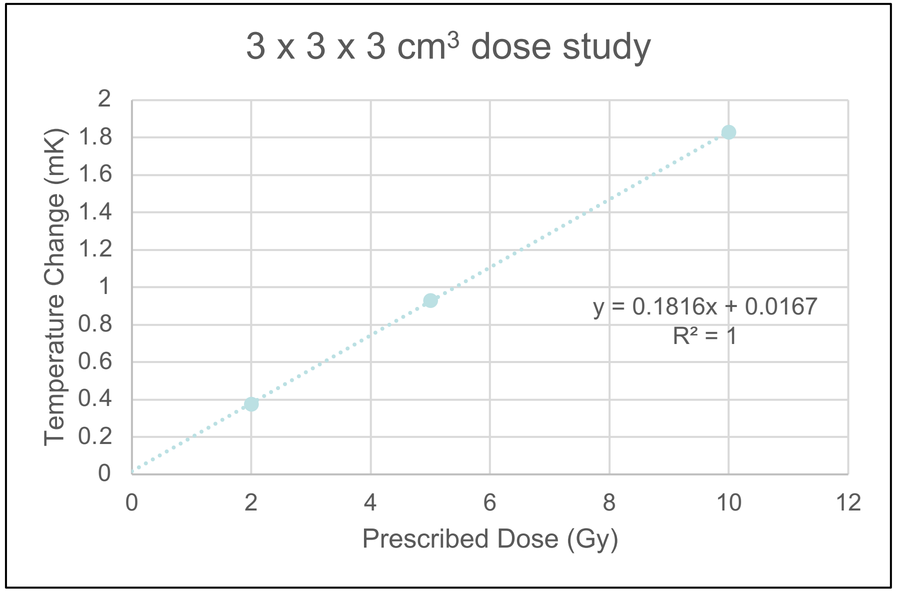
Spot Size + Position: Birmingham CMOS Pixel Sensor

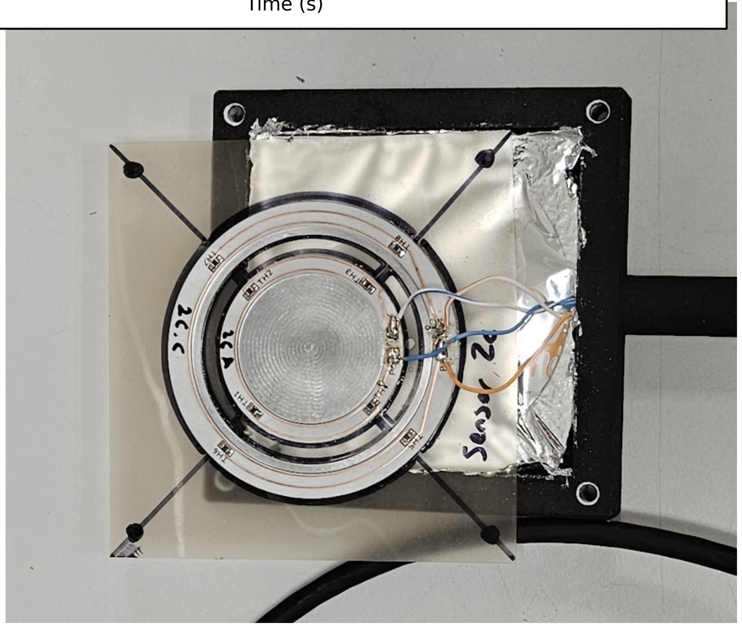
Enclosure: Peli 1510 flight case with patch panel

The NPL Transmission Calorimeter (TC)

- A thin aluminium core with embedded thermistors
  - 45 mm diameter
  - 0.6 mm thickness, approximately 1.2 mm WET
  - High performance 7 W/mK thermal conductivity dielectric PCB connecting thermistors
- Twin core design:
  - Primary core to measure radiation-induced temperature change
  - Secondary core to compensate for ambient temperature fluctuations
- Results:
  - Linear response with dose in 3 x 3 x 3 cm^3 cube
  - Measures 1.96 ± 0.04 mK for 10 Gy delivery
  - Performance evaluated at different dose rates and different energies

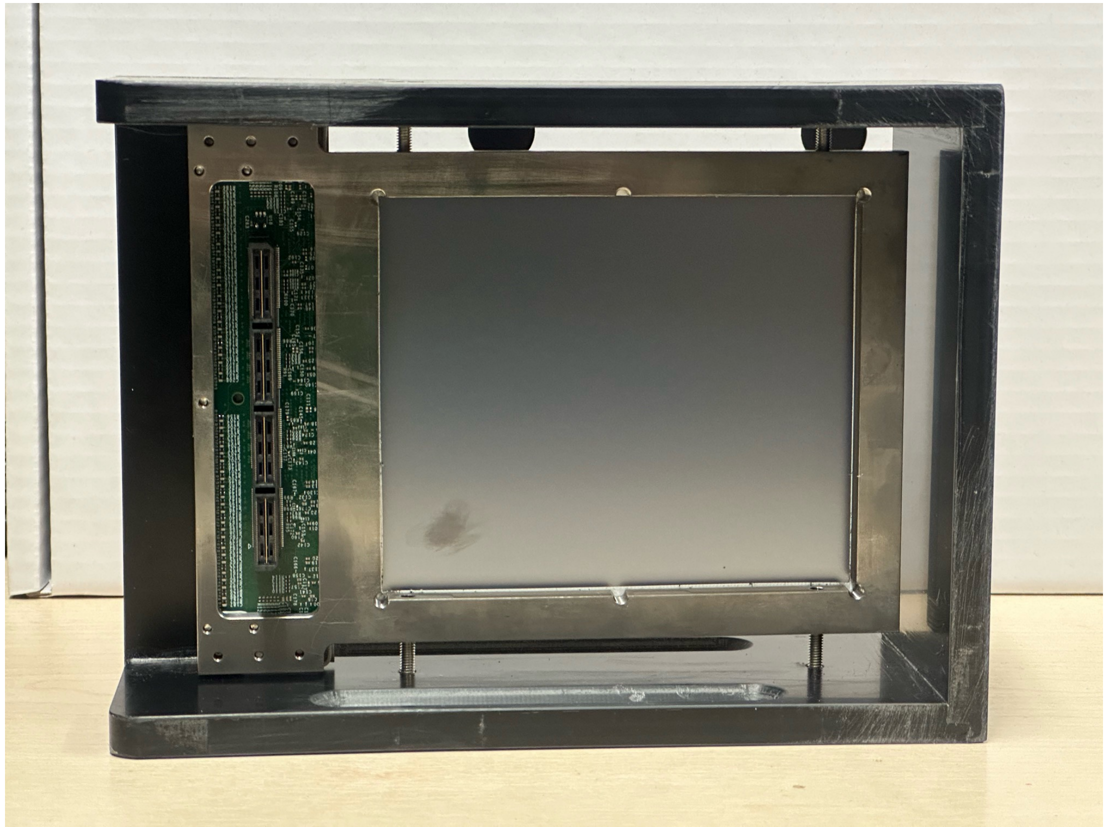


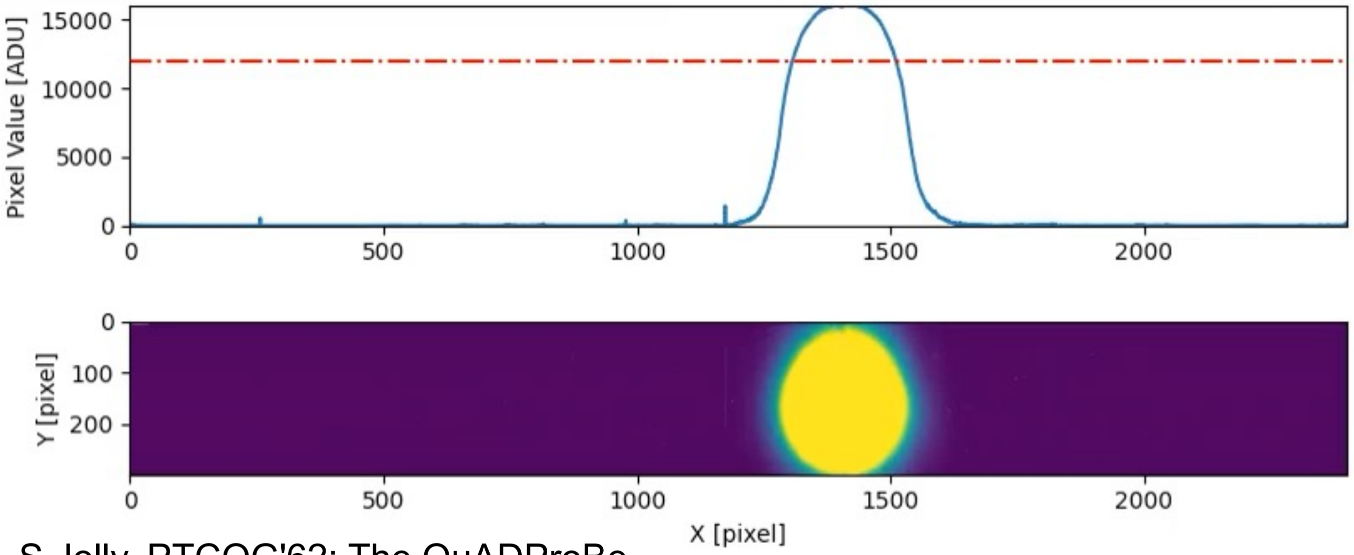


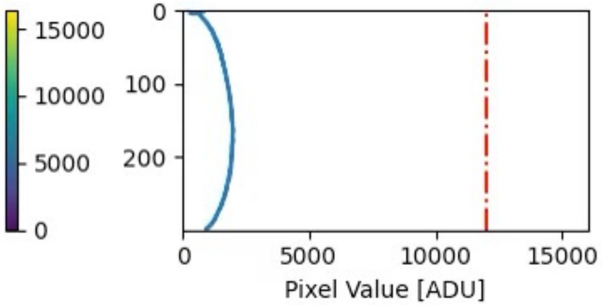


The Birmingham CMOS Pixel Sensor

- 2D large format CMOS pixel sensor LASSENA:
  - Developed at RAL (UK) X-ray imaging; marketed by Nordson
  - 2,400 x 2,800 pixels each 50x50 μm^2
  - 12 x 14 cm^2 active area
  - Readout along one side to allow tiling of sensors over a 24x(Nx12) cm^2 area
  - Active thickness of 8 um silicon plus 700 um of support silicon.
  - 34 fps full frame readout via a rolling shutter (28 ms integration time).
- NIMA 2022: 10.1016/j.nima.2022.166703
- Jinst 2023: 10.1088/1748-0221/18/03/P03014







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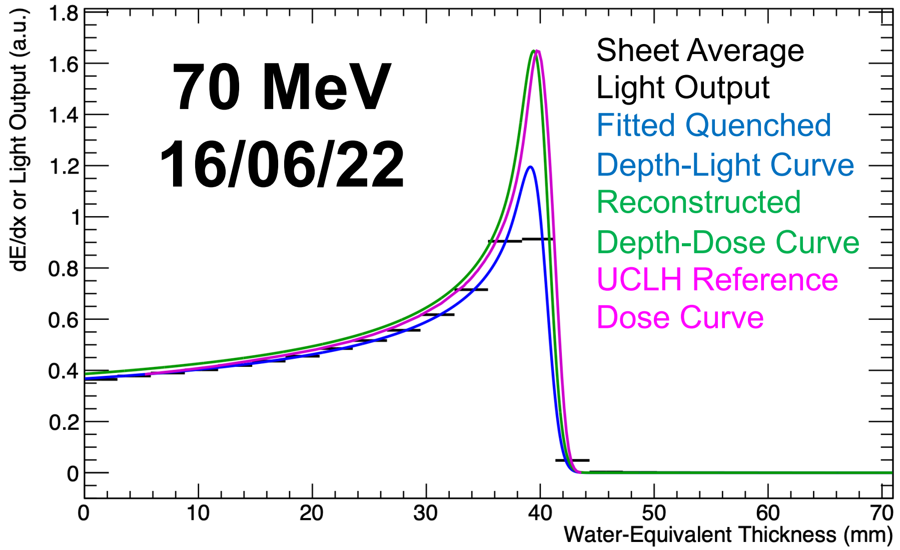
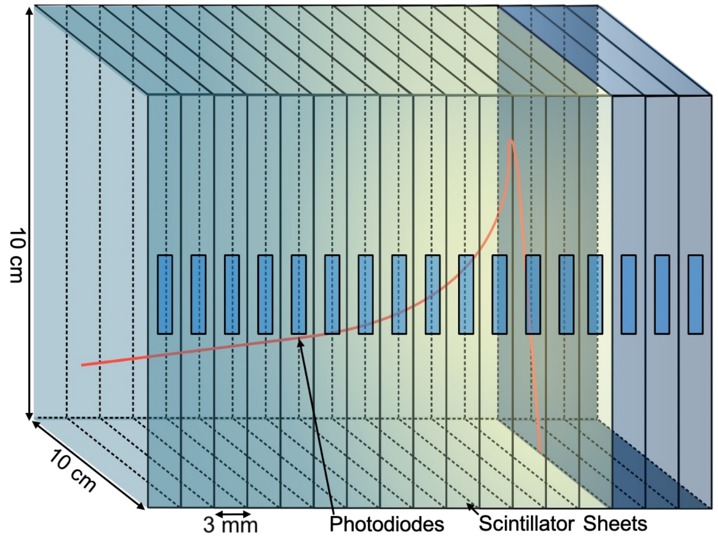
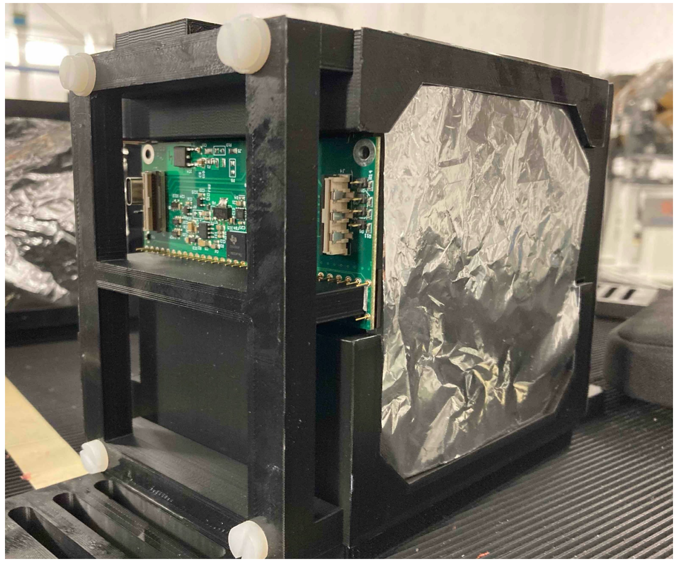
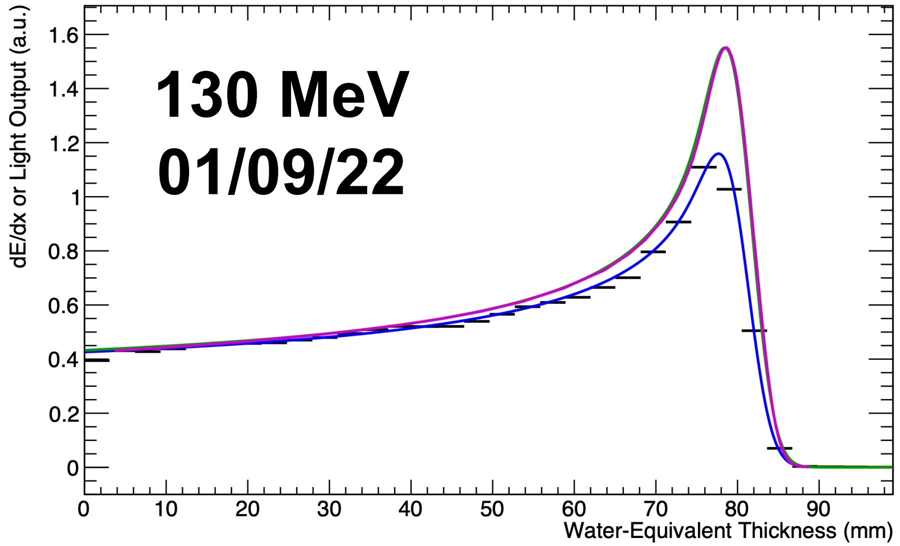
The UCL QuARC

- The Quality Assurance Range Calorimeter (QuARC) constructed from plastic scintillator:
  - Protons intercepted by a series of optically-isolated polystyrene scintillator sheets.
  - Measure light output with photodiodes.
  - Light output of each sheet nonlinear to dose, but quenching described by Birks' Law:
    - Fit data with analytical depth-light model.
    - Reconstruct Bragg depth-dose curve and measure proton range.
  - Photodiodes coupled to fast, modular electronics and an FPGA to read light levels at over 5 kHz.
  - FPGA connects to on-board PC (Raspberry Pi) via USB.
  - On-board DAQ runs web server: connect over network for full data viewing and control.



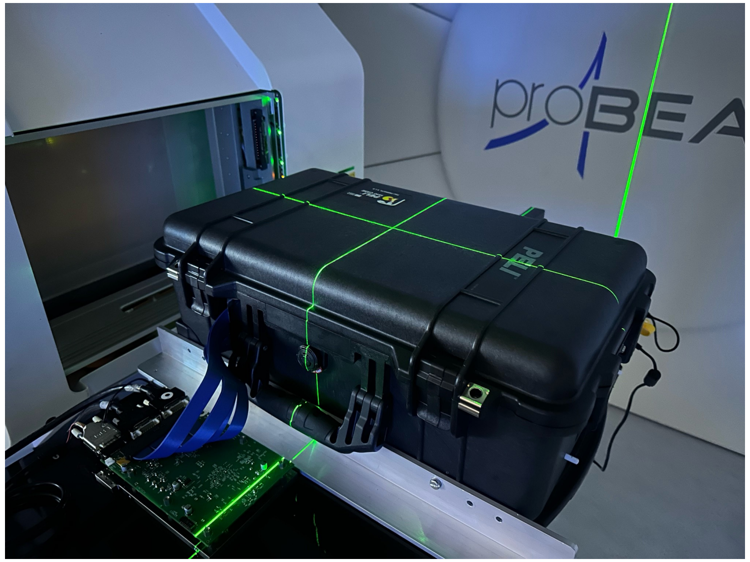




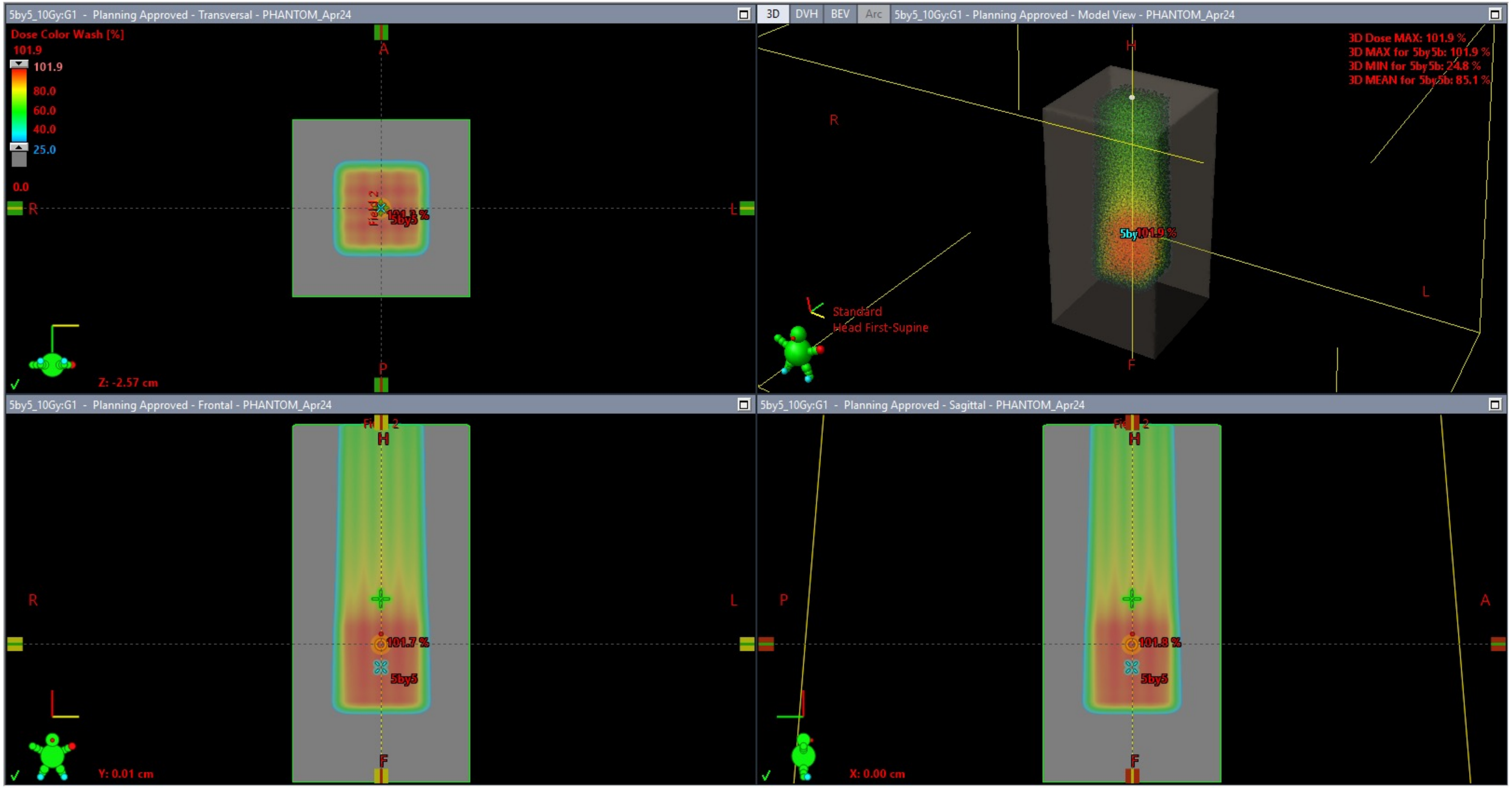


UCLH Beam Tests

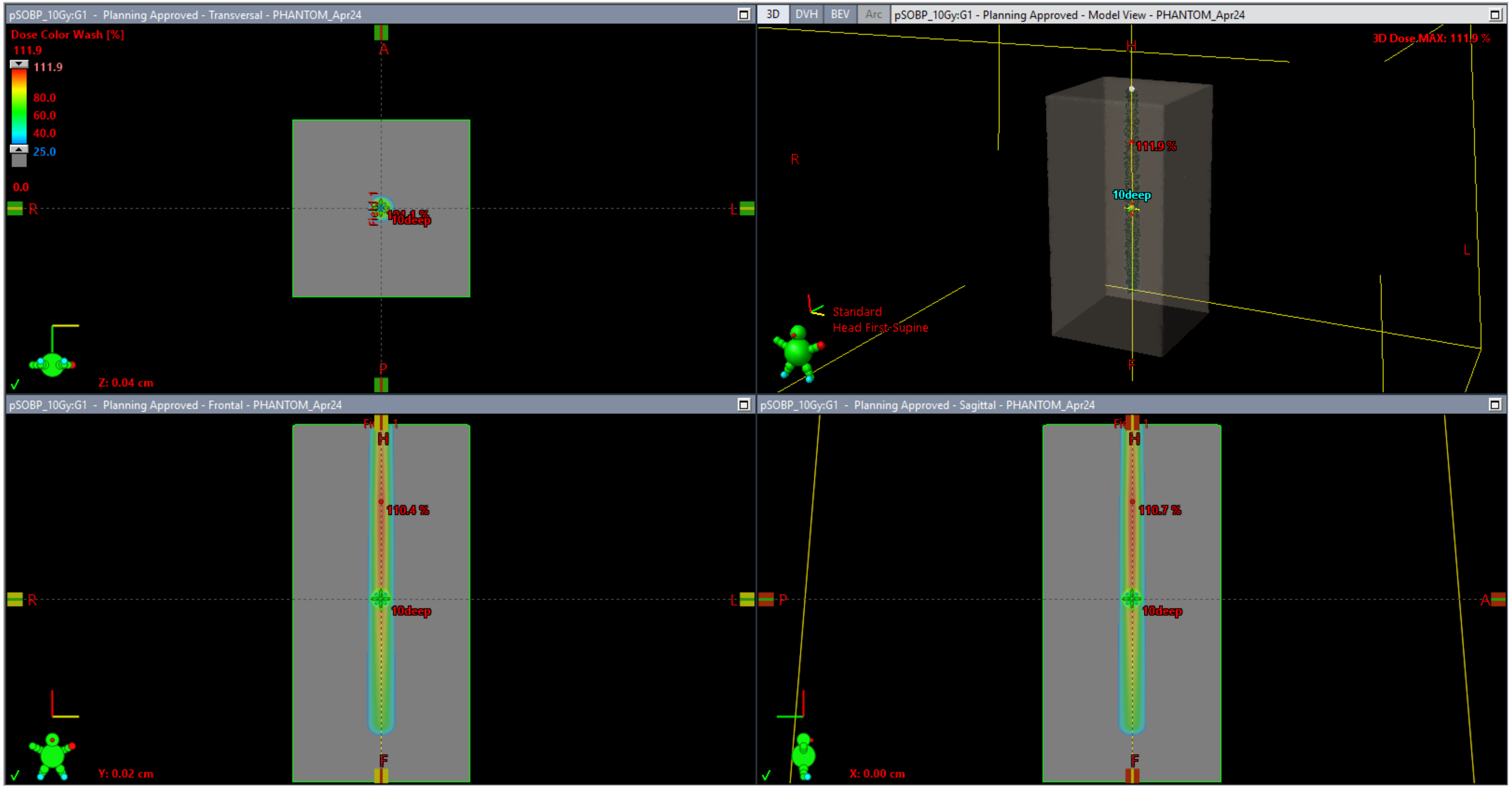
- Two nights of tests at UCLH
- 4 QA treatment plans to test:
  - 3 x 3 x 3 and 5 x 5 x 5 box fields
  - Single spot SOBP
  - "Slice" field to test pixel sensor readout.
- Some teething problems:
  - Noisy readout from QuARC
  - Dead pixels/areas on pixel sensor
  - Couch position interlock
  - Different gantry room for each night



UCLH 5 x 5 x 5 Box Field Plan

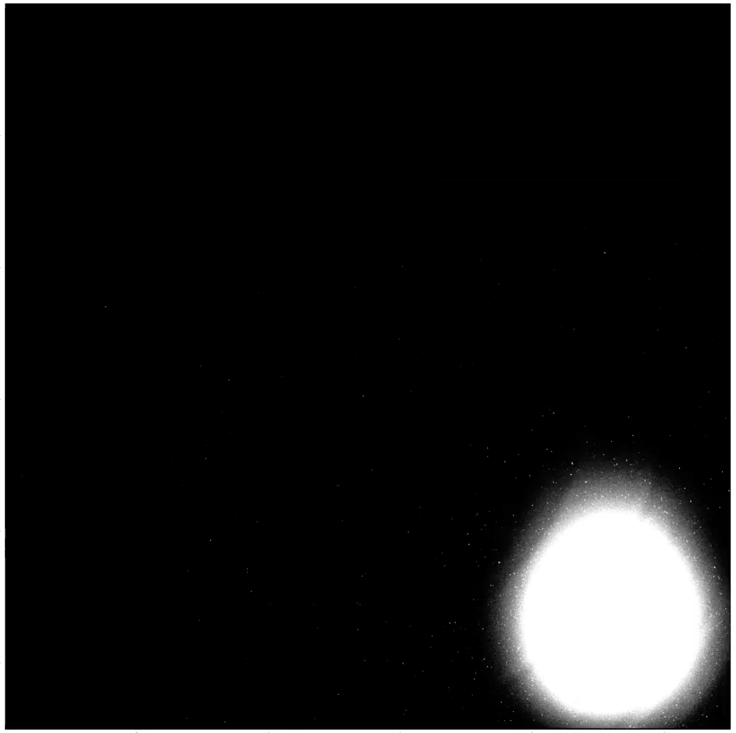


UCLH Single Spot SOBP Plan

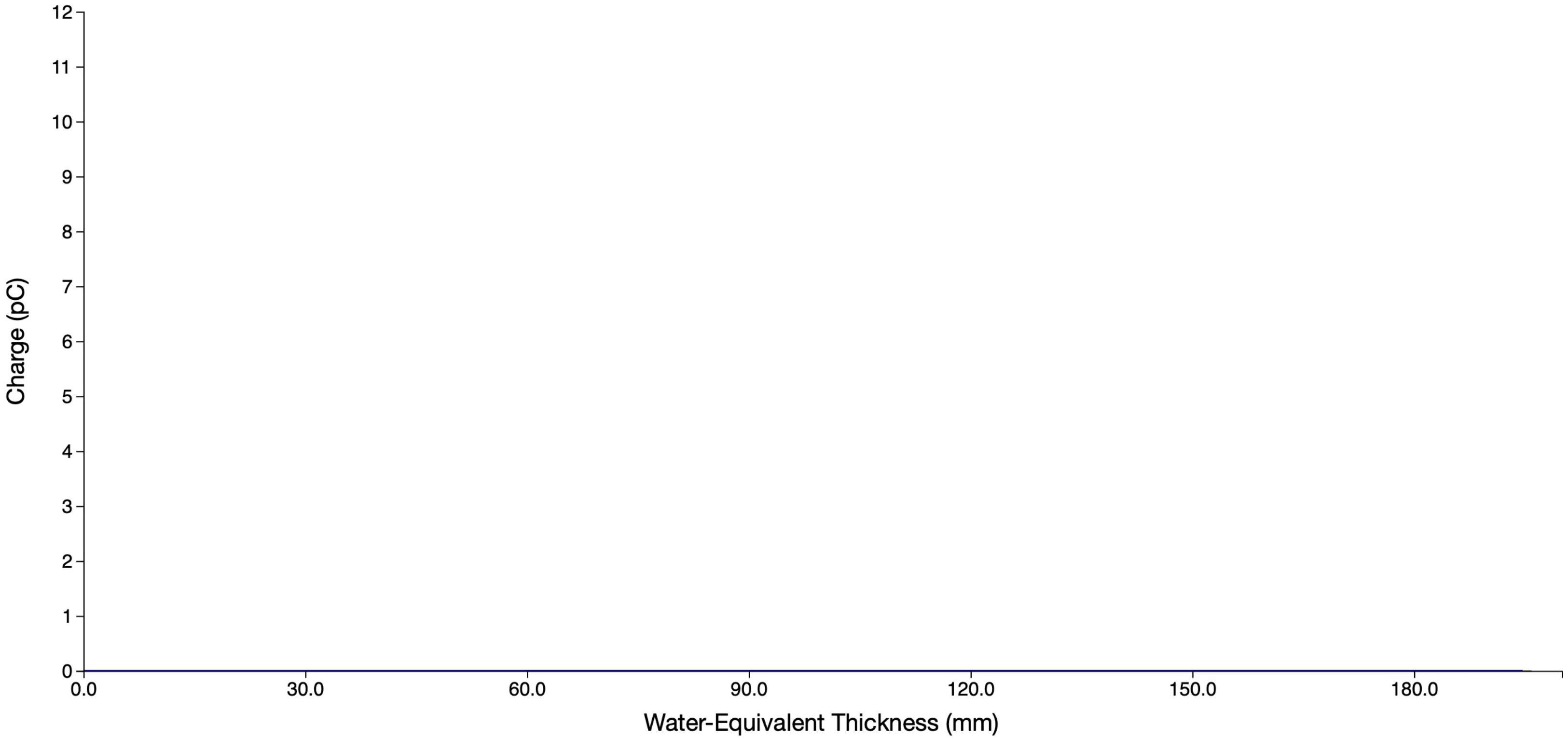


UCLH Beam Test Results (Preliminary)

Pixel Sensor



QuARC



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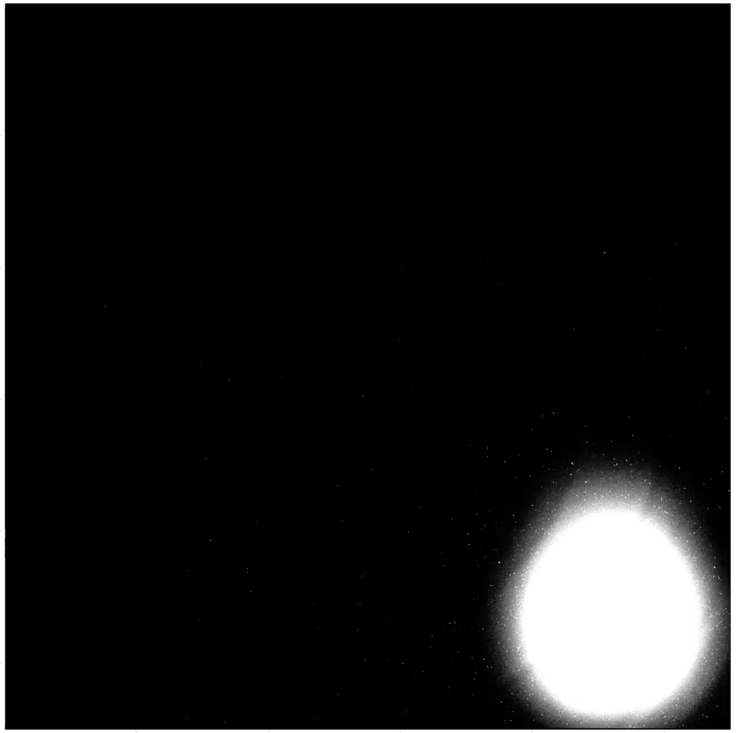
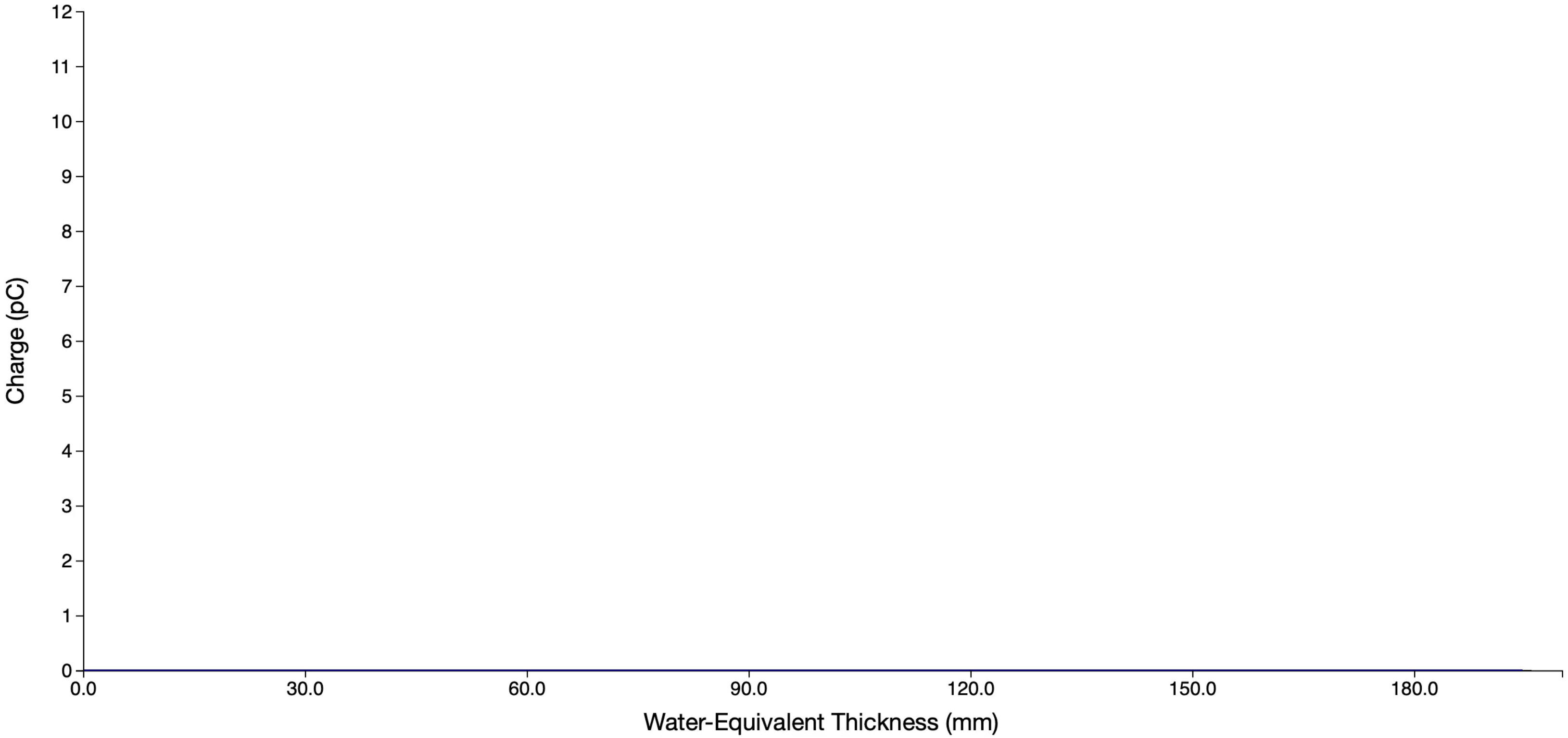
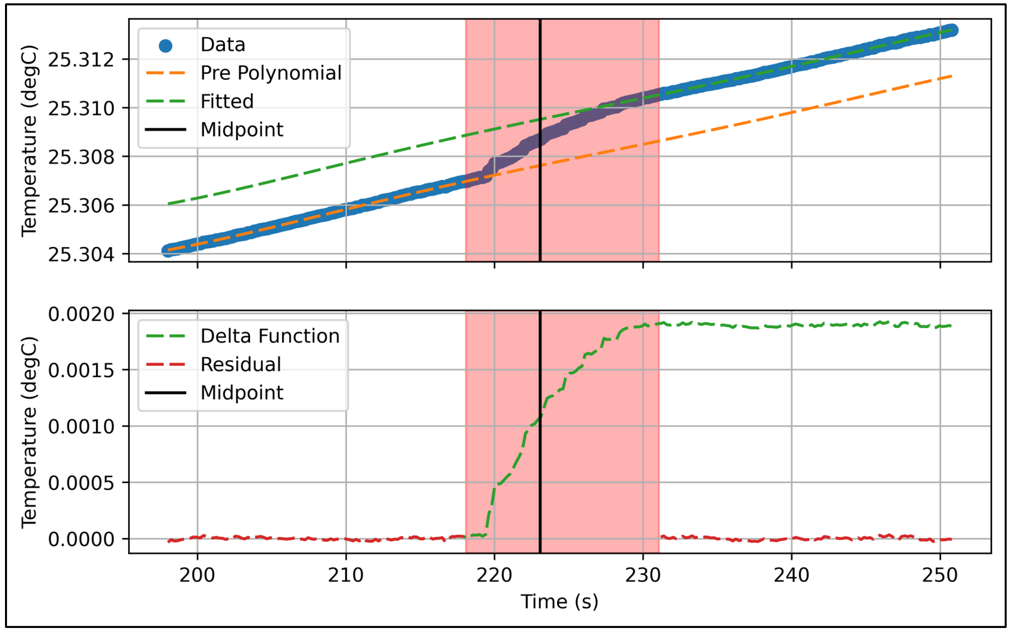
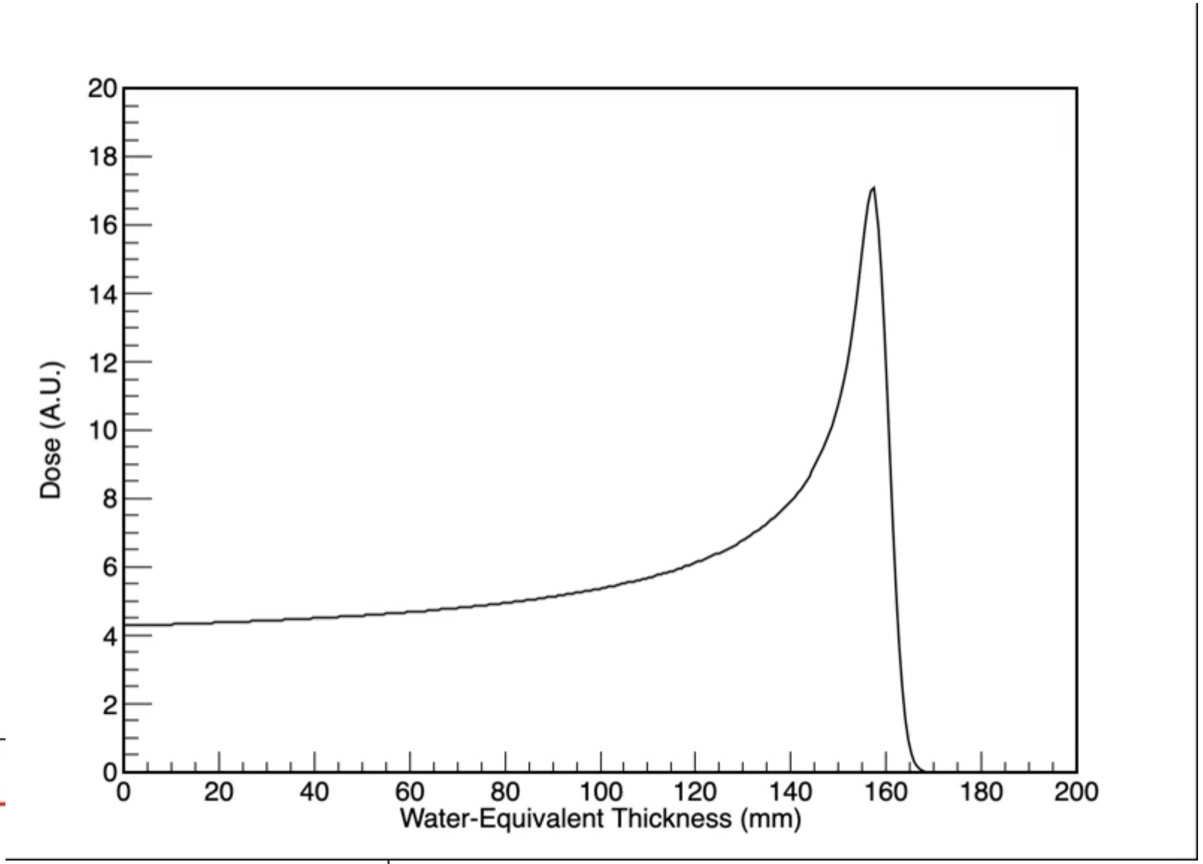


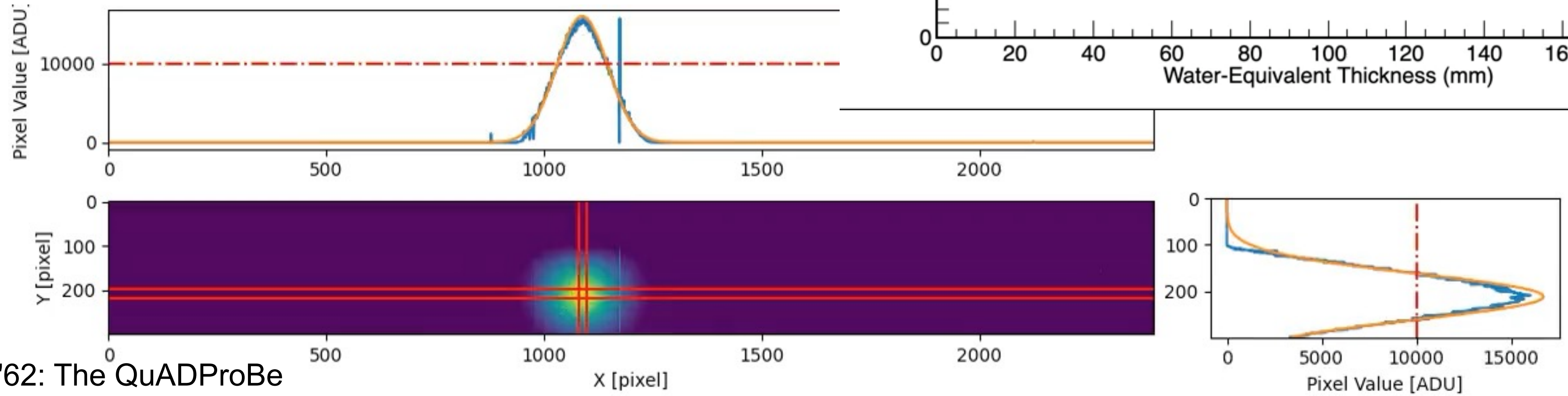
QuARC



Combined Data Output

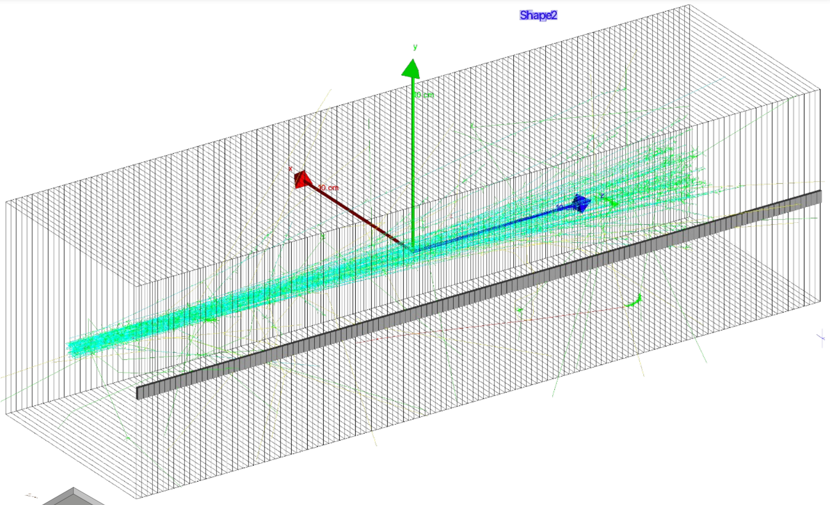


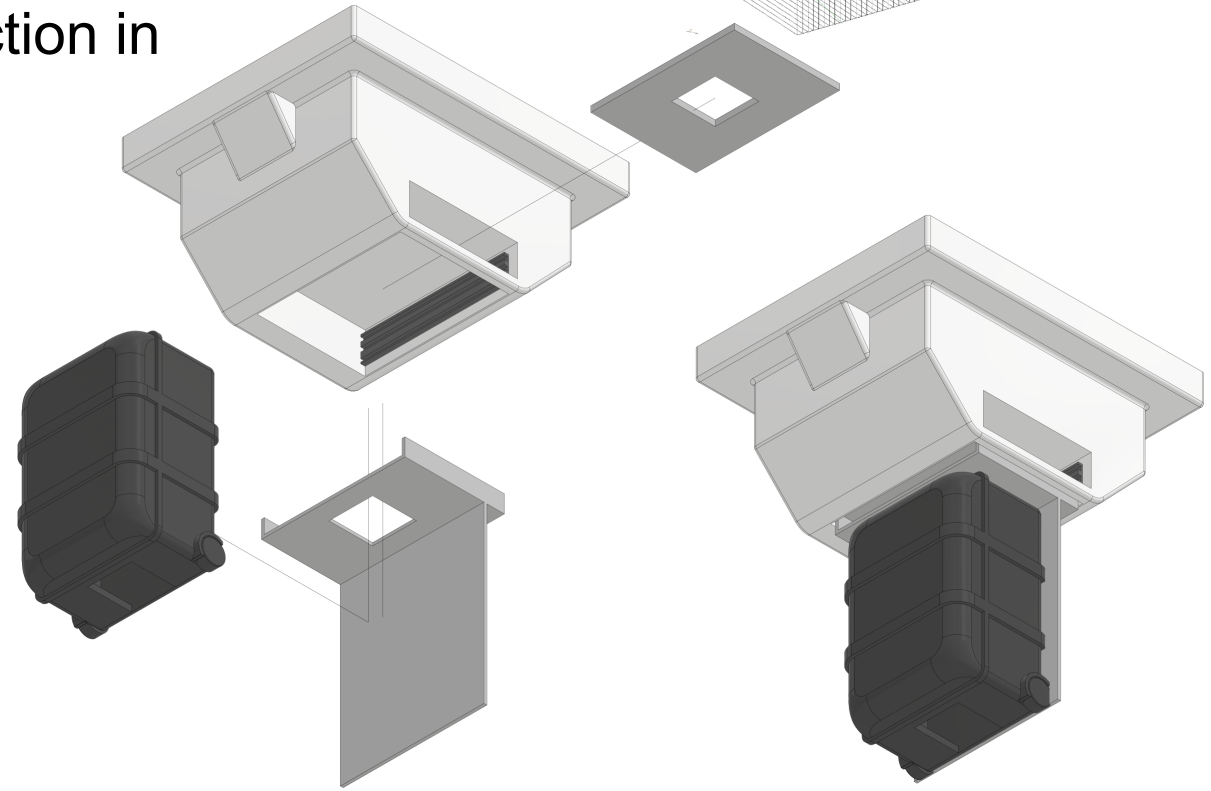




Conclusions

- Taking simultaneous measurements of all key parameters is possible!
- Prototype detector needs refinement but demonstrated principle.
- Questions for the community:
  - Is 3D volumetric dose reconstruction in simulation clinically acceptable?
  - Optimal volume for PSQA?
- Next steps:
  - Integrated DAQ.
  - Faster readout.
  - Nozzle mount.
  - Realistic treatment plans.





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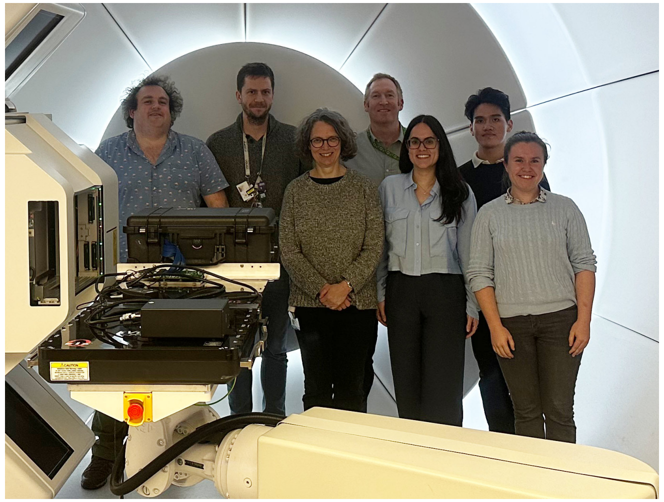

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