Time structure characterization of (UHDPP) beams from proton and electron accelerators using Timepix3

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Outline

- Motivation and Introduction
- AdvaPIX Timepix3 detectors
- Time structure characterization of UHDPP (FLASH radiotherapeutic) beams
  - Proton beam
  - Electron beam
- Conclusions

FLASH radiotherapy

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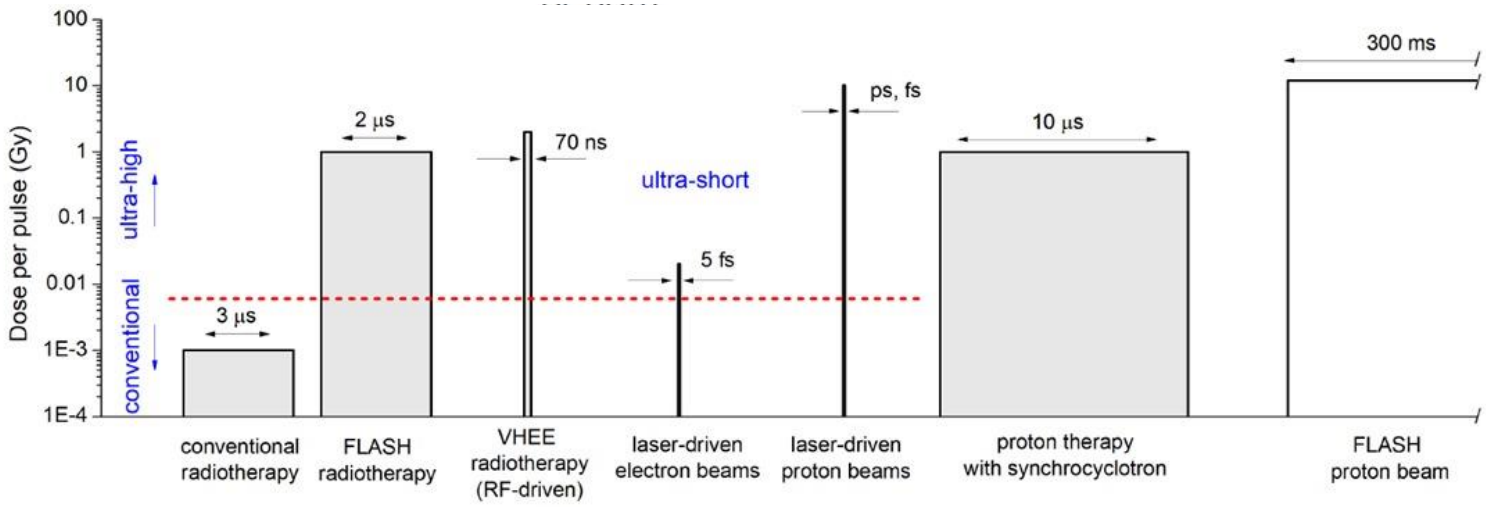
FLASH radiotherapy has recently gained significant momentum due to its potential benefits, which include:

- Reduced damage to surrounding healthy tissues
- Shorter treatment times
- Improved patient comfort and outcomes



Ultra-high dose-per-pulse (UHDPP) beams

- Delivery times typically below 100 ms
- Delivered dose above 1.6 Gy per one beam pulse or dose rate above 40 Gy/s

Monitoring of UHDPP beams in FLASH radiotherapy

UHDPP beam monitoring for FLASH RT

UHDPP beam monitoring including time structure characterization (not only) in FLASH radiotherapy is frequently faced with several difficulties:

- Beam monitors intercept the primary beam
- Saturation effects due to delivering ultra-high dose-per-pulses rates
- Short irradiation times, frequently within the range of few μs
- High frequency beam modulation

UHDPP beam monitoring for FLASH RT

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Out-of-field measurement

Time resolution below µs

UHDPP beam monitoring for FLASH RT

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- High frequency beam modulation

Out-of-field measurement

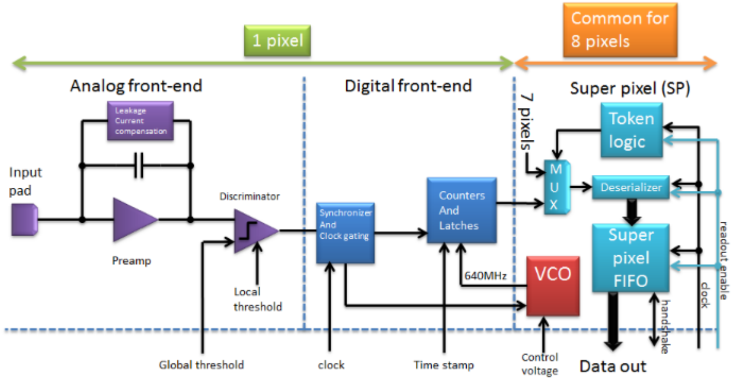
Time resolution below μs

Timepix 3
- 1.6 ns time resolution
- Saturation avoided out-of-field
- Secondary radiation field decomposition

AdvaPIX Timepix3

Timepix 3 chip:

- 256 x 256 pixels, 55 µm pixel pitch
- Sensitive area 14 x 14 mm^2
- Simultaneous measurement of TOA and TOT
- Fast TOA with 1.56 ns precision
- Data driven readout



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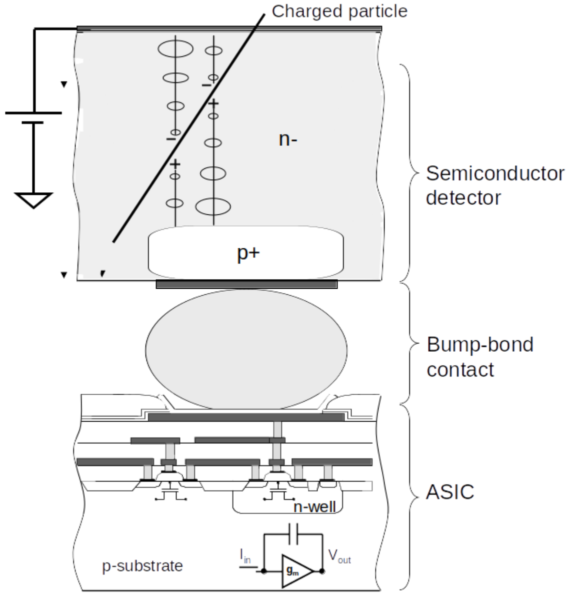
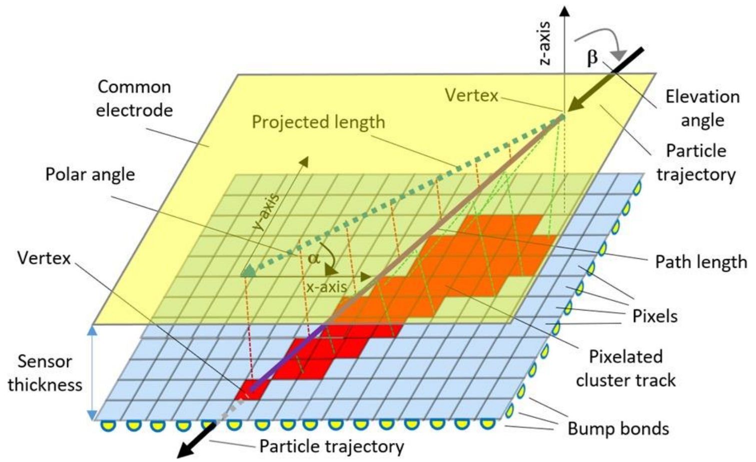


AdvaPIX TPX3 detector:

- Sensitive material: Si, CdTe, …
- Sensor thickness: 100 – 1500 µm
- Readout speed 40 Mhits/s per sensor area
- Energy resolution ~ 1 keV @ 60 keV, ~ 3 keV @ 122 keV
- Minimal detectable energy ~ 3 keV for photons



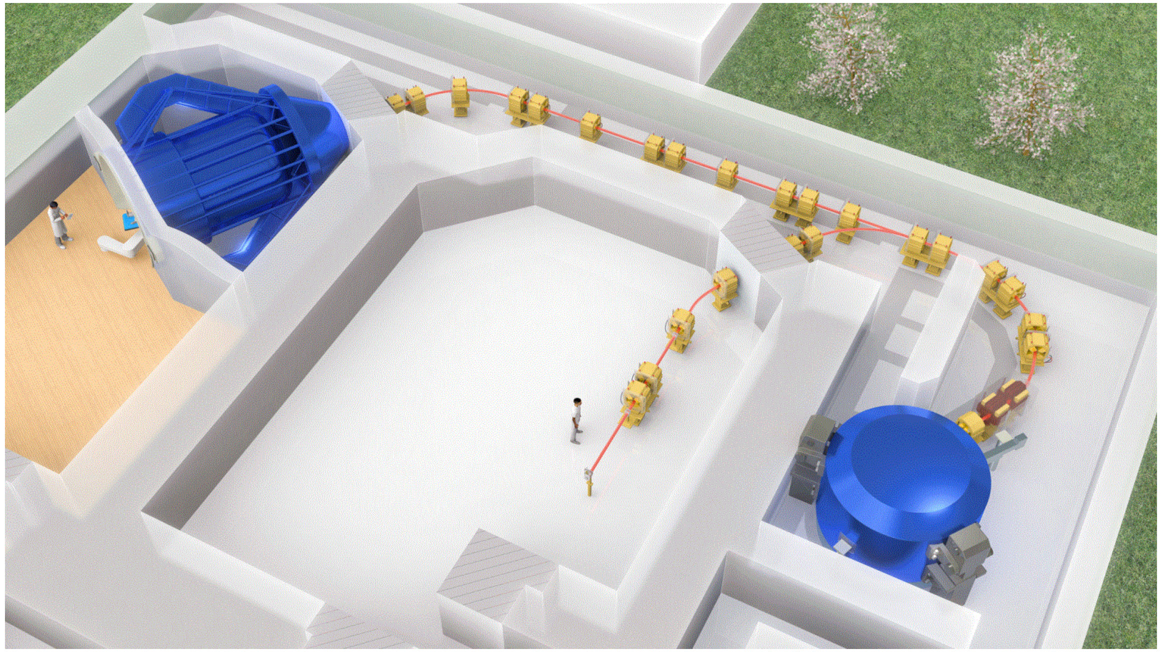
UHDPP proton beam characterization

Experimental setup – proton UHDPP

University Proton Therapy Dresden, Germany

OncoRay (ZIK) National Center for Radiation Research in Oncology Dresden

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF



Primary beam setup:

- Stationary proton pencil beam
- Generated by isochronous cyclotron
- 220 MeV primary beam energy
- Conventional dose rates or short UHDR beam pulses
- Varying pulse lengths and beam current

Experimental setup – proton UHDPP

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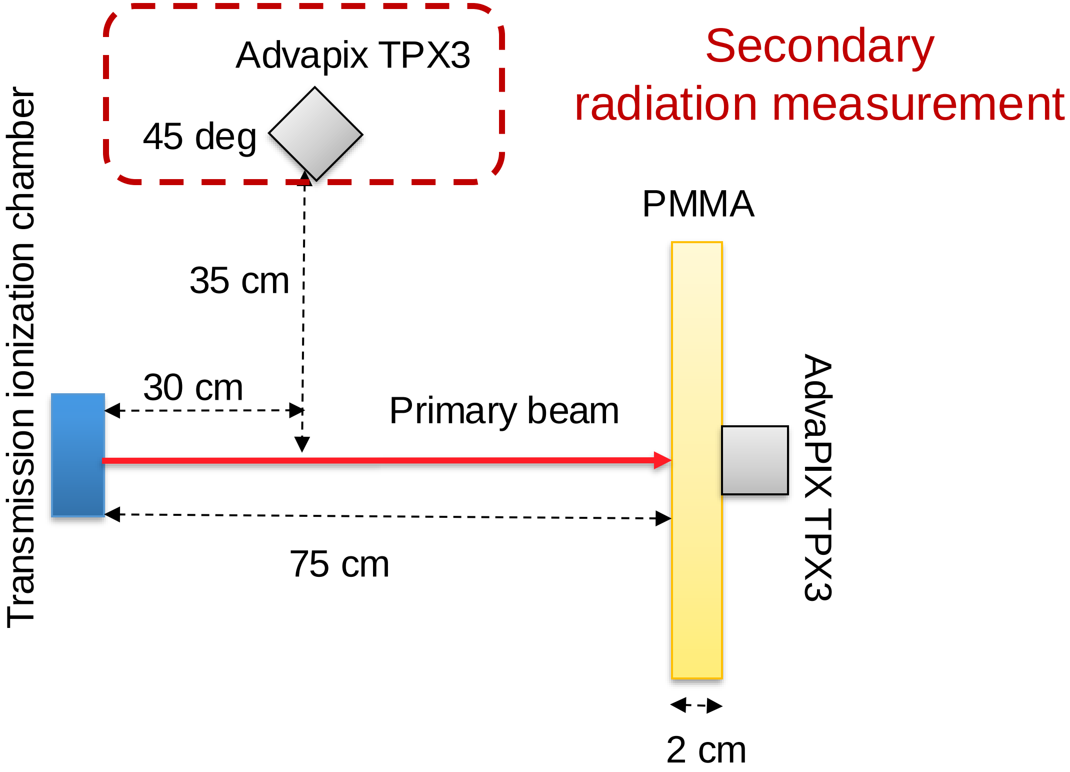
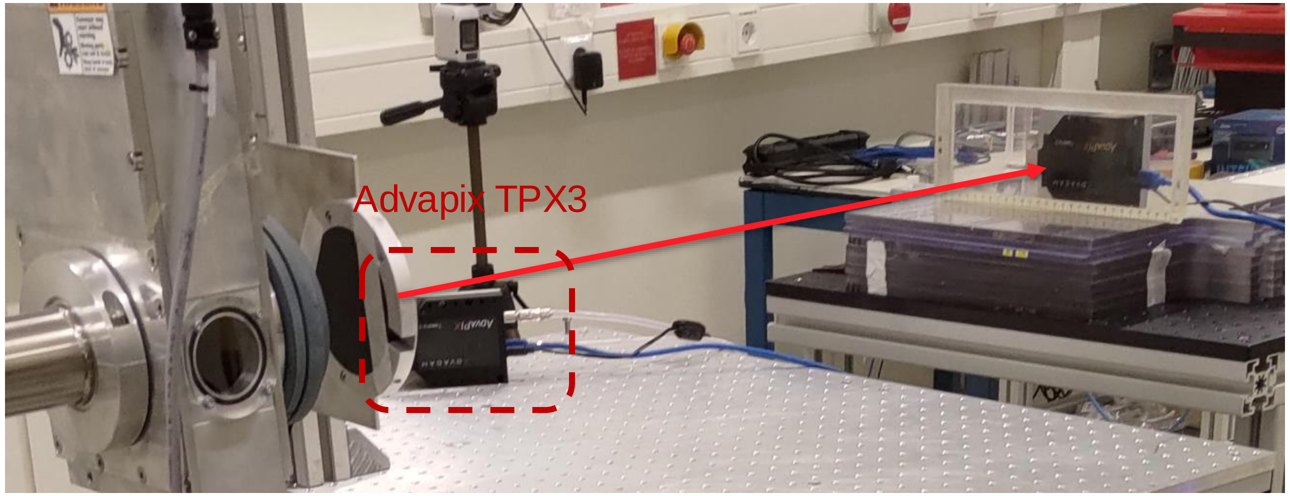
University Proton Therapy Dresden, Germany





AdvaPIX TPX3:

- Si, 1000 µm
- TOT and TOA measurement
- Data-driven mode

Measure delivered dose rate, irradiation time per pulse (pulse length), pulse temporal structure.

Experimental setup – proton UHDPP

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Delivered pulse length [ms]	*Delivered current [nA]*	*Measured # of pulses by TPX3*	*Measured pulse length [ms]*	*Measured dose rate [uGy/s]*
2000	0.18	1	2020(20)	0.278(3)
1000	0.21	1	1000(10)	0.345(3)
800	0.28	10	806(8)	0.43(2)
300	0.57	1	300(3)	0.841(8)
40	4.00	10	40.2(4)	6.2(2)
20	8.06	10	20.2(2)	12.5(5)
4	41.80	4	3.99(4)	65(2)
4	20.73	7	3.98(4)	37(2)
3	67.22	10	3.00(3)	104(3)
1	39.13	14	0.98(1)	61(5)

Conventional therapy

Flash therapy

Frequency of delivered pulses was approximately 1 Hz

Experimental setup – proton UHDPP

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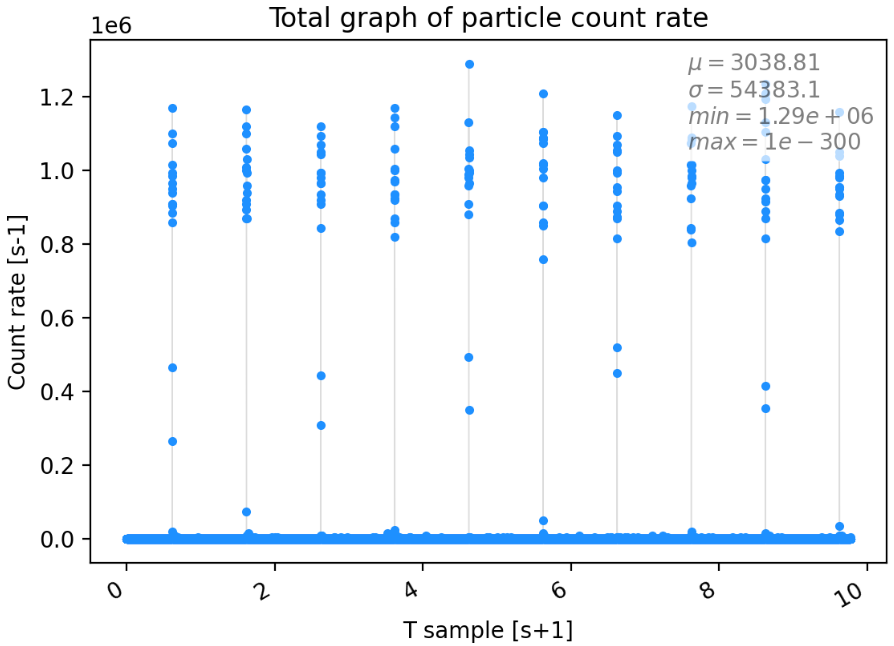
Individual pulses are clearly distinguished.



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4	20.73	7	3.98(4)	37(2)
3	67.22	10	3.00(3)	104(3)
1	39.13	14	0.98(1)	61(5)

Conventional therapy (rows 2000–300 ms)

Flash therapy (rows 40–1 ms)

Frequency of delivered pulses was approximately 1 Hz

Pulse length – proton UHDPP

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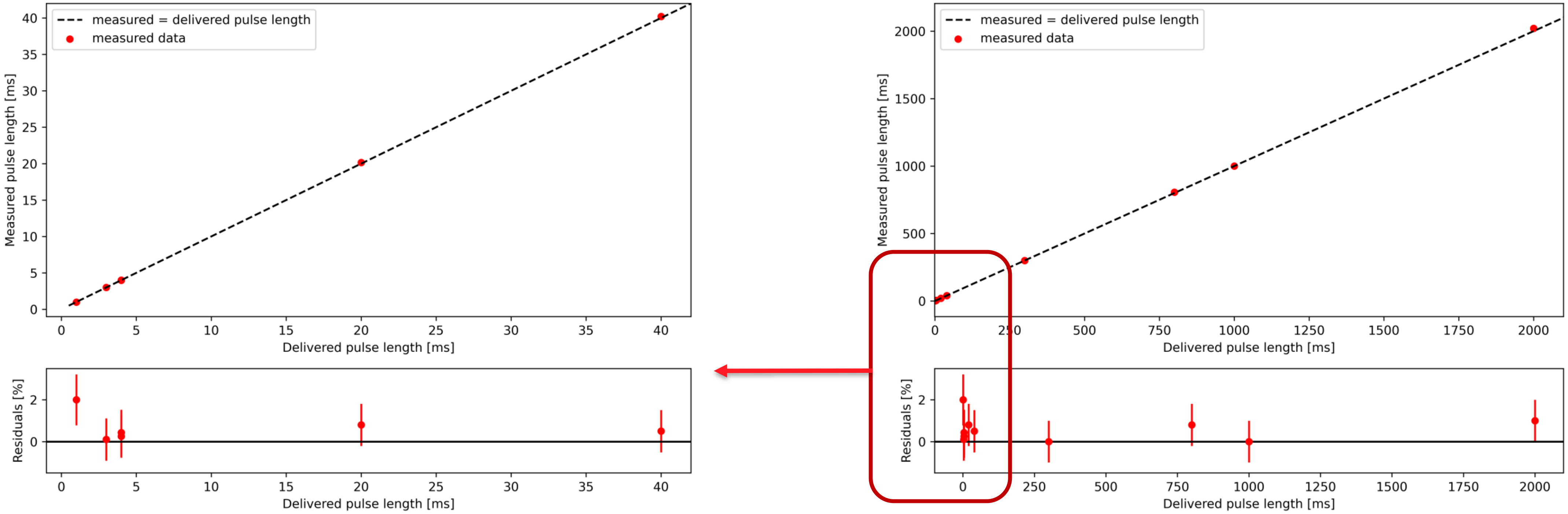
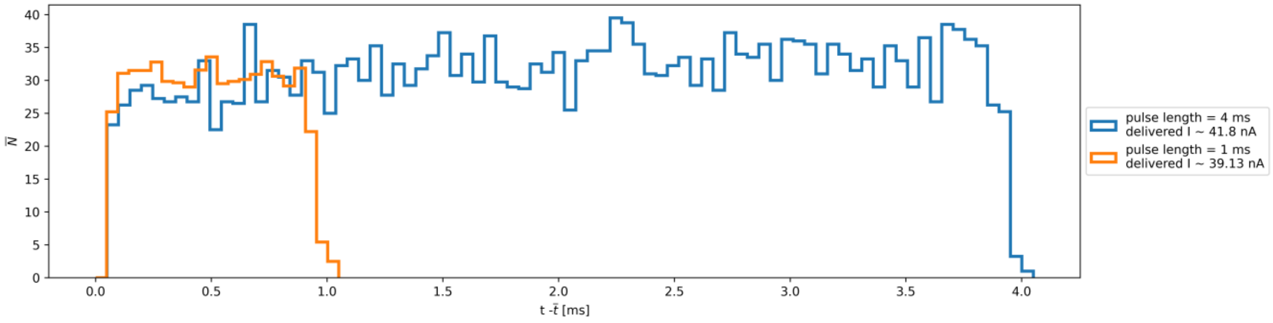
Flash radiotherapy is characterized by having very short irradiation times. Out-of-field measurement was used to determine pulse lengths. Start and end of pulse were determined by signal crossing fixed threshold.



Pulse structure – proton UHDPP

The average time structure of the pulses was investigated for the first time.



Bin size: 50 µs

Pulse structure – proton UHDPP

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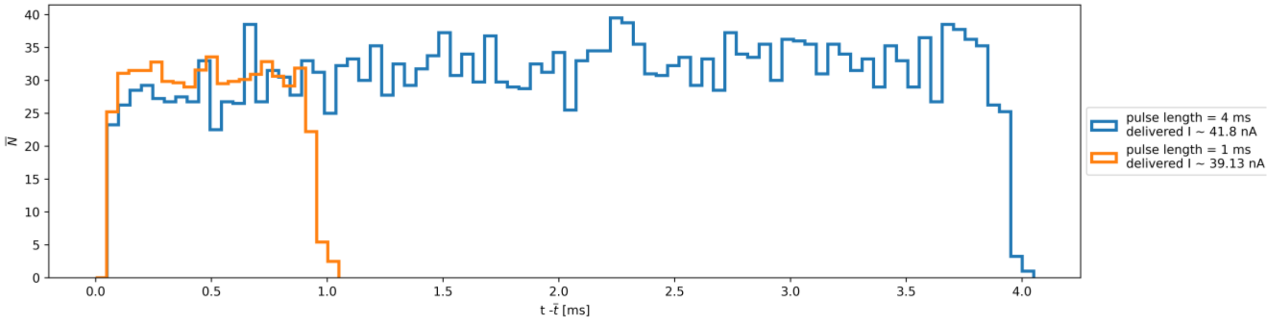
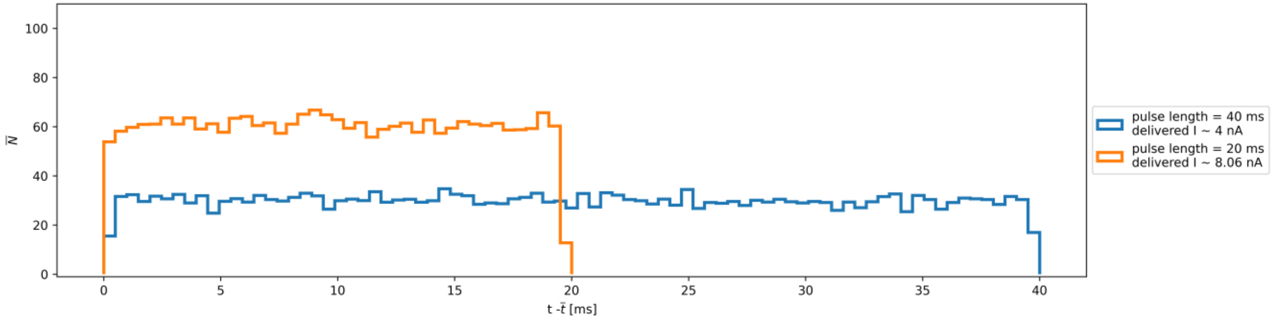
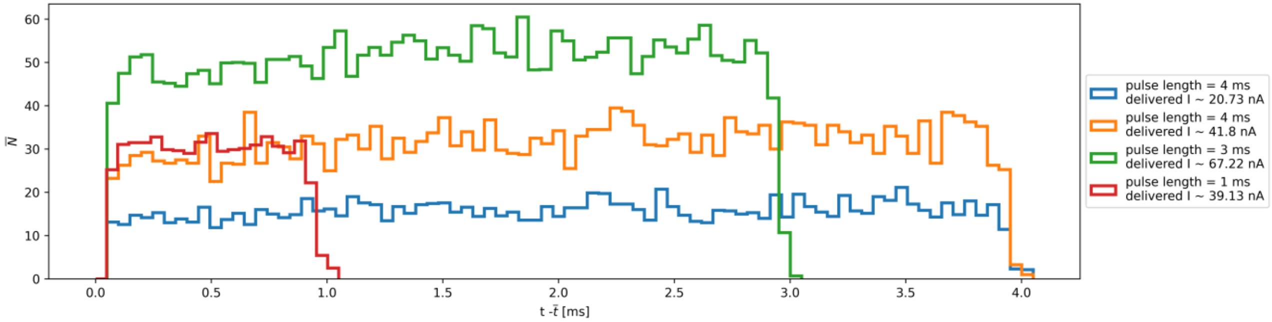


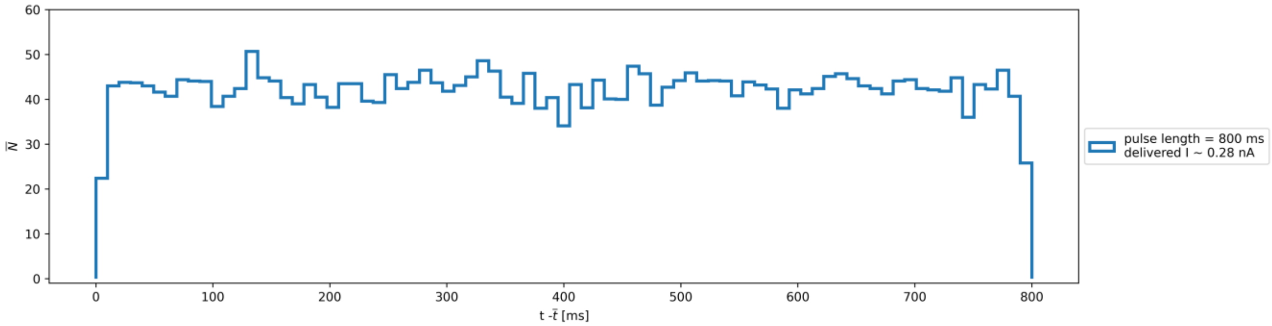
Bin size: 50 µs



Bin size: 500 µs



Bin size: 50 µs



Bin size: 10 ms

Secondary radiation – proton UHDPP

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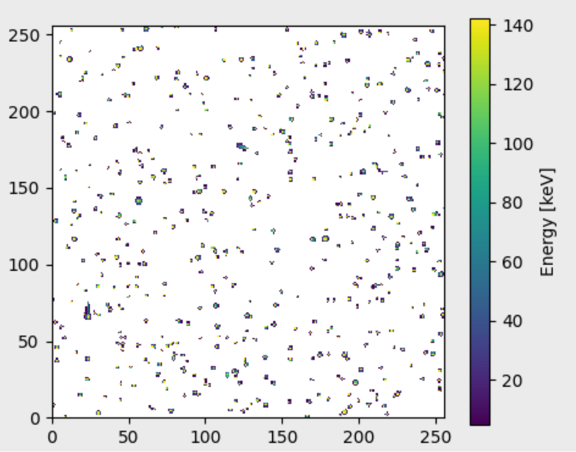
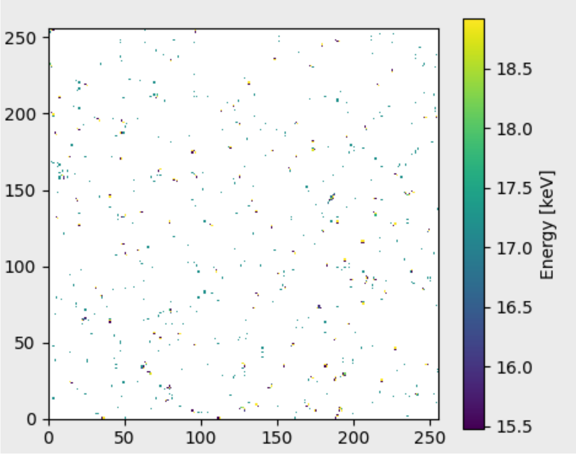
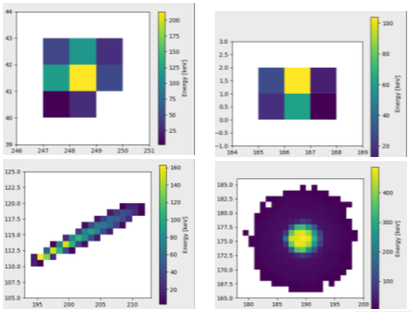
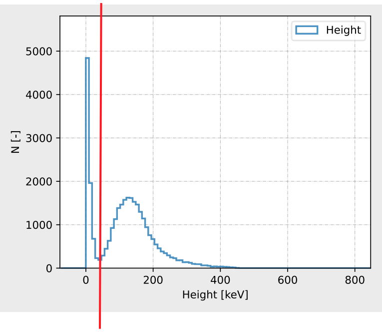
Radiation field can be decomposed into two components – both components contribute constantly throughout irradiation.



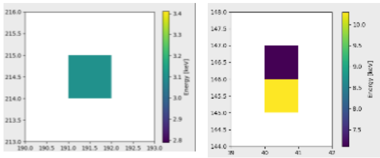


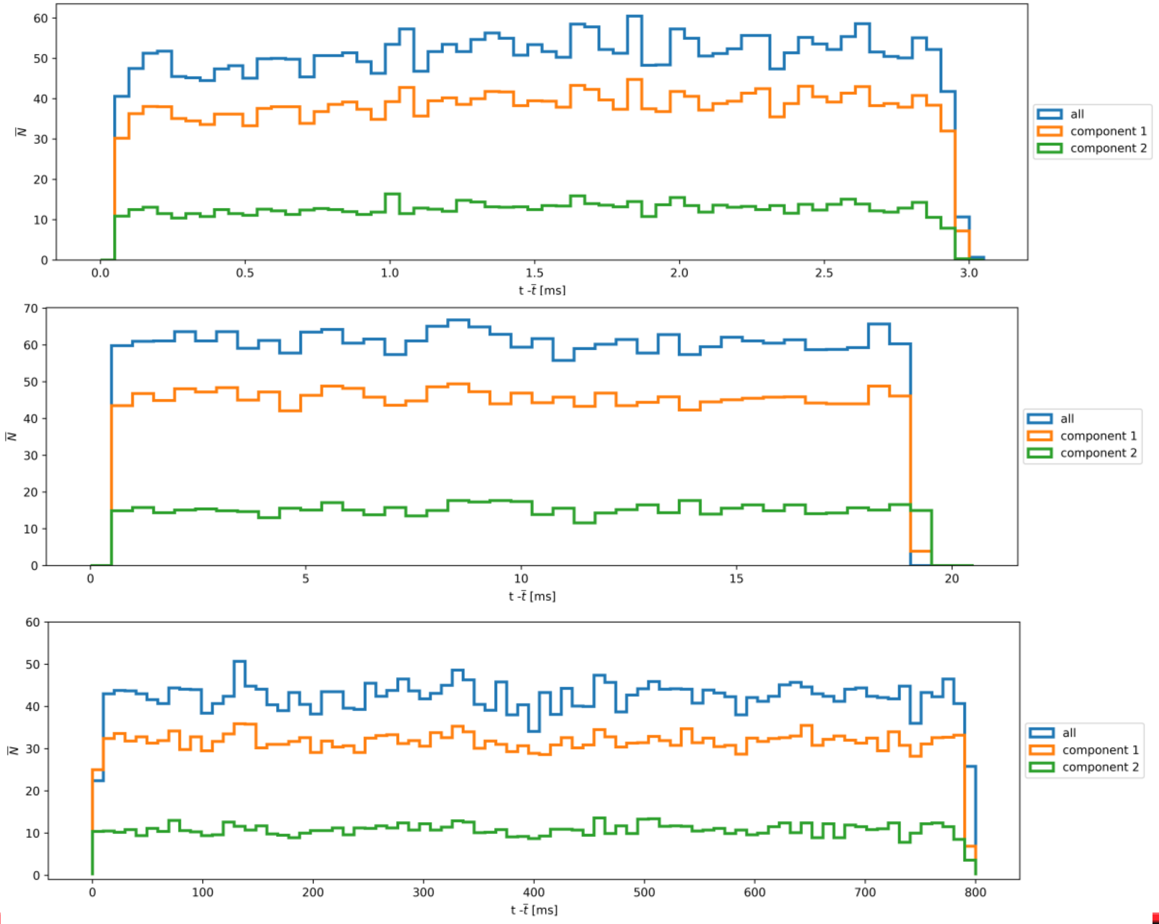
Component 1 ~ protons
+ high energy photons





Component 2 ~ low energy photons





Dose rate – proton UHDPP

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Different delivered beam currents, i.e. different delivered dose rates:

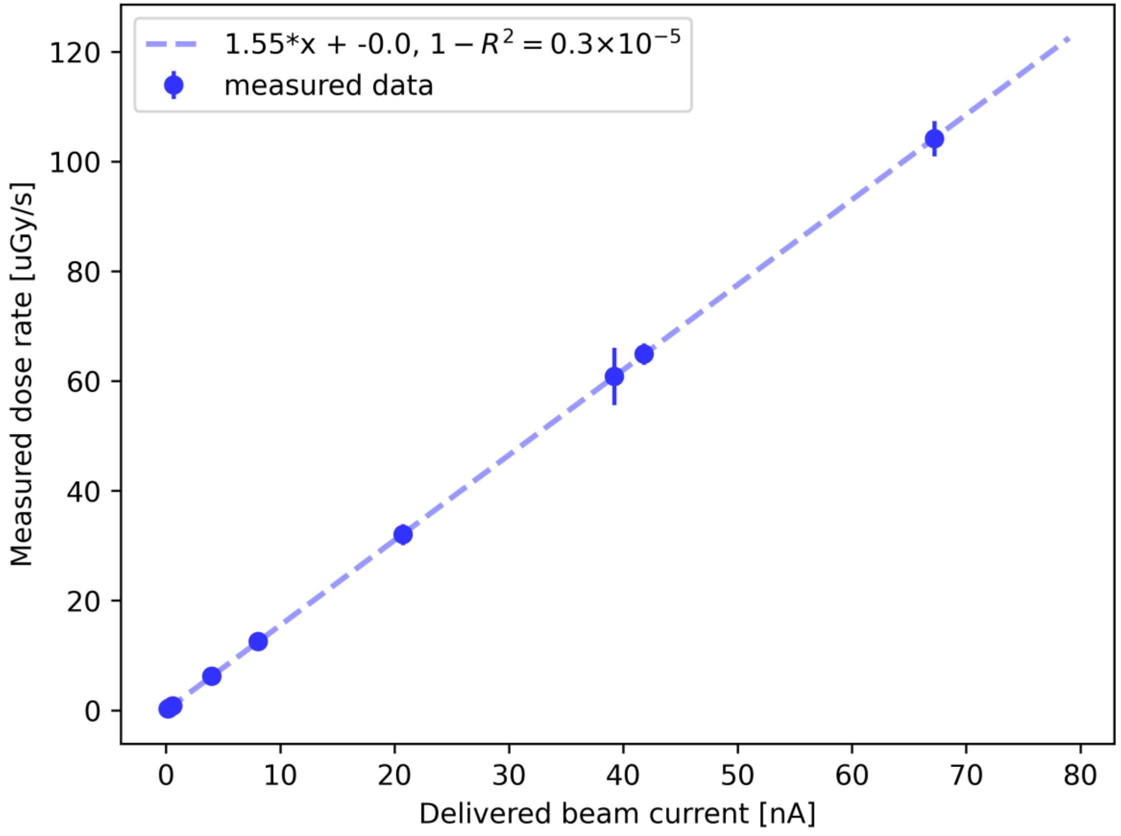
Delivered beam current [nA] ~ 1.4 * Delivered dose rate [Gy/s]

↓

Linear relationship between delivered beam current and measured dose rate

↓

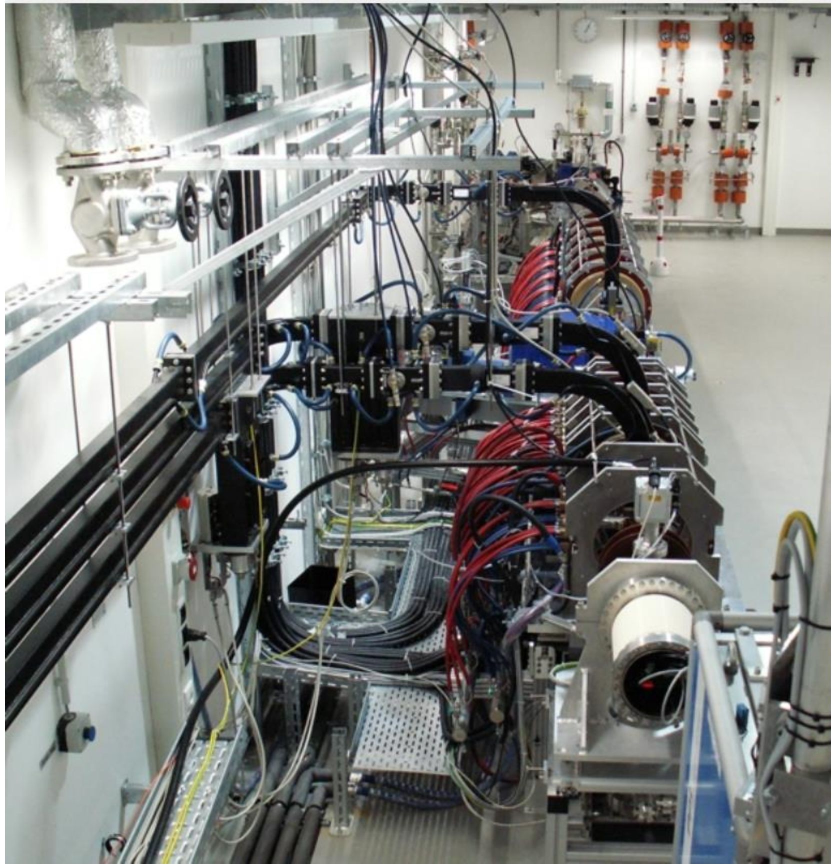
For a given experimental configuration, two (three) dose rate measurements are sufficient to establish the relationship between delivered beam current and measured dose rate.



UHDPP electron beam characterization

Experimental setup – electron UHDPP

Electron accelerator facility in the Physikalisch-Technische Bundesanstalt (PTB), Germany

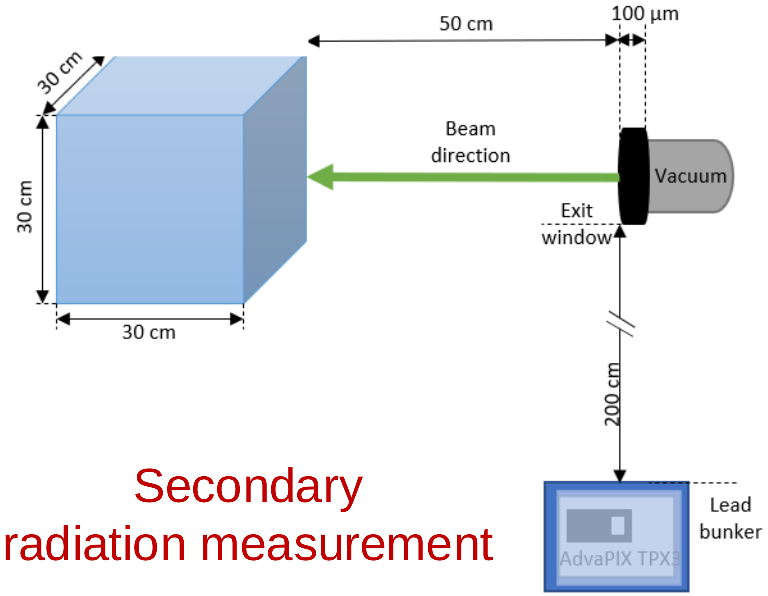


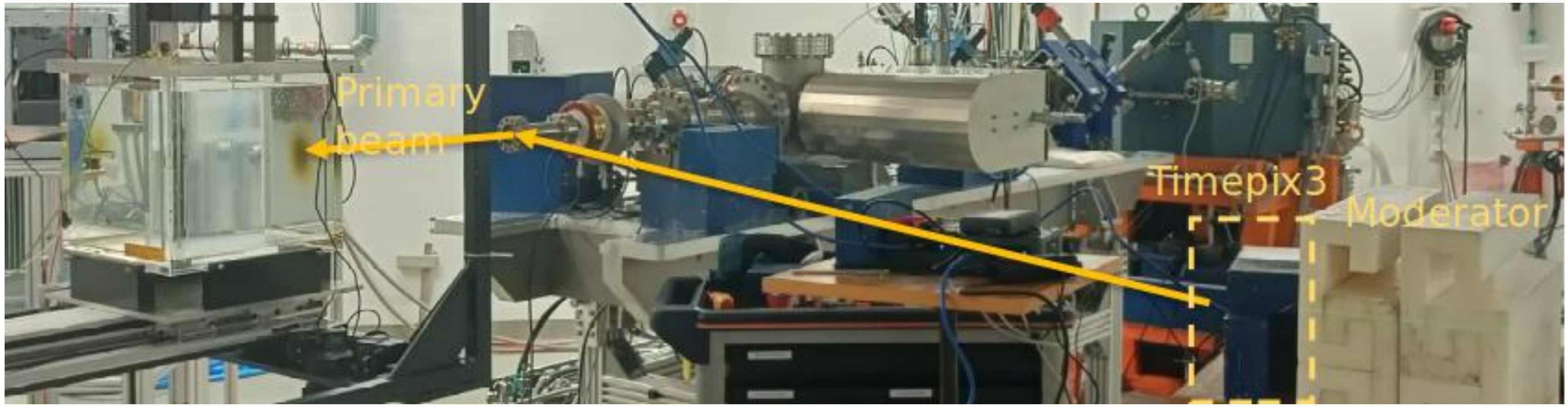
Primary beam setup:

- Ultra-high dose-per-pulse (UHDPP) electron beam
- Linear electron accelerator
- 20 MeV primary beam energy
- 0.1 mm Cu exit window
- Pulse lengths 1.18 – 2.88 μs
- Two LINAC configurations with estimated instantaneous delivered dose rate 0.81 $Gy \cdot \mu s^{-1}$ and 2.62 $Gy \cdot \mu s^{-1}$

Experimental setup – electron UHDPP

Electron accelerator facility in the Physikalisch-Technische Bundesanstalt (PTB), Germany





Secondary
radiation measurement

Moderator

AdvaPIX TPX3:

- Si, 1000 µm
- TOT and TOA measurement
- Data-driven mode

Measure delivered dose rate, irradiation time per pulse (pulse length), pulse time structure.

Experimental setup – electron UHDPP

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Electron accelerator facility in the Physikalisch-Technische Bundesanstalt (PTB), Germany

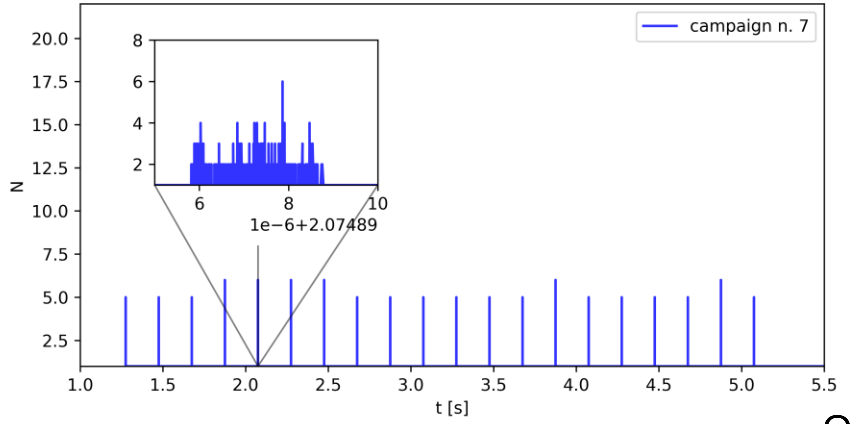
	Campaign #	*Pulse length [µs]*	*LINAC configuration (estimated dose rate [Gy·µs^{-1}])*	*# of delivered pulses*
Configuration 2	1	1.18	2.62	21
	2	1.52	2.62	21
	3	1.82	2.62	20
	4	2.10	2.62	21
	5	2.36	2.62	20
	6	2.64	2.62	20
	7	2.88	2.62	20
Configuration 0	8	1.18	0.81	21
	9	1.52	0.81	22
	10	1.82	0.81	21
	11	2.10	0.81	21
	12	2.36	0.81	21
	13	2.64	0.81	21
	14	2.88	0.81	20

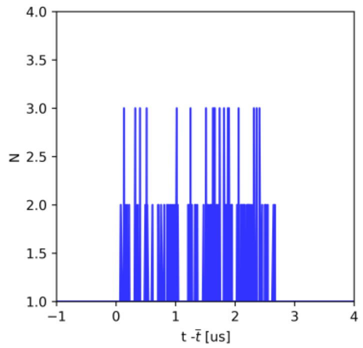
Frequency of delivered pulses was fixed to 5 Hz

Experimental setup – electron UHDPP

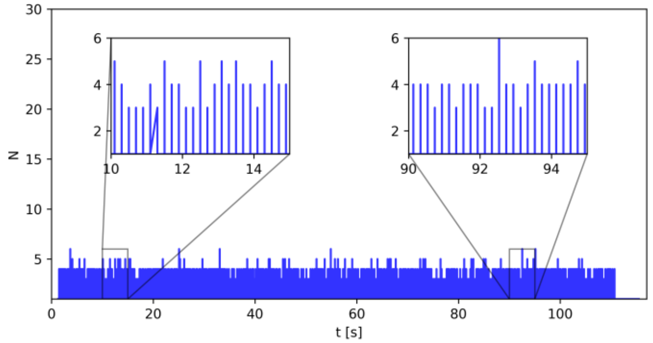
Electron accelerator facility in the Physikalisch-Technische Bundesanstalt (PTB), Germany

Pulses with ~ 1 μs length were clearly distinguished. Correct frequency of 5 Hz was recovered for all measurement campaigns.





One pulse (1.6 ns time binning)



Pulse frequency of 5 Hz was measured even for longer acquisition times

Configuration 2 (campaigns 1–7)

Configuration 0 (campaigns 8–14)

Campaign #	Pulse length [μs]	LINAC configuration (estimated dose rate [Gy·μs^{-1}])	# of delivered pulses
1	1.18	2.62	21
2	1.52	2.62	21
3	1.82	2.62	20
4	2.10	2.62	21
5	2.36	2.62	20
6	2.64	2.62	20
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9	1.52	0.81	22
10	1.82	0.81	21
11	2.10	0.81	21
12	2.36	0.81	21
13	2.64	0.81	21
14	2.88	0.81	20

Frequency of delivered pulses was fixed to 5 Hz

Pulse length – electron UHDPP

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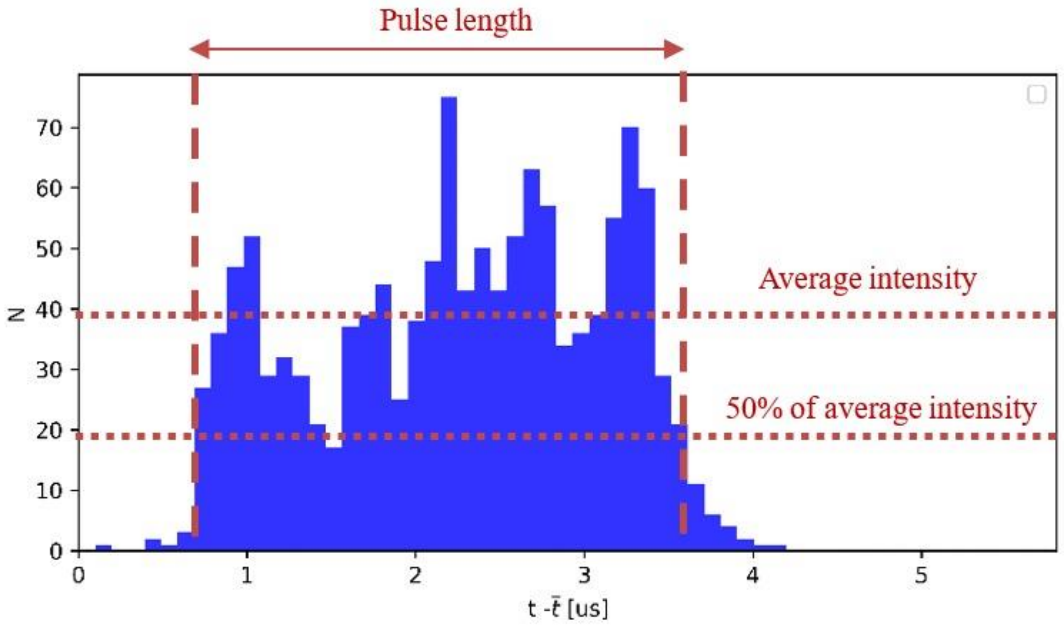
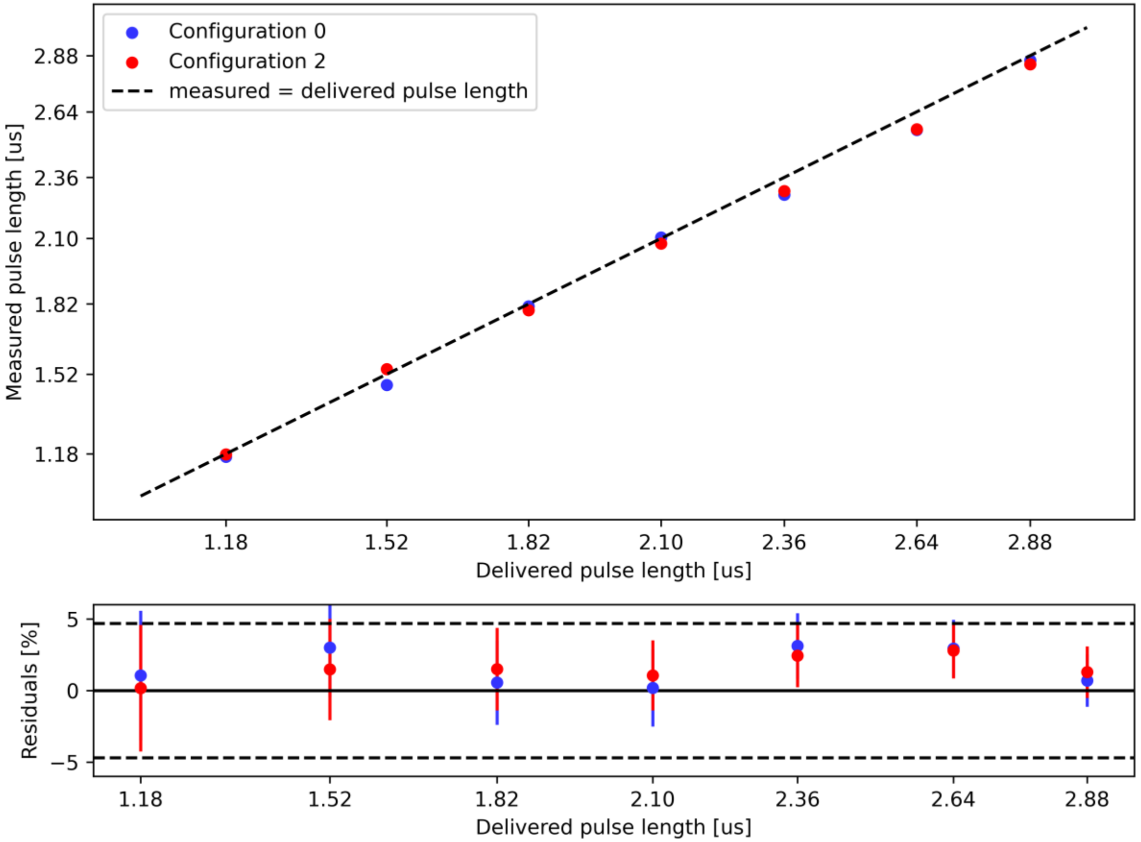
Start and end of pulse are determined by signal crossing 50% of the mean signal intensity - consistent with the pulse length definition used in ICT measurements.



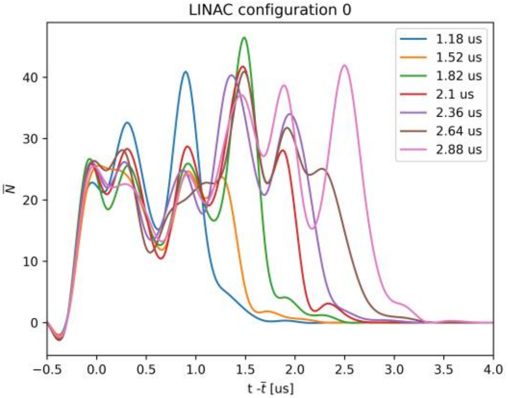
Data binned in 100 ns time intervals

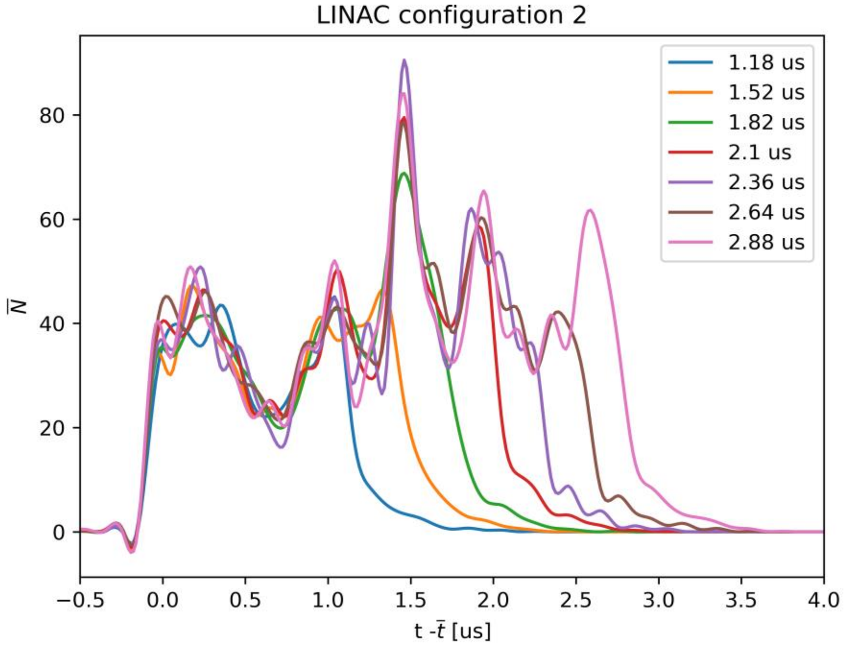


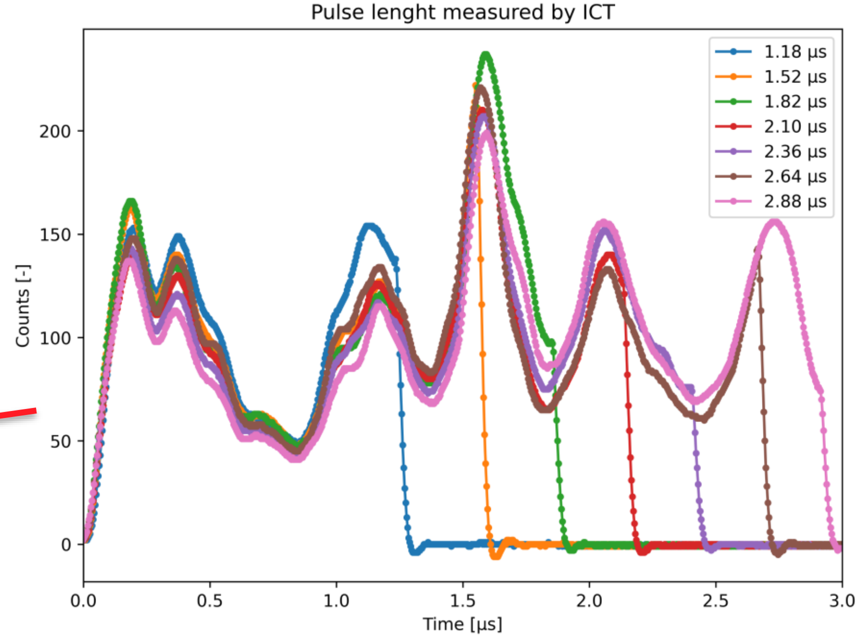
Pulse structure – electron UHDPP

Despite variations in pulse length, the average time structure measured by out-of-field positioned detector remains remarkably consistent.

Pulse structure measured in beam by ICT







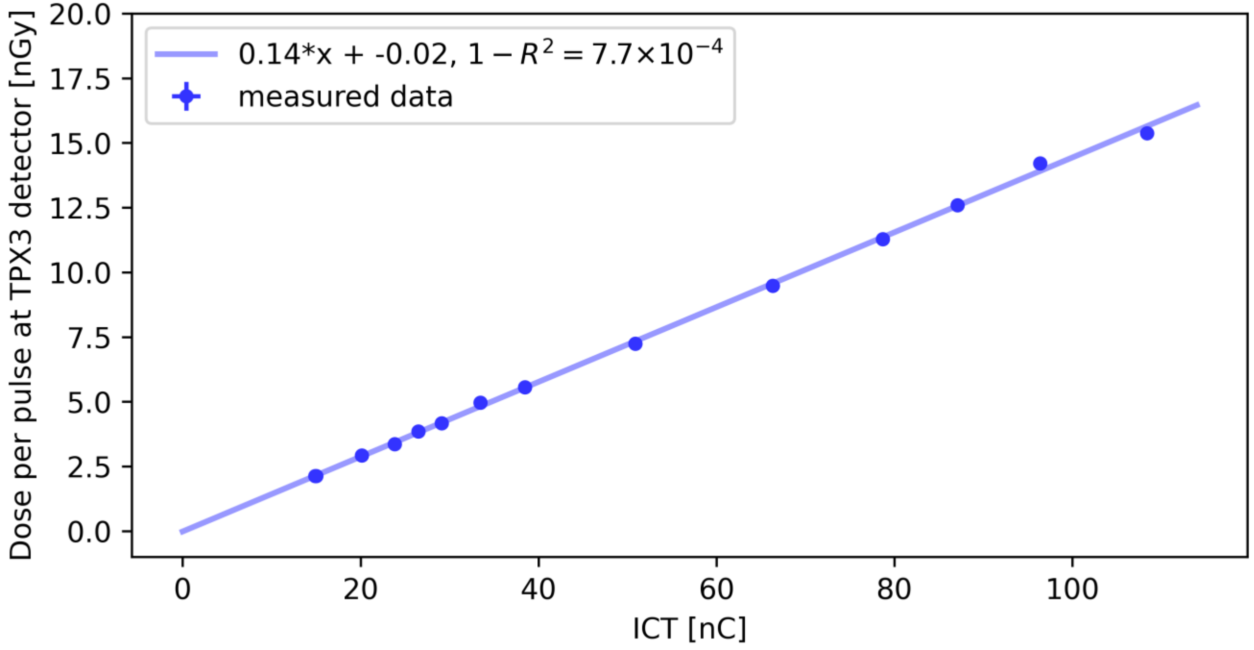
Dose rate – electron UHDPP

Different delivered dose per pulse (~ 1-8 Gy/pulse) corresponds to different delivered charge measured in beam by ICT

↓

Linear relationship between delivered ICTs and measured dose rate (nGy/pulse!)

↓



For a given experimental configuration, two (three) dose rate measurements are sufficient to establish the relationship between ICTs and measured dose rate.

Conclusions

AdvaPIX Timepix 3 positioned **out-of-field** proved to be a powerful detector for beam monitoring in (FLASH) radiotherapy as demonstrated for electron and proton beams.

- Individual beam pulses are clearly identified and the correct pulse count and pulse frequency are found.
- Pulse length is determined from secondary radiation measurements.
- Time beam structure is recognized.
- Linear relationship between delivered and measured dose rate was found – Timepix3 out-of-field dose measurement can be used to determine delivered dose once the linear relationship is established with few initial measurements.