In-field and out-of-field microdosimetric characterization of proton beams using the Timepix3 detector

Cristina Oancea[1], Lukas Marek[1,5], Jiri Pivec[1], Carlos Granja[1], Jan Jakubek[1], Elisabeth Bodenstein[2], Jörg Pawelke[2,3] Jaroslav Solc[4], Zdenek Vykydal[4]

[1] ADVACAM, U Pergamenky 12, 170 00 Prague 7, Czech Republic

[2] Oncoray - National Center For Radiation Research In Oncology, Faculty Of Medicine And University Hospital Carl Gustav Carus, Technische Universität Dresden, Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany

[3] Helmholtz-zentrum Dresden-Rossendorf, Institute Of Radiooncology - Oncoray, Dresden, Germany

[4] Czech Metrology Institute (CMI), Okruzi 31, Brno, Czech Republic

[5] Institute of Particle and Nuclear Physics, Faculty of Mathematics and Physics, Charles University, Czech Republic

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cristina.oancea@advacam.com

Outline

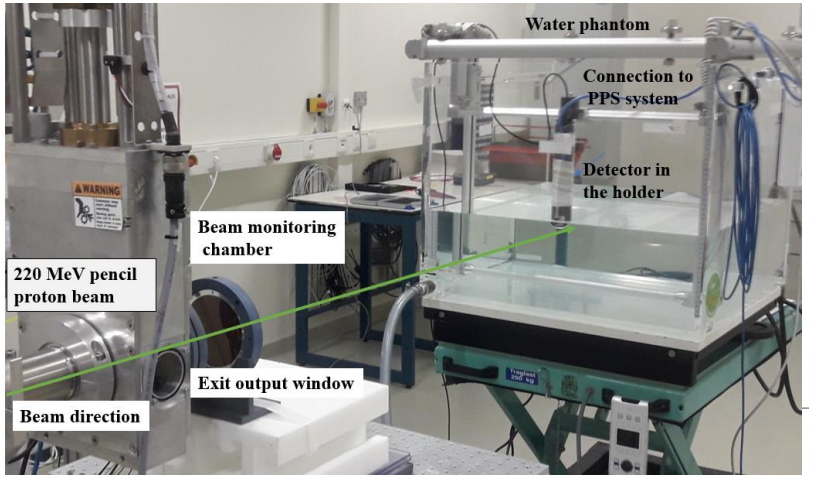
- Aim
- Experimental setup in proton beams
- Timepix3 detector
- Calibrations in the reference neutron fields
- Results
- Summary

Motivation

- **Aim:** Spectral and component characterization of secondary particles produced in proton beams using a pixel detector
- Spectral tracking and **LET measurements** of **light** and **heavy charged particles** in a water-phantom
- Flux and dose rate of the **scattered radiation** (protons, electrons, X rays, gamma, neutrons)

Experimental setup

Experimental setup

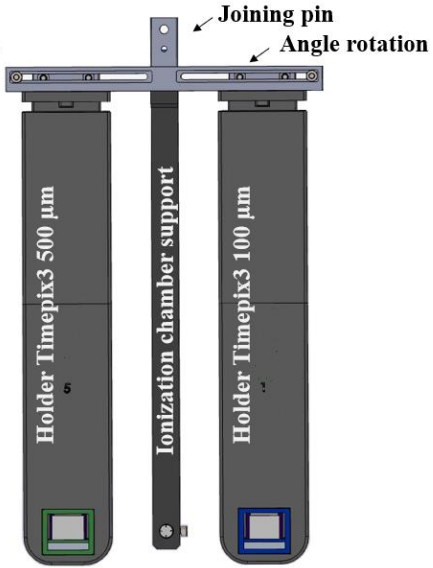


University Proton Therapy Dresden, horizontal research beamline (IBA cyclotron)

- **Stationary 220 MeV proton pencil beams**
- Pulsed beam structure with specified dose rates from **0.01 to 360 Gy/s**
- Timepix3 placed laterally (24 positions) perpendicular to the beam direction
- Multiple depth measurements ranging from the entry region to distal of the Bragg peak (BP).

Experimental setup

Detection system

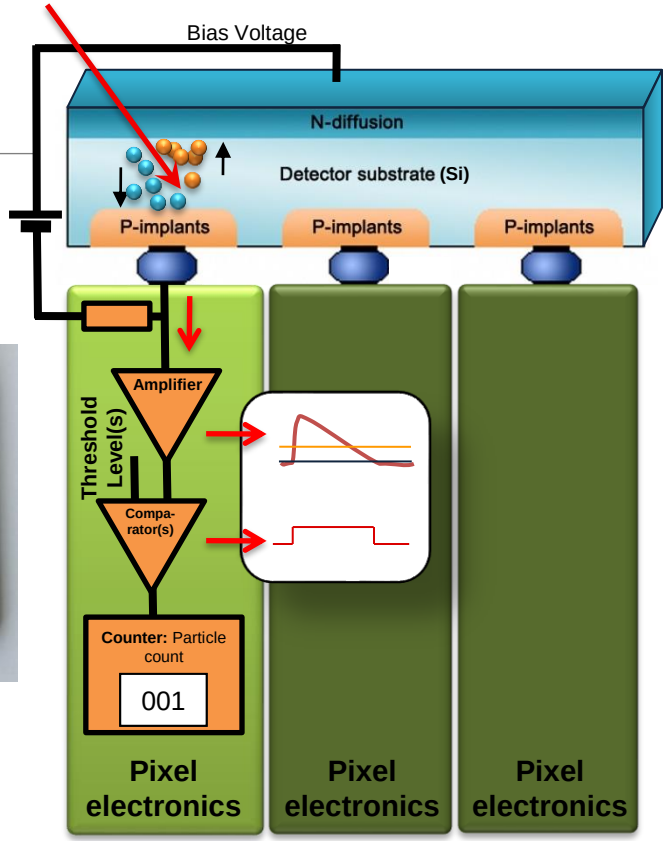


Beam parameters

Pulse length [s]	Intensity [nA]	MU [nA*s]
10	0.03	0.3
5	0.06	
3	0.1	
1	0.3	
0.1	3	
0.05	6	
0.01	30	
0.005	60	
0.003	100	

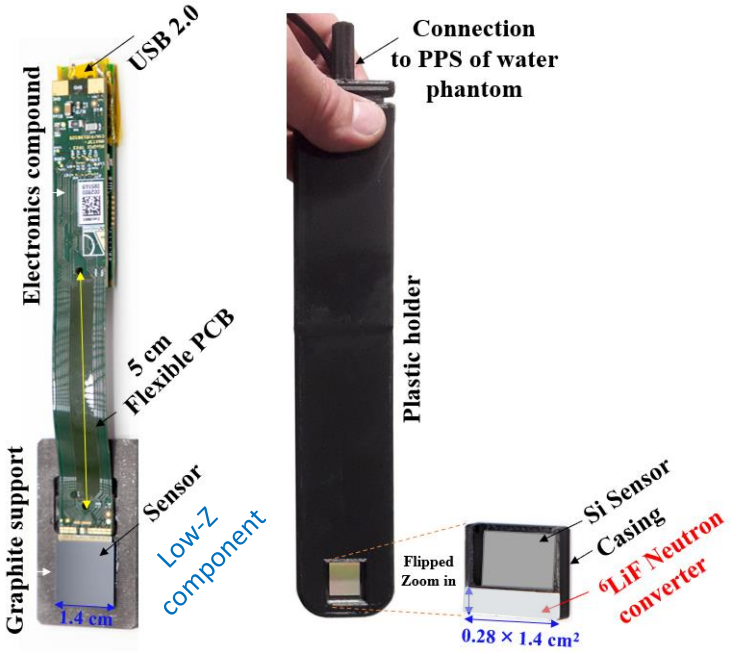
Timepix3 – a hybrid semiconductor pixel detector

- Hybrid semiconductor pixel detector Timepix family from CERN which provide per-pixel response of:
  - energy
  - time
  - counting
- Over 65 000 pixels
- Pixel pitch 55 µm
- Energy threshold 3 keV for silicon sensors
- Time resolution 1.6 ns for Timepix3 chips



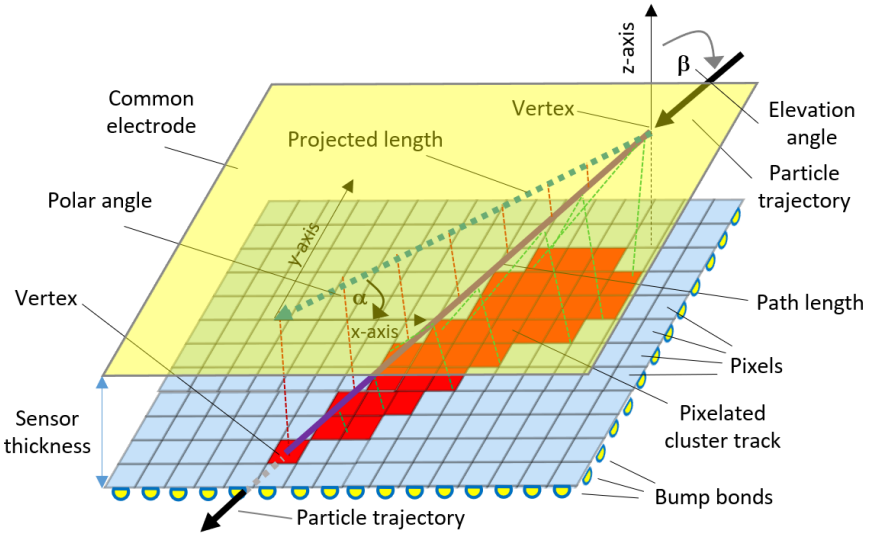
MiniPIX Timepix3-Flex pixel detector

Timepix3 Si 500 µm



- Customized **waterproof miniaturized radiation detector**
- ASIC chip with Si sensor in **low-Z** chipboard and **support**
- Sensor area: **14 mm × 14 mm = 65 k pixels** (55 µm x 55 µm)
- Simultaneous measurement of **deposited energy** and **time**
- **100%** detection efficiency for charged particles, wide FoV
- **Thermal neutrons** detected with ^{6}LiF converter

LET, flux and dose rate measurements



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❑ **Particle flux and DR**

- Per-pixel deposited energy
- Time of arrival of each particle

❑ **LET** in silicon

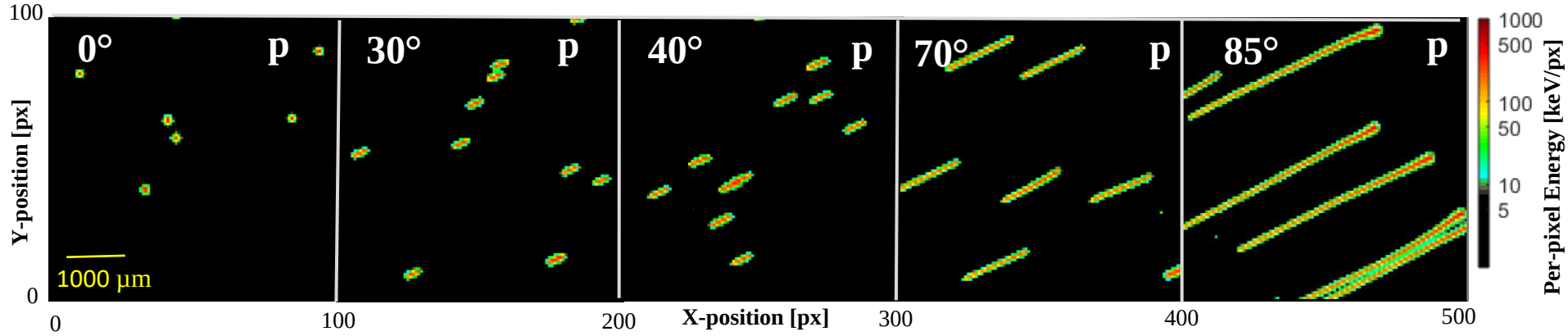
- **Wide range** (0.1 to >100 keV/μm)
- **Wide Field of View** (2π)

$LET = \frac{E}{x}$, **E** = cluster energy,
x = 3D length

Particle Tracking with TimePIX3

Directional LET measurements vs particle type and angle

- In-beam measurements, 31 MeV protons
- Precise measurement of position, deposited energy, time, direction



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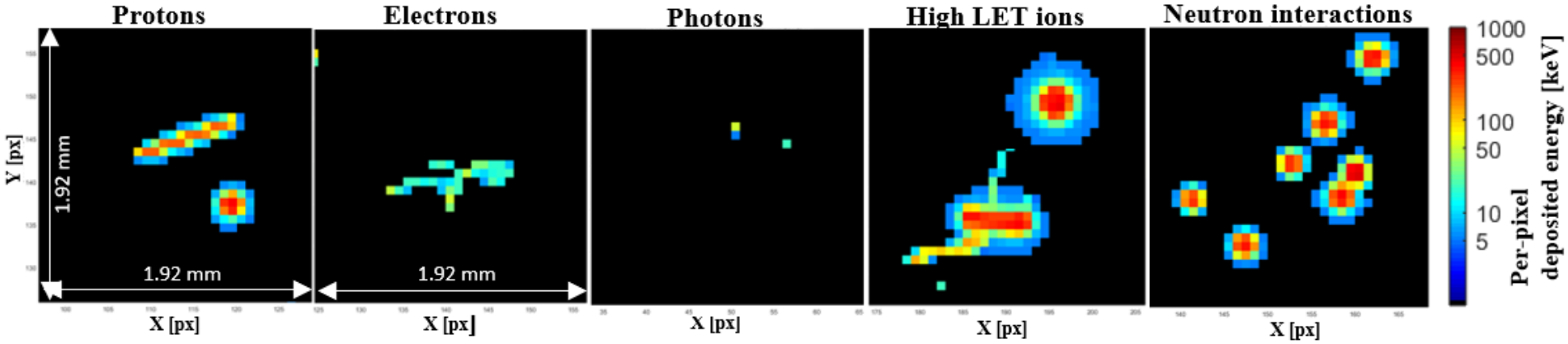
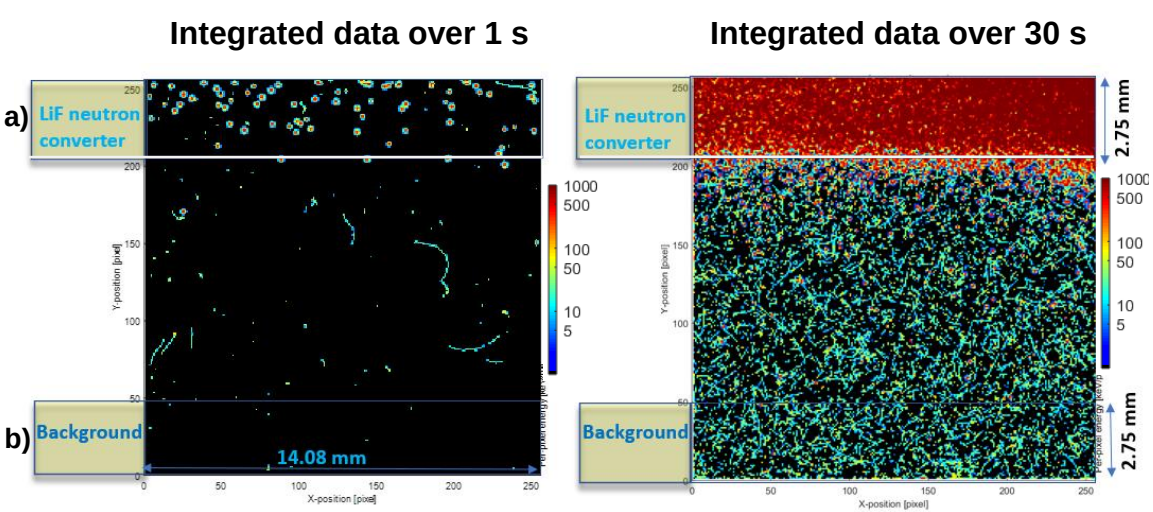
public research institution

Spectral tracking and imaging of single particles

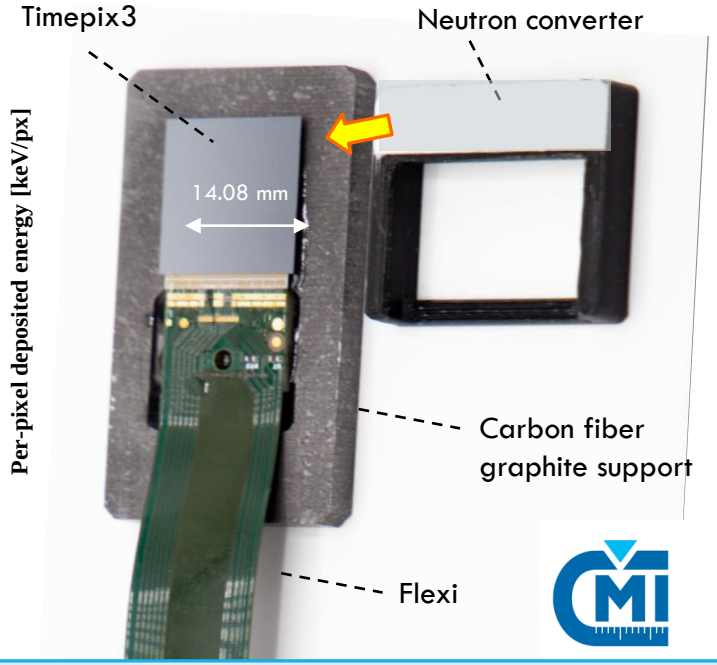


- Precise measurement of position, deposited energy, time, direction

Calibration of Timepix3 detector for thermal neutrons



Area displayed: 14 x 14 mm²

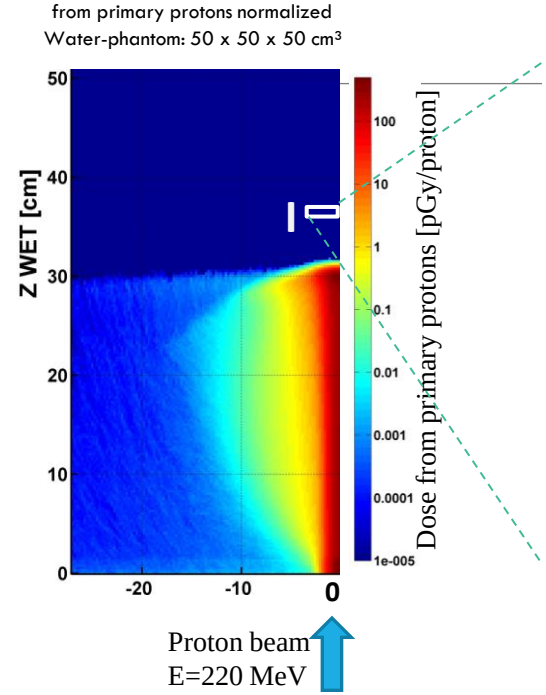


- Thermal neutron detection efficiency, k = 1.15% ± 0.038%

Results

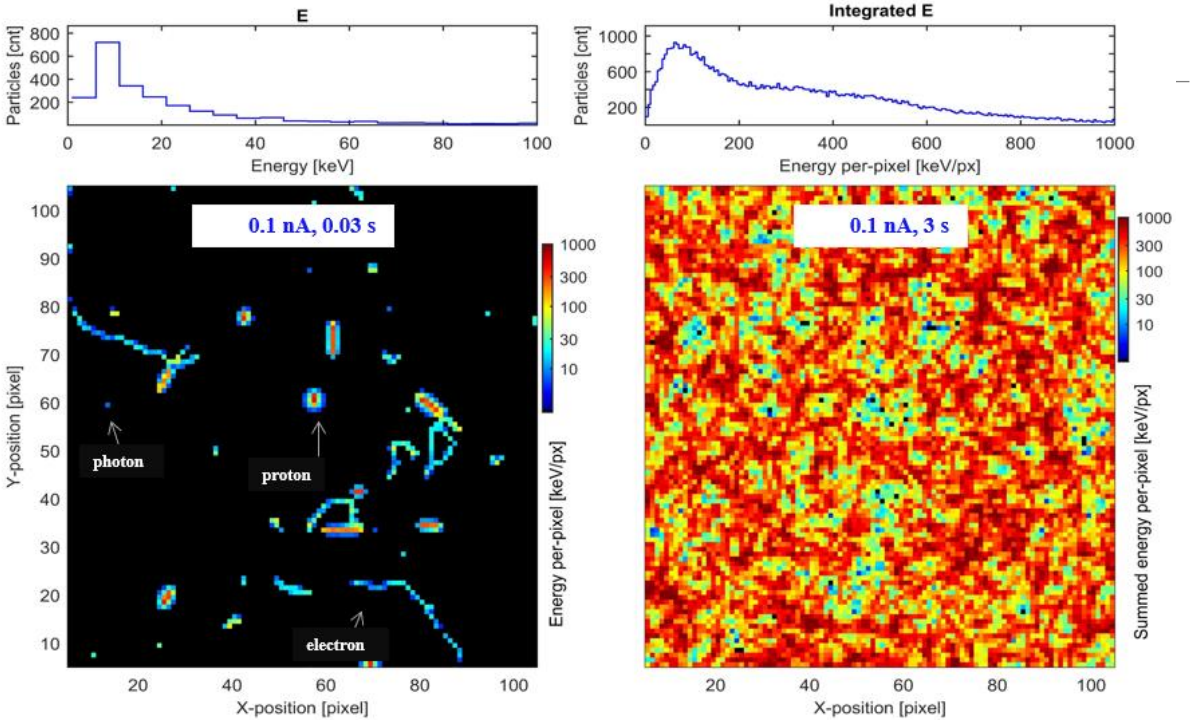
What is behind the Bragg peak?

MC simulation 2D dose



MC simulations provided by J. Solc, CMI

Measured deposited energy by Timepix3 in event mode

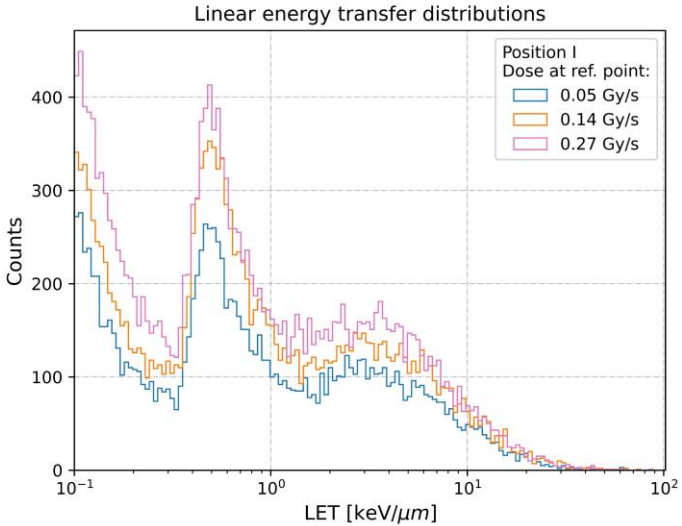


- Scattered particles due to neutron interactions

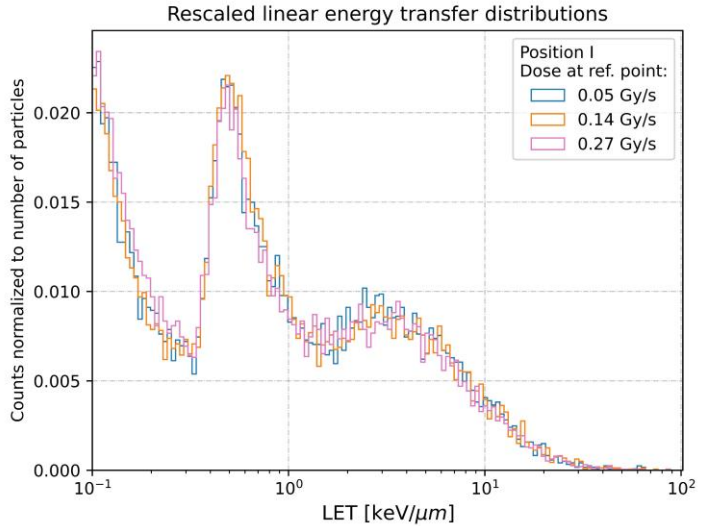
Normalization of the LET spectrum

low-intensity beams, 5 cm behind the BP

LET measured at low-DR



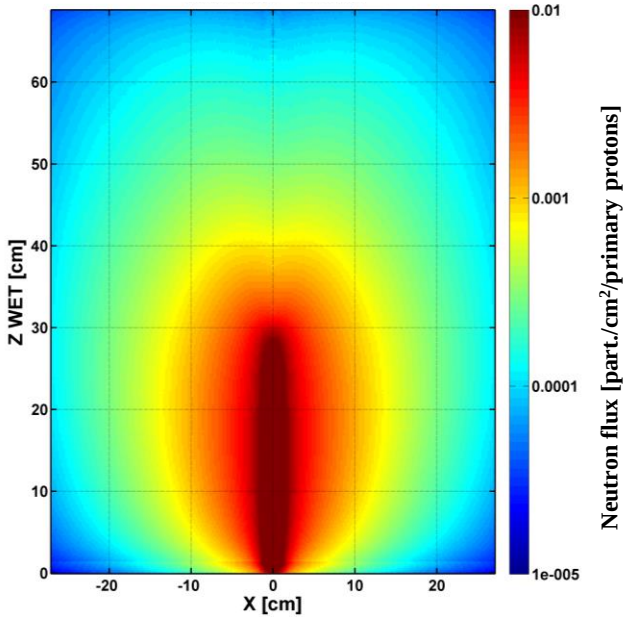
LET normalized by number of particles



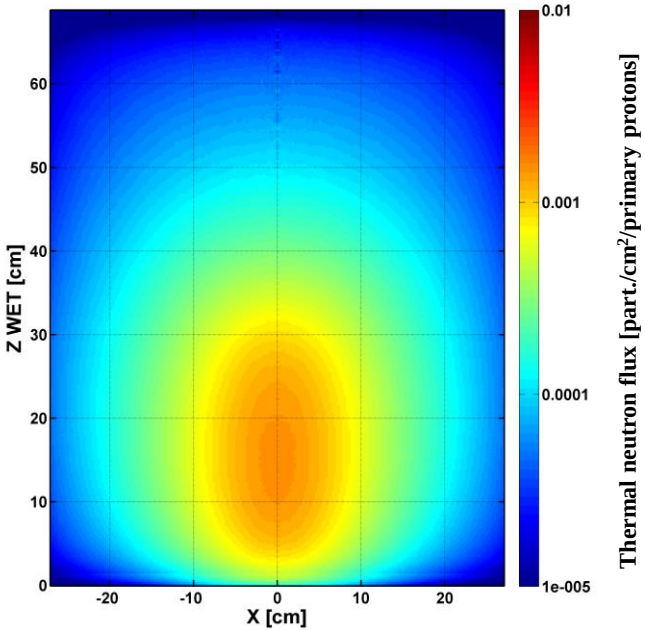
- *Same LET distribution over different field intensities*

MC simulation of neutron fluence inside a water-phantom

MC simulation of spatial distribution of all neutron fluence*



MC simulation of spatial distribution of thermal neutron fluence*



*Provided by J. Solc, CMI

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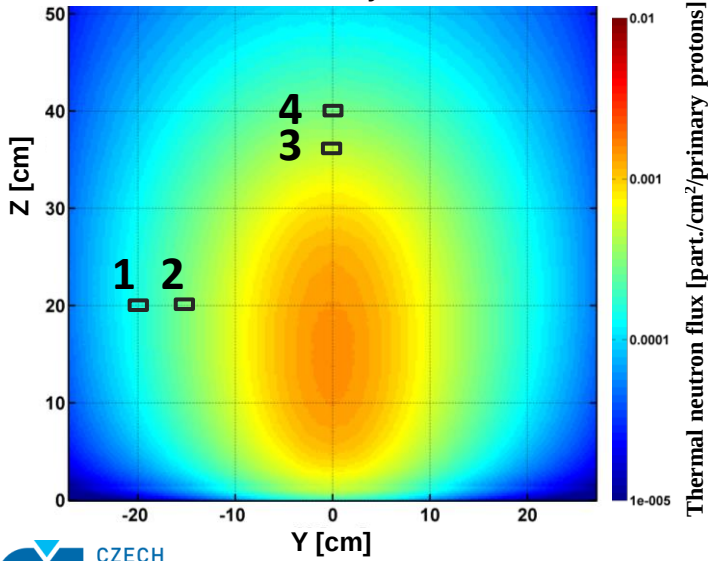
Preliminary results: thermal neutron flux in proton beams

MC simulation of spatial distribution of thermal neutron fluence

Provided by CMI



Measured thermal neutron flux for a DR at the reference point of 0.27 Gy/s

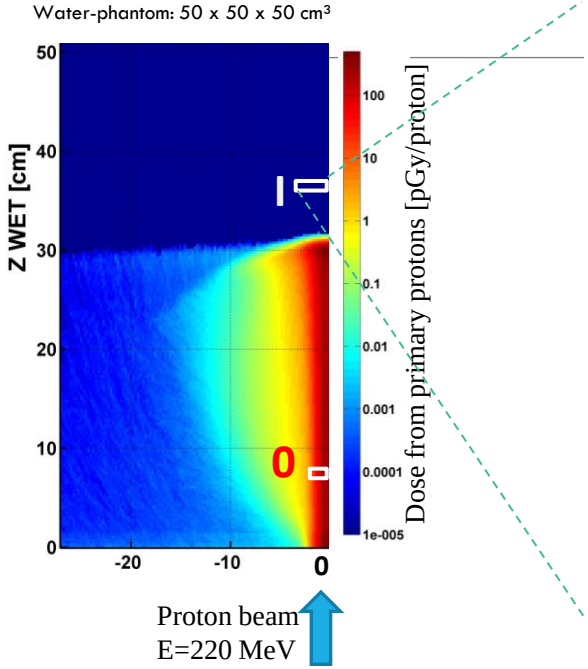
Position inside water	Φ with detection efficiency constant [particles/cm²/s]
1	1.2E+04
2	2.7E+04
3	4.1E+04
4	2.5E+04

- *Thermal neutron flux in a water phantom should be an unneglected component*

What is behind the Bragg peak at FLASH DR?

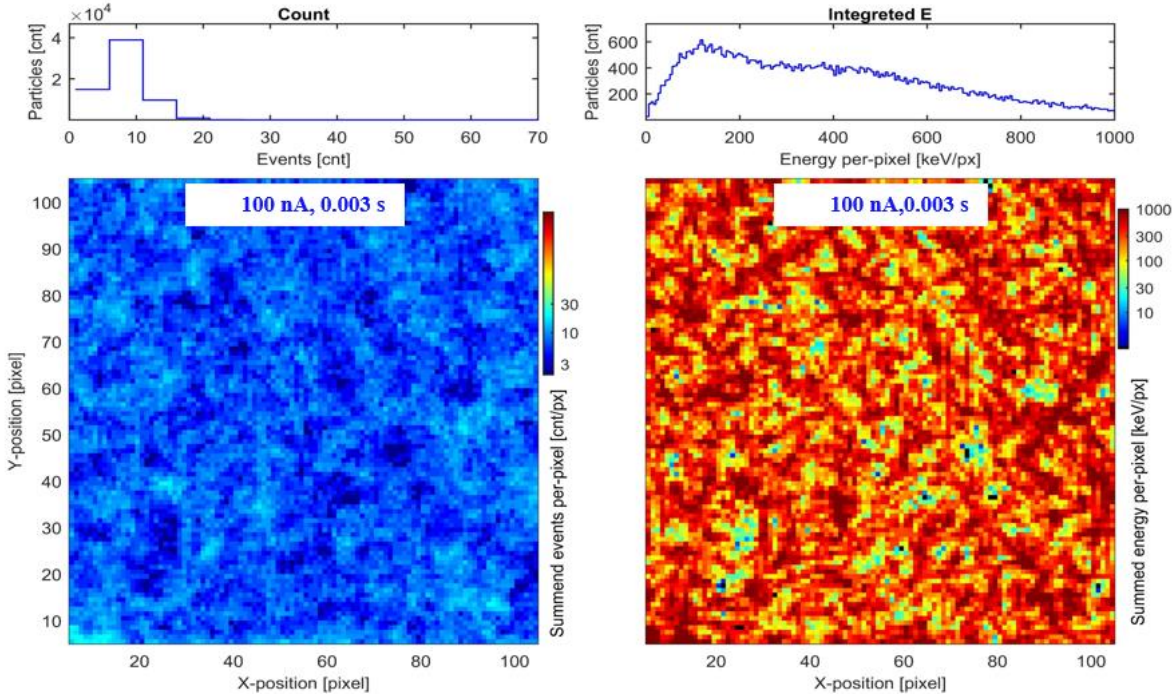
MC simulation 2D dose

from primary protons normalized
Water-phantom: 50 x 50 x 50 cm³



MC simulations provided by J. Solc, CMI

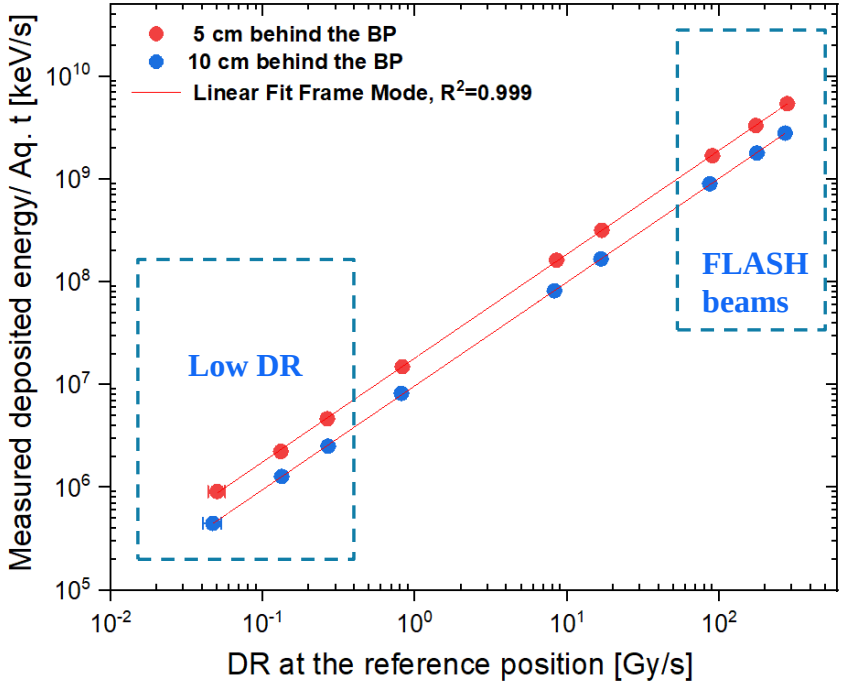
Timepix3 detector operated in integrated mode



- Scattered particles due to neutron interactions

Linear deposited energy response for wide range of dose rates (DR)

from conventional to FLASH-like proton beams



- *Linear response of deposited energy*
- *Conversion from deposited energy to dose in Si and dose in water*

Oancea et al submitted to Physica Medica, 2022

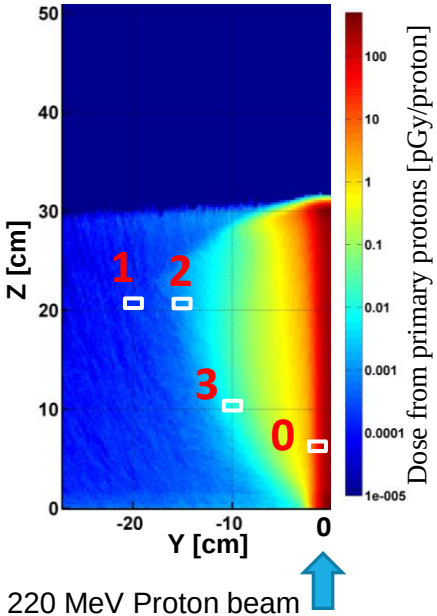
Deposited energy of scattered radiation lateral to the BP

Measured deposited energy by Timepix3 detector

MC simulation 2D dose

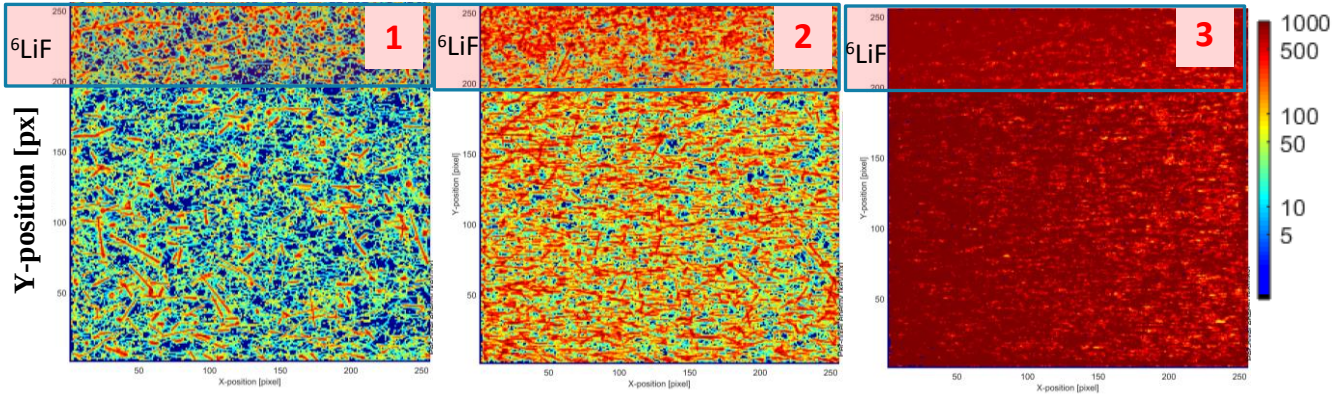
from primary protons normalized

Water-phantom: 50 x 50 x 50 cm³



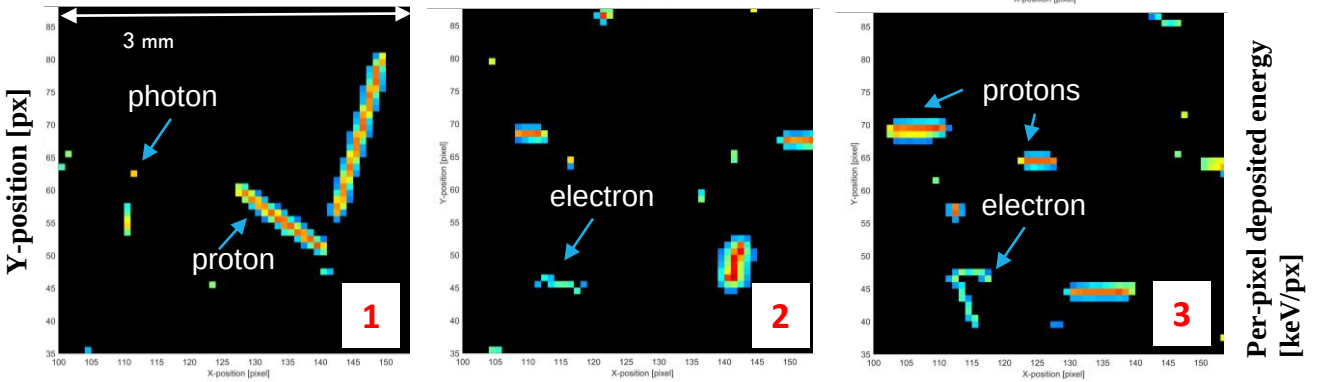
Integrated frame, 10 s

Entire sensor region = 2 cm²



Single frame, 0.1 s

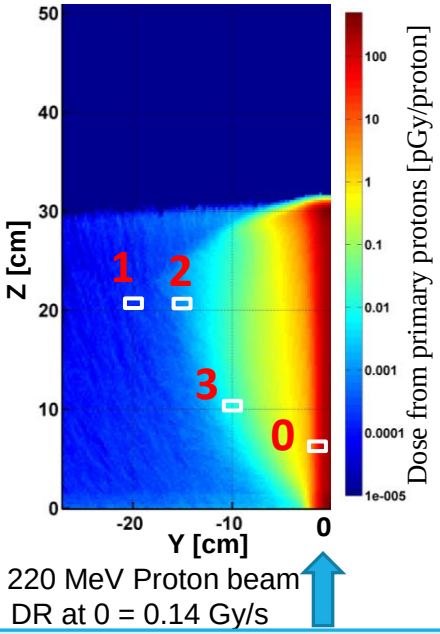
Small region of sensor: 4%



Results: Flux & DR of scattered particles

MC simulation 2D dose

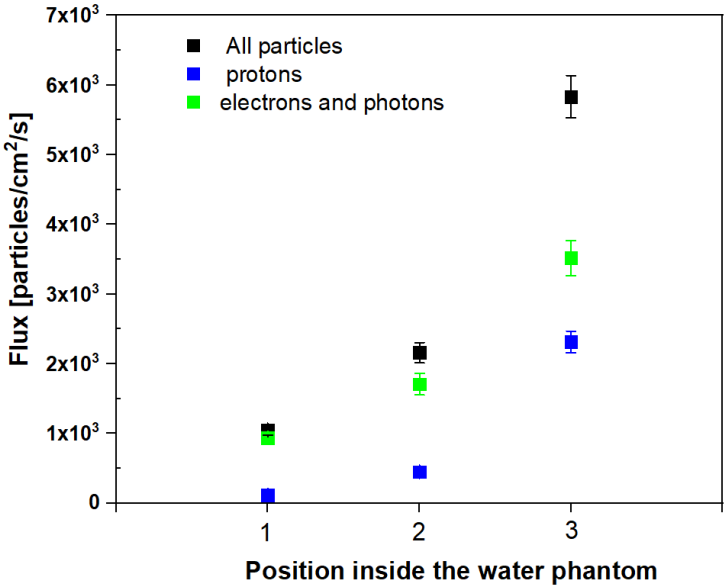
from primary protons normalized



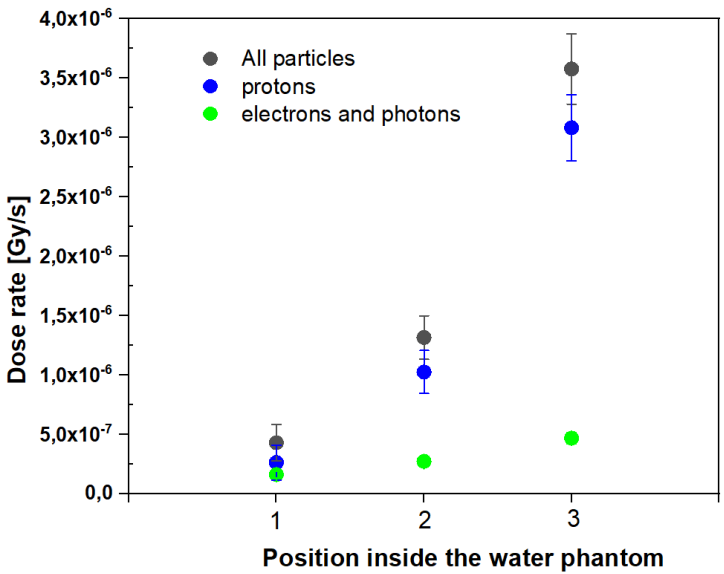
220 MeV Proton beam

DR at 0 = 0.14 Gy/s

Particle flux



Dose rate

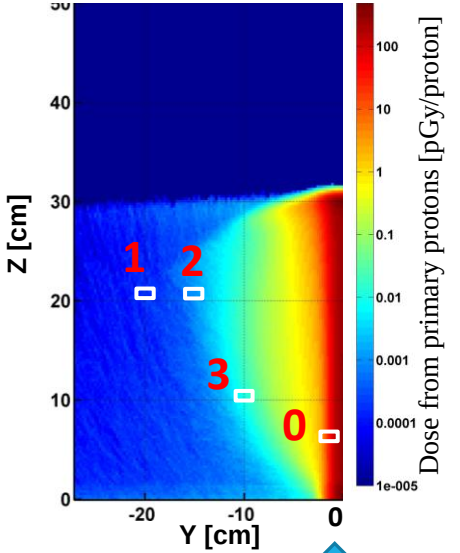


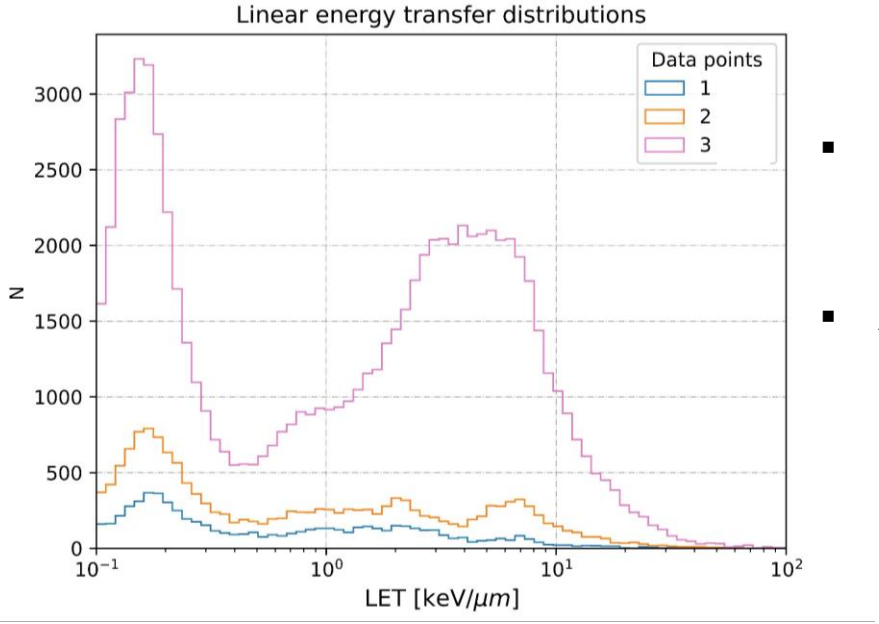
- *In agreement with MC simulations*

Results: LET histograms of stray radiation

MC simulation 2D dose

from primary protons normalized*





- *Predominantly low-LET particles*
- *At position 3 scattered particles with high-LET*

*Provided by CMI

DR at 0 = 0.14 Gy/s

Summary

- The newly developed MiniPIX TimePIX3-Flex was used to characterize the stray radiation fields of conventional and UHDR proton beams produced in a water phantom
- A methodology for the characterization of secondary radiation produced in proton beams (composition, flux, deposited energy and dose rate) in water was developed
- Linear response of deposited energy in silicon over a wide range of DR (from 0.14 Gy/s to 270 Gy/s)
- A new method for measuring the thermal neutron flux in proton beams was established.

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- http://uhdpulse-empir.eu/
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Jan Jakubek
Carlos Granja
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Jiri Pivec

Jörg Pawelke
Elisabeth Bodenstein
Sebastian Gantz

Jaroslav Solc
Zdenek Vykydal

Contact at **cristina.oancea@advacam.com**

Thank You!