Implementation and validation of clinical proton beam model in GATE and GPU-accelerated MC code FRED for quality assurance and detector development applications

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J-PET collaboration

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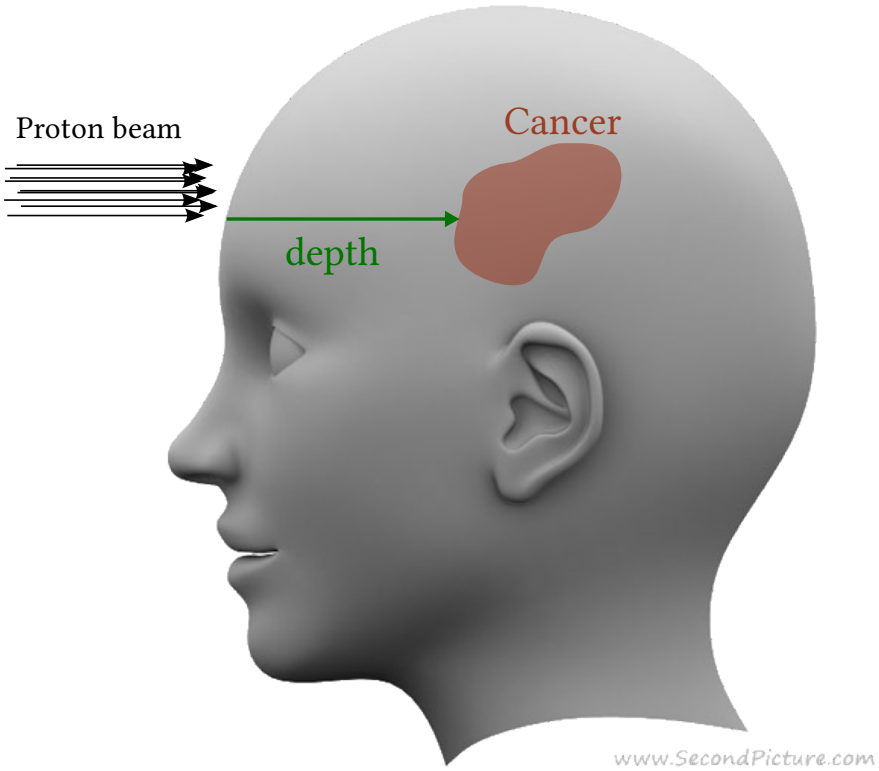
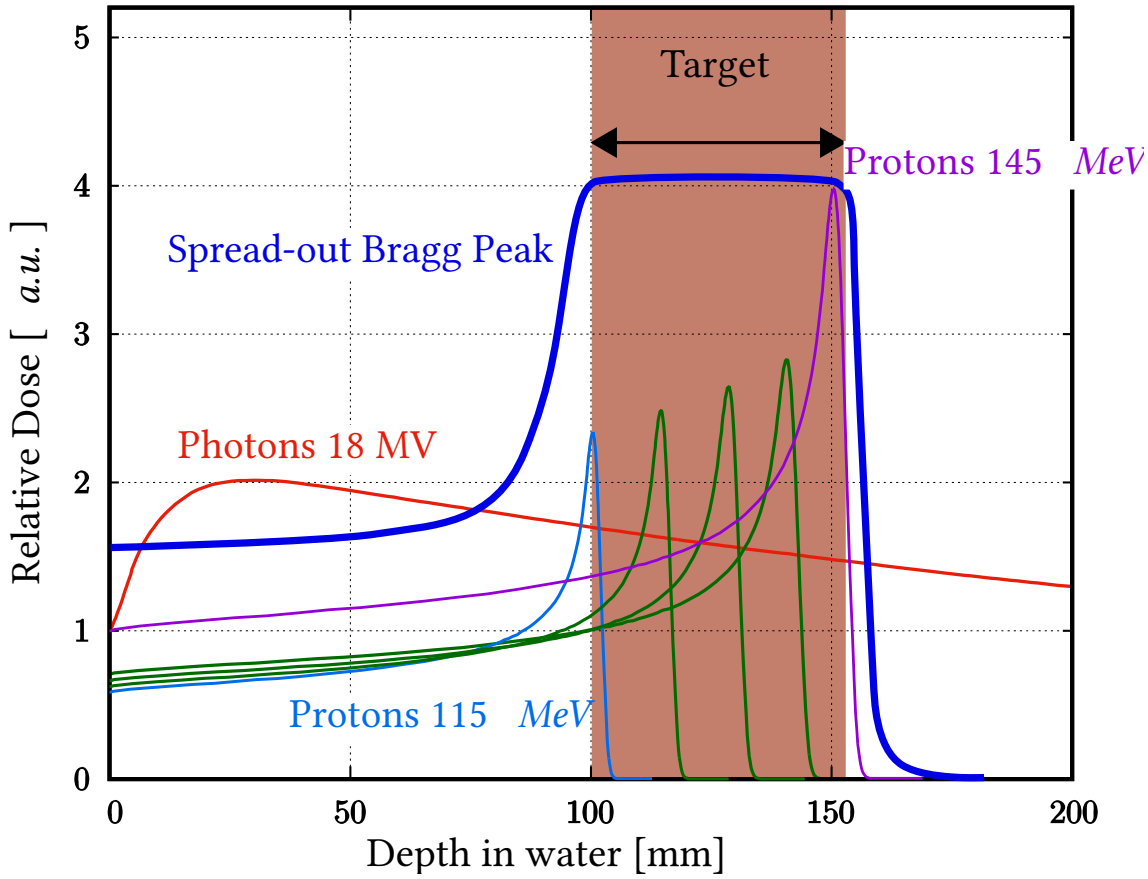
CCB

3rd Symposium on Positron Emission Tomography
Kraków, 2018

Proton therapy





Main objectives of radiotherapy:

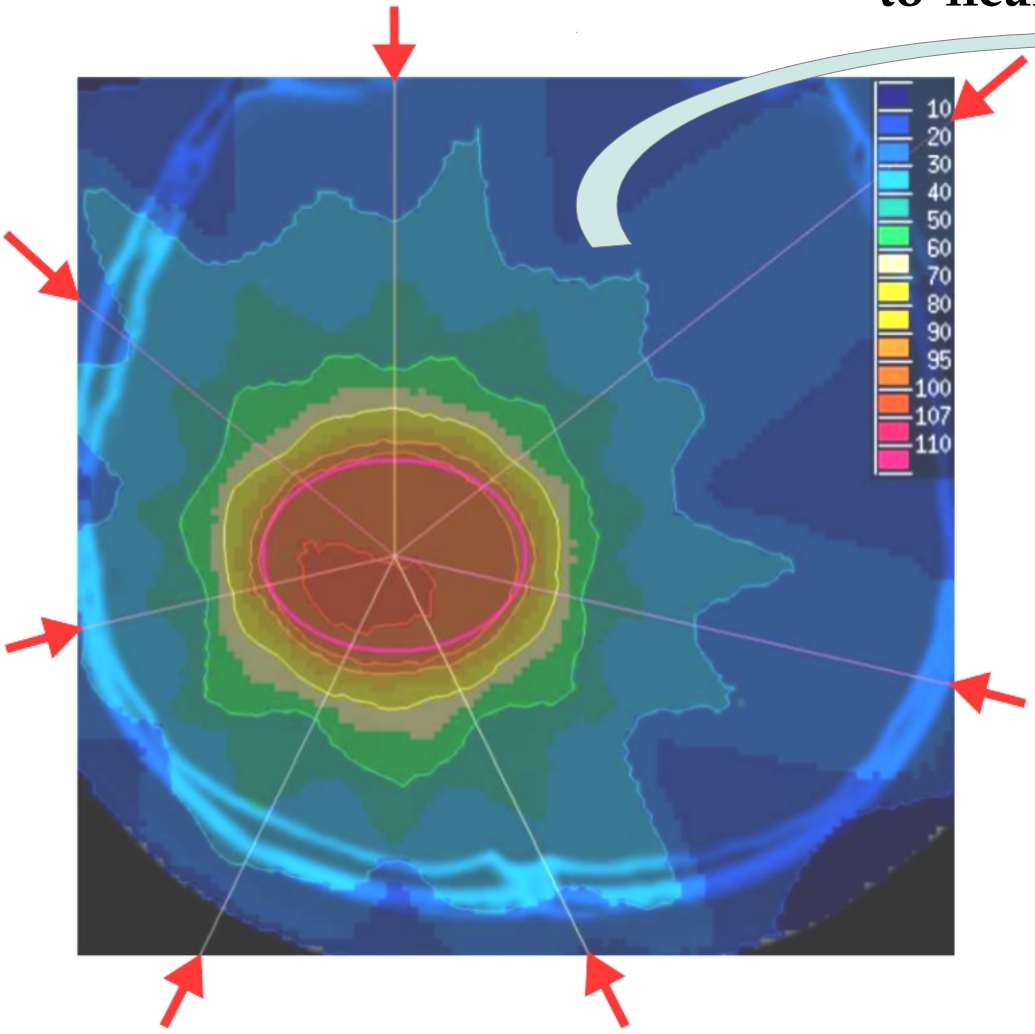
- deliver required dose to cancer volume
- minimise dose delivered to healthy tissue

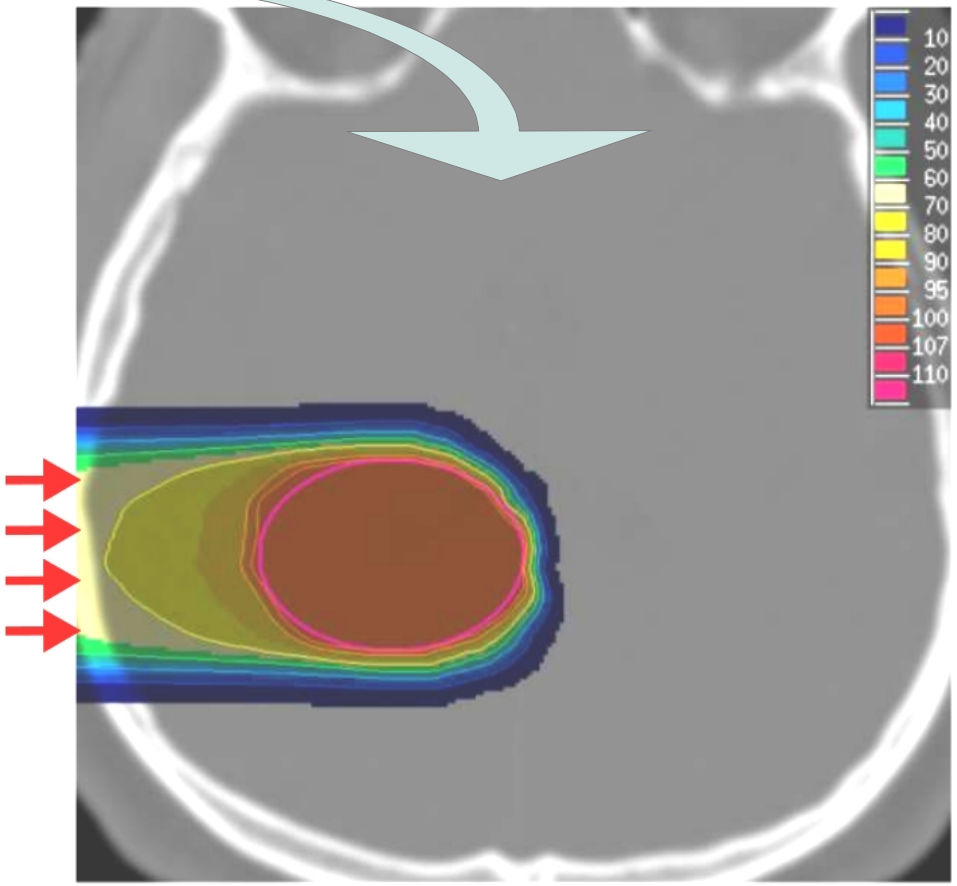
Protons vs photons

Gamma treatment

~3x less integrated dose to healthy tissue

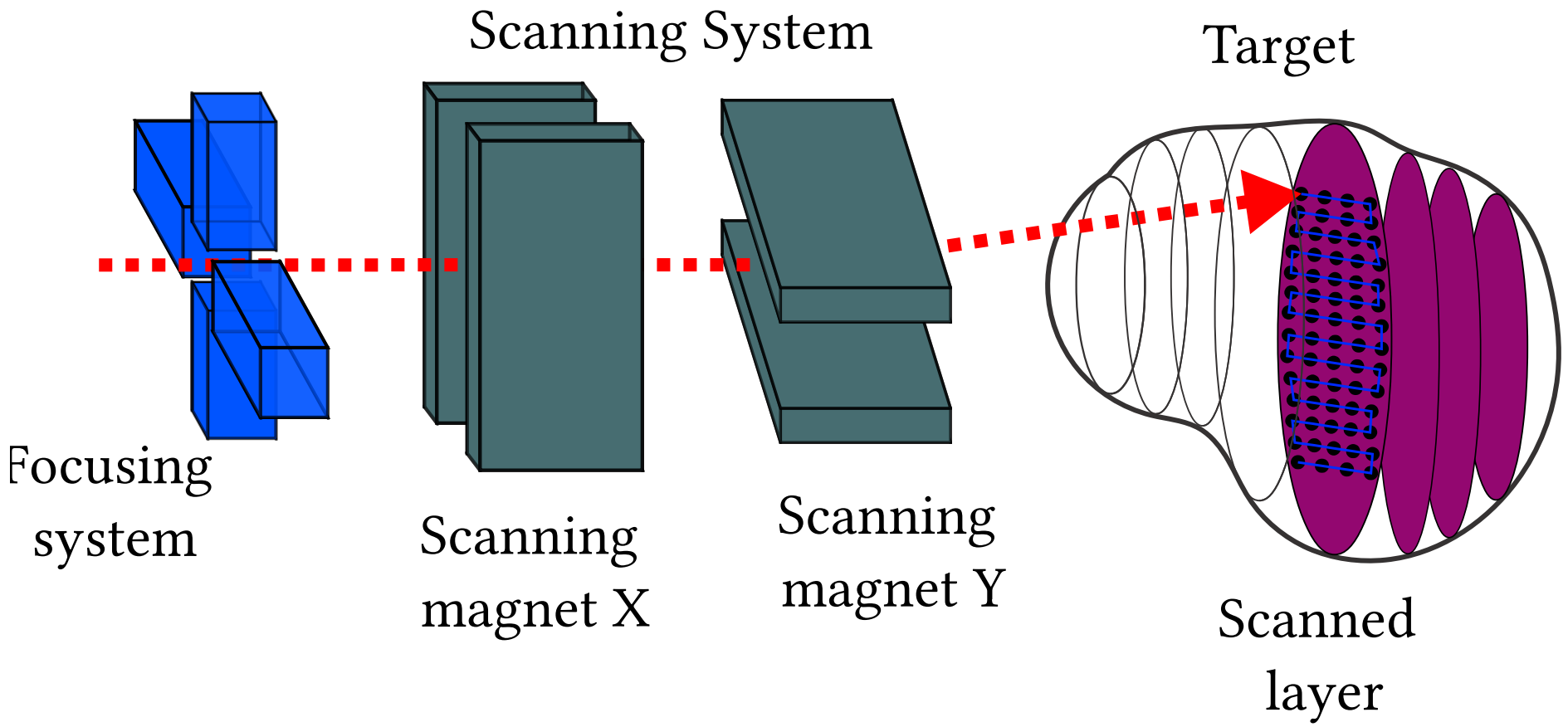
Proton treatment





Proton beam with finite range allows for more precise target coverage minimising dose delivered to healthy tissue

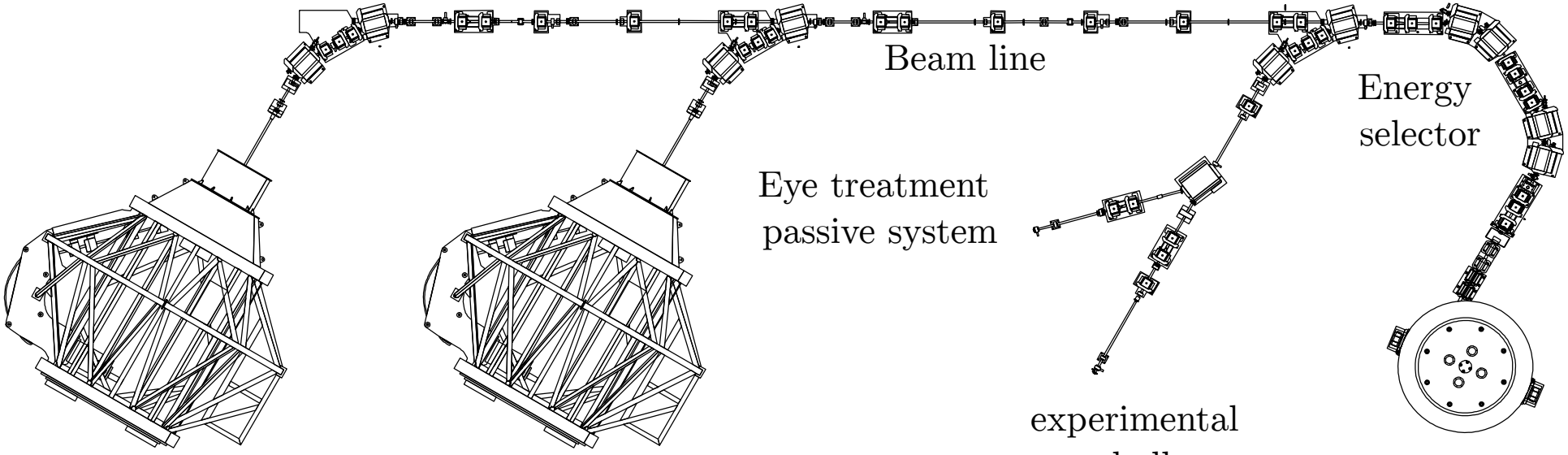
Scanning pencil beam



Narrow pencil beam is deflected by set of magnets scanning the target volume point by point and layer by layer

Jan Gajewski

Bronowice Cyclotron Centre in Kraków



Proton beam in gantry room

Energy: 70-226 MeV

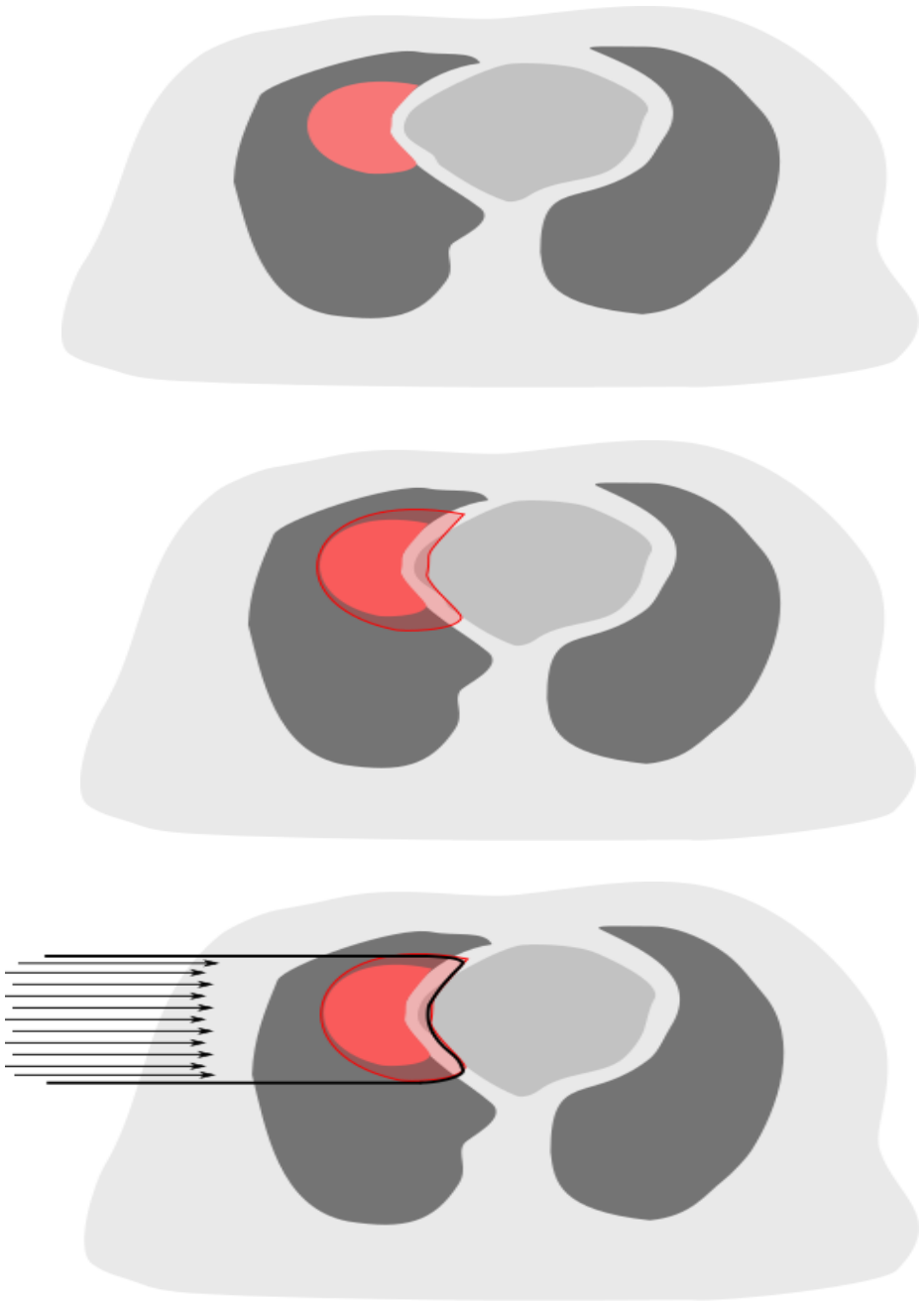
BP depth in H_2O: 42-320 mm

Spot size (σ): 2.7-6 mm

Gantry angle: 0-360°

Beam current: up to 300nA

Treatment uncertainty



- Beam properties
(energy/range, spot position/size)

- CT calibration
(HU to proton stopping power)

- Patient positioning/motions

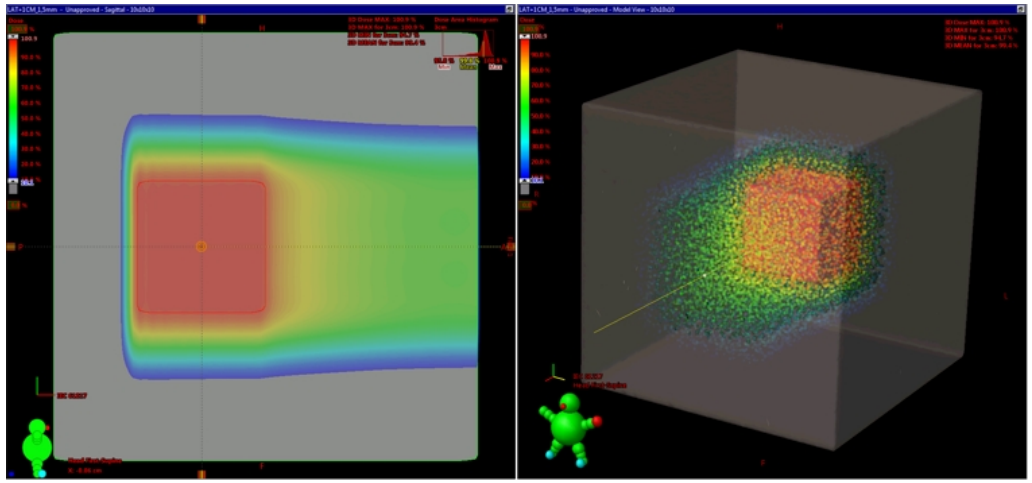
- Patient anatomical changes
(one plan for ~30 fractions)

- dose calculation algorithms

Margins in treatment plan

3-7mm (3.5% of range + 1mm)

TPS and MC codes



Treatment Planning System

Analytical calculations

Measured dose distribution rescaled and calculated in voxel

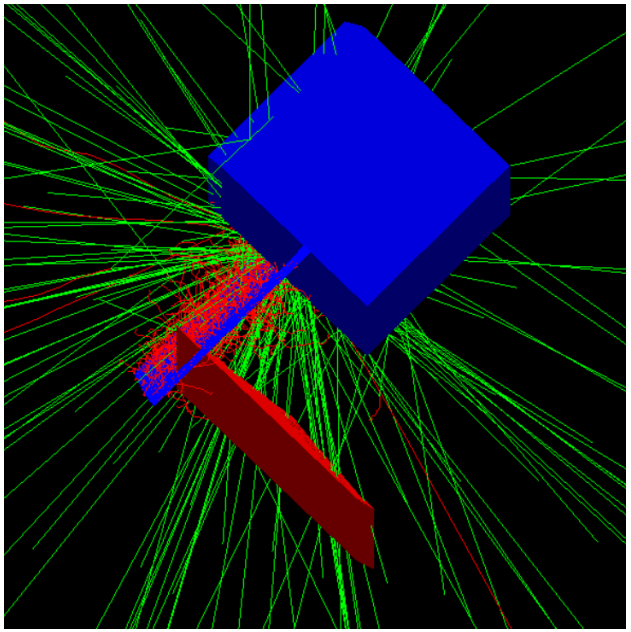
Ray Station, Eclipse ...

Monte Carlo

Physical interactions

Particle by particle energy deposition integrated in each voxel

Fluka, Geant4/Gate/TOPAS, Shield-HIT, gPMC, Fred ...



FRED and GATE MC codes

GATE (GEANT4)

- optimised for medical applications (detector development, ion therapy)
- any geometry, CT import
- β^+ emitter/prompt gamma production
- PET detectors
- Actors for scoring
- CPU calculations
- 2-7E2 protons/s
- single beam in water 1E7 primaries - 5h

Fast paRticle thErapy Dose evaluator – FRED

- optimised for proton radiotherapy
- limited geometry, CT import
- Variable RBE calculations
- GPU and CPU calculations
- 3-10E6 protons/s
- single beam in water 1E7 primaries - 30s

FRED and GATE MC codes

-Actors for scoring

- CPU calculations

- 2-7E2 protons/s

- single beam in water 1E7 primaries - 5h

- GPU and CPU calculations

- 3-10E6 protons/s

- single beam in water 1E7 primaries - 30s

Both MC codes require beam characterisation at CCB in order to properly predict experimental and clinical data

Two projects - one beam model

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

FNP Reintegration (A. Ruciński, M. Garbacz, A. Skrzypek, J. Gajewski, foreign partners)

Final goal: indicate which radio-biological models are significant for specific clinical indications based on CCB clinical data

See: M. Garbacz talk *Clinical validation of Fred Monte Carlo code in Krakow proton beam therapy centre*

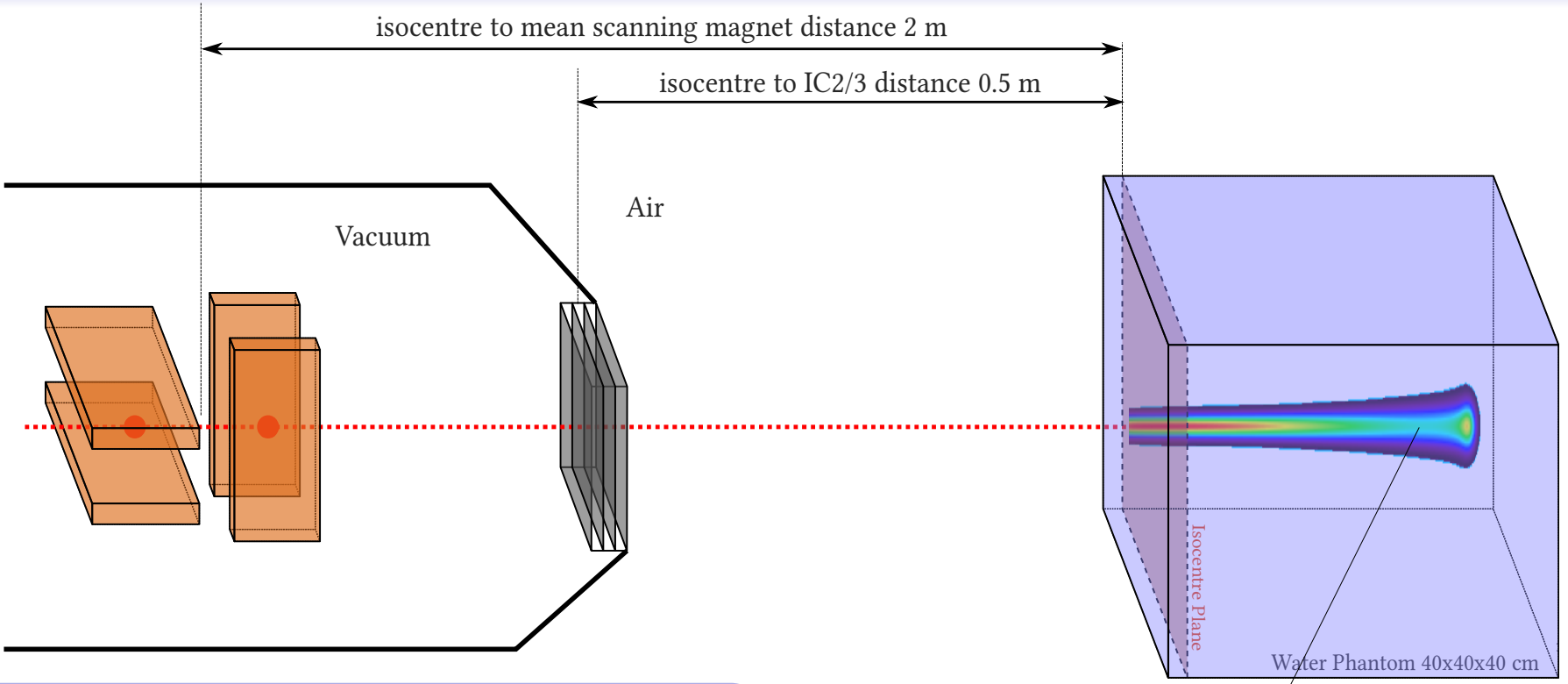
J-PET for beam range monitoring in proton radiotherapy

NCBiR Lider VIII (A. Ruciński, M. Pawlik-Niedźwiedzka, J. Gajewski, J-PET collaboration)

Final goal: propose a solution and project of prototype for beam range monitoring at CCB

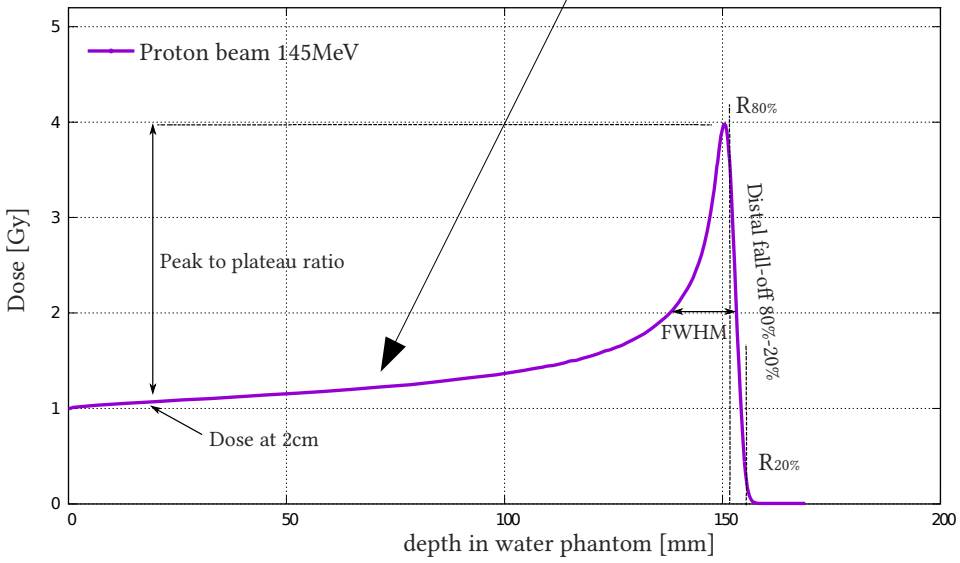
See: J. Baran talk *Feasibility study of the JPET technology for the proton beam range verification in proton radiotherapy - preliminary results*

Beam model description



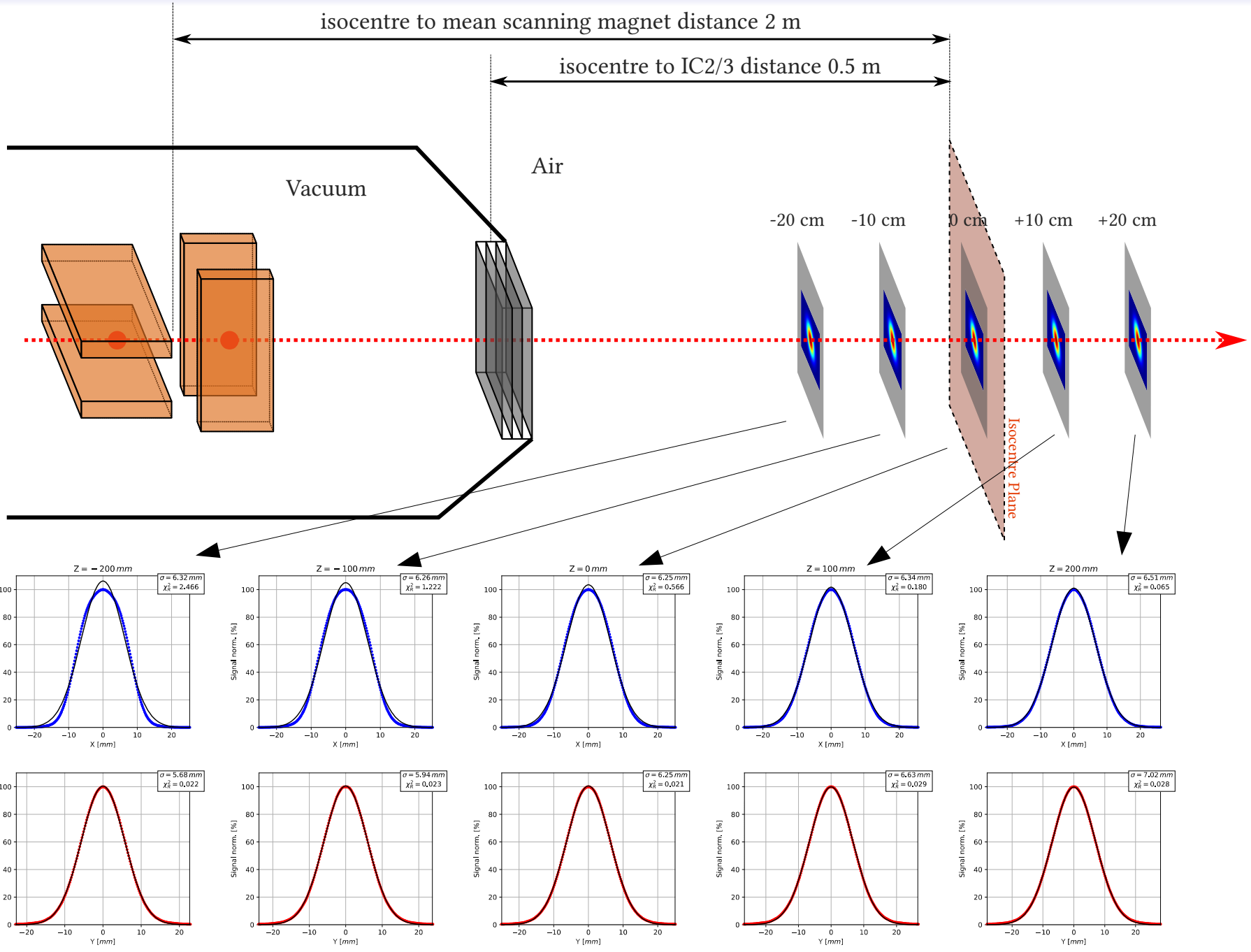
Bragg Peak parameters

- $R_{80} \approx 0.022 \cdot E_0^{1.77}$ (*proton range*)
- **width of BP (FWHM)**
- **peak to plateau ratio**
- **distal fall-off (σ_{mono} + range straggling)**

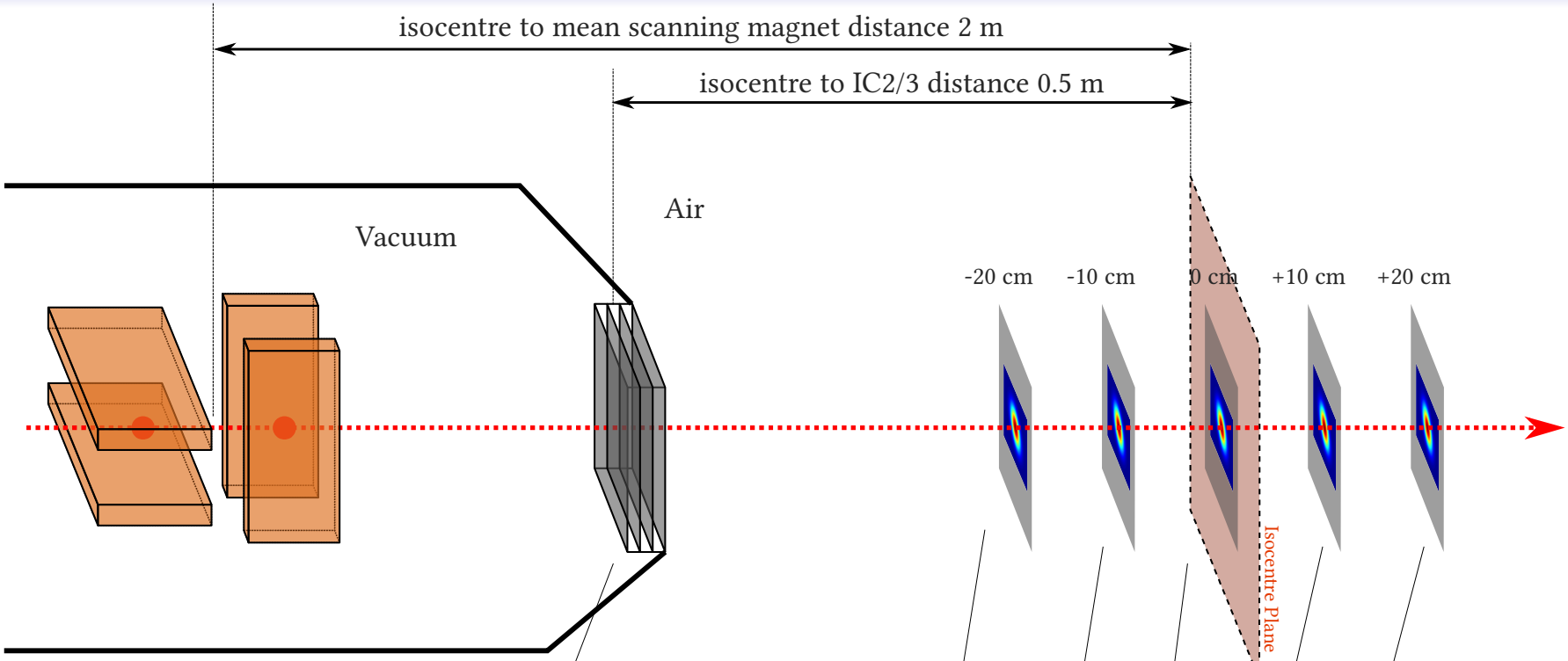


Jan Gajewski

Beam model description

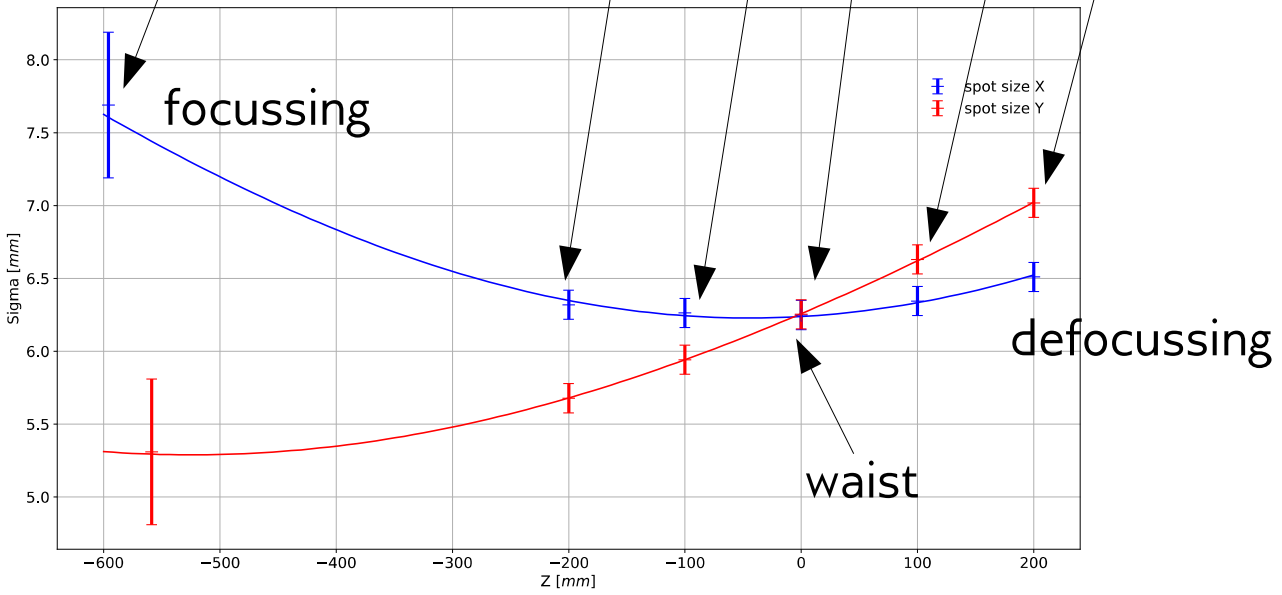


Beam model description



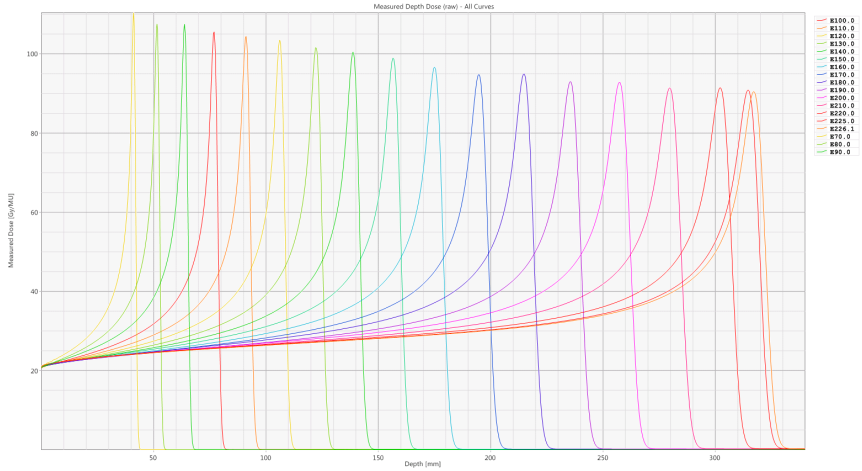
$$\sigma^2 = a + b \cdot Z + c \cdot Z^2$$

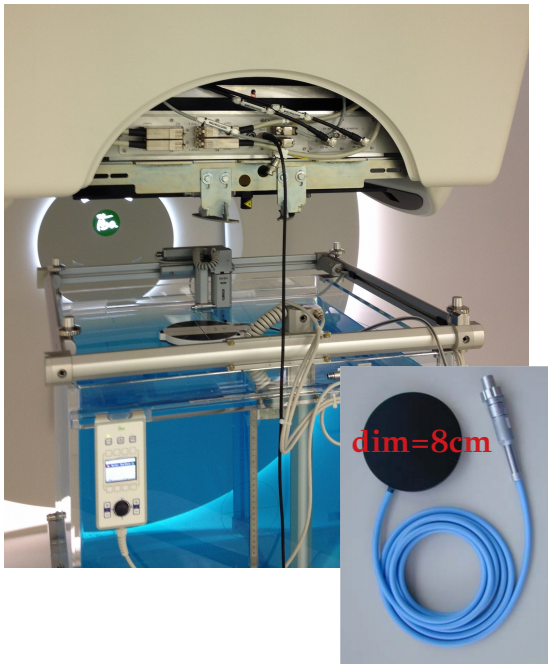
Transverse sigma is related to emittance parameters



Commissioning and QA measurements

Bragg peaks every 10MeV

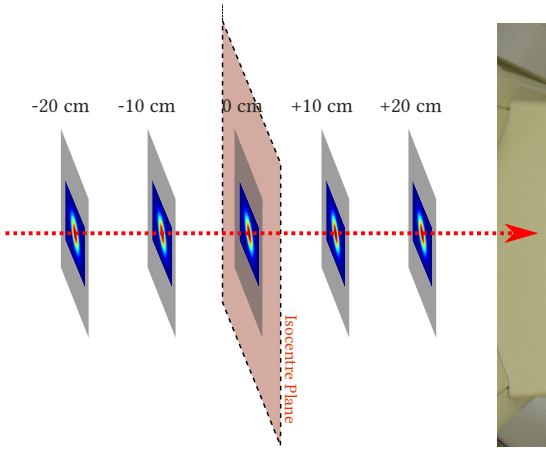


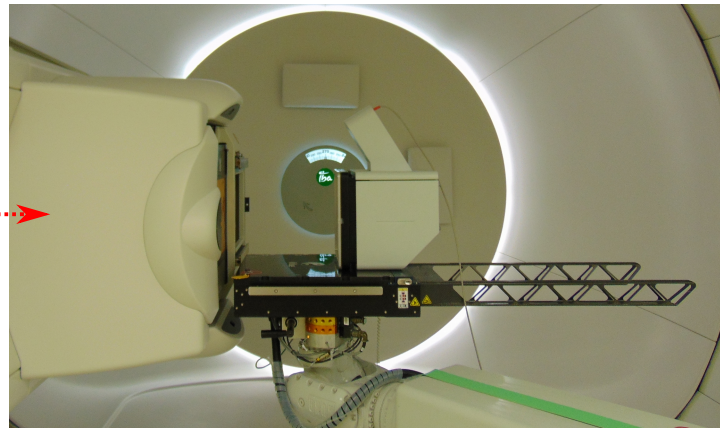


Commissioning:
- every 10MeV

Periodic QA:
- Weekly: 5 energies ($R_{90\%}$: ±1mm)
- Semiannual: every 10MeV ($R_{80\%}$-$R_{20\%}$: ±10%, FWHM: ±4%, $D_{max}/D_{plateau}$: ±3.5%)

Spot size in air at different distance from isocentre

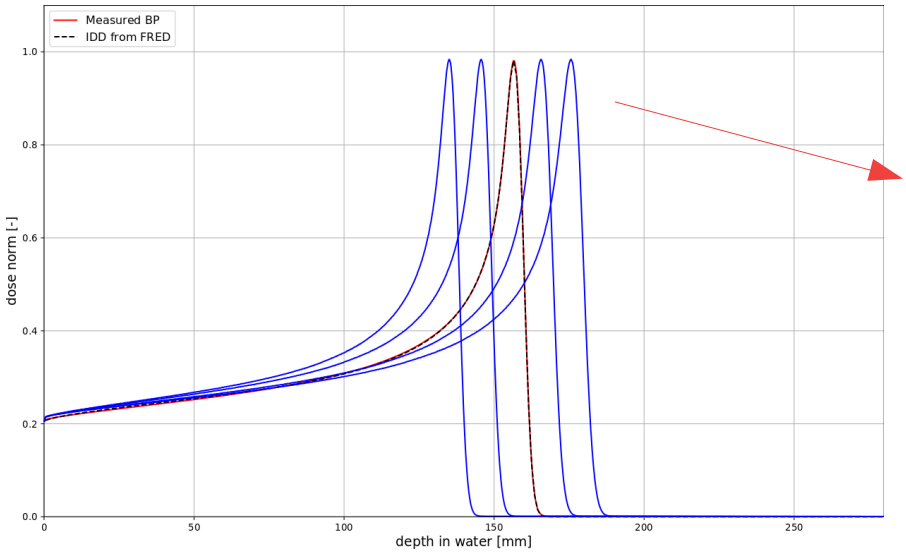




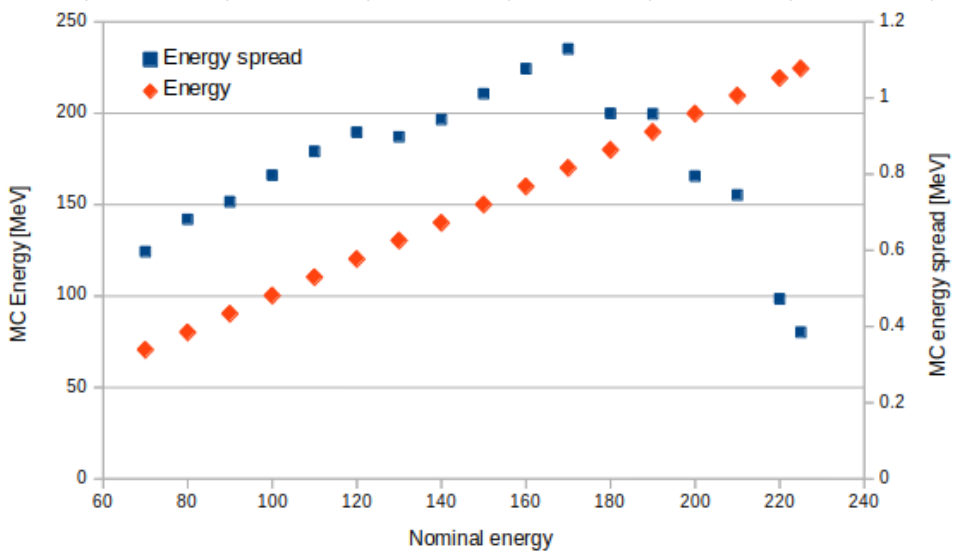
Commissioning:
- 5 distances: +/-20cm,+/-10cm, 0cm

Periodic QA:
- Daily: 3 energies at isocentre (±0.5mm)
- Monthly: 2 distances every 10MeV (±0.6mm or ±15%)
- Semiannual: all 5 distances (±0.6mm or ±15%)

MC phase space - energy



Energy	E_Fred	pSpread_Fred	scalingFactorR2cm_TPS_FRED	scalingFactorBP
70	70.60	.00844610	0.68653561081433	0.67512080242096	1.58	1.58
80	80.10	.00850703	0.74397778525267	0.75185207319528	1.47	1.47
90	90.30	.00805366	0.81318994111884	0.83007813057593	1.32	1.32
100	100.20	.00795347	0.88053228674638	0.89770366502837	1.24	1.24
110	110.30	.00779362	0.94954533728310	0.96333724125788	1.18	1.18
120	120.20	.00756808	1.01592086593989	1.02402581783925	1.14	1.14
130	130.30	.00689084	1.08175962767248	1.06393015425269	1.08	1.08
140	140.00	.0				
150	150.00	.0				
160	159.90	.0				
170	170.00	.0				
180	179.90	.0				
190	189.70	.0				
200	199.70	.0				
210	209.60	.0				
220	219.20	.0				
225	224.40	.0				



For each nominal energy:

10 sim. ±5% energy

X

6 sim. ±30% momentum spread

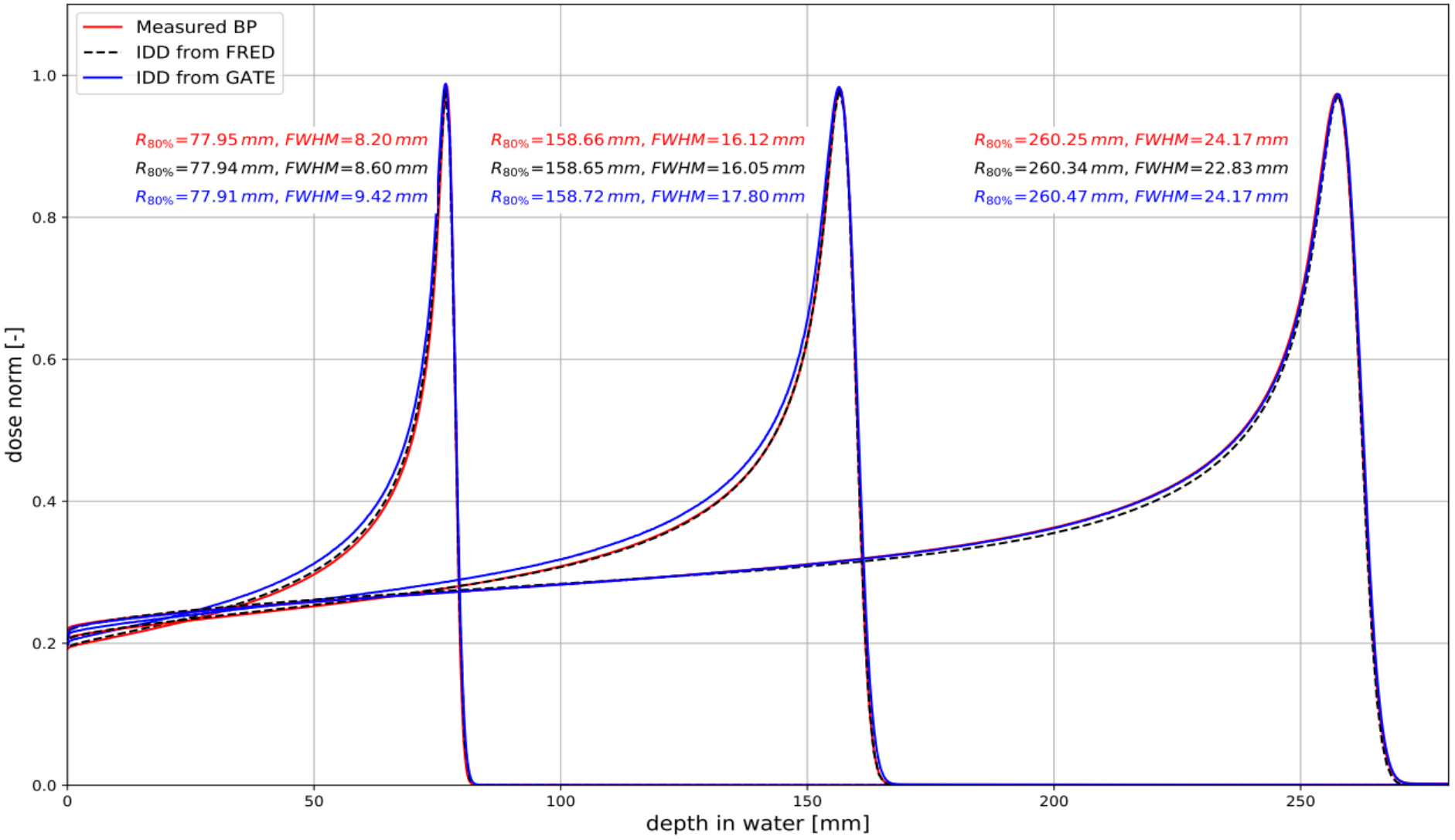
X

Simulations in 10 MeV step for 17 energies with 1E6 protons

=

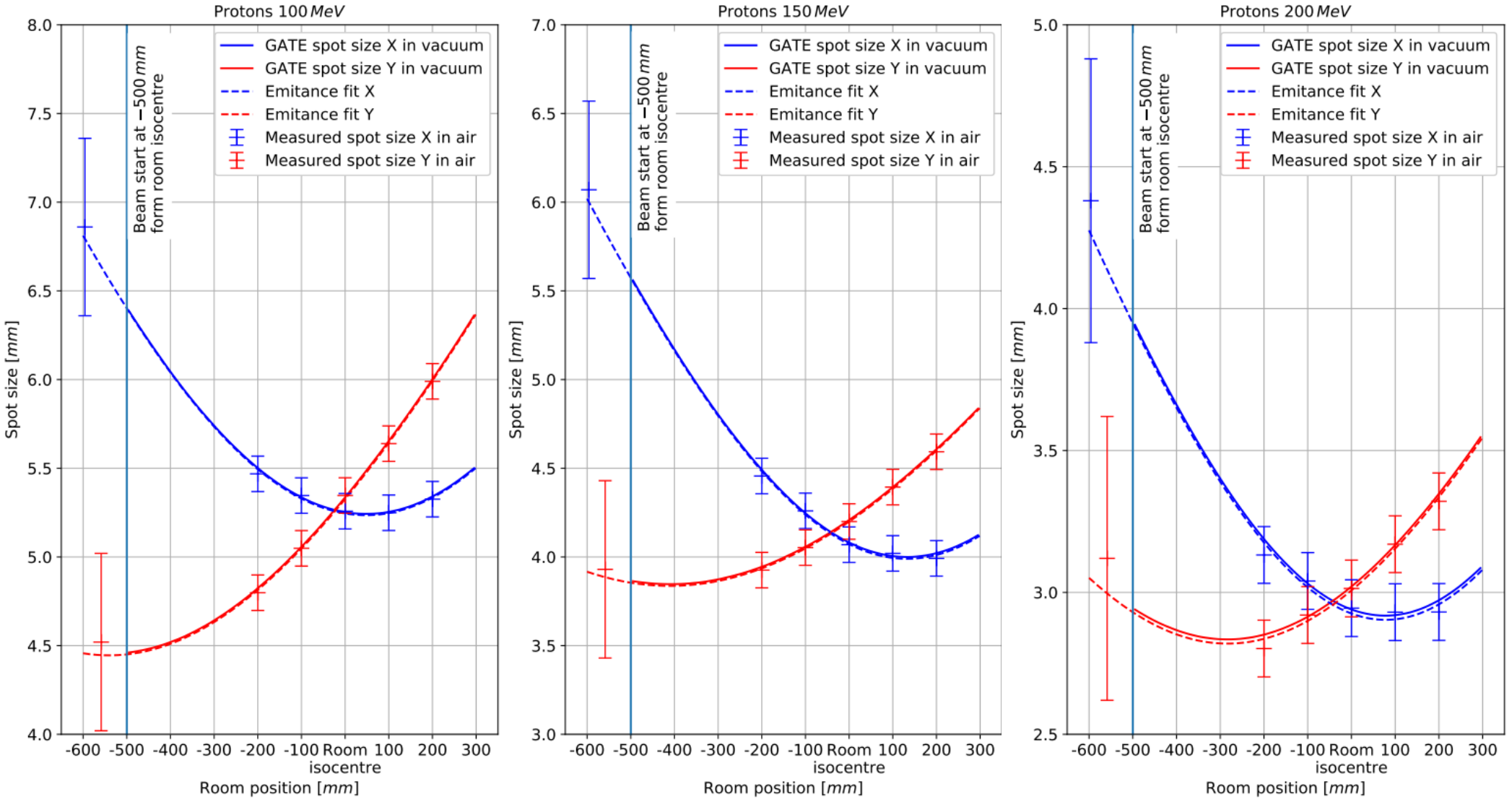
>1309 simulations (1h on 40 GPUs – Prometheus)

MC phase space - energy



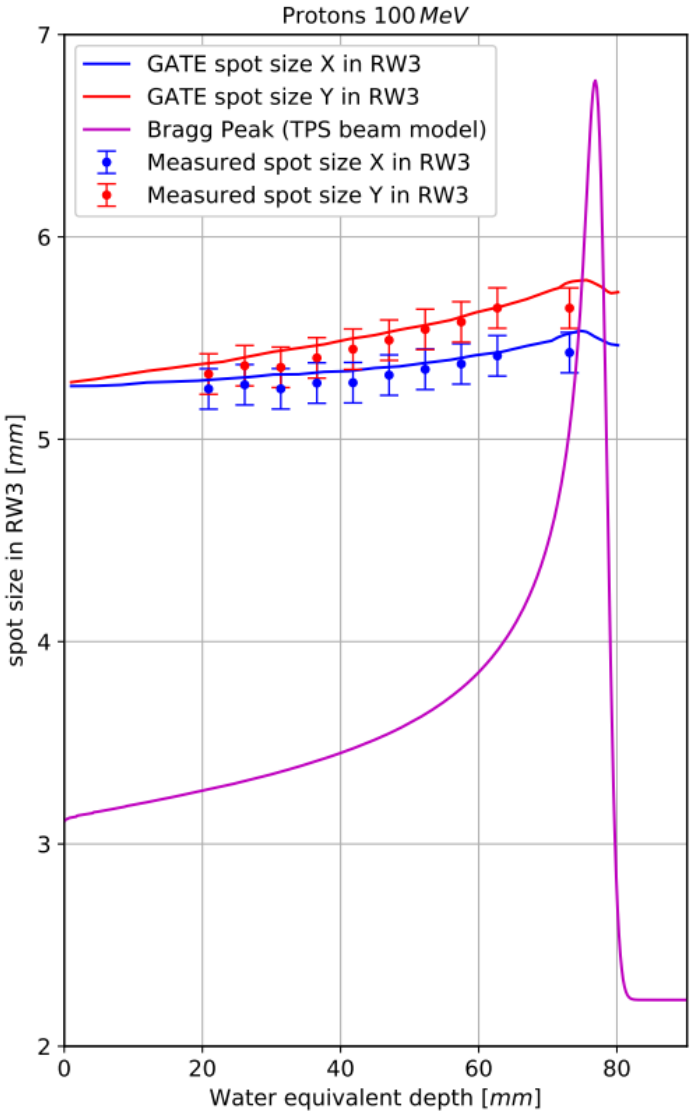
Range $R_{80\%}$ agrees within 0.3%
FWHM agrees within 2mm

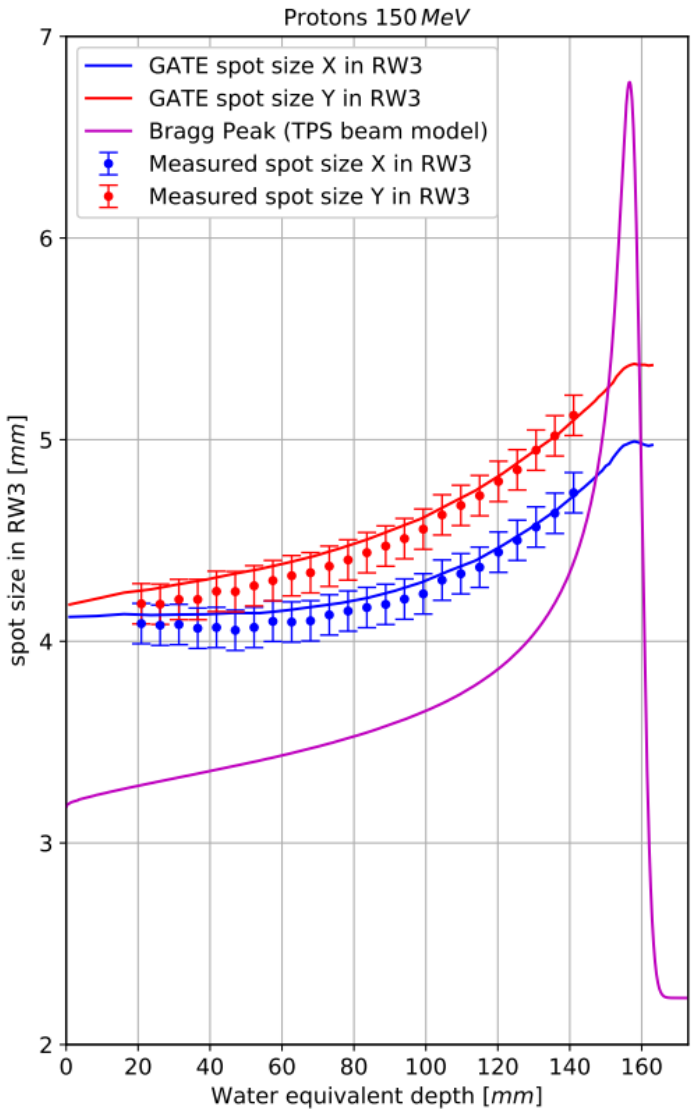
MC phase space – beam shape

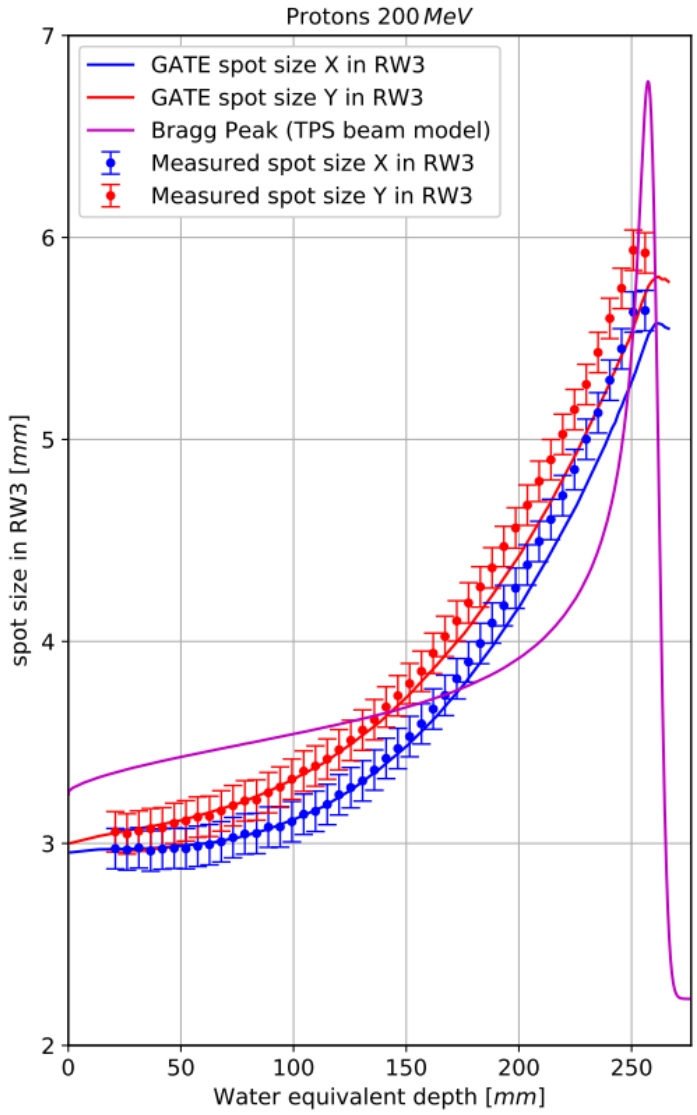


Emittance (beam optical characterisation) reproduced accurately

Spot size validation for GATE







Spot size in solid phantom within measurement uncertainty

Summary

- Software tools for semi-automatic beam model preparation based on standard measurements

- Accurate beam model characterisation in FRED and GATE MC:

  - Fast FRED GPU MC code for proton therapy dose computation
  - General-purpose GATE CPU MC code for detector development

- FRED MC + CCB beam model validated with measurements and clinical data – see Magdalena Garbacz presentation

- GATE MC code + CCB beam model validated with measurements and ready for J-PET simulations – see Jakub Baran presentation