Summary of scintillator based Quality Assurance Detector for Proton Beam Therapy

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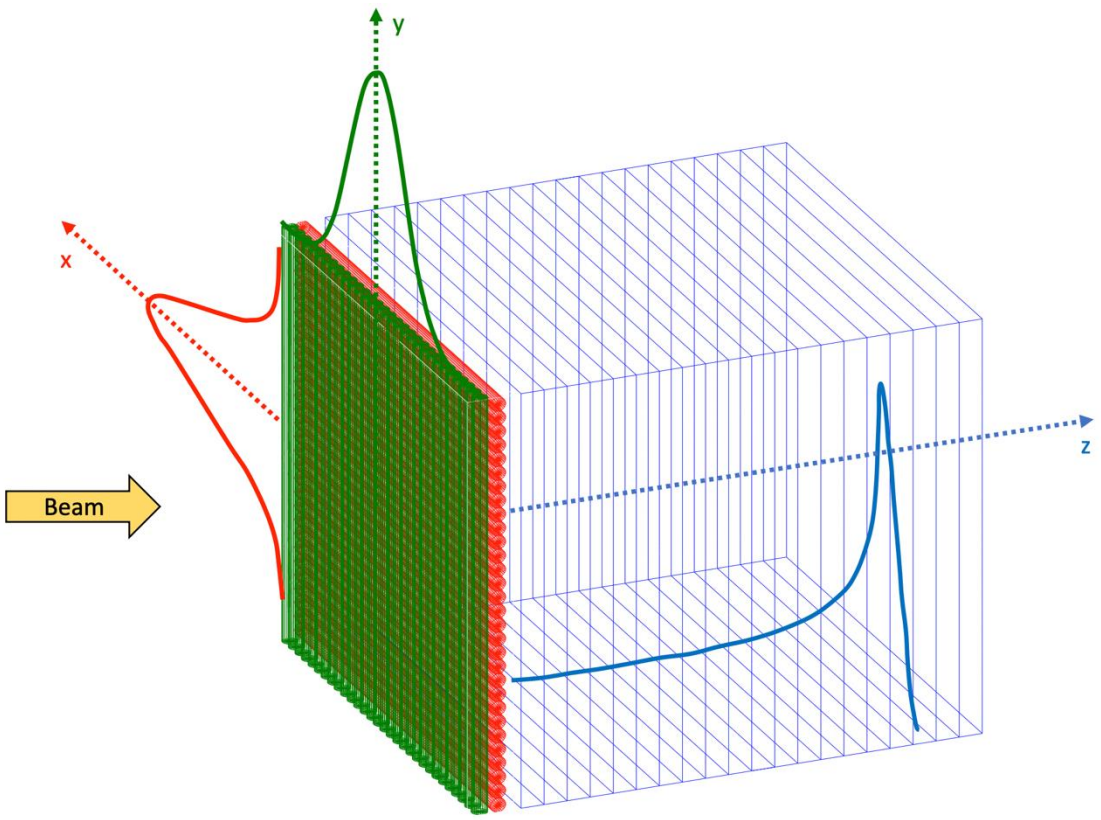
Detector Layout

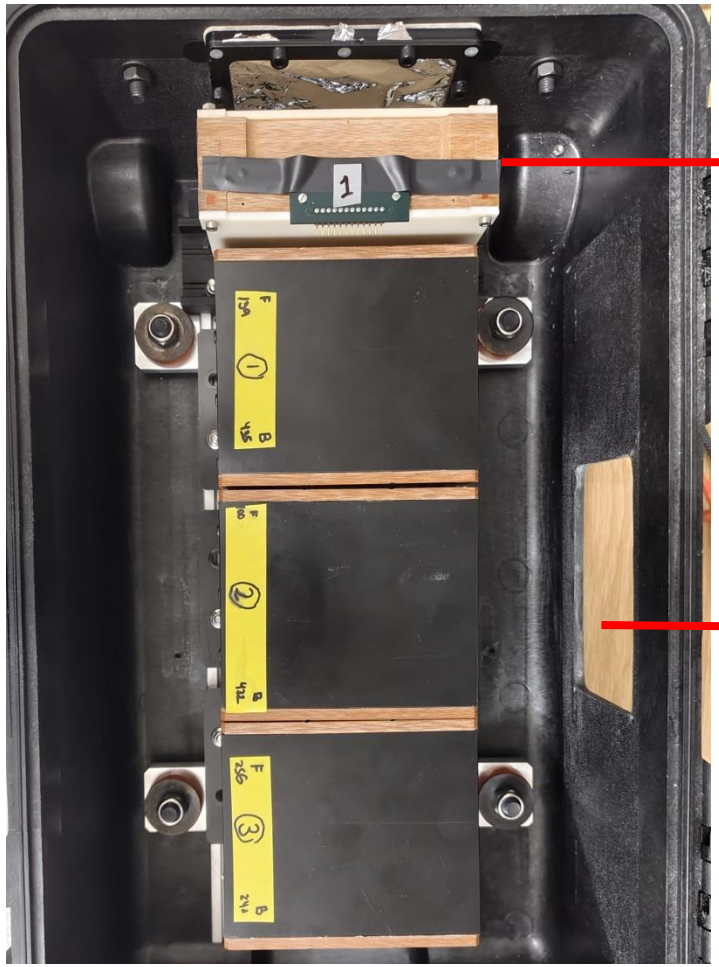
Integrated system for range, spot position and size reconstructed with single beam delivery.



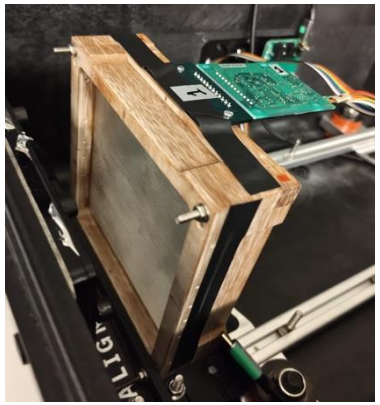
- **Quality Assurance Range Calorimeter** (QuARC) based on 10 cm×10 cm×3 mm polystyrene scintillator + Hamamatsu S12915-16R photodiode + modular ADC electronics.
  - Real-time range reconstruction: 6 kHz data-rate, 40 Hz range fitting
  - Suitable technology at FLASH rates.
  - Independent dual-sided readout to estimate horizontal beam position on Bragg peak reconstruction.
  - Developed in collaboration with UCL
- **Beam profile monitor** based on Saint-Gobain BCF-60 scintillating fibers: diameter 0.50 mm, 10 cm×10 cm array active window + Hamamatsu S13865 128-photodiodes array. Analog multiplexed output signal at up to 4 MHz.
  - Data acquisition currently based on Multifunction I/O (slow data saving and transfer).
  - Developed at INFN-Bari
- **Integrated system** tested for the first time in 2025 at Trento with clinical proton beams (**NEW**)

Detector Layout

Integrated system for range, spot position and size reconstructed with single beam delivery.



Scintillating Fibre (SciFi) Profile Monitor



Quality Assurance Range Calorimeter

Relevant Experimental Measurement Campaigns

- **Quality Assurance Range Calorimeter**
  - 2022 tested at The Christie NHS. A Varian Cyclotron provides 245 MeV beam with an instantaneous FLASH dose rate of up to 112.7 Gy/s and nozzle current of up to 56.4 nA.
    - Preliminary FLASH performance published in 2025 on Frontiers in Oncology : https://doi.org/10.3389/fonc.2025.1622231
  - 2022 tested at PARTREC UMCG in Groningen for FLASH range QA measurements.
  - Other test campaigns for pristine Bragg peak and SOBP measurements.

- **SciFi beam profile monitor**
  - 2024 tested at @LinearBeam with experimental linear proton beam

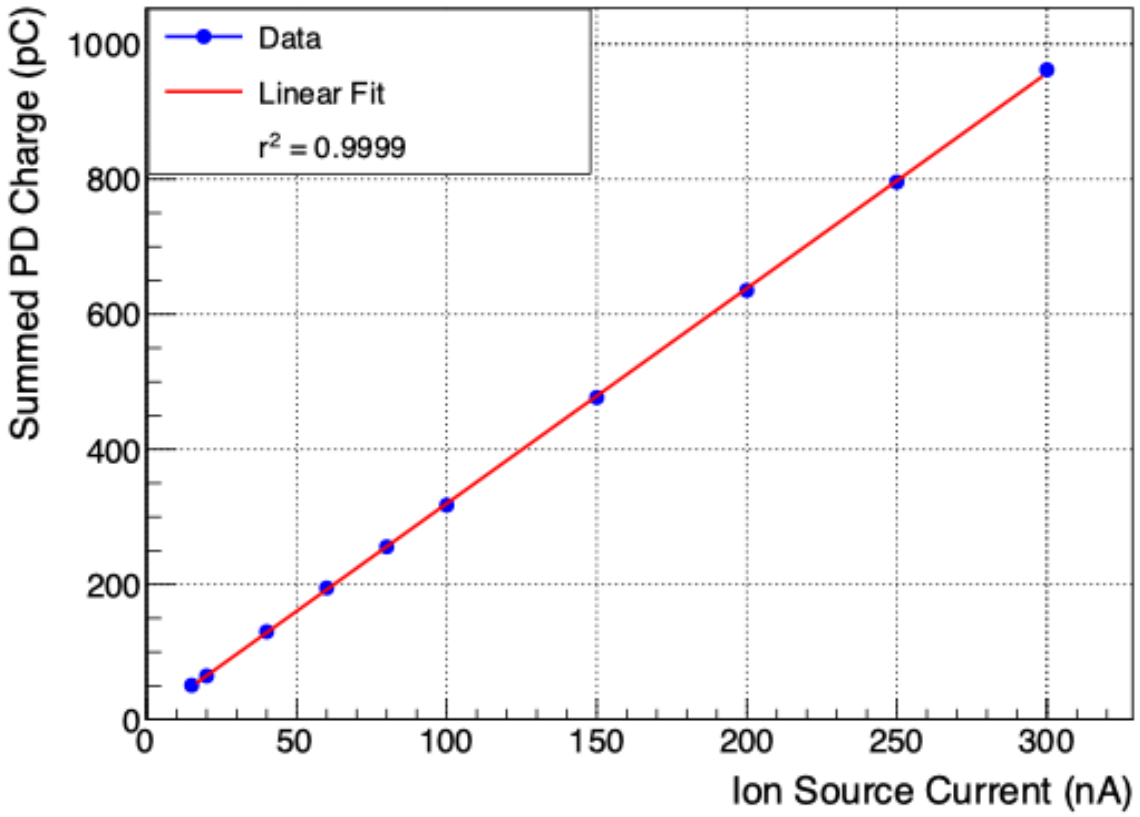
- **Integrated system**
  - 2025 tested for the first time at Trento with clinical proton beams (**NEW**)
  - Measurements involved:
    - Response linearity to ion source current and nozzle current.
    - Beam range, size, position measuremed at various energies and currents.
    - Beam position measurements (using horizontal translation stage to move the detector between -20 mm - +20 mm in 5 mm intervals).

- Full list of experimental runs: https://www.hep.ucl.ac.uk/pbt/wiki/Proton_Calorimetry/Experimental_Runs

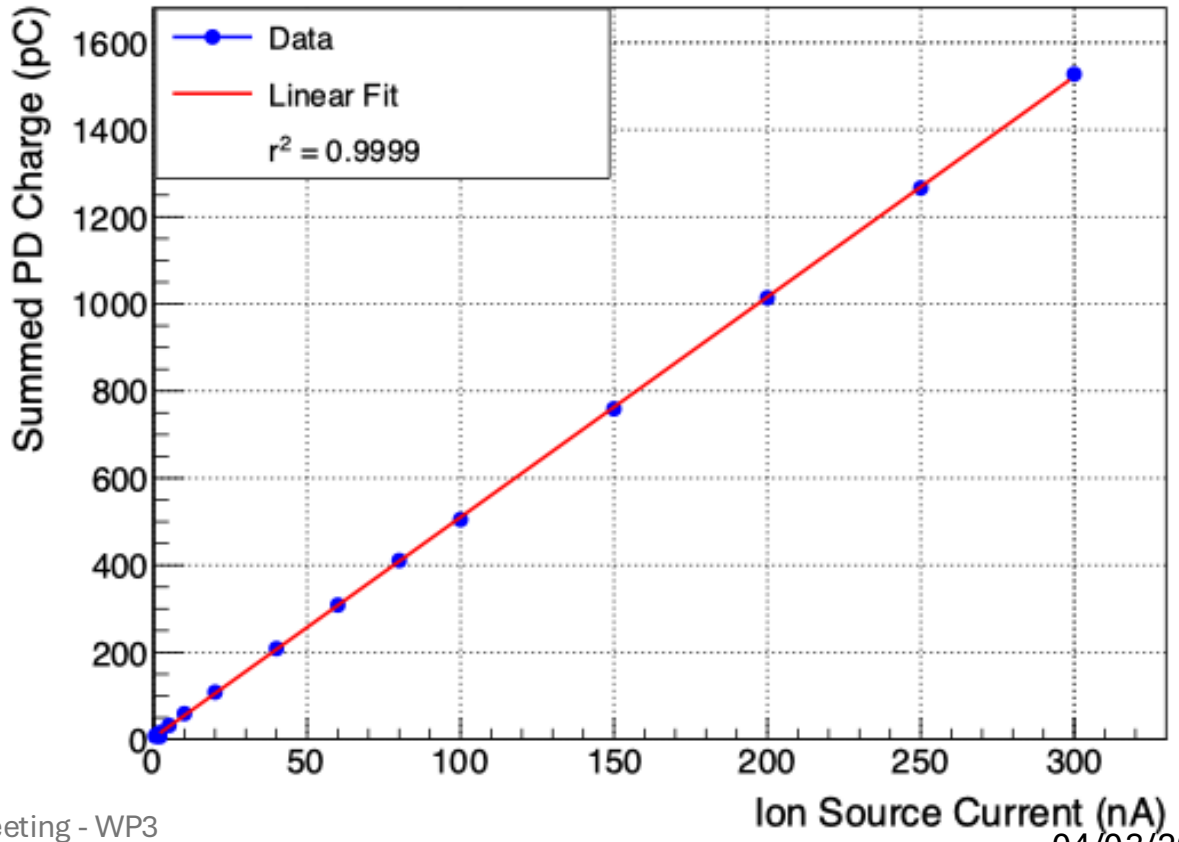
QuARC Response Linearity

Response linearity of entire QuARC detector by summing the average PD values across the measurement time to ion source current

179 MeV



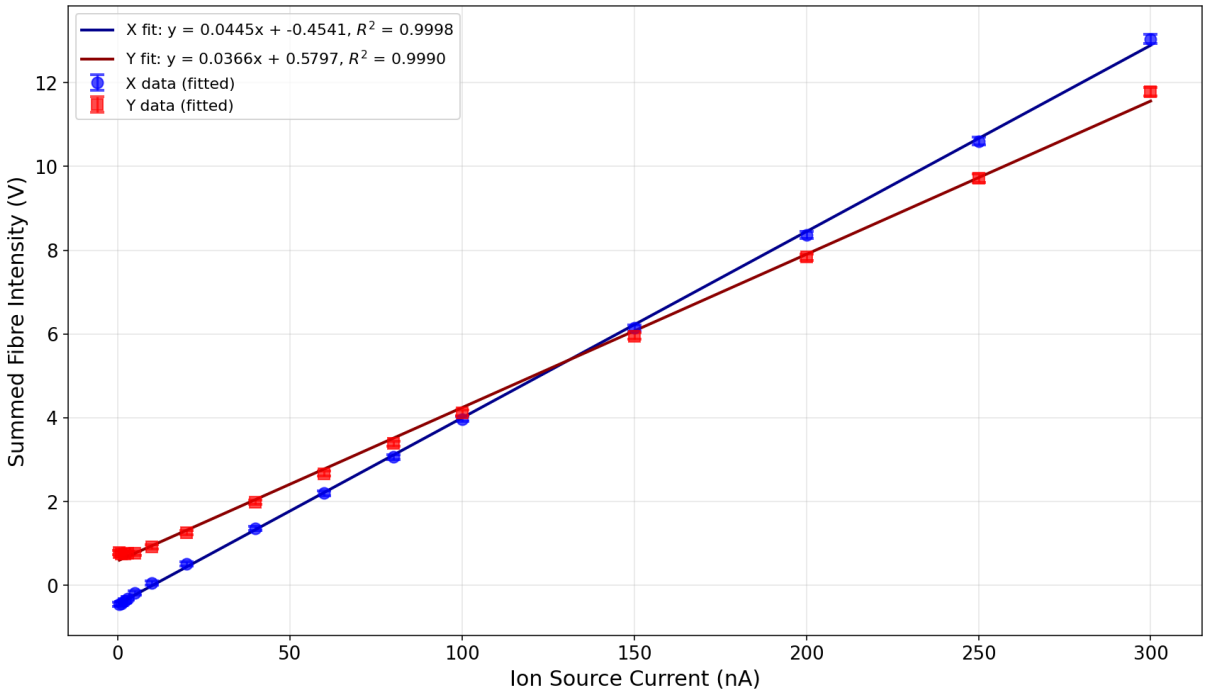
148 MeV



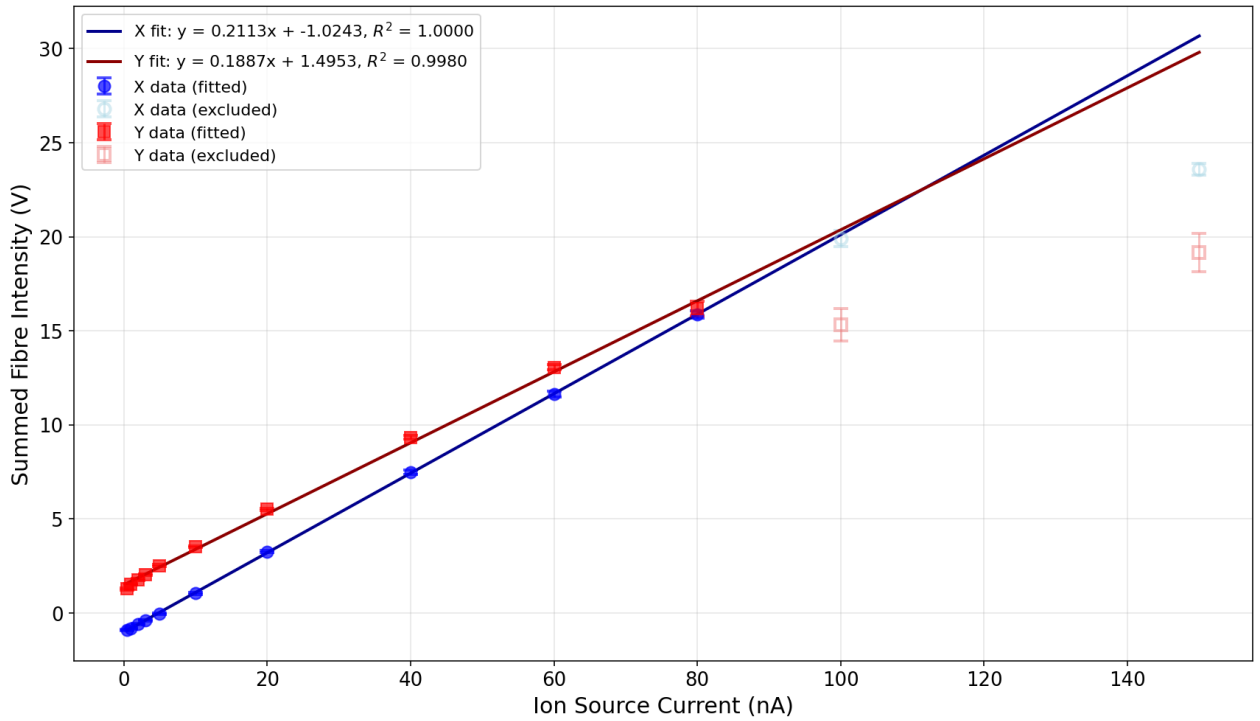
SciFi Response Linearity

Fibre array response to ion source current – demonstrates excellent linearity for entire current range for 148 MeV and in unsaturated region (up to ~80 – 100 nA) for 228 MeV. Error bars represent the mean fluctuation of the pixel value across each measurement.

148 MeV

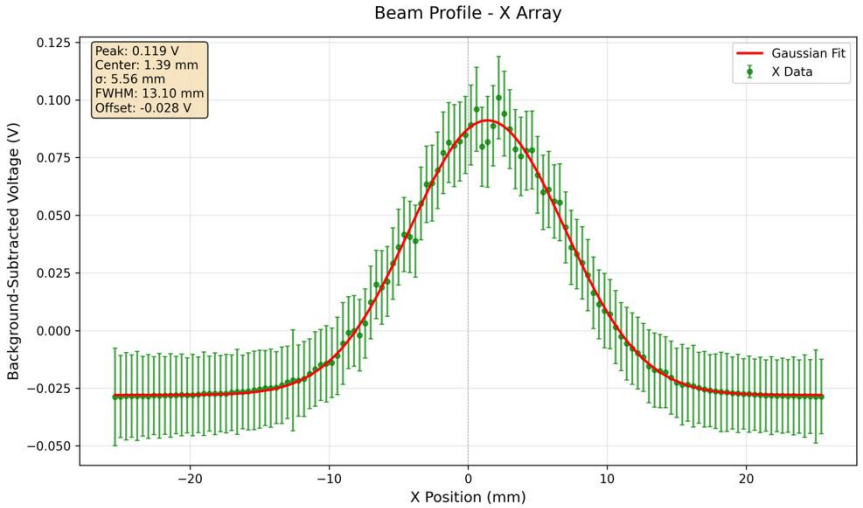


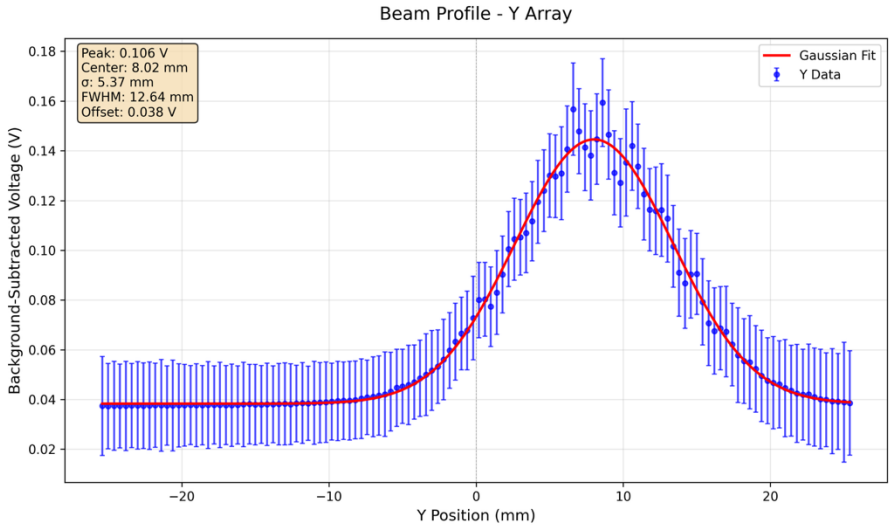
228 MeV



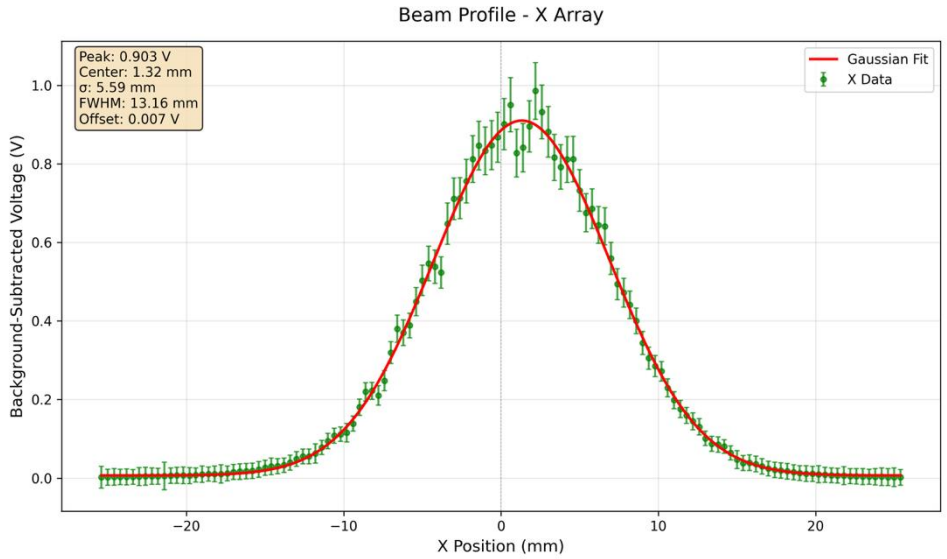
SciFi Beam profile reconstruction 148 MeV

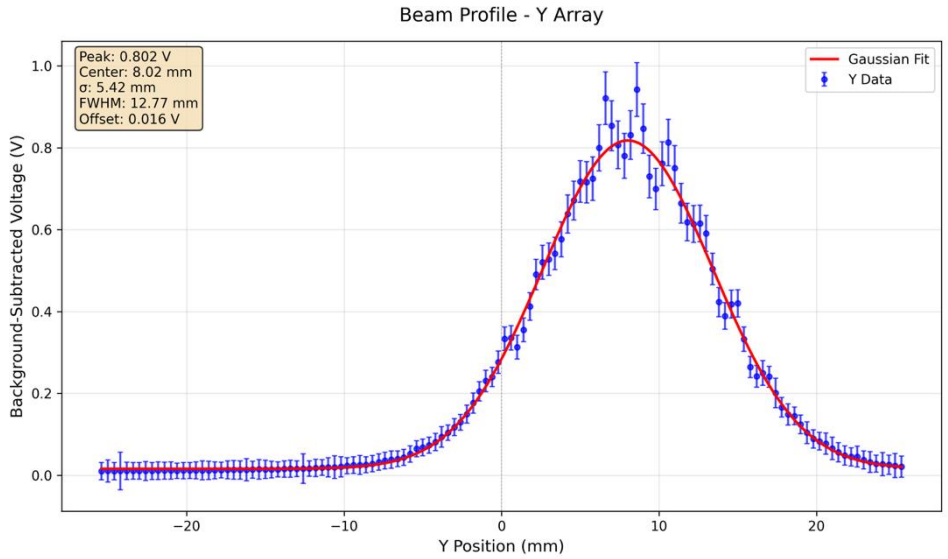
40 nA





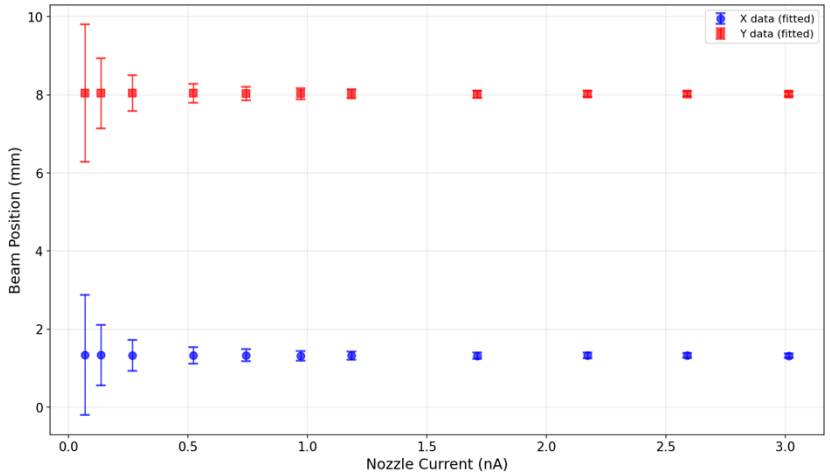
300 nA

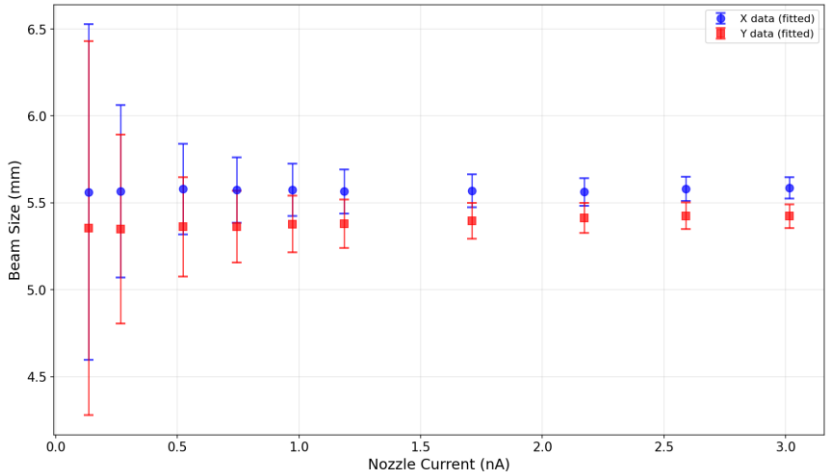




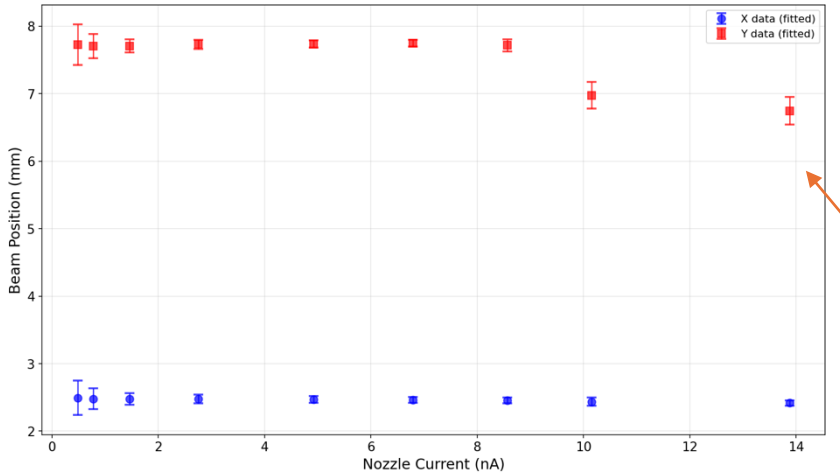
Beam Position and Size Stability

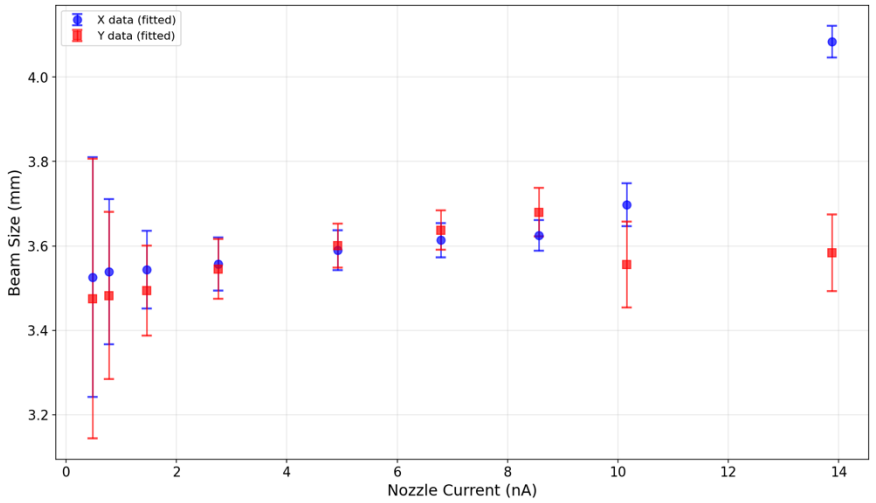
148 MeV





228 MeV



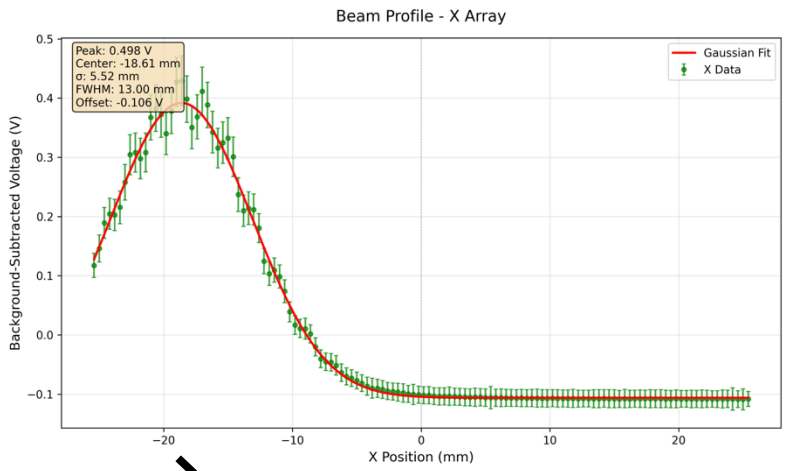


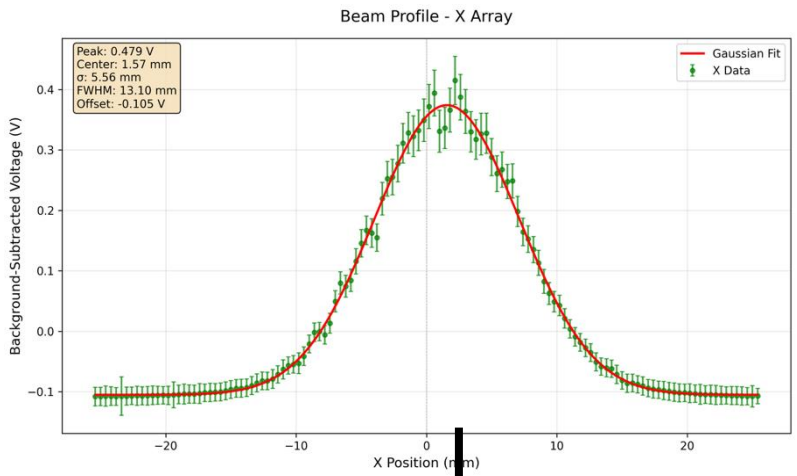
Saturation in the profile measurement

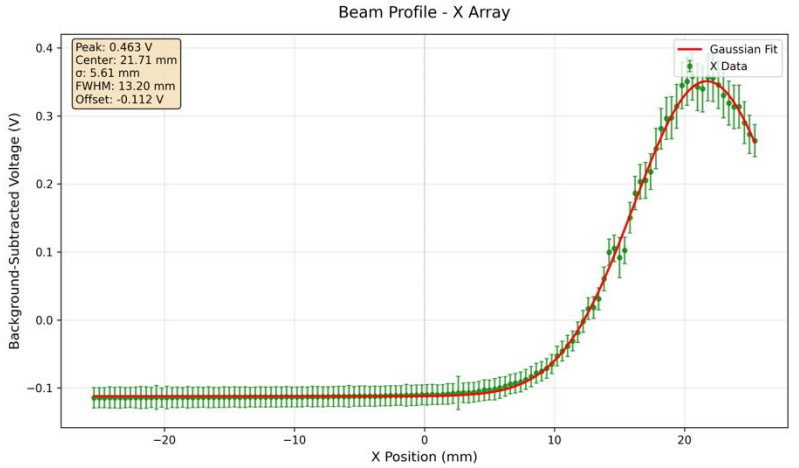
Beam position/size determined from the mean (μ_x , μ_y) / standard deviation (σ_x , σ_y) of the Gaussian fit applied to the beam profile measurement. The error bars represent the uncertainty of the fit. Estimated size in close agreement with that calculated from 1D Gaussian profile projection from radiochromic film reference measurements

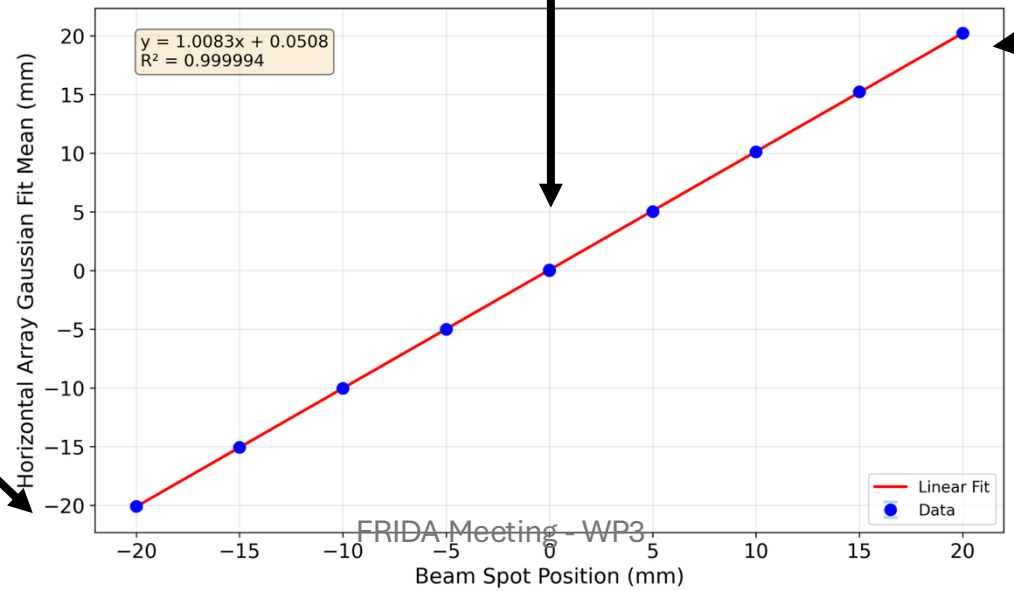
SciFi Position Response

Response of the Fibre Array at different horizontal positions using the translating stage between +/- 20 mm

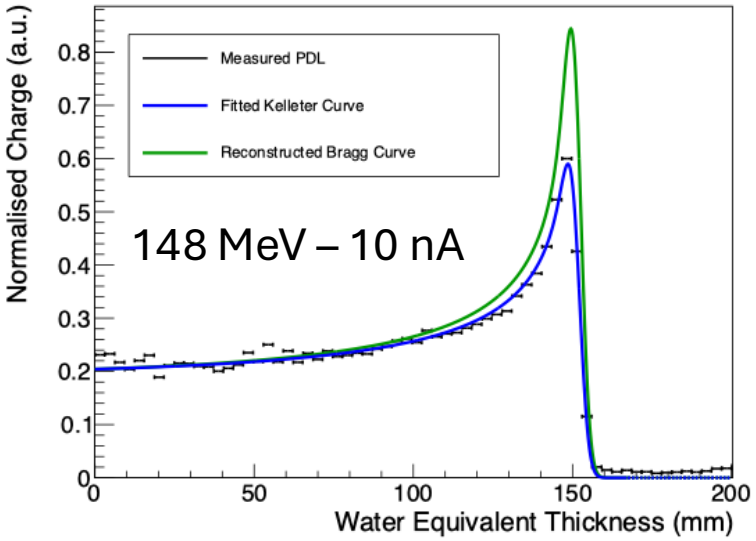




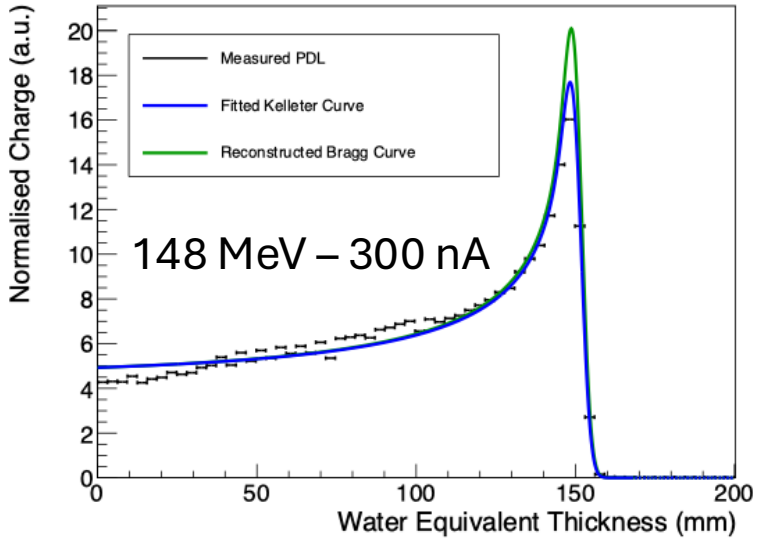




Range Measurements

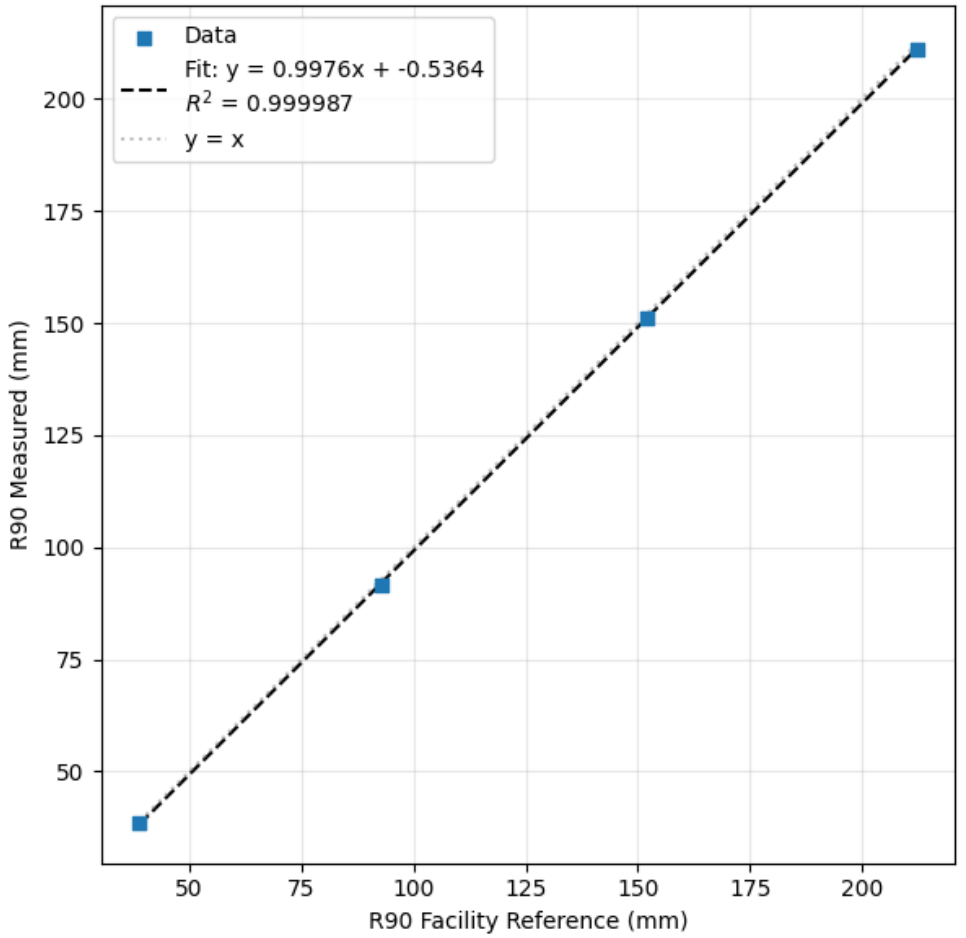


Energy: 146.99 MeV
R90 (distal 90%): 150.94 mm
R80 (distal 80%): 151.58 mm
Delta R80 (distal - proximal): 5.31 mm
Peak-to-Plateau ratio: 4.12



Energy: 146.59 MeV
R90 (distal 90%): 150.21 mm
R80 (distal 80%): 150.87 mm
Delta R80 (distal - proximal): 5.49 mm
Peak-to-Plateau ratio: 4.06

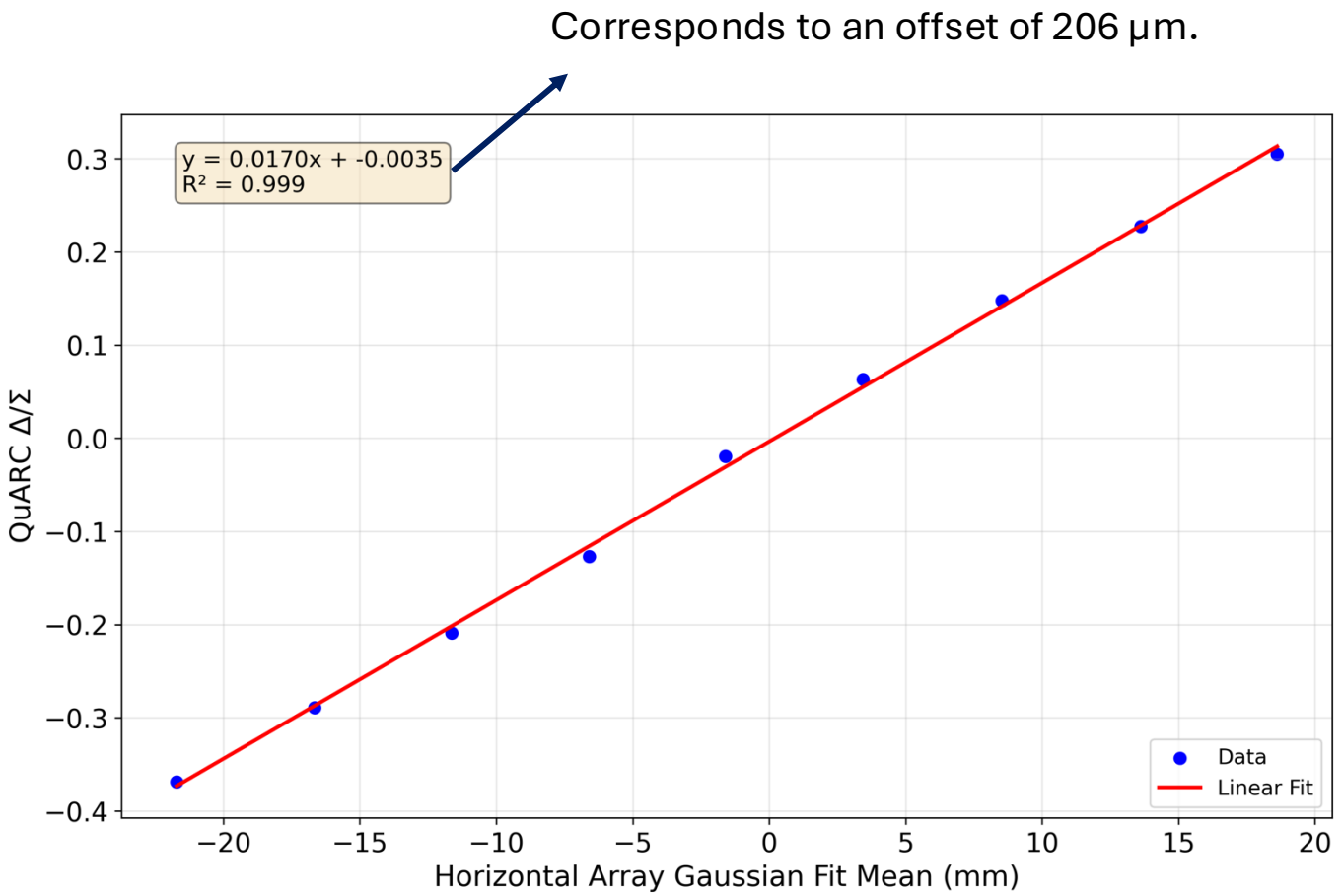
Comparing the R90 values from the QuARC measurements (using the R90 of the reconstructed Bortfeld curve), to the reference effective R90 values at isocentre provided by TIFPA.



QuARC + Fibre Position Measurements

- Possible to obtain relative horizontal position measurement from QuARC due to dual-sided photodiode read out.

- Mean of $^{\Delta}/_{\Sigma}$ of the each of the photodiode pairs per scintillator sheet calculated for horizontal position scan and correlated with μ calculated from horizontal fibre array.



Conclusions

- Fibre array beam size measurements agree with film measurements
  - Also investigating why there is large fluctuations across each run which cause the large error bars.
- Fibre beam position measurements match horizontal stage translation and both fibre array and QuARC position measurements correlate well.
- QuARC range measurements (R90) in close agreement with reference R90 values.
- Both QuARC and fibre array showed excellent linearity with ion source current (R^2>0.999) but less linear with nozzle current (measured by beam monitor).

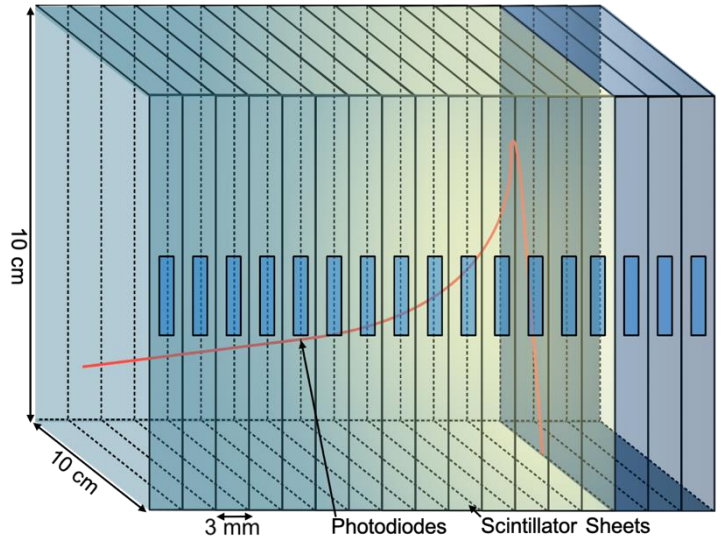
Next Steps

- Integrated FPGA-based DAQ for both range calorimeter and SciFi modules
- New digital readout for SciFi module to extend the electronics dynamic range, improve saturation limits and test linearity at FLASH rates.
- New module with squared 0.25 mm fibers

SPARE

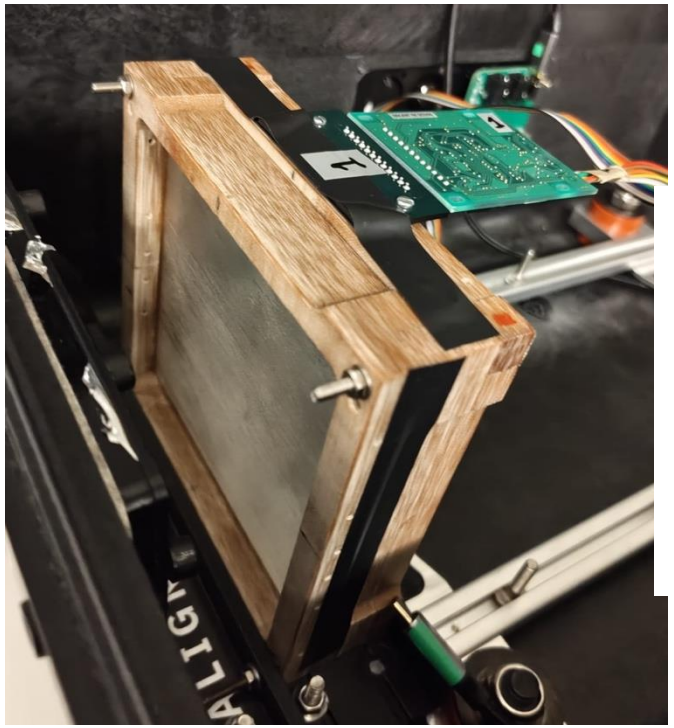
QuARC

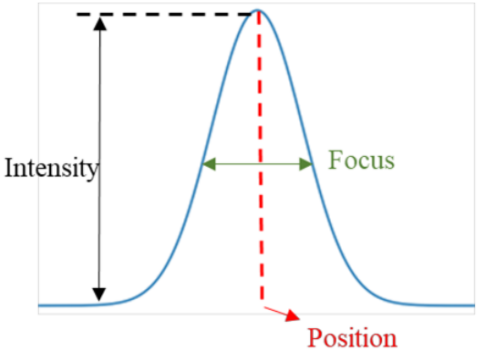
- The Quality Assurance Range Calorimeter (QuARC) constructed from plastic scintillator sheets:
  - Protons intercepted by a series of optically-isolated polystyrene scintillator sheets.
    - 4 modules – 32 sheets per module.
  - Light output measured with photodiodes.
    - 2 photodiodes coupled to each sheet.
  - Light output of each sheet nonlinear to dose, quenching described by Birks' Law:
    - Data fitted with analytical depth-light model (*Kelleter Fit*).
    - Reconstruct Bragg depth-dose curve (*Bortfeld Fit*) 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.



SciFi Profile Monitor

- The Scintillating Fibre (SciFi) Array monitor constructed from two orthogonal arrays of plastic scintillating fibres:





- 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-photodiode array (Hamamatsu S13865), 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
- FPGA high period of RESET clock (reset) = 50 us, low period (integration) 950 us – overall 1 ms for measurement.

2025 Trento Experiment Overview

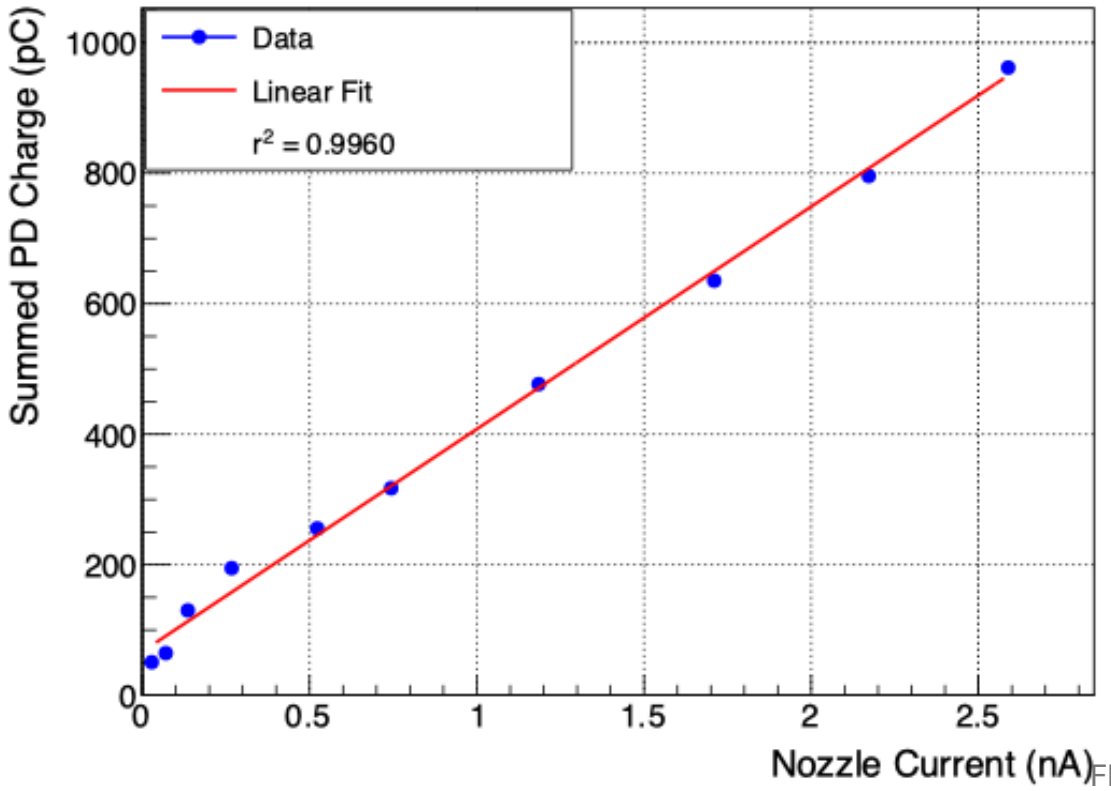
- 3 nights of measurements at TIFPA with detector installed on biology beam line to enable both FLASH and CONV:
  - Night 1: QuARC
    - Calibrations and Bragg Peak measurements
    - A couple FLASH measurements
  - Night 2: Combined QuARC + SciFi:
    - Dynamic range testing (fibres at low gain)
    - Beam position measurements
  - Night 3: SciFi Measurements
    - Dynamic range testing (fibres at low gain)
    - Different spot sizes (varying energy)
- Detailed experiment itinerary can be found here: https://www.hep.ucl.ac.uk/pbt/wiki/Proton_Calorimetry/Experimental_Runs/2025/Trento_2025-09

QuARC Response Linearity

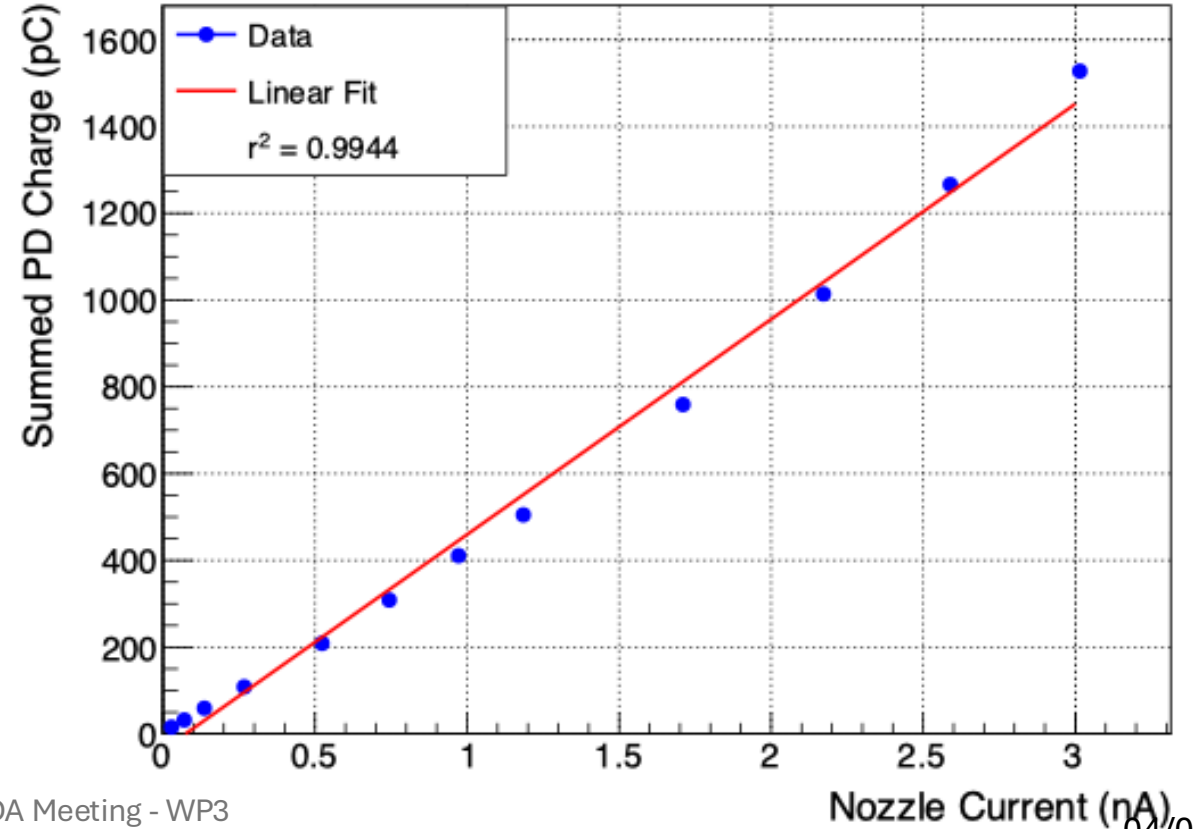
Response linearity of entire QuARC detector by summing the average PD values across the measurement time to nozzle current (calculated using beam monitor measured proton counts and times).

QuARC response appears to be less linear with nozzle current than with ion source current.

179 MeV



148 MeV

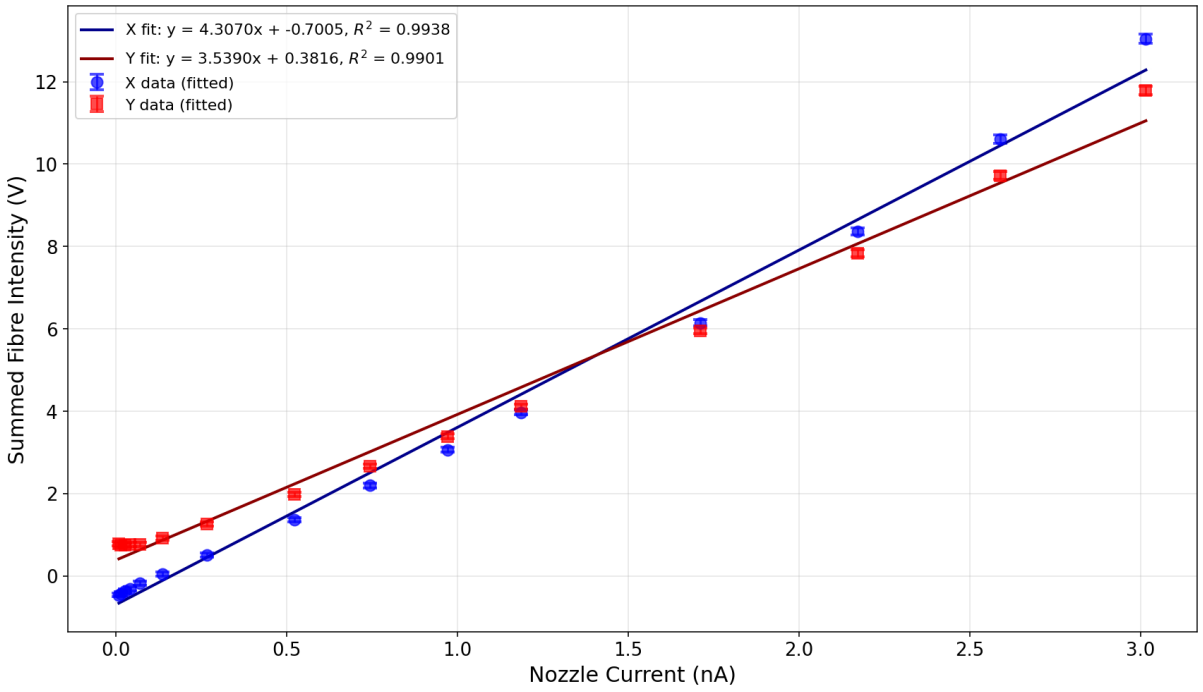


SciFi Response Linearity

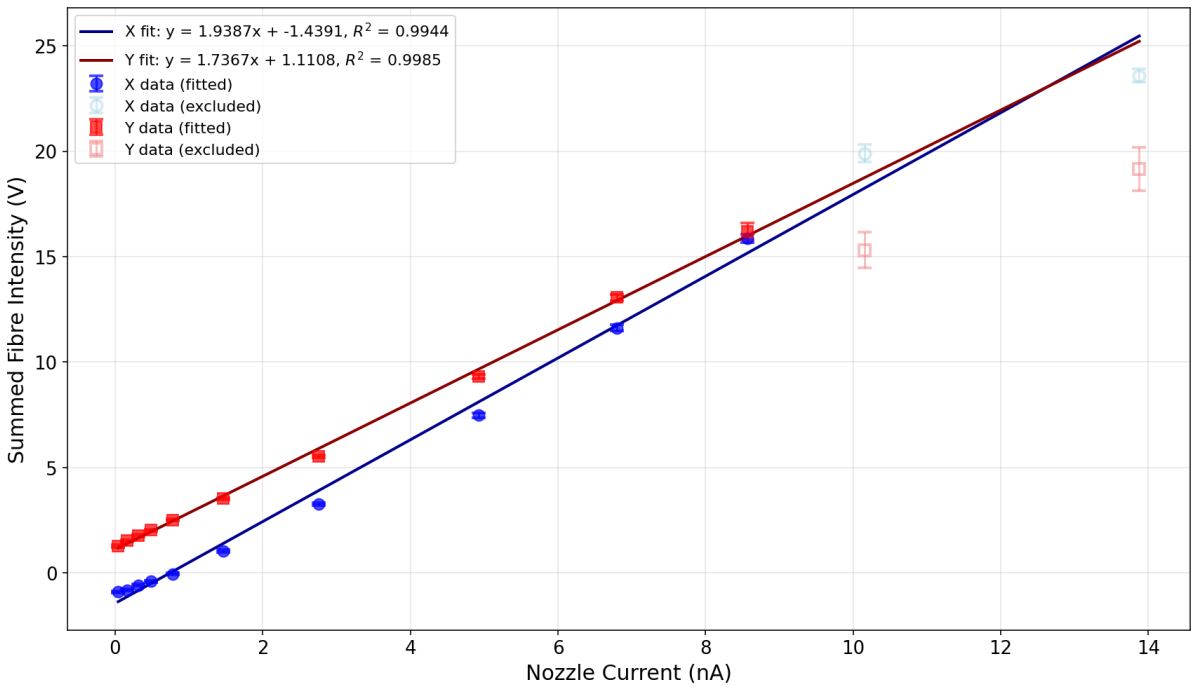
Fibre array response to nozzle current (calculated using beam monitor measured proton counts and times).

Fibre array response also appears to be less linear with nozzle current than with ion source current.

148 MeV



228 MeV

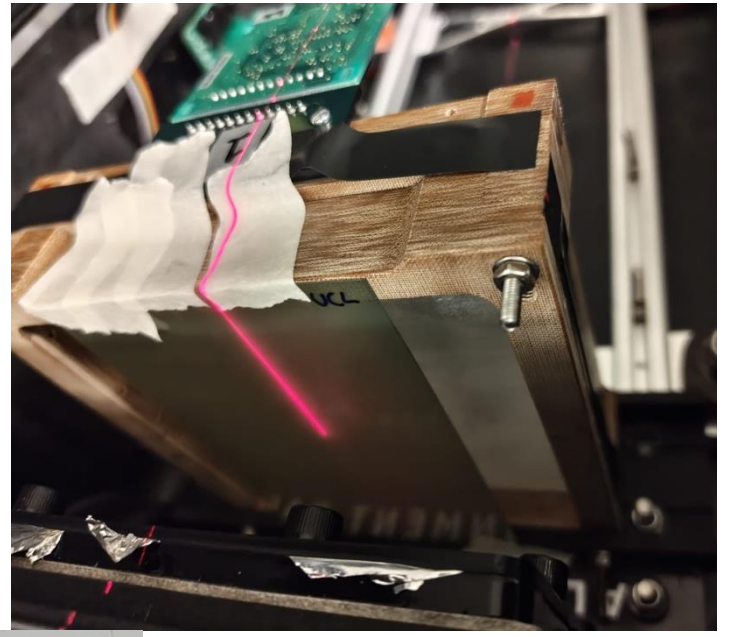


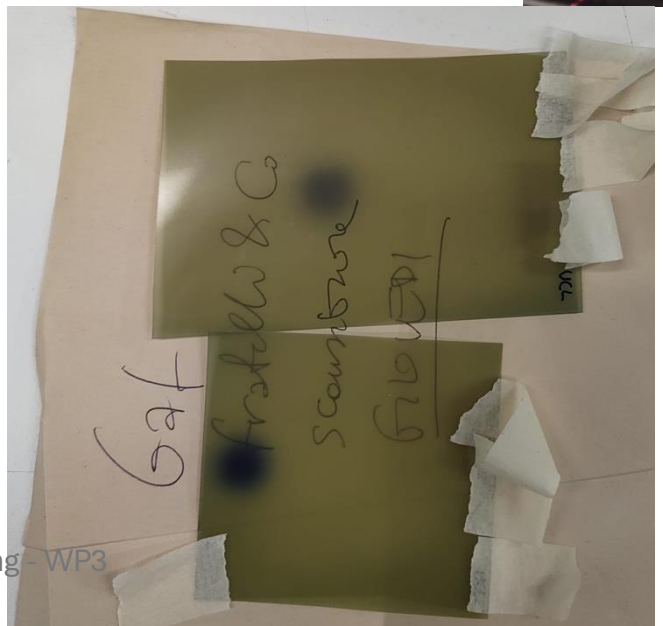
SciFi and Film Beam Profile Comparison

- 2 measurements performed at end of night 3 to compare beam size measured on radiochromic film to that by the fibre arrays, since the fibre array measurements were systematically larger than the reference beam sizes at isocentre.

- Radiochromic film attached directly in front of first fibre array (Y array).

- Measurements at 228 MeV and 148 MeV.





148 MeV Gaussian Fit Parameters

	Fibre Array	Film 2D Gaussian	Film 1D Gaussian Slice	Film 1D Gaussian Projection	TIFPA Reference
σ_x (mm)	5.538 ± 0.938	5.491 ± 0.001	5.423 ± 0.012	5.588 ± 0.011	4.516
σ_y (mm)	5.339 ± 1.062	5.353 ± 0.001	5.198 ± 0.012	5.399 ± 0.019	4.514

228 MeV Gaussian Fit Parameters

	Fibre Array	Film 2D Gaussian	Film 1D Gaussian Slice	Film 1D Gaussian Projection	TIFPA Reference
σ_x (mm)	3.502 ± 0.117	3.396 ± 0.001	3.338 ± 0.003	3.421 ± 0.005	2.92
σ_y (mm)	3.479 ± 0.135	3.502 ± 0.001	3.450 ± 0.003	3.530 ± 0.003	2.9

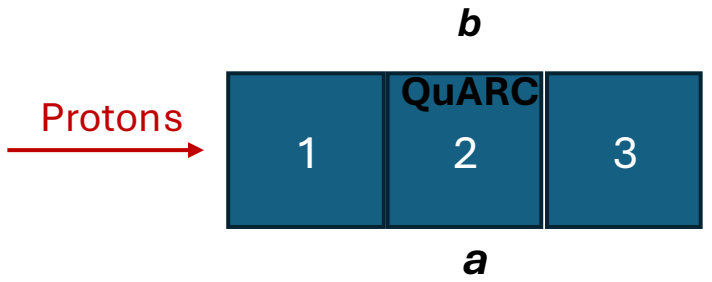
Horizontal Beam Position Scan

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

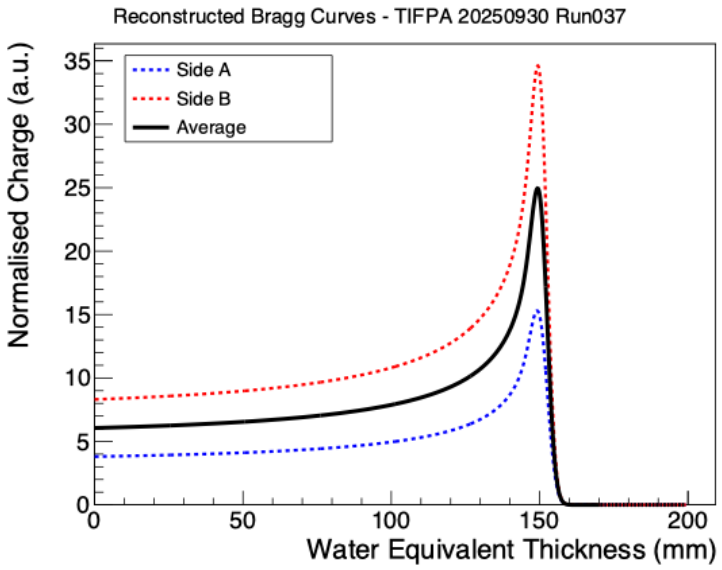
- QuARC measurements to investigate effect of horizontal beam position on Bragg Peak reconstruction and range measurement (by averaging the reconstructed Bortfeld curve measured on the *a* and *b* sides.

- 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:

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



Position Scan: 148 MeV Bragg Curves

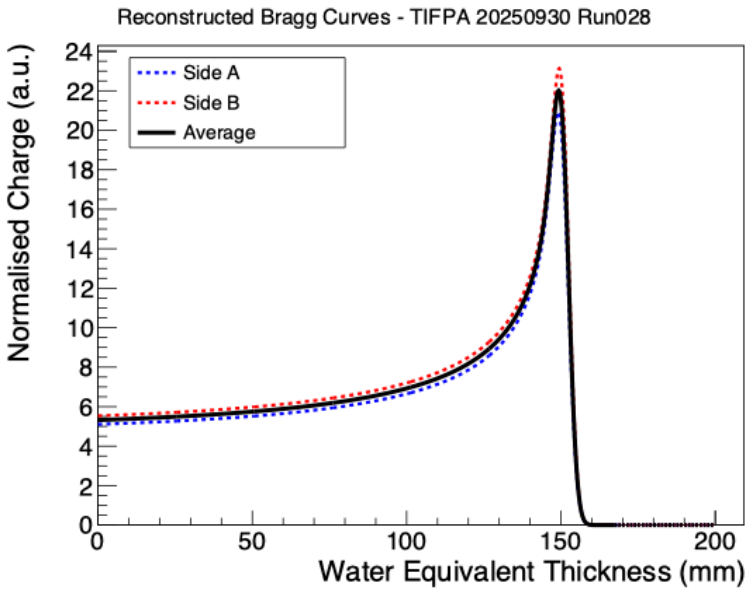


Beam 20mm to left

A: R_0 = 151.47 mm, E_0 = 146.91 MeV

B: R_0 = 151.51 mm, E_0 = 146.93 MeV

Avg: R_0 = 151.49 mm, E_0 = 146.92 MeV

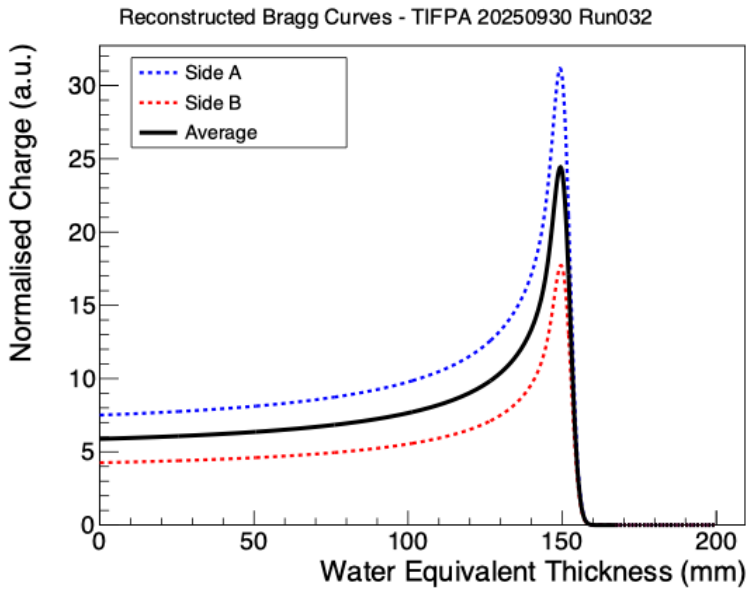


Beam in centre

A: R_0 = 151.29 mm, E_0 = 146.81 MeV

B: R_0 = 151.51 mm, E_0 = 146.93 MeV

Avg: R_0 = 151.4 mm, E_0 = 146.87 MeV



Beam 20mm to right

A: R_0 = 151.46 mm, E_0 = 146.90 MeV

B: R_0 = 151.73 mm, E_0 = 147.05 MeV

Avg: R_0 = 151.60 mm, E_0 = 146.96 MeV

Consistent range reconstruction across entire range of beam spot positions.