Novel Instrumentation for Real-time Dosimetry and Beam Monitoring for VHEE UHDR Radiotherapy

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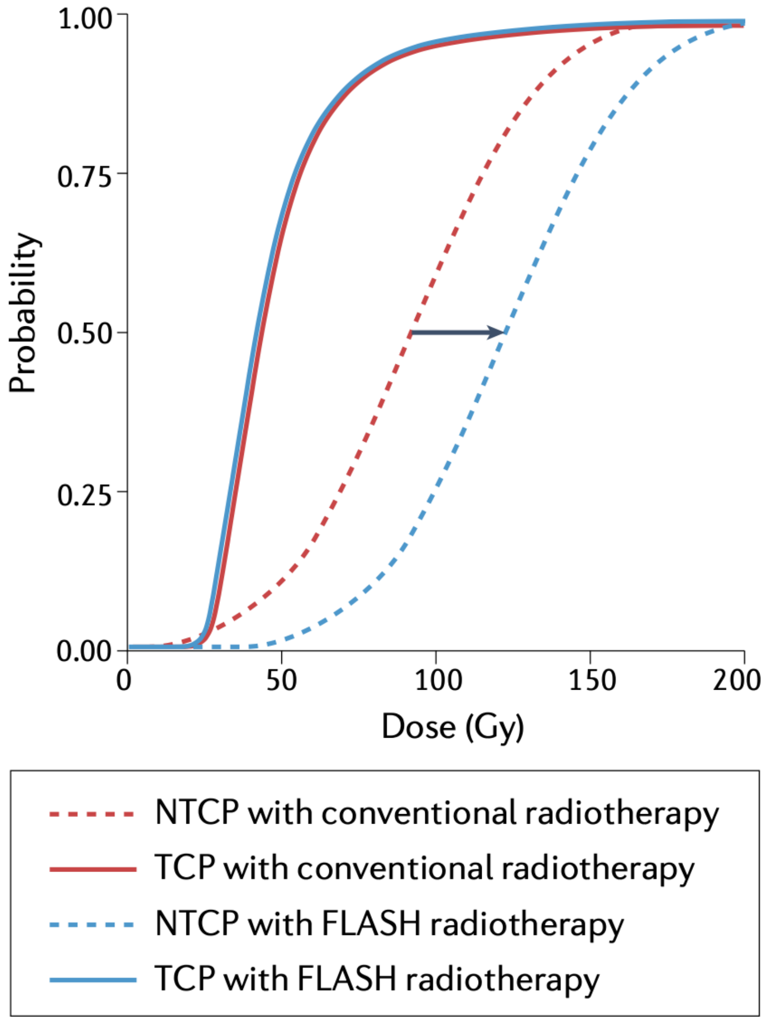
The FLASH Effect

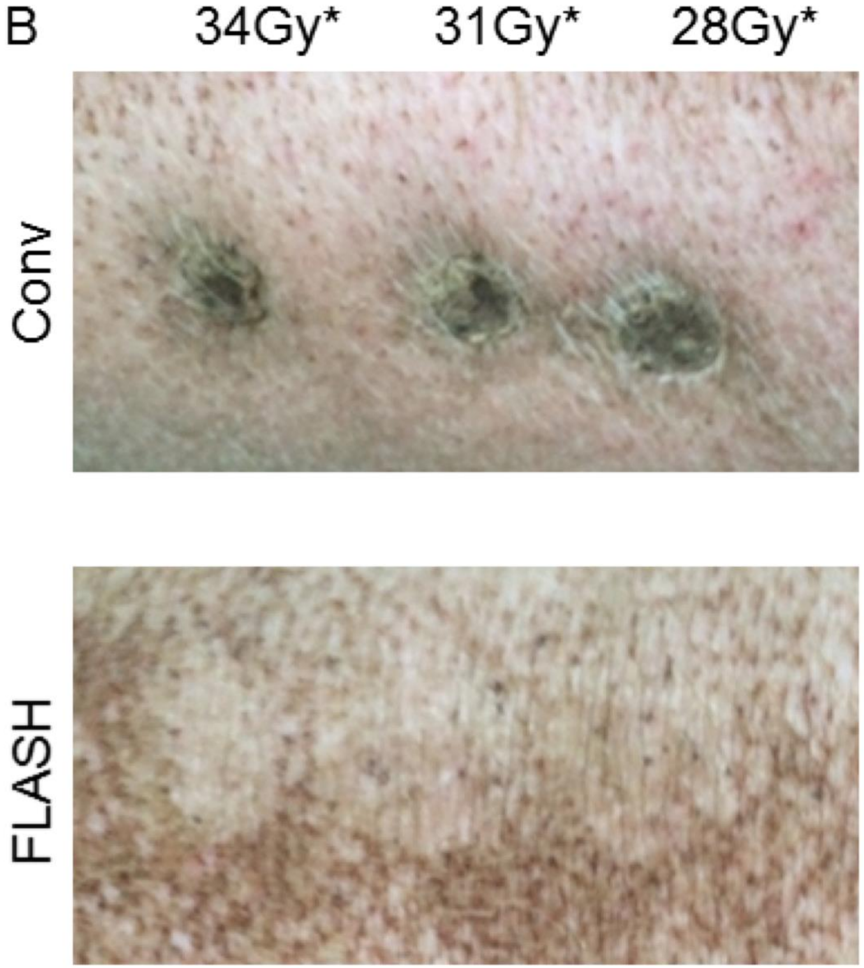
- Increased differential response between healthy and cancerous tissues when dose delivered at ultrahigh dose rates (> 40 Gy/s).
- Normal tissue sparing can allow for higher doses to treat tumours.
- Significantly reduces treatment times (< 100 ms for FLASH) and “freezes” organ motion.



Vozenin, MC., Bourhis, J. & Durante, M. Towards clinical translation of FLASH radiotherapy. *Nat Rev Clin Oncol* **19**, 791–803 (2022).

The FLASH Effect

- Healthy tissue sparing observed in virtually all radiation modalities.
  - Majority of experiments/trials with low energy electrons and shoot-through protons.
- So far, 2 completed clinical trials:
  - Skin lymphoma with 6 MeV electrons (CHUV, 2019).
  - Bone metastases with 250 MeV (shoot-through) protons (Cincinnati, 2020).
  - Further trials ongoing.
- FLASH mechanism still not fully understood.

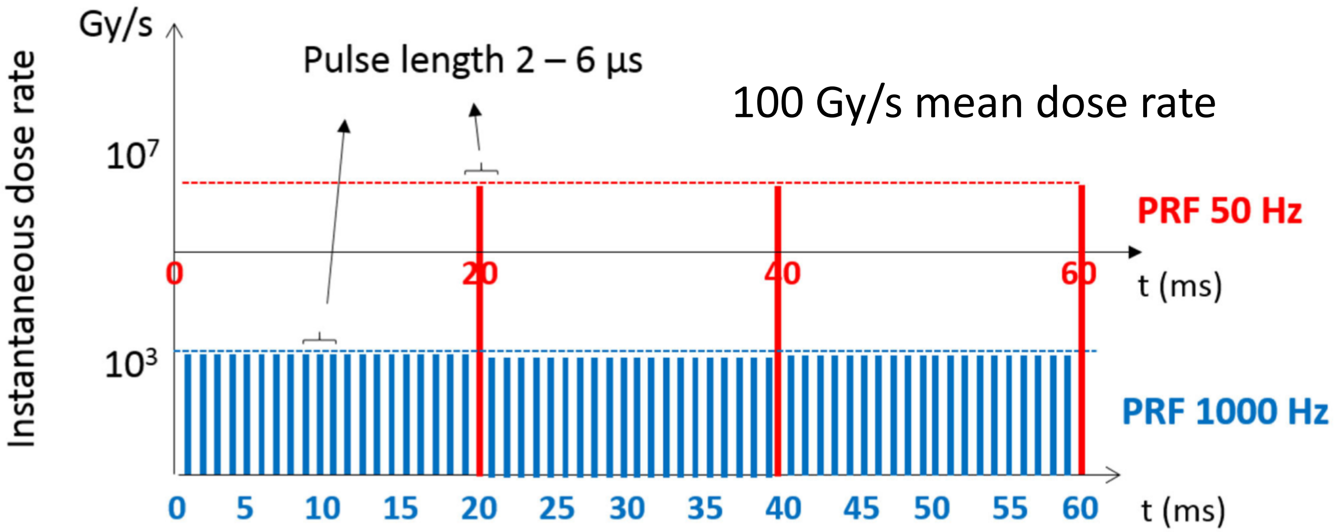


Vozenin MC, De Fornel P, Petersson K, Favaudon V, Jaccard M, Germond JF, Petit B, Burki M, Ferrand G, Patin D, Bouchaab H, Ozsahin M, Bochud F, Bailat C, Devauchelle P, Bourhis J. The Advantage of FLASH Radiotherapy Confirmed in Mini-pig and Cat-cancer Patients. Clin Cancer Res. 2019 Jan

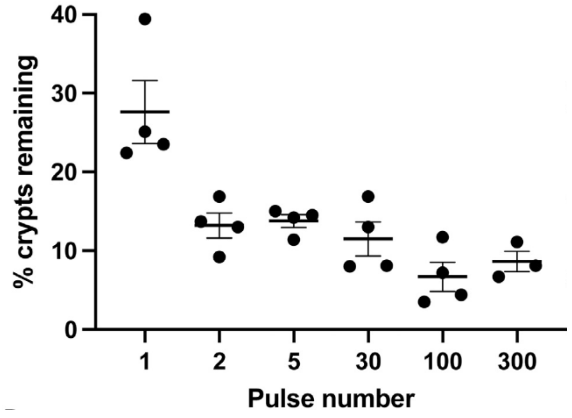
The FLASH Effect – Dose Rates

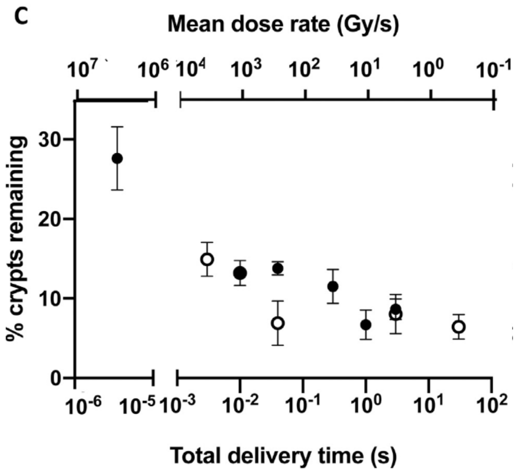
- 3 important parameters:
  - Mean dose rate
  - Dose per pulse
  - Instantaneous dose rate

- Still not decided which parameters FLASH effect depend on - most likely:
  - Total treatment time
  - Mean dose rate



Vignati, A. et al. Beam Monitors for Tomorrow: Challenges for Electron and Photon FLASH RT (2020)

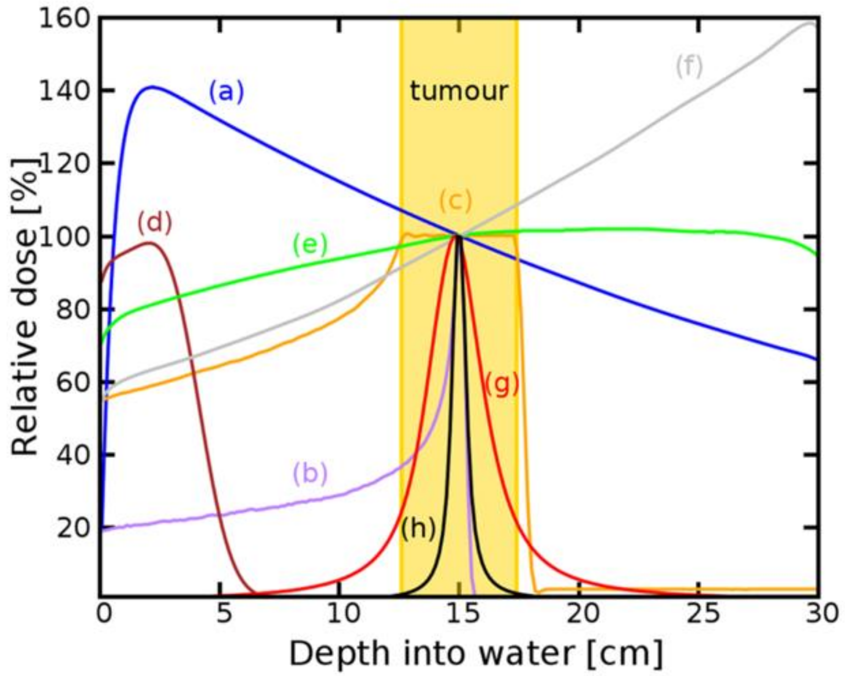




Jia-Ling Ruan, et al. rradiation at Ultra-High (FLASH) Dose Rates Reduces Acute Normal Tissue Toxicity in the Mouse Gastrointestinal System (2021)

Very High Energy Electrons (VHEE) for RT

- Very High Energy Electrons (VHEE) of 100 – 250 MeV promising option for FLASH RT with deep-seated tumours.
- Easier to produce larger intensities required for FLASH at greater depths than other modalities.
- Preliminary treatment plans suggest better dose conformality than VMAT.

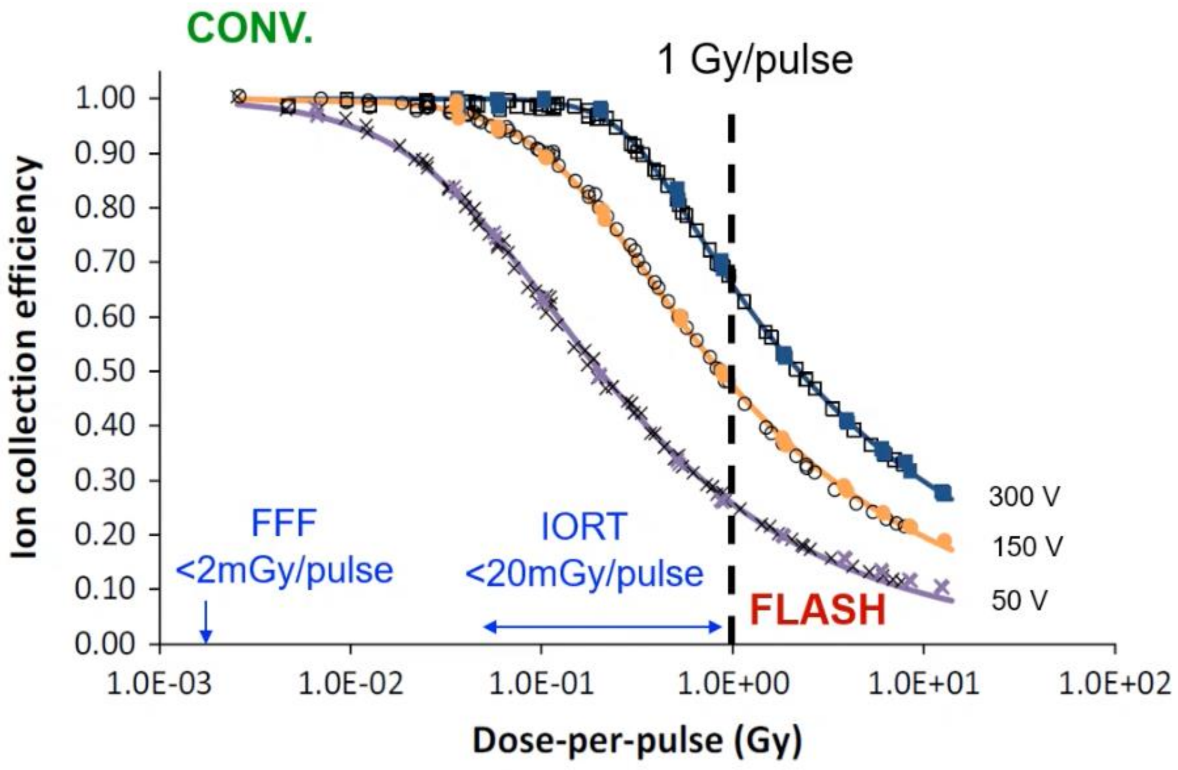


a) Photon
b) Proton
c) SOBP
d) 20 MeV e-
e) 200 MeV VHEE
f) 1 GeV VHEE
g) Focussed VHEE
h) Focussed VHEE

Kokurewicz, K et al. (2019). *Sci. Rep.*, *9*(1).

Challenge for Dosimetry of UHDR Beams

- Ionisation chambers saturate in UHDR conditions required for FLASH.
- Correction factors can account for decrease in ion collection efficiency at UHDR but introduce large uncertainties.
- Collection time of transmission ICs (order of μs) too slow for FLASH beam monitoring.



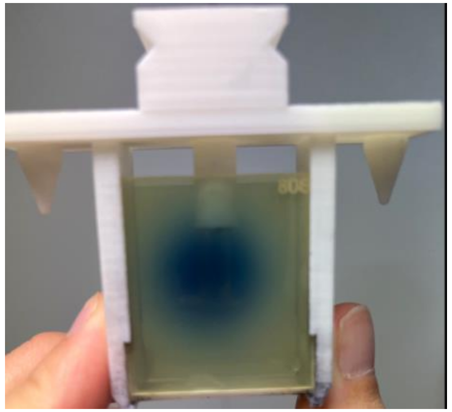
Petersson et al., Med Phys 44 (2017) 1157

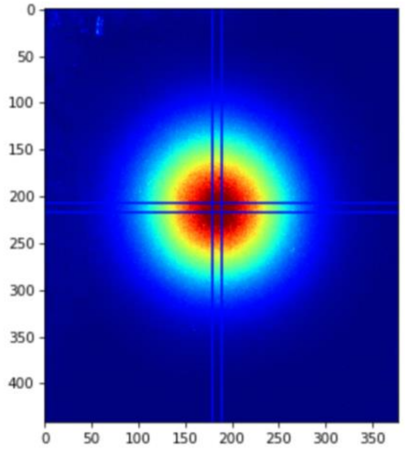
Radiochromic Film Dosimetry

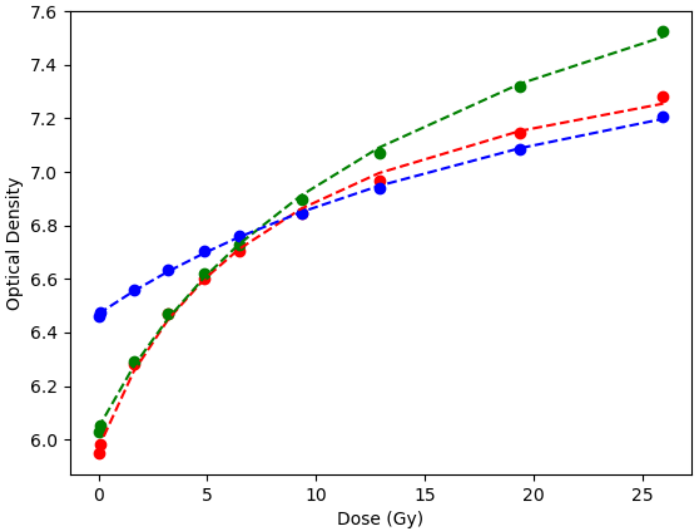
- Passive dosimetry method considered to be dose-rate independent.

- Widely used as reference dosimetry for many UHDR experiments.
  - Used at CLEAR for almost all UHDR studies.

- Calibrated to low energy clinical electron beam at CHUV and analysed using custom analysis code.





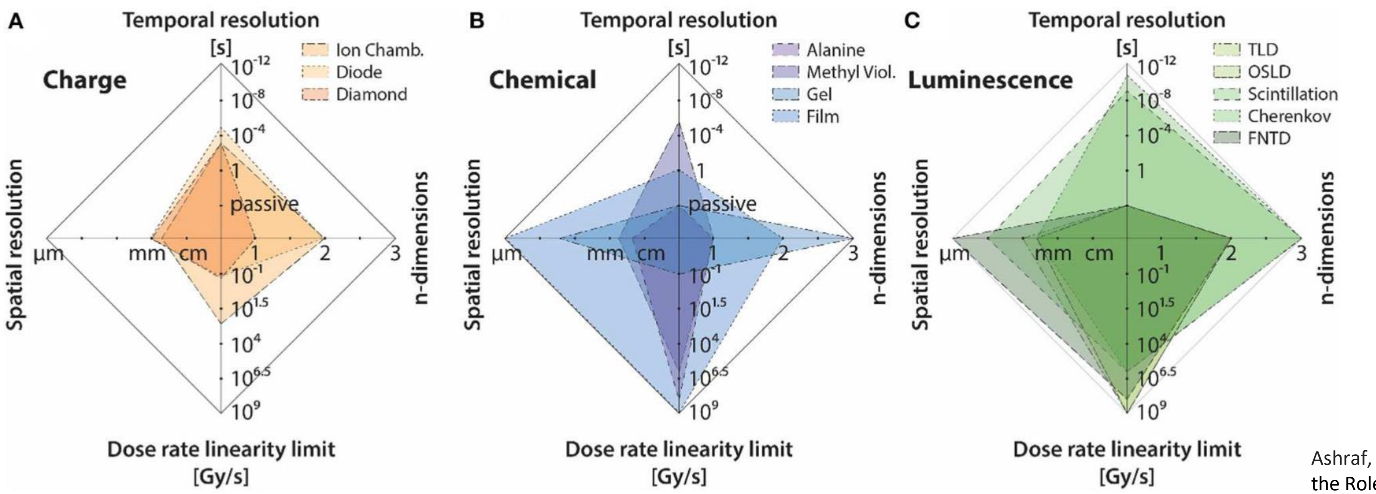


Requirements for UHDR Dose Monitor

1. A response the does not saturate at the dose rates needed for FLASH.
2. High temporal resolution.
3. High spatial resolution.
4. Minimal perturbation on the beam.
5. Large area to cover entire beam.

Potential Options for UHDR Dosimetry

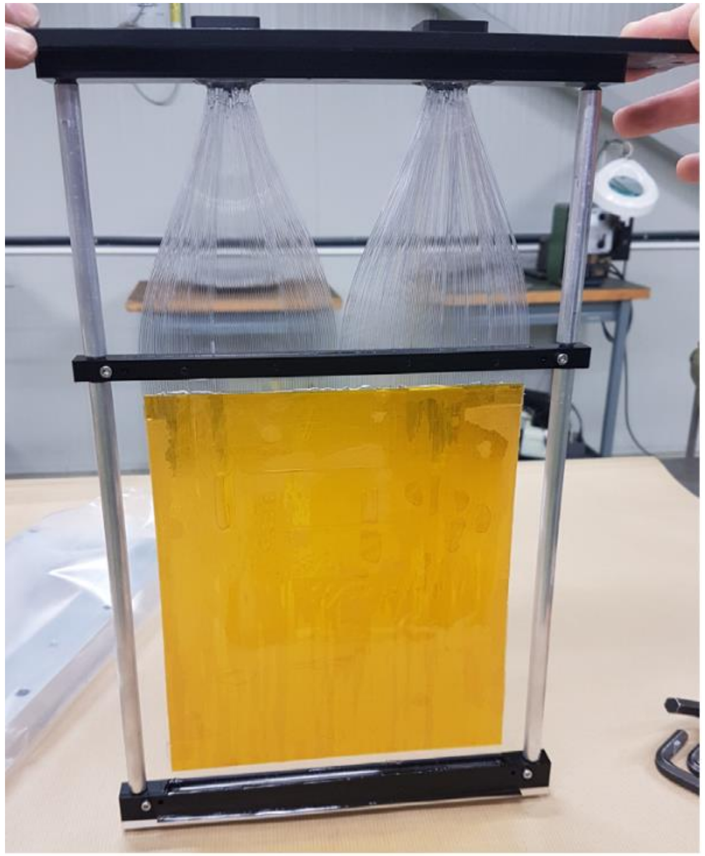
- Modified ionisation chamber geometry and design, e.g., ultra-thin plane parallel ion chambers
- Solid-state detectors e.g., diamond detectors, Si/SiC detectors
- Radioluminescence detectors –scintillators, fibres, gas monitors, screens, Cherenkov.
- Accelerator Beam Instrumentation - current transformers, pick-up monitors etc.



Ashraf, M. et al. Dosimetry for FLASH Radiotherapy: A Review of Tools and the Role of Radioluminescence and Cherenkov Emission (2020).

Fibre Optic Monitors

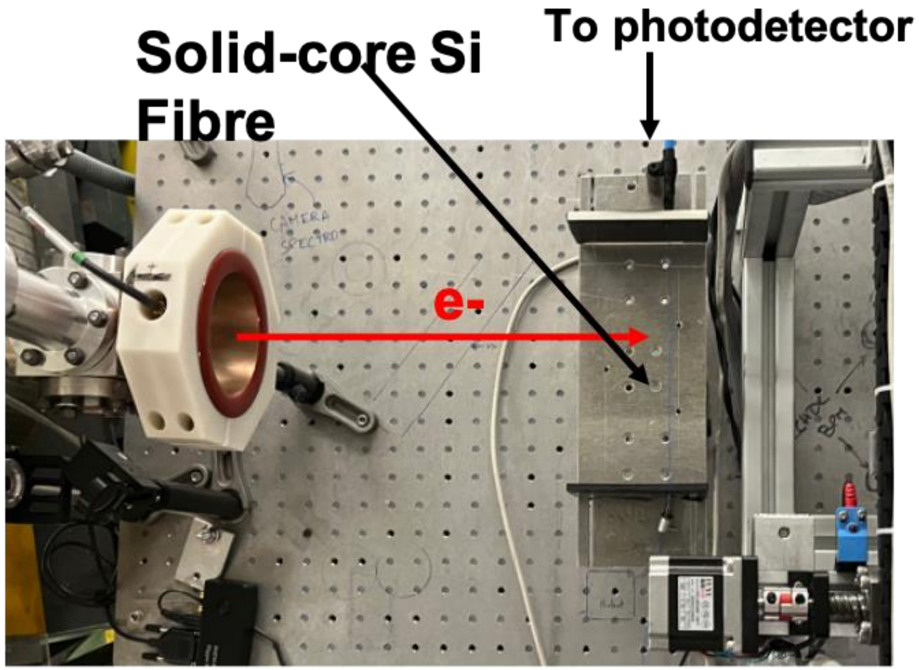
- Currently used in CERNs North Experimental Area beamlines.
- Consist of a 2D array of fibres capable of measuring beam intensity and profile.
- High spatial and temporal resolution.
- Low material budget.
- Different fibre types depending on requirements
  - Scintillating – plastic, YAG, liquid scintillator, hollow-core gas-filled.
  - Solid-core silica fibres – measures Cherenkov radiation.

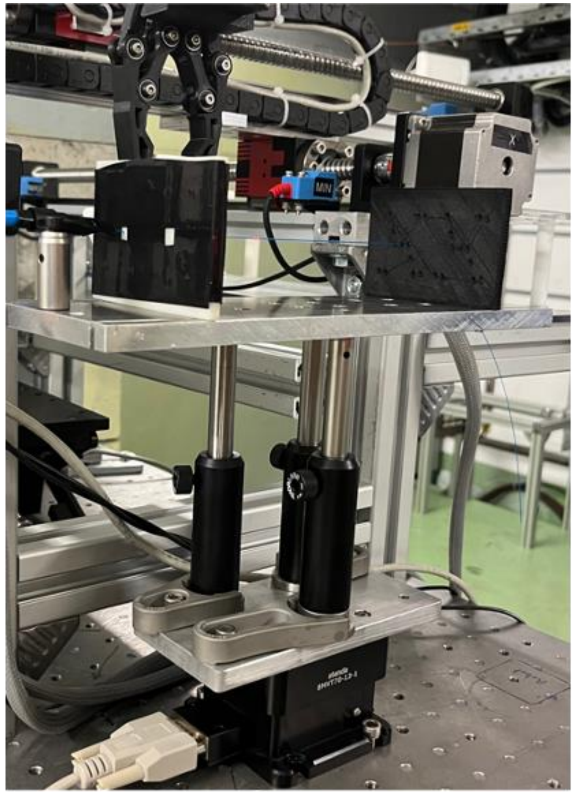


Ortega Ruiz, I et al. *Nuclear Inst. and Methods in Physics Research, A 951 (2020)*

Fibre Optic Monitors: First Tests at CLEAR

- 200 μm solid-core Si fibre, with 20 cm length sensitive region tested with 200 MeV electrons at CLEAR with a beam size $\sigma \sim 1.5$ mm .
- Tested with SiPM, PMT and CCD photodetectors.





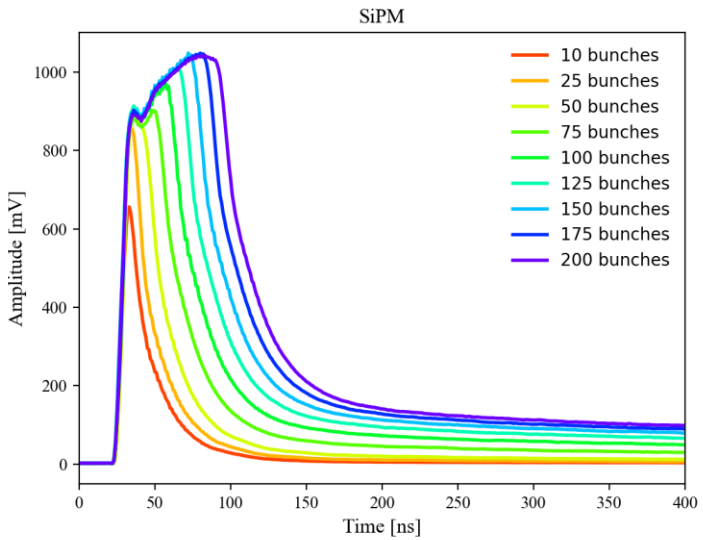
Fibre Optic Monitors: SiPM & PMT

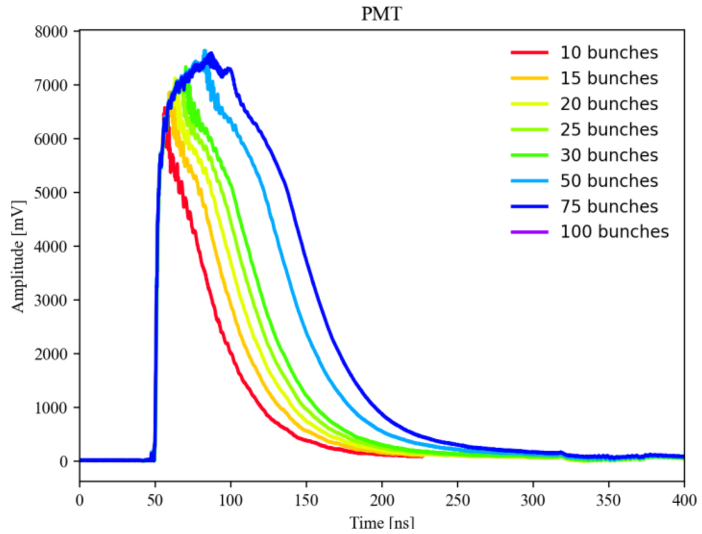
SiPM Setup

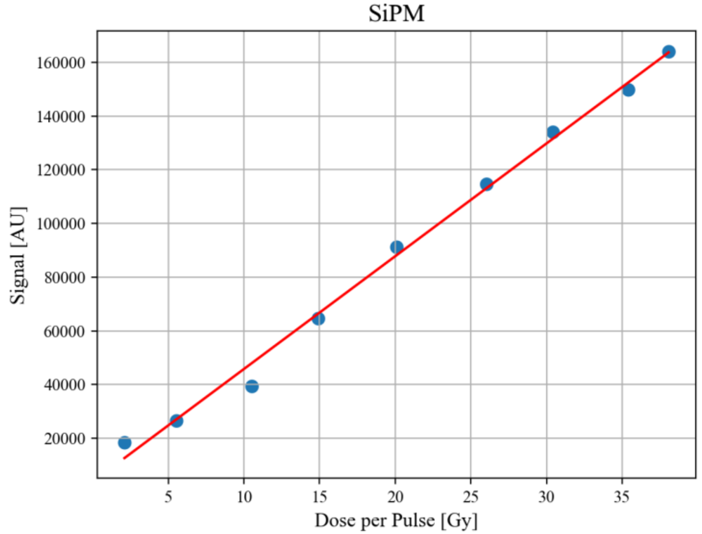
- Linear response seen up to **38 Gy/pulse**.
- SiPM response begins to saturate around 50 bunches.

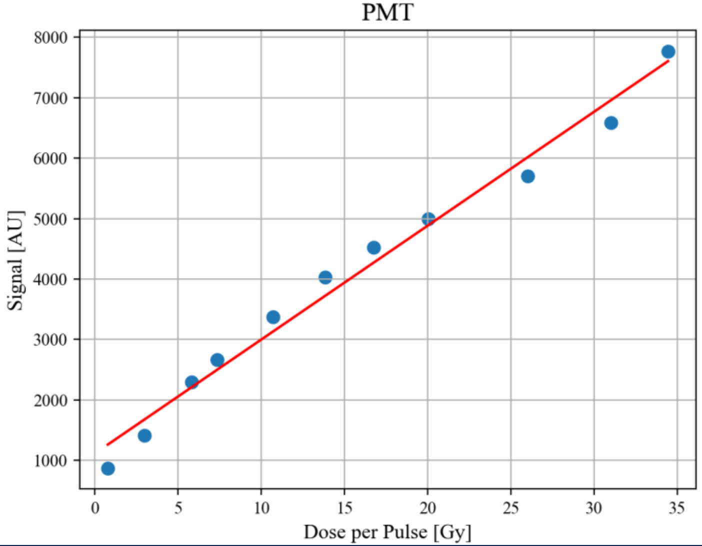
PMT Setup

- Near linear response seen up to **20 Gy/pulse**.
- Non-linearities in PMT response occurs after this due to saturation and changes in instantaneous dose rate.





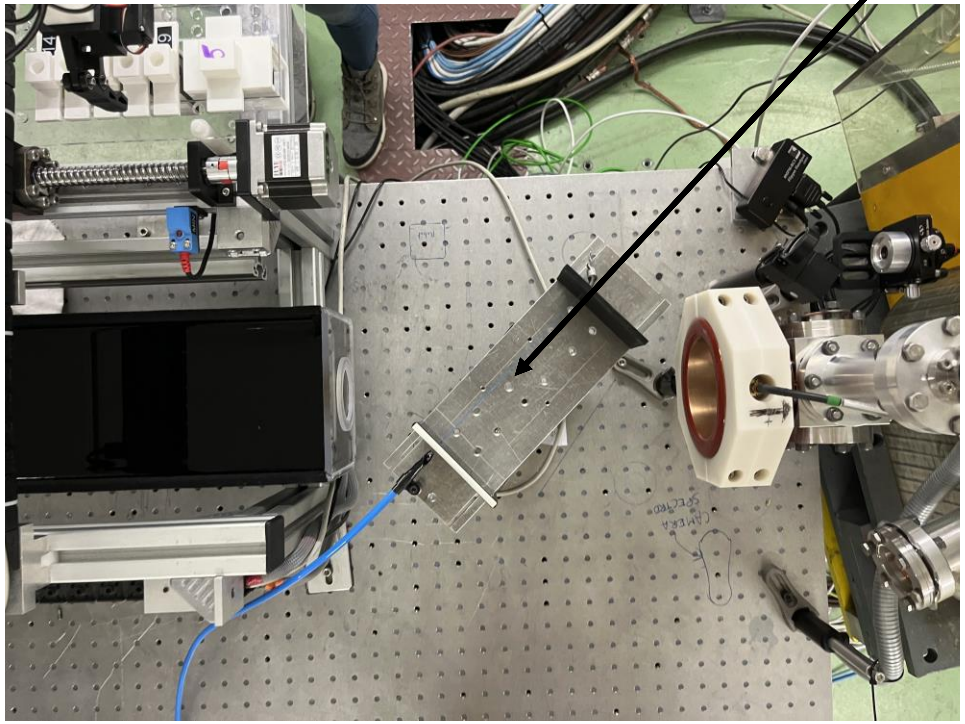




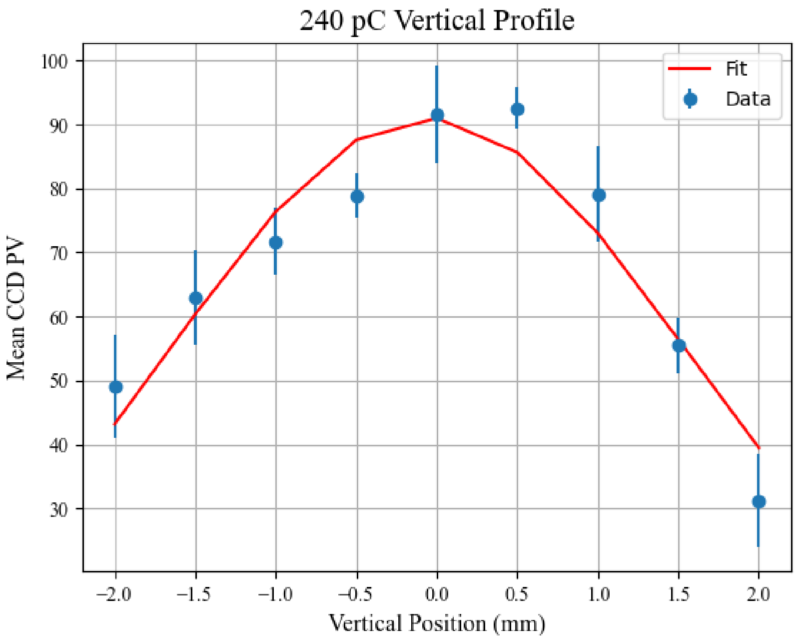
Fibre Optic Monitors: CCD Readout

- Fibre oriented at 46° to maximise Cherenkov captured.
- CCD should allow for larger dynamic range and ability to read an entire array at once.

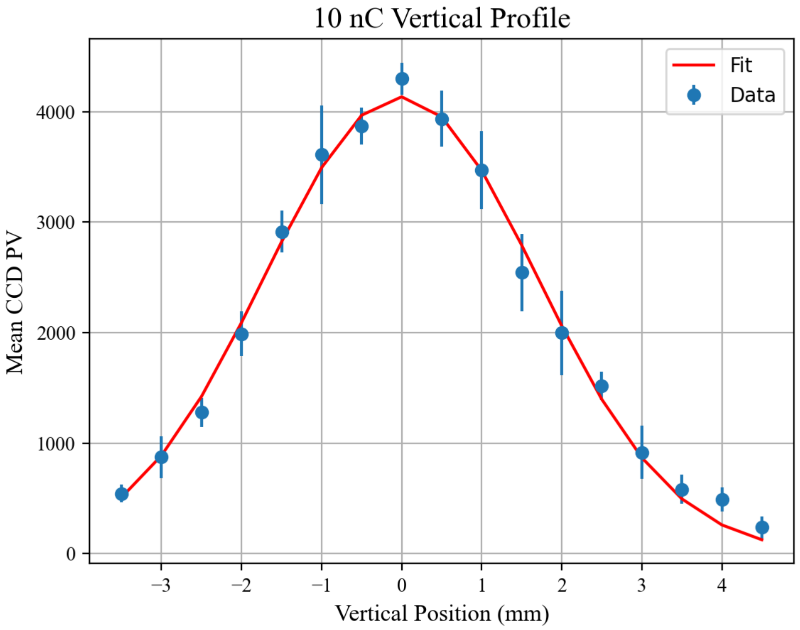
Si fibre at 46°



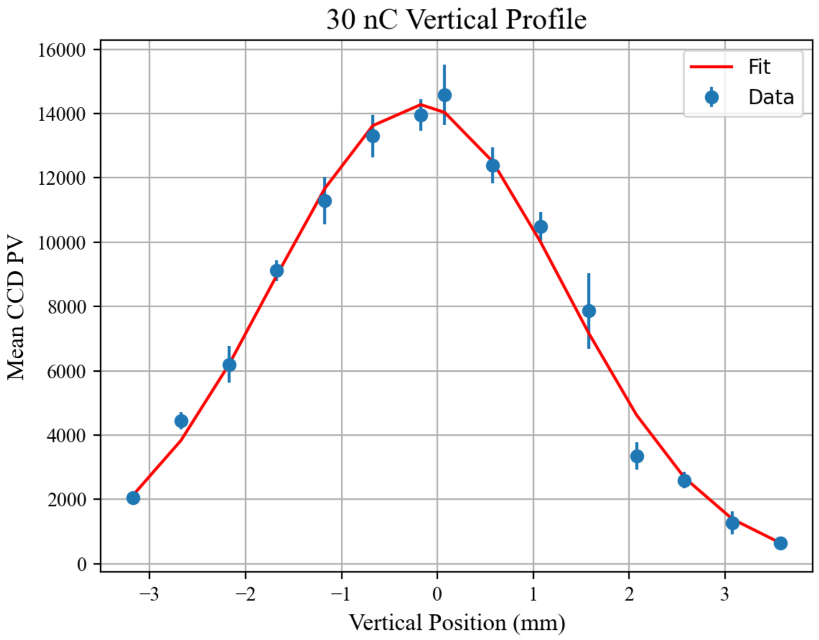
Fibre Optic Monitors: CCD Readout



$A = 97.721\ (\pm 4.5725)$
$\sigma = 1.972\ (\pm 0.1329)\ mm$



$\mathrm{A} = 4089.668\ (\pm 102.7204)$
$\sigma = 1.719\ (\pm 0.0509)\ mm$

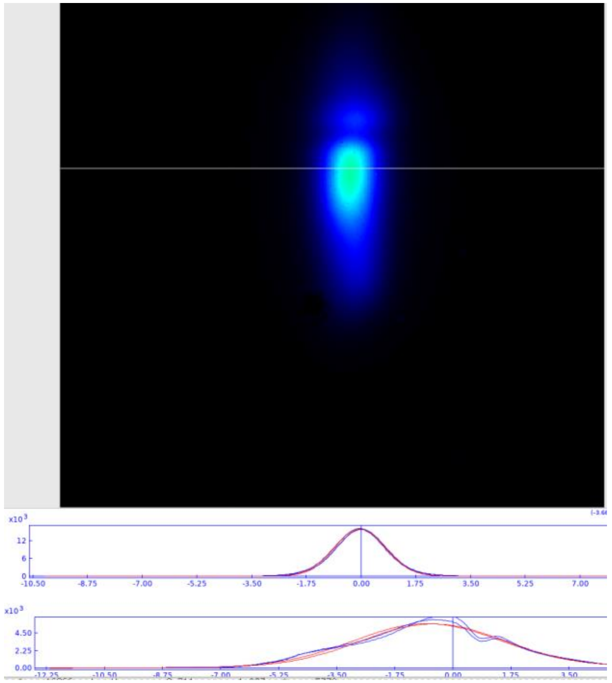


$\mathrm{A} = 14280.982\ (\pm 531.1588)$
$\sigma = 1.521\ (\pm 0.0704) mm$

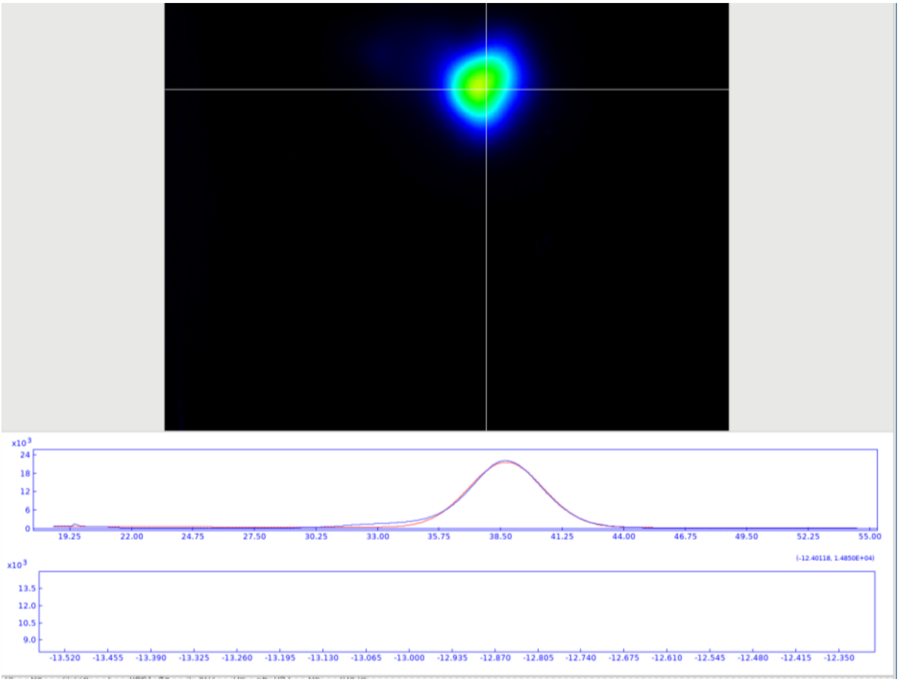
Fibre Optic Monitors: CCD Readout

Charge	Fibre Beam Size	YAG Screen Beam Size
240 pC	$1.972\ (\pm 0.1329)\ mm$	$2.187\ (\pm 0.0639)\ \mathrm{mm}$
10 nC	$1.719\ (\pm 0.0509)\ mm$	$1.831\ (\pm\ 0.0591)\ \mathrm{mm}$

240 pC

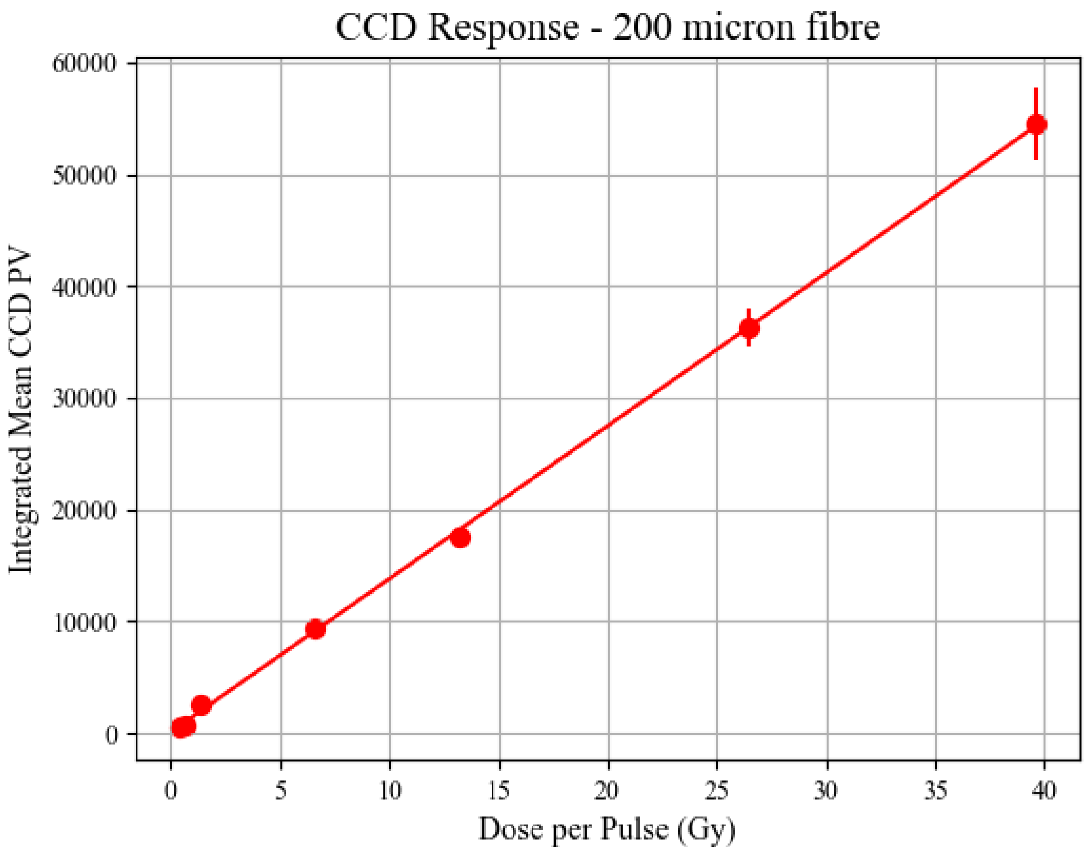


10 nC

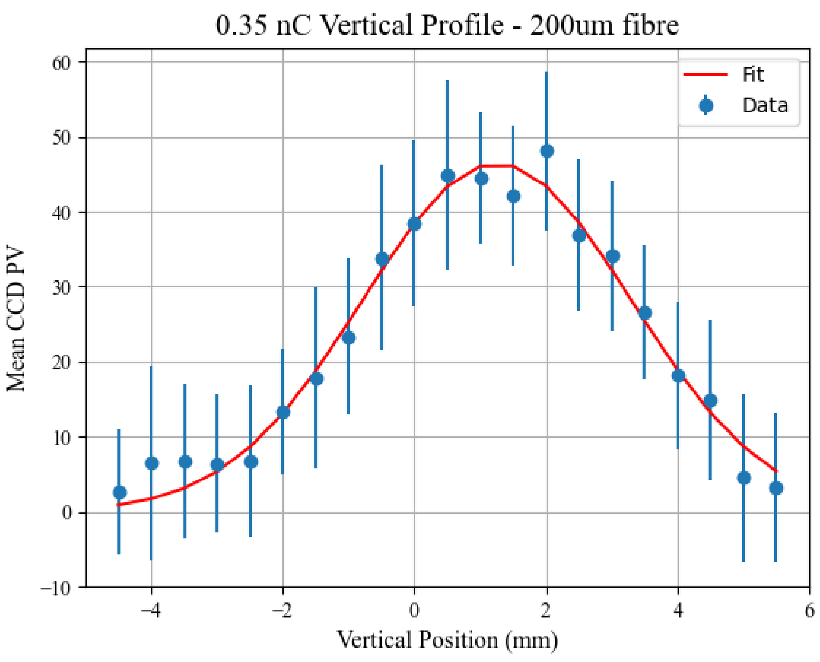


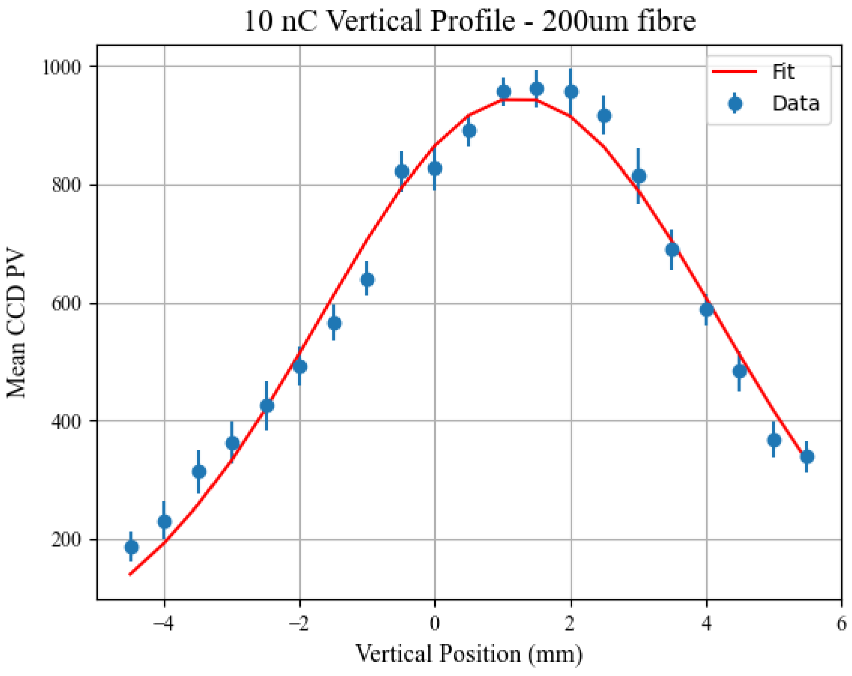
Fibre Optic Monitors: CCD Readout

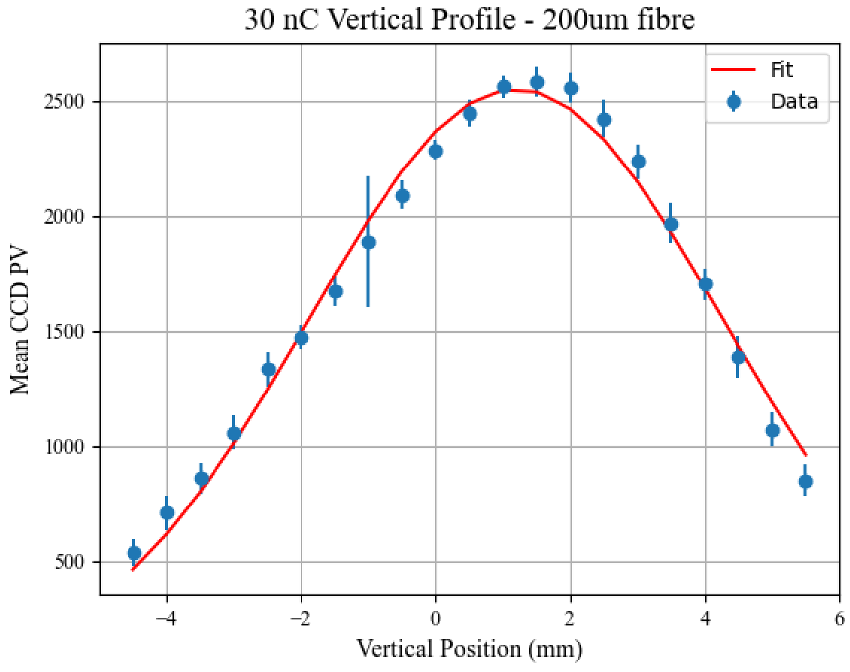
- Linear response seen up to **39 Gy/pulse** (30 nC).
- Signal-to-noise ratio is low below pulse charges of 1 nC - reducing accuracy of beam profile and intensity measurement.



Fibre Optic Monitors: CCD Readout







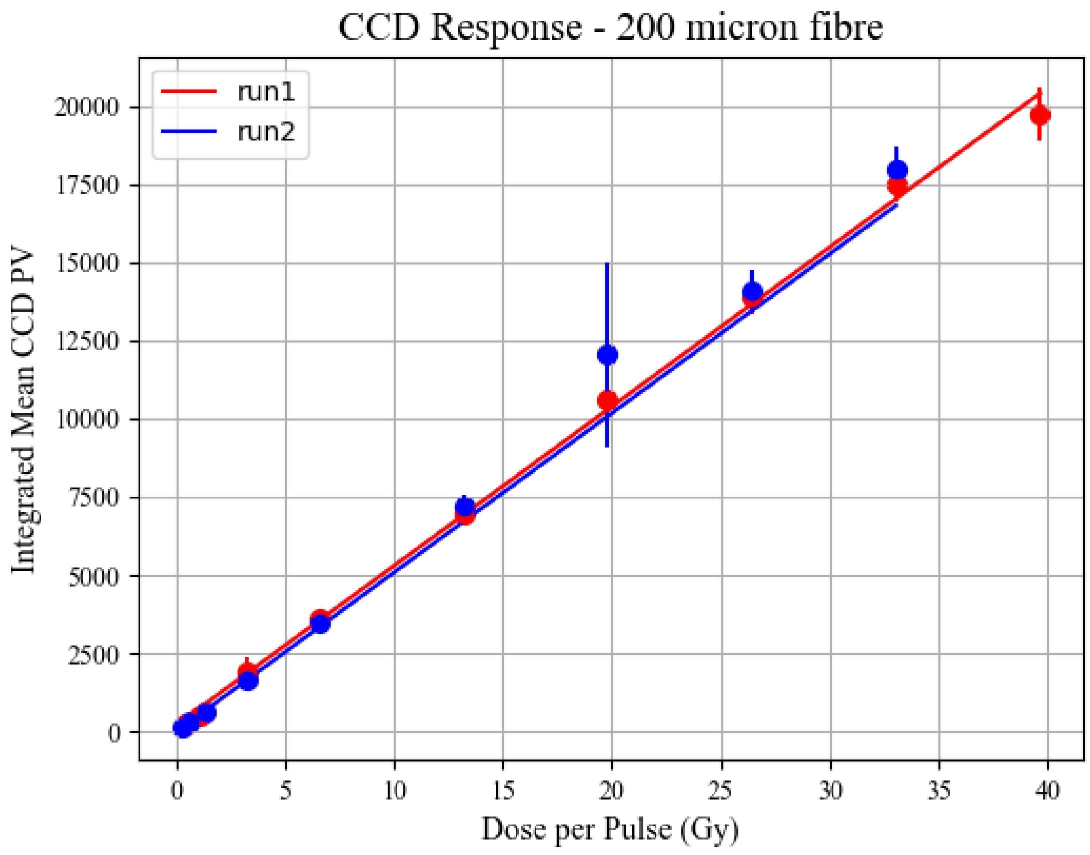
$A = 46.409(\pm 2.4216)$
$\sigma = 2.045\ (\pm 0.1260)\ mm$

$A = 945.999\ (\pm 30.8752)$
$\sigma = 2.936\ (\pm 0.1318)\ mm$

$A = 2549.635\ (\pm 62.6777)$
$\sigma = 3.085(\pm 0.1081)\ mm$

Fibre Optic Monitors: CCD Readout

- Linear response seen up to **39 Gy/pulse** (30 nC).
- Signal-to-noise ratio improved at lower pulse charges below 1 nC using shorter transport fibre.



Fibre Optic Monitors: Final Remarks

- Fibre optic detector shown to be able to effectively measure beam profile and have a linear response through the dynamic range well into the UHDR regime.

- Next challenge is to modify setup so that it can work perpendicular to the beam and not require an angle:
    - Use fibres that have a better attenuation for the Cherenkov light.
    - Use scintillating fibres instead?

- Final goal – test a 2D fibre array and dosimetrically characterise its response to radiochromic film in water.

Thank you for your attention! ☺