The Quality Assurance Detector for Proton Beam Therapy (QuADProBe)

Joseph Bateman, Febian, Harry Barnett, Matthew Warren, Andreas Korn, Simon Jolly

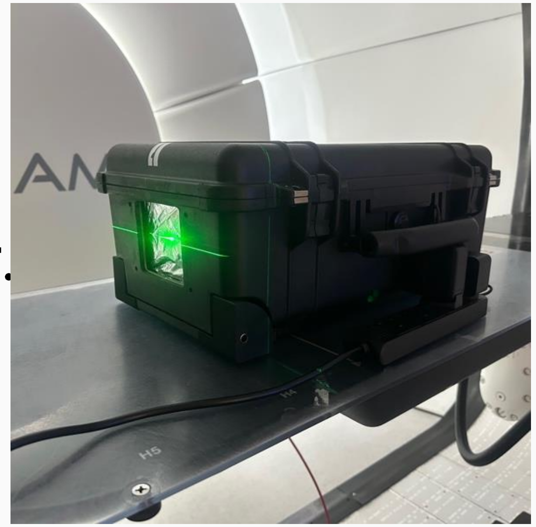
University College London

Raffaella Radogna

University of Bari

QuADProBe Design Brief

- Able to make direct QA measurements of dose, spot size, spot position and range on a spot-by-spot basis during delivery of a treatment plan.
- Quick to set up: mountable to clinical nozzle.
- Robust: will survive a clinical environment.
- Easy to use: simple set up and interface.
- No software installation: on-board DAQ controlled through web browser.
- Easy to maintain: modular assembly so repair and upgrade straightforward.

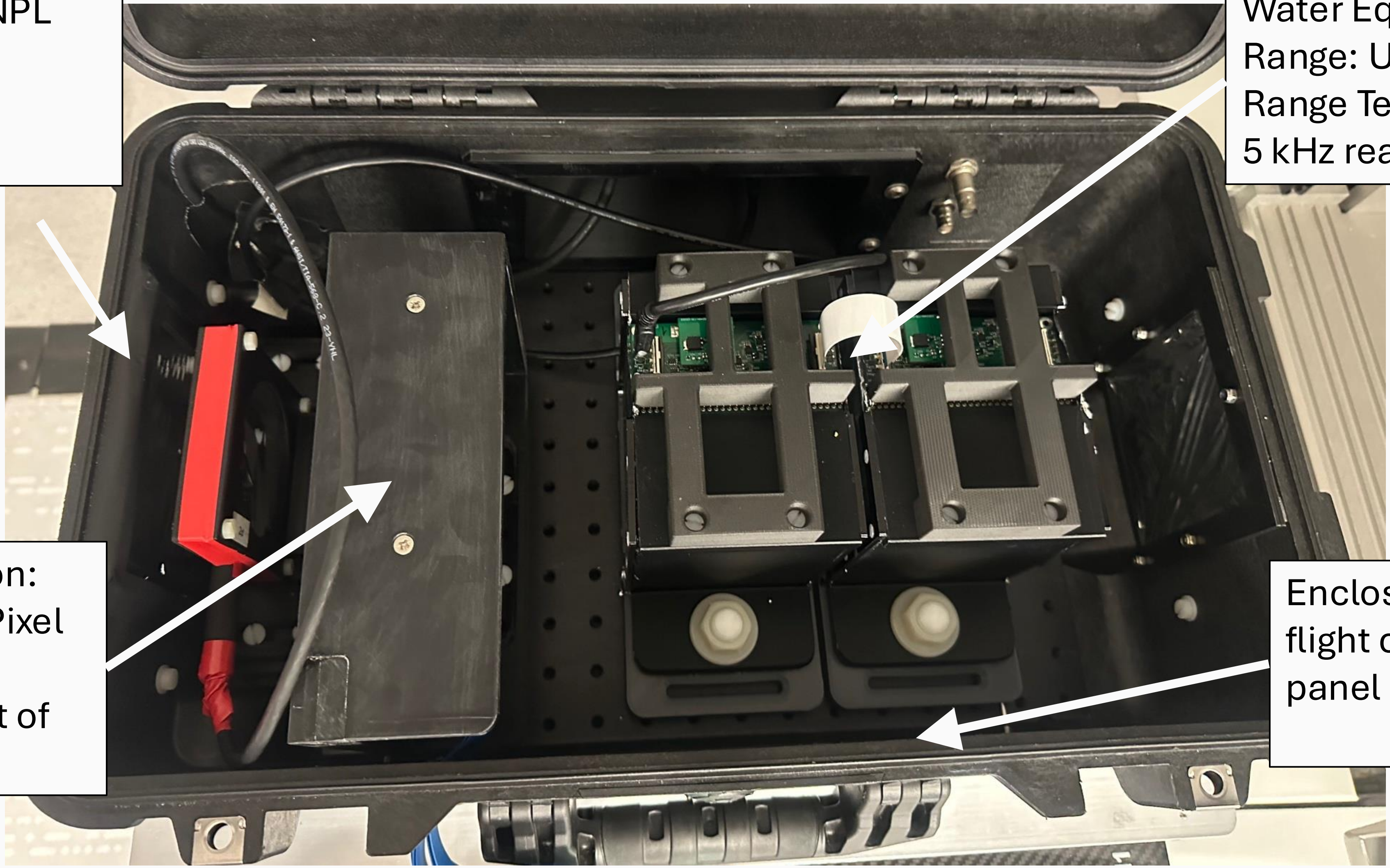


The QuADProBe v1

Absolute Dose: NPL Transmission Calorimeter (TC)
10 Hz readout

Water Equivalent Range: UCL QuARC Range Telescope
5 kHz readoout

Protons

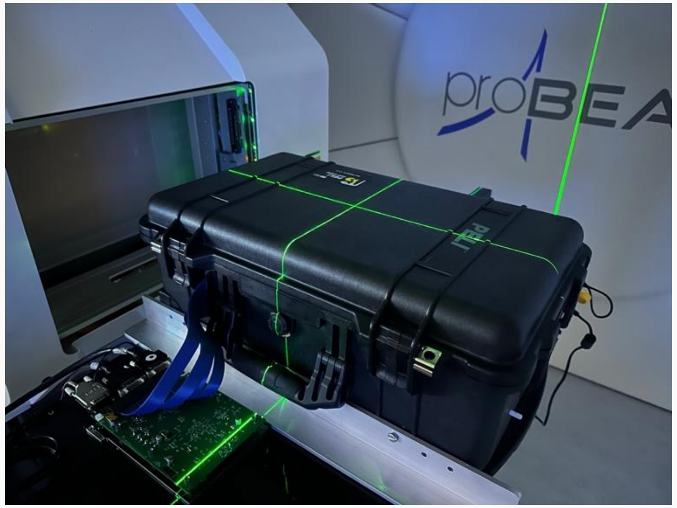


Spot Size + Position: LASSENA CMOS Pixel Sensor
Full frame readout of 35 fps

Enclosure: Peli 1510 flight case with patch panel

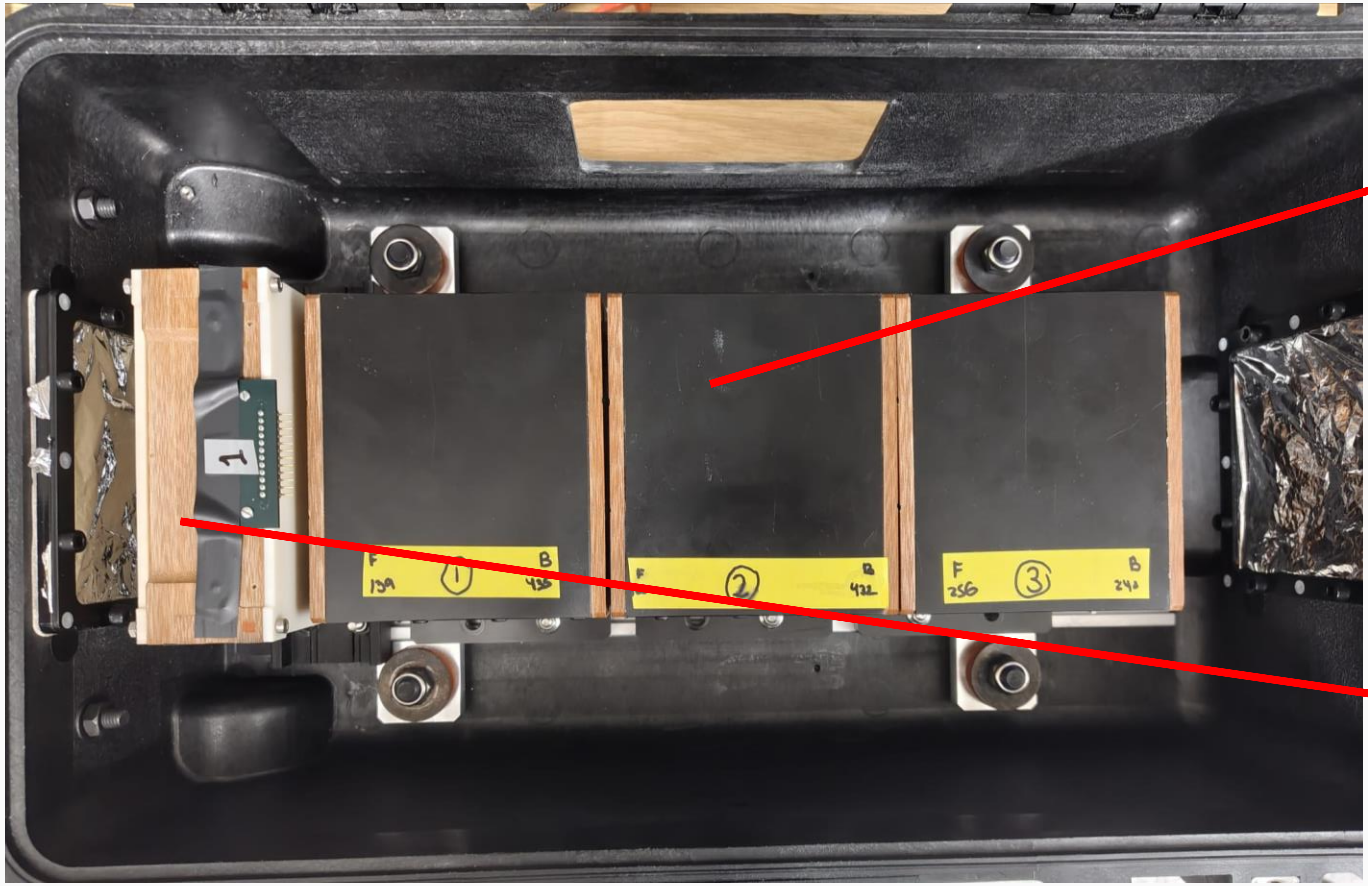
1st QuADProBe Beam Test at UCLH (2024)

QuADProBe positioned on couch and QA plan delivered → Measure: spot size, position, energy and dose for every pencil beam → Measurements used as input for TOPAS MC simulation to reconstruct 3D dose distribution → Comparison of dose distribution to TPS

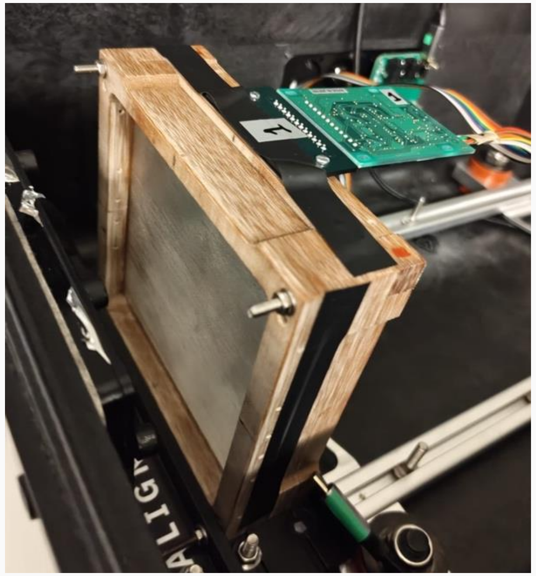


QuADProBe v2

QuARC

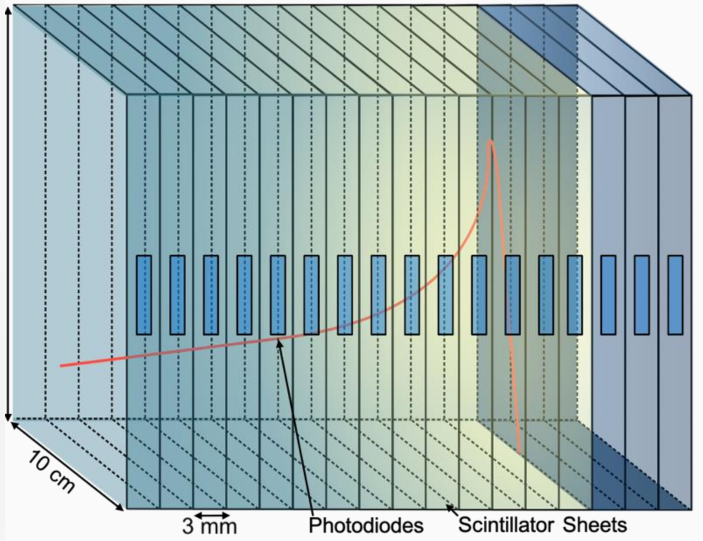


SciFi Tracker



The QuARC

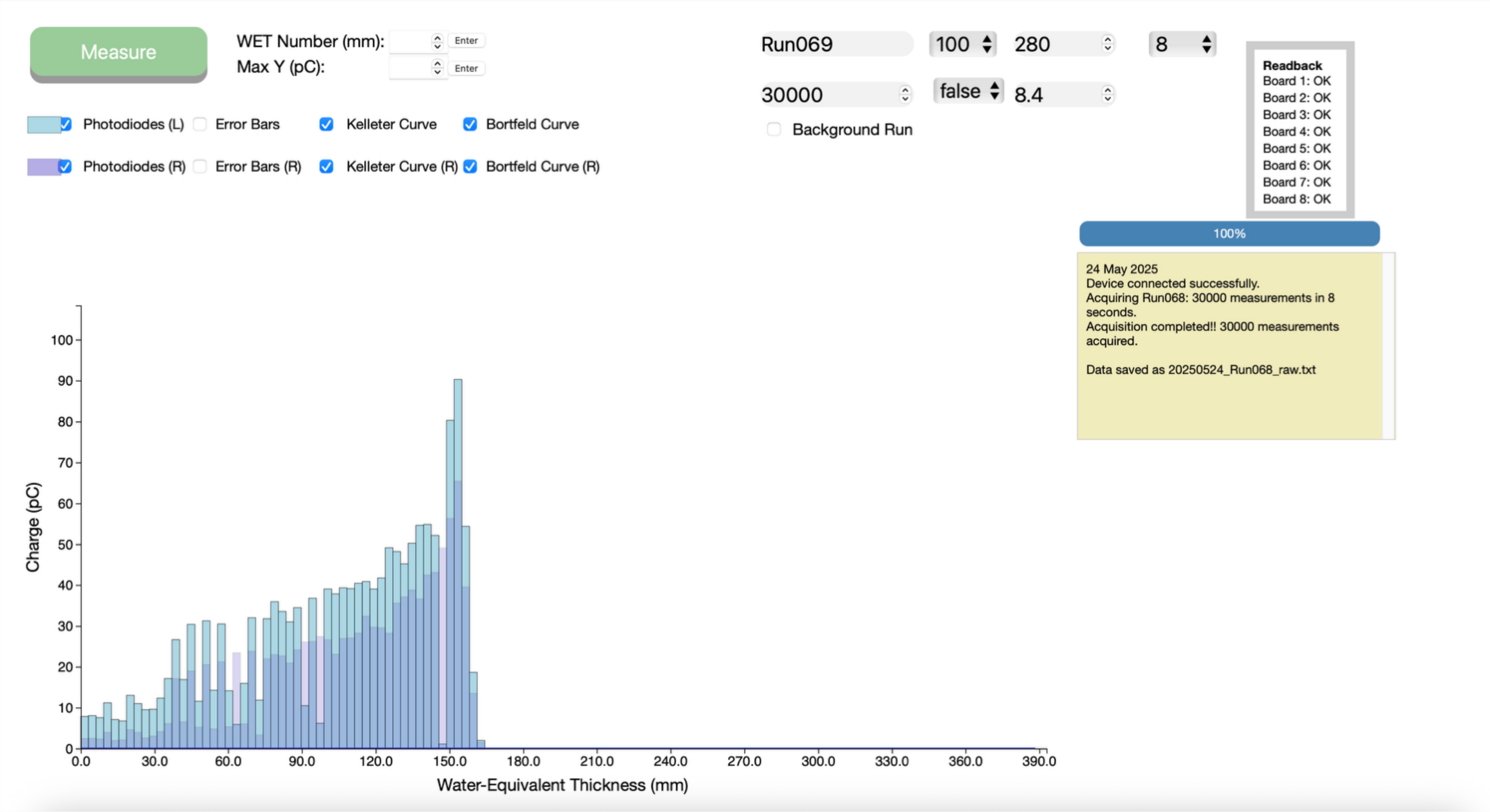
- The Quality Assurance Range Calorimeter (QuARC) constructed from plastic scintillator:
  - Protons intercepted by a series of optically-isolated polystyrene scintillator sheets.
  - Measure light output with photodiodes.
  - Light output of each sheet nonlinear to dose, but quenching described by Birks' Law:
    - Fit data with analytical depth-light model.
    - Reconstruct Bragg depth-dose curve and measure proton range – doesn't require empirical correction.
  - 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.
  - Connection to on-board PC via ethernet/WiFi.
- Key benefits:
  - Plastic scintillator inexpensive and water-equivalent.
  - Range reconstructed with single beam delivery.
  - Easy detector setup and no optical artefacts.



QuARC GUI

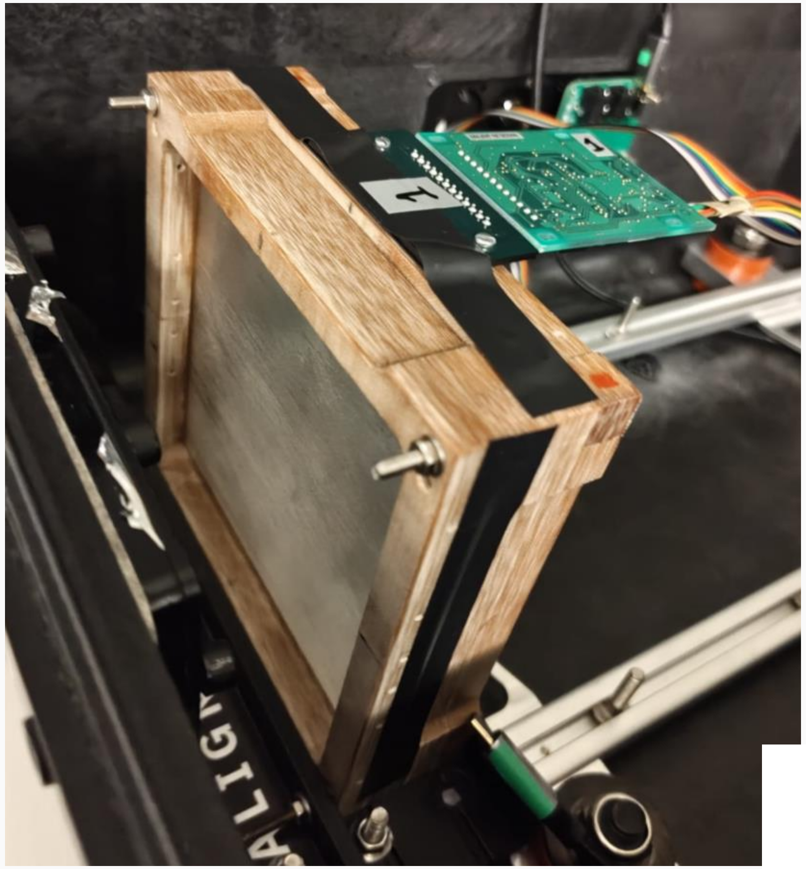
- QuARC controlled entirely via web GUI.
- Range measurements made and displayed in real-time.
- Raw data captured at 5 kHz and saved to text file for post-processing.
- Live calibrated and fitted data displayed at 25 Hz.

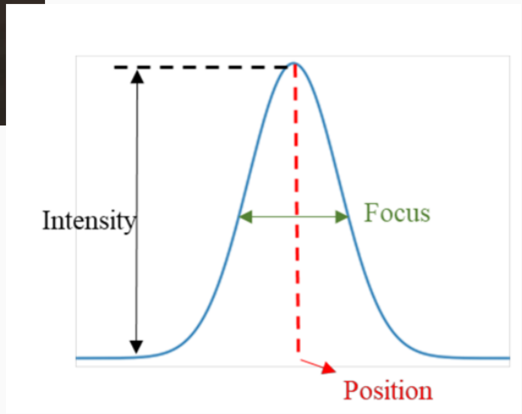
150 MeV. Beam 1cm to the left



SciFi Profile Monitor

- 2 orthogonal 10 cm x 10 cm arrays made of BCF-60 plastic scintillating fibres by Saint-Gobain, 0.50 ± 0.13 mm diameter. Emission peak at 530 nm.
- 128-photodiodes array (Hamamatsu S13865), single and cascade operation. Image size: 51.2 x 0.6 mm, pixel pitch 0.4 mm
- Hamamatsu C9118-02 CMOS driver circuit provides multiplexed data at up to 4 MHz.
- Analogic video output from the pixels array readout using NI USB-6366 Multifunction I/O.
- In low gain the dark output voltage is typ. 0.005 mV, max 0.1 mV
- The saturation output voltage is min. 3 V typ 3.5 V
- Frame rate of 1kHz.

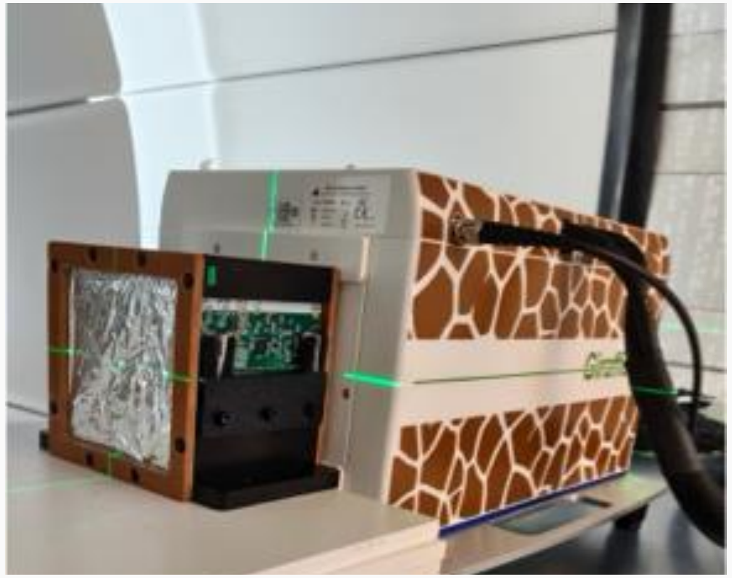


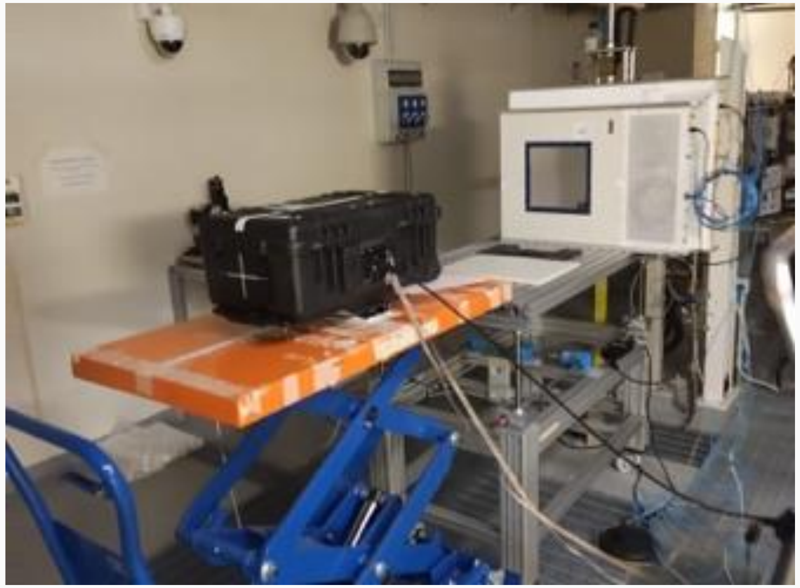


2025 Experimental Beam Tests

- Prague PTC in April 2025 – 4 QuARC modules with new electronics – measurements in clinical treatment room
- UCLH in May 2025 - 4 QuARC modules with new electronics - measurements in clinical treatment room
- Trento PTC in October 2025 – 3 QuARC modules and SciFi monitor – measurements in fixed beamline research room

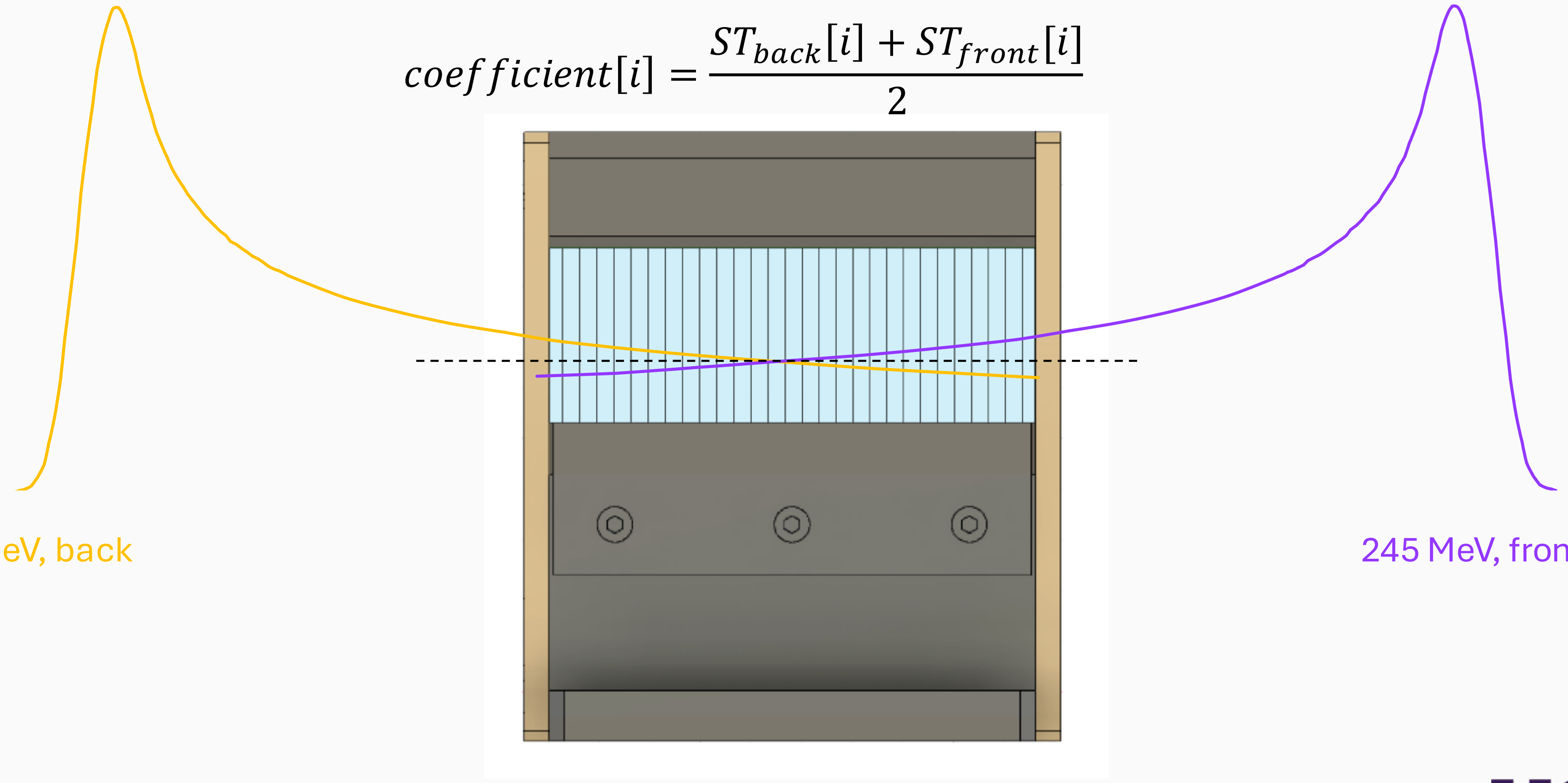
2025 Experimental Beam Tests



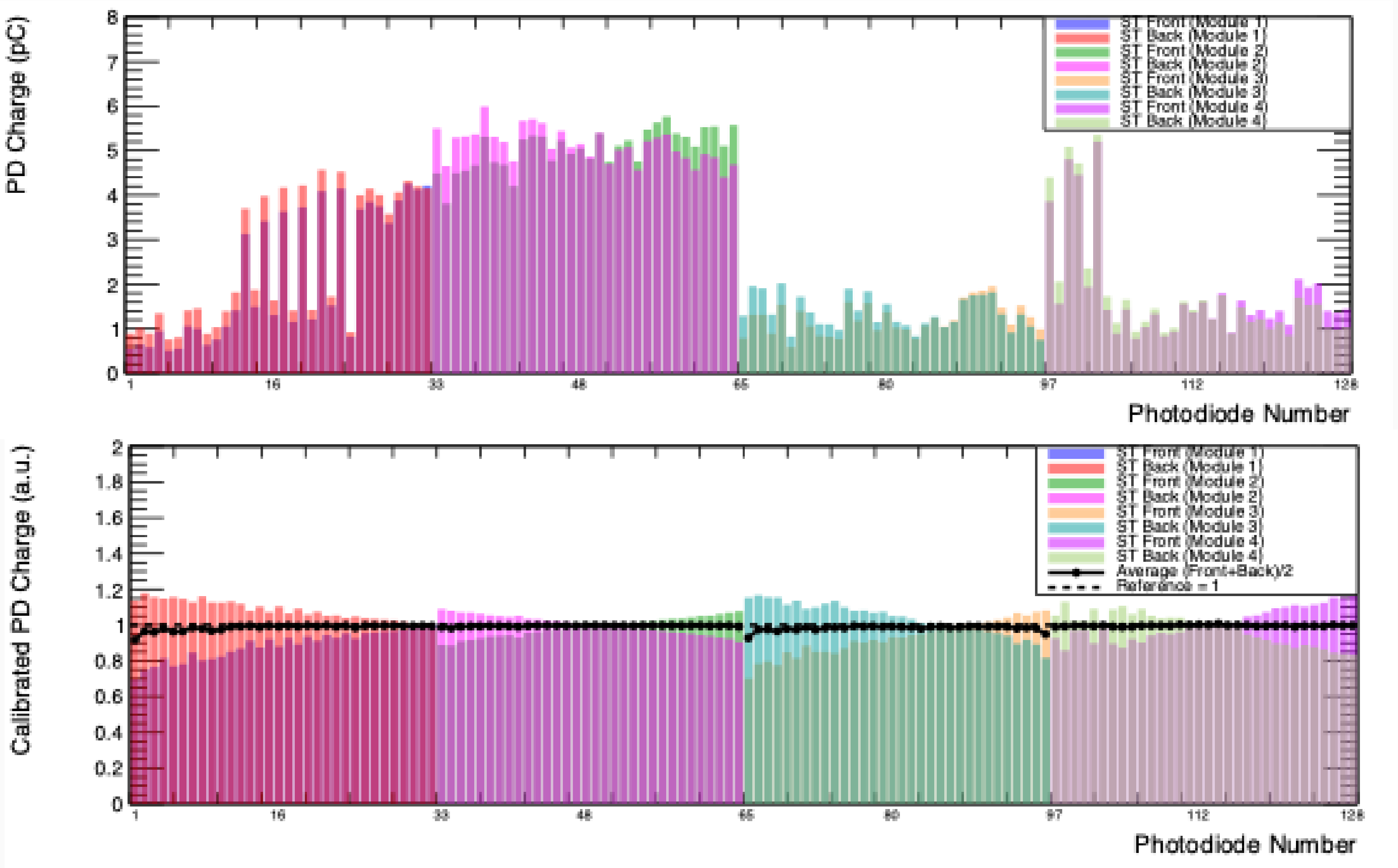


Detector Calibration

$$coefficient[i] = \frac{ST_{back}[i] + ST_{front}[i]}{2}$$

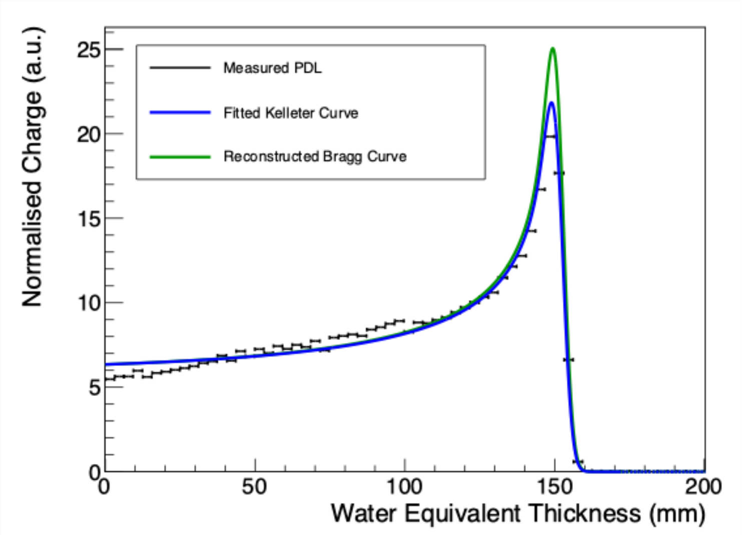


Shoot-through 245 MeV per-module measurements



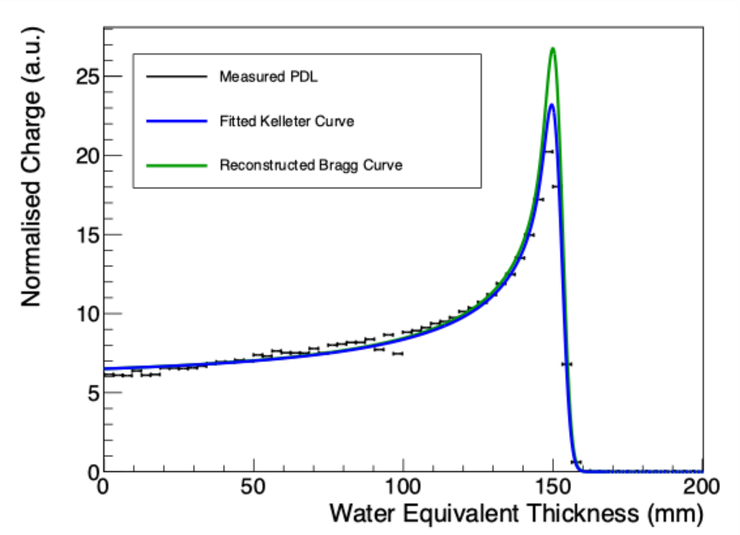
Trento 148 MeV Range Measurement

A



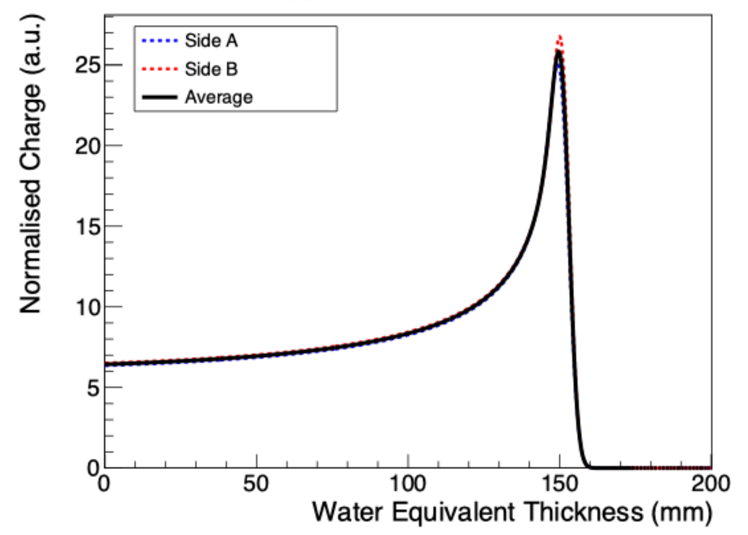
R90 151.01 mm

B



R90 : 151.49 mm

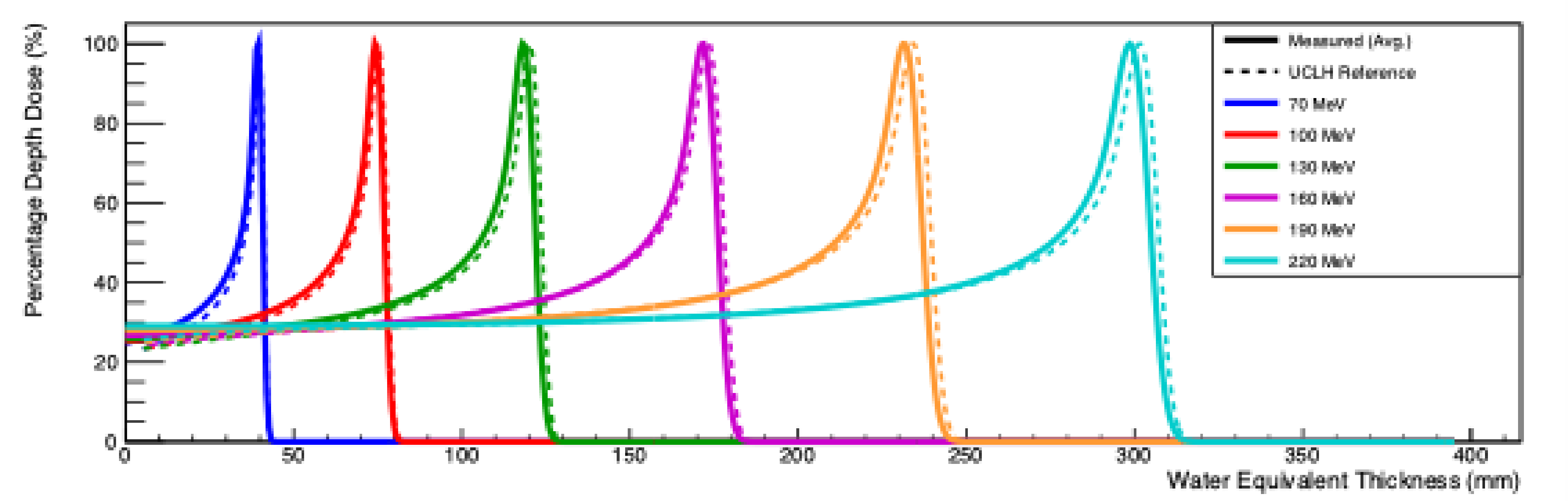
Avg



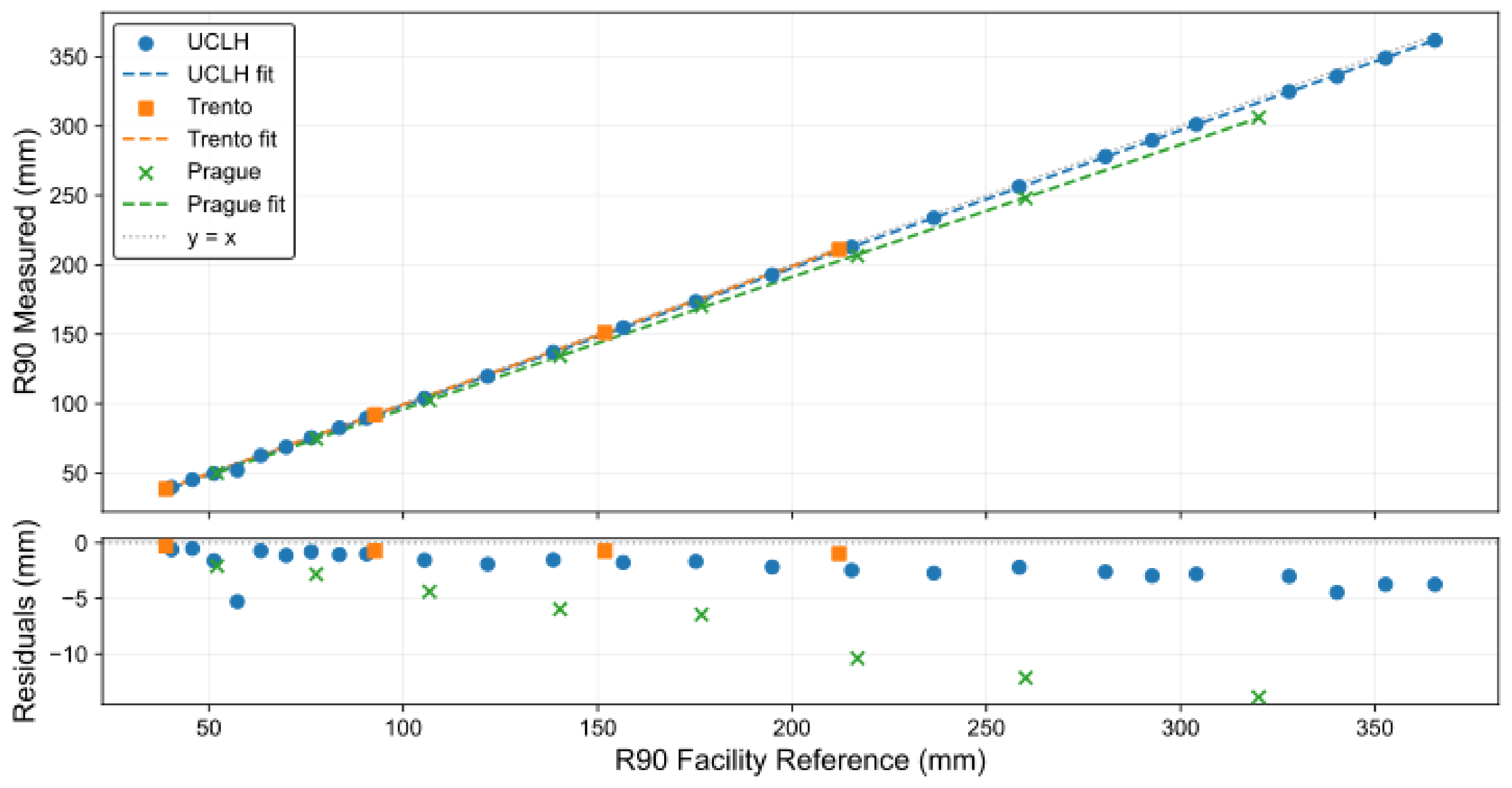
R90: 151.25 mm

Facility reference R90: 152 mm

UCLH Range Measurements

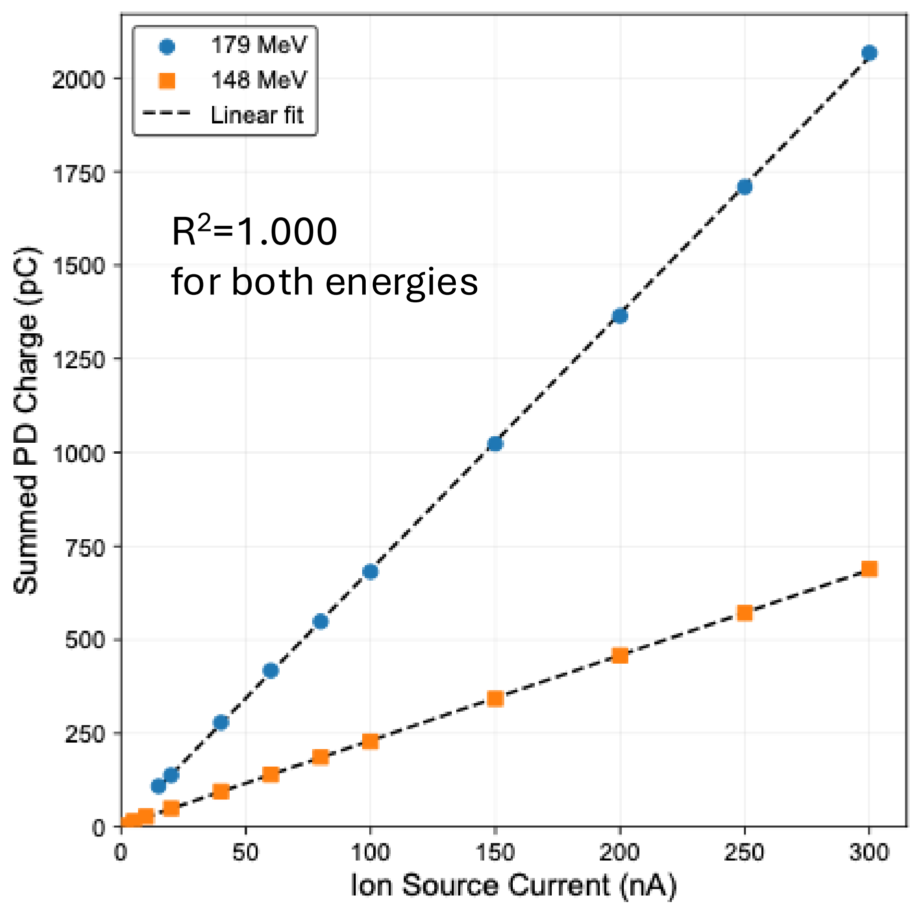


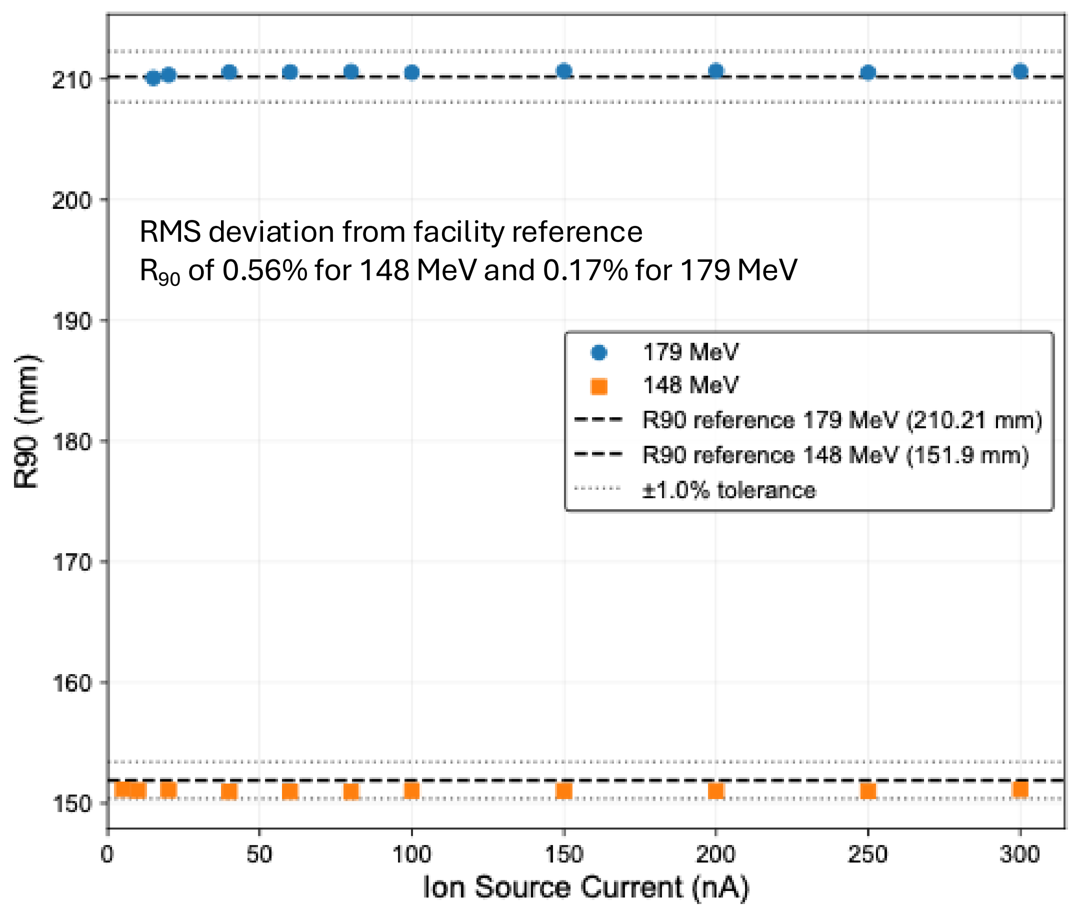
Range Measurements



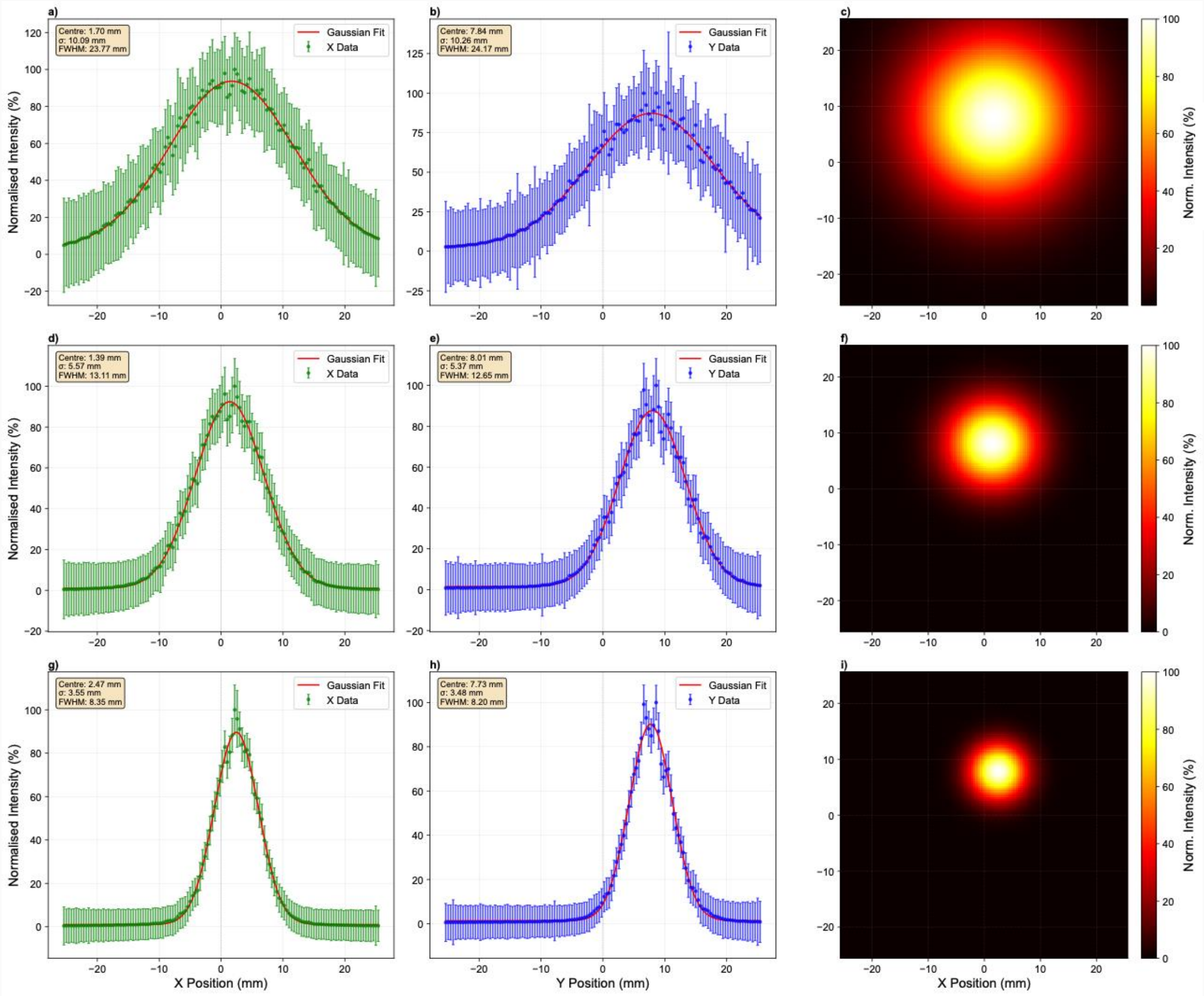
Facility	Gradient	Intercept	R^2	Root Mean Squared Deviation (mm)
UCLH	0.993	-0.856	1.000	2.481
Trento	0.996	-0.237	1.000	0.726
Prague	0.953	0.623	1.000	8.345

QuARC Response Linearity Measurements





Profile Measurements

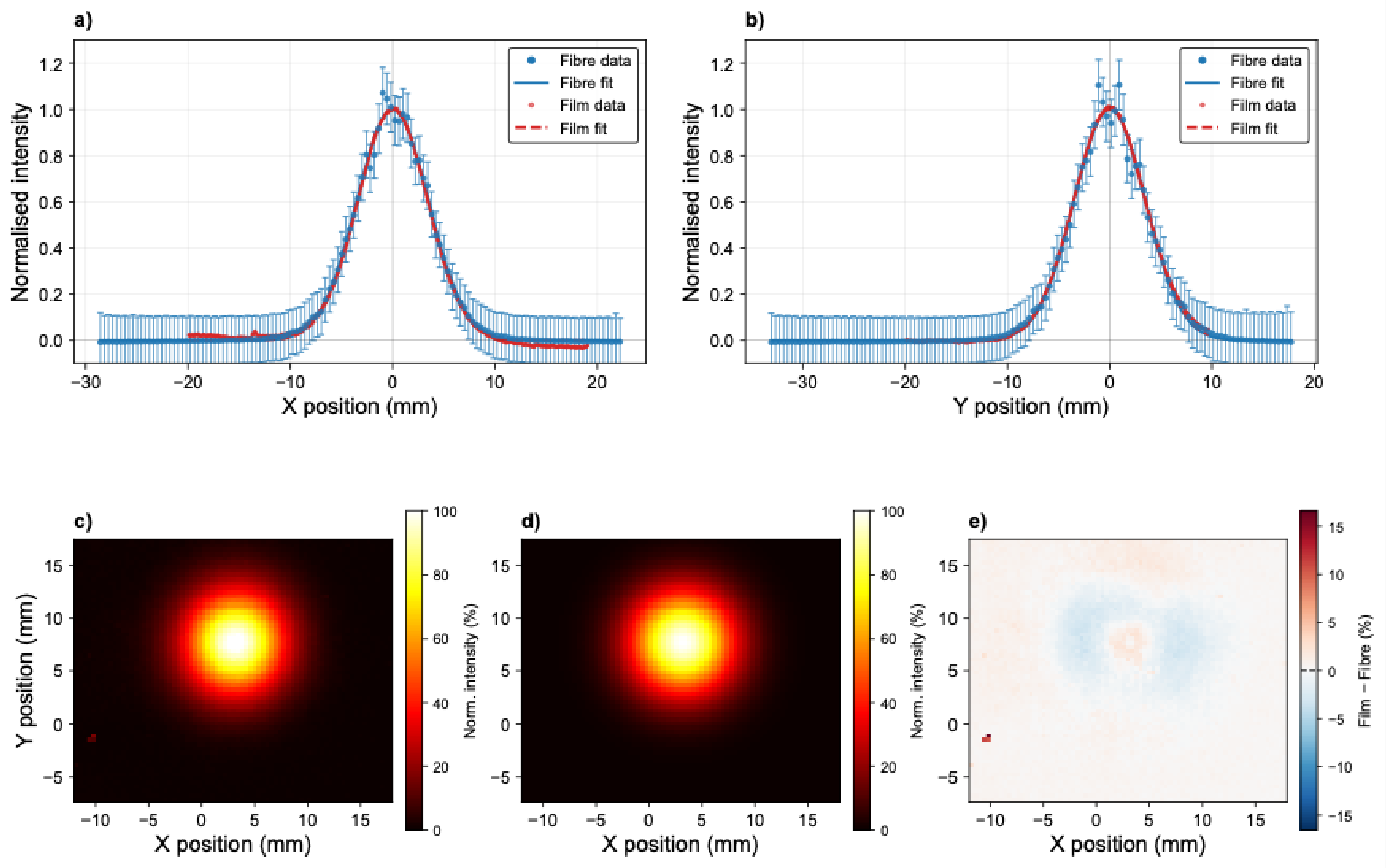


Proton Beam Energy (MeV)	μ_x(mm)	μ_y(mm)	σ_x(mm)	σ_y(mm)
70	1.704 ± 0.503	7.82 ± 0.633	10.70 ± 1.100	10.26 ± 1.033
148	1.390 ± 0.177	8.007 ± 0.204	5.565 ± 0.216	5.373 ± 0.239
228	2.474 ± 0.098	7.733 ± 0.101	3.547 ± 0.110	3.485 ± 0.112

Large error bars on individual photodiode pixels from fluctuations over 10s acquisition. Will be addressed in upgrade of SciFi DAQ

Energy (MeV)	Mean X error (%)	Mean Y error (%)
70	21.7	24.2
148	12.0	11.9
228	7.2	7.5

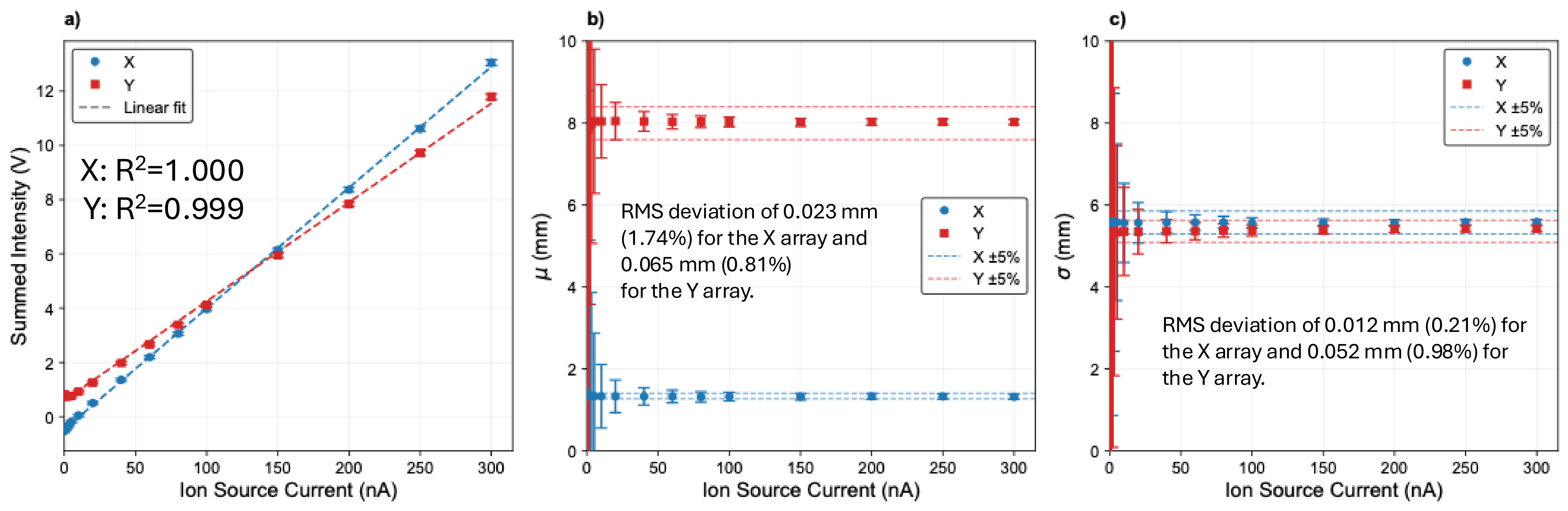
Spot Profile Measurements



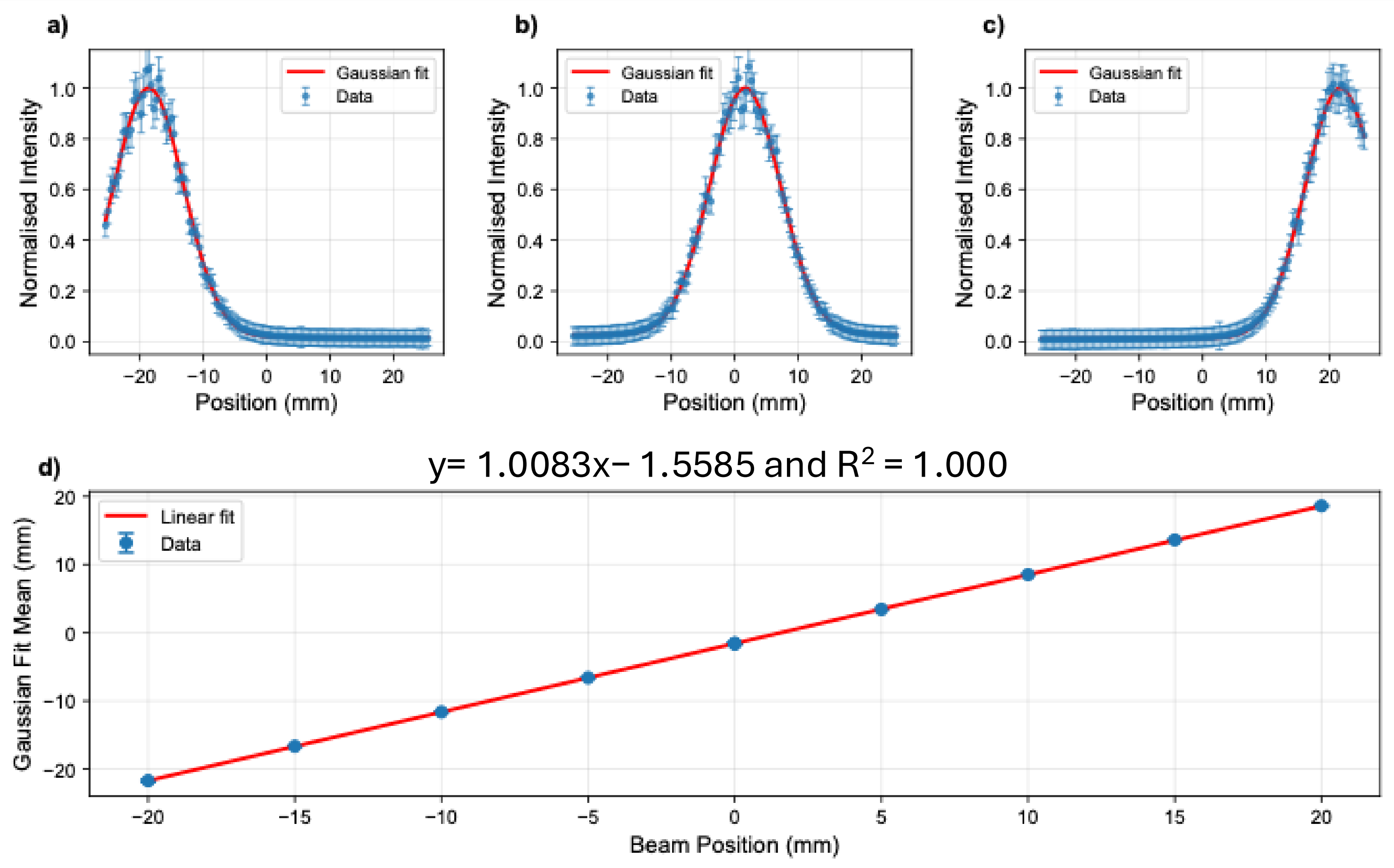
	σ_x(mm)	σ_y(mm)
Fibres	3.502 ± 0.139	3.479 ± 0.142
Film	3.421 ± 0.005	3.530 ± 0.003
Difference	0.080	-0.051

Residuals between the two 2D profiles has a mean difference of -0.884%

Fibre Array Response Linearity



Fibre Array Position Measurements



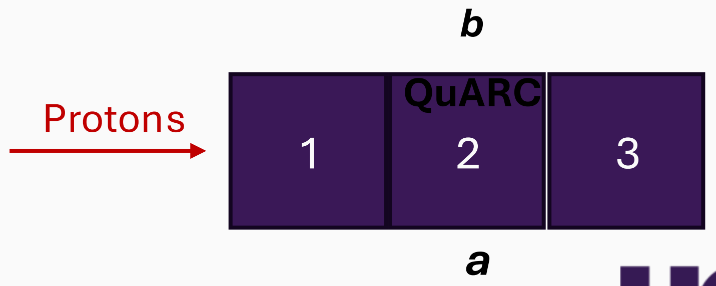
Horizontal Beam Position Scan

- Detector moved horizontally using translating stage between −20 mm – +20 mm in 5 mm intervals.

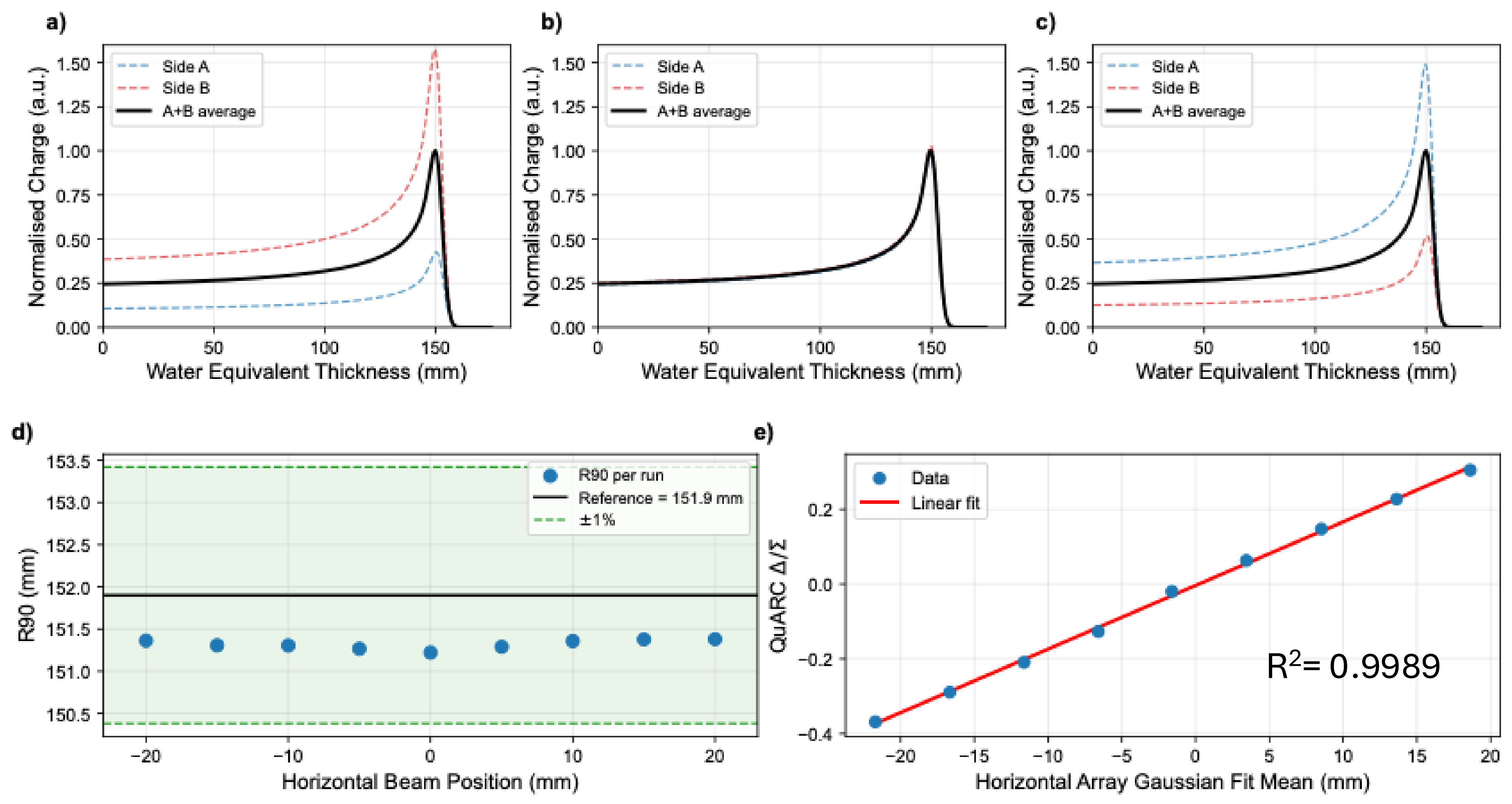
- QuARC measurements to investigate effect of horizontal beam position on Bragg Peak reconstruction and range measurement (by averaging the reconstructed Bortfeld curve measured on the *a* and *b* sides.

- Dual-sided photodiode readout of scintillator sheets also allows for a ‘relative position’ measurement through calculating $^{\Delta}/_{\Sigma}$ of the each of the photodiode pairs per scintillator sheet:

$$\frac{\Delta}{\Sigma}[i] = \frac{PD_a[i]-PD_b[i]}{PD_a[i]+PD_b[i]}$$

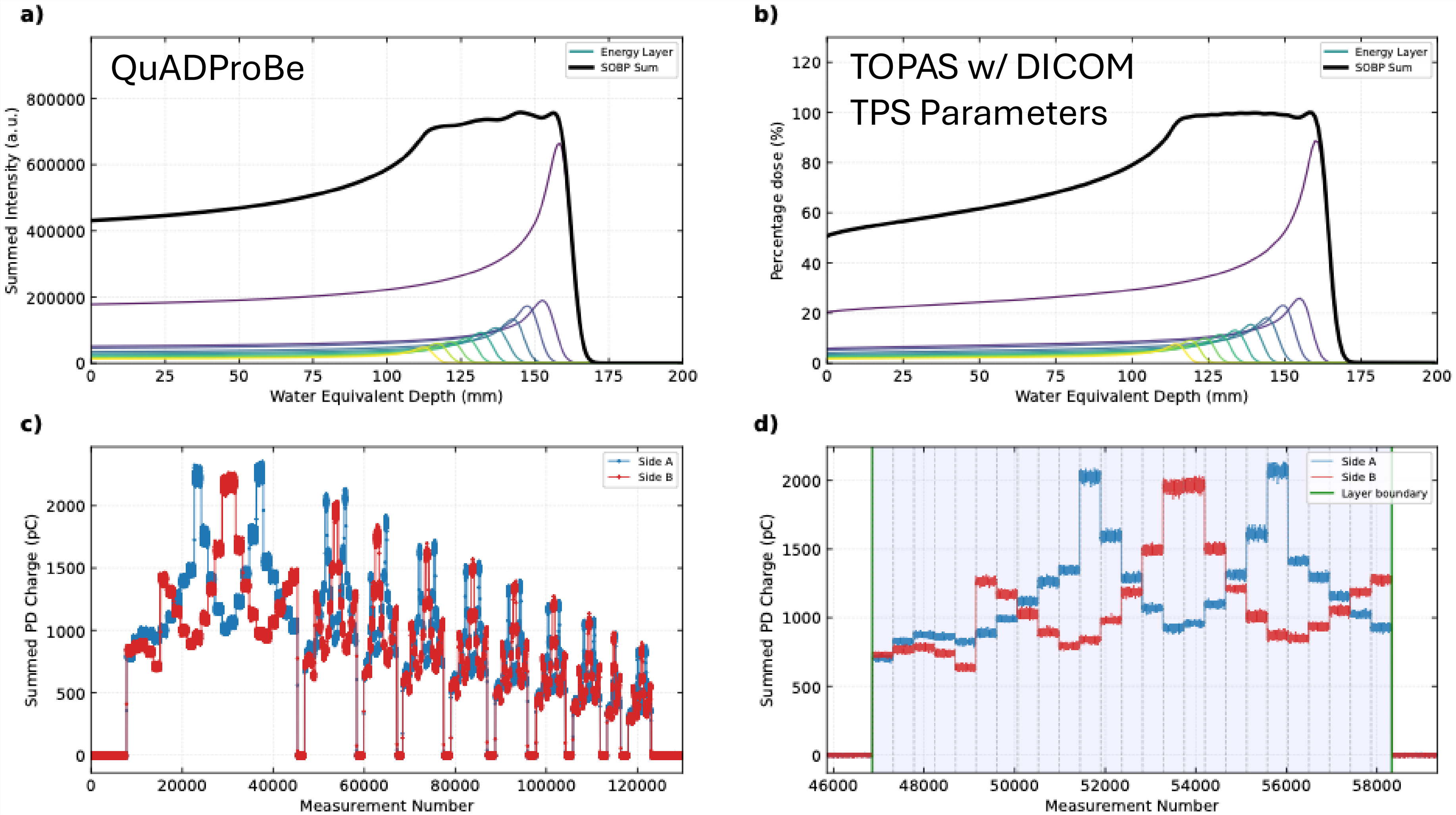


Combined Position Measurements

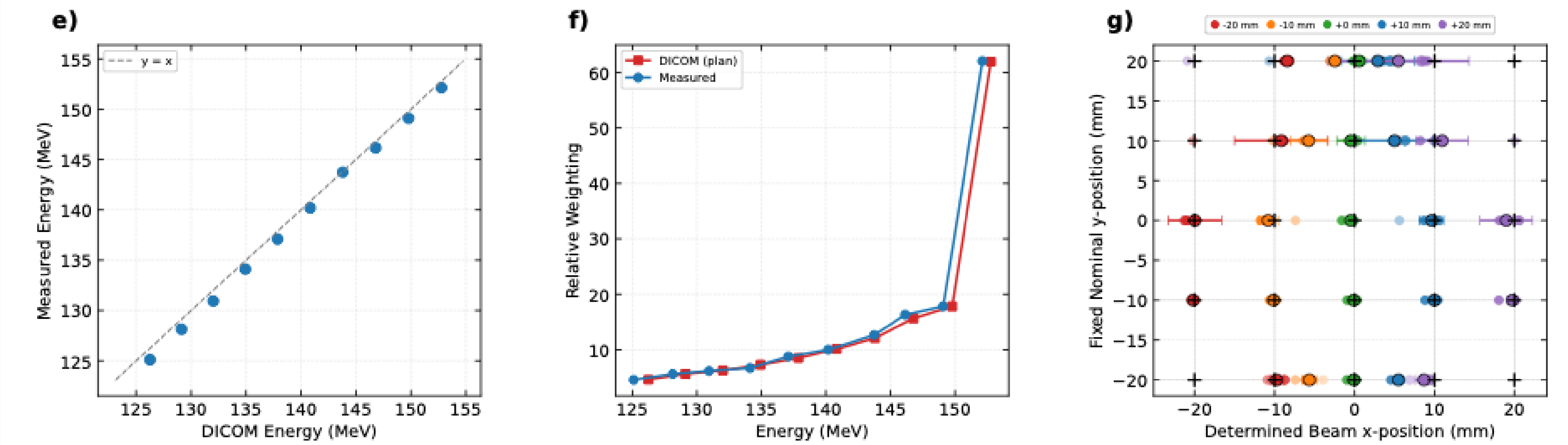


0.390% RMS deviation from the facility reference R90

SOBP Measurements

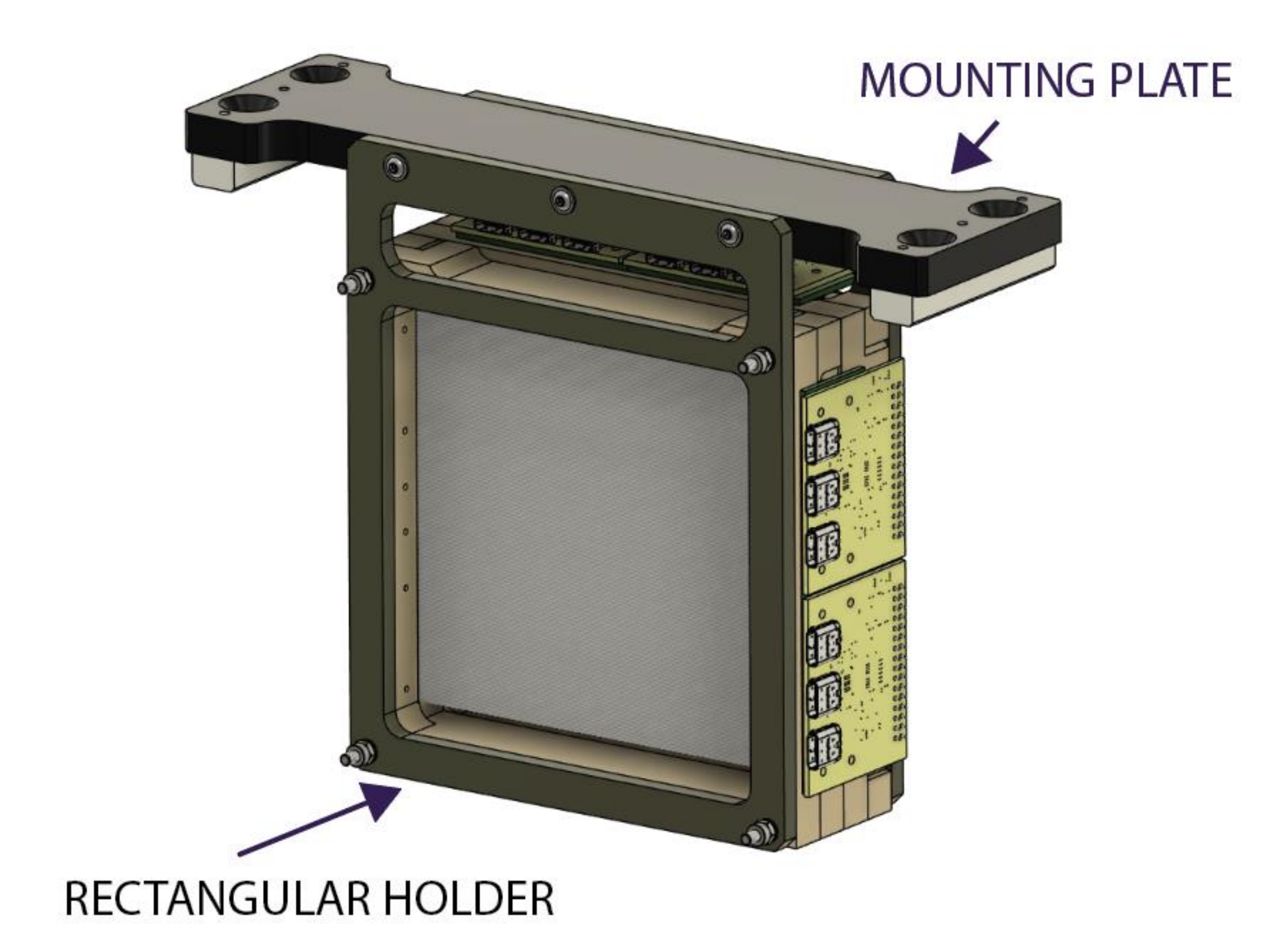


SOBP Measurements

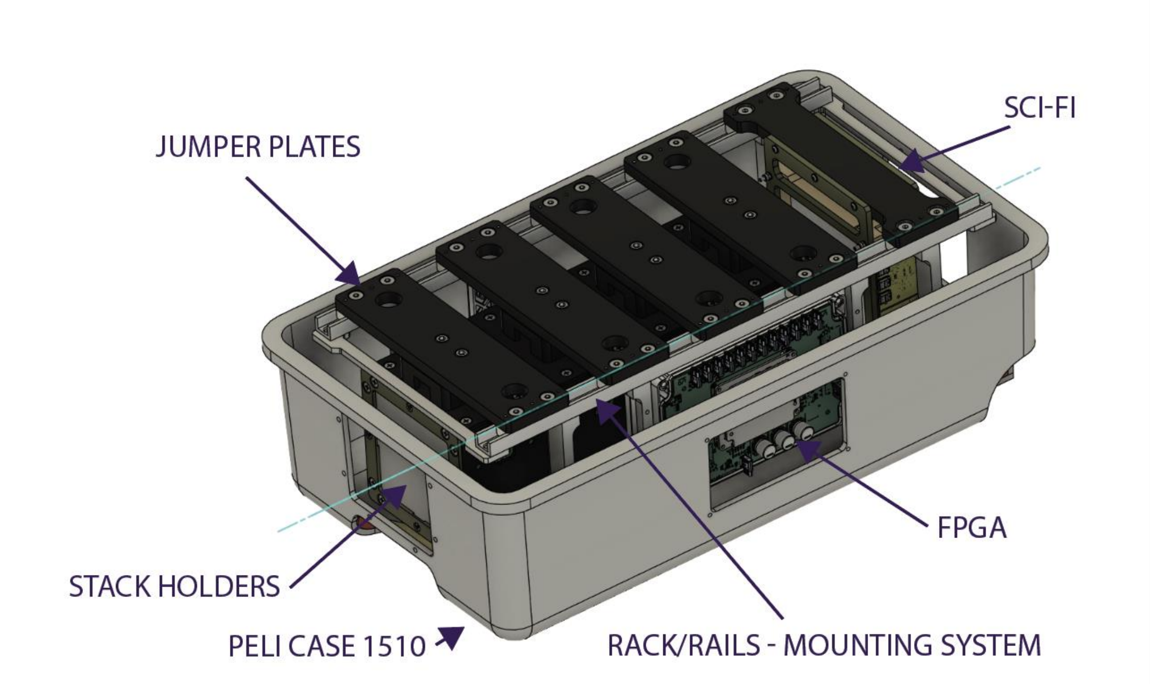


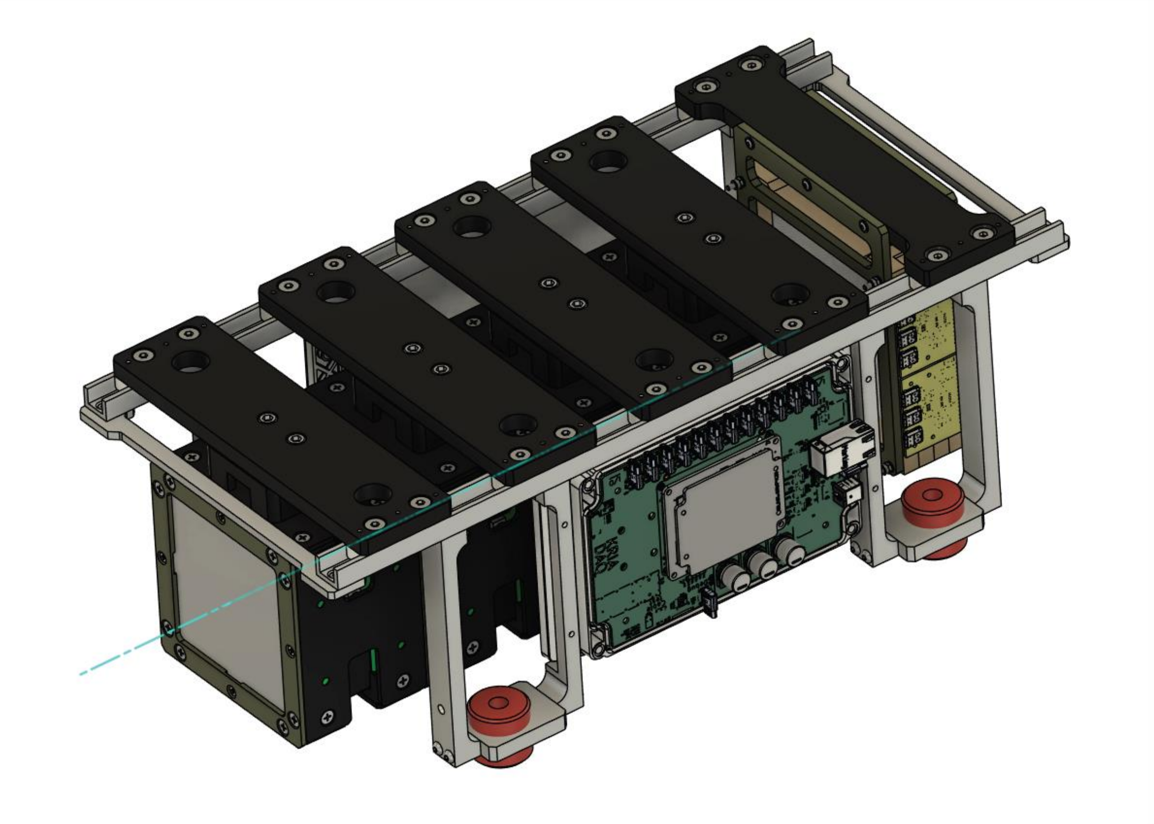
SciFi

- The SciFi assembly itself remains largely unchanged; the main change is how it interfaces with the new mounting system.
- The SciFi holder has its own individual mounting plate.
- The rectangular holder frames will be manufactured from Tufnol, the same material used for the stack end clamps.
- Tufnol provides the additional rigidity required, particularly as the assembly is supported at relatively few points.
- Although the SciFi assembly is relatively lightweight, the holder should be as robust as possible.
- The mounting plate follows a very similar design and mounting principle to the stack bridges.



QuADProBe v3 – Mechanical Overview (Harry Barnett, UCL)

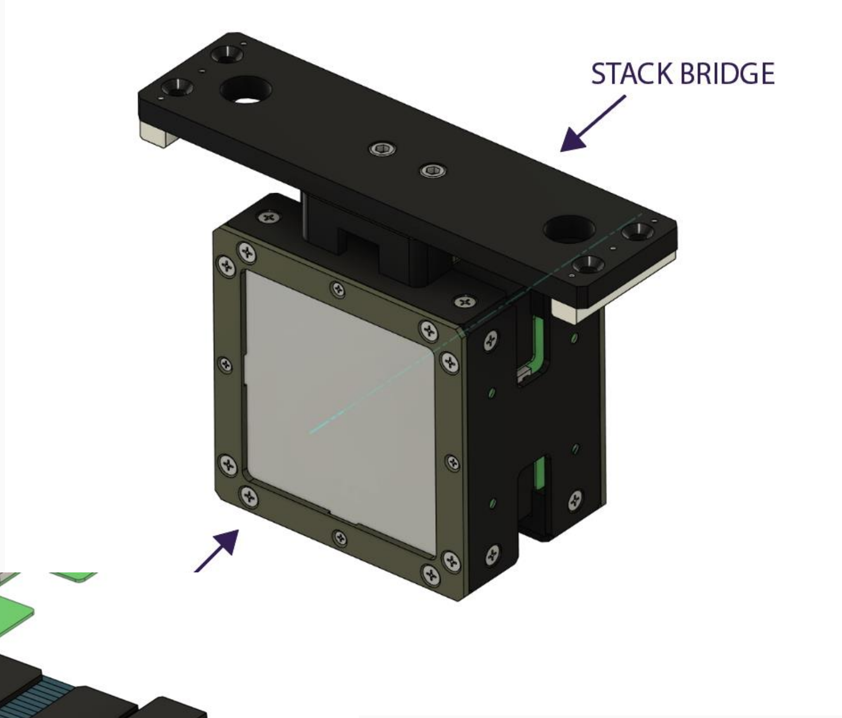


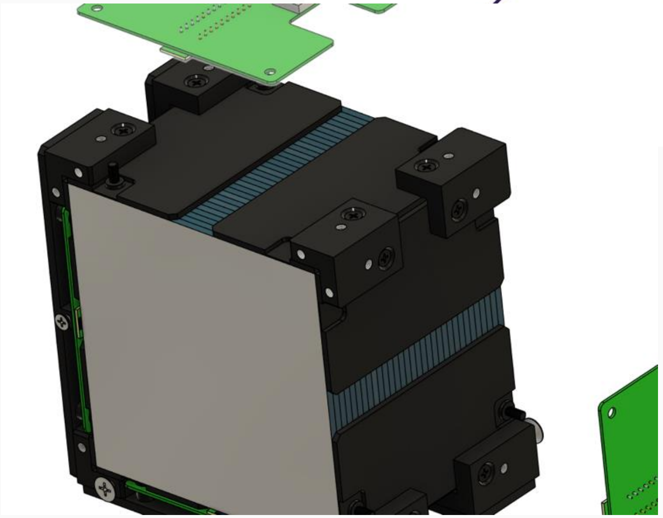


- Entire rail system moved upwards into the box.
- Designed for improved ease of access, ease of use, and overall accessibility.
- New layout allows all electronics to be mounted directly onto the racks.
- Electronics are shock-dampened and isolated from the outer box.
- Increased protection against knocks, impacts, and rough handling.
- Overall goal: a more accessible, robust, and durable system.

QuARC – 4-sided readout

- Each QuARC module will be readout on all 4-sides.
- Improving resolution to 2.5mm from 3mm.
- Improves range measurement capability of large fields by removing any position-dependent artifacts.
- Relative position measurements throughout range telescope to track pencil beam trajectory





SciFi

- Each scintillating fibre array will be readout with 2x 128 0.4mm pitch photodiode arrays.
- Hamamatsu S17825-128 photodiode arrays that have digital readout of up to 8.335 kHz.
- Allows for full integration of spot size, position and range measurement readout..
- $10x10cm^2$ sensitive area.

Transmission Calorimeter

- Ongoing collaboration with Sam Flynn *et al* at NPL who are developing the Transmission Calorimeter.
- Will eventually be integrated into the detector but not immediately.
- Main issues are readout speed etc and instead may be used as a calibration for the SciFi or QuARC to calibrate to absolute dose for individual spots.

QuADProBe v3 DAQ

- Replacing USB104 FPGA and Raspberry Pi5 readout of QuARC and and separate Zybo FPGA and NI USB6366 analogue readout of SciFi monitor with a single Kria controlling both for an integrated readout of range, size and position.
  - Replacing SciFi photodiode arrays with equivalent digital readout out arrays.

- Targeting readout speed of 5-6 kHz with eventual aim of providing individual spot detection and fitting.

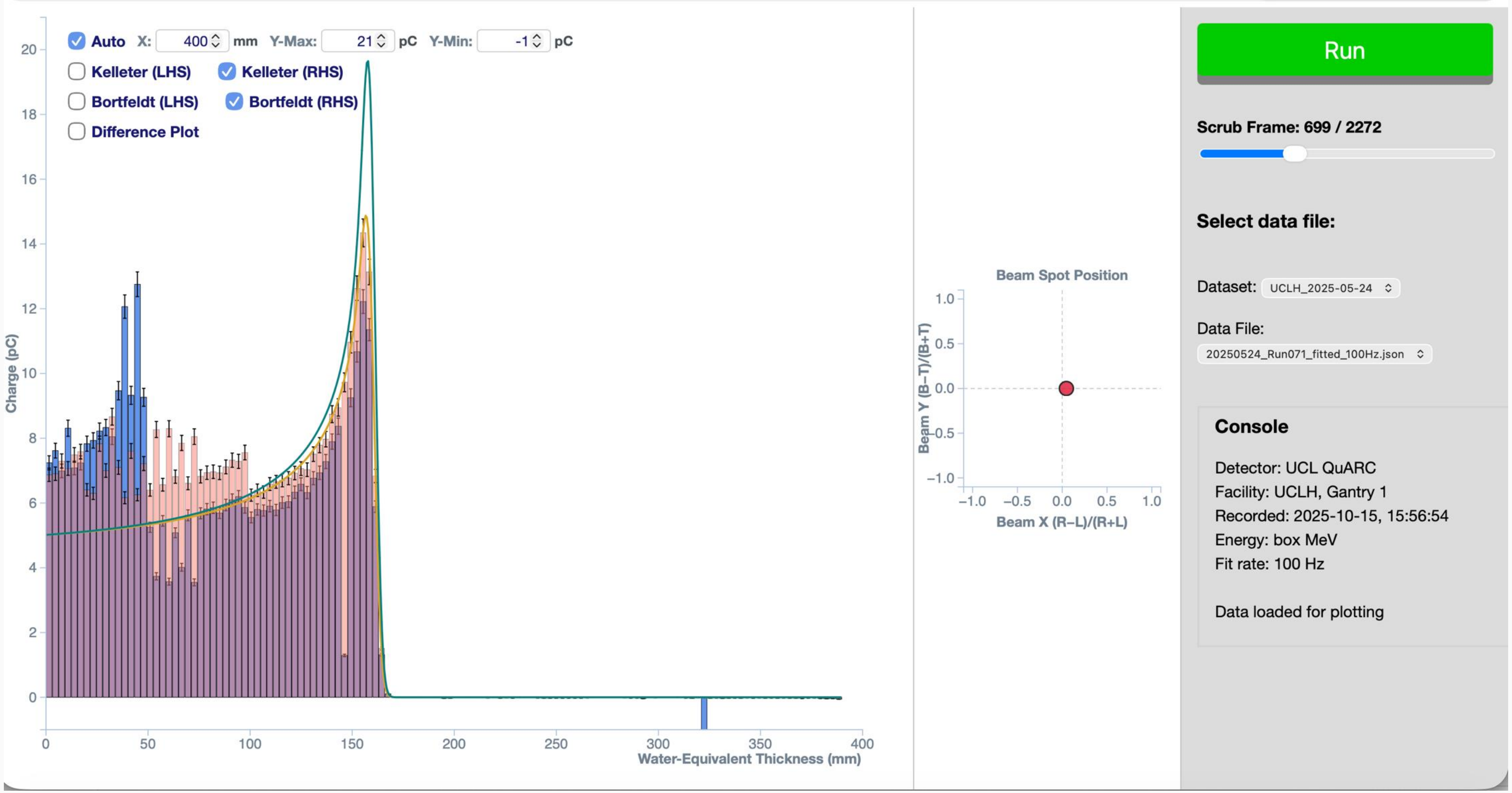
- Kria will host a Python web server to display live proton beam range and profile measurements at 25 Hz.

QuADProBe v3 DAQ

- Moving towards firmware-based fitting within the Kria to allow for faster fitting of individual spot parameters and minimise computational load on Kria.
    - PhD student (Febian) researching ML-based fitting of quenched Bragg Curve rather than analytical Kelleter model.
    - Extension into carbon and other ion species to account for fragmentation tail.
    - Further potential extension to SOBP fitting for conformalFLASH beams using ridge filters.

QuADProBe v3 DAQ

https://www.hep.ucl.ac.uk/pbt/QuARC-GUI/replay.html



QuADProBe v3 Experimental Plans

- Detector characterisation experiment plans at:
  - UCLH
  - Christie
  - Clatterbridge
  - PSI
  - Maastro
  - Heidelberg
  - MedAustron
  - Prague
  - DCPT Aarhus
- Detector characterisation of individual pristine Bragg Peaks across entire clinical energy range as well as simple QA fields such as single-spot position SOBP and Cube Fields.
- Potential to test example patient plans also.

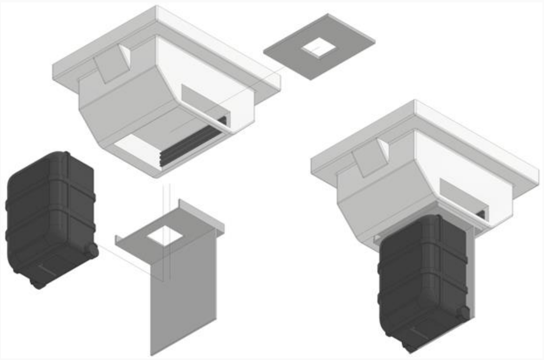
Potential proposals for QuADProBe Clinical Implementation

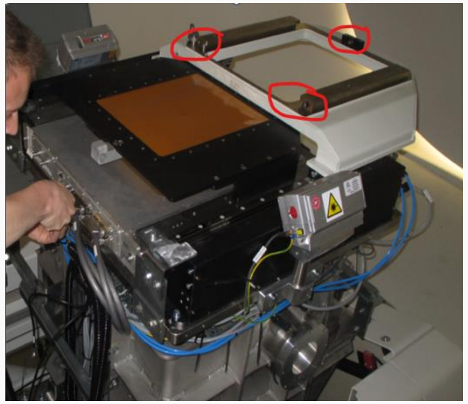
- Main goal is to be inline with direction of clinical particle therapy QA (both Machine QA + PSQA) workflows.
  - Potential to also be SFRT and shoot through FLASH and conformalFLASH-ready.
  - Implementation as part of upright particle therapy QA also.
- Bare minimum: implemented as current machine QA detectors and measurement-based PSQA detectors.
- Previous suggested method (as a method for centres without log-file access i.e. UCLH): nozzle-mount detector

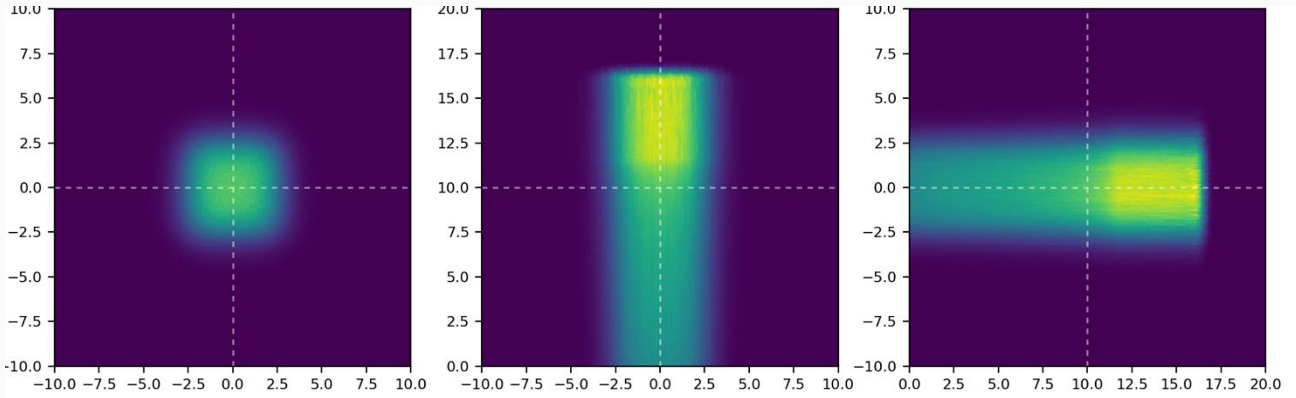
Potential proposals for QuADProBe Clinical Implementation

- Previously proposed method (as a method for centres without log-file access i.e. UCLH): nozzle-mount detector and measure individual spot parameters and use to recalculate treatment plan with Monte Carlo simulation or other dose calculation engine.

1. Mount QuADProBe to nozzle and run treatment plan
2. Measure: spot size, position, energy and dose for every pencil beam
3. Measurements used as input for MC simulation/IDC to reconstruct 3D dose distribution
4. Comparison of PSQA dose distribution to TPS







Potential proposals for QuADProBe Clinical Implementation

- Additional verification layer in centres where log-file based recalculation for PSQA is used.
- Nozzle-mounted verification of individual spot parameters to directly compare to machine recorded parameters and planned parameters.
- Either, as part of PSQA i.e. on a dry-run for a patient treatment plan.
- Or through an entirely different QA process e.g. a more complex plan delivered as part of daily QA.

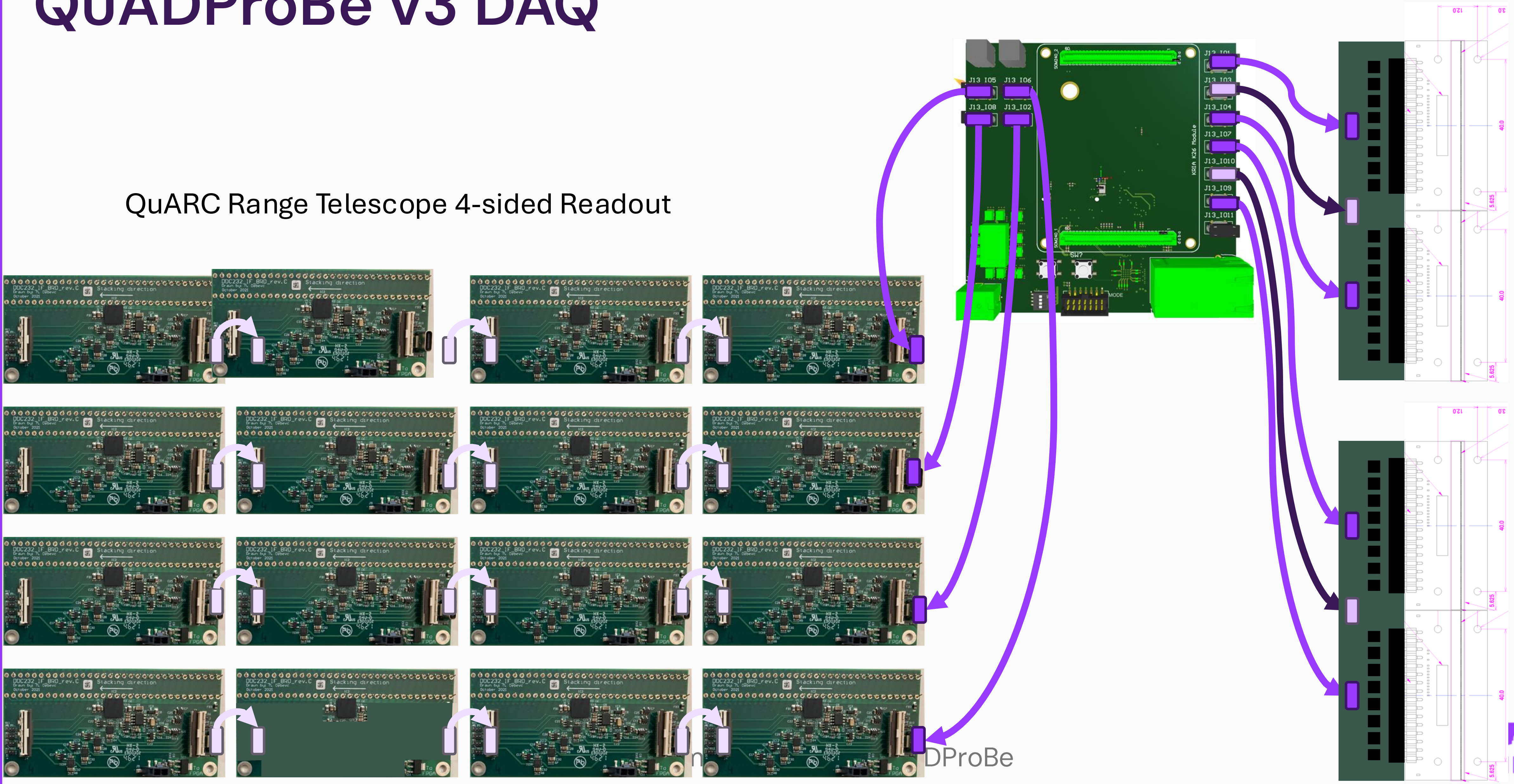
Potential proposals for QuADProBe Clinical Implementation

- Possibility to address failure modes involved in the treatment delivery process up to the point measurement.
    - i.e. covers all of the risk failure modes as log file-based PSQA and additionally addresses the risk of relying on machine self-reported parameters.

- Additional considerations:
    - Whether to rely on beam model or perform additional independent measurements to generate separate beam model for spot profile measurements at different distances from nozzle – if detector is nozzle-mounted or placed on treatment couch at isocentre.

QuADProBe v3 DAQ

SciFi Monitor 10x10cm Readout



DProBe