Biological dose calculations with variable RBE for proton therapy using Monte Carlo code FRED

J. Gajewski[1], M. Garbacz[1], L. Grzanka[1], G. Battistoni[3], M. Durante[4], D. Kabat[9], N. Krah[5], K. Krzempek[1], V. Patera[6], M. Pawlik-Niedźwiecka[1,2], E. Pluta[9], I. Rinaldi[7], E. Scifoni[4], T. Skóra[9], A. Skrzypek[1], F. Tommasino[8], A. Schiavi[6], A. Ruciński[1]

(1) THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

(6) SAPIENZA UNIVERSITÀ DI ROMA

(2) JAGIELLONIAN UNIVERSITY IN KRAKÓW

(9) MARIA SKLODOWSKA-CURIE INSTITUTE – ONCOLOGY CENTER

(8) UNIVERSITY OF TRENTO - Italy

(4) TIFPA

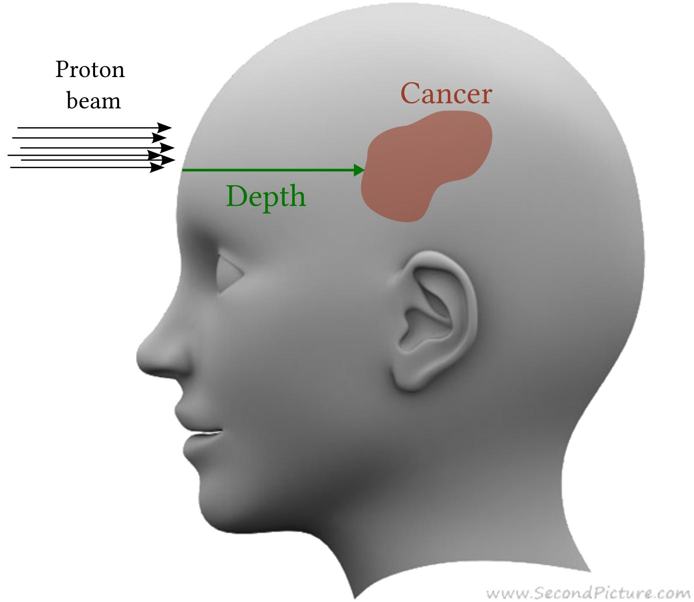
(7) MAASTRO CLINIC

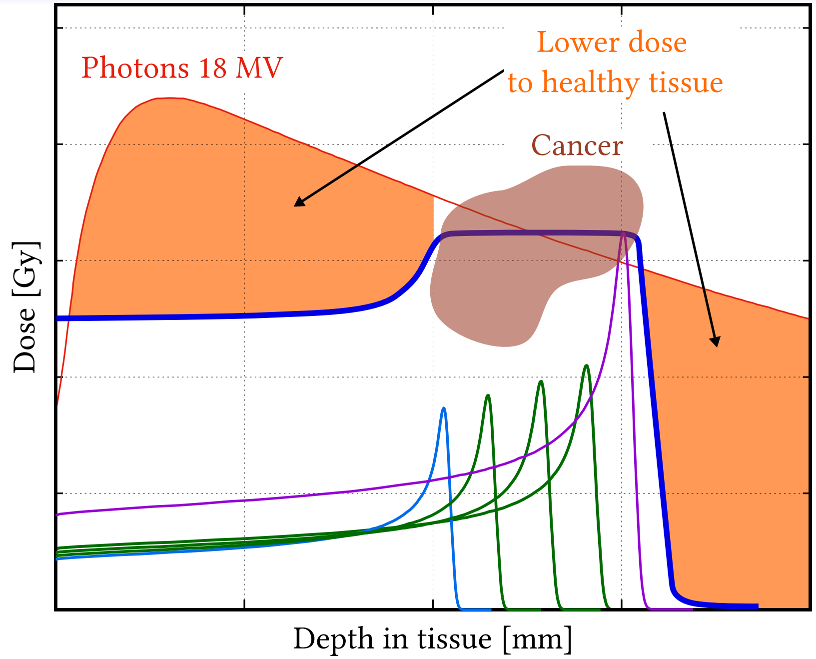
(3) INFN

(5) cnrs

3rd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics
Kraków, 2019

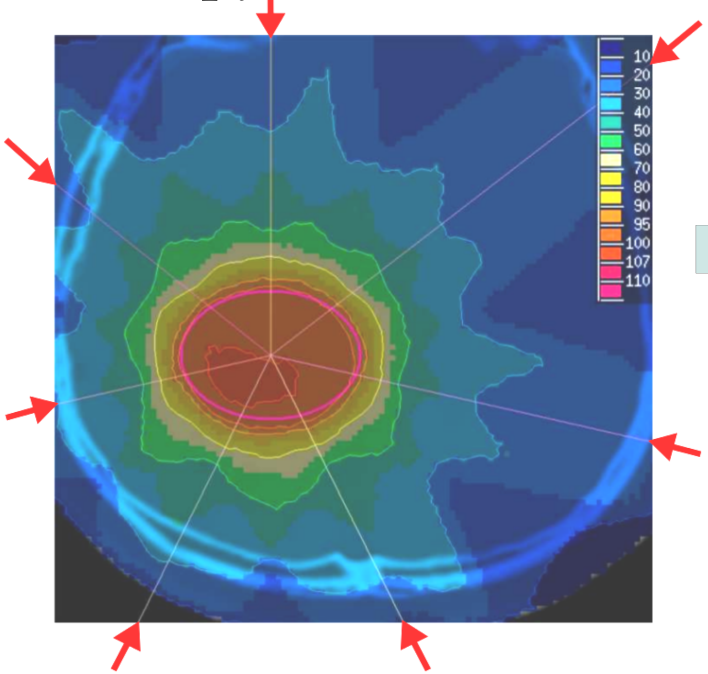
Photon vs proton therapy



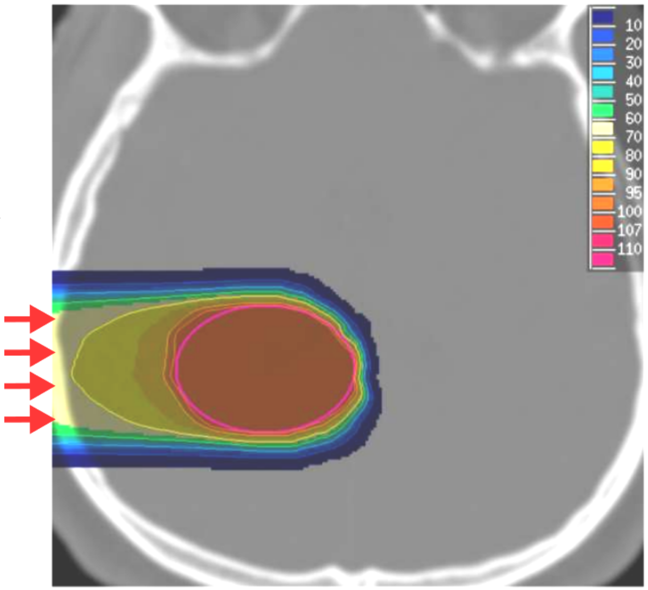


Photon therapy

Proton therapy



~3x lower dose to healthy tissue



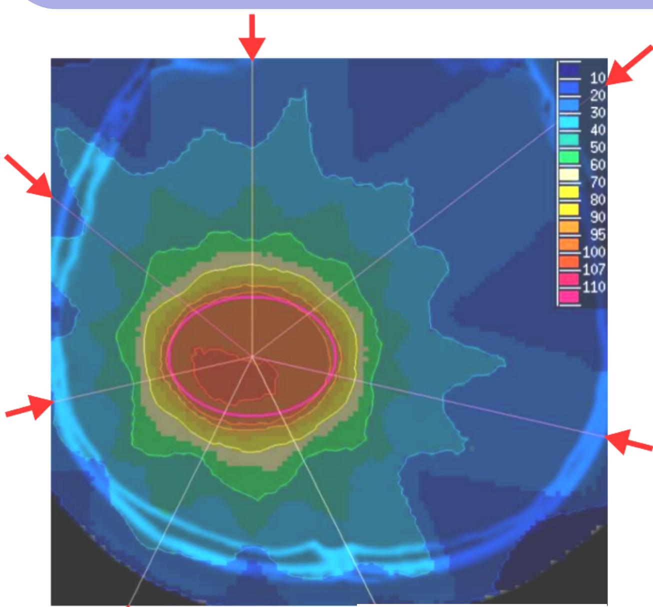
Biological effects – photon therapy

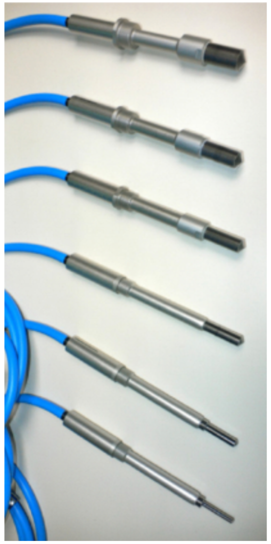
Photon therapy

TCP/NTCP depends on D_{phys}

TCP – Tumor Control Probability

NTCP – Normal Tissue Complication Probability





Dose phys.

Clinical effect

Biological effects – proton therapy

Photon therapy
TCP/NTCP depends on D_{phys}

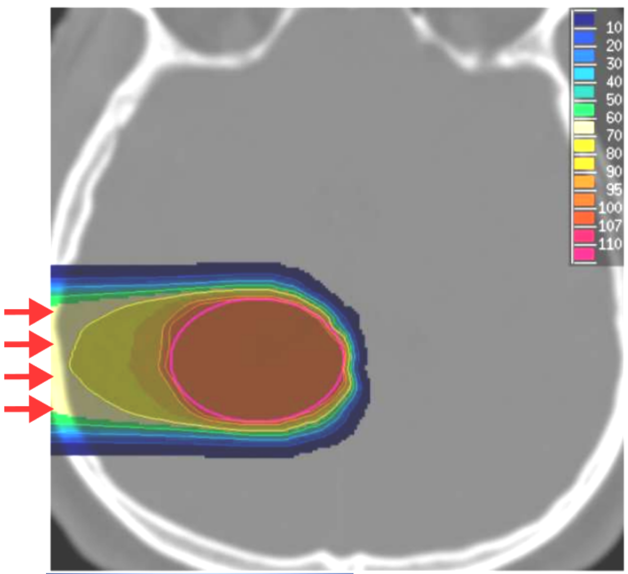
Proton therapy
TCP/NTCP depends on D_{biol}

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

TCP – Tumor Control Probability

NTCP – Normal Tissue Complication Probability

RBE – Relative Biological Effectiveness



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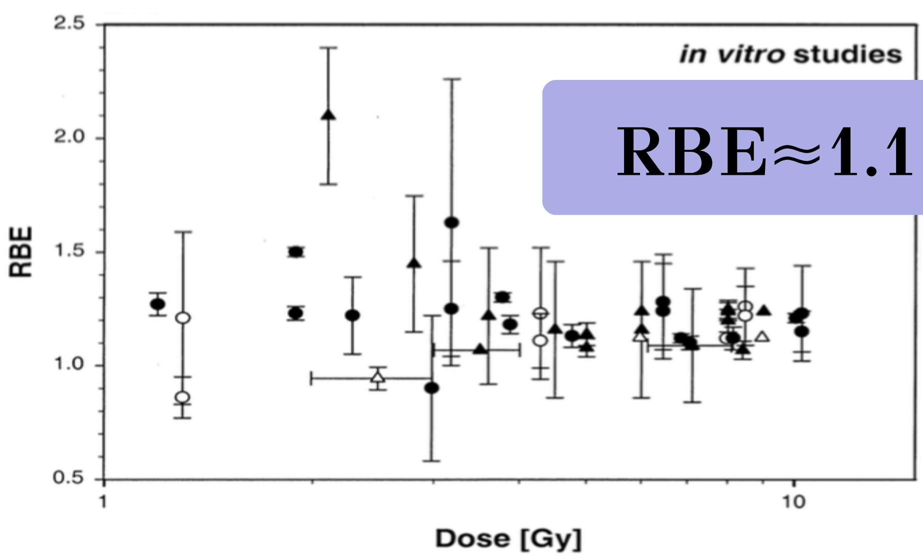
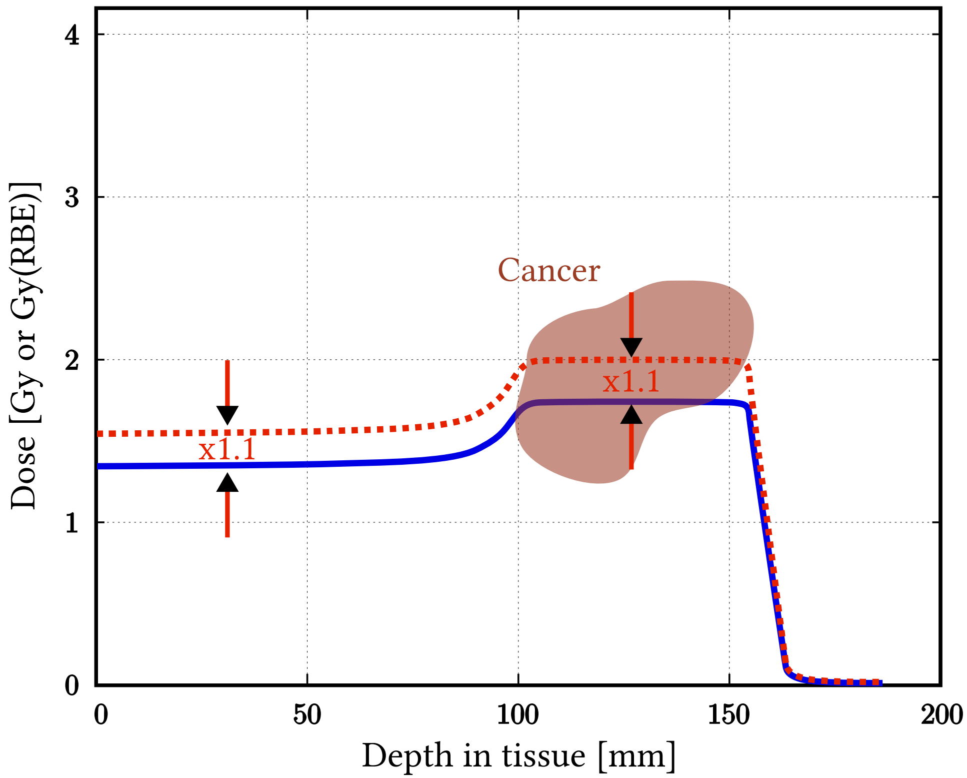


RBE≈1.1

Paganetti et al. PMB 2001



Biological effects – proton therapy

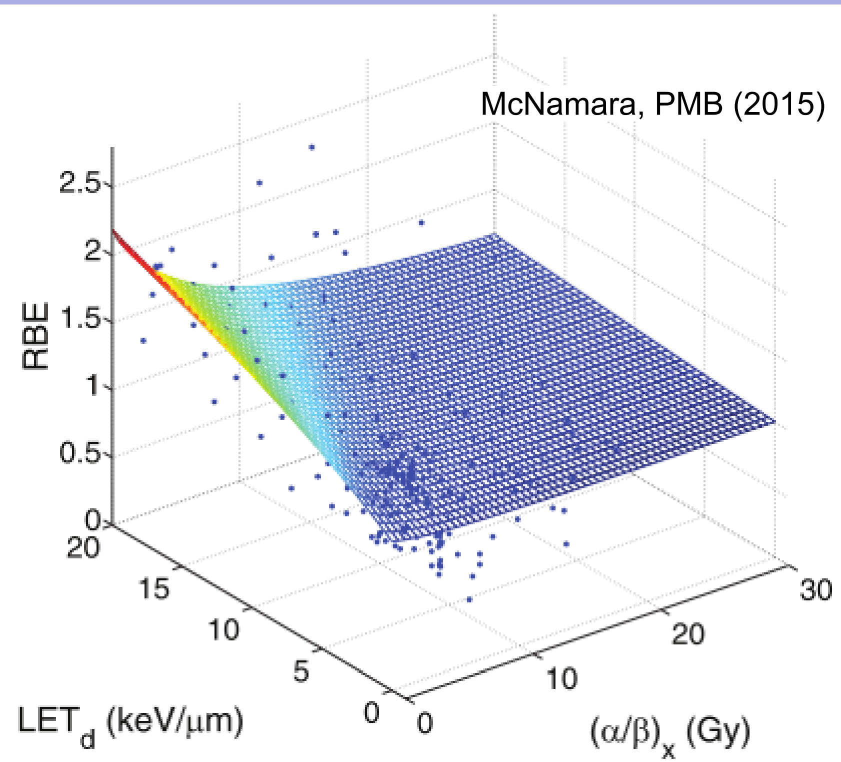
Photon therapy
TCP/NTCP depends on D_{phys}

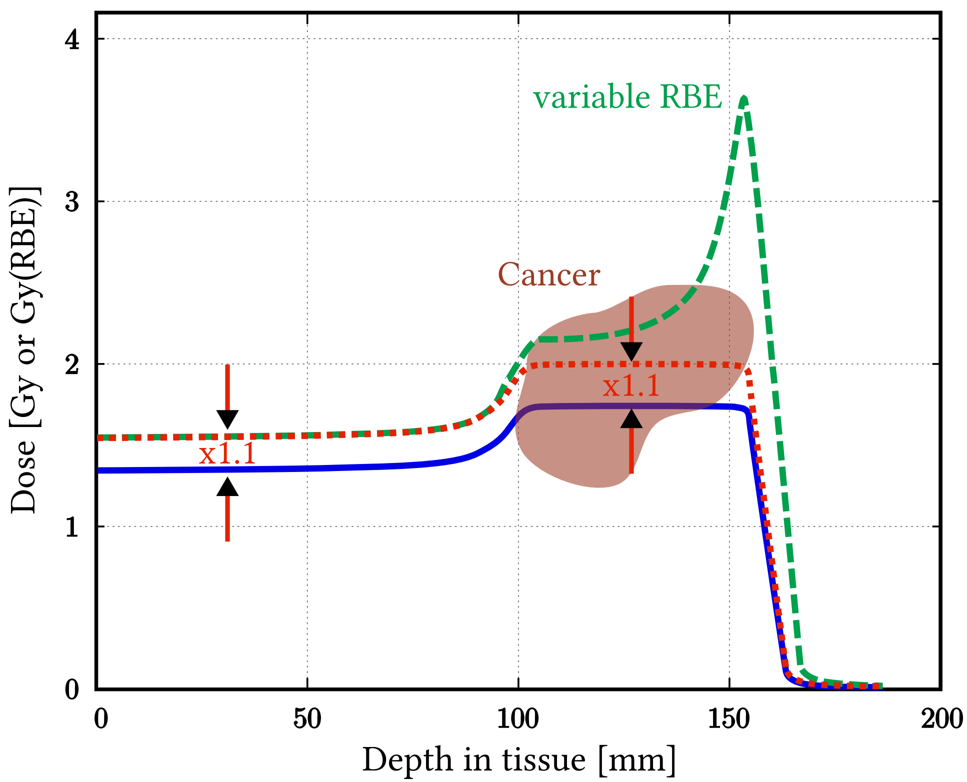
Proton therapy
TCP/NTCP depends on D_{biol}

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

RBE depends on:

- **dose/fractionation scheme**
- **tissue type (α/β)**
- **beam quality (LET, particle type)**
- **dose rate (FLASH)**





Bilogical dose - presentation outline

Physics modeling:

- proton beam model
- CT calibration
- Experimental validation

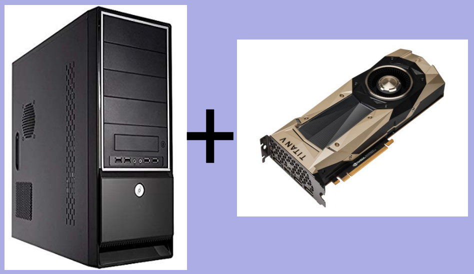
$$D_{biol} = D_{phys} \cdot RBE$$

RBE modeling:

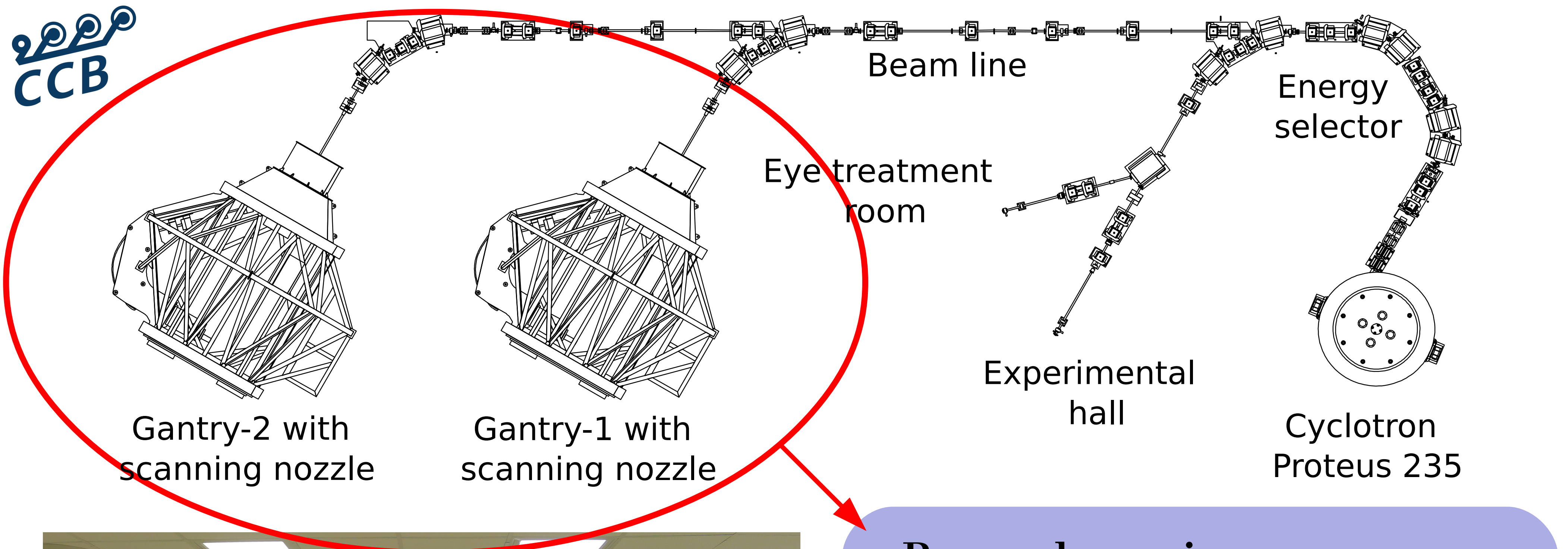
- tissue type (α/β)
- LET calculation
- Variable RBE model

Fast paRticle thErapy Dose evaluator – FRED

- 2^{nd} class Monte Carlo code (A. Schiavi et al., 2017):
  - condensed history for continuous processes
  - single steps for nuclear events
- Flexible geometry and CT import
- Various RBE models
- GPU and CPU calculations
- Tracking rate: 3-10E6 proton/s
- Single beam in water 1E7 protons – 30s
- Treatment plan in CT - ~ 4 min



Bronowice Cyclotron Centre (CCB)



Proton beam in gantry room

Energies: 70-226 MeV

Range in water: 42-320 mm

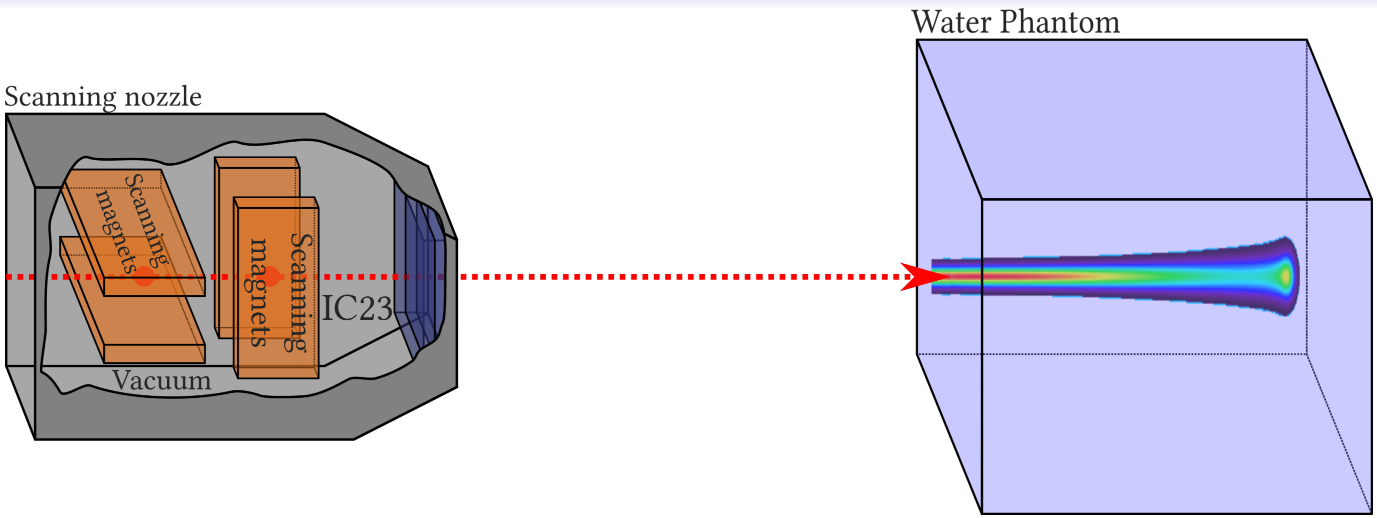
Range shifter: 50 mm

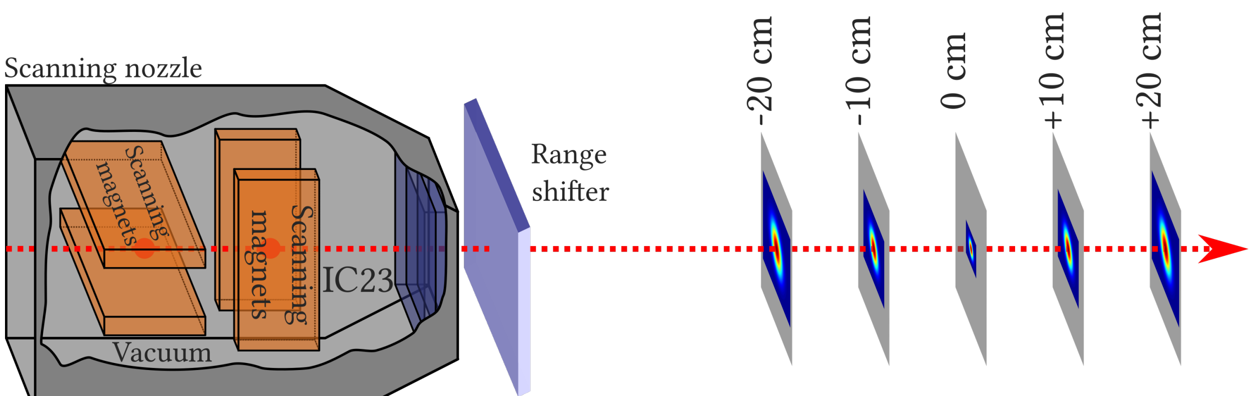
Beam size (σ): 2.7-6 mm

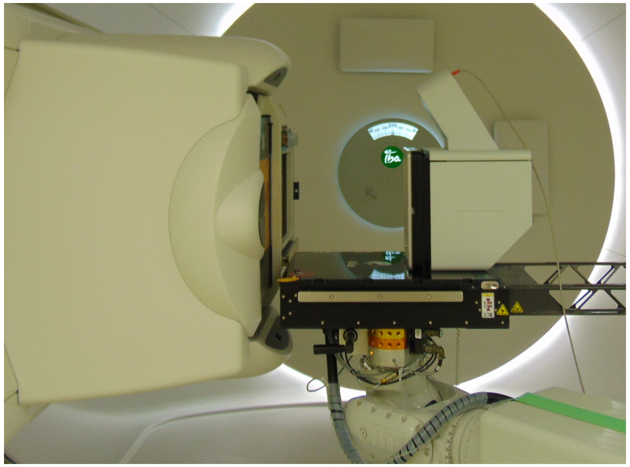
Gantry angle: 0-360°

Beam current: do 300nA

Beam Model in FRED





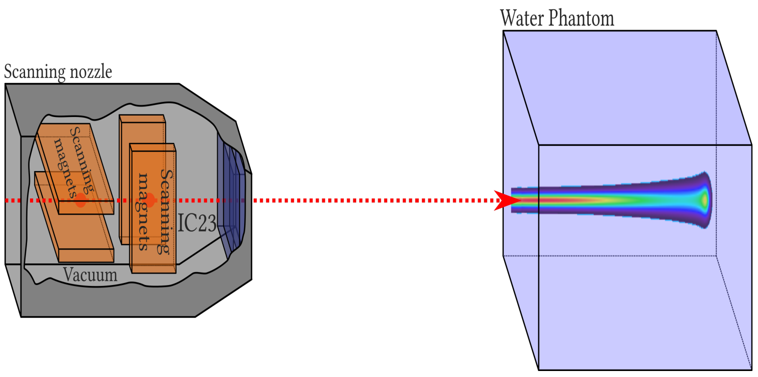


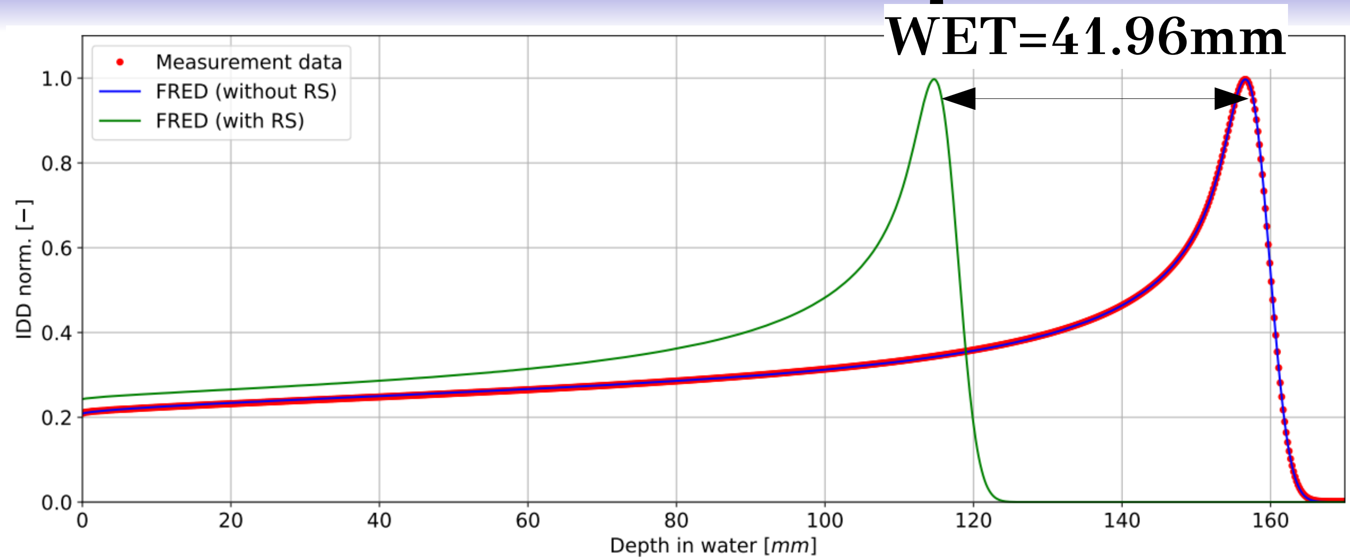
Beam model based on commissioning data

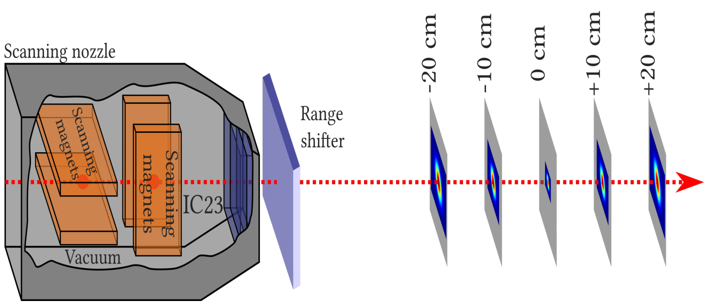
(integrated depth dose and lateral beam shape)

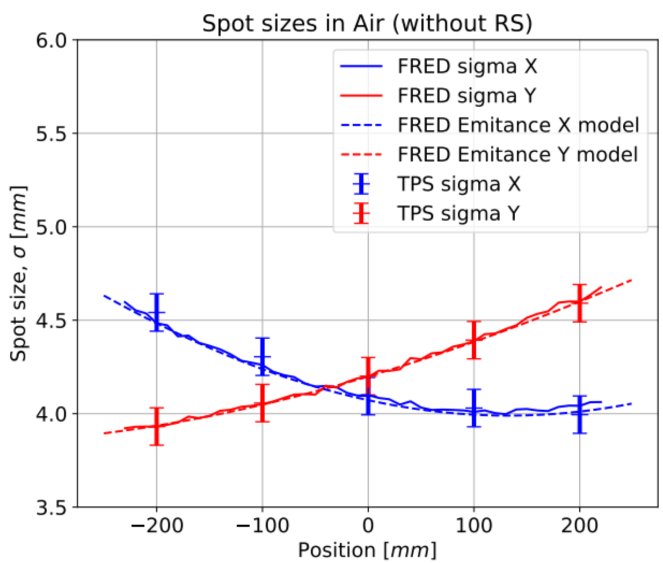
17 energies in range 70 – 225 MeV

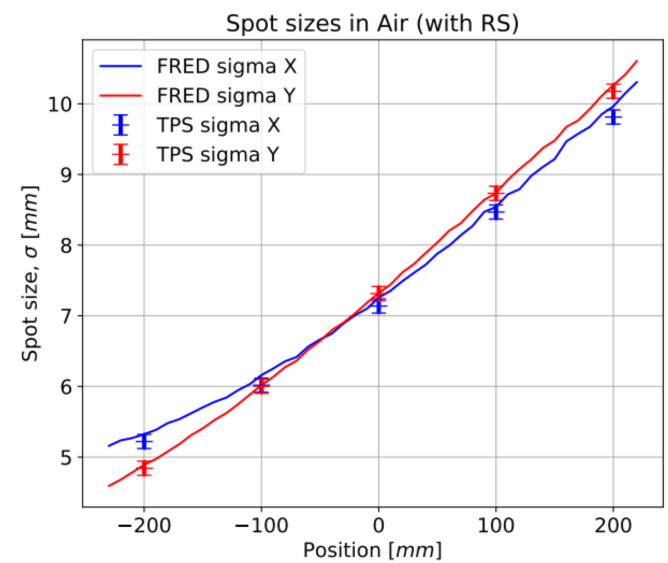
Beam Model in FRED – 150 MeV example









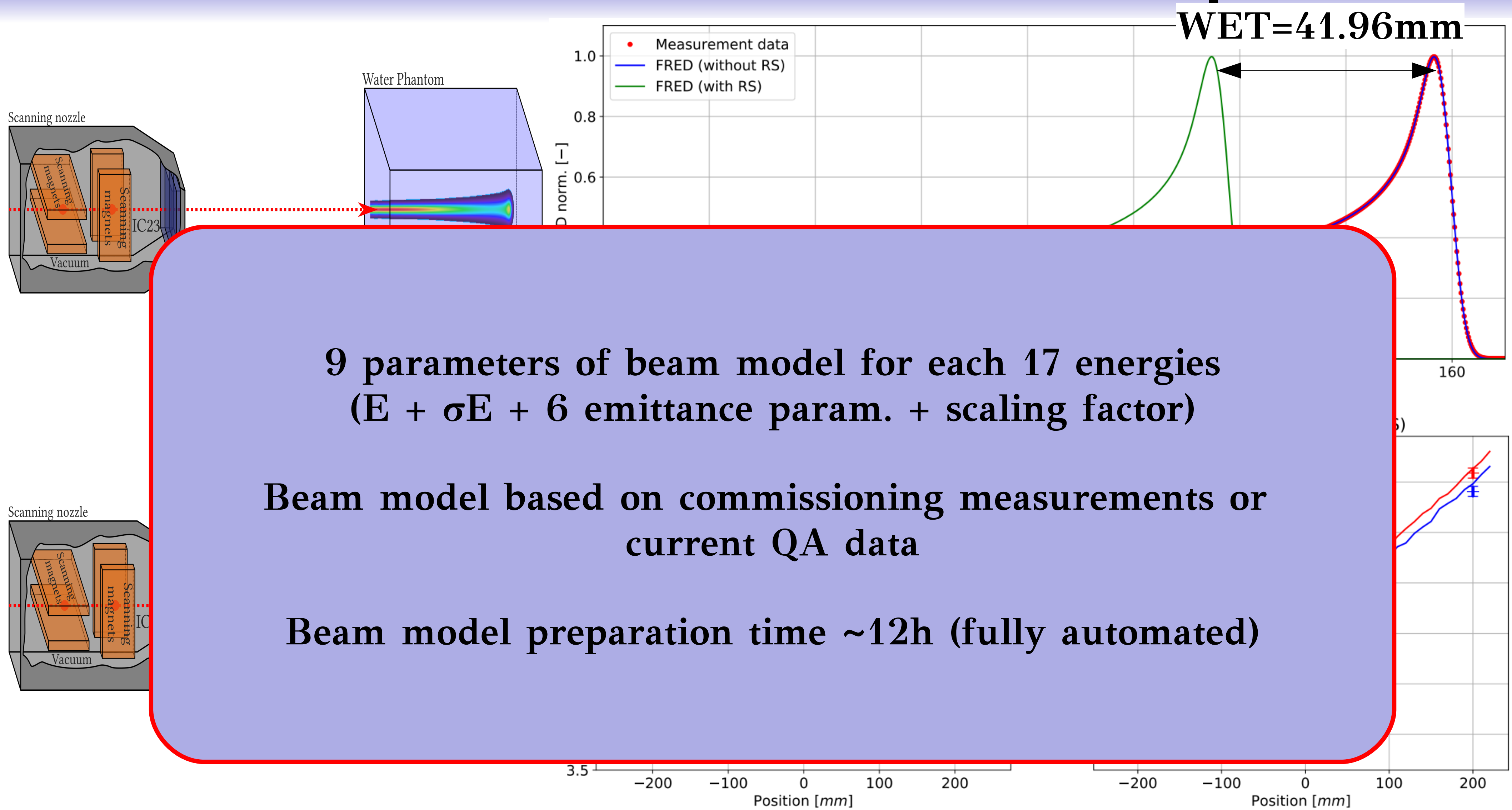


Range agreement ($R_{80\%}$) <0.1mm (dose agreement <2%)

Range shifter WET agrees with measurement ±0.03mm

Spot sizes in air agree within ±0.2mm

Beam Model in FRED – 150 MeV example



9 parameters of beam model for each 17 energies
(E + σE + 6 emittance param. + scaling factor)

Beam model based on commissioning measurements or current QA data

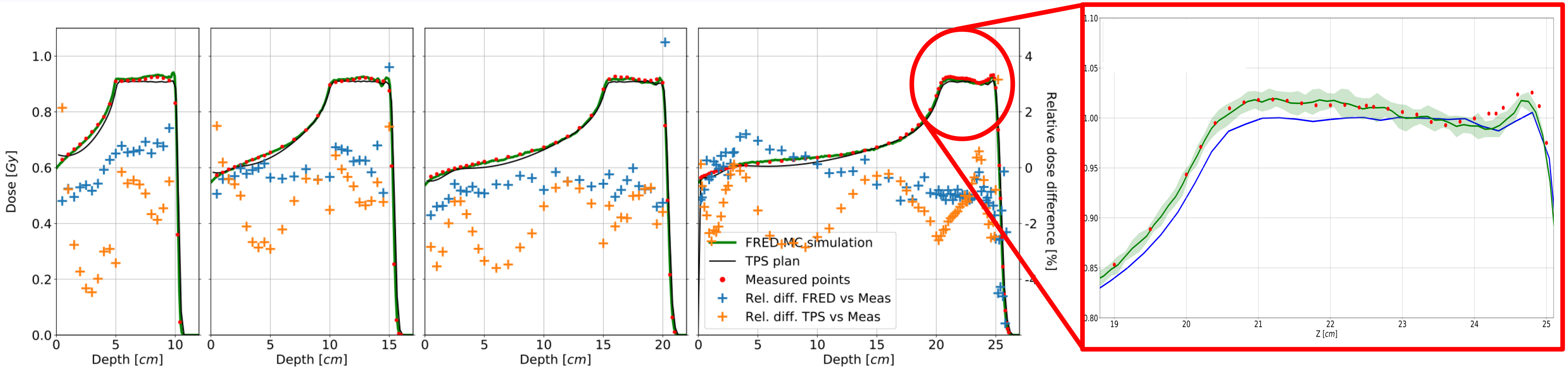
Beam model preparation time ~12h (fully automated)

Range agreement ($R_{80\%}$) <0.1mm (dose agreement <5%)

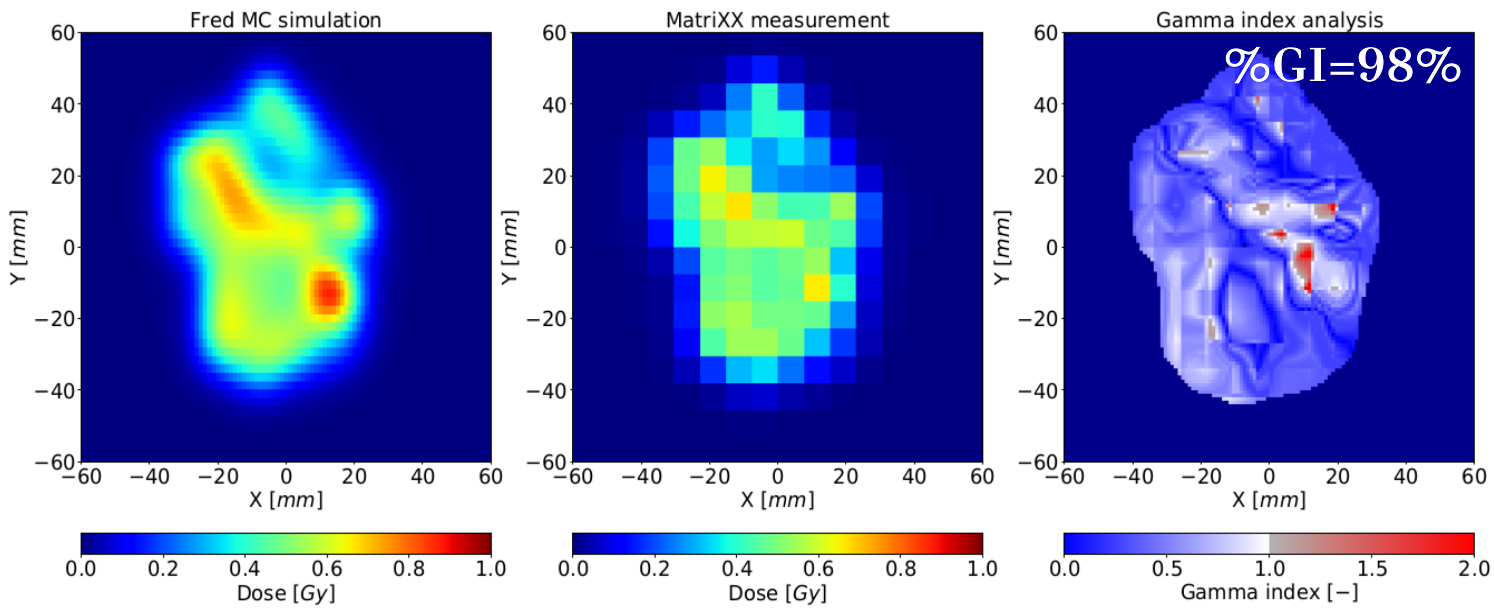
Range shifter WET agrees with measurement ±0.03mm

Spot sizes in air agree within ±0.2mm

Validation in water



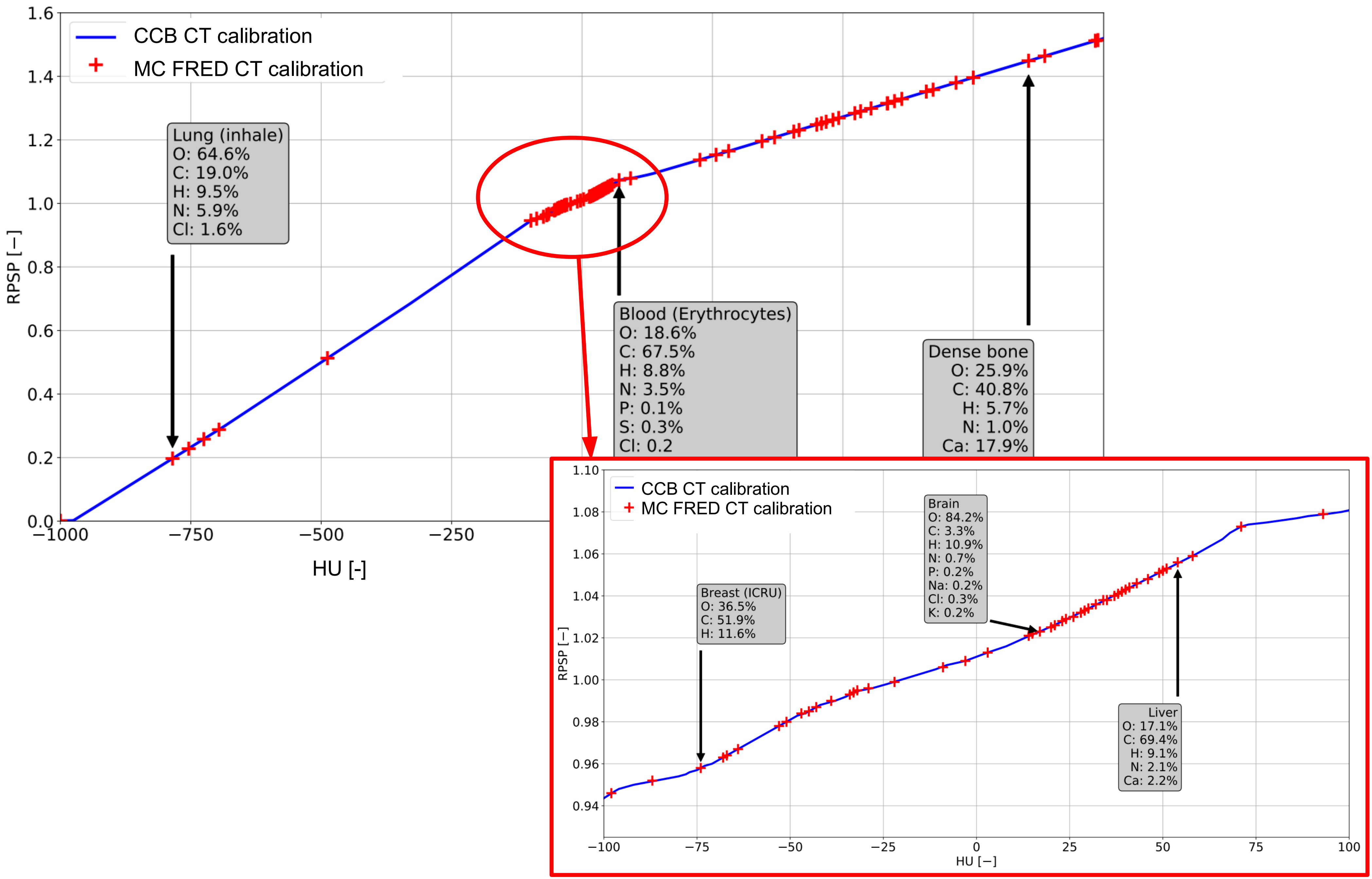
Dose agreement in SOBP <2%



Gamma index test using CCB protocol (2mm/3%)

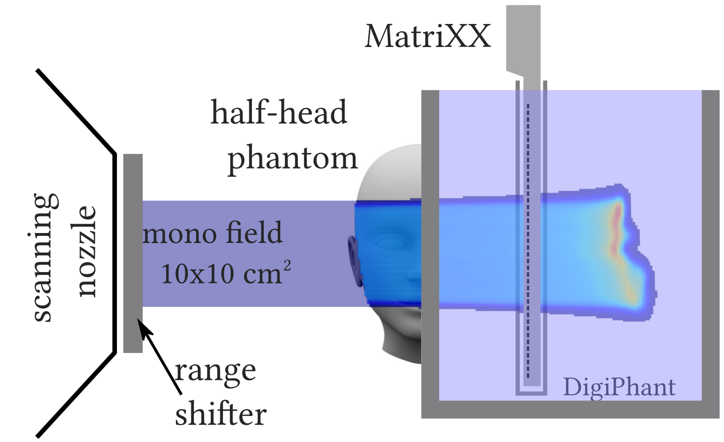
Gamma index passing rate for 182 simulated and measured layers was 97.9%

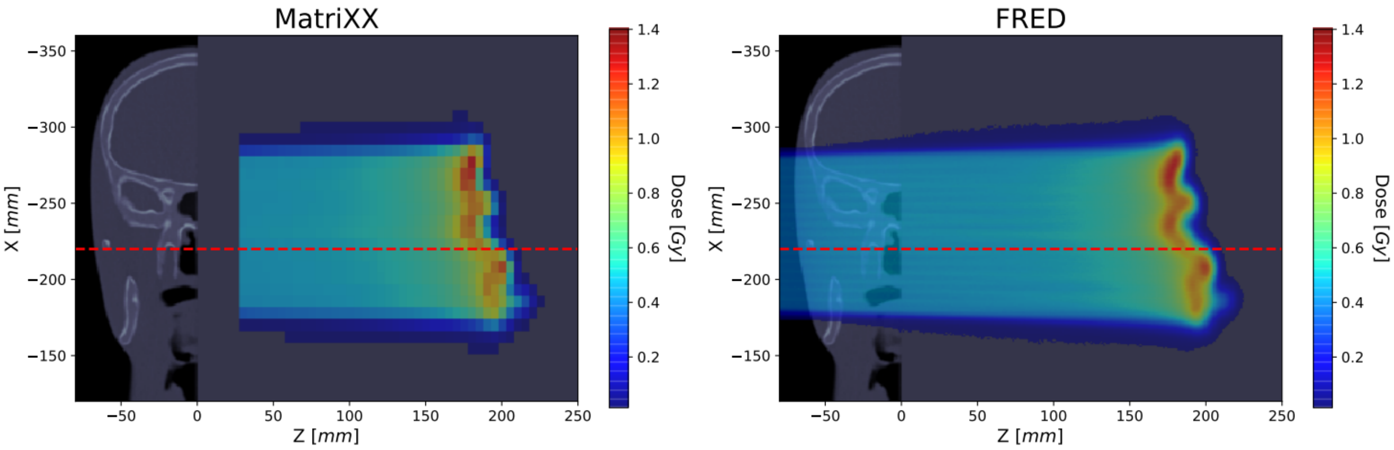
CT calibration

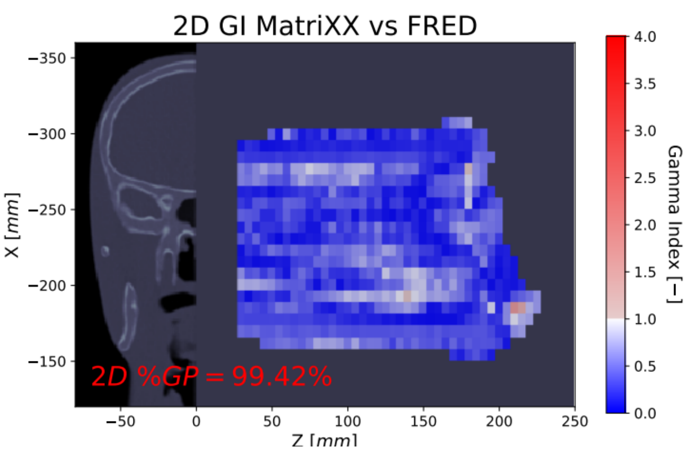


Validation in heterogeneous media

- Heterogeneous head phantom
- MatriXX measurement in water
- Single energy: 100, 150 and 200 MeV
- Range shifter







3D Gamma index (2mm/2%) passing rate for all measurements >99%

FRED - biological dose with variable RBE

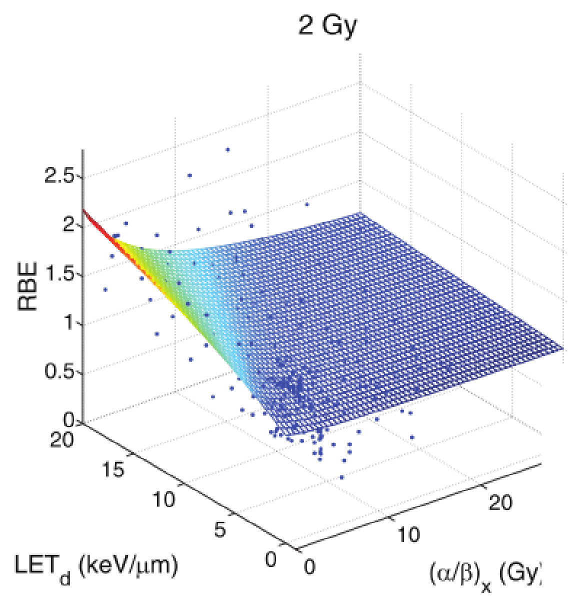
Function of LET

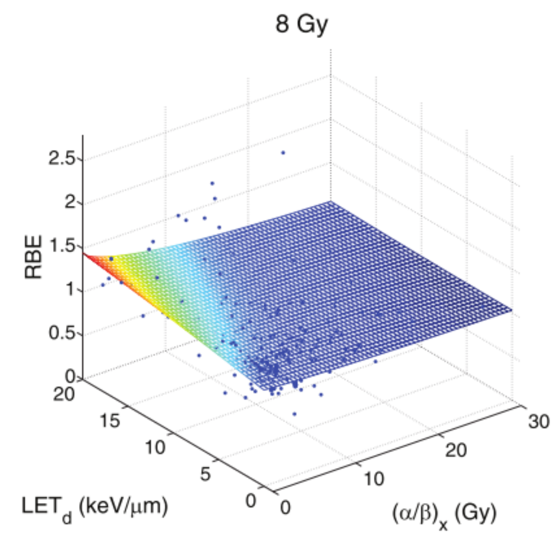
$$\mathrm{RBE}\left(D_p, \overbrace{\frac{\alpha_p}{\alpha_x}, \frac{\beta_p}{\beta_x}}, \left(\frac{\alpha}{\beta}\right)_x\right) = \frac{D_x}{D_p} = \frac{\sqrt{\left(\frac{\alpha}{\beta}\right)_x^2 + 4\frac{\alpha_p}{\alpha_x}\left(\frac{\alpha}{\beta}\right)_x D_p + 4\frac{\beta_p}{\beta_x} D_p^2} - \left(\frac{\alpha}{\beta}\right)_x}{2D_p}$$

D_p causes the same biological effect as D_x

Variable RBE models:

Wedenberg (Wedenberg et al., 2013)
Wilkens (Wilkens and Oelfke, 2004)
Chen (Chen and Ahmad, 2012)
Carabe (Carabe at al., 2012)
McNamara (McNamara at al., 2015)
… and other





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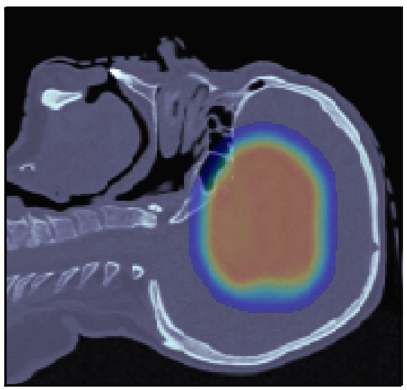
D_p causes the same biological effect as D_x

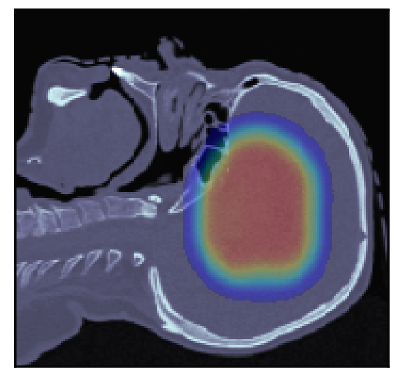
Physical dose



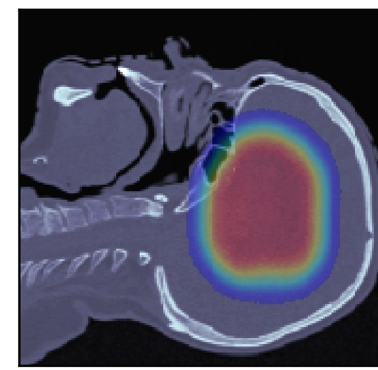
LET and variable RBE

Biological dose

Carabe

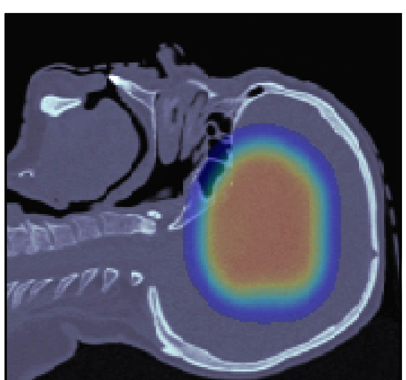


Chen

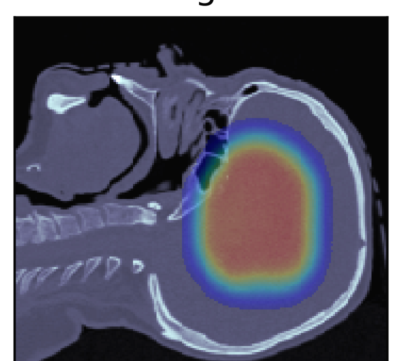


RBE=1.1

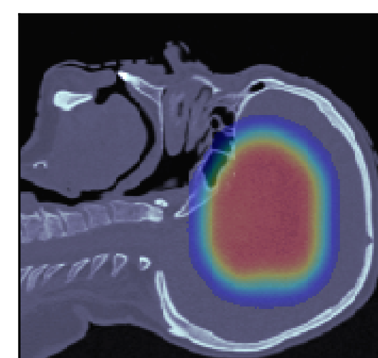
constant 1.1



Wedenberg



Wilkens



FRED dLET validation

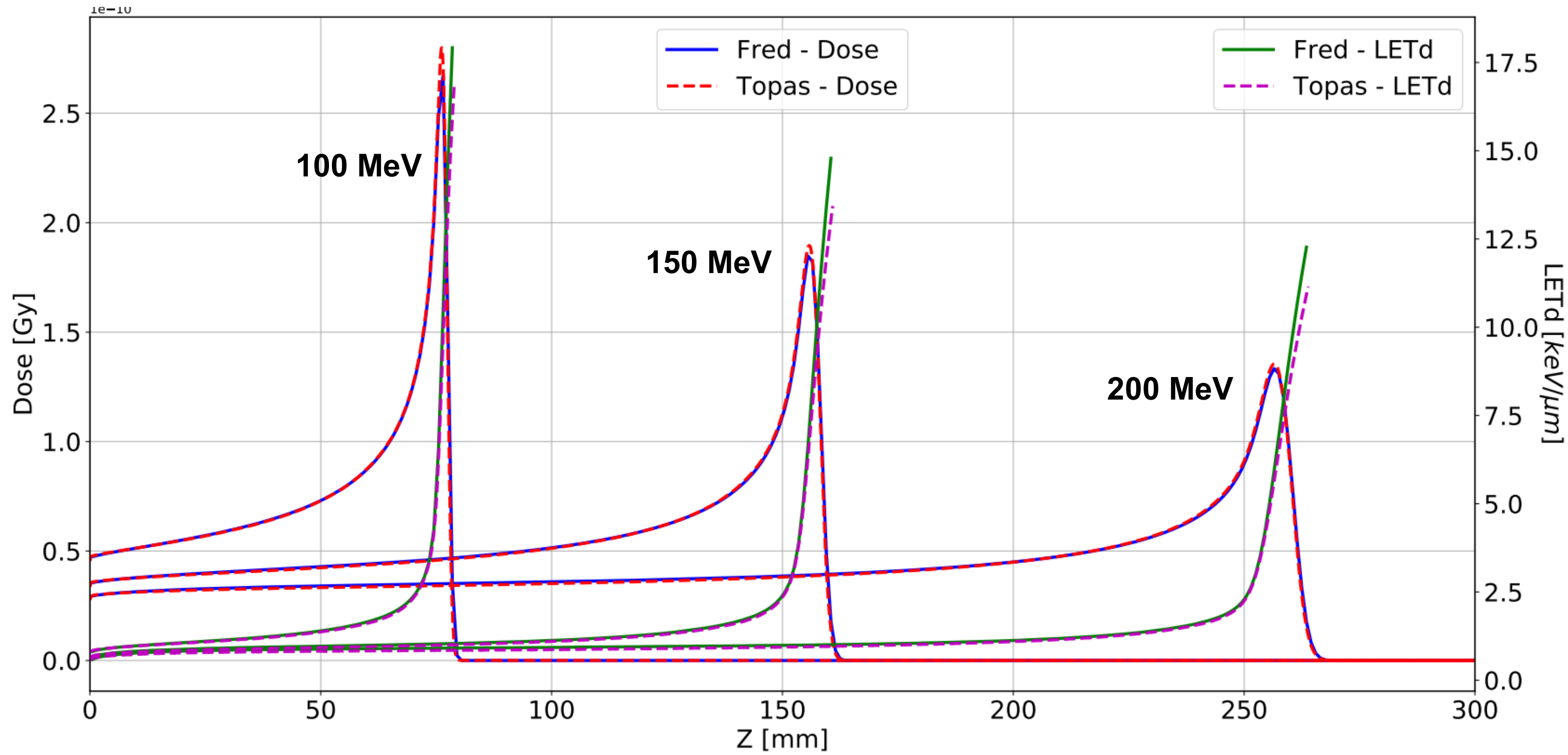
Dose-averaged LET validated against TOPAS calculations

Depth dLET distributions

In progress

Lateral dLET profiles

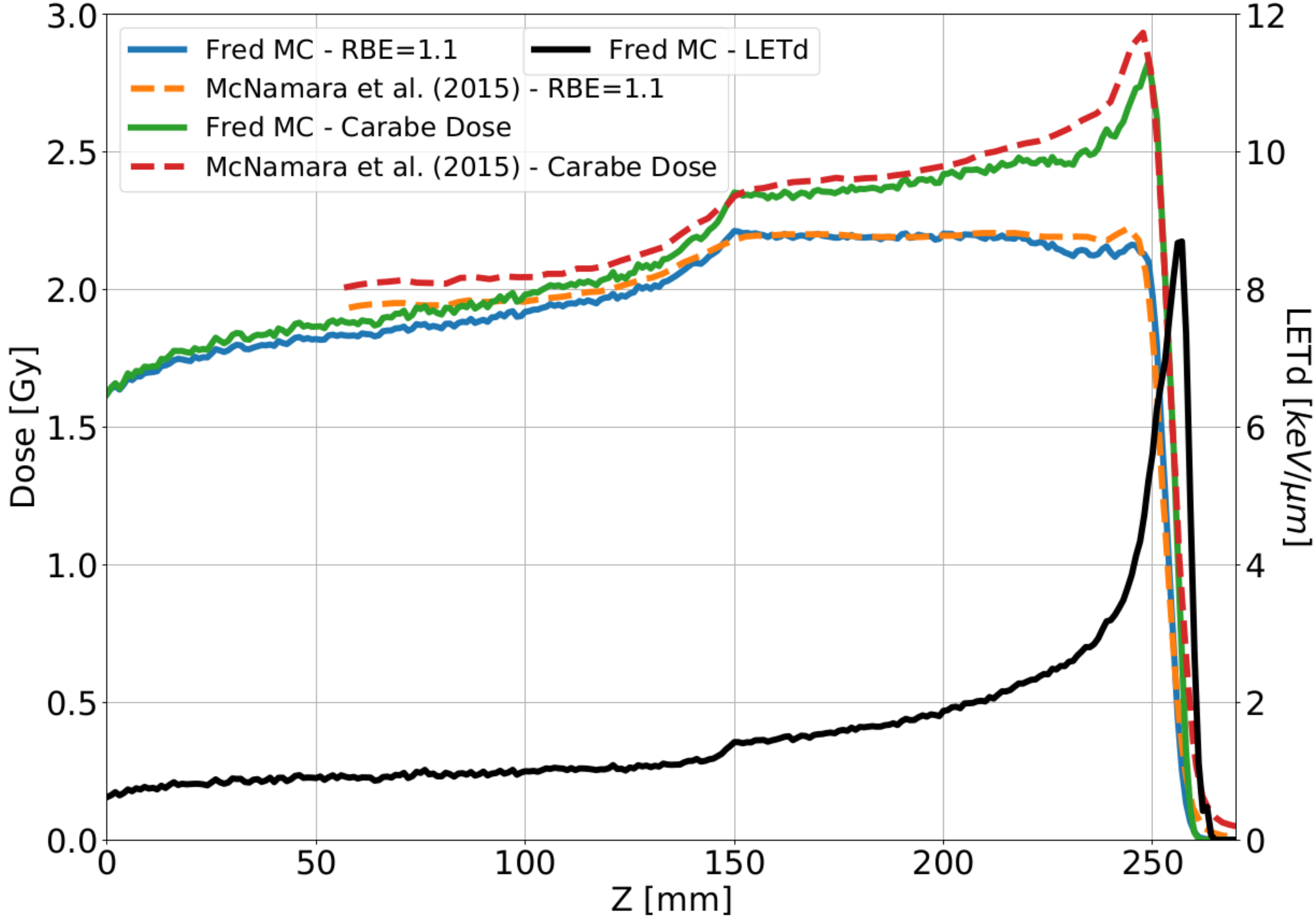
Complicated geometry and SOBP



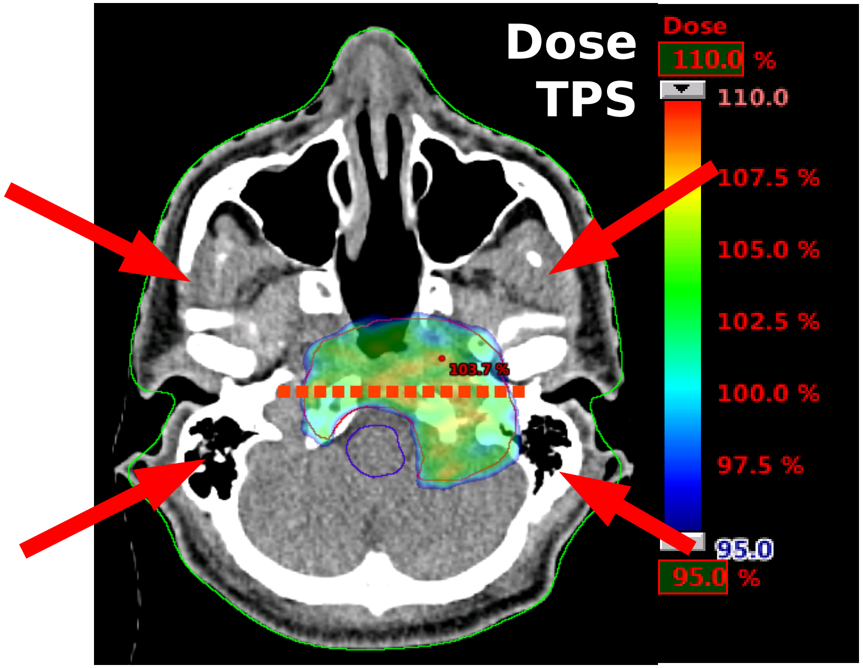
dLET in agreement with TOPAS MC

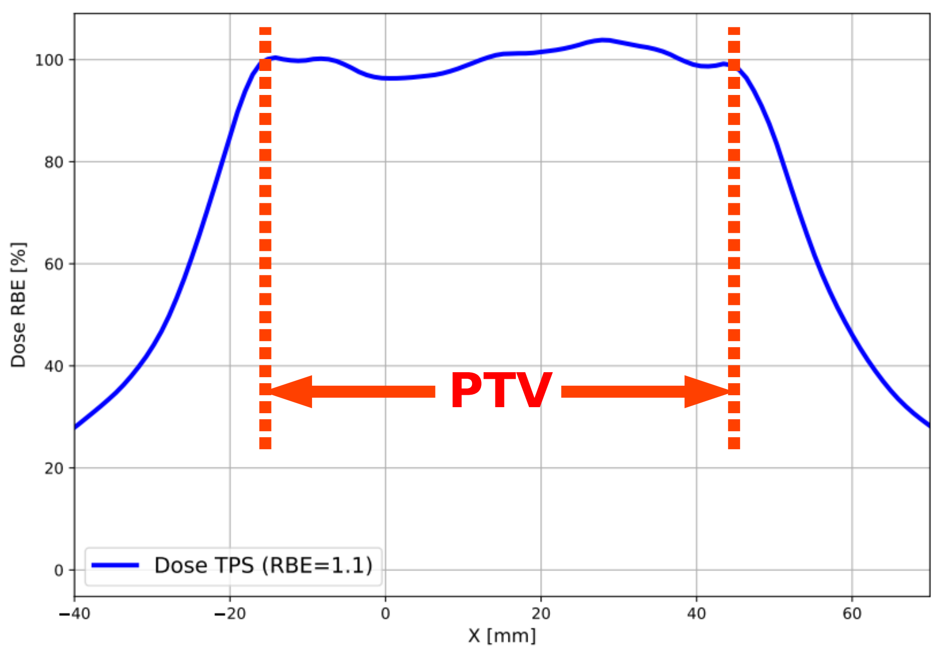
FRED - biological dose with variable RBE

Biological dose with Carabe RBE model comparable with literature



Variable RBE - case study





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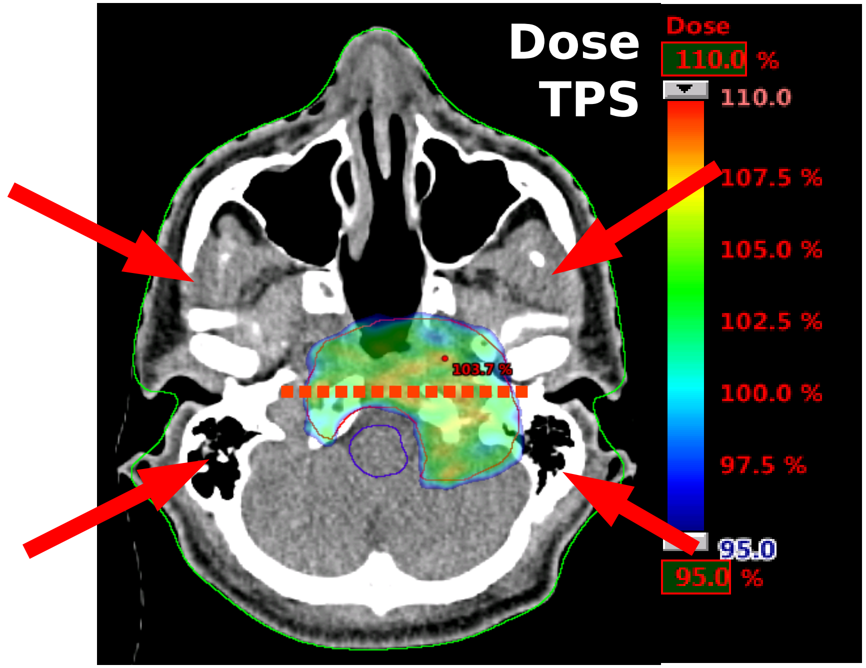
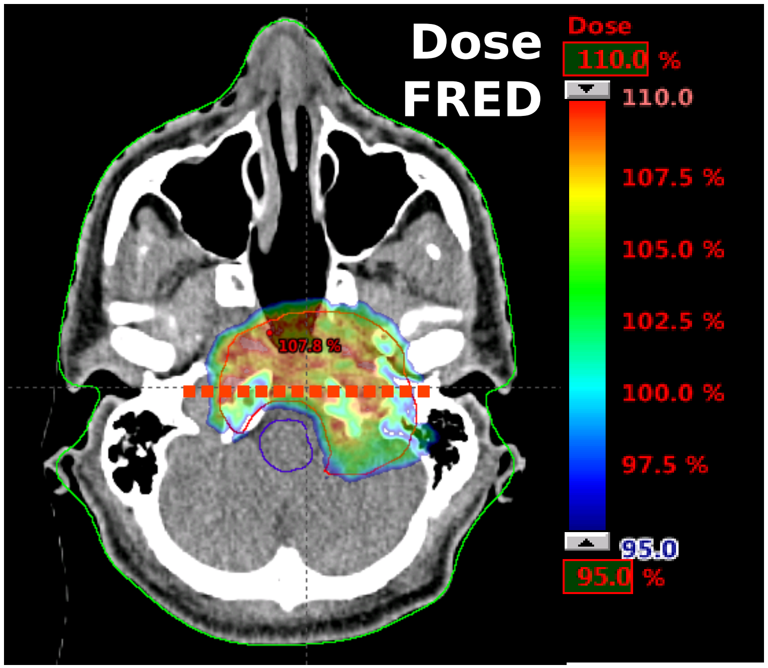
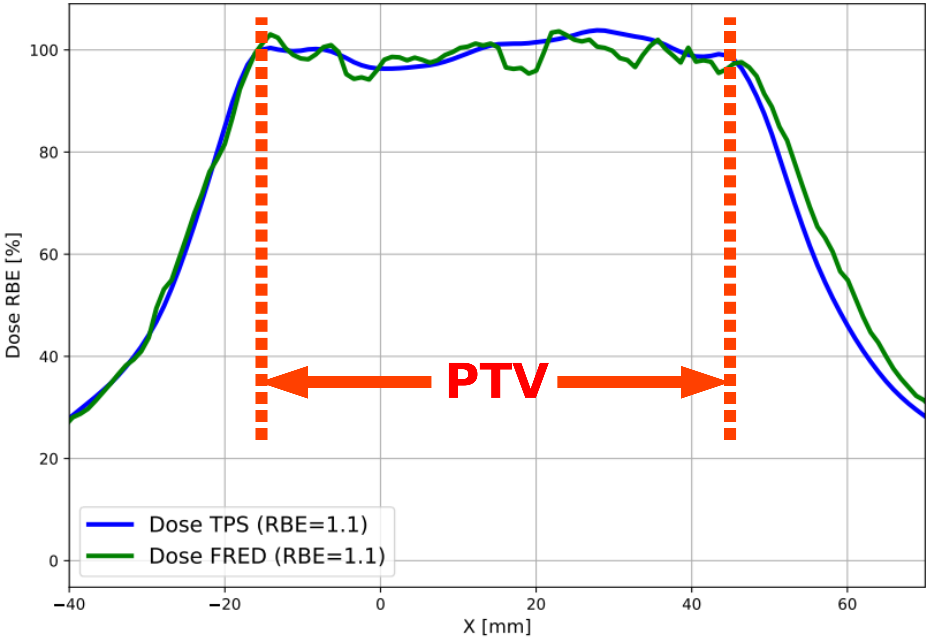
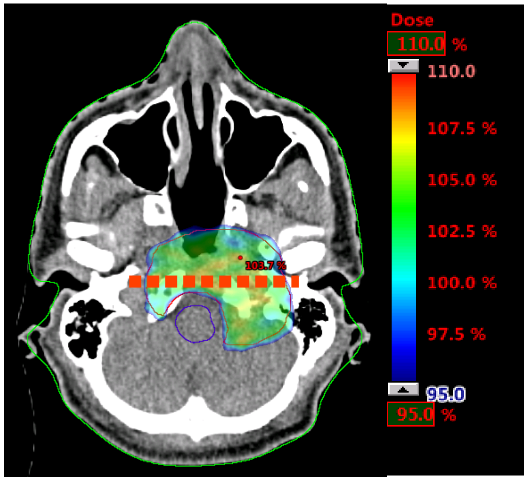


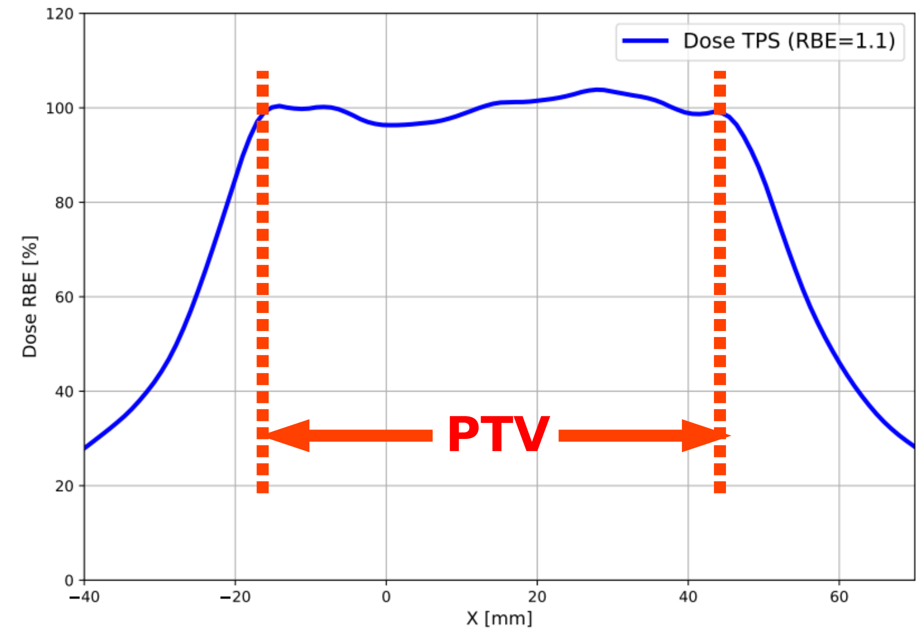




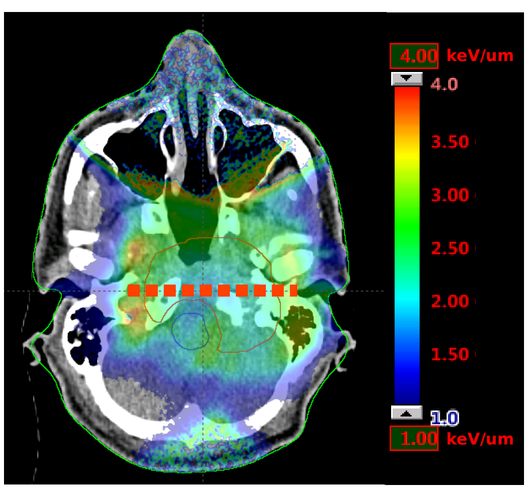
Variable RBE - case study

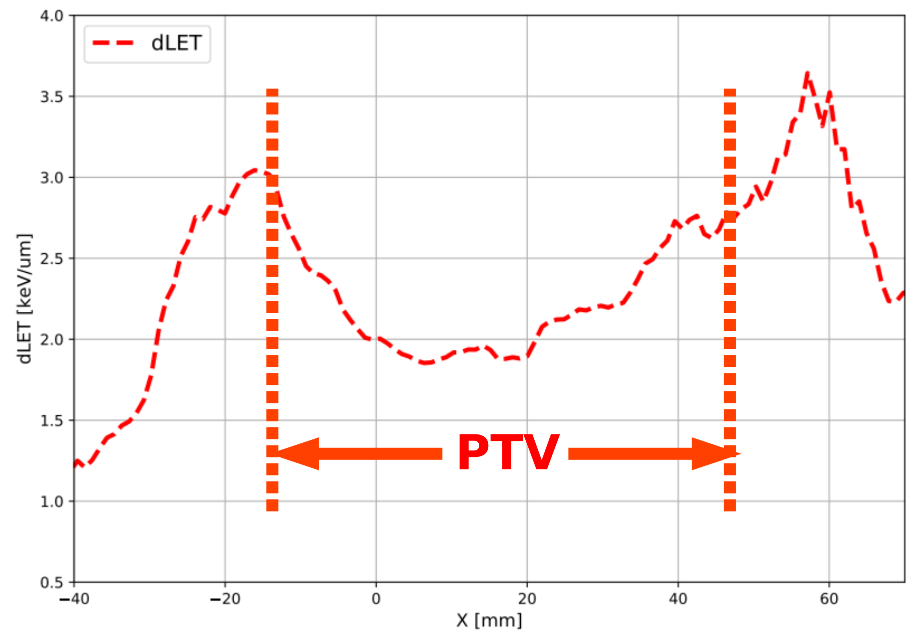
Dose TPS (RBE=1.1)





dLET





Variable RBE - case study

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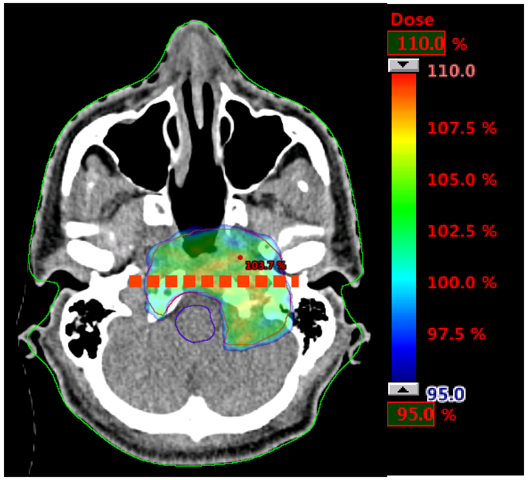

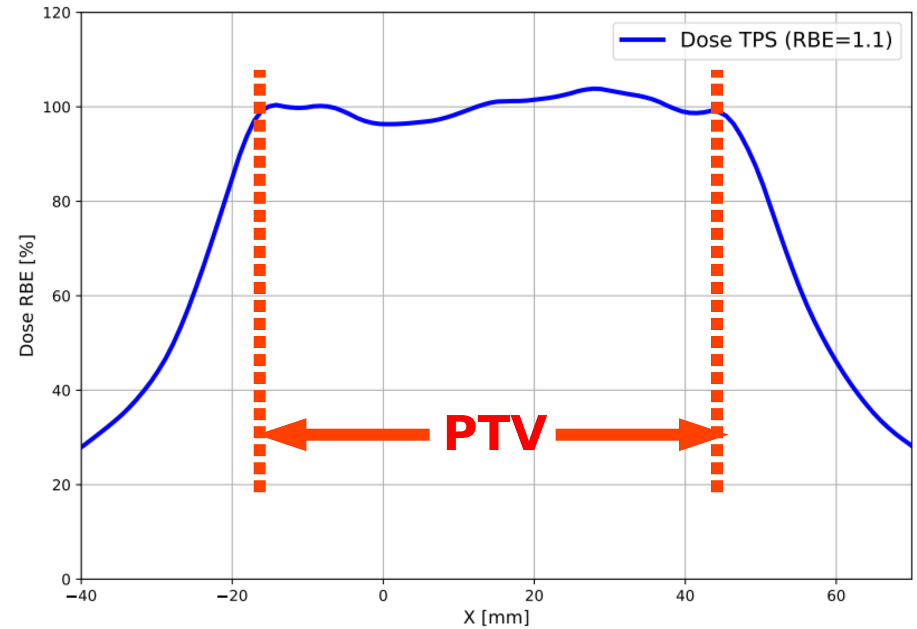

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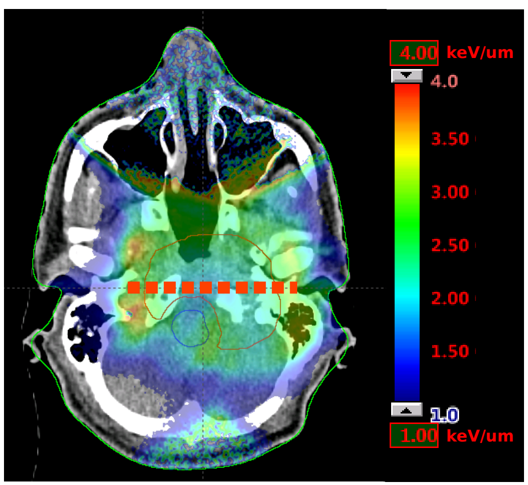
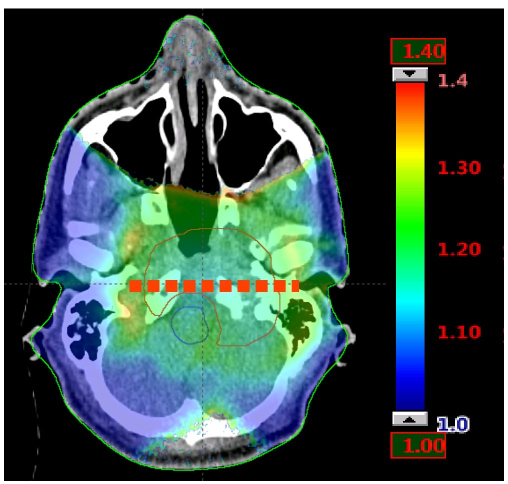
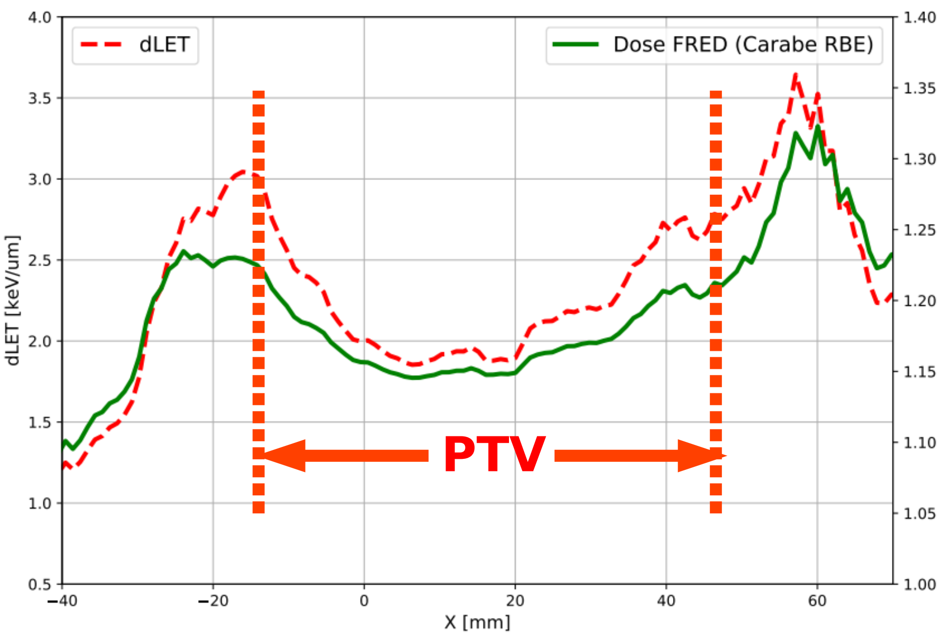


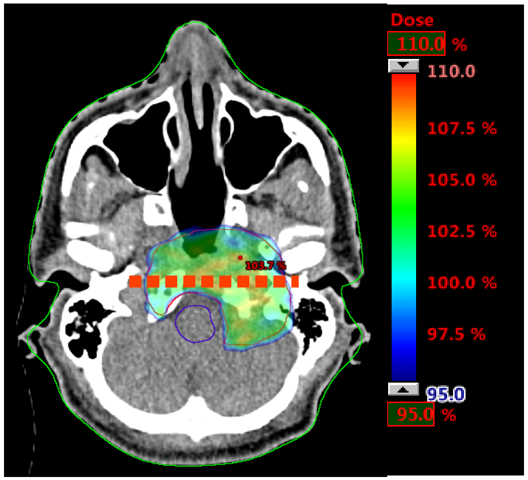
RBE Carabe



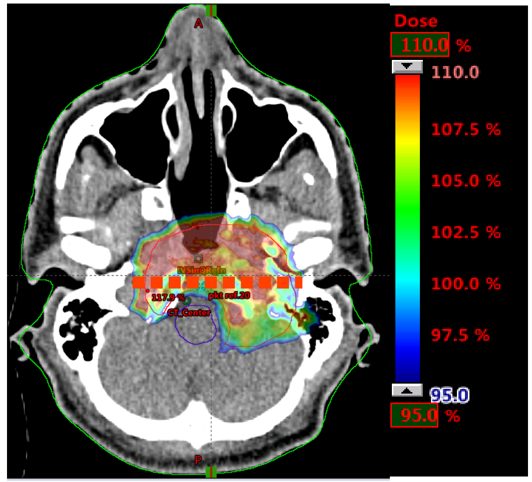


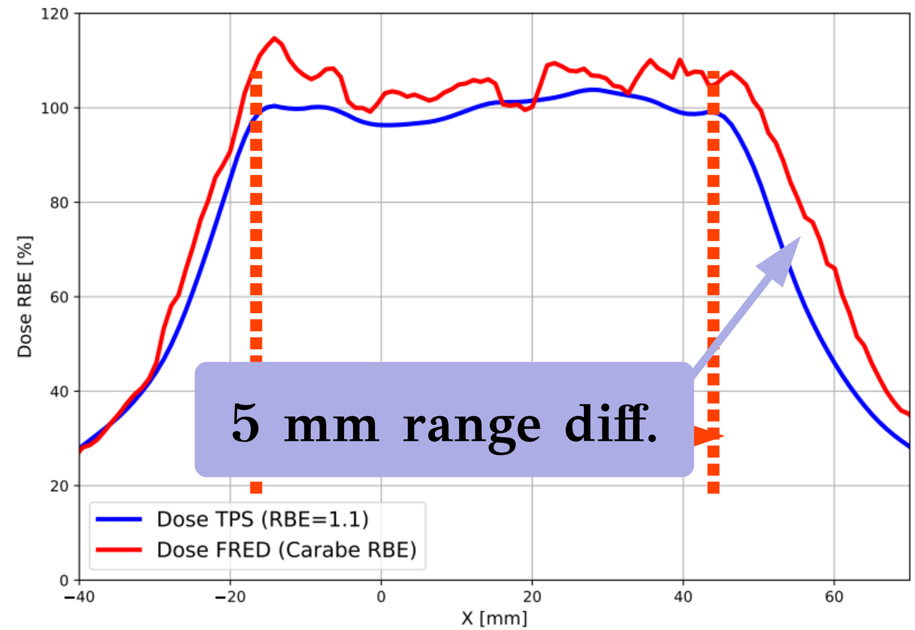
Variable RBE - case study

Dose TPS (RBE=1.1)



Dose bio. Carabe





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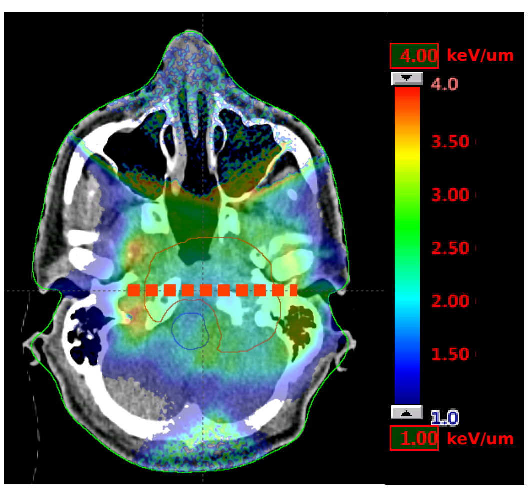

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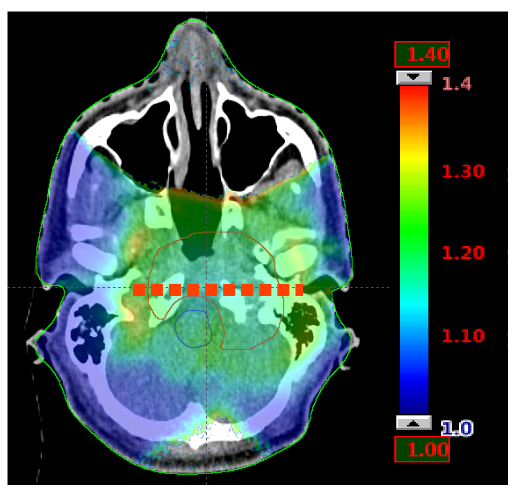
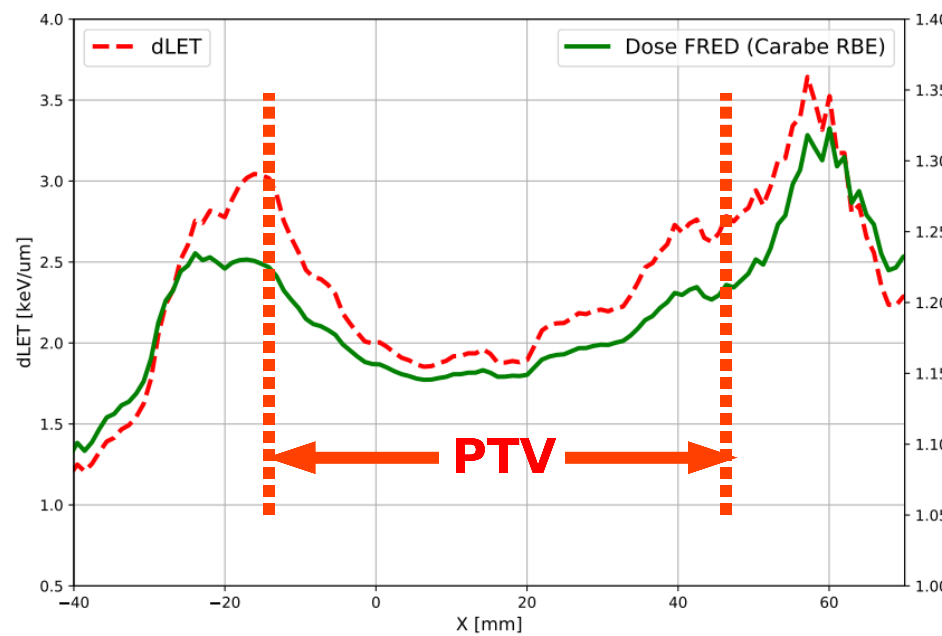
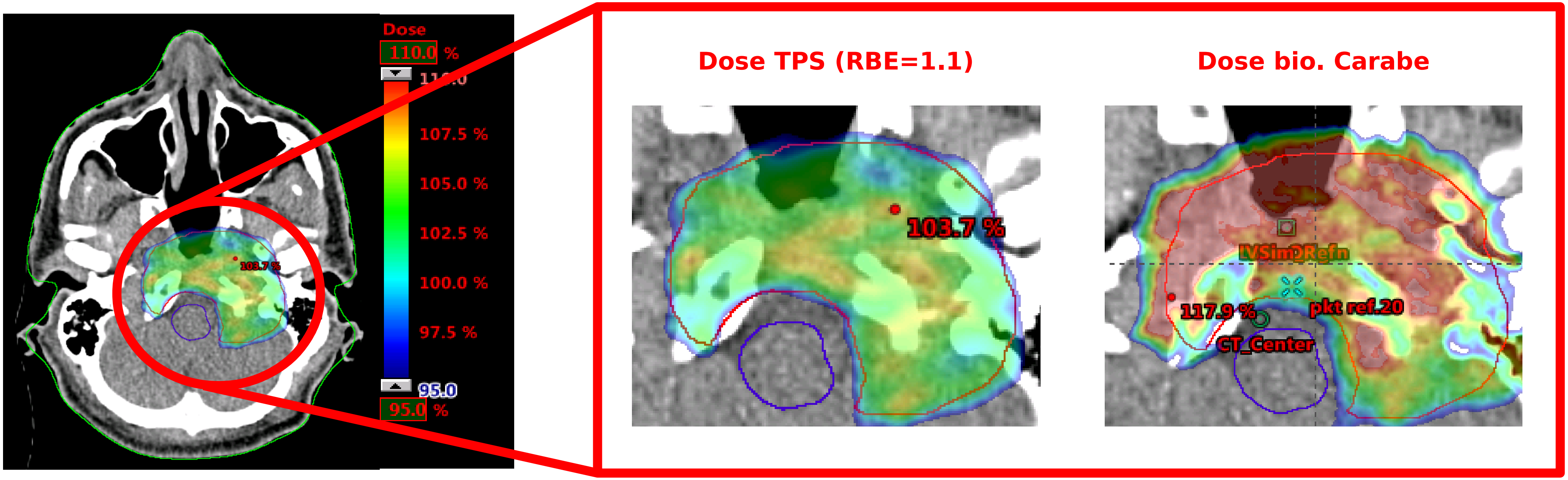
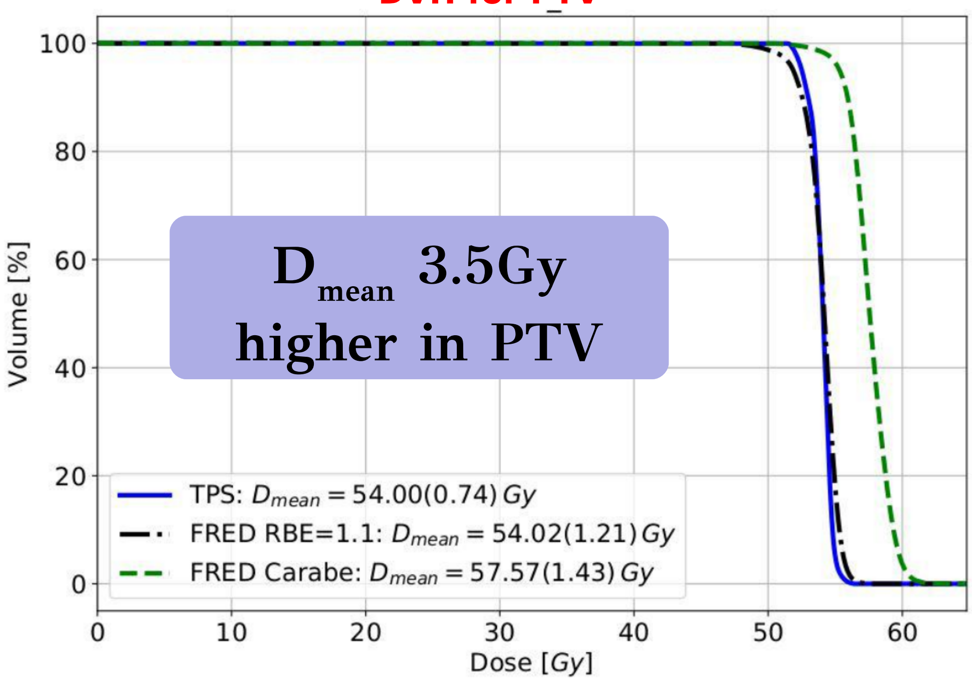


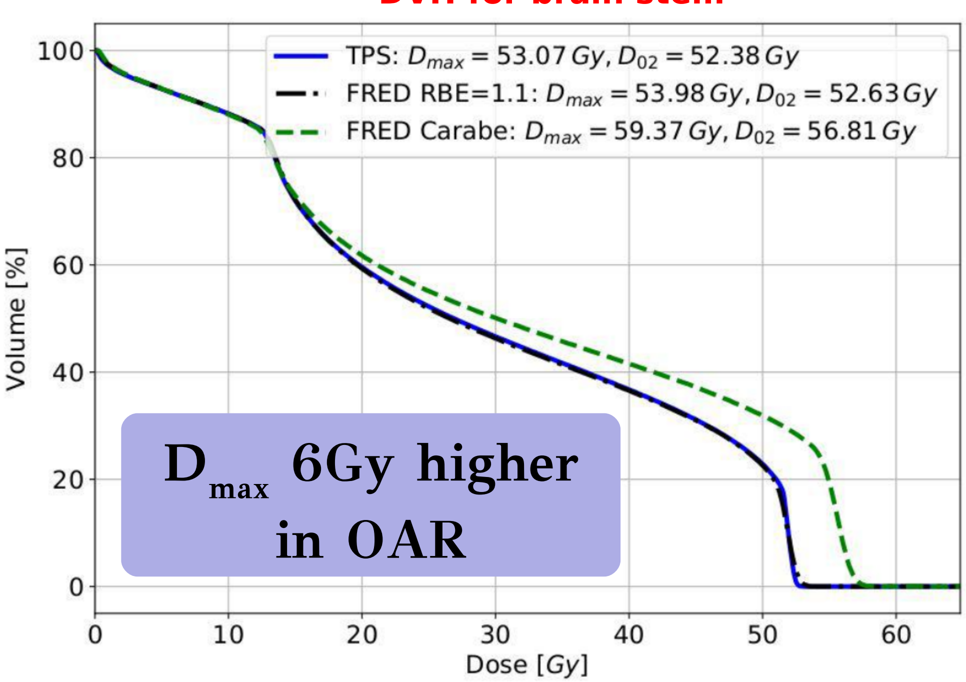


Variable RBE - case study





D_{mean} 3.5Gy higher in PTV



D_{max} 6Gy higher in OAR

Variable RBE – 10 patients

10 Head&Neck patients treated as CCB

PTV	RBE=1.1	Carabe RBE
D_{mean}	100.1% (0.0%)	107.9% (0.8%)
HI_{D5D95}	6.0% (0.4%)	9.4% (0.5%)

Brain stem	RBE=1.1	Carabe RBE
D_{max}	52.2Gy (1.6Gy)	59.4Gy (1.8Gy)
D_{02}	50.8Gy (1.8Gy)	55.6Gy (2.1Gy)

PTV D_{mean} up to ~8% higher that prescribed dose

OAR (brain stem) D_{max} up to 7.2Gy higher than calculated in TPS

Conclusions

- Fast and automatic beam model preparation for FRED MC (requires only commissioning measurements data)
- Beam model validated experimentally in homogeneous and heterogeneous media
- Routine for biological dose calculations for patient treatment plans
- Current Activities:
  - Simple interface FRED ↔ TPS ECLIPSE
  - Further dLET validation
  - Experimental validation of beam size and dLET in water
  - Analysis of biological dose with variable RBE for 100 patients