Bringing HEP Detector Technology to the Clinic:

Development of the Quality Assurance Detector for Proton Beam Therapy (QuADProBe)

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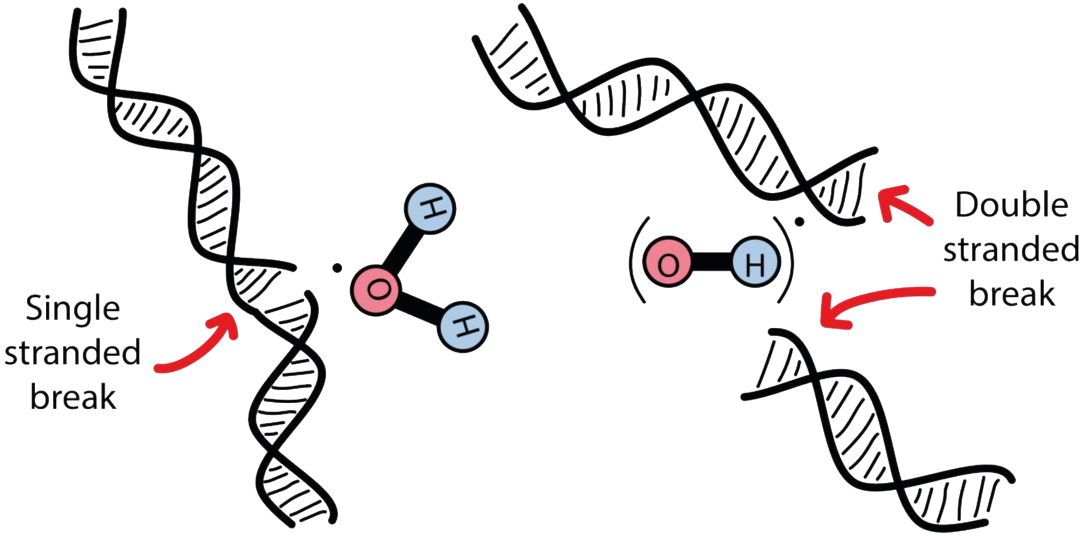
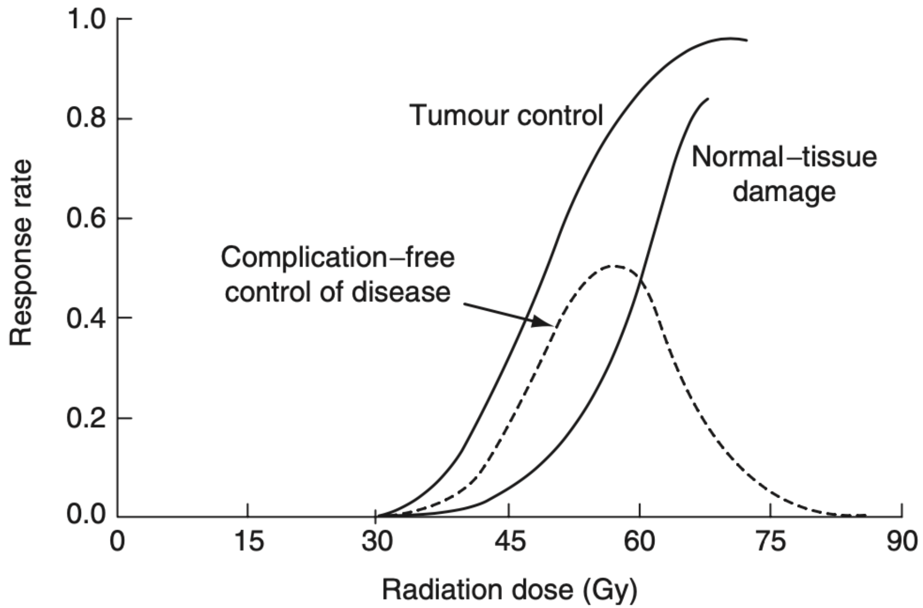
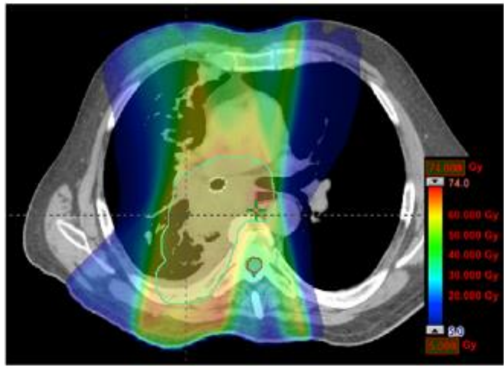
Cancer Treatment With Radiotherapy

- Radiotherapy main curative modality in ~40% of cancer.
- Cell death occurs through DNA damage.
- Absorbed dose ∝ Damage to DNA
- Ultimate goal – maximise radiation dose to tumour whilst minimising dose to healthy tissue – **<u>therapeutic window</u>**.







Radiotherapy Treatment Room

 http://thefarbercenter.com/blog/wp-content/uploads/2011/10/linac-room.jpg

Radiotherapy Treatment Room

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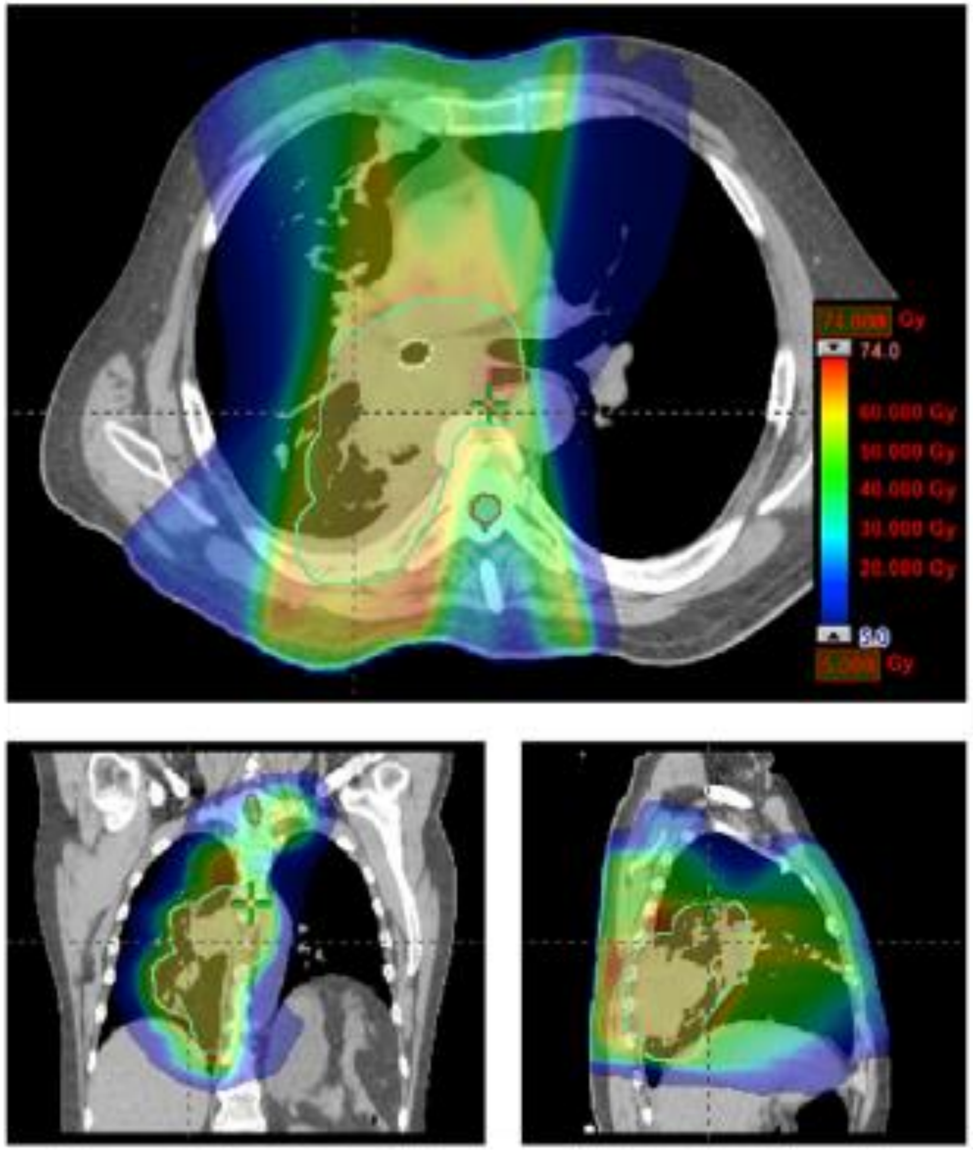
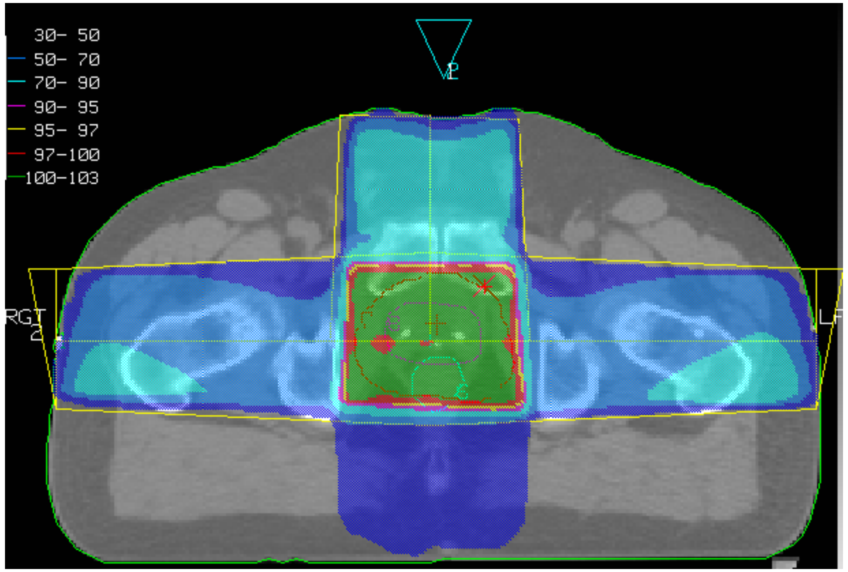
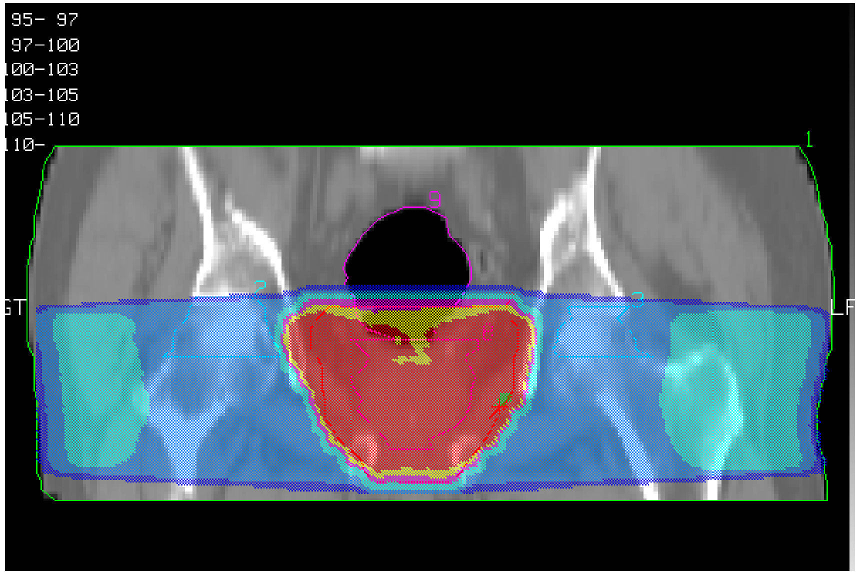
VMAT Radiotherapy

Radiotherapy Dose Deposition

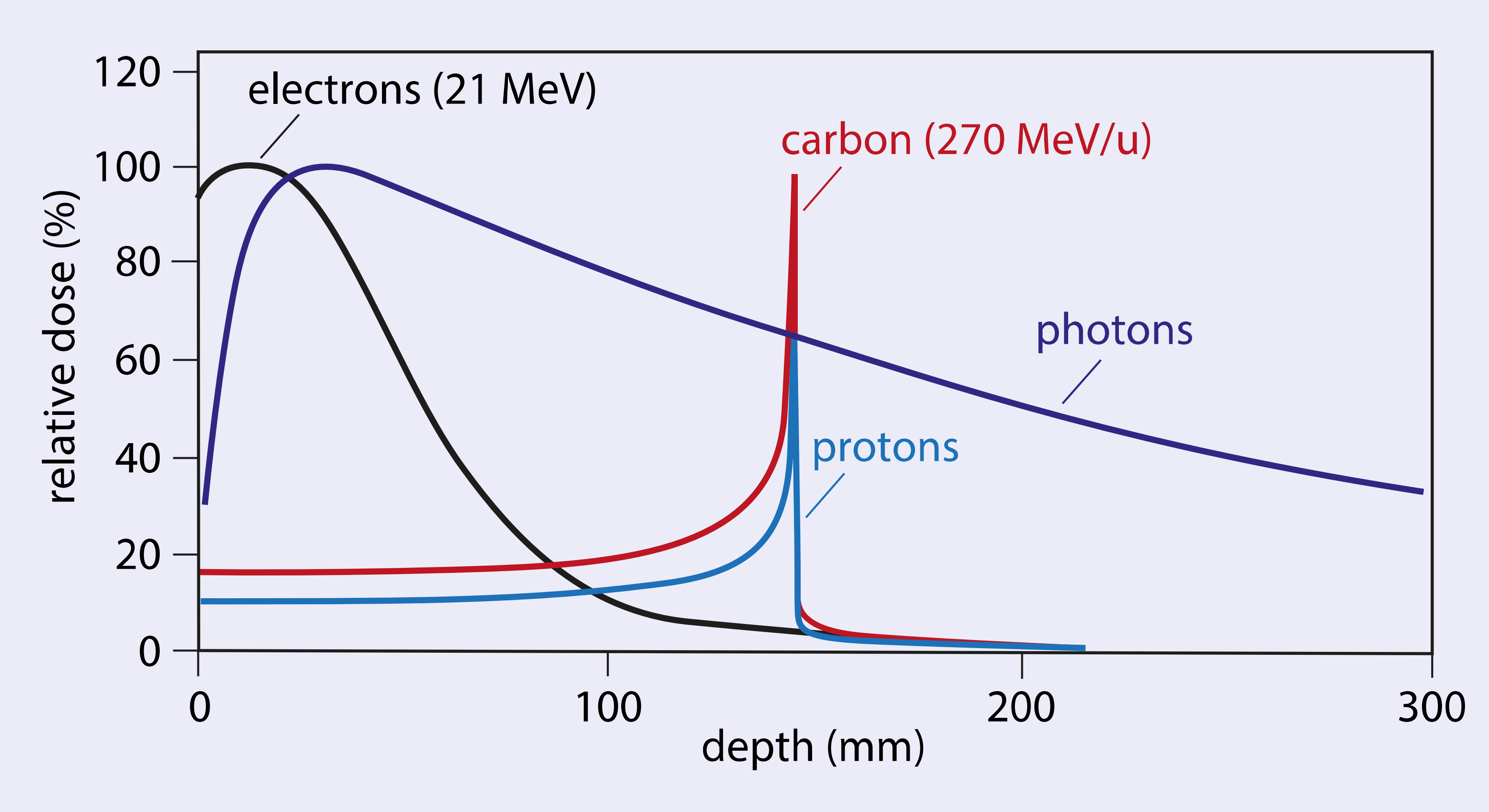






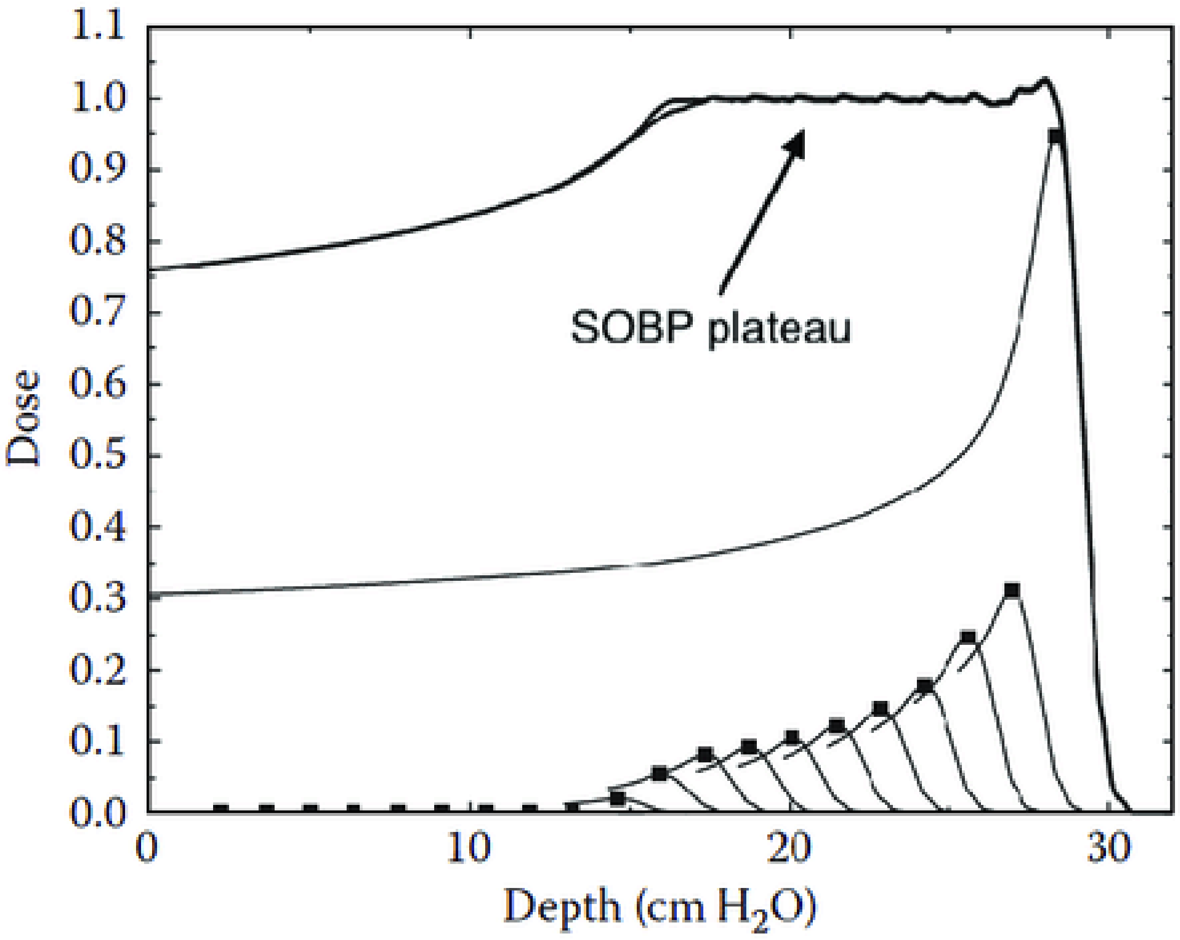
Particle Dose Distribution

- Unlike X-rays, charged particles stop!
- Electrons, being lighter, scatter and spread out.
- Protons deposit most dose at the *end* of their path: the **Bragg Peak**.



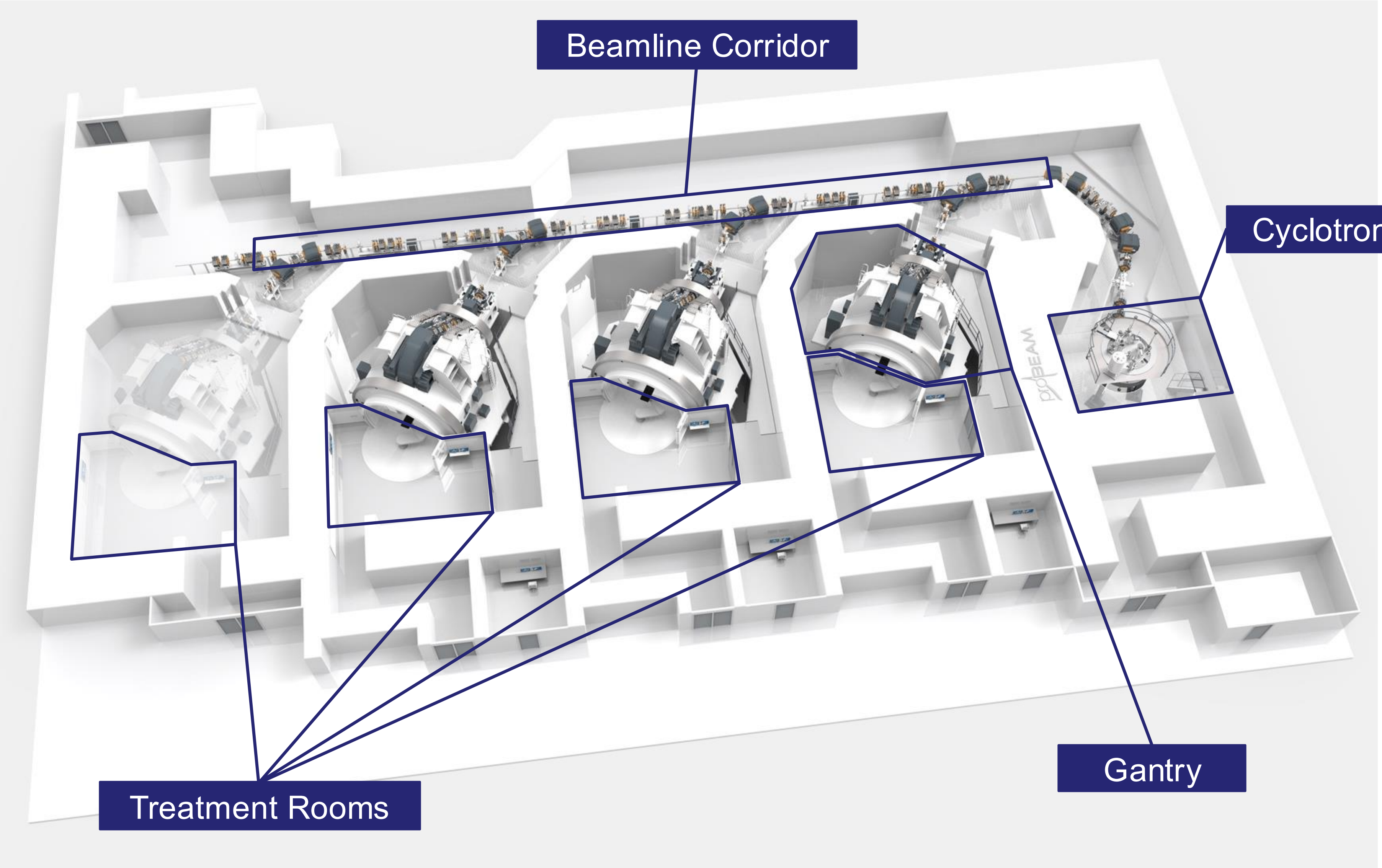
Particle Dose Distribution

- Protons can be 'painted' over the tumour depth since their stopping range depends on energy.
- About 70 – 230 MeV is sufficient energy to cover entire range of tumour depths.
- A plateau is created over the tumour by superimposing Bragg peaks at different energies and intensities.

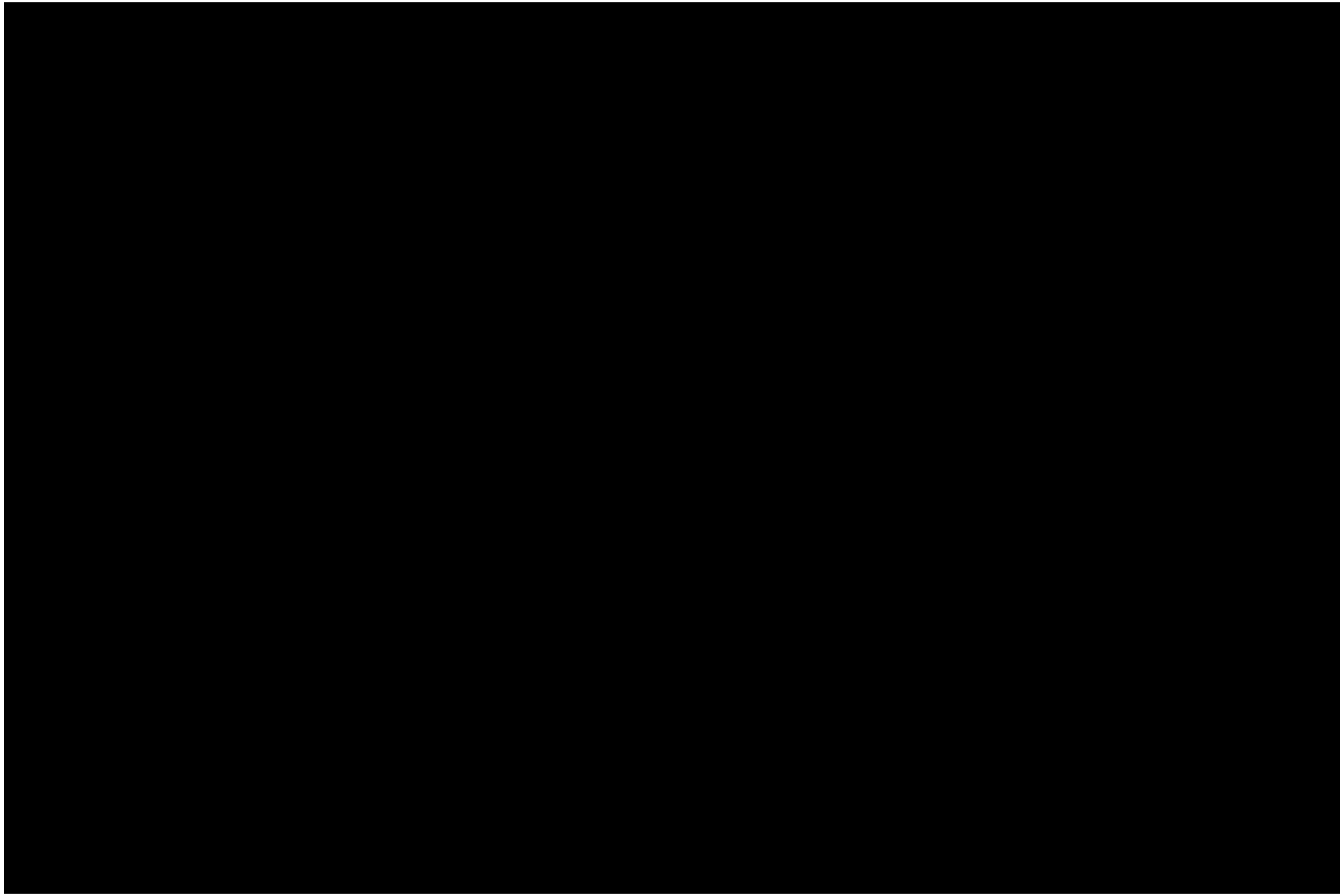


UCLH Proton Therapy

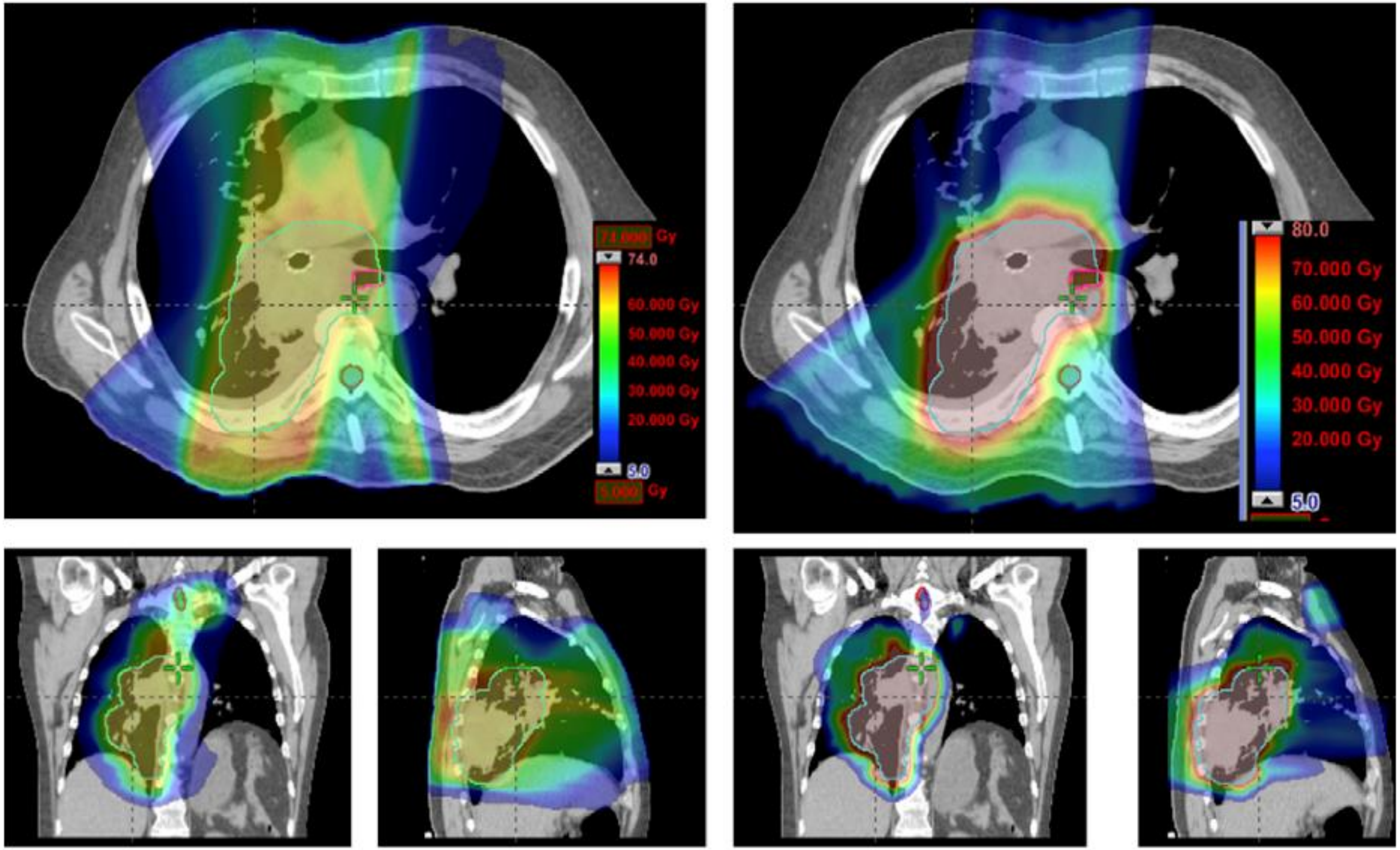
UCLH Proton Therapy Facility



Scanning The Bragg Peak



Proton vs Photons



Zhang X, Li Y, Pan X, et al. *Int J Radiat Oncol Biol Phys.* (2010); 77 (2): 357–366 [DOI: 10.1016/j.ijrobp.2009.04.028](https://doi.org/10.1016/j.ijrobp.2009.04.028)

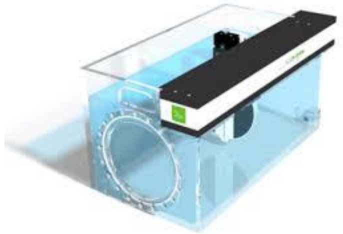
PBT QA

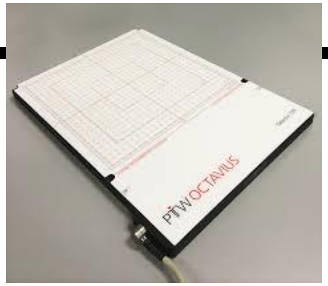
- Since the dose is heavily localised with PBT, extensive quality assurance (QA) needs to performed on the proton beams to ensure the dose is delivered **exactly** where it needs to be.
- 4 key quantities to verify in proton therapy QA:
  - Dose
  - Range (i.e. energy of the proton beam)
  - Spot Size
  - Spot Position

PBT Machine QA Detectors

Speed

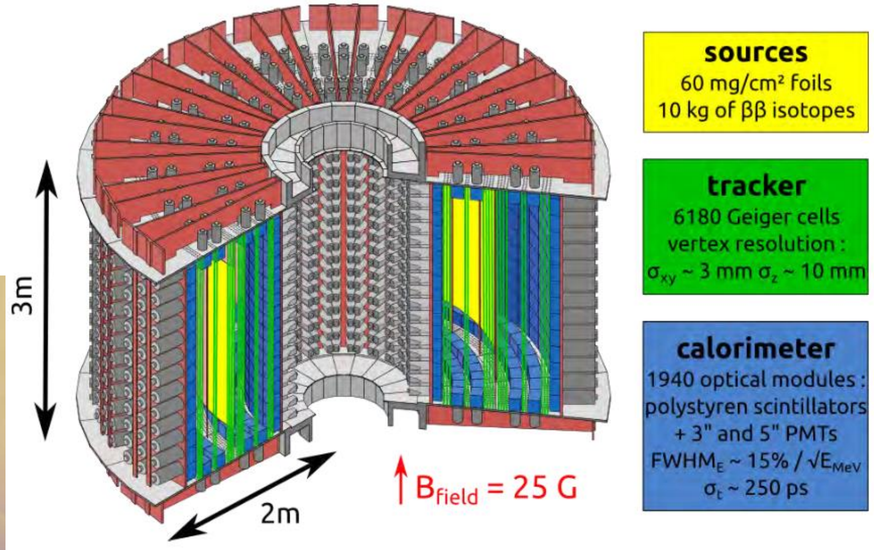
Robustness





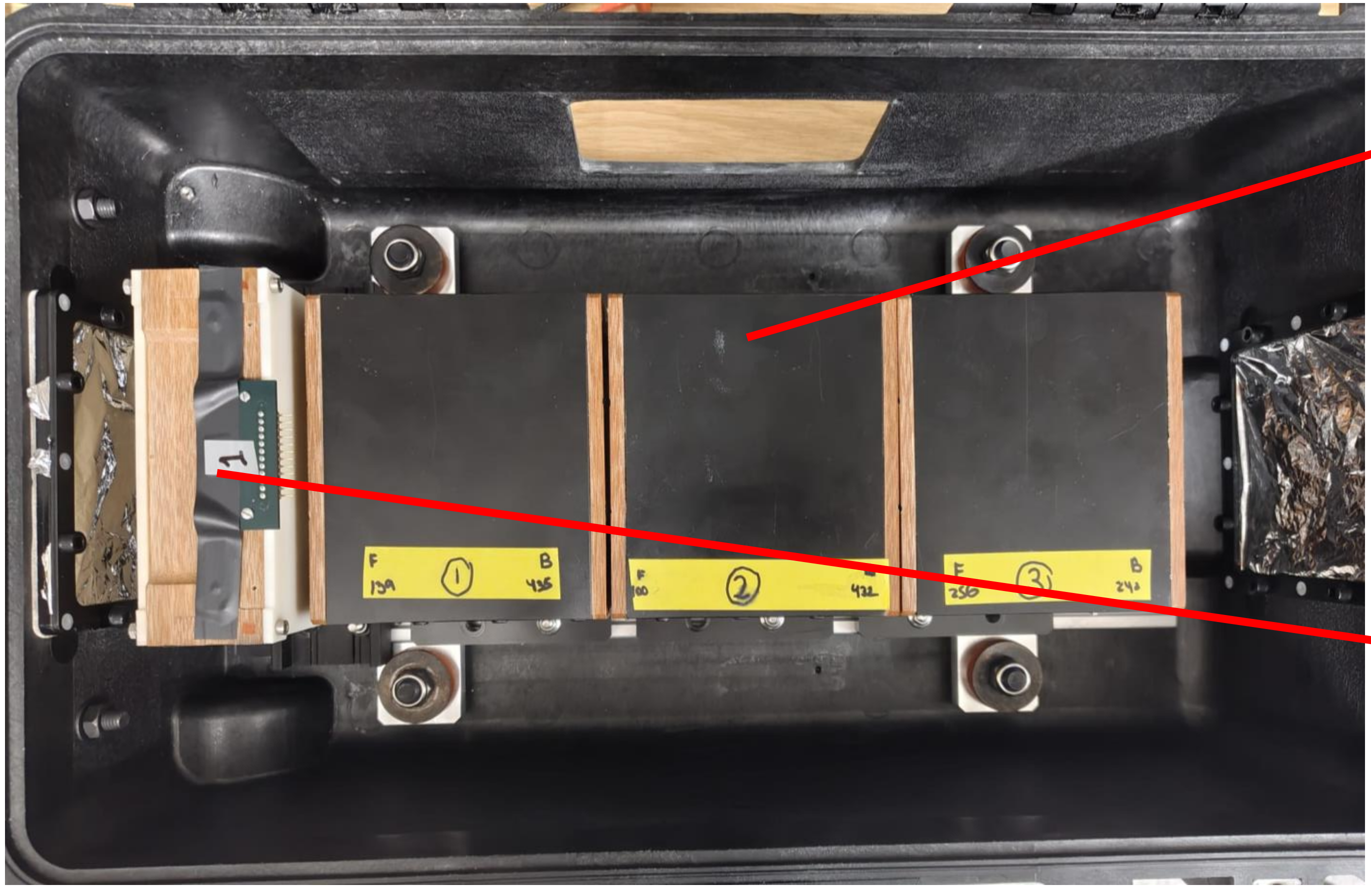
UCL HEP to PBT

- Since 2011, involvement has grown from facility design assistance to detector development.
- What technological solutions will assist clinical workflow? Proton CT, Quality Assurance.
- SuperNEMO experiment measures beta decays from radioactive source with high precision:
  - Plastic scintillator modules record beta energy with nanosecond timing.
- What applications in PBT are there for fast water equivalent plastic scintillator…

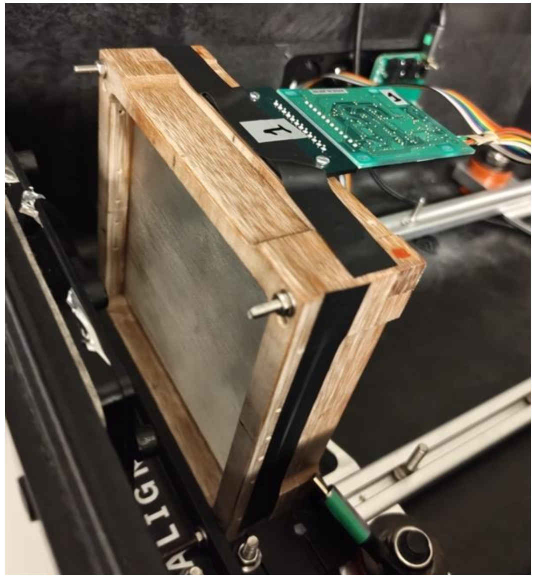


QuADProBe

QuARC

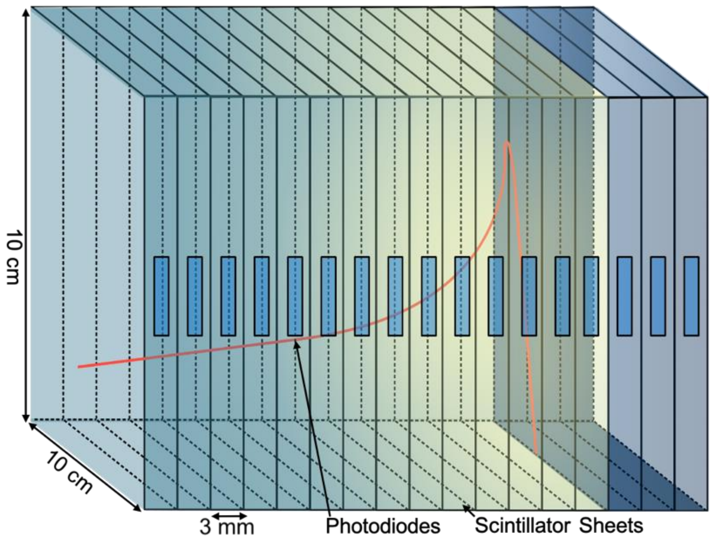


SciFi Tracker



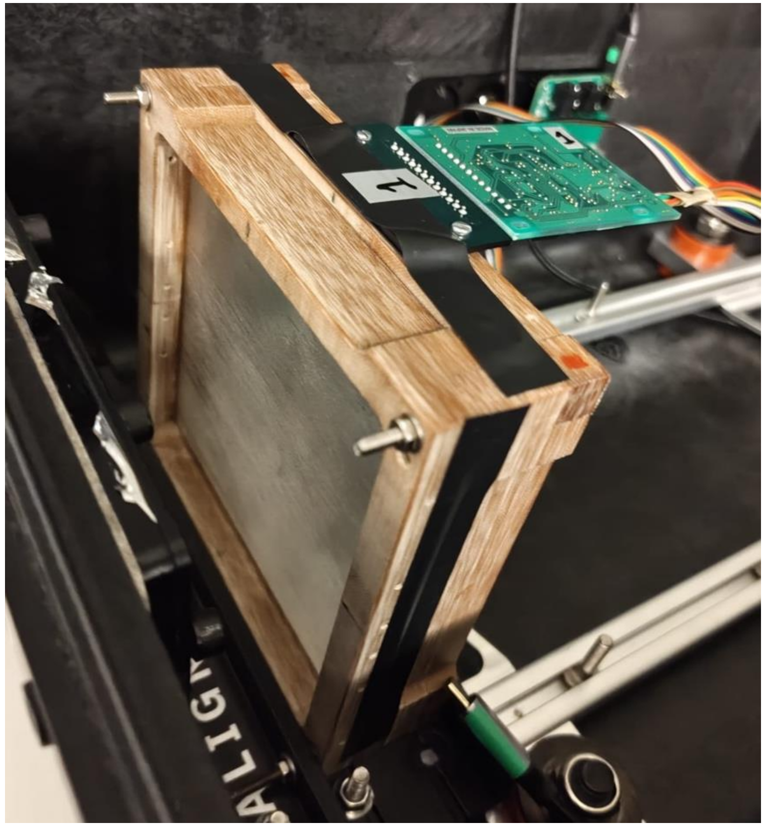
The QuARC

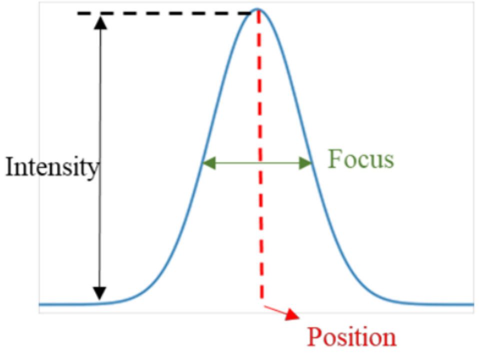
- The Quality Assurance Range Calorimeter (QuARC) constructed from plastic scintillator:
  - Protons intercepted by a series of optically-isolated polystyrene scintillator sheets.
  - Measure light output with photodiodes.
  - Light output of each sheet nonlinear to dose, but quenching described by Birks' Law:
    - Fit data with analytical depth-light model.
    - Reconstruct Bragg depth-dose curve and measure proton range.
  - 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.



SciFi Profile Monitor

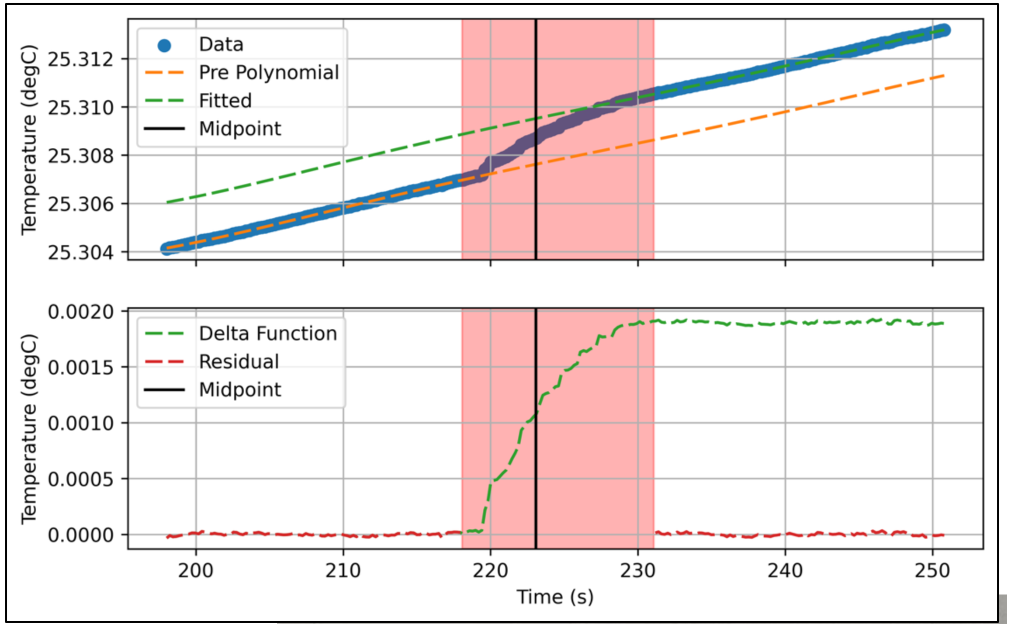
- 2 orthogonal 10 cm x 10 cm arrays made of BCF-60 plastic scintillating fibres by Saint-Gobain, 0.50 ± 0.13 mm diameter. Emission peak at 530 nm.
- 128-photodiodes array (Hamamatsu S13865), single and cascade operation. Image size: 51.2 x 0.6 mm, pixel pitch 0.4 mm
- Hamamatsu C9118-02 CMOS driver circuit 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
- MCLK 1 MHz. Suggested min. reset time 10us and suggested min. integration time 17+4x128 clocks = 529 us.
- FPGA high period of RESET clock (reset) = 50 us, low period (integration) 950 us

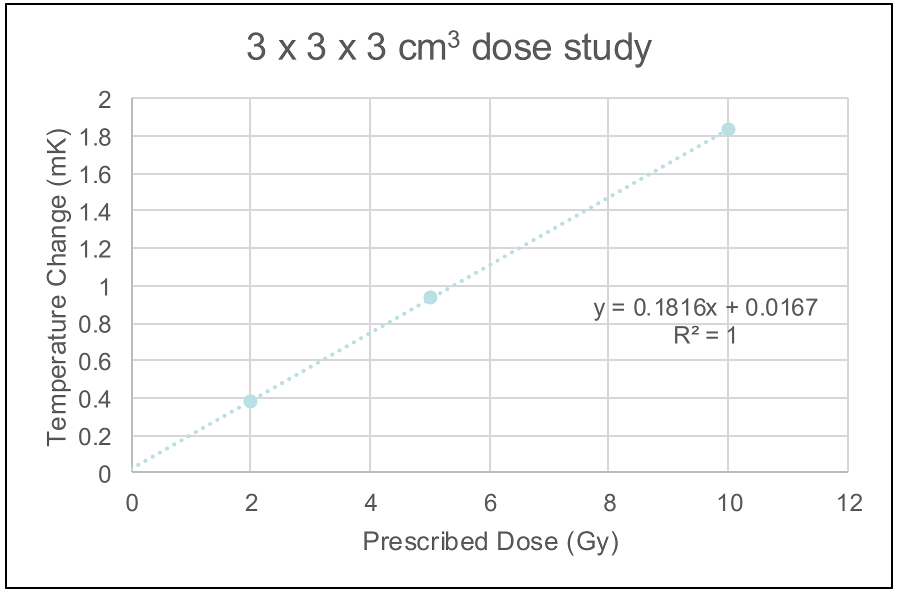


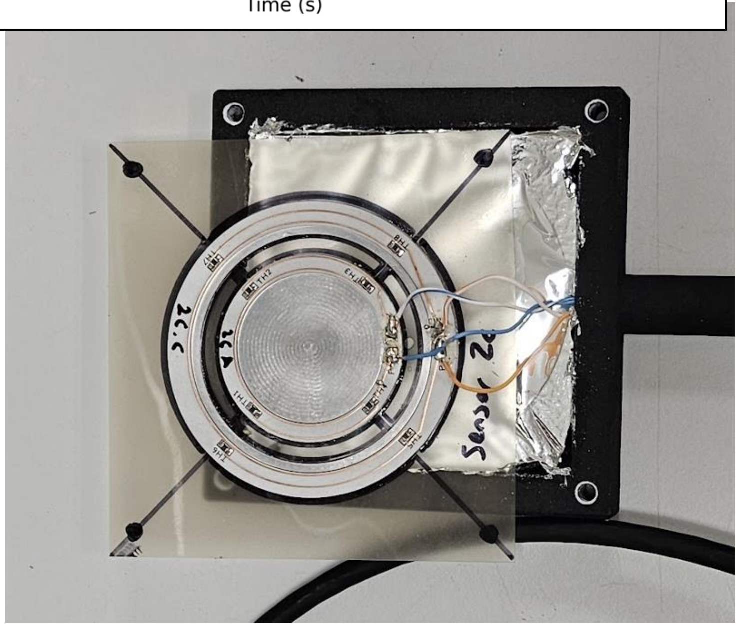


The NPL Transmission Calorimeter (TC)

- 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

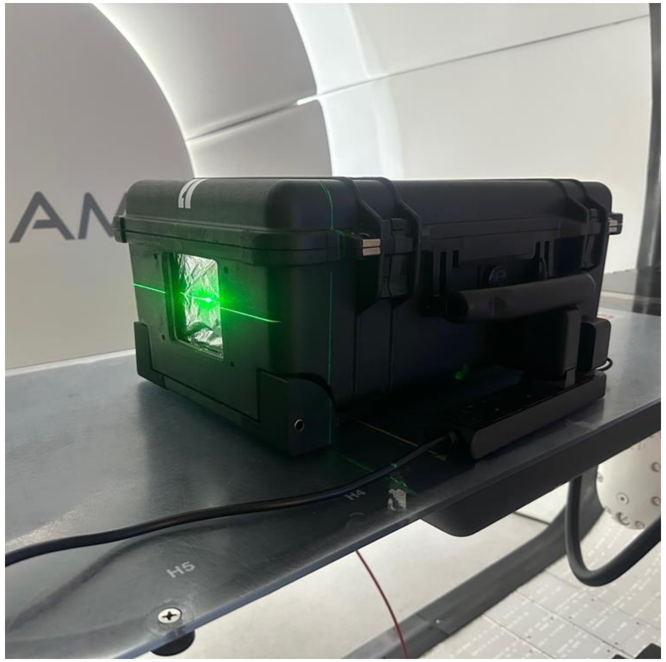






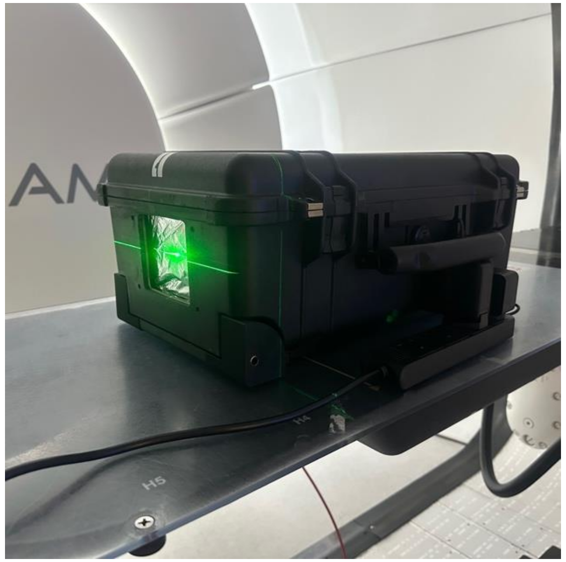
QuARC Design Brief

- Able to make direct range measurements.
- 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.



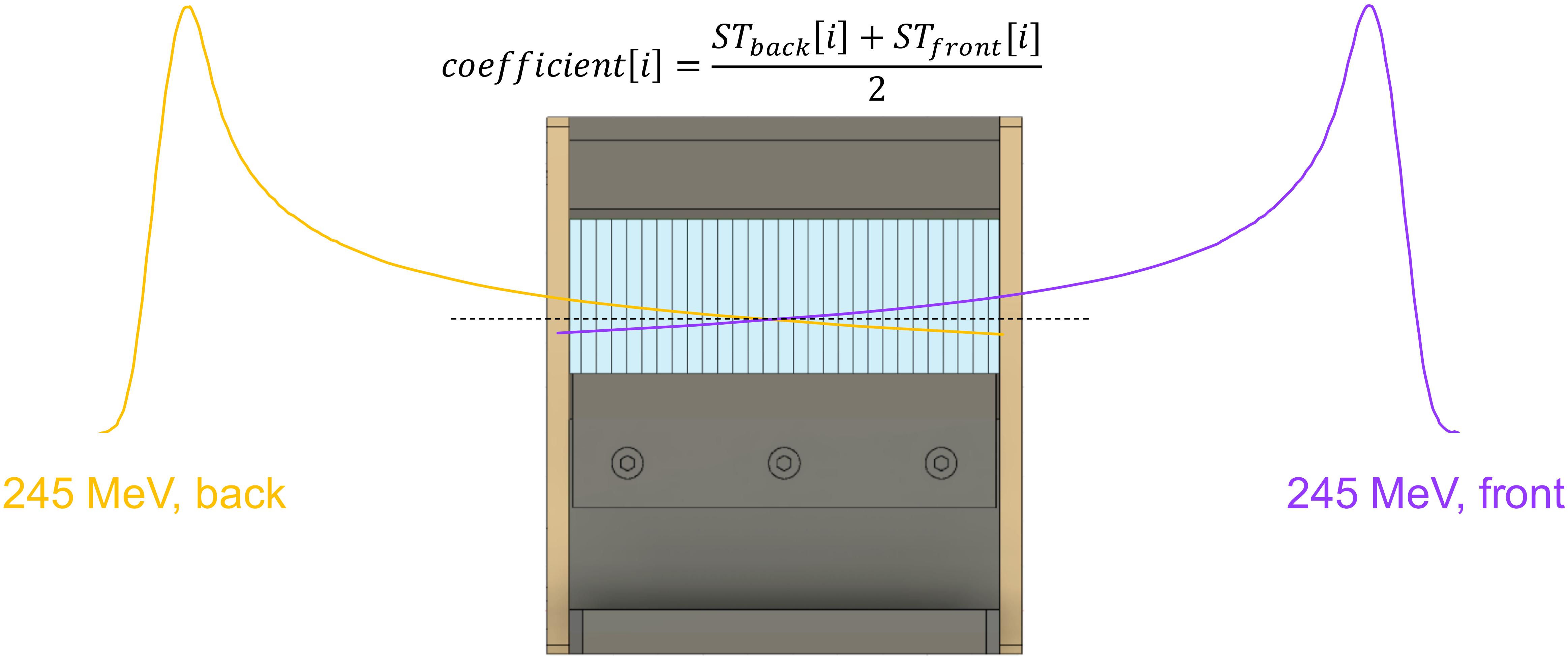
UCLH Beam Tests

- Beam tests at UCLH to evaluate photodiode performance with clinical beams.
- Detector setup with 4 modules (32 sheets, 96 mm total depth per module) to test pencil beam energies between 70–245 MeV.
- Determine range reconstruction accuracy and demonstrate fast live range reconstruction capabilities with web GUI.
- Pristine Bragg peaks, SOBP and position variation.



Detector Calibration

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



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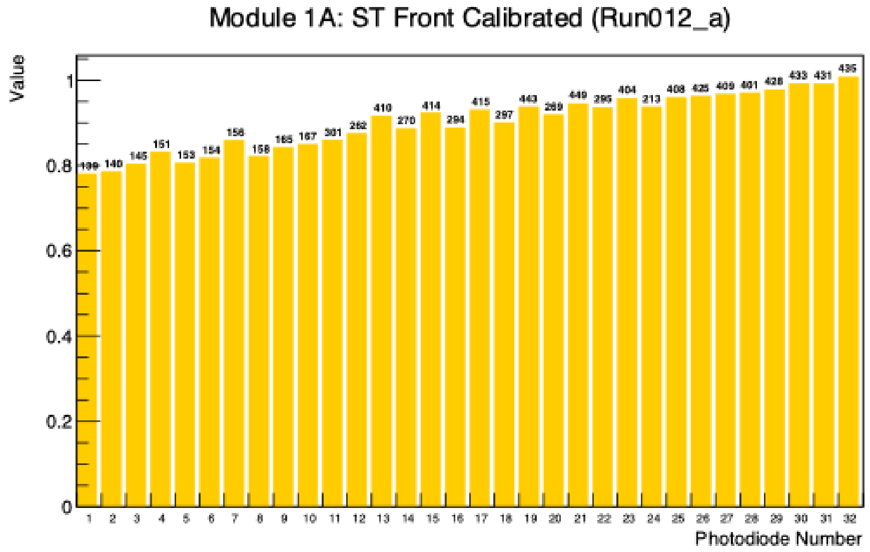

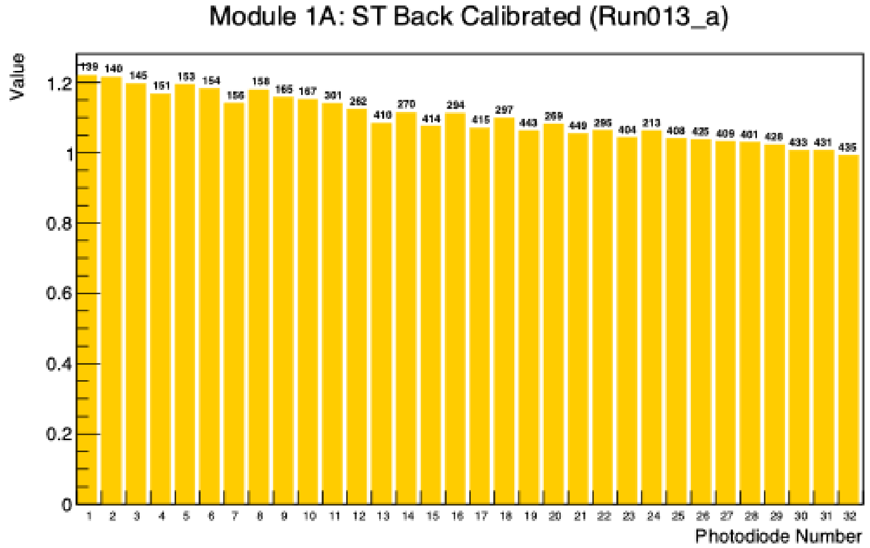

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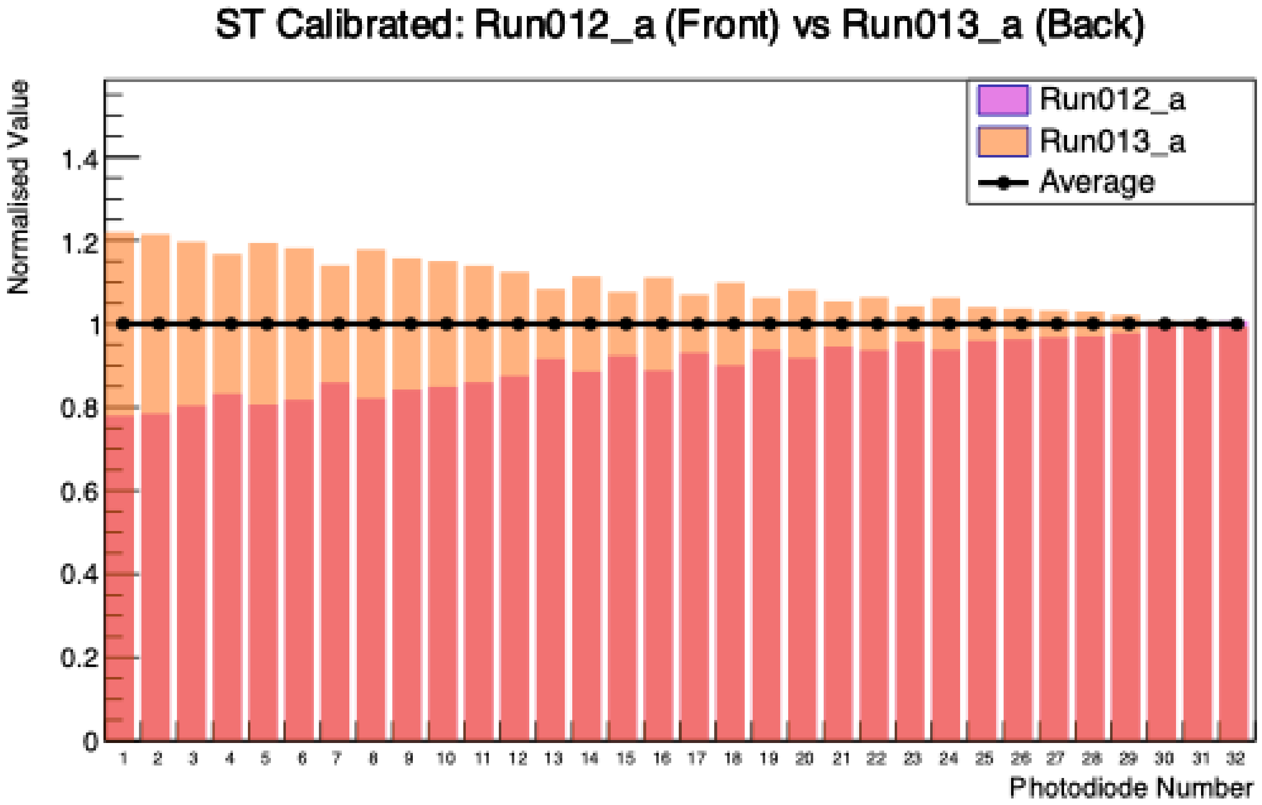
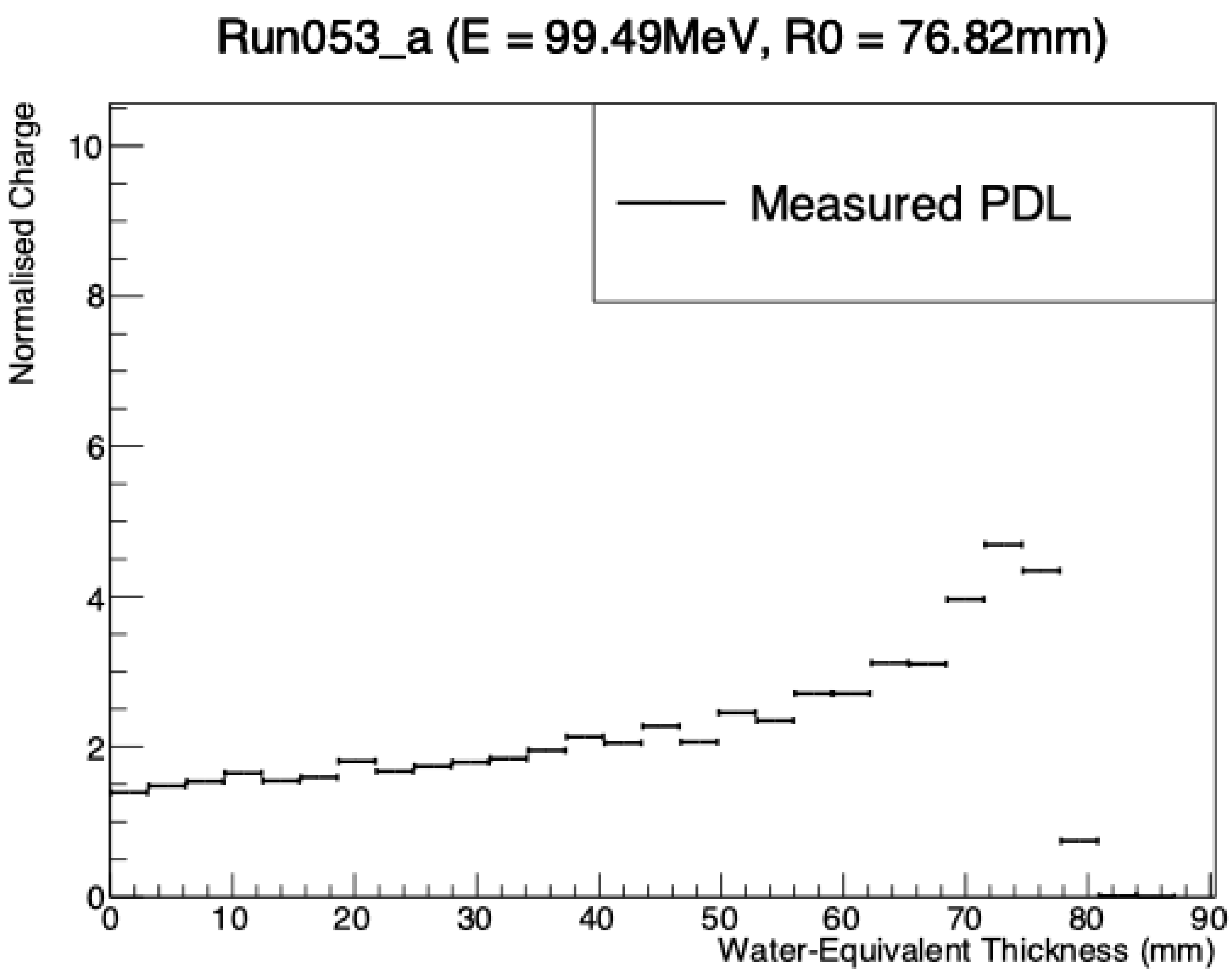
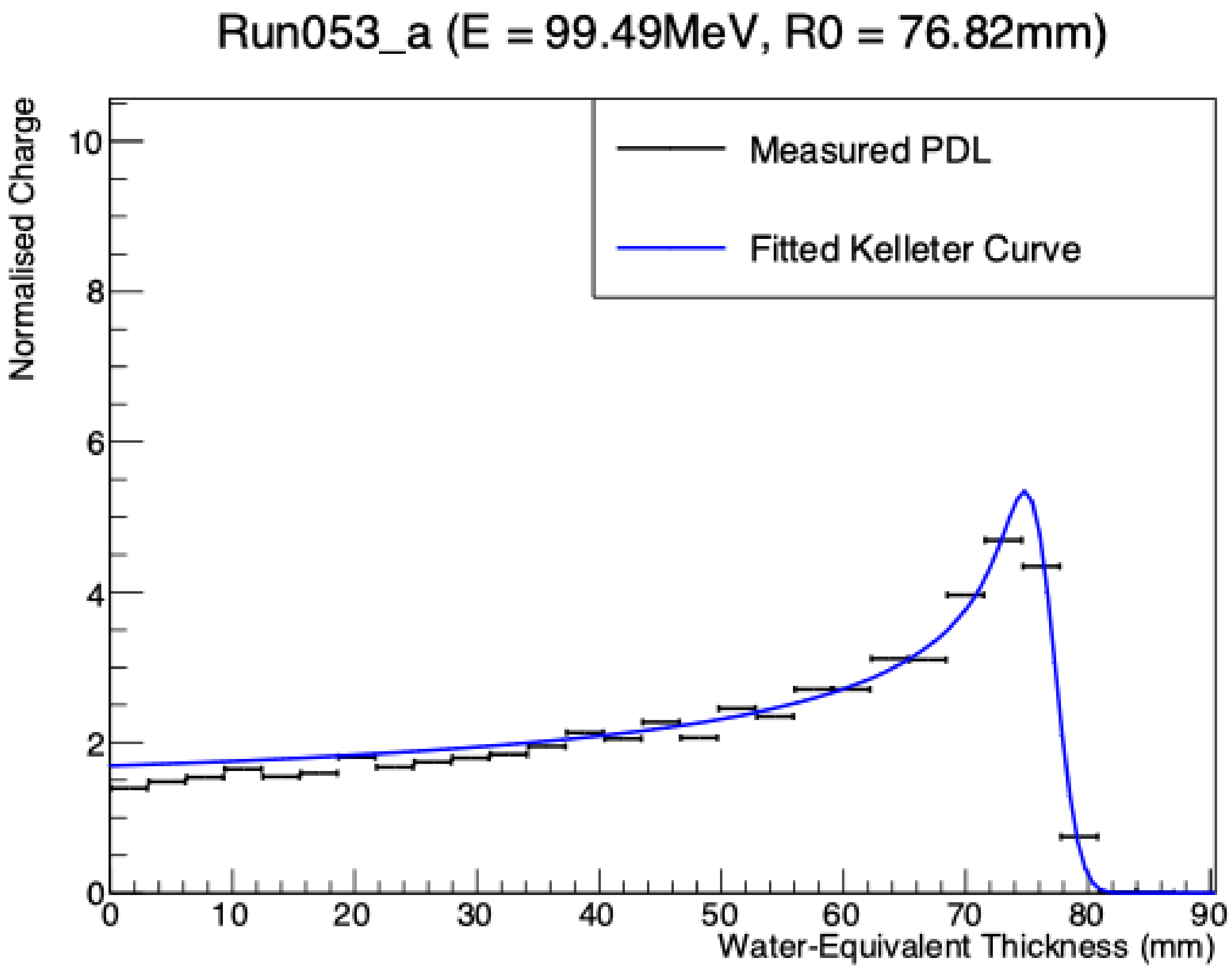


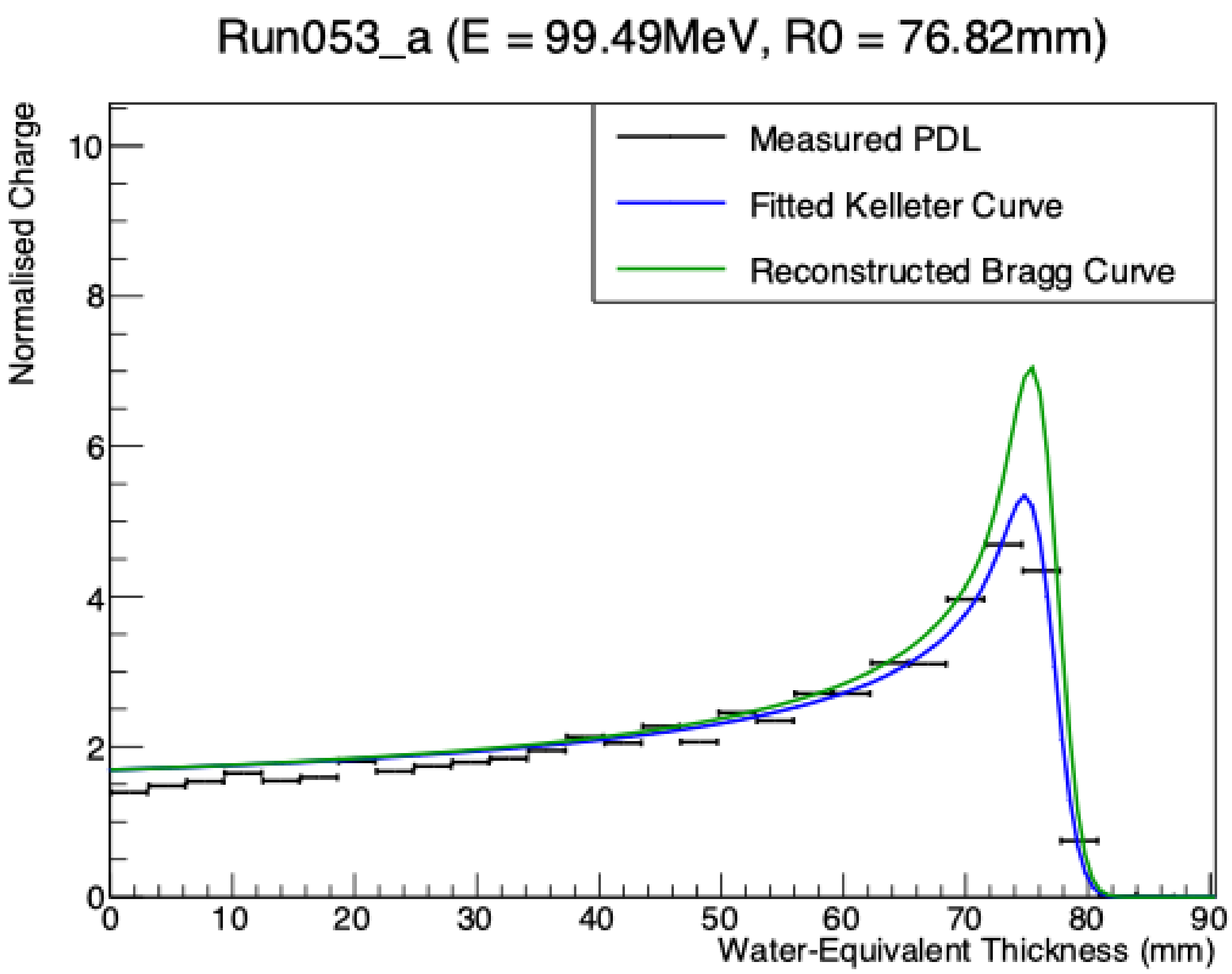
Bragg Peak: 100 MeV



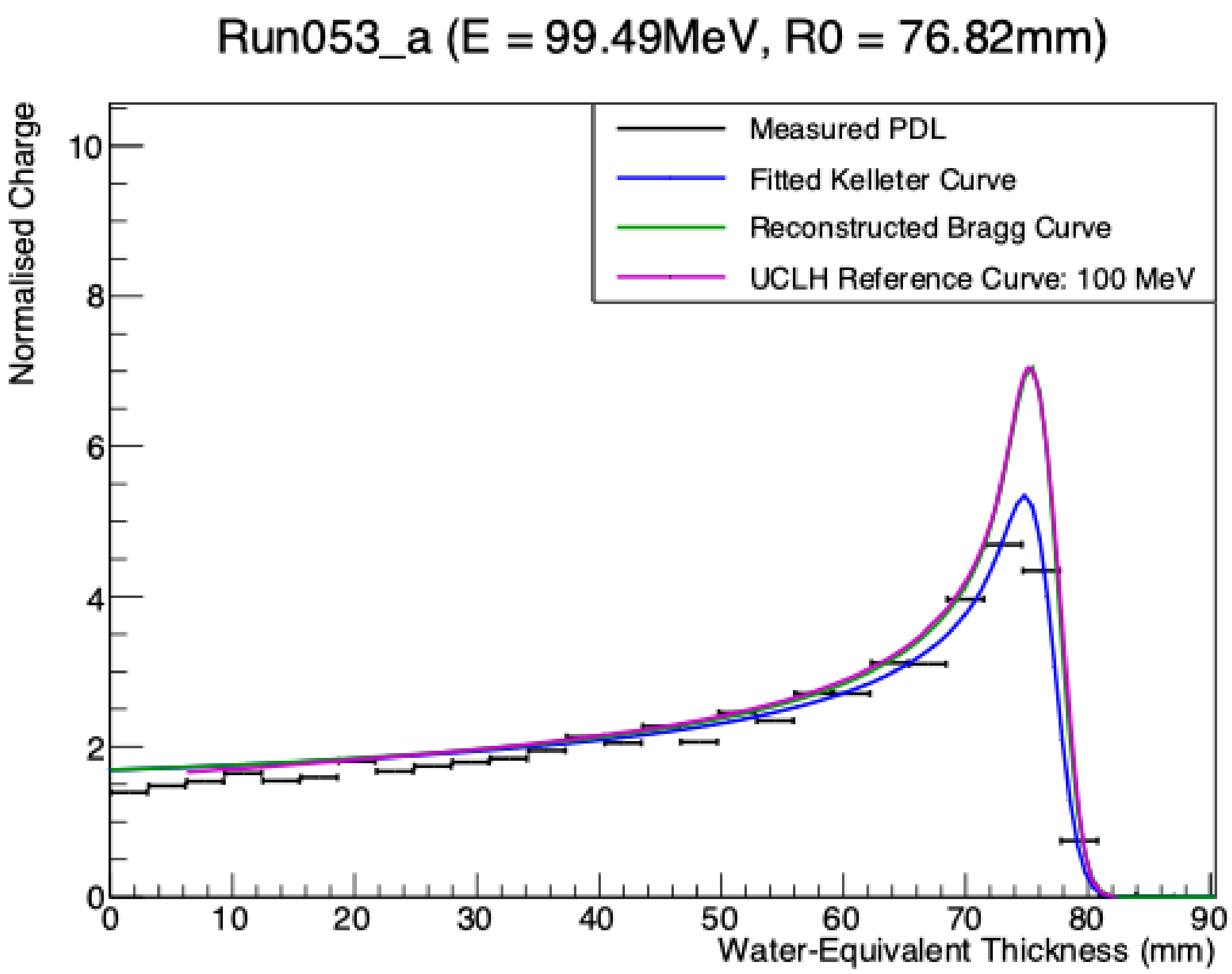
Bragg Peak: 100 MeV



Bragg Peak: 100 MeV

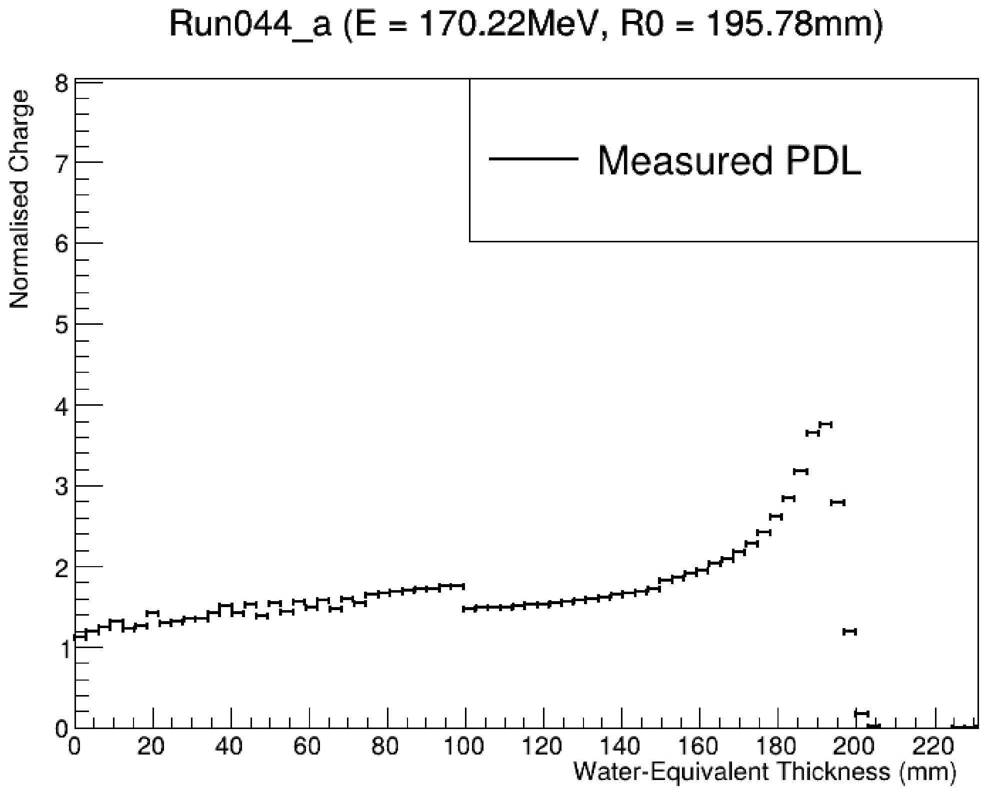


Bragg Peak: 100 MeV

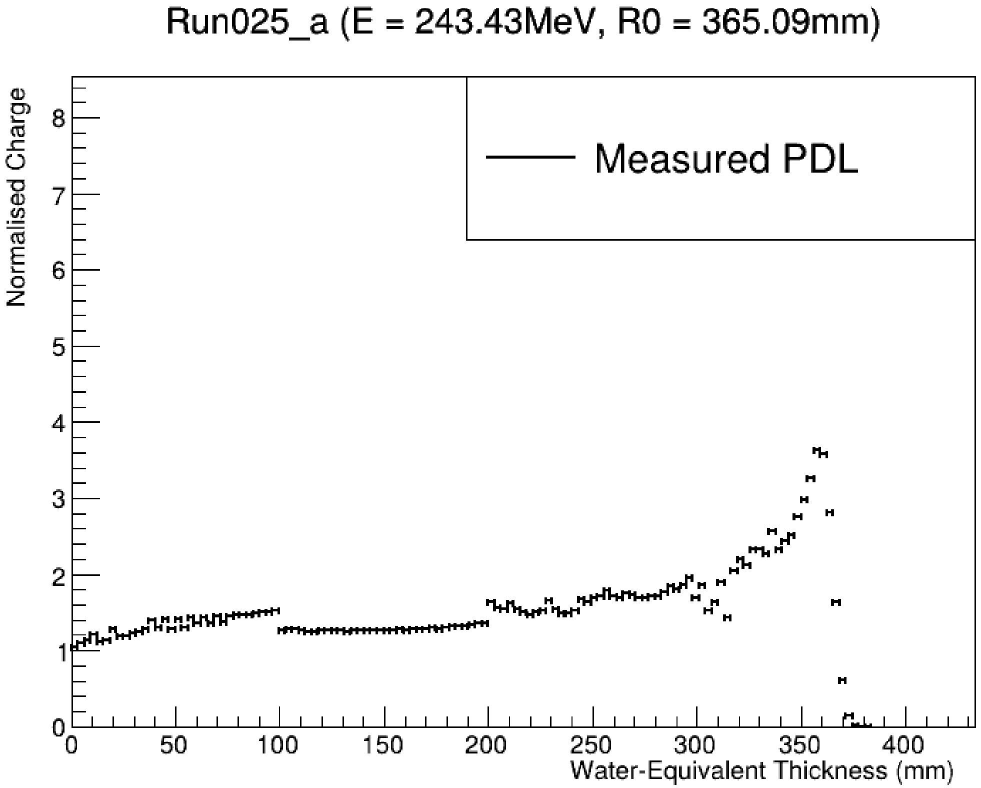


More Bragg Peaks

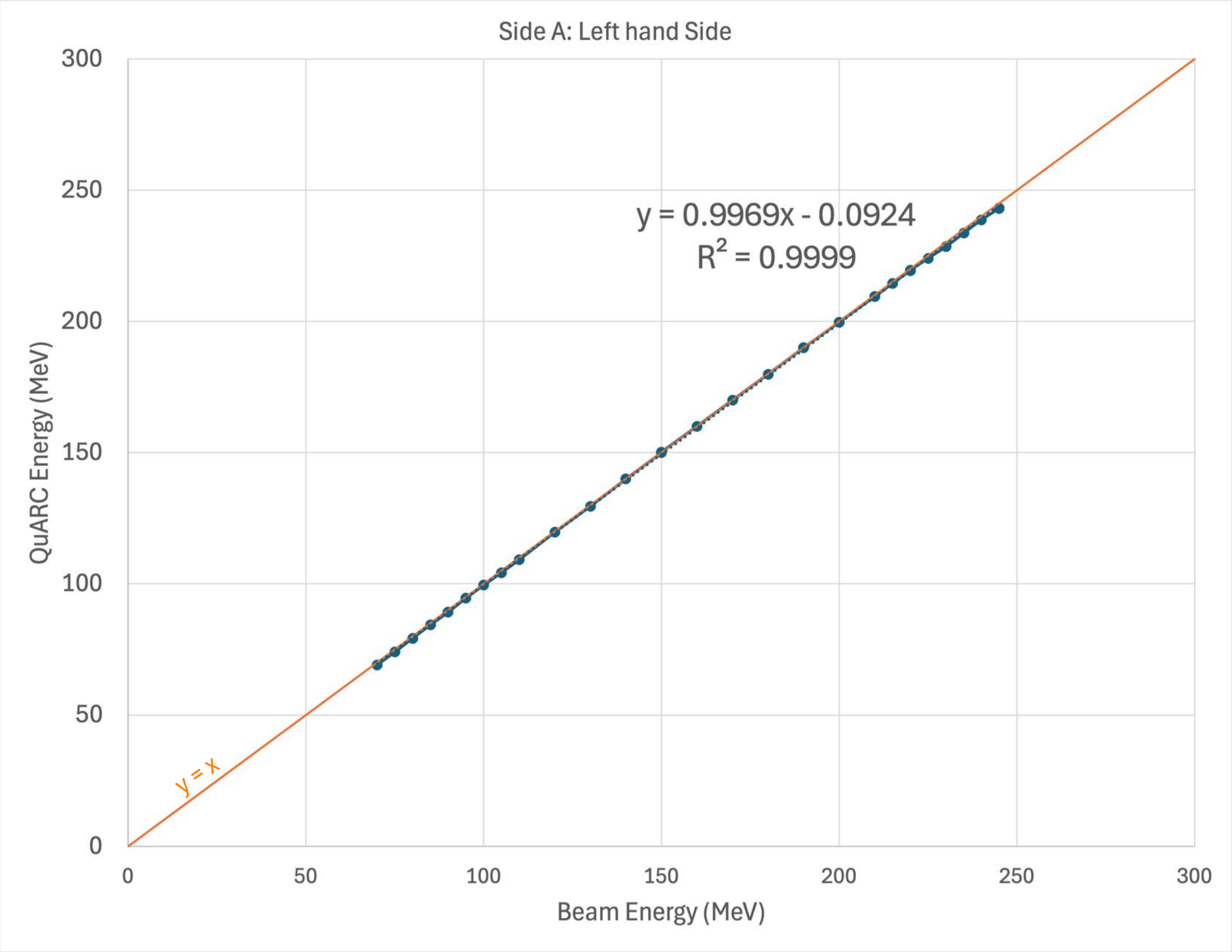
170 MeV



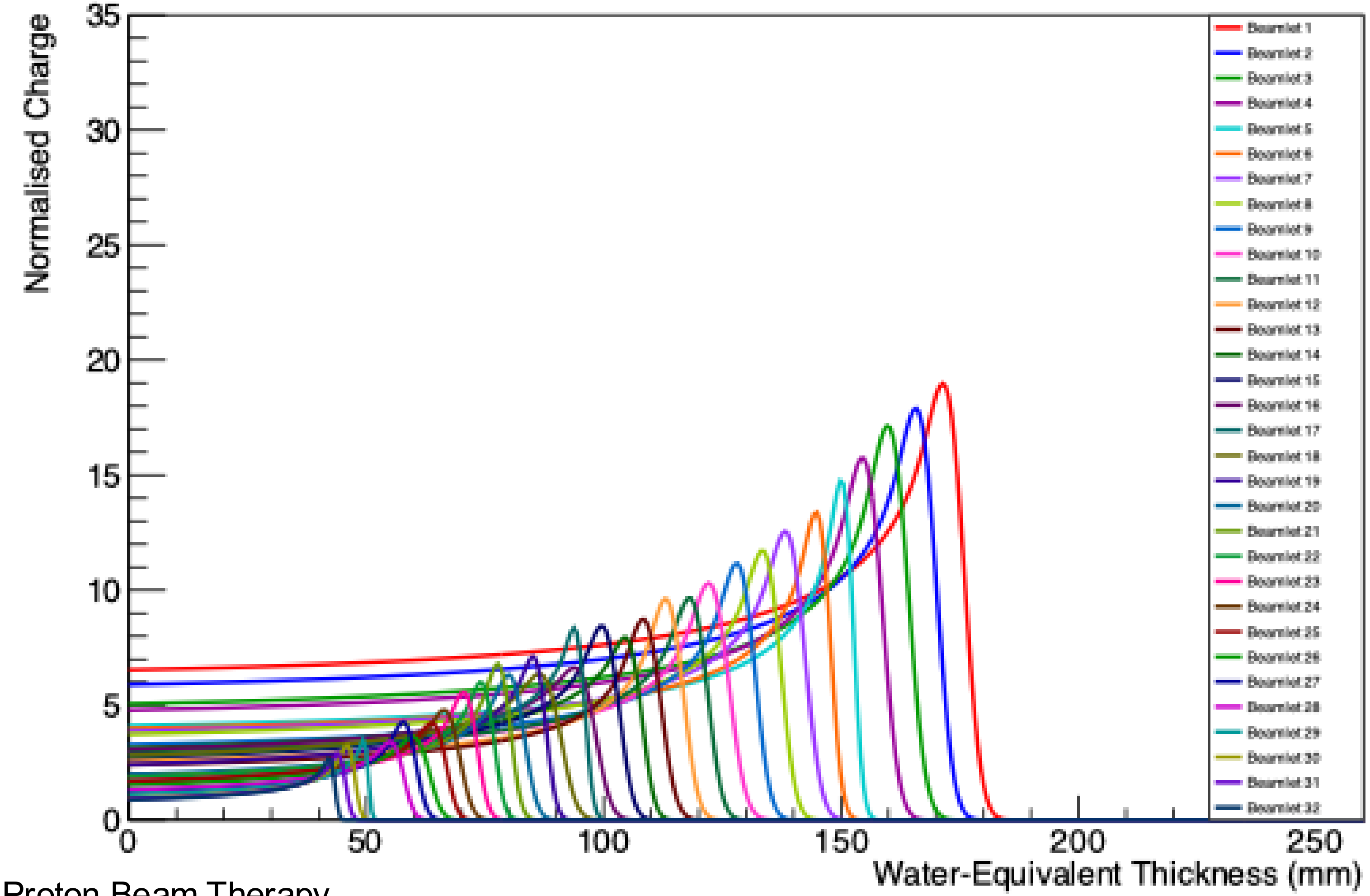
245 MeV



Energy Comparison

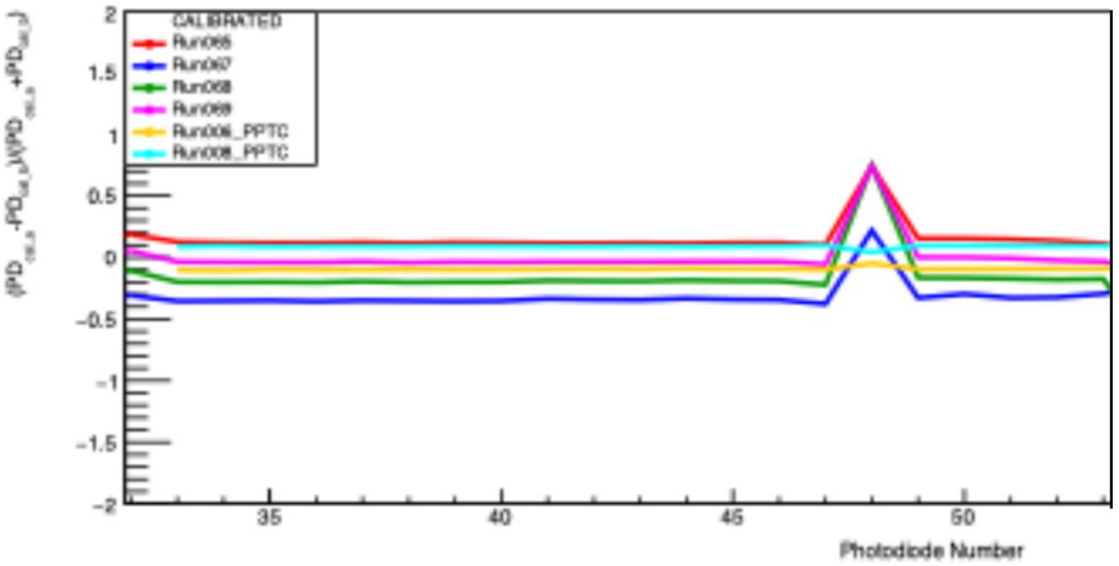


Reconstructed Bragg Curve for all BPs

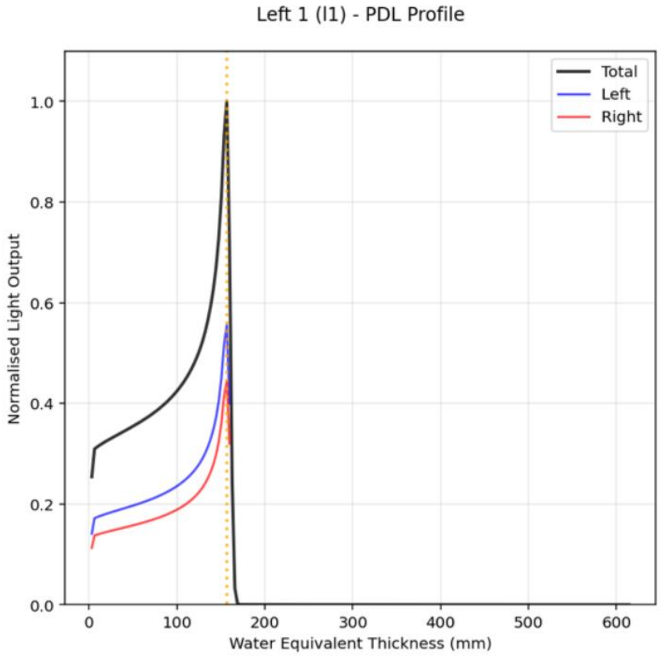


QuARC Position Measurements

$$shift[i] = \frac{PD_A[i] - PD_B[i]}{PD_A[i] + PD_B[i]}$$



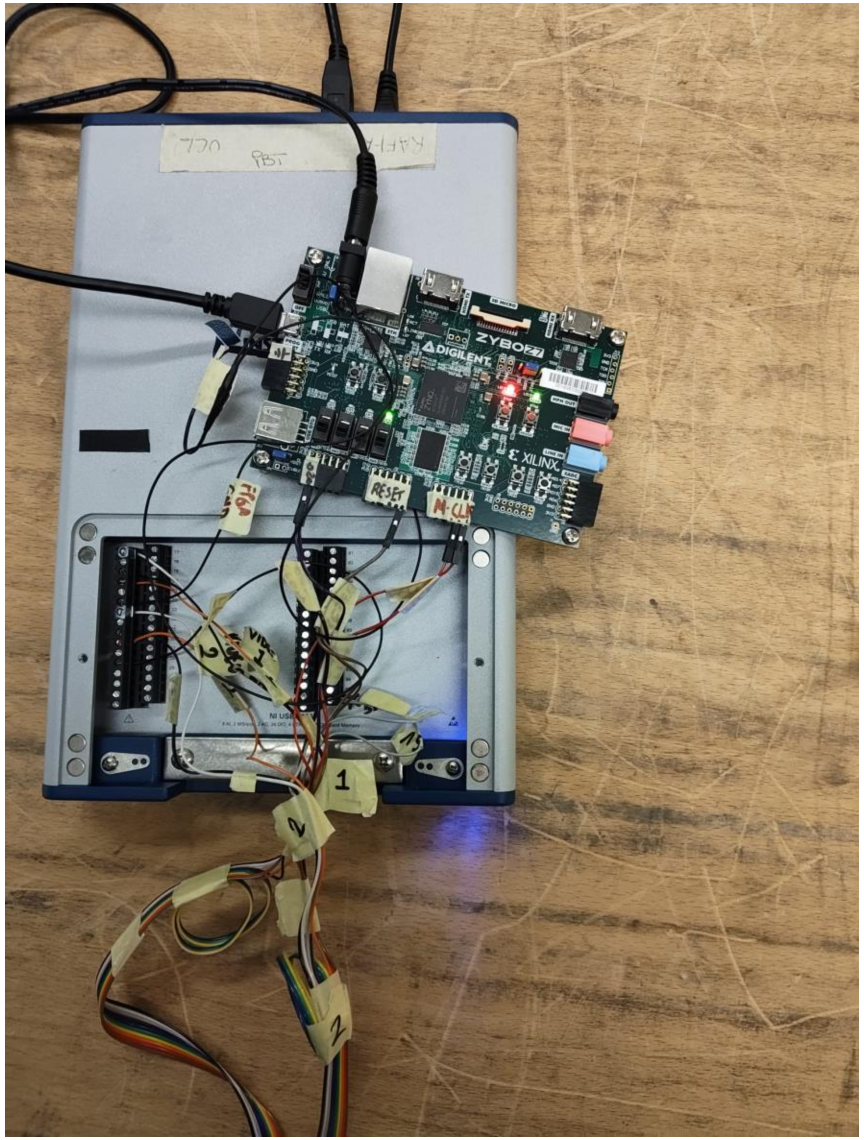
1cm R
2 cm L
1 cm L
centered

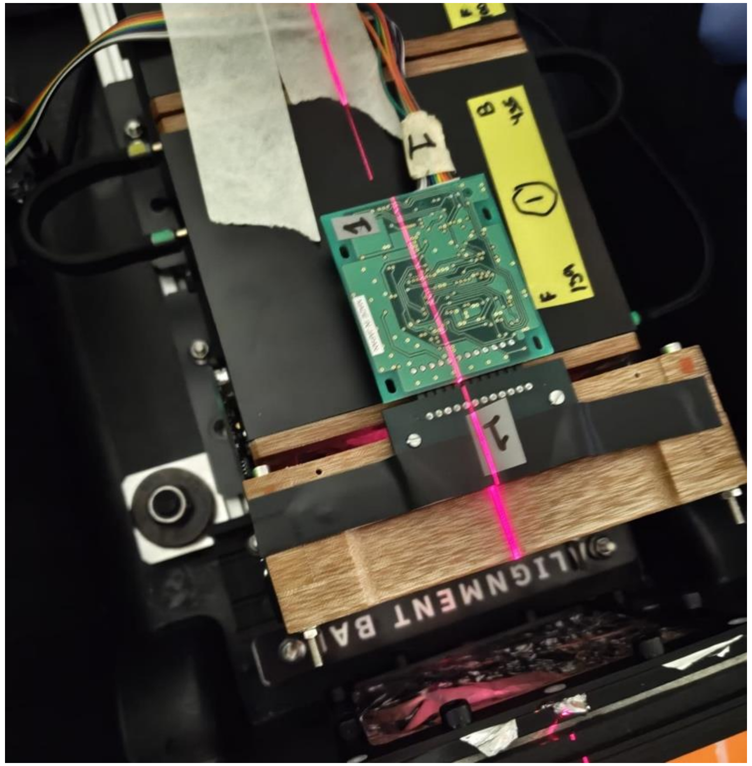


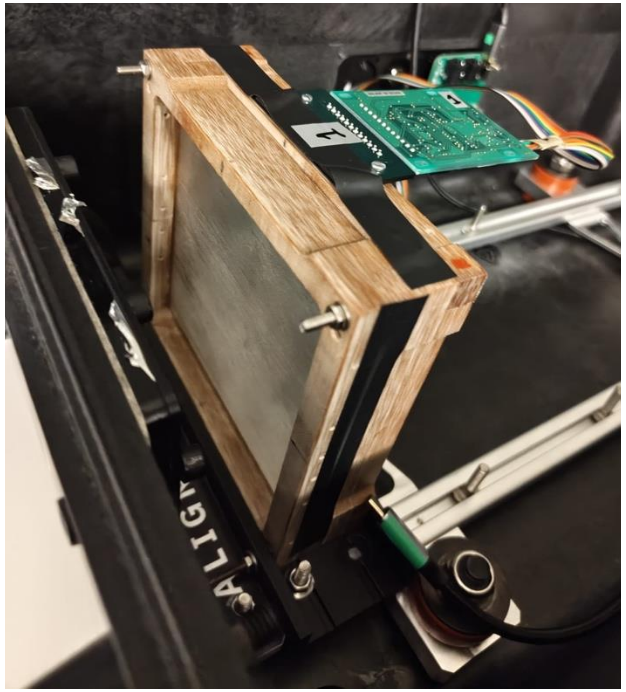
Trento Beam Test Summary and Prelim Results

- 3 nights of measurements in the research room at Trento PTC
  - Night 1: QuARC
    - Calibrations and Bragg Peak measurements scaling current up to FLASH (briefly).
  - Night 2: Combined QuARC + SciFi:
    - Dynamic range testing (fibres at low gain)
    - Beam position measurements
  - Night 3: SciFi Measurements
    - Dynamic range testing (fibres at low gain)
    - Different spot sizes (varying energy)

SciFi Measurements

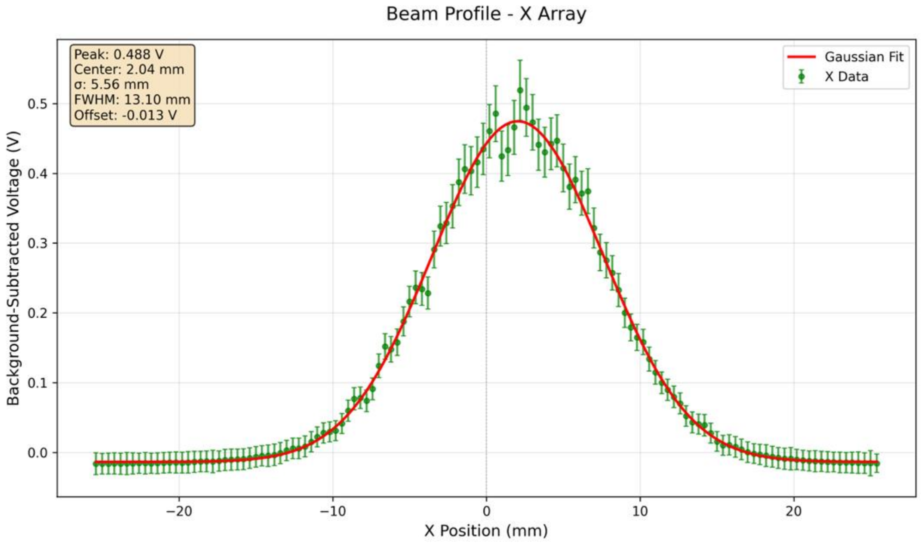


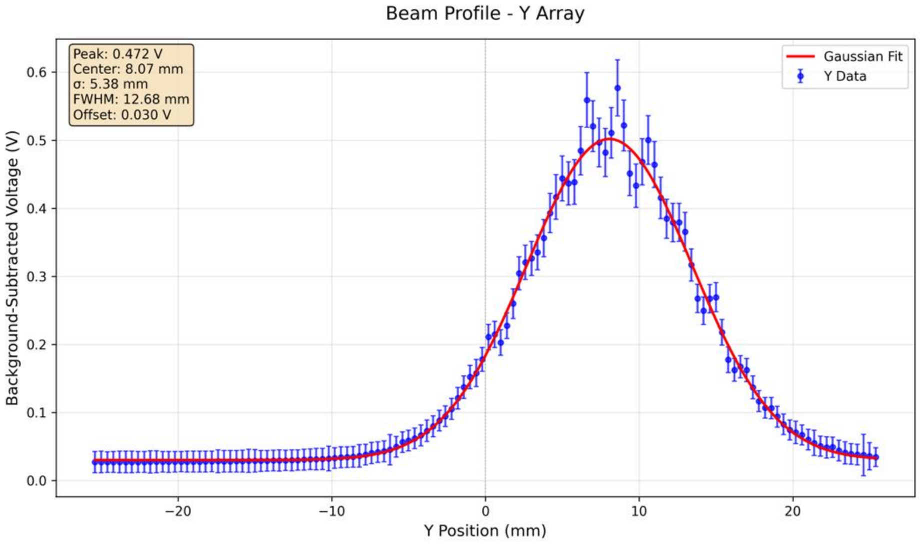




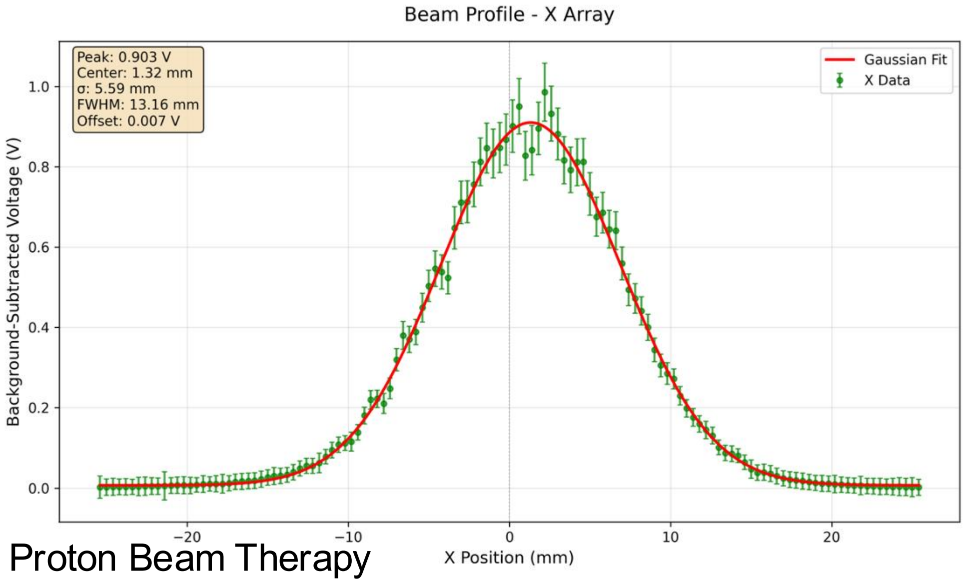
148 MeV 300 nA Profiles at Low Gain and High Gain

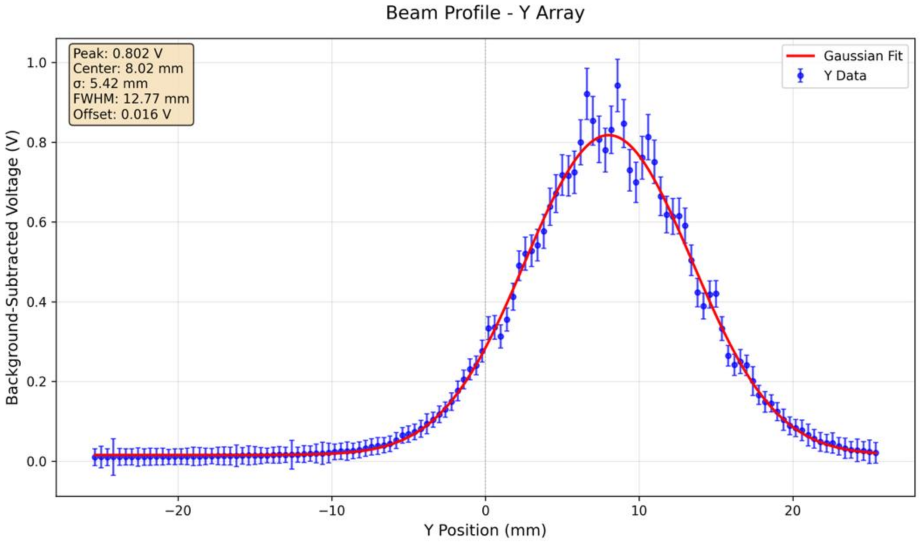
Low gain



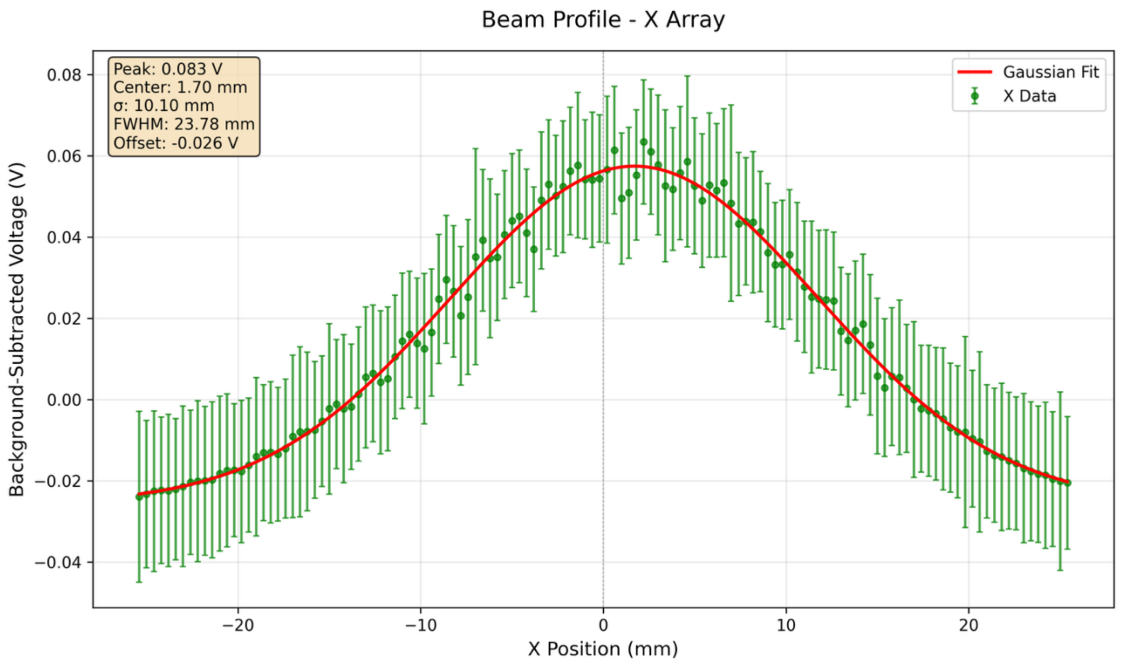


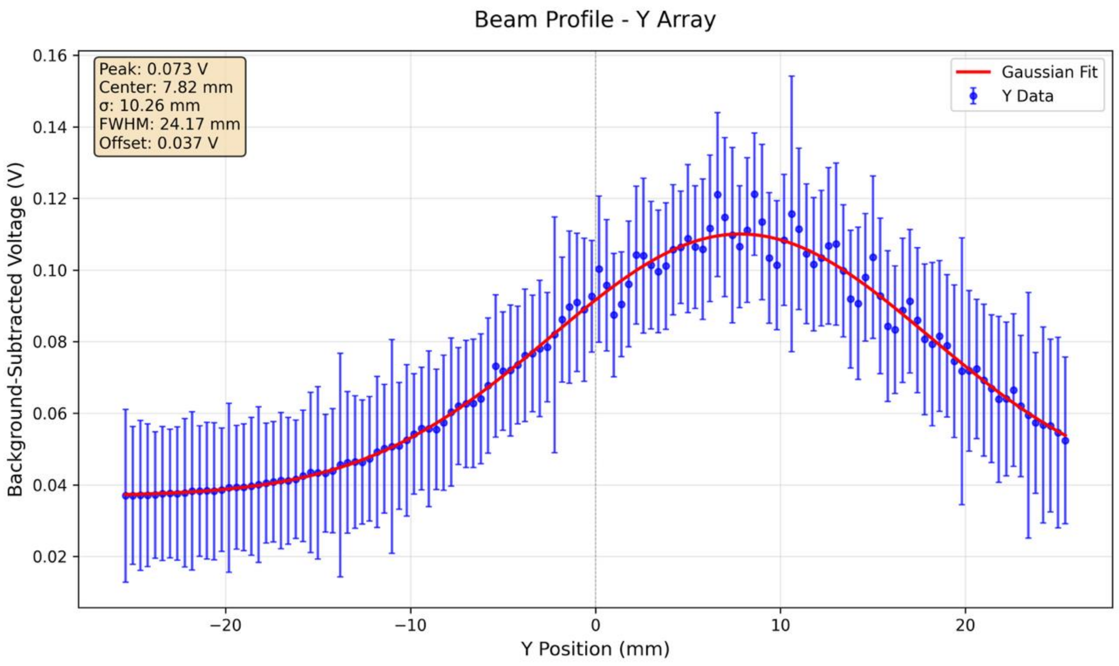
High gain



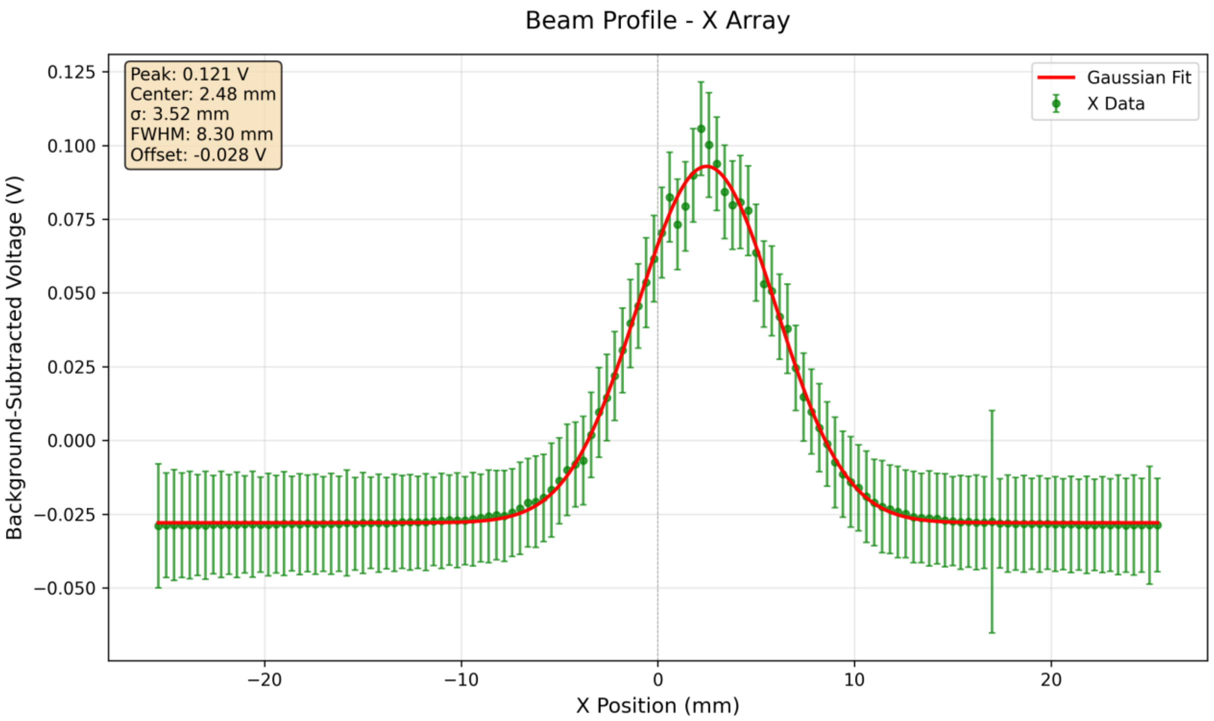


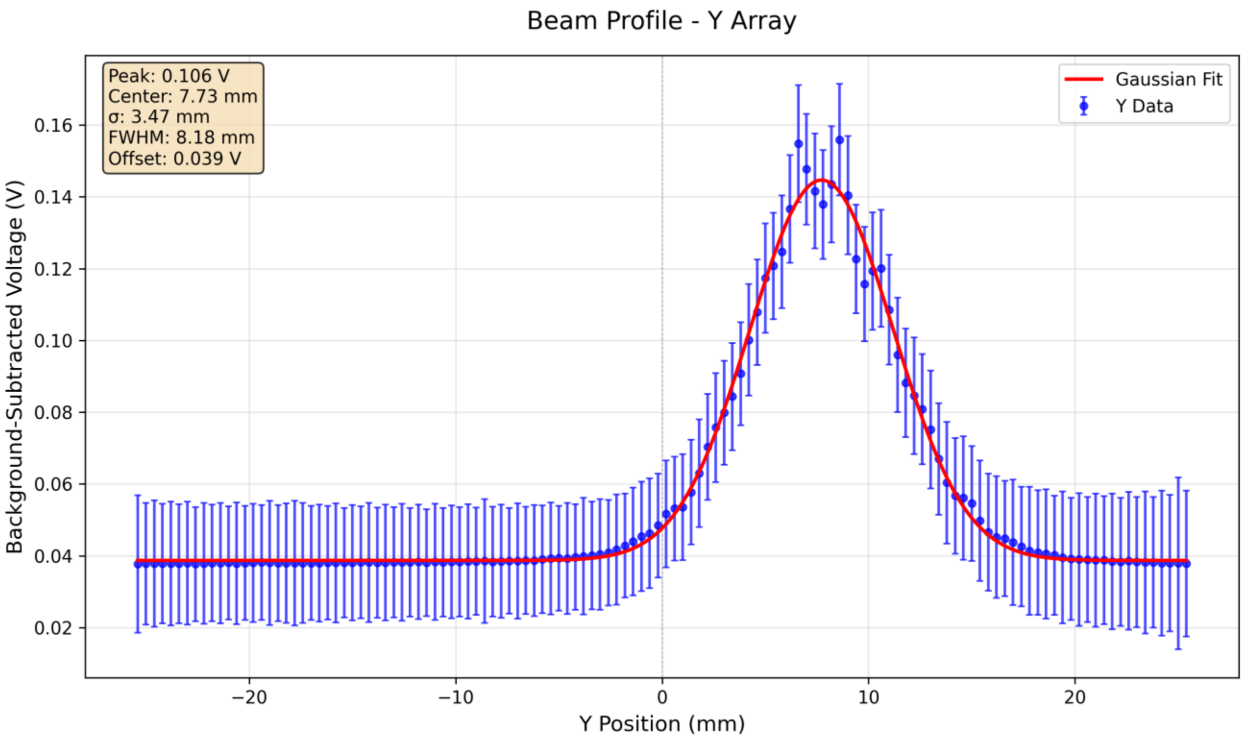
70 MeV 300 nA (max ion source current) High Gain



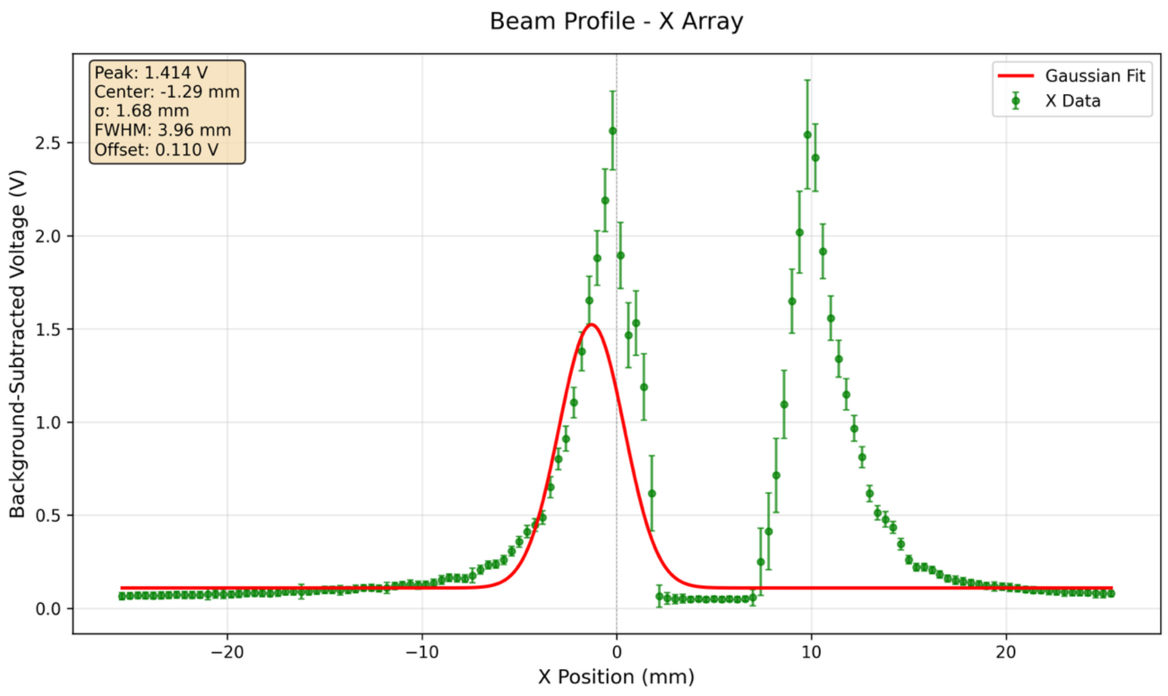


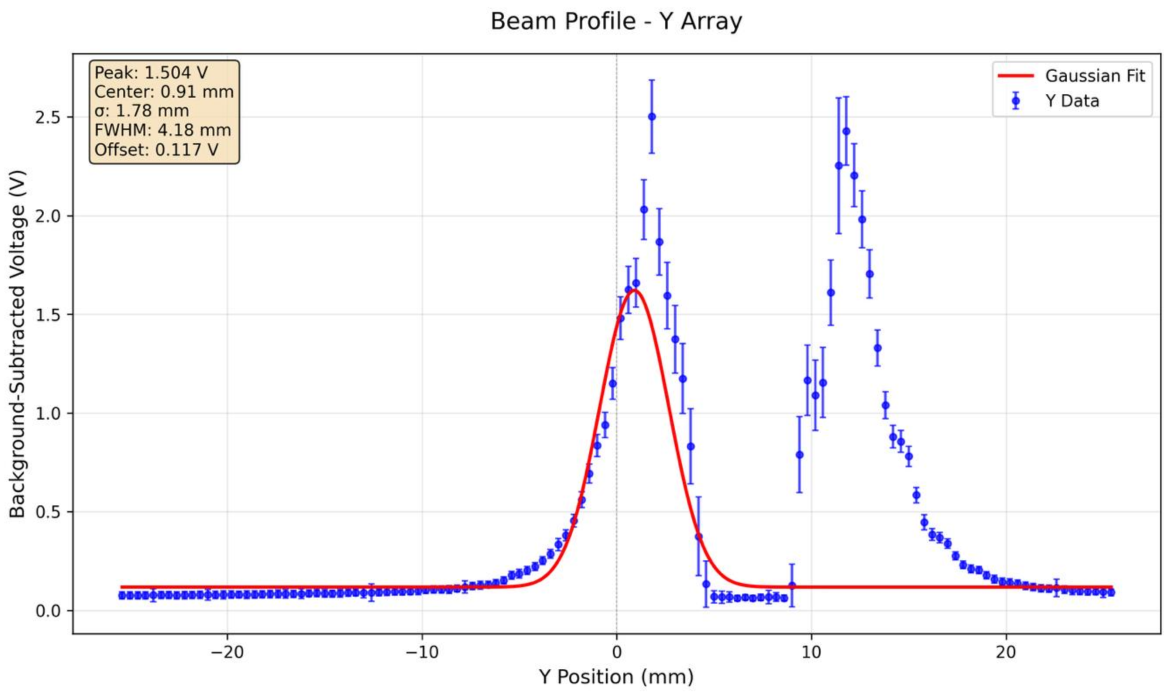
228 MeV 5 nA High Gain



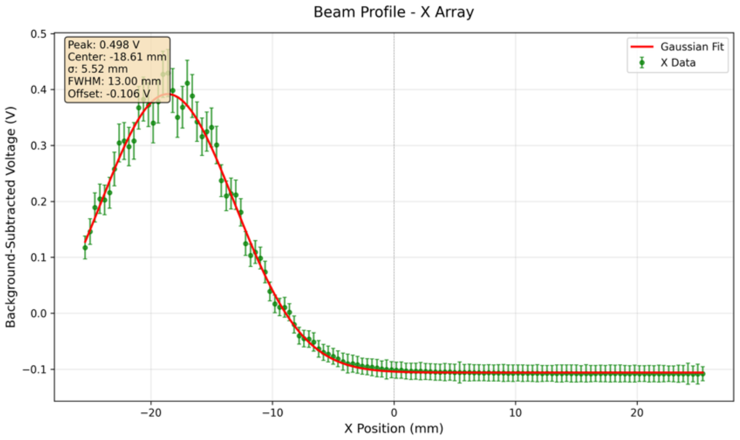


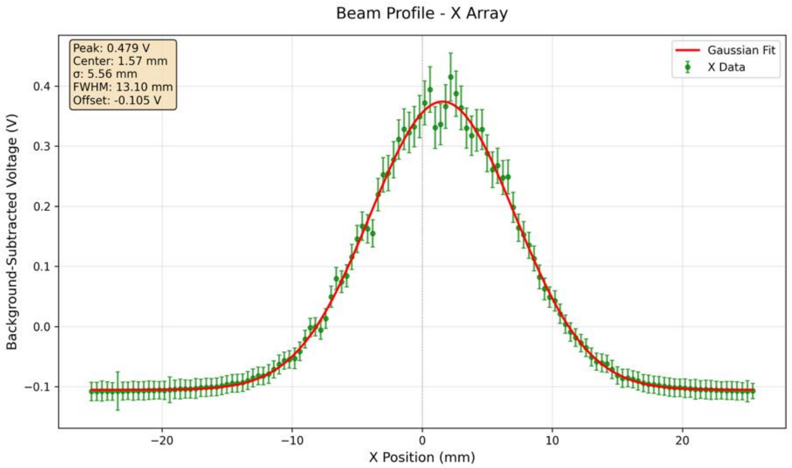
228 MeV 300 nA High Gain

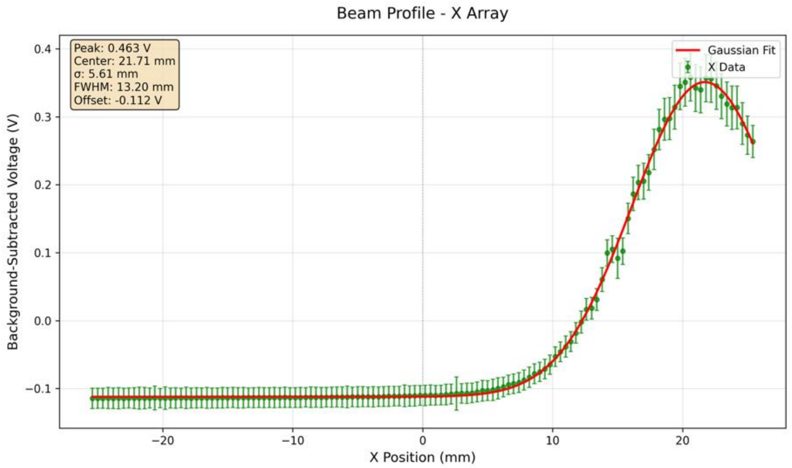


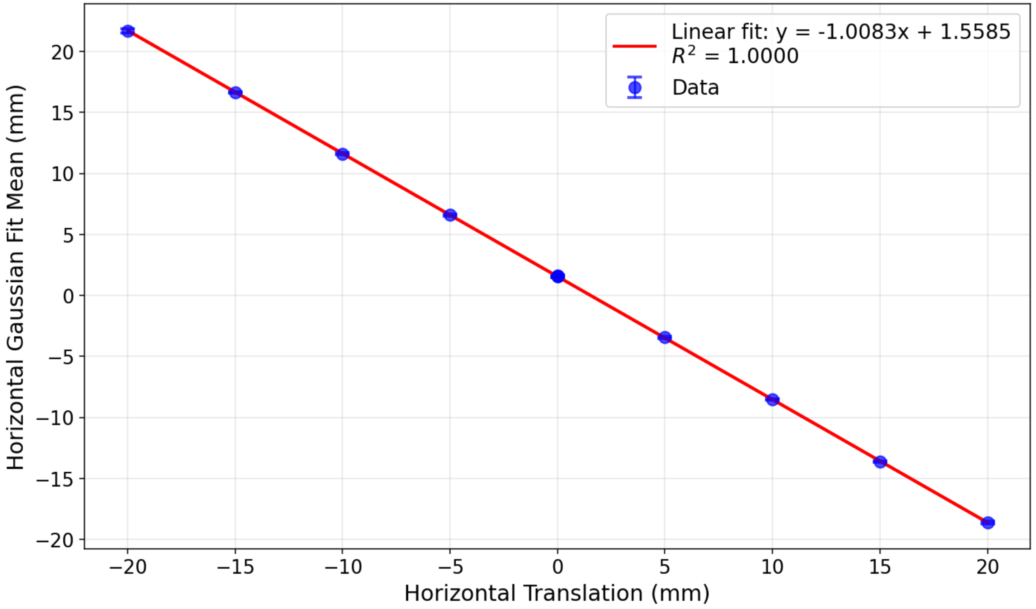


Position measurements using stage translation at 148 MeV 300 nA



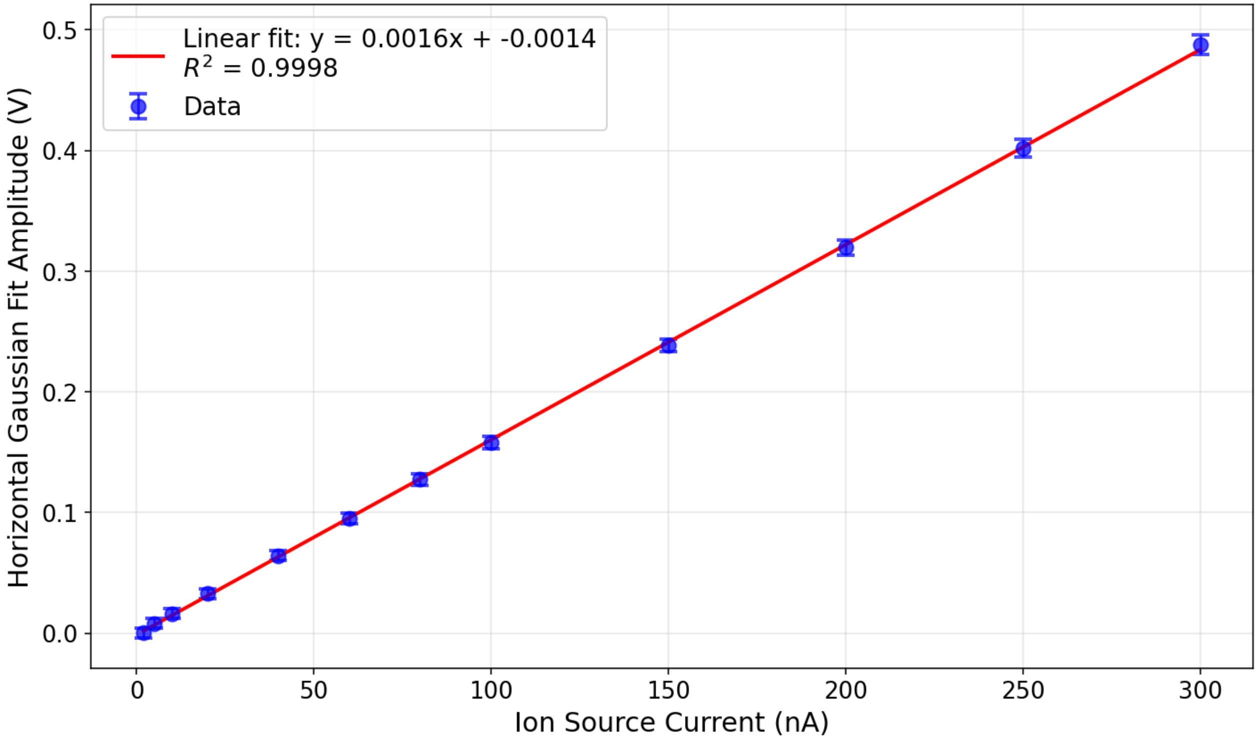




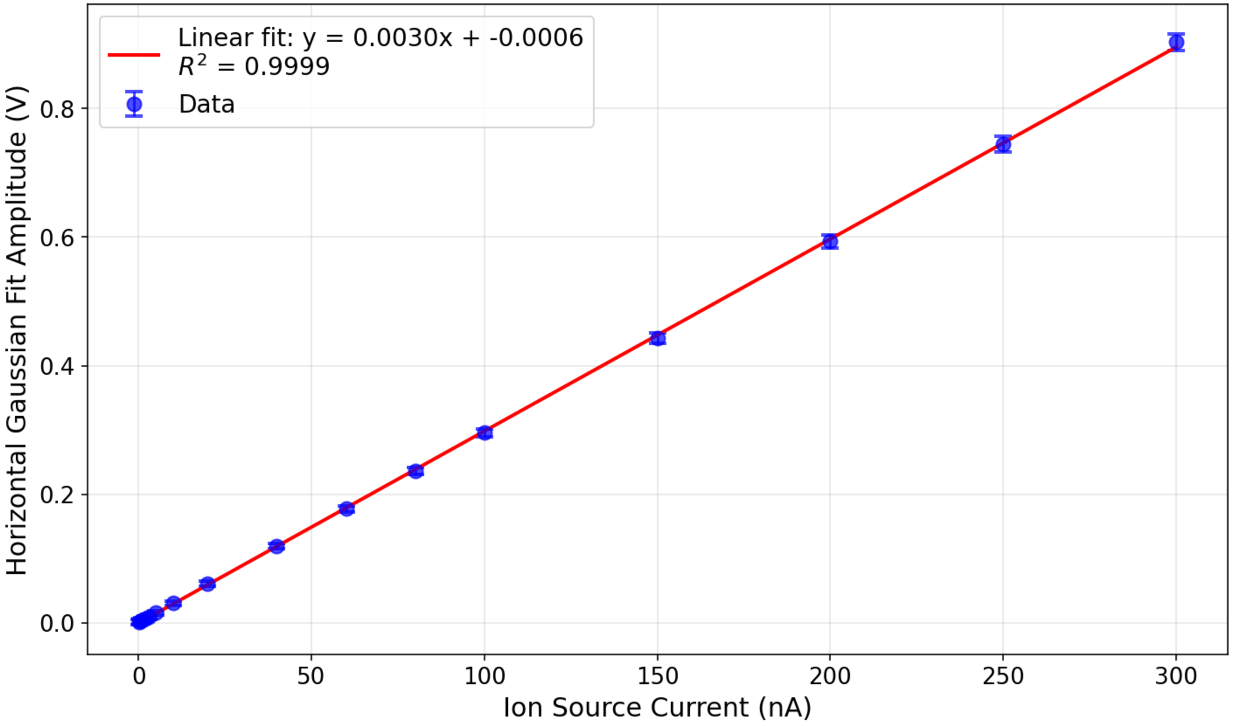


Response Linearity at 148 MeV (using Amplitude of Gaussian Fit on Horizontal Array)

Low gain

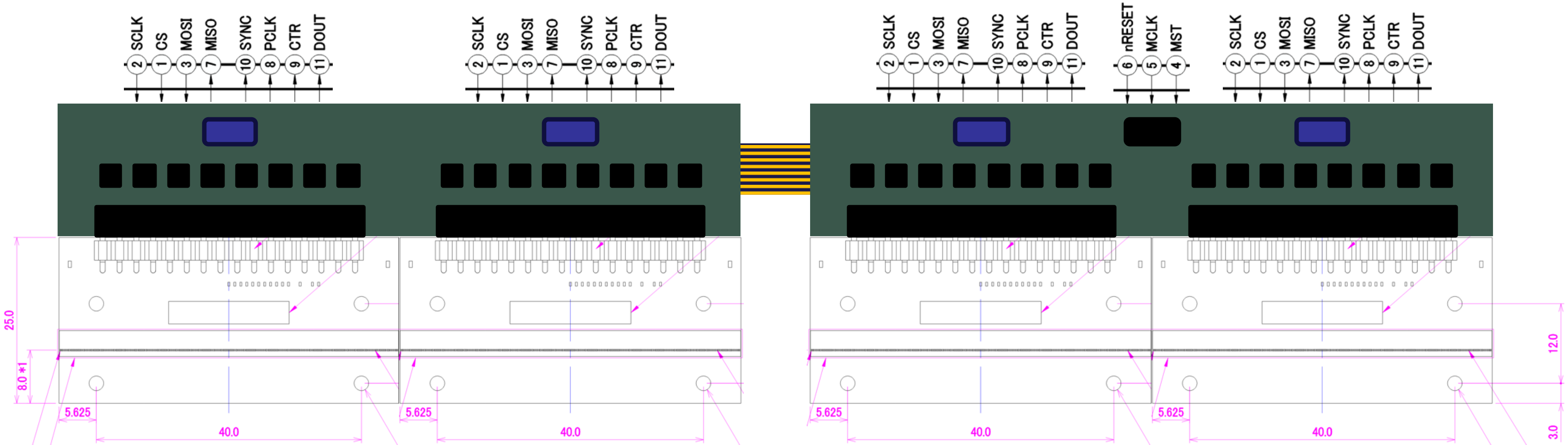


High gain

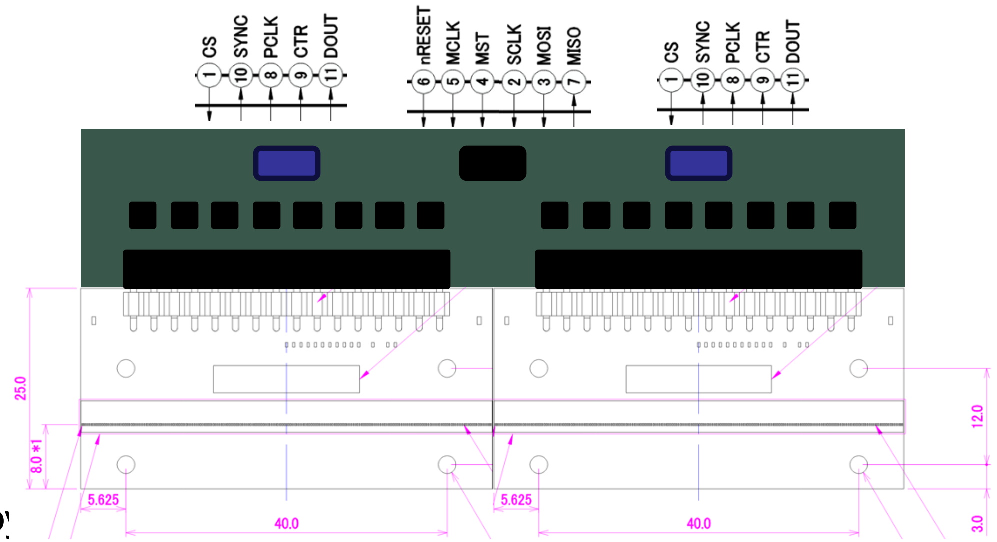


Kria SciFi Readout

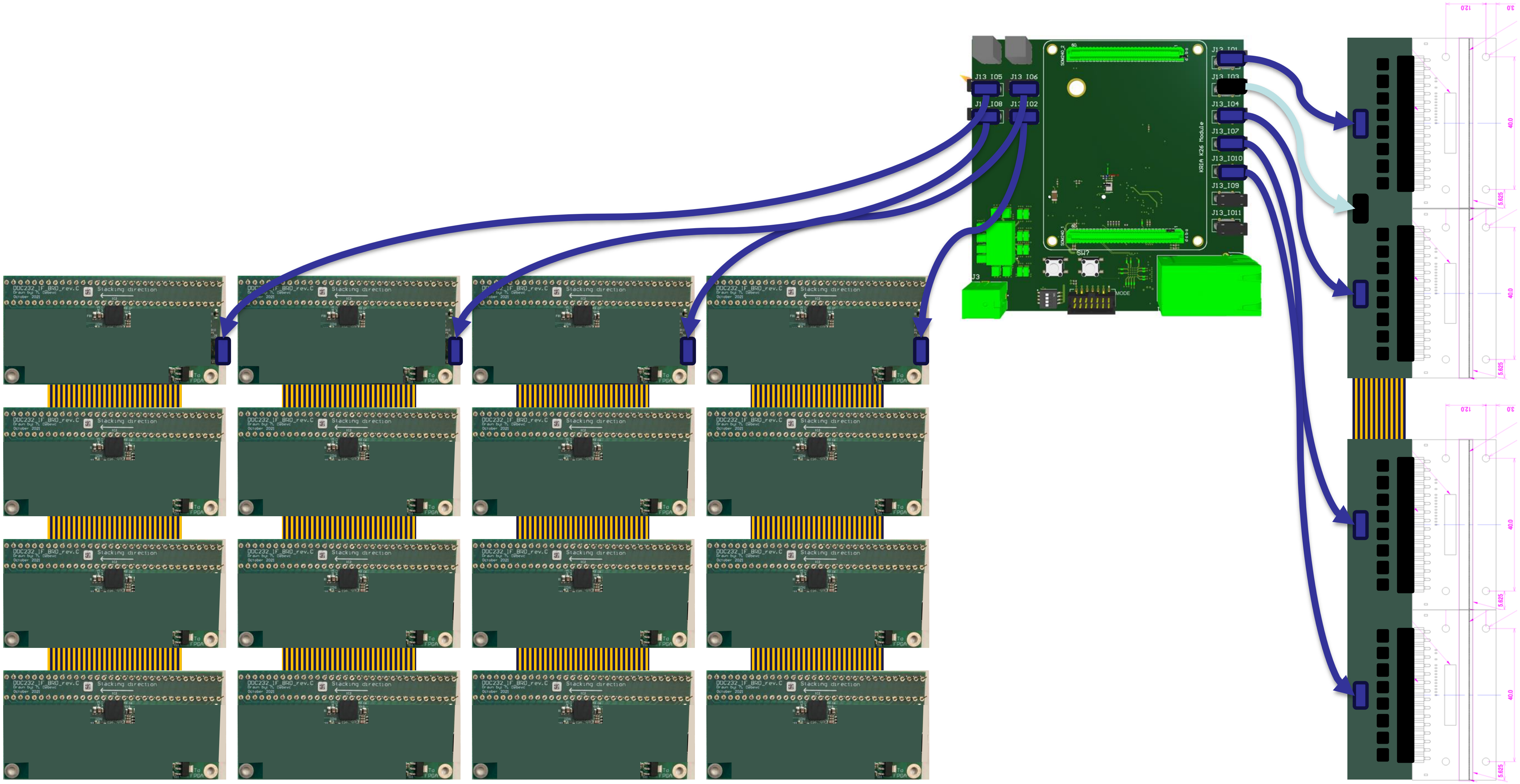
Option 1



Option 2



Kria QuADProBe Readout



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Conclusions

- Making our way towards a clinically usable QuARC:
  - Only 2 cables needed for setup.
  - Web browser interface.
  - Robust enclosure with built-in shock absorption.
  - Nozzle mount and improved electronics in the pipeline.

- R&D on QuADProBe progressing rapidly:
  - SciFi arrays installed at HIT; new fibre arrays on their way.
  - Updated electronics provides complete system integration.

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