

Towards including radiation quality in proton therapy treatment planning and dosimetry

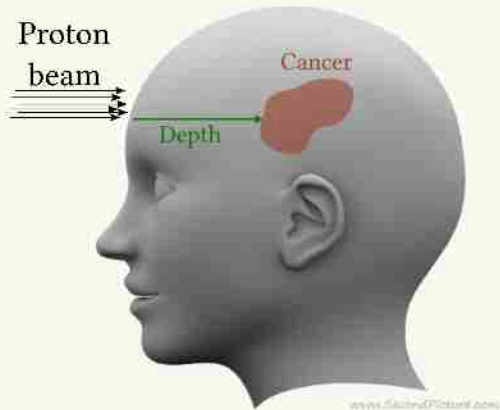
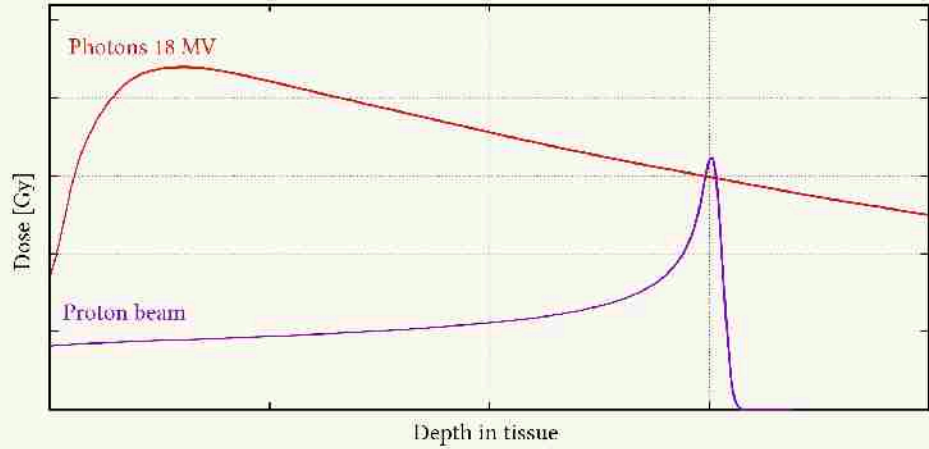
Jan Gajewski



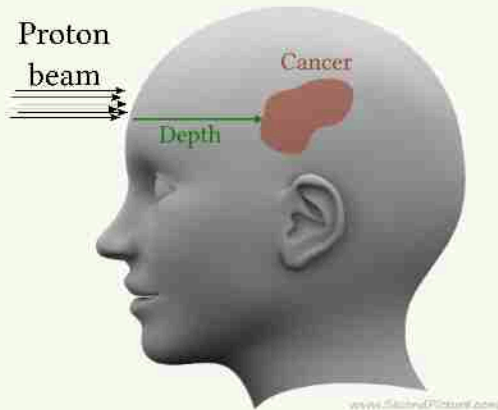
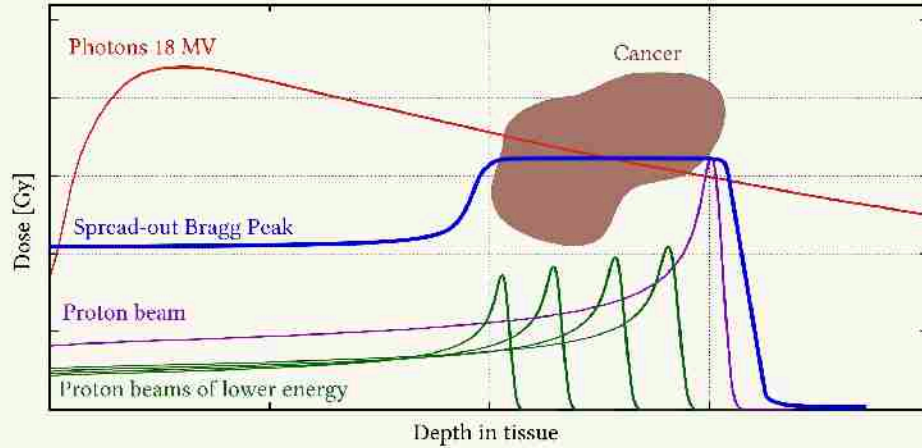
THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

Kraków, 22.04.2021

Proton Beam - energy and intensity modulation

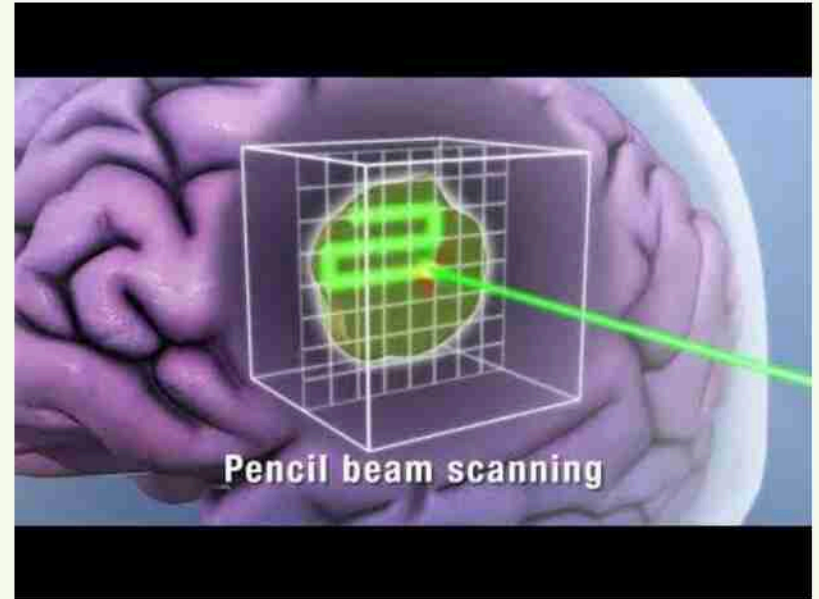
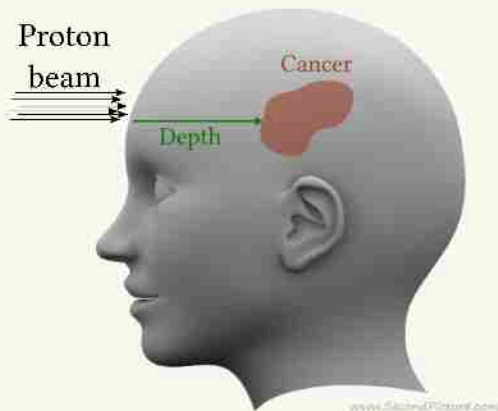
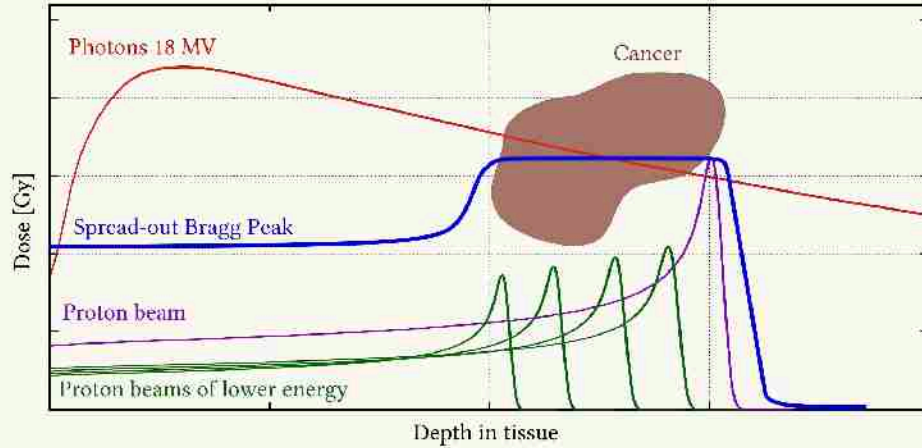


Proton Beam - energy and intensity modulation



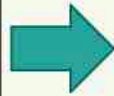
www.SchmidPittner.com

Proton Beam Scanning



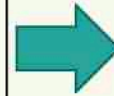
Motivation

Photon energy spectrum similar at any point



Biological effect correlated with deposited dose

Broad proton spectrum at different points



Biological effect dependent on dose and proton energy spectrum (radiation quality)

Outline

- State-of-the-art clinical methods for:
 - Proton facility commissioning
 - Treatment planning
 - Dosimetry
 - ... and their limitations

- Introducing radiation quality in proton therapy:
 - Treatment planning
 - Computational methods
 - Dosimetrical methods

Before we start
the treatment:

Commissioning of
Treatment Planning System

TPS commissioning for proton beam



Kraków, Poland



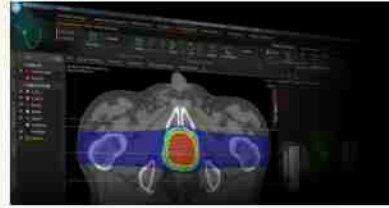
Maastricht, the Netherlands



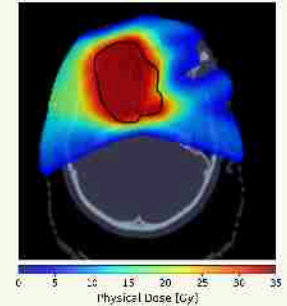
Atlanta, US

TPS commissioning for proton beam

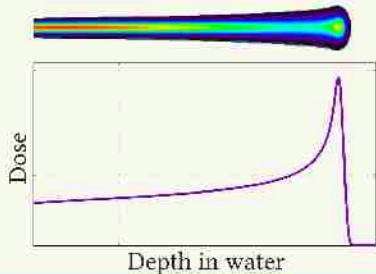
Treatment Planning System



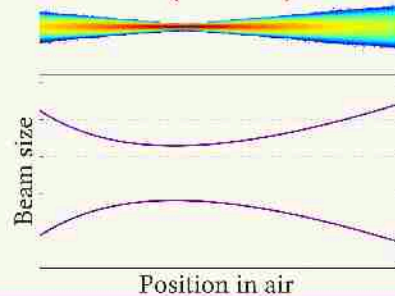
Accurate dose calculations



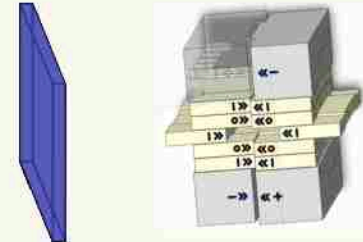
Depth dose distribution
(in water)



Lateral beam propagation
(in air)

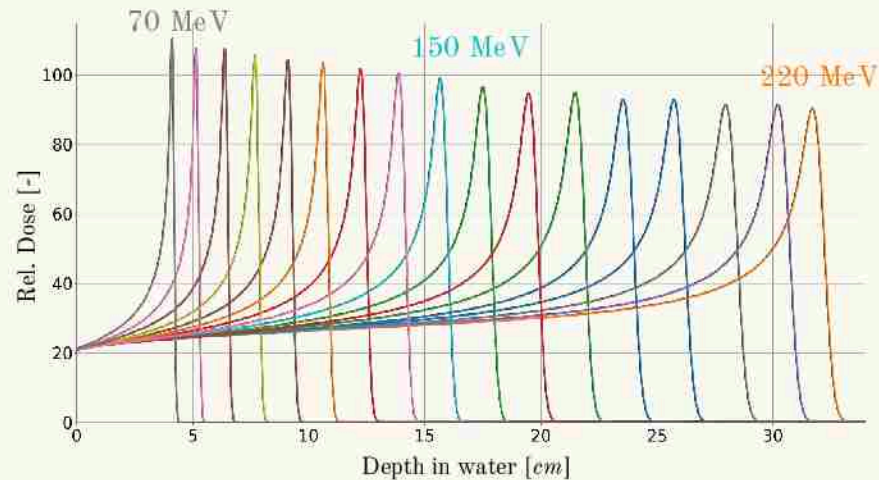
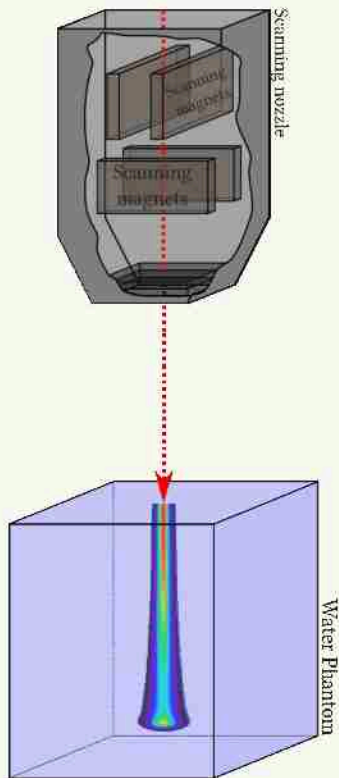


Beam modifiers
(range shifters and collimators)



TPS commissioning for proton beam

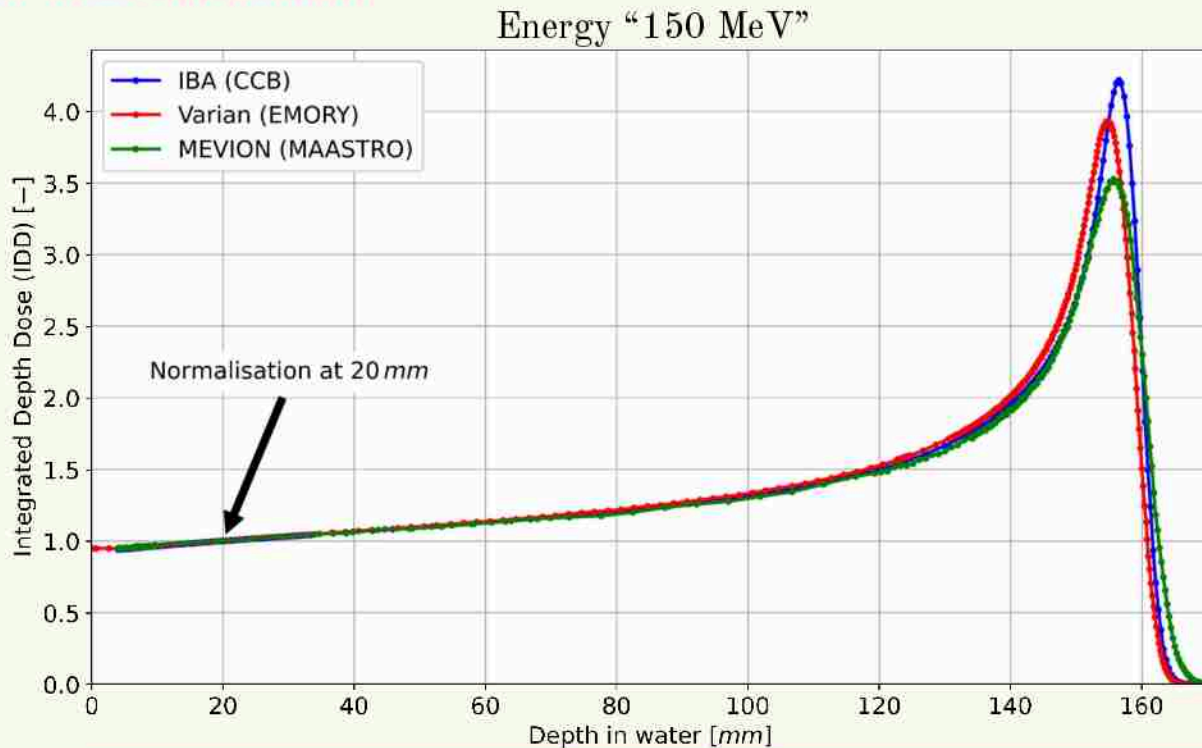
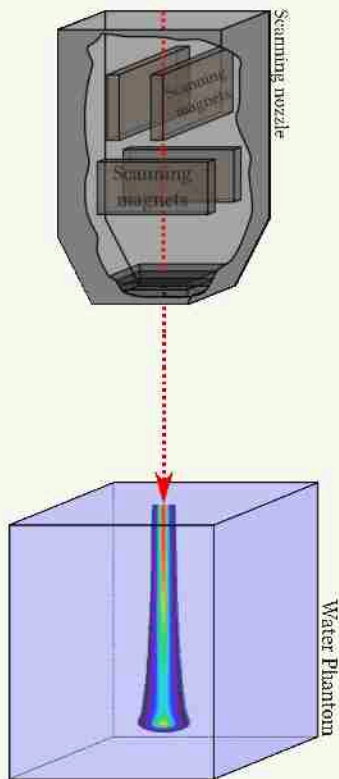
Step 1: Characterise depth dose distribution



Available energy range to be characterised

TPS commissioning for proton beam

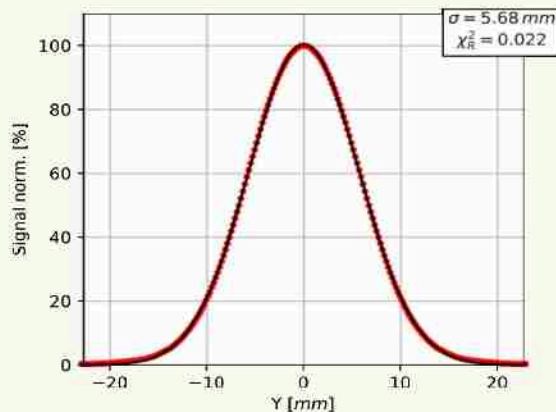
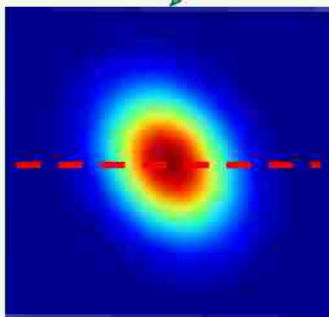
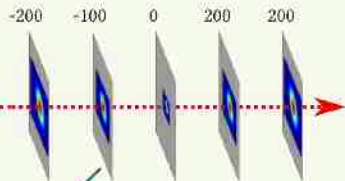
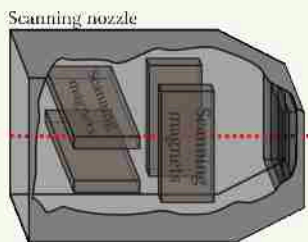
Step 1: Characterise depth dose distribution



"Proton Energy" does not mean always the same

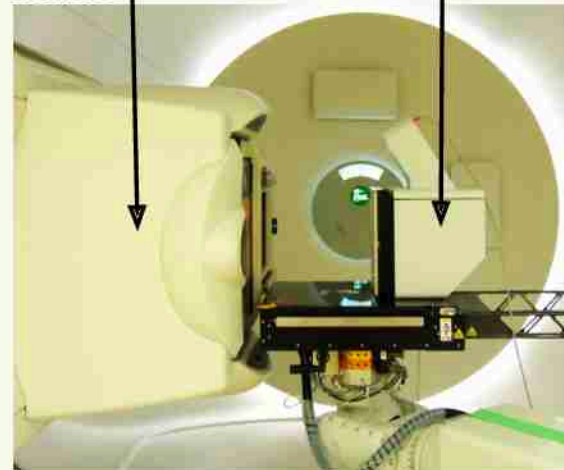
TPS commissioning for proton beam

Step 2: Characterise lateral beam propagation



Scanning nozzle

Lynx (IBA)

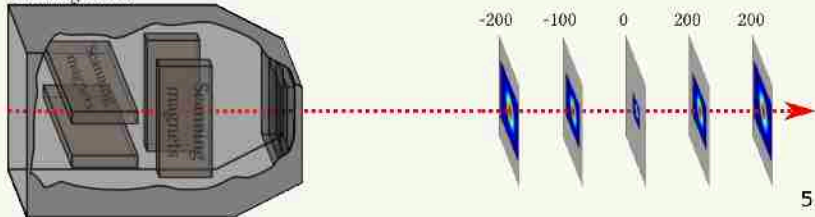


Gaussian lateral beam shape

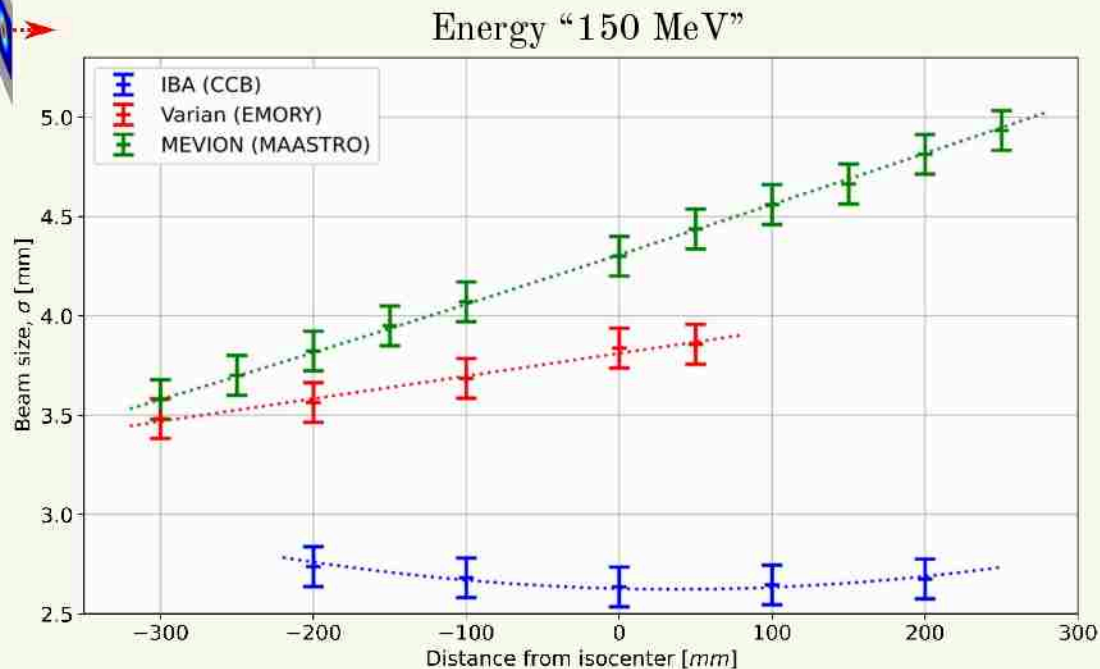
TPS commissioning for proton beam

Step 2: Characterise lateral beam propagation

Scanning nozzle

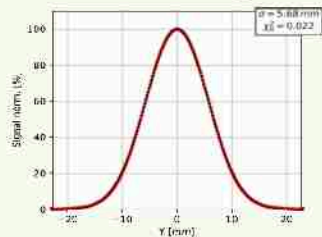
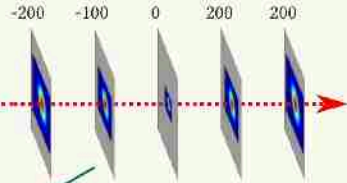
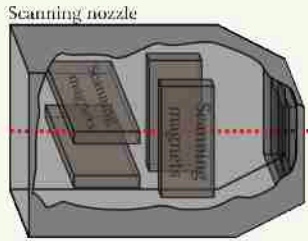


Beam sizes
(σ of gaussian shape)
2-10mm

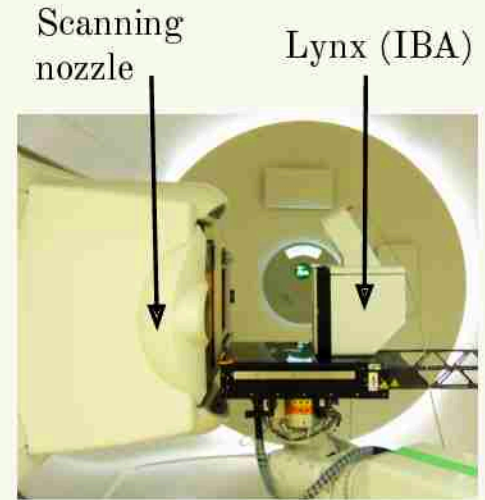
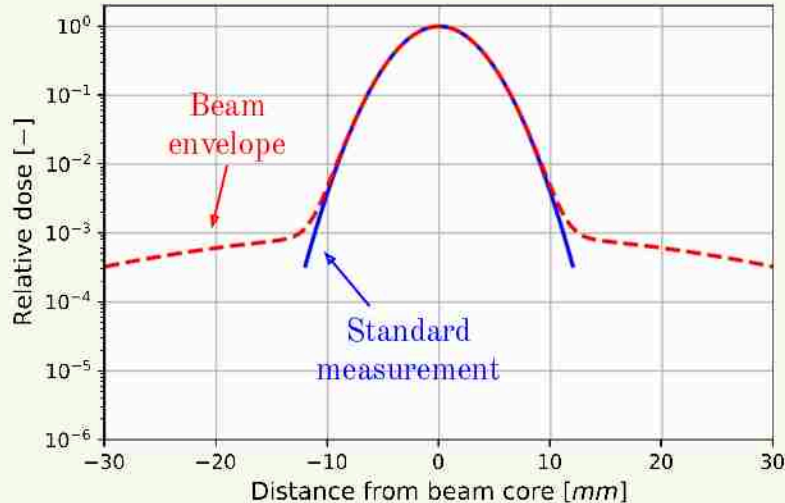


TPS commissioning for proton beam

Step 2: Characterise lateral beam propagation



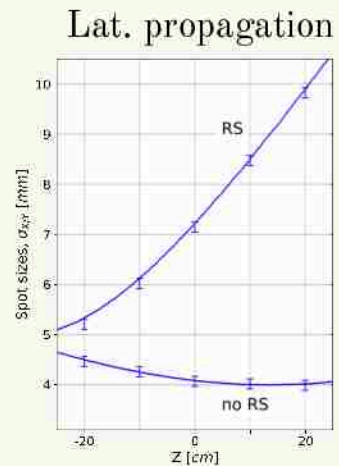
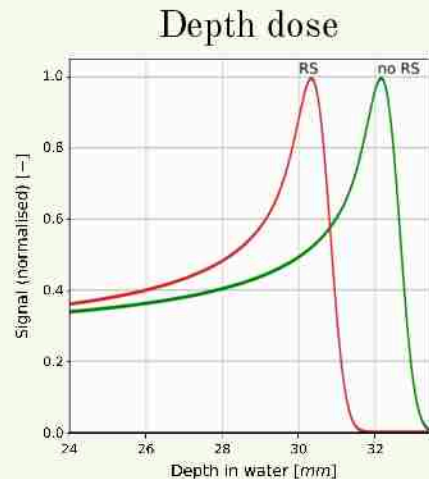
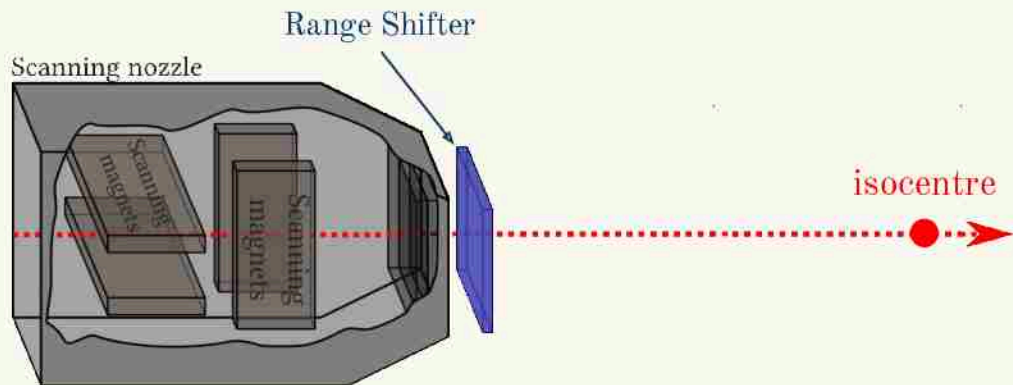
Log scale



Wide detector dynamic range for beam envelope measurements

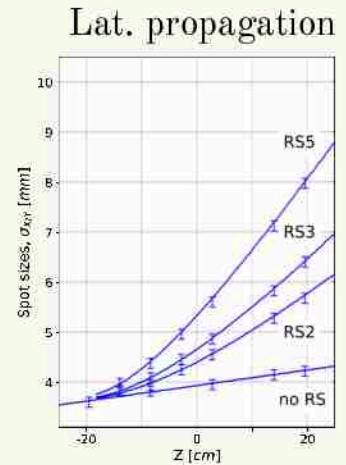
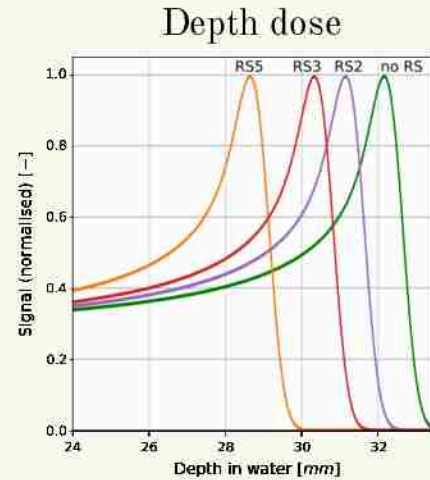
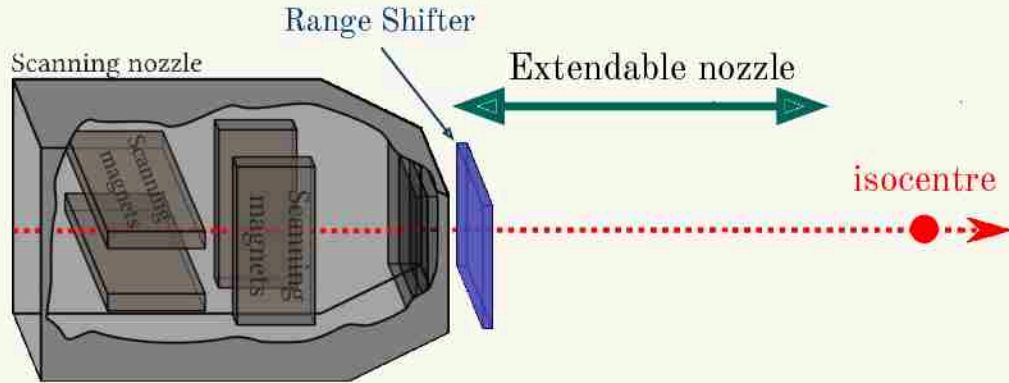
TPS commissioning for proton beam

Step 3: Characterise beam modifiers



TPS commissioning for proton beam

Step 3: Characterise beam modifiers



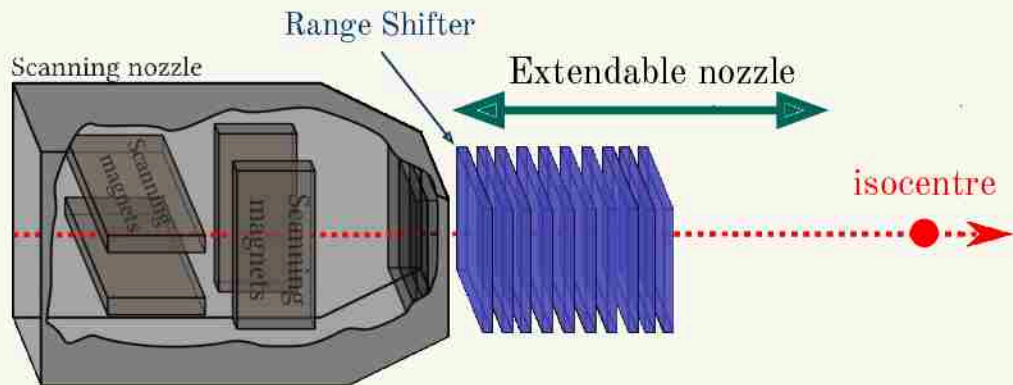
Single Range Shifter



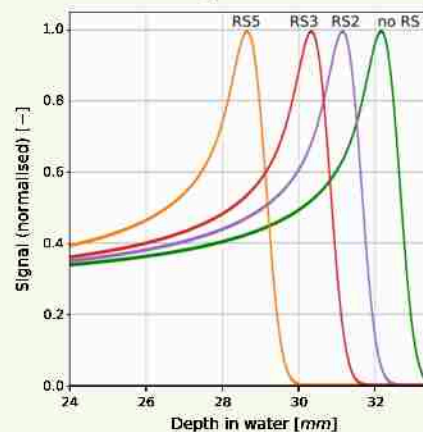
5 Range Shifters
+
Extendable nozzle

TPS commissioning for proton beam

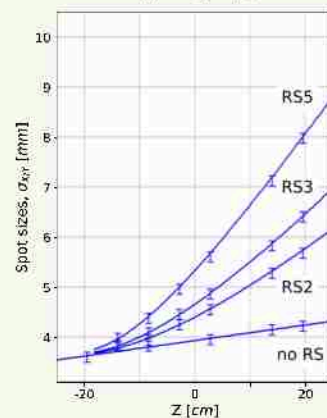
Step 3: Characterise beam modifiers



Depth dose



Lat. propagation



Single Range Shifter



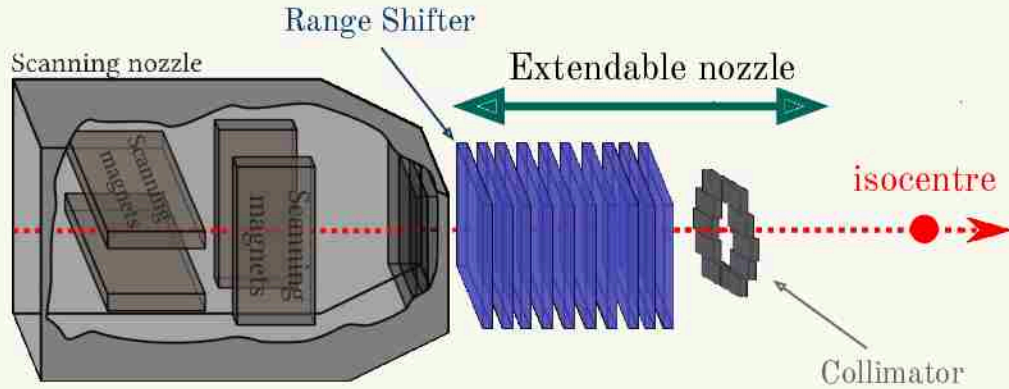
5 Range Shifters
+
Extendable nozzle



17 Range Shifters
+
Extendable nozzle
+
Adaptive Collimator

TPS commissioning for proton beam

Step 3: Characterise beam modifiers



Single Range Shifter



5 Range Shifters
+
Extendable nozzle

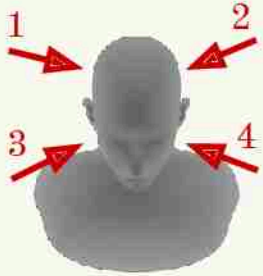


17 Range Shifters
+
Extendable nozzle
+
Adaptive Collimator

State-of-the-art
Proton Treatment
Planning

Proton Treatment Planning in TPS (IMPT)

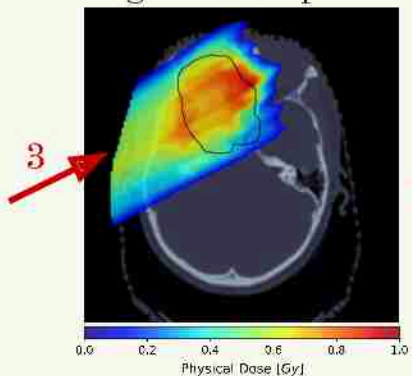
Intensity Modulated Proton Therapy



Heterogeneous fields sum up to homogeneous dose distribution

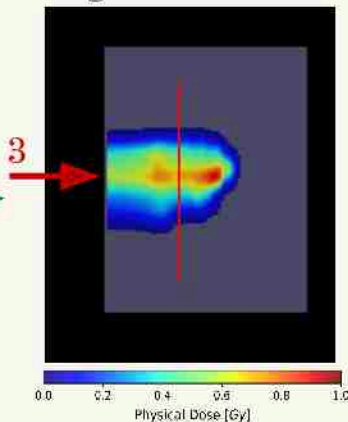
Treatment Planning Quality Assurance

Single field in patient

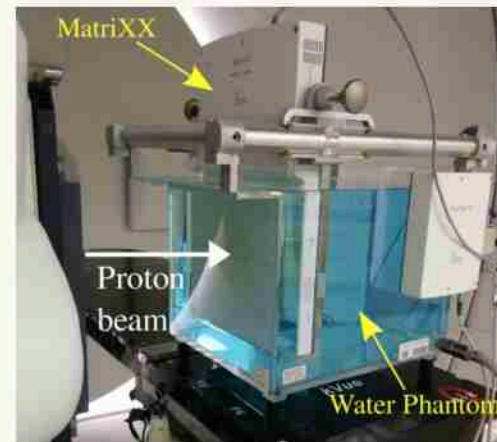


Recalculation
to water

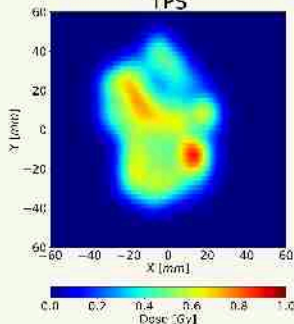
Single field in water



Measurement in
water phantom

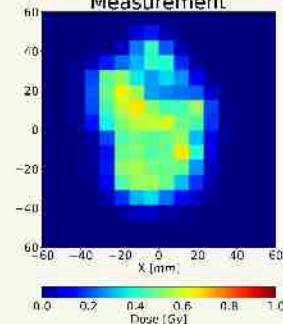


TPS



Comparison and
Analysis

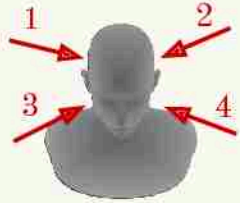
Measurement



Proton therapy limitations:

Physical and Biological
uncertainties

Physical uncertainty: calculation method



Pencil Beam Algorithm

Proton Stopping Power
converted from
photon attenuation coefficient
(Computer Tomography)

Pencil Beam Algorithm

Monte Carlo

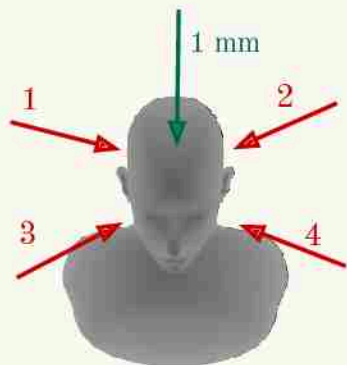
Monte Carlo

Modelling of particle
interaction with medium
elements

Physical uncertainty: patient positioning

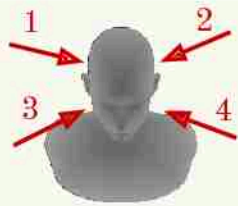
Nominal Plan

Patient shift by 1mm



Patient mispositioning can lead to unexpected dose distribution

Biological dose: constant RBE



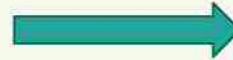
Relative Biological
Effectiveness

Physical dose

Biological dose

$$RBE = \frac{D_x}{D_p}$$

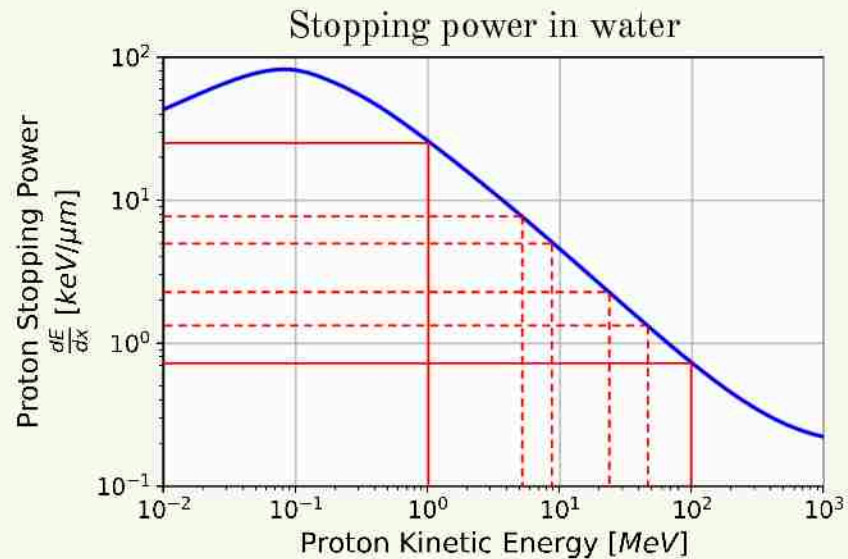
RBE = 1.1



Biological Dose

$$D_{biol} = D_{phys} \cdot RBE$$

Radiation Quality

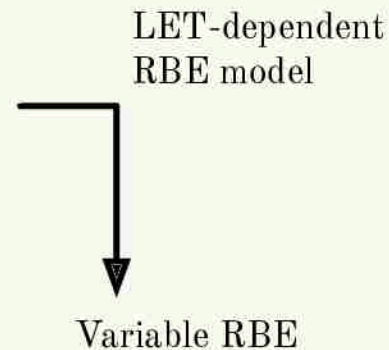
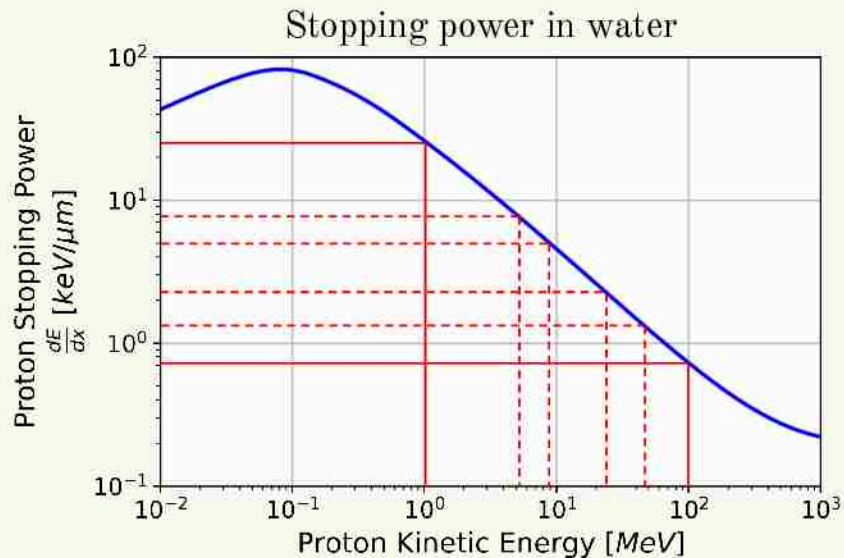


Linear Energy Transfer

$$LET = \frac{dE}{dx}$$

Radiation Quality

Dose-averaged LET



Linear Energy Transfer

$$LET = \frac{dE}{dx}$$

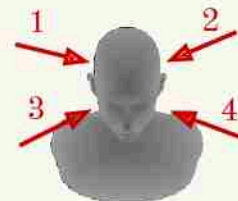
Dose-averaged LET

$$LET_D = \frac{\int Dose \cdot LET}{\int Dose}$$

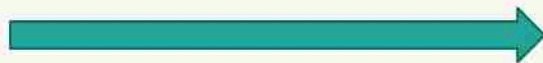
Biological uncertainty

Physical dose

Biological dose



Constant RBE = 1.1



Variable RBE(LET_D)



*Ruciński, ..., Gajewski, et al.,
Acta Phys. Pol. B (2020)*

*Garbacz, ..., Gajewski, et al.
submitted to Radiother. Oncol.*

Limitations

Commissioning

- Complicated **dose envelope** measurements
- **No radiation quality** characterised

Treatment Planning

- **Constant RBE** = 1.1
- Analytical systems
- Time constraints of Monte Carlo

Quality Assurance

- No radiation quality
- Measurements in **homogeneous phantoms**
- **Beam time** needed (10-20% more beam time for patients)

Beyond state-of-the-art:

GPU-accelerated Monte Carlo
for proton therapy

Fast paRticle thERapy Dose Evaluator - FRED

The logo for FRED, featuring the word "Fred" in a stylized, glowing font with a blue and yellow gradient, set against a dark blue background.

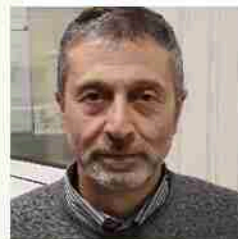
www.fred-mc.org

Monte Carlo code
for research and QA in proton therapy
A. Schiavi et al. (2017)

- Fast calculations on GPU
- Flexible geometry and CT import
- Variable RBE models
- Physics important in proton therapy



SAPIENZA
UNIVERSITÀ DI ROMA



V. Patera



A. Schiavi

FNP REINTEGRATION (2016-2020)

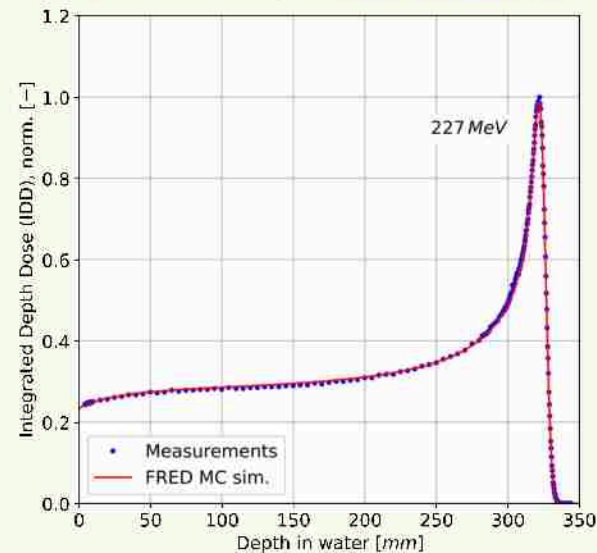
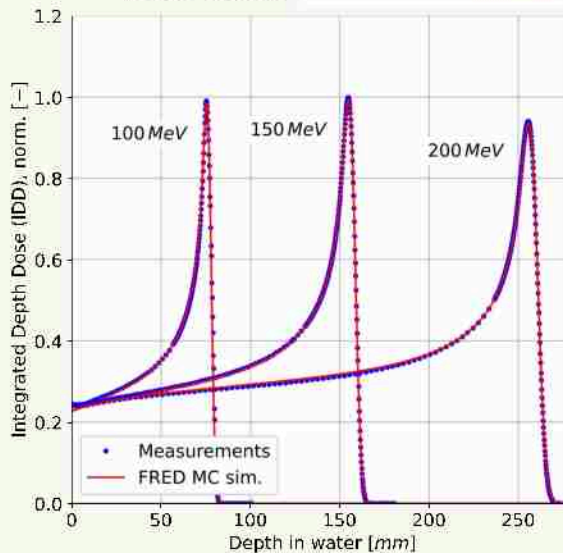
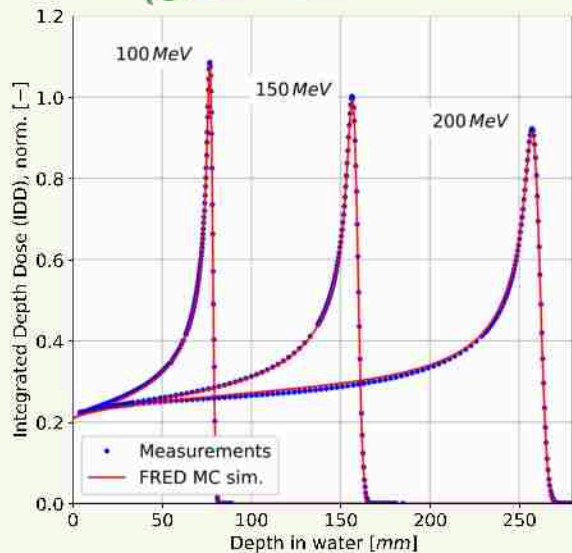
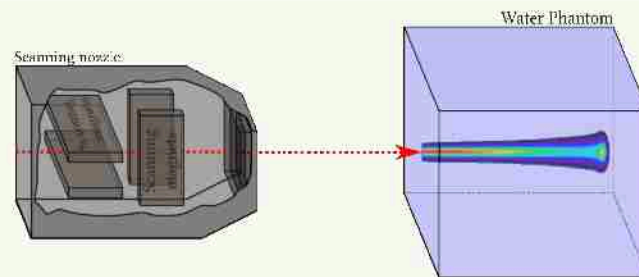
*Quantification of biological range
uncertainties towards an improved patient
treatment in CCB Cracow proton beam
therapy centre*



A. Ruciński

FRED commissioning

Step 1: Characterise depth dose distribution

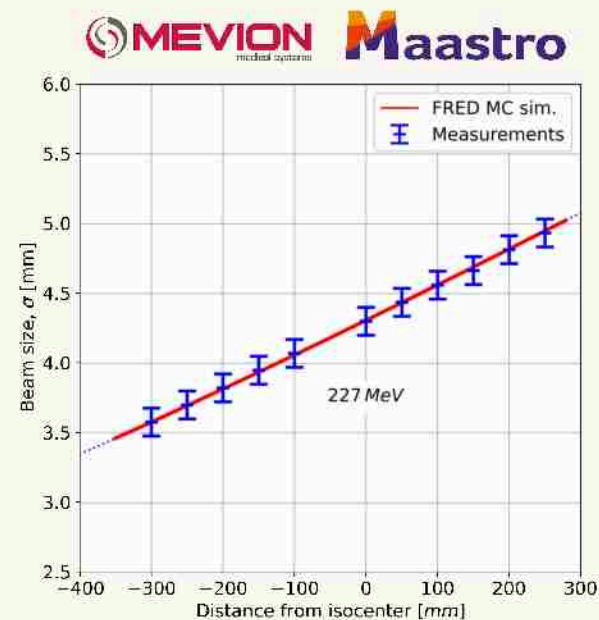
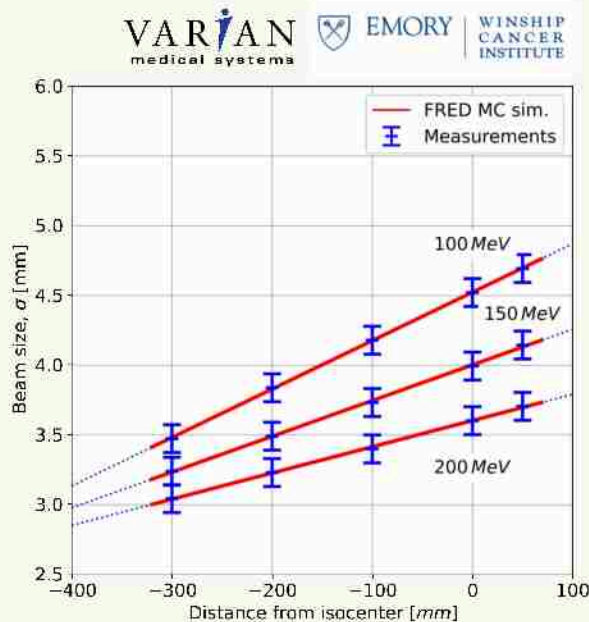
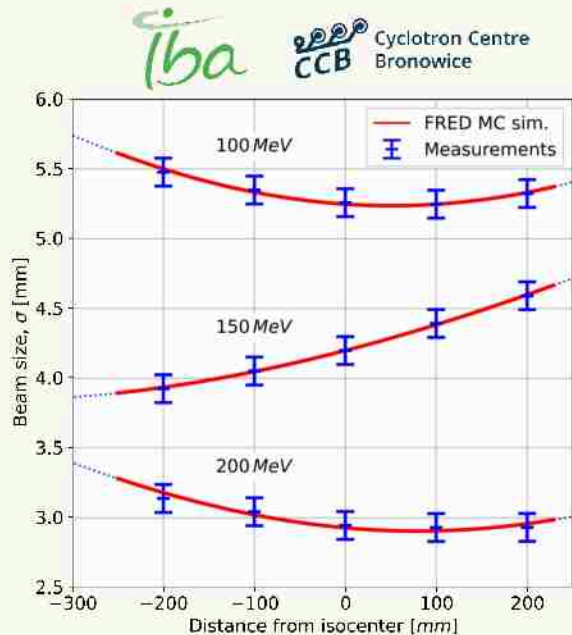
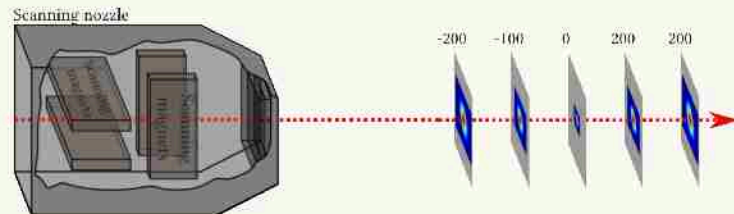


Bragg Peak range and FWHM agree within 0.1 mm

Gajewski, et al., *Front. Phys.* (2020)
Gajewski, et al., *Front. Phys.* (2021)

FRED commissioning

Step 2: Characterise lateral beam propagation

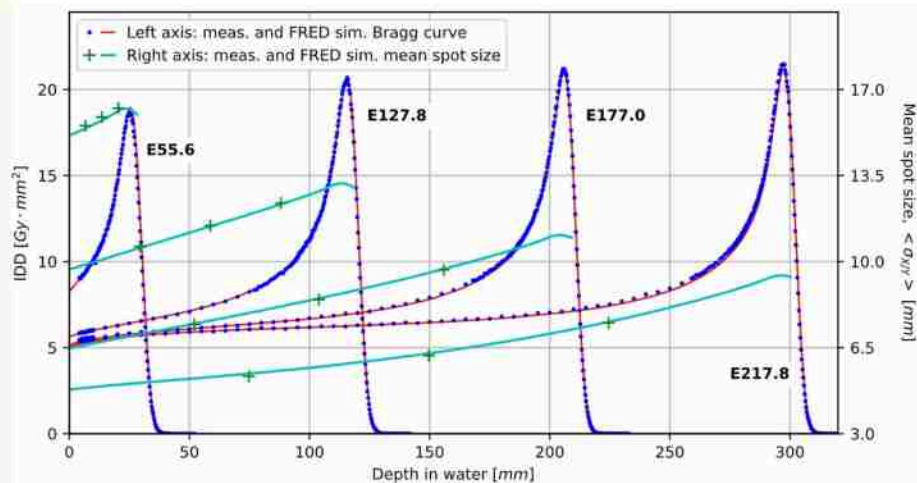


Simulated lateral beam sizes agree with measurement data < 0.05 mm

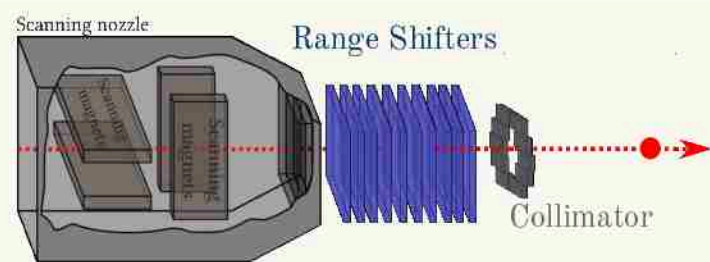
Gajewski, et al., *Front. Phys.* (2020)
Gajewski, et al., *Front. Phys.* (2021)

FRED commissioning

Step 3: Characterise beam modifiers

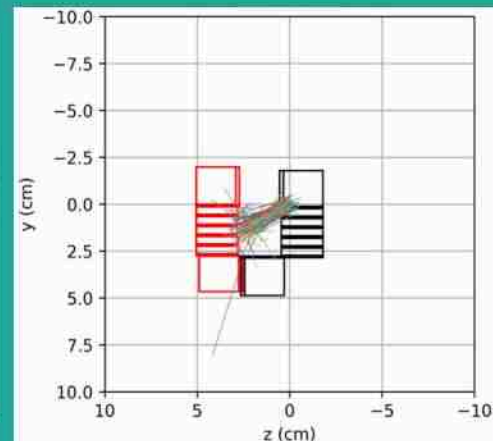
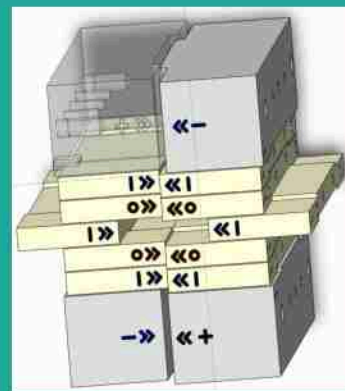


Beam size in air behind RSs within ± 0.2 mm
Beam size in water behind RSs within ± 0.6 mm
Beam range behind RSs within ± 0.1 mm



Adaptive Collimator

14 movable leaves (Ni) of complex geometry



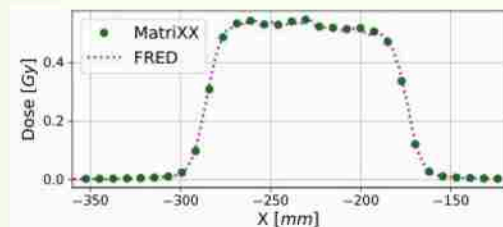
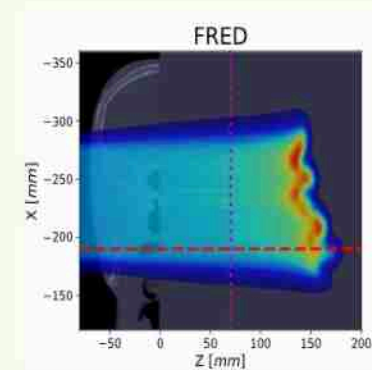
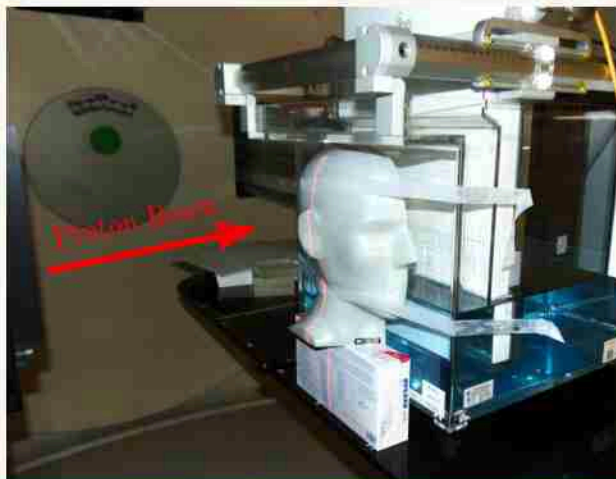
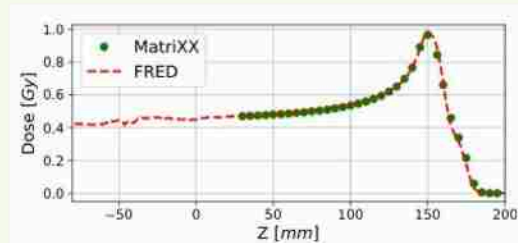
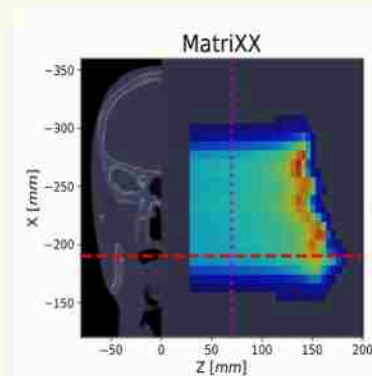
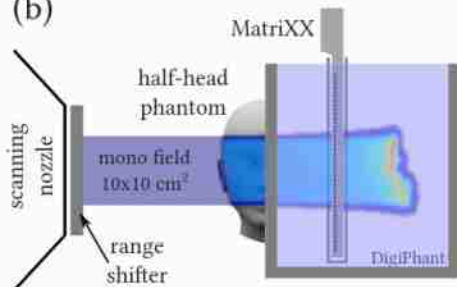
Gajewski, et al., *Front. Phys.* (2020)

FRED experimental validation

(a) CIRS phantom





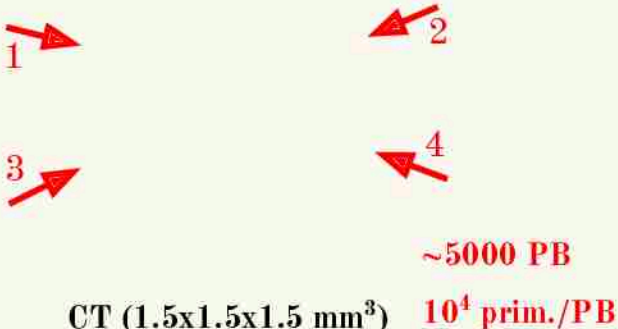


(b)










Gajewski, et al., *Front. Phys.* (2021)

Time performance of FRED Monte Carlo

	 2 x NVIDIA TITAN GPU	  2000 x Intel(R) Xeon(R) E5-2660 v3 CPU cores
 <p>150 MeV 10^8 prim.</p> <p>Water (1 mm³ voxel)</p>	<p>30 s</p>	<p>17 min</p>
 <p>1 2 3 4</p> <p>~5000 PB 10^4 prim./PB</p> <p>CT (1.5x1.5x1.5 mm³)</p>	<p>7 min</p>	<p>131 min</p>

FRED application for patient quality assurance

	 	 	 	
Beam model	Implemented and validated	Implemented and validated	Implemented and validated	Beam model preparation
Retrospective analysis	~100 treatment plans	~300 treatment plans	13 treatment plans	Work in progress
Routine patient quality assurance	work in progress (collaboration with CCB and Commercialisation Task Group at IFJ)	FRED used for patient QA on a daily basis	FRED not used now	Work in progress

FRED applications for research

- Treatment planning studies

- Impact of CT calibration →
- Necrosis occurrence →

Collaboration with **Maastrro**

Magdalena Garbacz (IFJ)

- GPU-based treatment plan optimisation

- 4D optimisation (moving organs)
- Robust optimisation

- 4D applications

- PET activation (β^+ activity)

Research agreement (2020)



THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

PAUL SCHERRER INSTITUT



Radiation Quality characterisation

NCBiR LIDER XII grant submitted in March 2021

Characterisation of mixed radiation fields in proton therapy

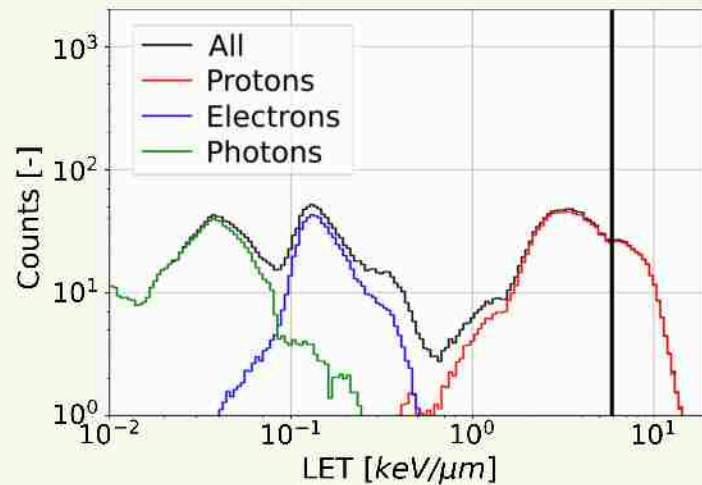


The National Centre
for Research and Development

Motivation: Radiation Quality in proton therapy

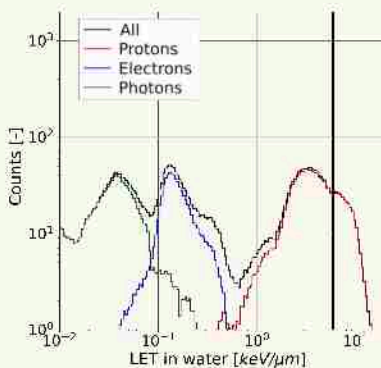
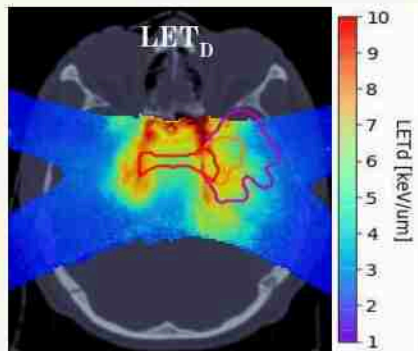
Is the averaged LET_D value sufficient to describe radiation quality?

$LET_D \approx 6 \text{ keV}/\mu\text{m}$

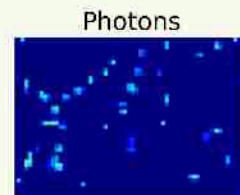
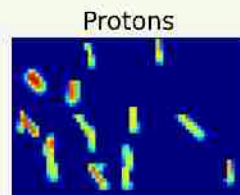
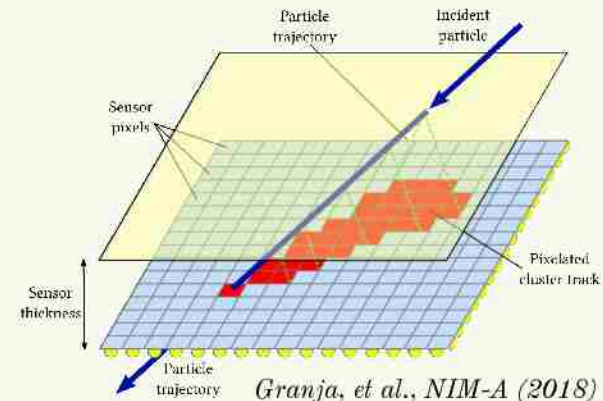


Methods for Radiation Quality characterisation

Grant objective 1: Computational
LET spectra scoring in Monte Carlo

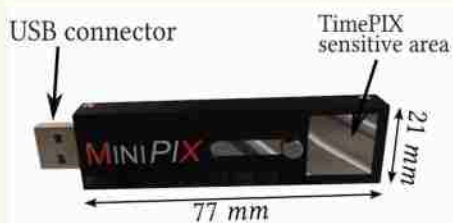


Grant objective 2: Experimental
Detector for LET spectra measurements

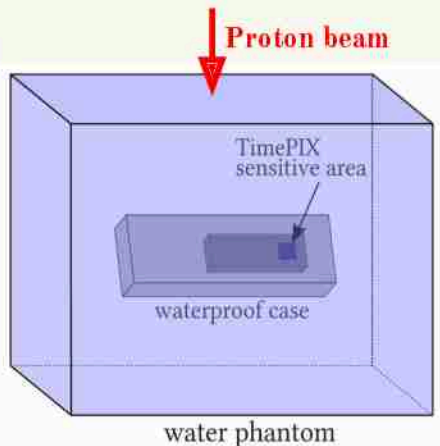


Granja, ..., Gajewski, et al., Nucl. Instrum. Methods Phys. Res. (2020)

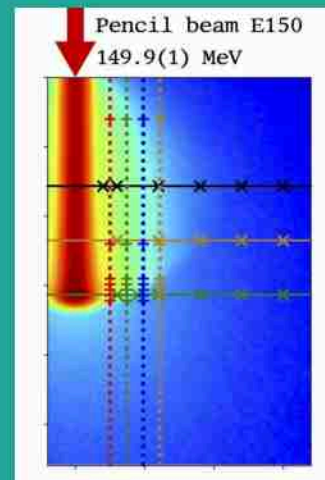
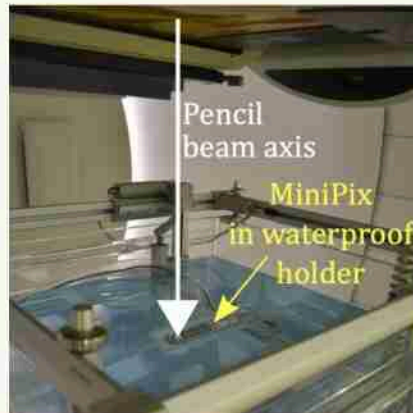
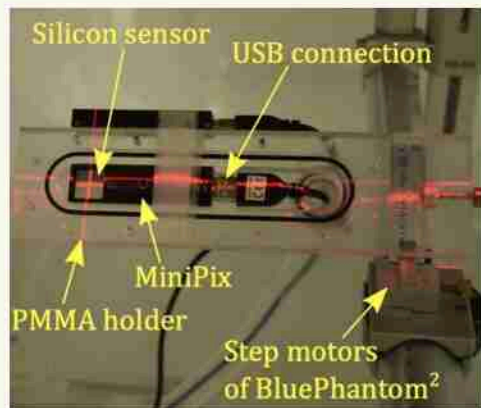
Pilot experiments with TimePix



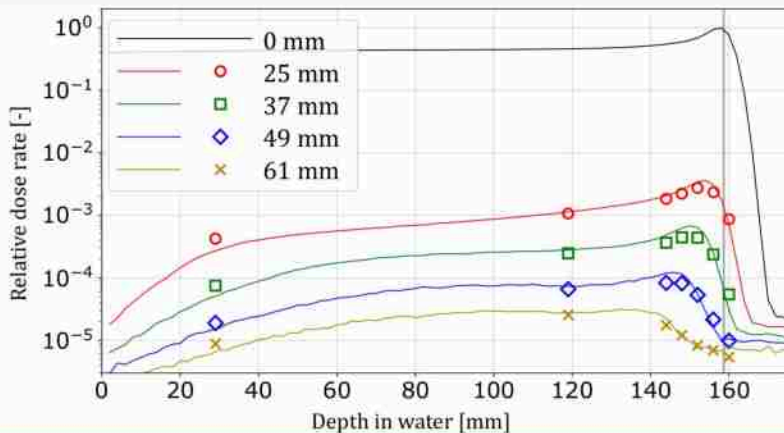
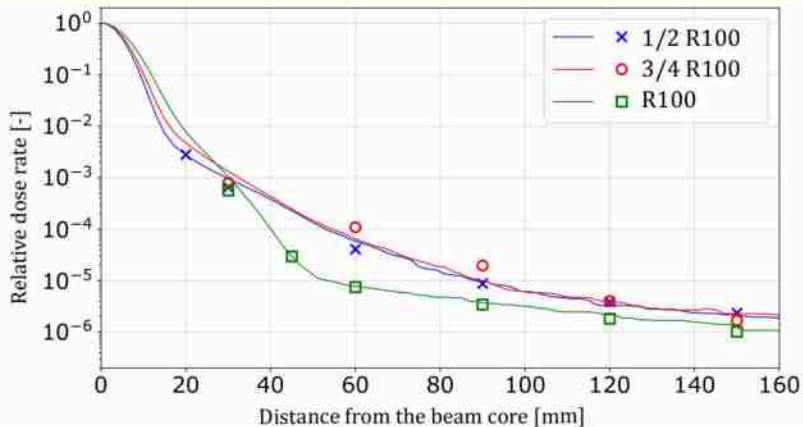
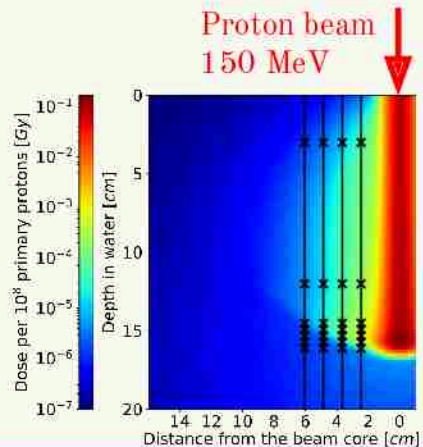
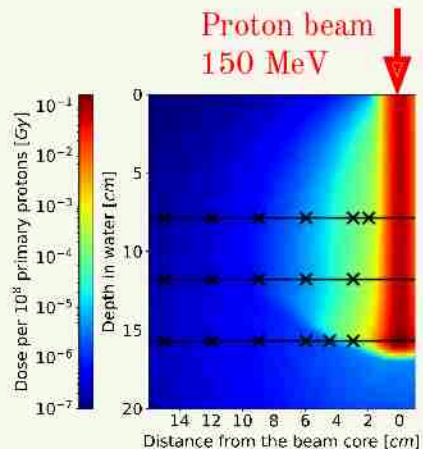
MiniPix TimePix detector:
Silicon sensor 300 μm
size: 14x14 mm²



- Single pencil beams in air/water
- 100, 150 and 200 MeV
- With and without Range Shifter
- Up to 15 cm off the beam core
- ~300 meas. points



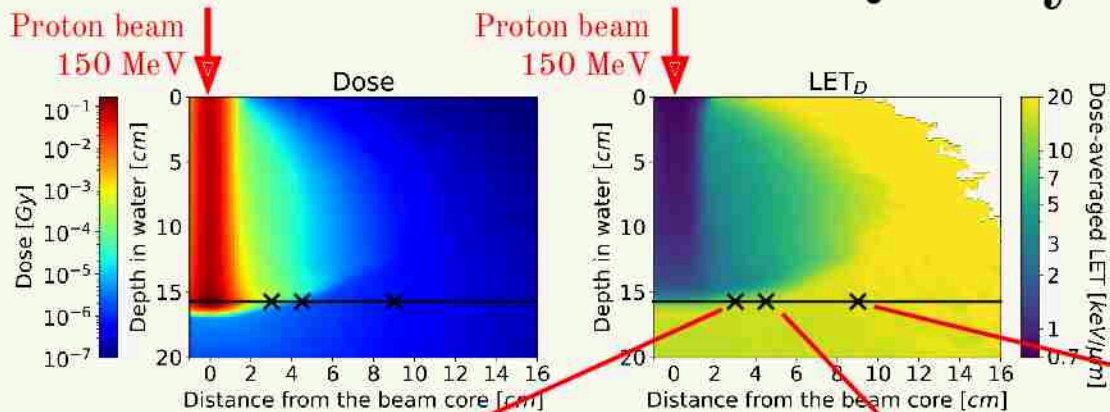
TimePix for dose measurements



Heterogeneous fields sum up to homogeneous dose distribution

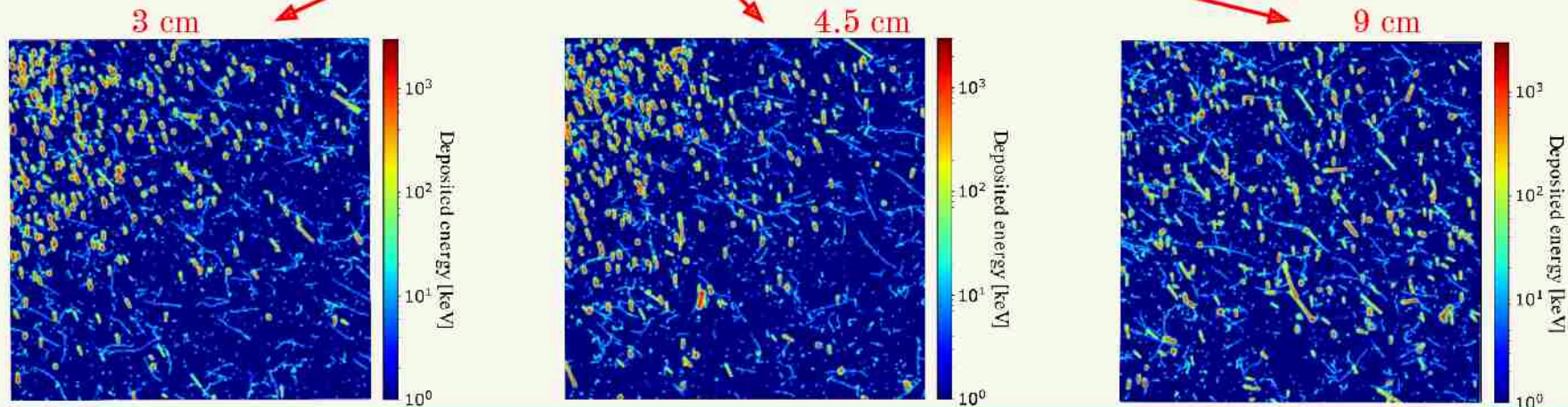
Stasica, ..., Gajewski, et al.
Front. Phys. (2020)

TimePix for Radiation Quality characterisation

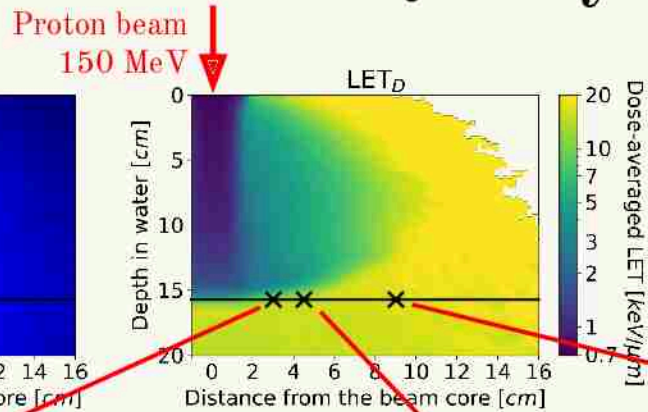
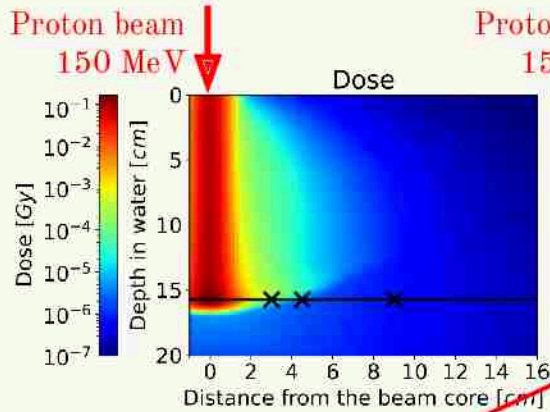


Paulina Stasica master thesis

Publication in preparation



TimePix for Radiation Quality characterisation



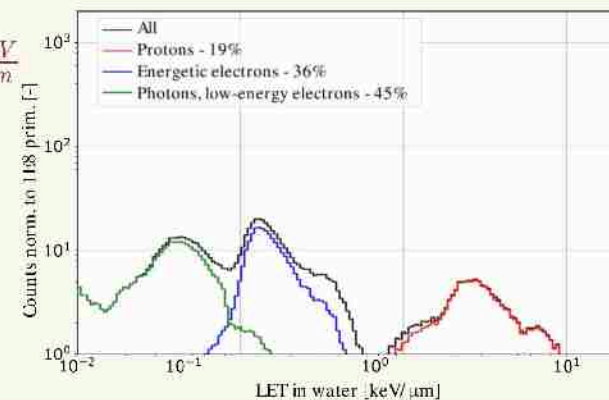
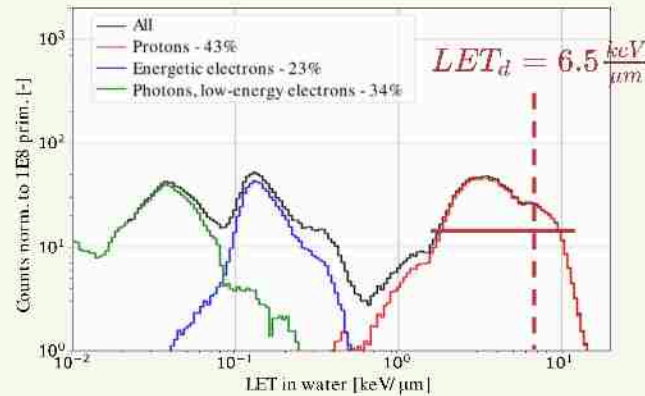
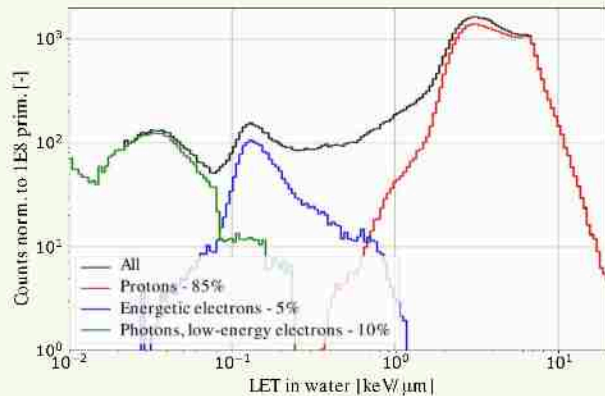
Paulina Stasica master thesis

Publication in preparation

3 cm

4.5 cm

9 cm



Summary

- State-of-the-art clinical methods for:
 - Treatment Planning System commissioning
 - Patient treatment planning
 - Dosimetry for patient quality assurance
- Dose envelope measurements
- Analytical system - time consuming Monte Carlo
- Constant RBE - no radiation quality
- Measurements in homogeneous phantoms
- GPU-accelerated Monte Carlo FRED
- Introducing radiation quality in proton therapy:
 - Computational methods based on Monte Carlo calculations
 - Experimental methods based on TimePix semiconductor pixel detector

Thank You for Your attention

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