GPU-accelerated Monte Carlo code FRED for clinical applications in proton therapy

Jan Gajewski, M. Garbacz, J. Baran, M. Rydygier, N. Mojżeszek, K. Czerska
K. Krzempek, P. Stasica, A. Skrzypek, R. Kopeć, Antoni Rucinski

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AGH

M. Pawlik-Niedźwiecka, Sz. Niedźwiecki, G. Korcyl — JAGIELLONIAN UNIVERSITY IN KRAKOW

V. Patera, A. Schiavi — SAPIENZA UNIVERSITÀ DI ROMA

C. Chang, L. Lin — EMORY WINSHIP CANCER INSTITUTE

E. Scifoni, F. Tommasino — INFN Istituto Nazionale di Fisica Nucleare

E. Pluta — MARIA SKLODOWSKA-CURIE INSTITUTE – ONCOLOGY CENTER

I. Rinaldi, G. Vilches-Freixas — Maastro

C. Granja, C. Oancea — ADVACAM Imaging the Unseen

N. Krah — CREATIS

Krakow PBT facility (Cyclotron Centre Bronowice - CCB)

- IBA Proteus C-235
- Clinical operation from Oct 2016
- 2 x gantry (>300 H&N patients treated)
- Eye treatment room
- Experimental hall

Monte Carlo tool needed for QA and research

In 2017 Antoni Runiński came from Rome and brought

GPU-accelerated MC
Fast paRticle thErapy Dose evaluator
FRED
(A. Schiavi, V. Patera - Rome Uni.)

CCB (IBA)

Cyclotron Centre Bronowice

MAASTRO (Mevion)

Maastro

EMORY (Varian)

EMORY | WINSHIP CANCER INSTITUTE

Outline

- Pencil Beam Model parameterization
- Specific beam models:
    - CCB, Krakow, Poland - IBA
    - EMORY, Atlanta, GA, U.S. - Varian
    - MAASTRO, Maastricht, the Netherlands - Mevion
- Beam model validation
- Patient plan simulations
- FRED performance
- LET validation

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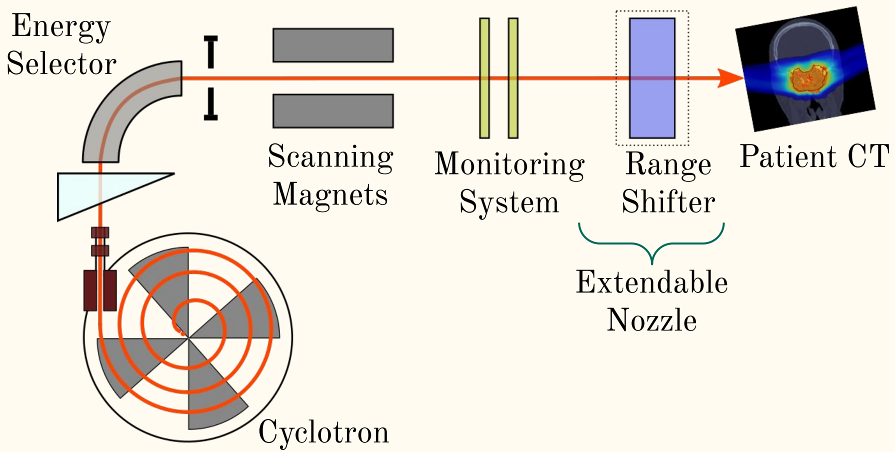
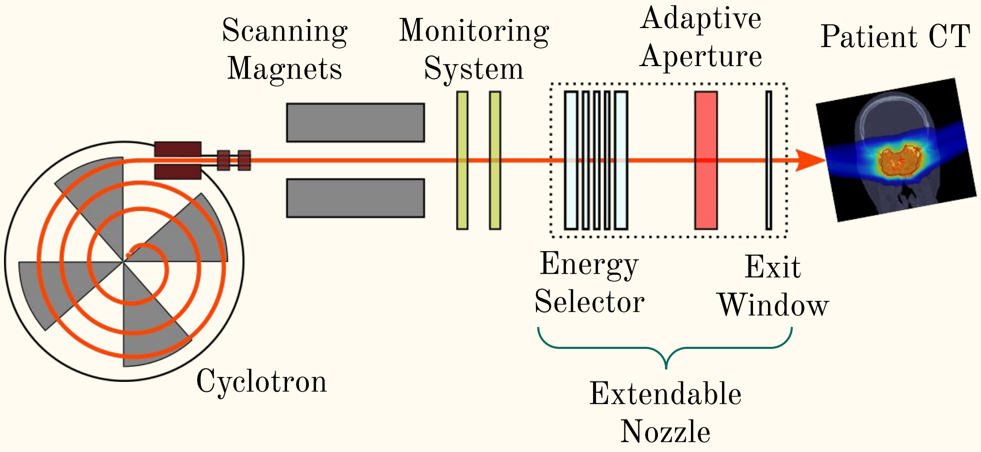
Pencil Beam Model Phase Space

CCB (IBA) & EMORY (Varian)



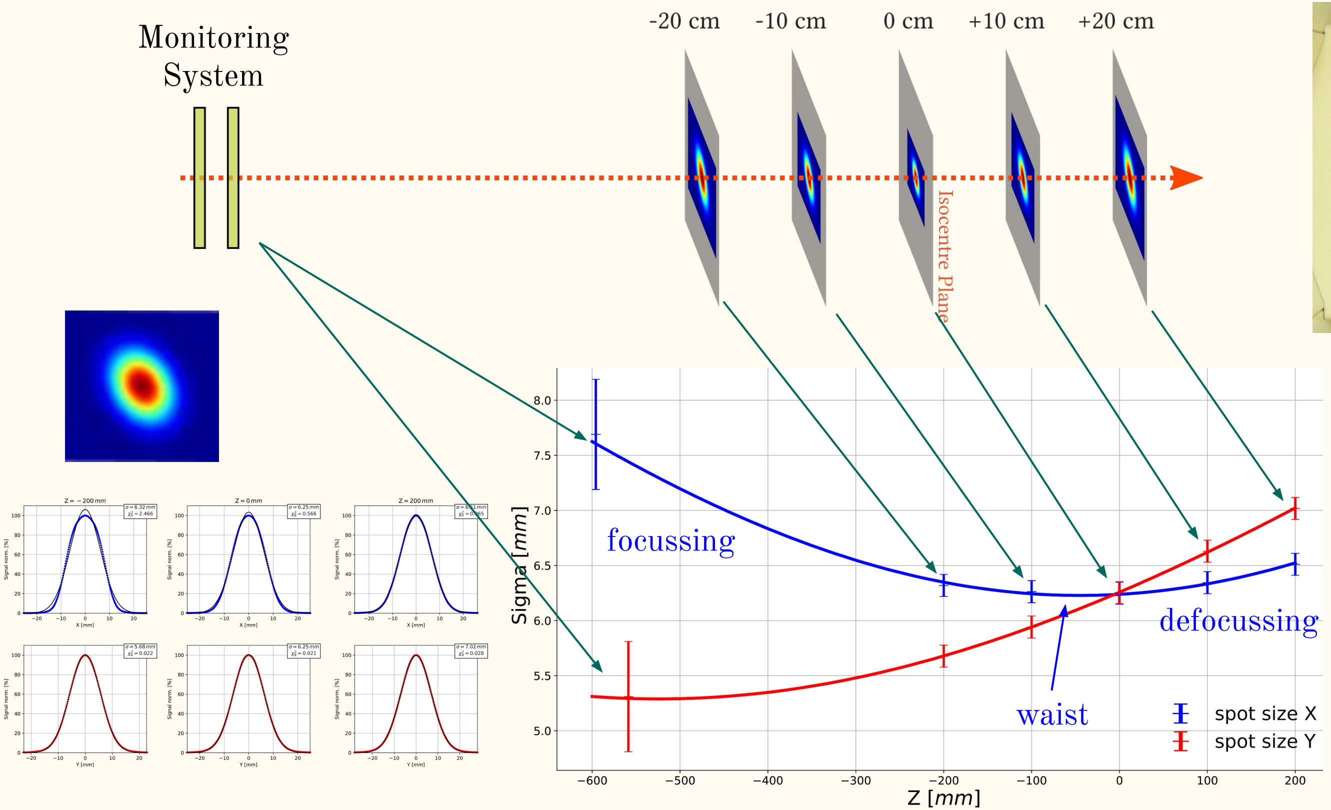
MAASTRO (Mevion)

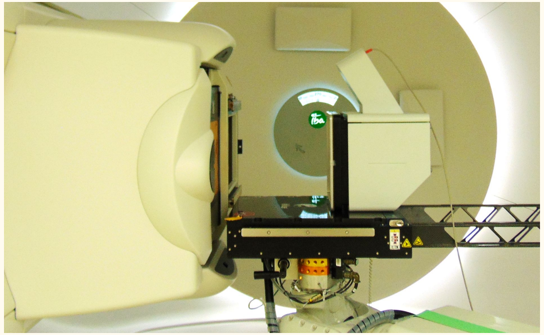


Beam model depends on the design

Pencil Beam Model Phase Space

Step 1: Characterise lateral beam propagation





Parameters describing the lateral propagation:

$\varepsilon_{x/y}, \alpha_{x/y}, \beta_{x/y}$

$$\sigma^2(z) = \epsilon \cdot \left(\beta - 2 \cdot \alpha \cdot z + \frac{1+\alpha^2}{\beta} \cdot z^2\right)$$

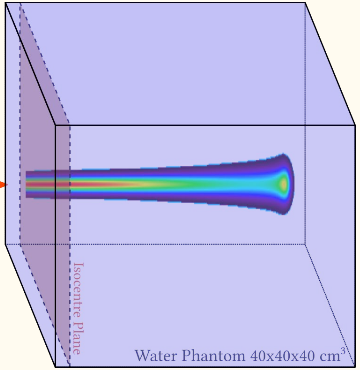
or simplified:

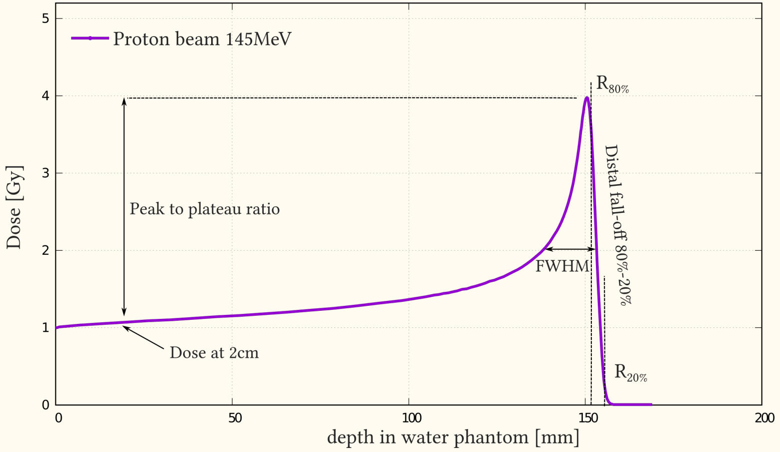
$S_{x/y}, VSD_{x/y}$

$$\sigma(z) = S \cdot z + VSD$$

Pencil Beam Model Phase Space

Step 2: Characterise depth dose distribution

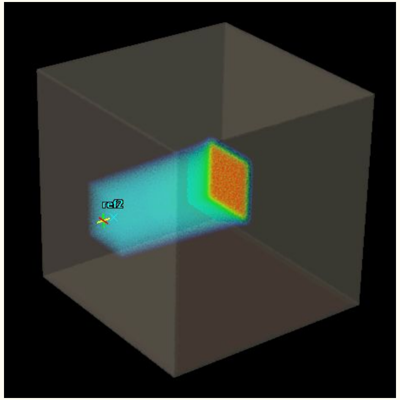




BP meas.

2 x parameters describing the initial energy and energy spread

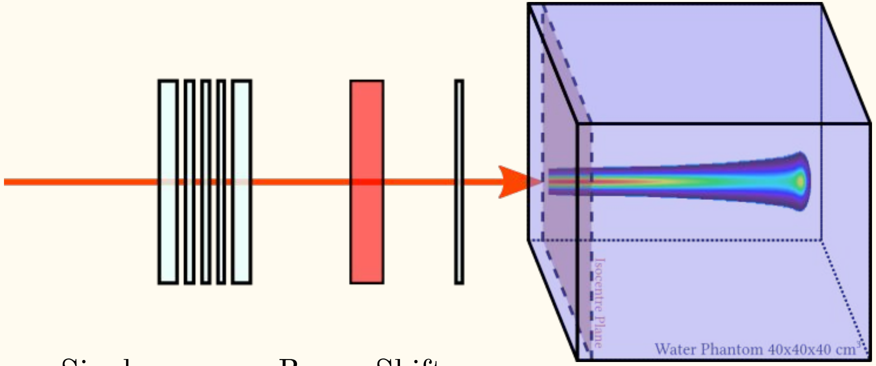
Mono. field meas.



1 parameter describing the scaling factor (protons/MU)

Pencil Beam Model Phase Space

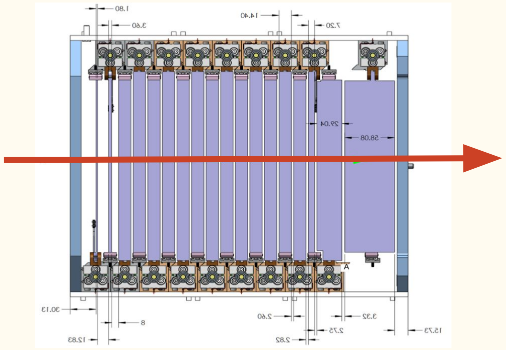
Step 3: Characterise Range Shifters and Apertures



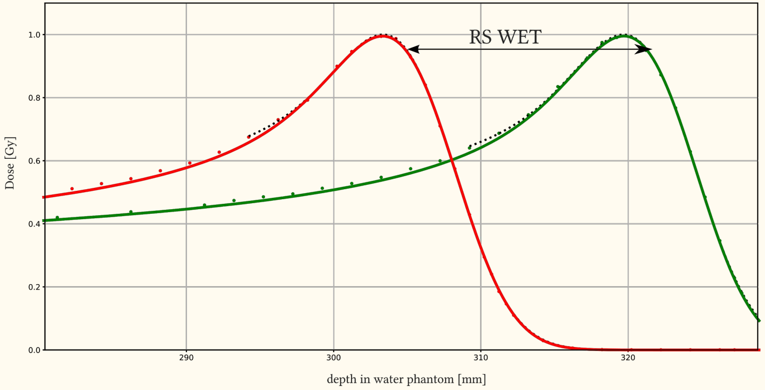
For each element define:

- Geometry (size)
- Position (re. isocentre)
- Material (composition/density)

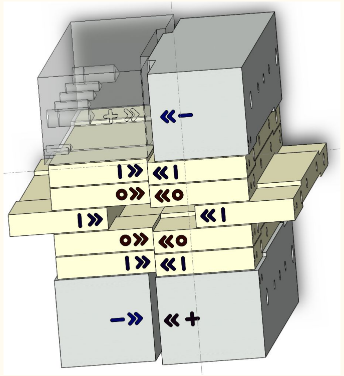
Single or many Range Shifters



BP shift measurements



Adaptive Aperture



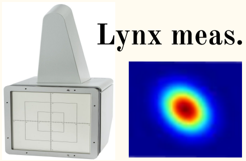
Facility specific model parameters in MC

	CCB (IBA)	EMORY (Varian)	MAASTRO (Mevion)
Energy [MeV]	70-226 (10 MeV step)	70-242 (10 MeV step)	230 (only pristine energy)
Spot size at iso. [mm]	2.5-6.6	3.5-5.6	4.3 (only pristine energy)
Lateral propagation	Emittance (2x3 params)	VPS (2x2 params)	Emittance (2x3 params)
Range Shifter [cm]	36.7	20 / 30 / 50	19 RSs of various thick.
Snaut extension [cm]	fixed: 36.9 cm	extendable: 5-50 cm	extendable: 3.6-33.6 cm
Dosimetry technique	Markus (PTW) at 2 cm	PPC-40 (IBA) at 2 cm	PPC-05 (IBA) at ¼ BP range
Aperture	No	No	2x7 leaves movable

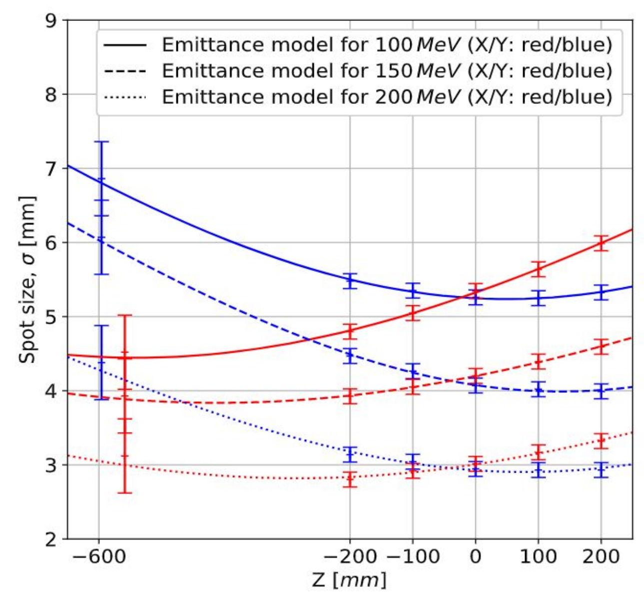
Gajewski et al. Commissioning of GPU-accelerated Monte Carlo code FRED for clinical applications in proton therapy, sub. to Frontiers in Physics

Gajewski et al. A GPU Monte Carlo to support clinical routinein a compact spot scanning proton therapysystem, sub. to Frontiers in Physics

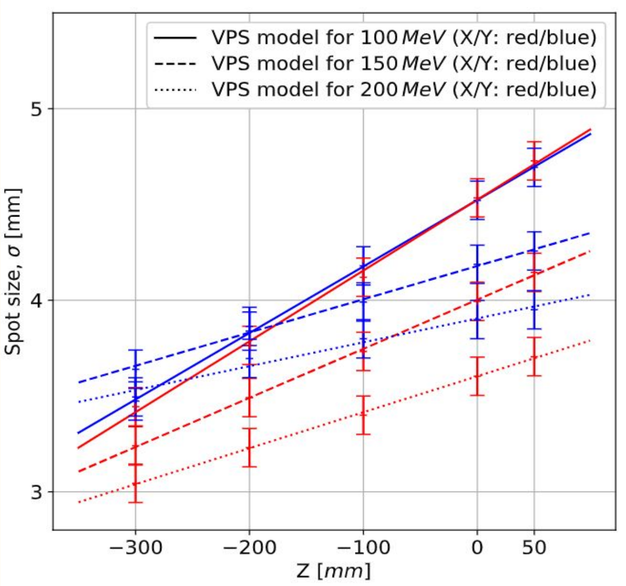
Beam model - lateral propagation



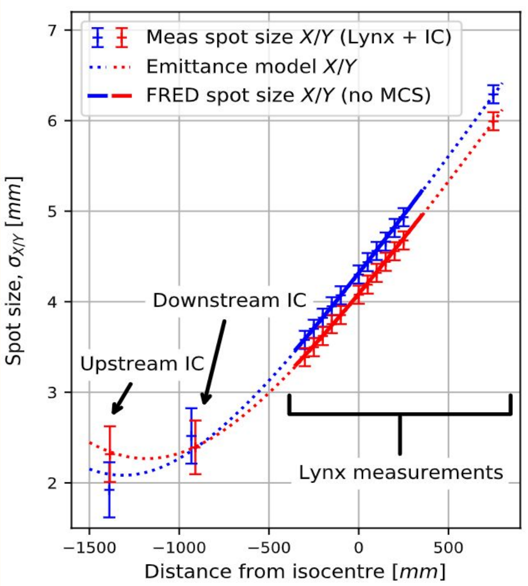
CCB (Krakow)



EMORY (Atlanta)



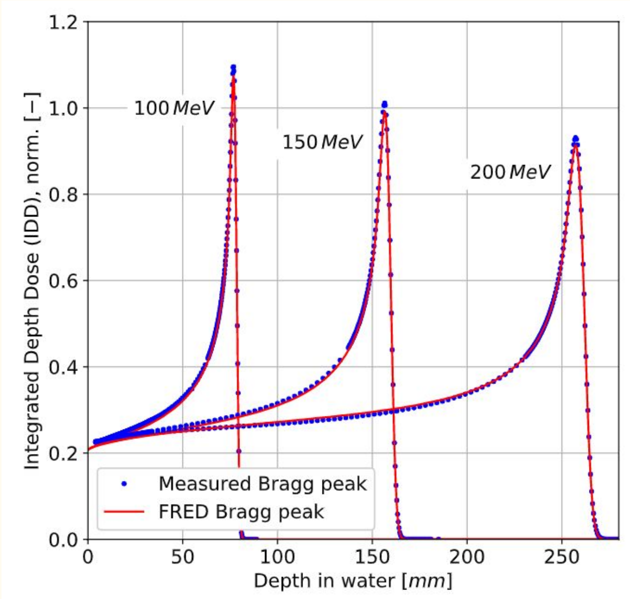
MAASTRO (Maastricht)



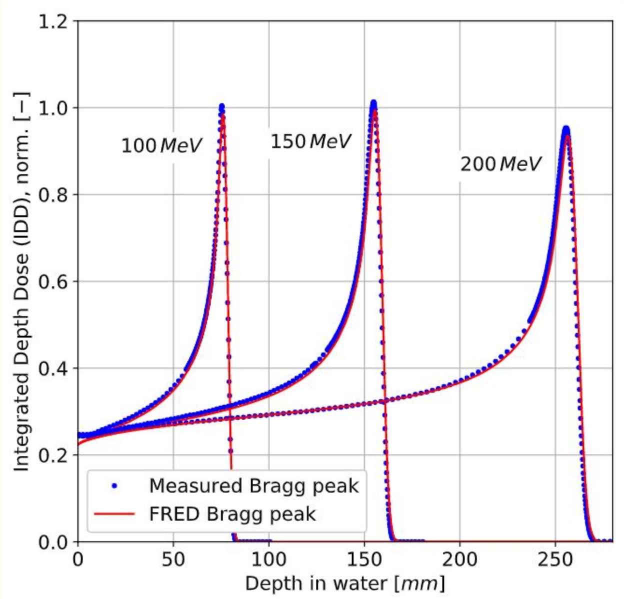
Emittance/VPS models fit to measurements data <0.05 mm

Beam model - Bragg peak in water

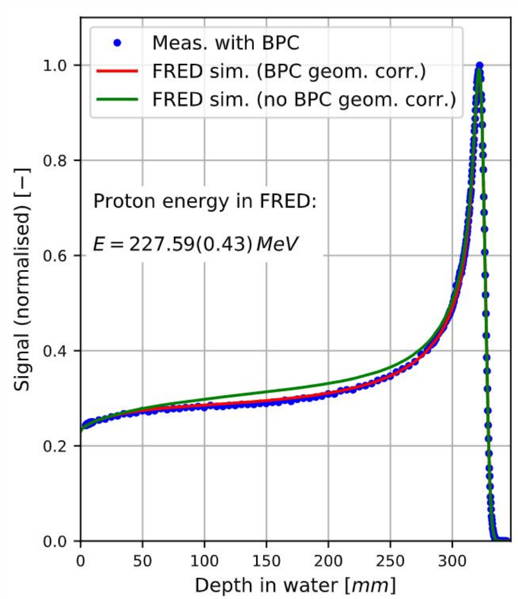
CCB (Krakow)



EMORY (Atlanta)

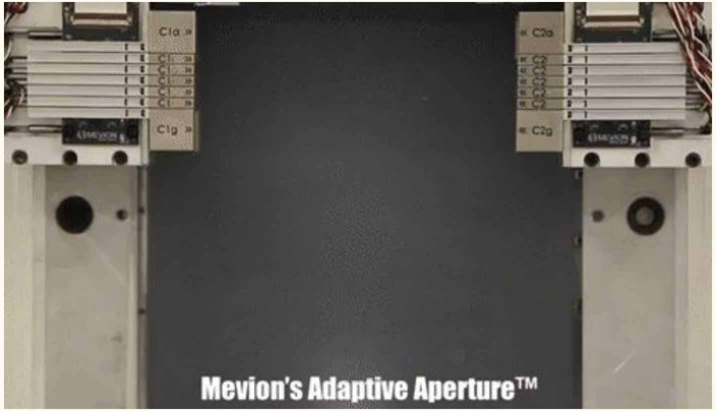


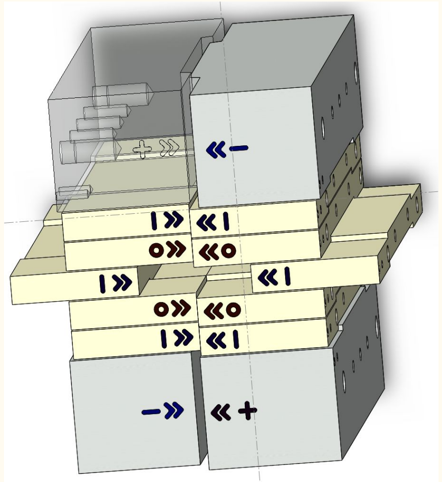
MAASTRO (Maastricht)

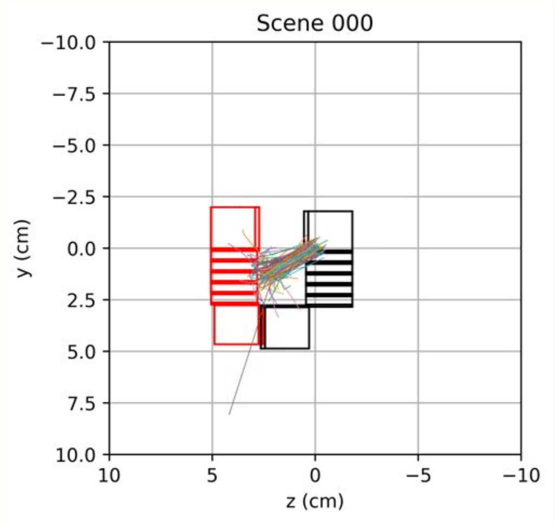


Bragg Peak range and FWHM agree within 0.1 mm (IC acceptance correction needed)

Beam model - Adaptive Aperture (MAASTRO)



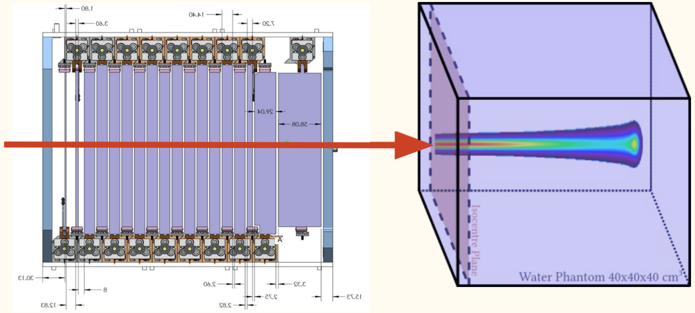


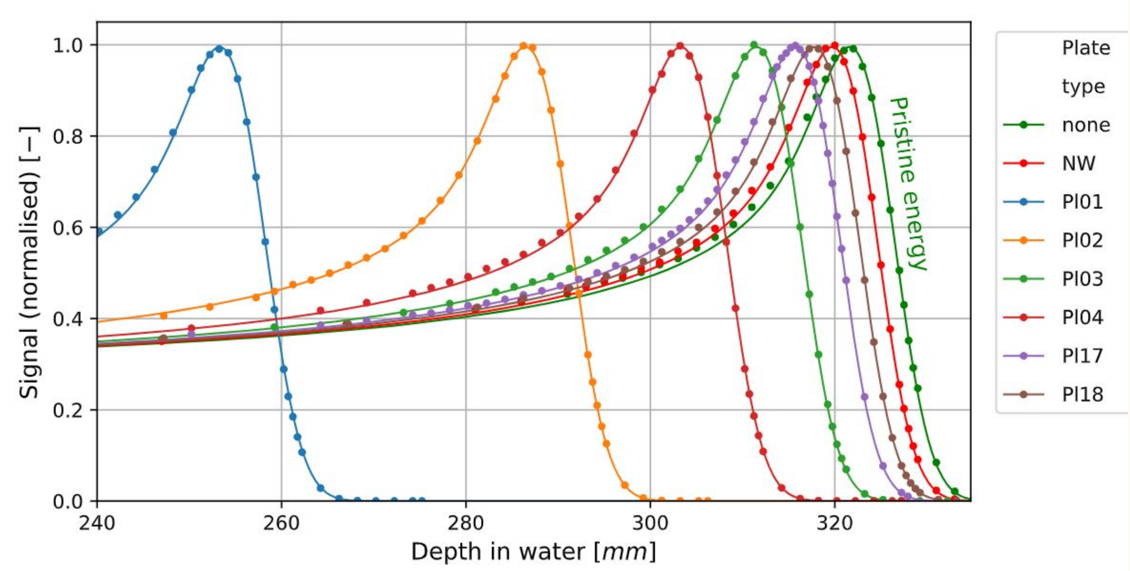


- Made of Ni
- consists of 14 movable leaves of complex geometry
- Implemented using 60 cuboid regions based on technical drawings

Validation - Range Shifters

MAASTRO (Maastricht)





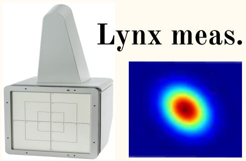
CCB: single RS

EMORY: 3 x RS (20/30/50 mm)

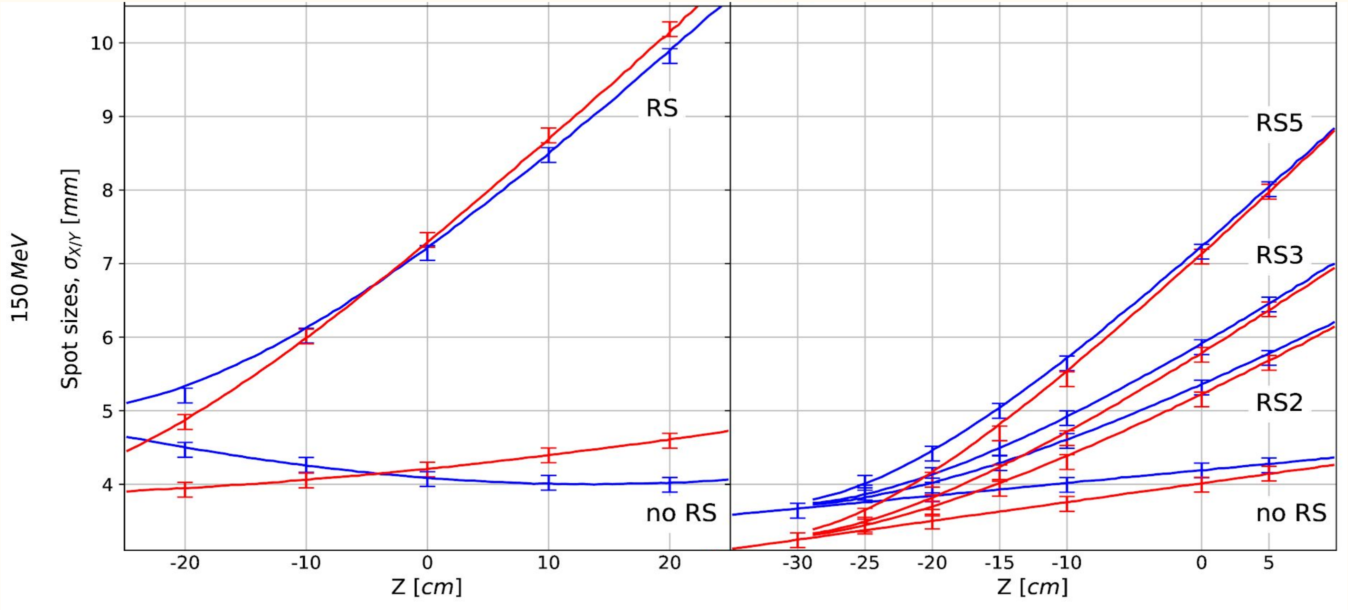
MAASTRO: 19 x RS (1.6 - 58 mm)

BP range behind Range Shifters agree with the measurements <0.1 mm

Validation - spot size in air

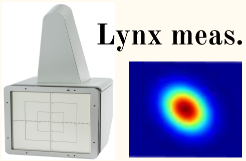


CCB (Krakow) **EMORY (Atlanta)**

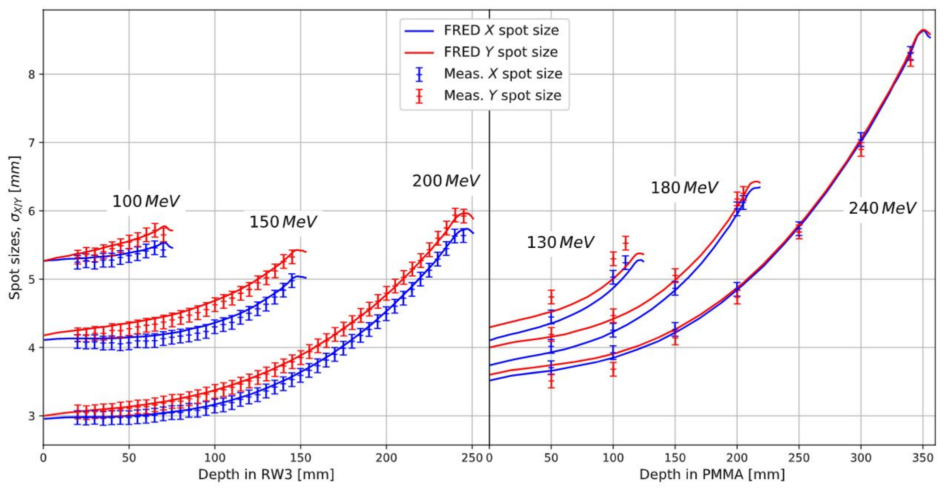


Spot size in air behind and without RS within ±0.2 mm

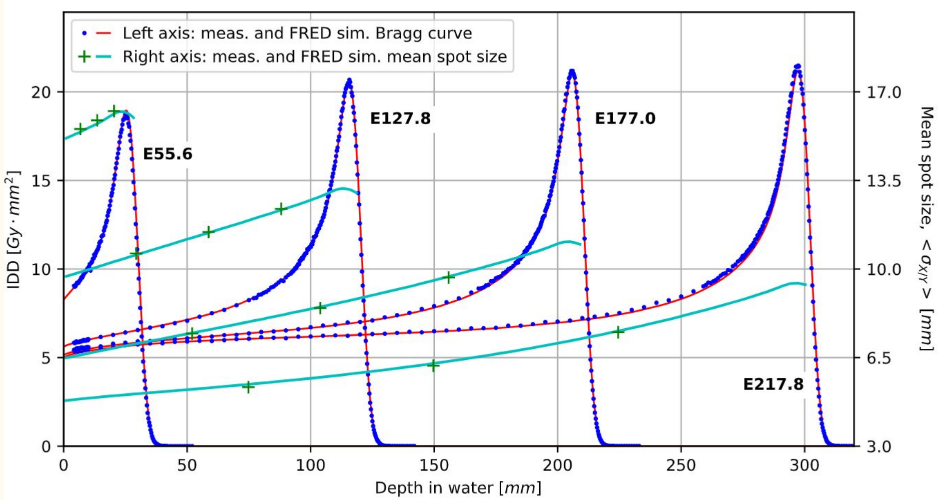
Validation - spot size in water/solid



CCB (Krakow) **EMORY (Atlanta)**



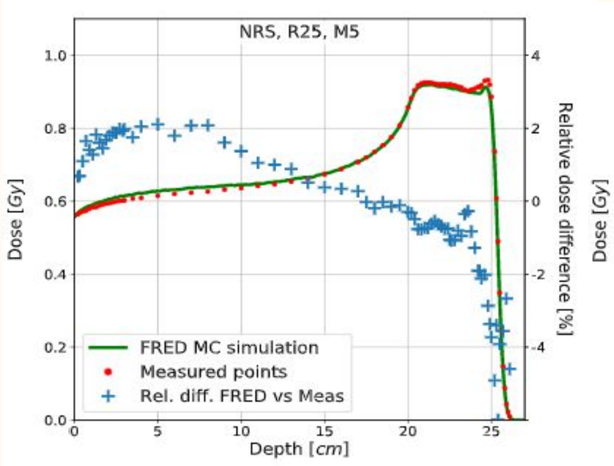
MAASTRO (Maastricht)



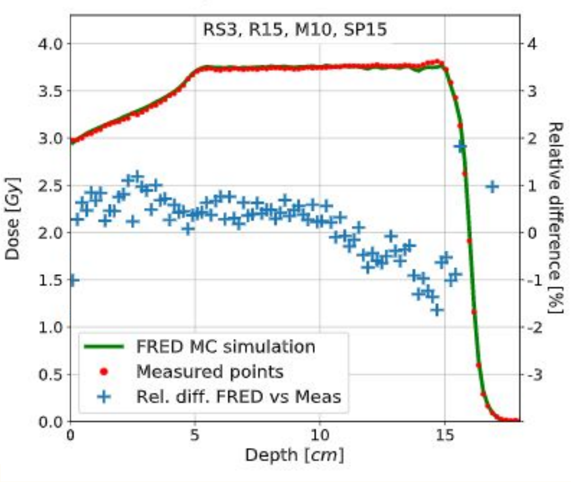
The spot size in water/solid phantoms within ± 0.6 mm

Validation - SOBP

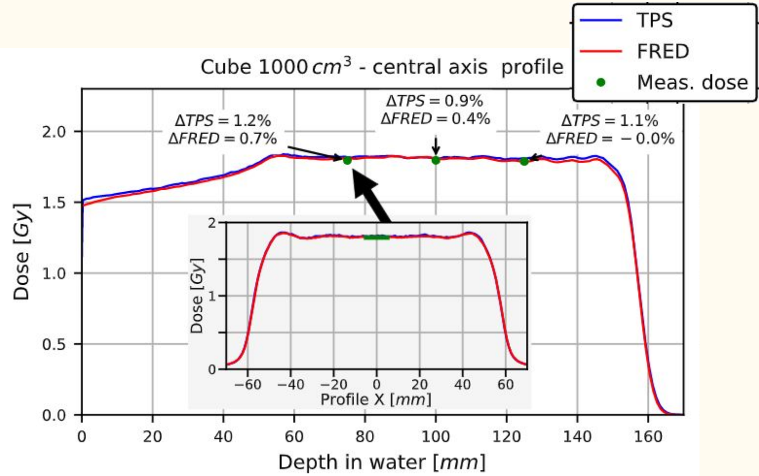
CCB: 5 x SOBP without RS



EMORY: 4 x SOBP Various RS and Snaut Position



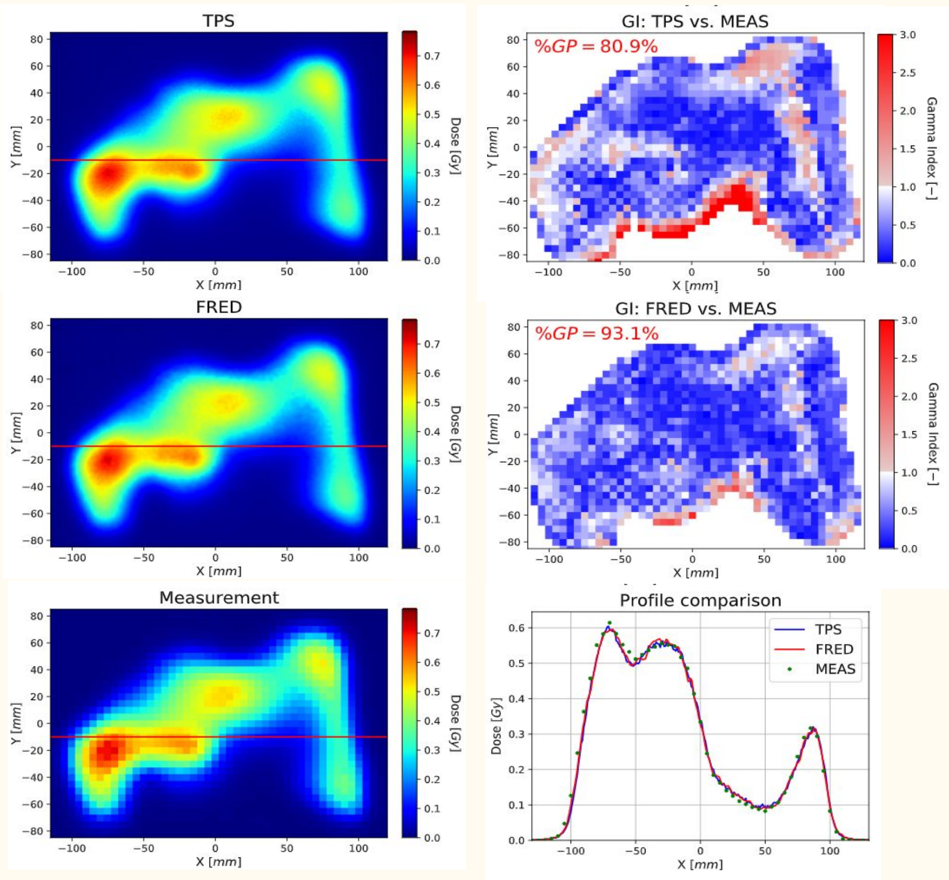
MAASTRO: 3 x SOBP Adaptive Aperture included



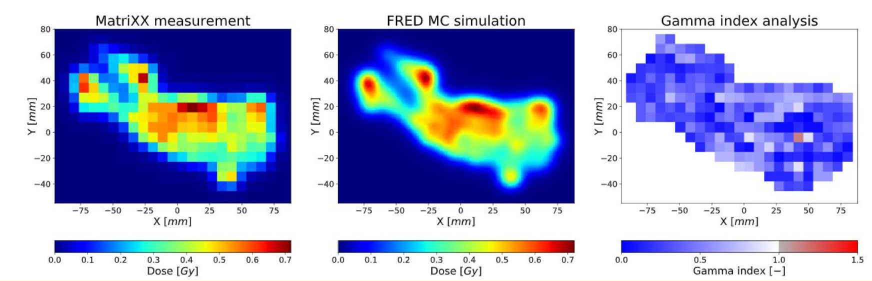
Relative dose difference <2%

Validation - patient QA

MAASTRO: ~600 meas.

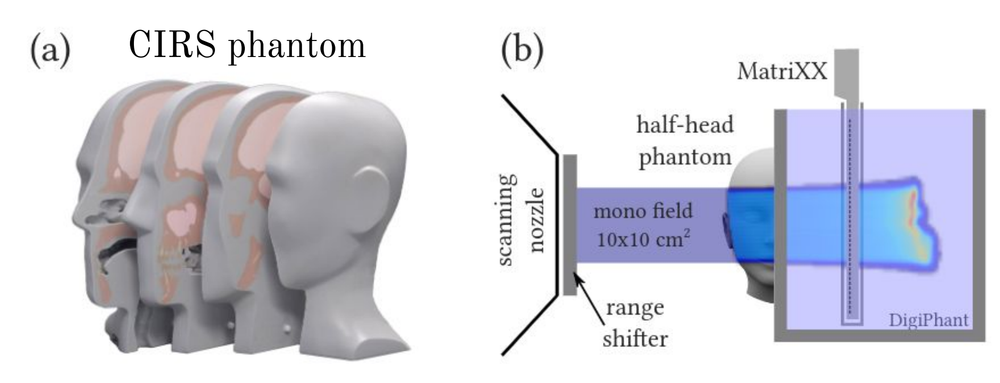


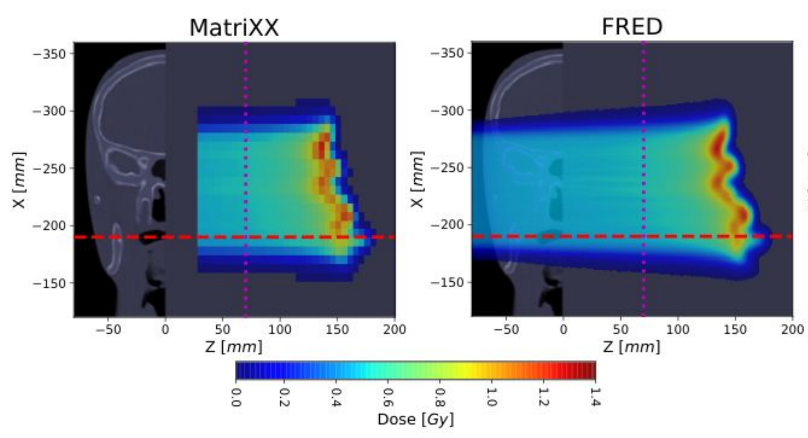
CCB+EMORY: 1077+52 meas.



Gamma index pass rate (2%/2 mm/2%) over 95%

Validation - heterogeneous media (CCB)





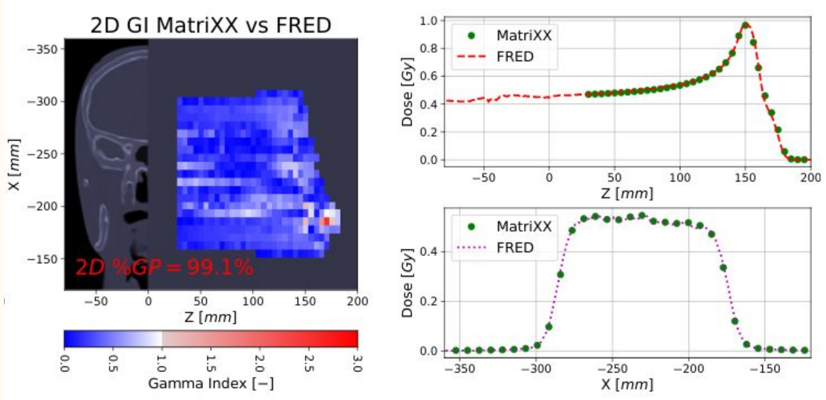
Mono. layers: 100/150/200 MeV (nRS/RS) ⇒ 6 plans

MatriXX detector in water

⇓

3D dose maps (pixel 5x7.6x7.6 mm^3)

3D GI pass rate (2%/2 mm/2%) >99%



Time performance of FRED MC engine

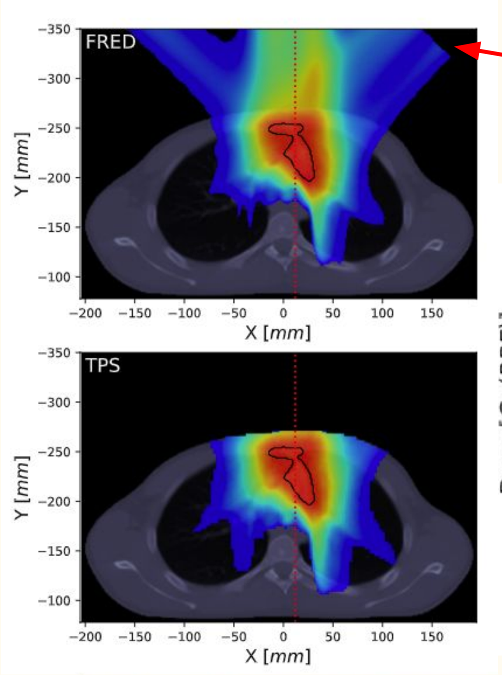
Simulation	prim./PB	Voxel size	time	Tracking rate
Single PB	10^8	1 mm^3	36 - 53 s	up to 10^7 prim./s
SOBP 0.5l	10^5	1 mm^3	$<$10 min	up to $5x10^6$ prim./s
Patient QA in water	10^5	1 mm^3	mean 2’35 min	mean $3.4x10^6$ prim./s
Patient plan in CT	10^4	1.5x1.5x1.5 mm^3	21s - 6’26 min	mean $2.9x10^6$ prim./s

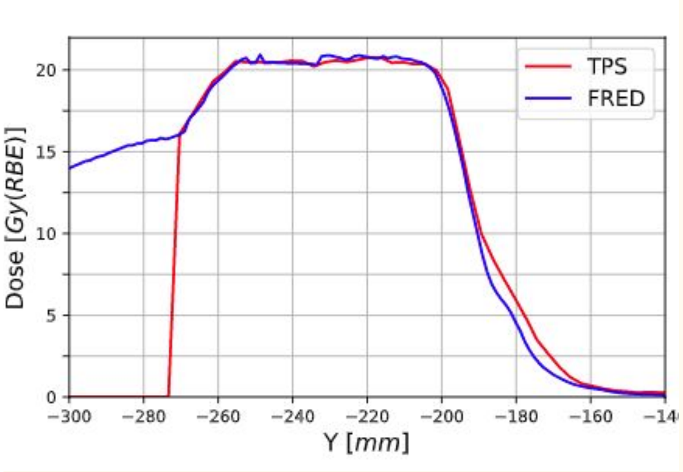
Automatic (no user activity required) beam model computation (303 simulations for CCB) in ~10h, including:

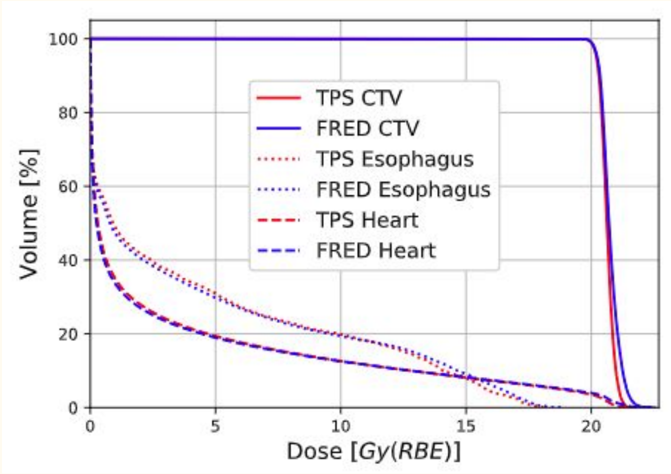
- characterisation of the beam lateral propagation
- the energy and energy spread optimisation
- optimisation of the scaling factor with monoenergetic 10x10 layers

Patient simulations (MAASTRO)

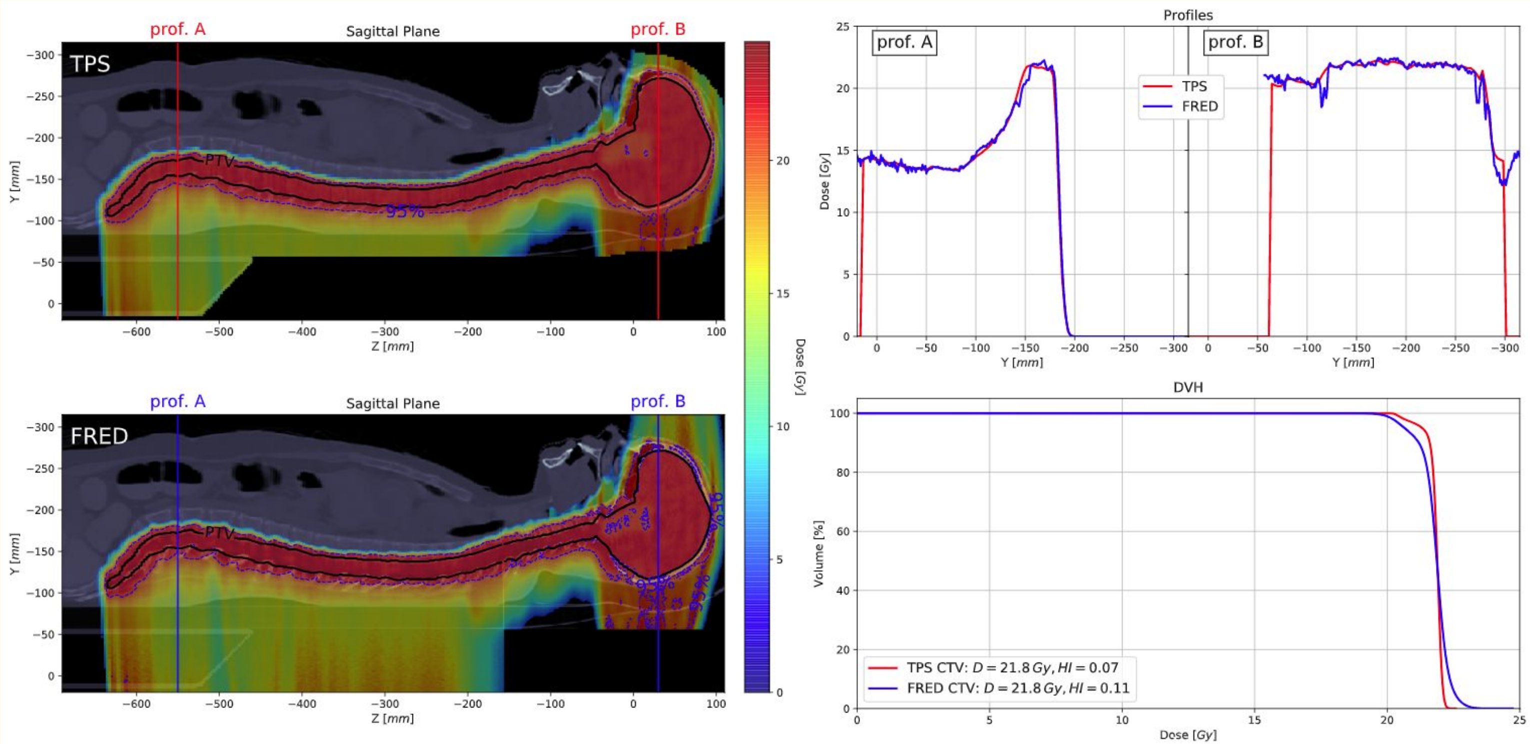
- Adaptive aperture present
- Nozzle overlapping with the CT
- MC-based TPS but in rescalled CT





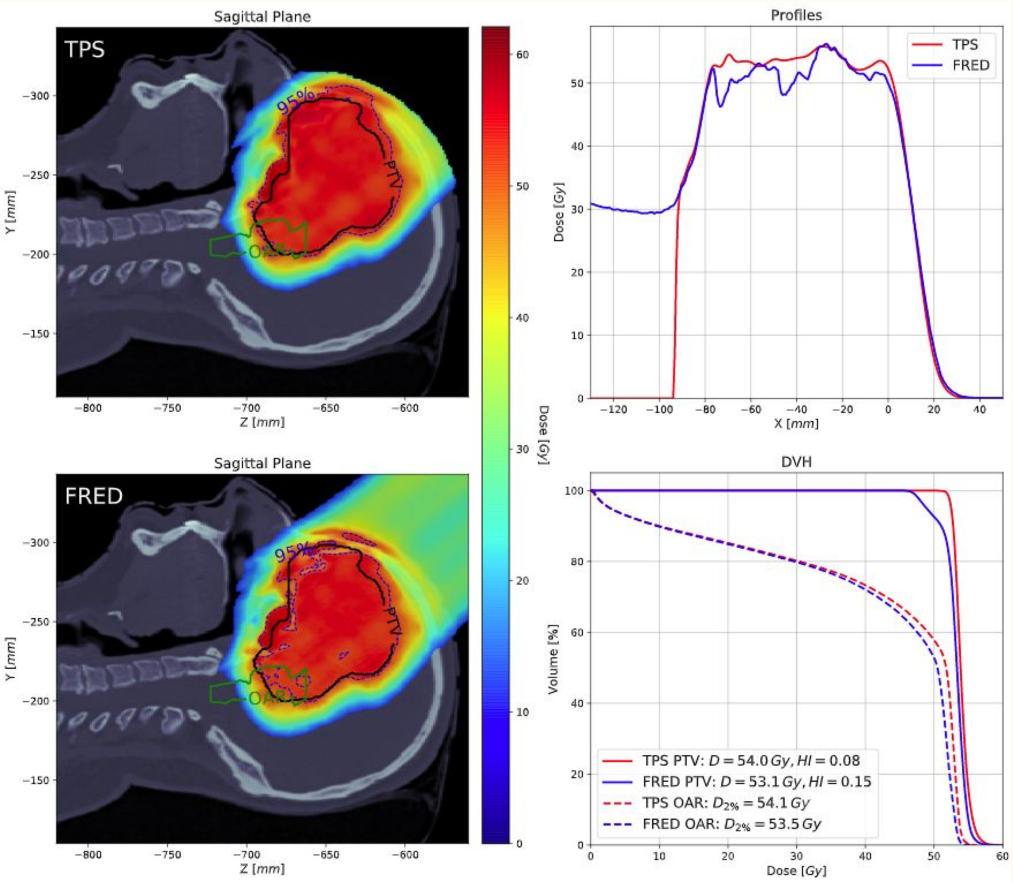


Patient simulations (EMORY)



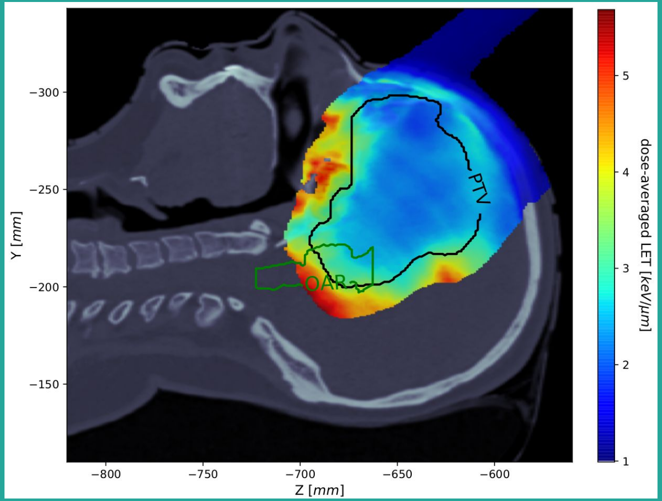
- Nozzle overlapping with the CT
- MC-based TPS but in rescalled CT

Patient simulations (CCB)

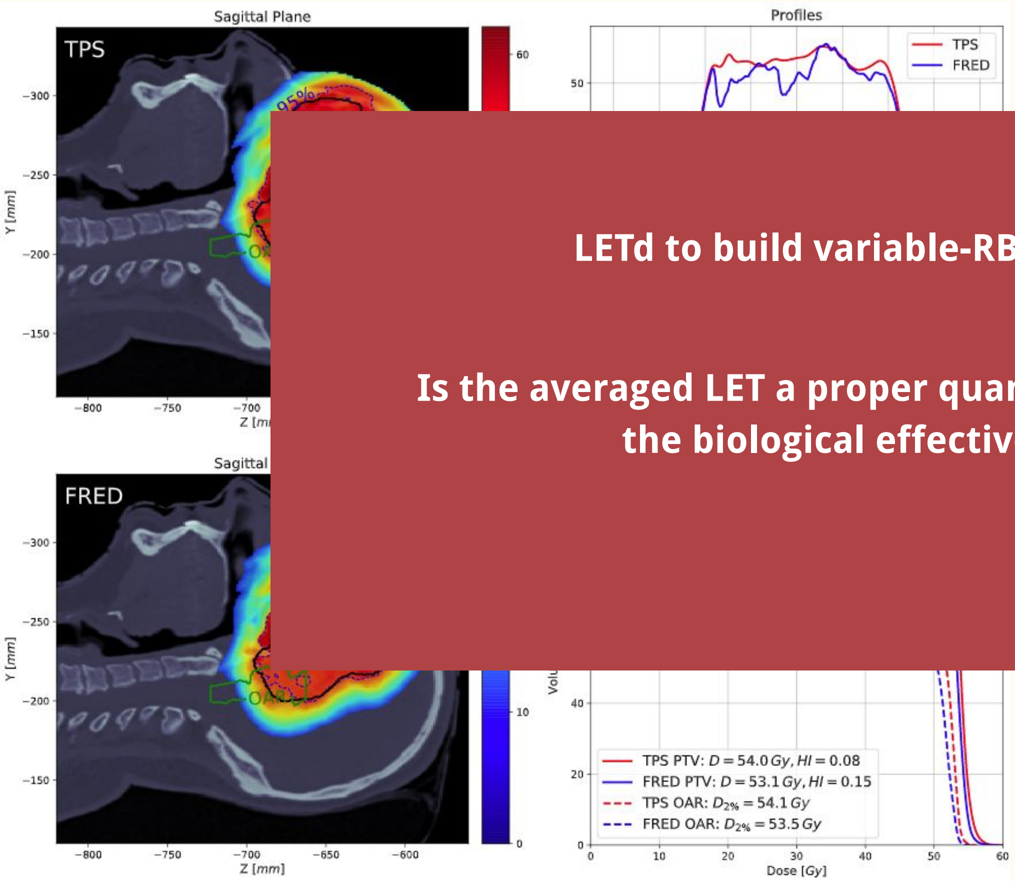


- Analytical TPS
- Analysis of 122 treatment plans
- Two papers in preparation by Magdalena Garbacz → next talk

Dose-averaged LET

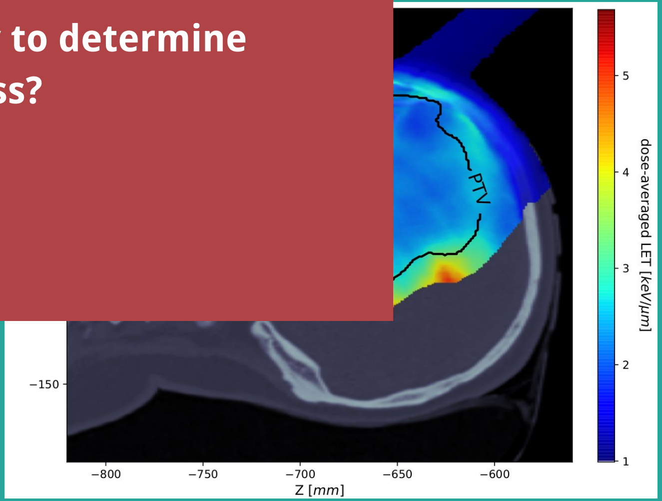


Patient simulations (CCB)



- Analytical TPS
- ntment plans
  ration by
  → next talk

d LET

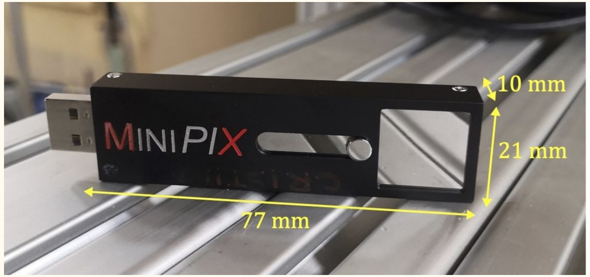


LETd to build variable-RBE models

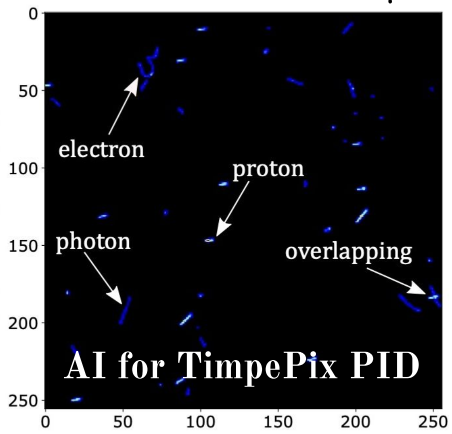
Is the averaged LET a proper quantity to determine the biological effectiveness?

Experimental validation of LET spectra

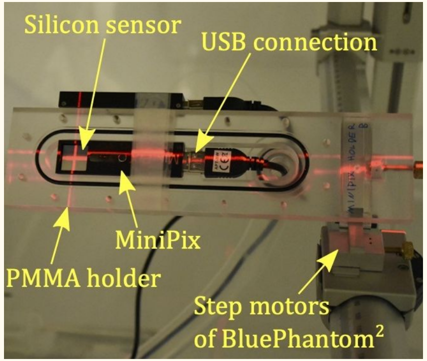
MiniPix TimePix detector
(Advacam, Prague, Czech Republic)



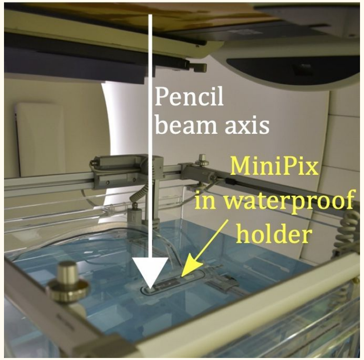
Pixelated silicon sensor 300 μm thick



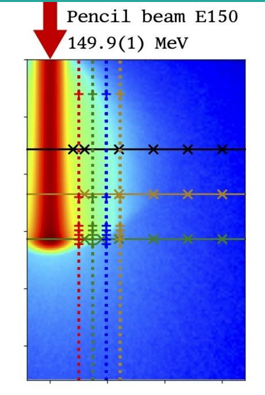
TimePix detector waterproof holder



Water phantom with 3D motors



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



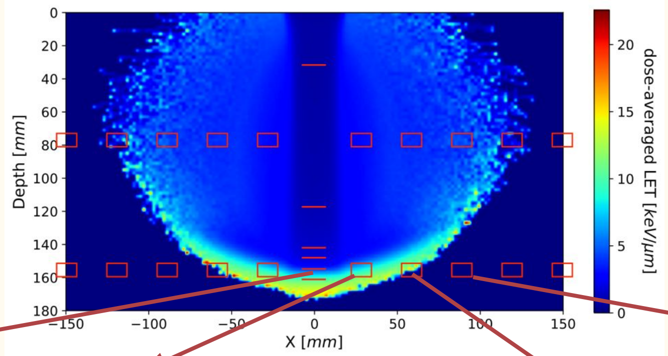
Stasica et al. A simple approach for experimental characterization and validation of proton pencil beam profiles, sub. to Frontiers in Physics

LET spectra (preliminary)

150 MeV proton beam

Meas. up to 15 cm off the beam

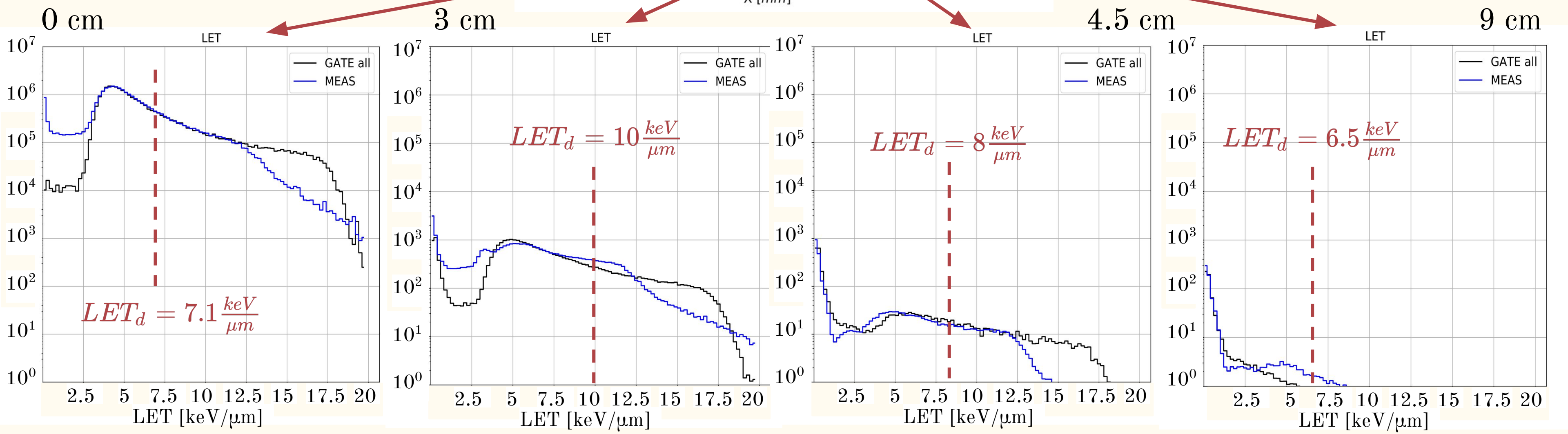
Results per 10^8 prim. (~1Gy BP)



Gate/Geant4 MC toolkit

Simulations to be optimised

Meas. analysis to be improved



Summary

- **Automated beam model** commissioning → prepare/adapt the beam model over night
- **Validation against measurements** → within clinical acceptance criteria
- **FRED performance** → patient dose simulations in minutes (high statistics)
- **LETd** scoring and **variable RBE models** implemented → treatment planning study
- **LET spectra** measurements → input to biologically-weighted dose optimization