PAUL SCHERRER INSTITUT PSI

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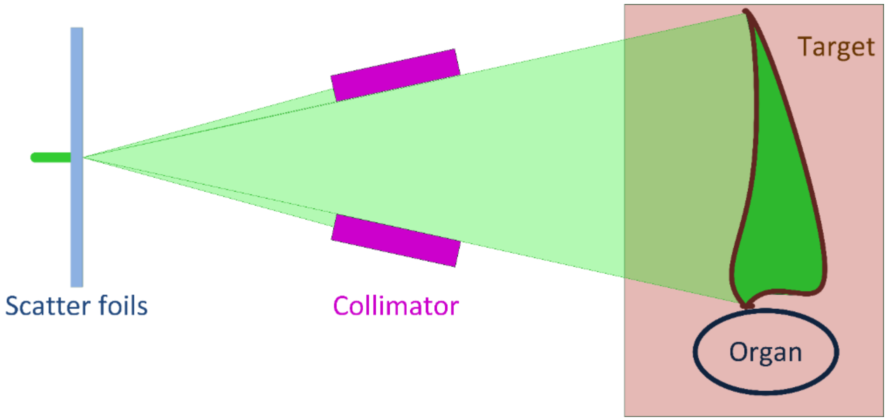
Current: University of Manchester, OPTIMA Consortium

Protons Do Play Dice:
Validating, Implementing And Applying Monte Carlo Techniques For Proton Therapy (ETH Diss 25698)

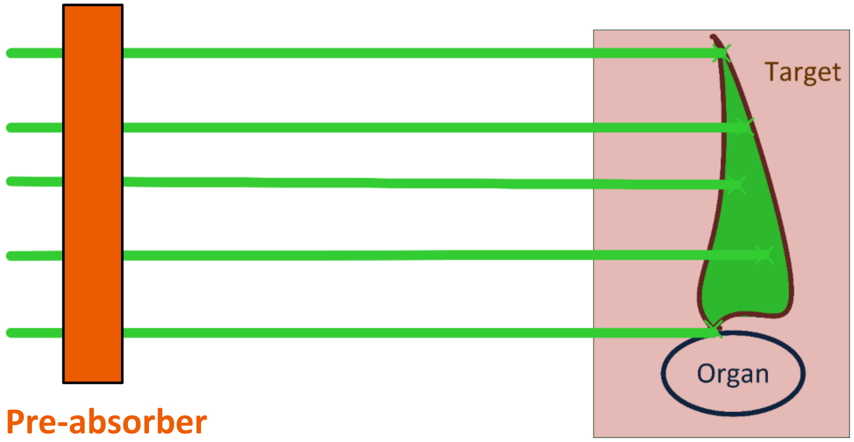
5th Annual Loma Linda Workshop, 22/07/2019 – 24/07/2019

Proton pencil beam scanning

- Passive scattering:
  - Broad beam
  - Lateral conformation: collimator



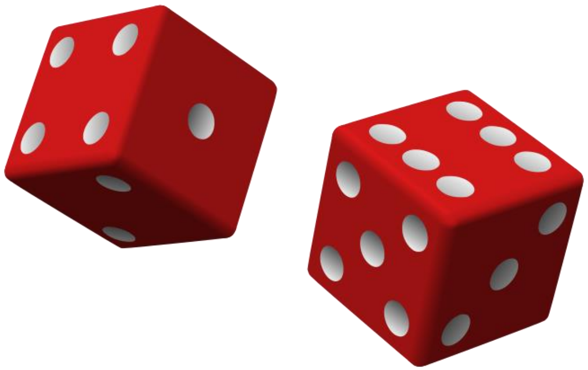
- Pencil beam scanning:
  - Small proton beams are directed into the patient
  - Depth is adjusted by energy change and pre-absorber usage

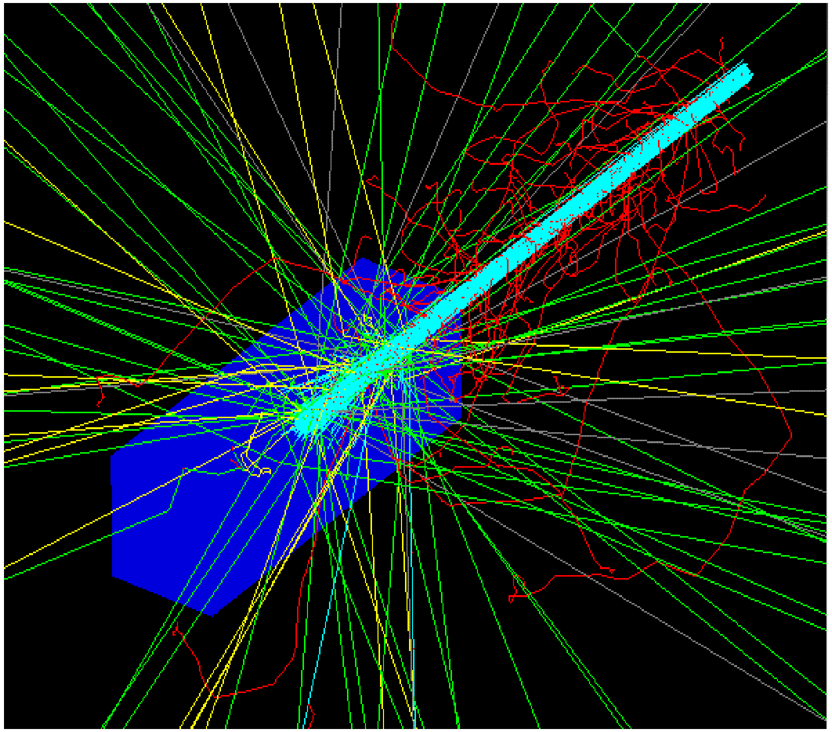


Monte Carlo Technique

Simulate protons passing through material:

- Physics models
- Probabilites for interactions
- Random numbers are sampled

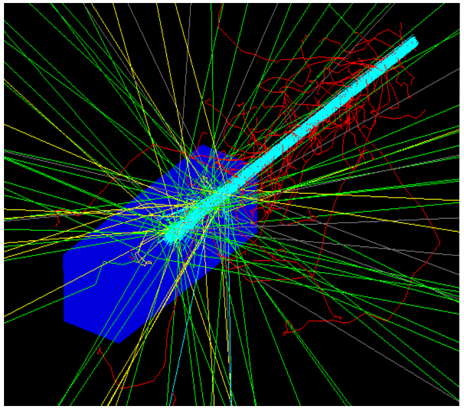




Proton = cyan
Electron = red
Gamma = green
Neutron = yellow

https://de.wikipedia.org/wiki/Datei:Two_red_dice_01.svg 4.12.18

Monte Carlo Technique

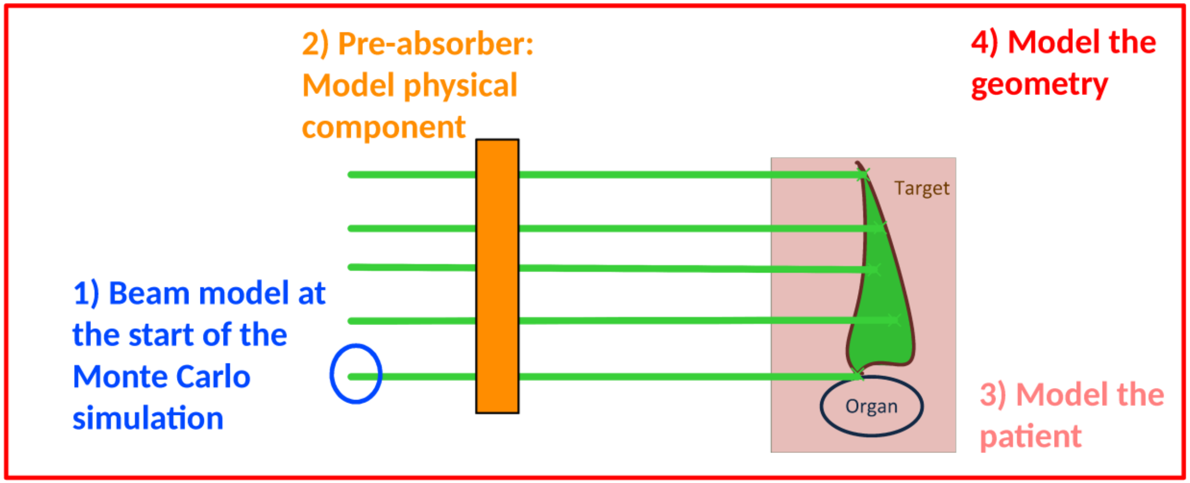


Simulate protons passing through material:

- Physics models
- Probabilites for interactions
- Random numbers are sampled

Geant4/TOPAS: (Perl et al 2012)

- Well validated (Testa et al. (2013), Grassberger et al. (2014), Fracchiolla et al. (2015))
- Institute/user specific setup
  - Beam model
  - Pre-absorber model
  - Patient
  - Geometry



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Outline

Protons Do Play Dice:

Validating, ***Implementing*** And ***Applying*** Monte Carlo Techniques For Proton Therapy.

Outline

Protons Do Play Dice:

Validating…

1. How accurate is the setup process?
2. How accurate is the absolute dose prediction?

Implementing…

3. How accurate are analytical dose calculations?
4. What is the combined error of calculation and delivery?

Applying…

5. How does collimation improve the lateral fall-off in water?
6. How does collimation improve the dose in the patient?

…Monte Carlo Techniques For Proton Therapy.

Validating Monte Carlo Techniques for Proton Therapy

1) How accurate is the setup process?

2) How accurate is the absolute dose prediction?

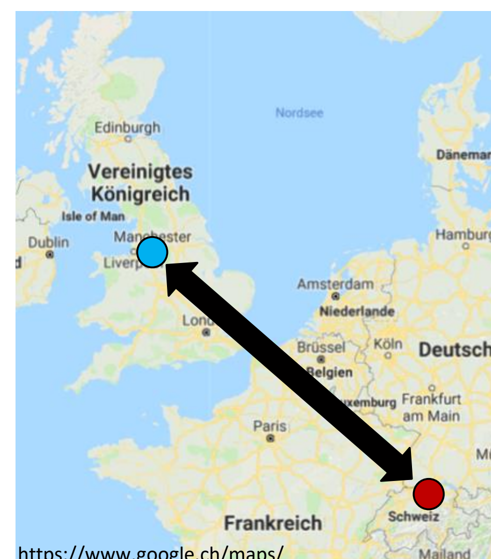
1) How accurate is the setup process?

Measurement data PSI Gantry 2

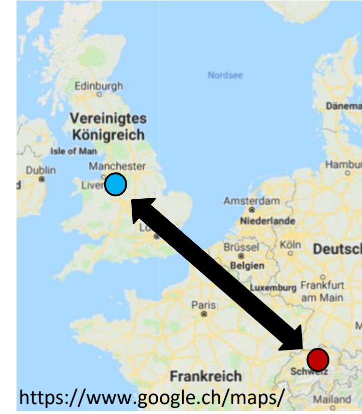
The PSI model 2 **independently** set up models **The Christie model**

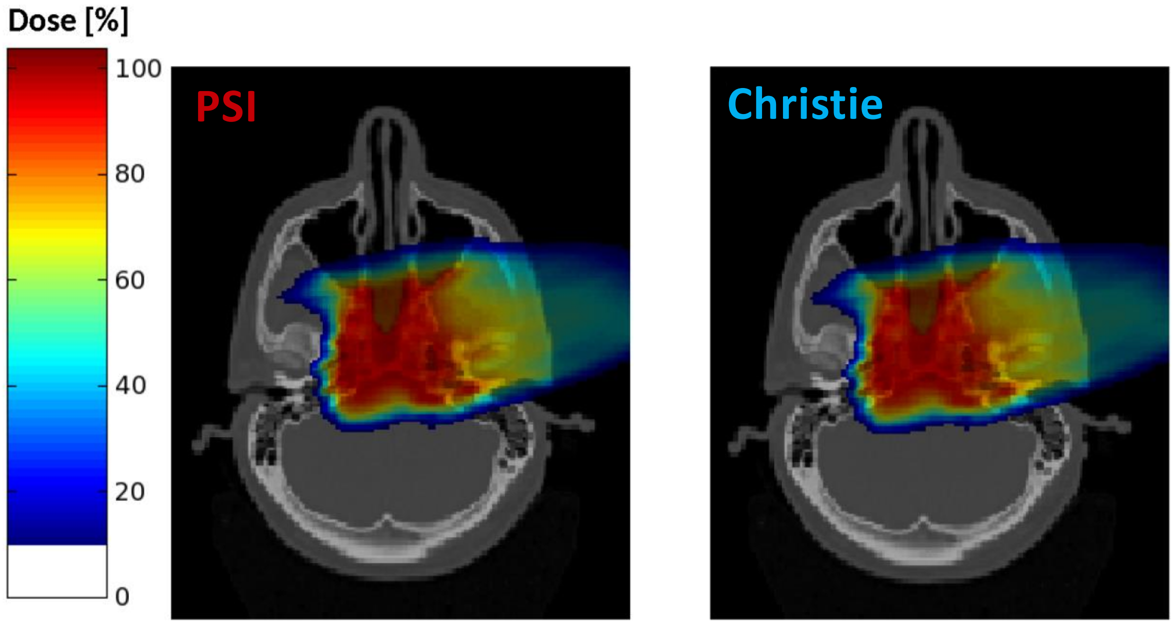
Compare dose results in simple geometric setups and in patient geometries

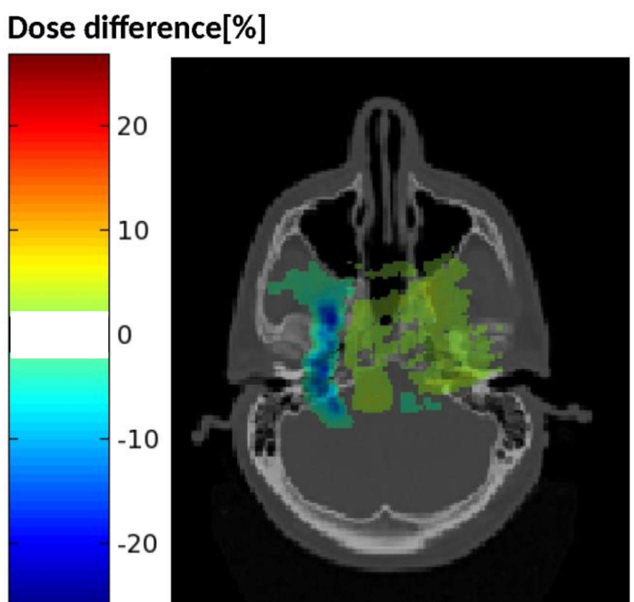
How much do Monte Carlo simulated doses depend on the model setup?



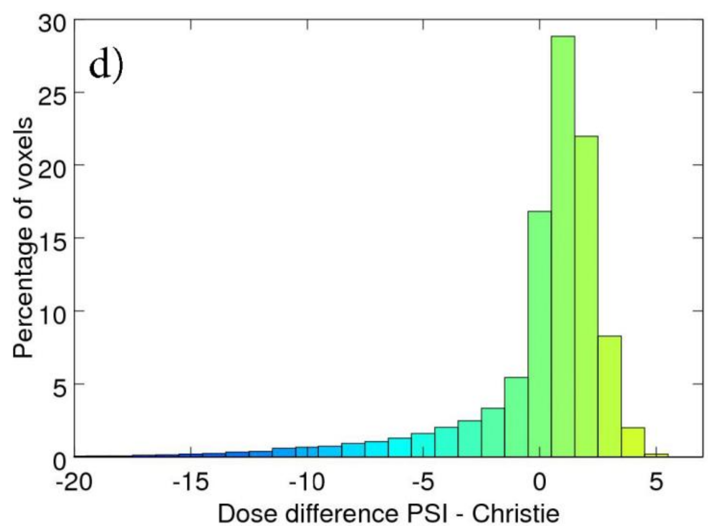
1) How accurate is the setup process?







Difference PSI - Christie



Winterhalter et al. (2019a), submitted to Medical Physics

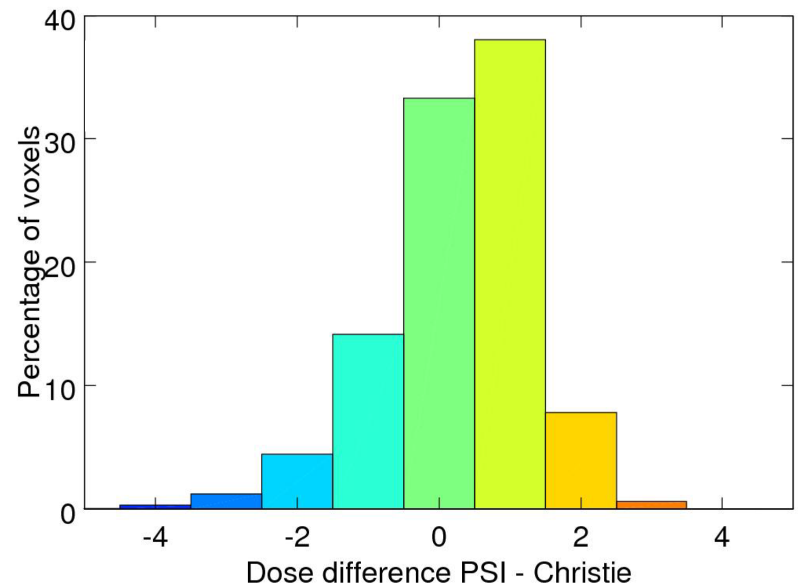
1) How accurate is the setup process?

- Critical parameters:

1) Ionization potential of the water used during the Monte Carlo setup
2) Modelling of objects

- Updated setup process

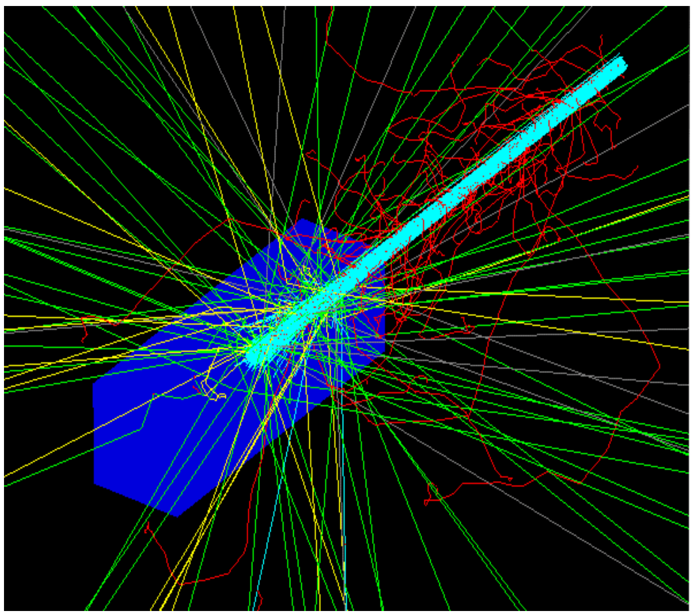
- After adjustments: differences within ±2.5%



Winterhalter et al. (2019a), submitted to Medical Physics

2) How accurate is the absolute dose prediction?

Monte Carlo simulations



Measurements

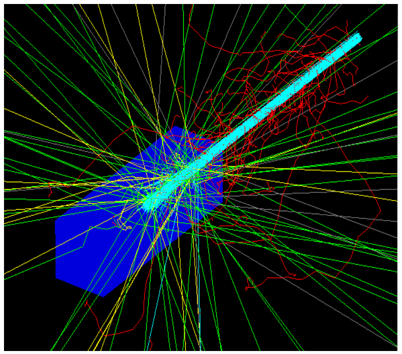
https://www.ptw.de/advanced_markus_electron_chambe.html, 12.12.18

Figure courtesy: Anna Fredh

Winterhalter et al. (2018a), Phys Med Biol 63.17

2) How accurate is the absolute dose prediction?

Monte Carlo simulations



Proton Numbers based on *Faraday cup* measurements.

Absolute doses simulated with *Monte Carlo*.

Measurements

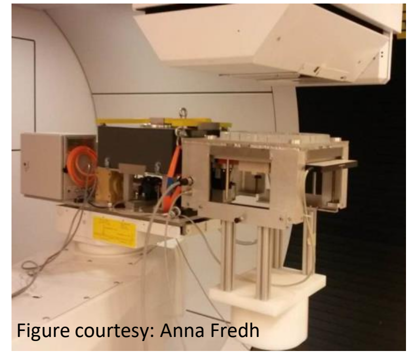
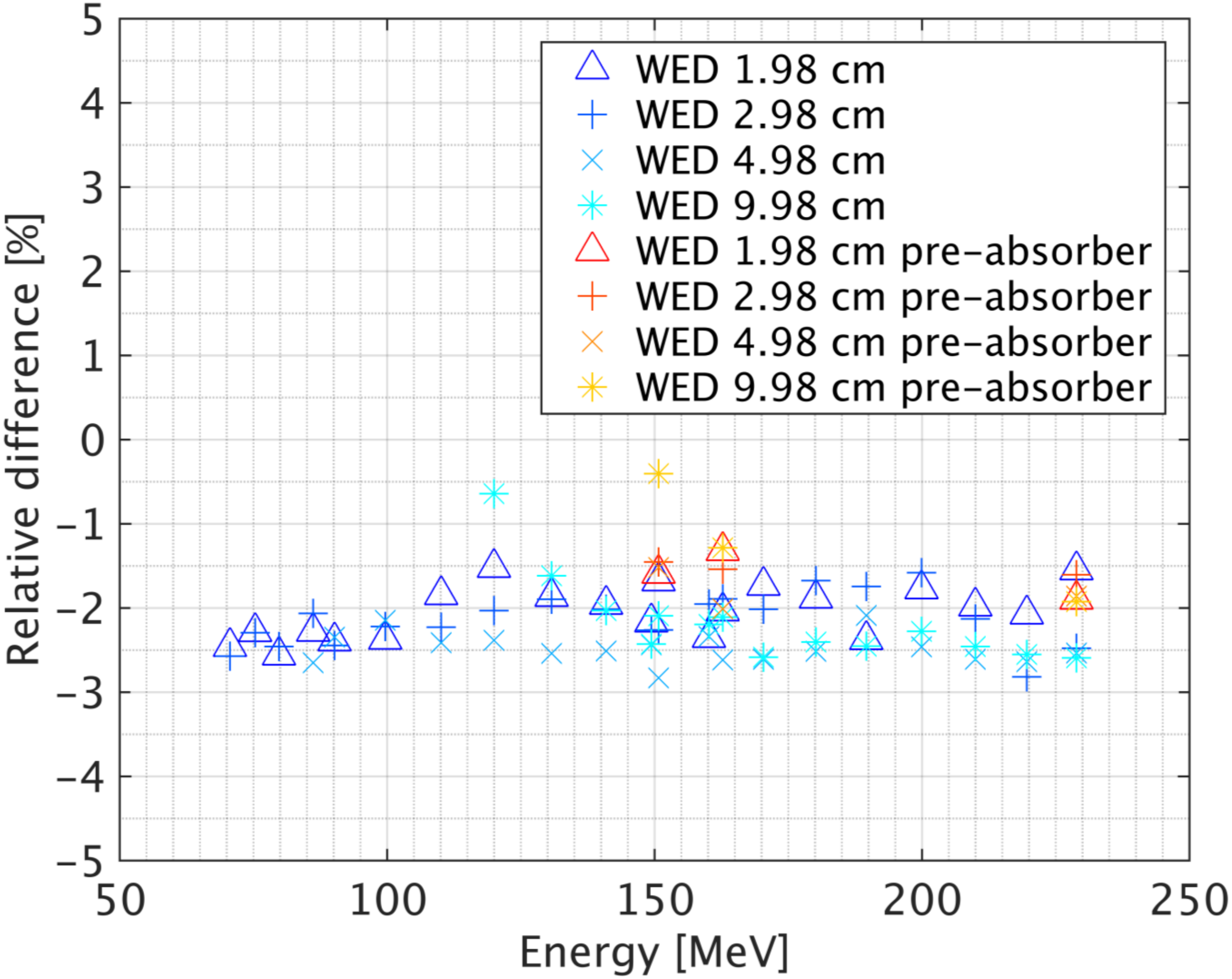


Figure courtesy: Anna Fredh

https://www.ptw.de/advanced_markus_electron_chambe.html, 12.12.18

Absolute doses measured with *ionization chambers*.

2) How accurate is the absolute dose prediction?



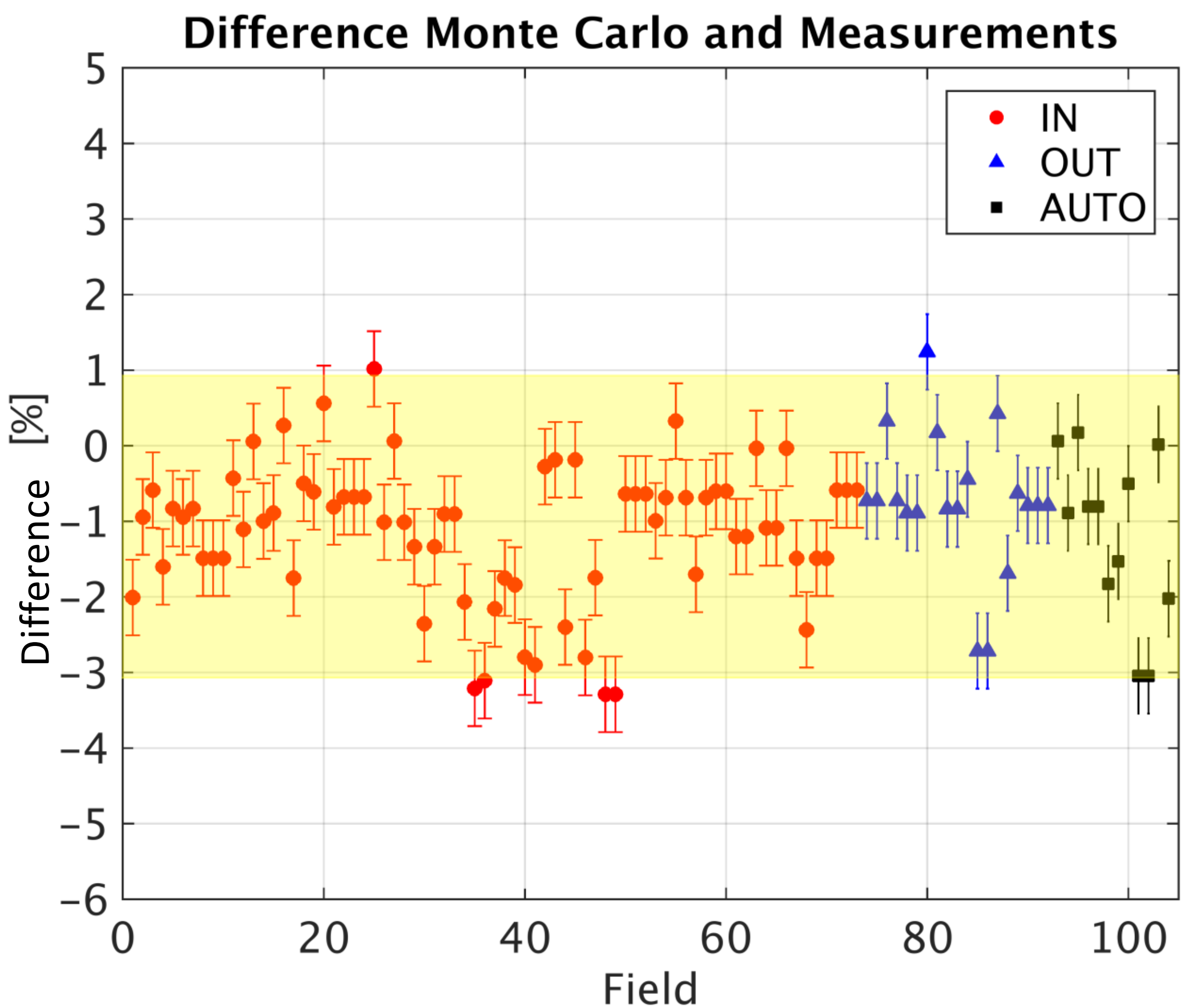
https://www.ptw.de/advanced_markus_electron_chambe.html, 12.12.18

Compare to energy layer measurements:

- Absolute dose offset: 2% Monte Carlo is systematically lower than measurements.
- No dependence on pre-absorber.

Winterhalter et al. (2018a), Phys Med Biol 63.17

2) How accurate is the absolute dose prediction?



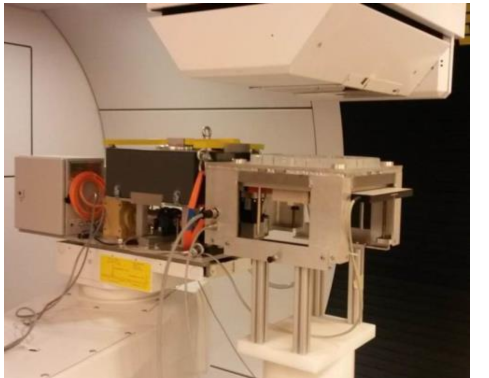


Figure courtesy: Anna Fredh

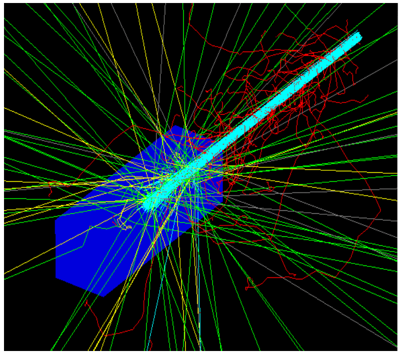
Compare to delivered clinical fields:

- 1% (mean value) absolute dose offset
- 94% of the fields agree within +-2% of this mean

Winterhalter et al. (2018a), Phys Med Biol 63.17

2) How accurate is the absolute dose prediction?

Monte Carlo simulations



Measurements

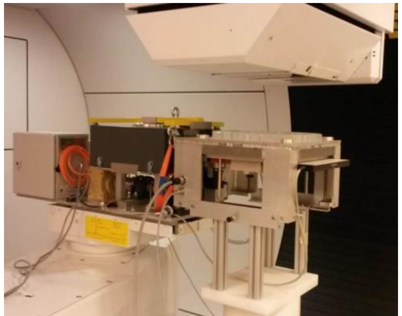


Figure courtesy: Anna Fredh


https://www.ptw.de/advanced_markus_electron_chambe.html, 12.12.18

Proton Numbers based on *Faraday cup* measurements.
Reproducibility: 0.4%
Nozzle extraction: 0.5%

Absolute doses simulated with *Monte Carlo*.
Differences between MC codes<1% (Goma 2015)

Absolute doses measured with *ionization chambers*.
Difference between two chambers: 1.4%
Accuracy chambers: 2.0%/2.3% (IAEA 2000)

IAEA (2000) Technical Reports Series No. 398.
Gomà (2015).Phys Med Biol, 60(8)

Summary 1: Validating Monte Carlo Techniques for Proton Therapy

1) How accurate is the setup process?

- Critical parameters identified
- Agreement within ±2.5%

Winterhalter et al. (2019a), submitted to Medical Physics

https://www.google.ch/maps/

2) How accurate is the absolute dose prediction?

- Absolute dose predictions within ±2%

Winterhalter et al. (2018a), Phys Med Biol 63.17

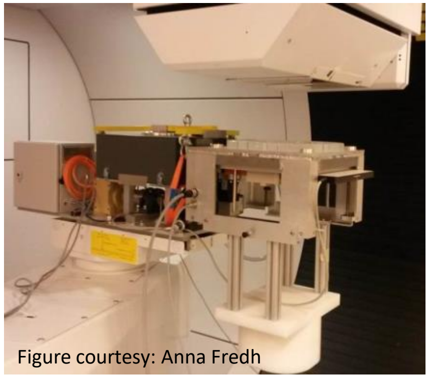


Figure courtesy: Anna Fredh

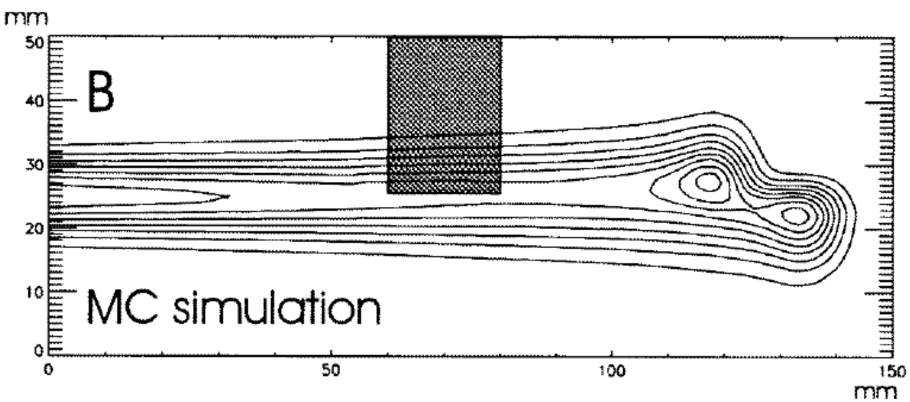
Implementing Monte Carlo Techniques for Proton Therapy

3) How accurate are analytical dose calculations?

4) What is the combined error of calculation and delivery?

3) How accurate are analytical dose calculations?

Monte Carlo

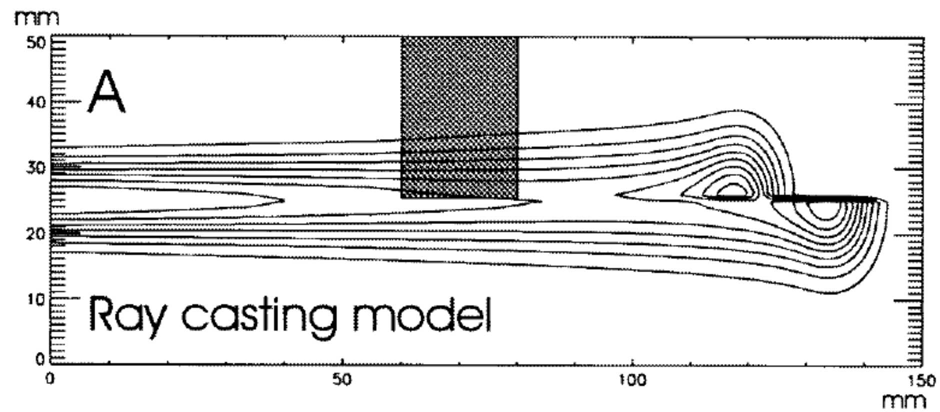


Tracks each particle

✓ «Gold-standard»

✗ Slow

Analytical calculations



$$D = ID(WED) \cdot w \cdot \frac{1}{\pi\sqrt{A_x \cdot A_y}} \cdot e^{-\Delta x^2/A_x - \Delta y^2/A_y}$$

$$D = \sum_{\tilde{x}} \sum_{\tilde{y}} \Phi(x - \tilde{x},\ y - \tilde{y}, z) \cdot K(\tilde{x}, \tilde{y}, WED)$$

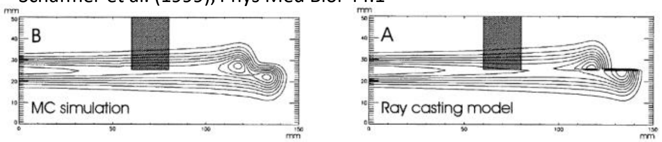
✗ Less accurate

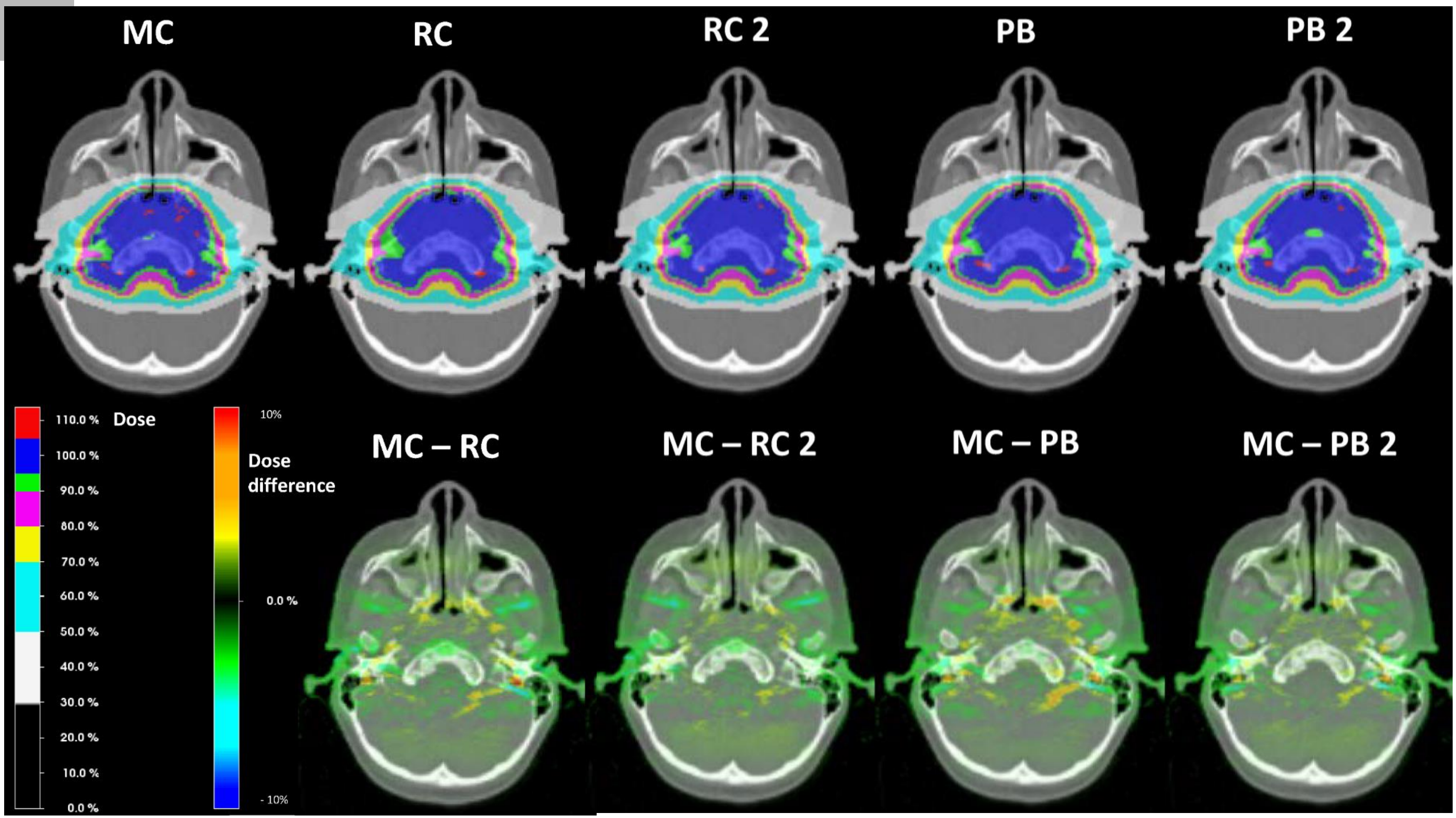
✓ Fast

Schaffner et al. (1999), Phys Med Biol 44.1

3) How accurate are analytical dose calculations?

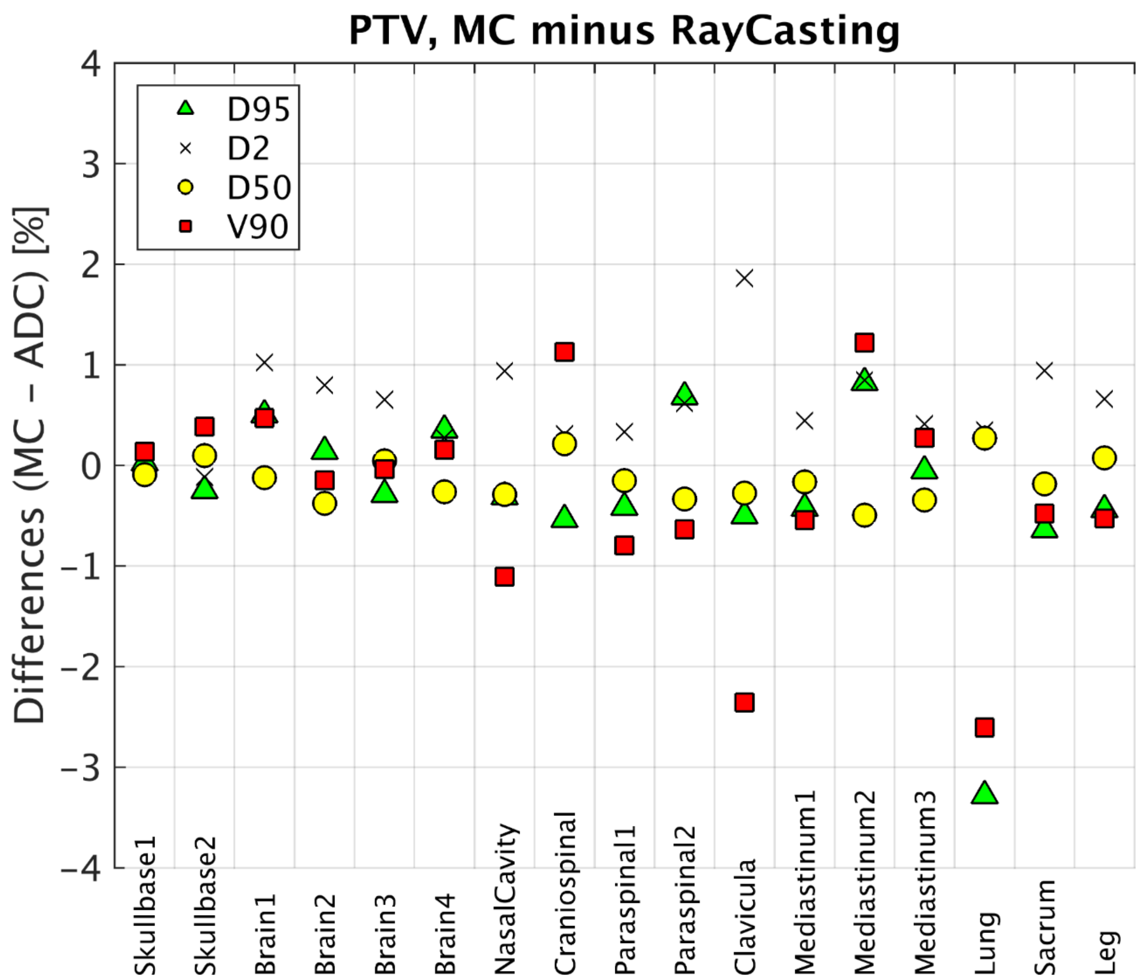
Schaffner et al. (1999), Phys Med Biol 44.1





Winterhalter et al. (2019b), Phys. Med. Biol.64 065021

3) How accurate are analytical dose calculations?



Clinical dosimetric indices:
agreement within ±5%

Analytical algorithms predict dose distributions with clinical sufficient accuracy, at least for the dose optimization.

Winterhalter et al. (2019b), Phys. Med. Biol.64 065021

4) What is the combined error of calculation and delivery?

Motivation - Patient Specific QA:

1) Verify the TPS dose calculation

2) Verify the plan data transformation
3) Verify that plan can be delivered

Measure each field in a water phantom.

(Lomax et al, 2004, Med Phys, 31
Trnkova et al 2016, Med Phys, 43)

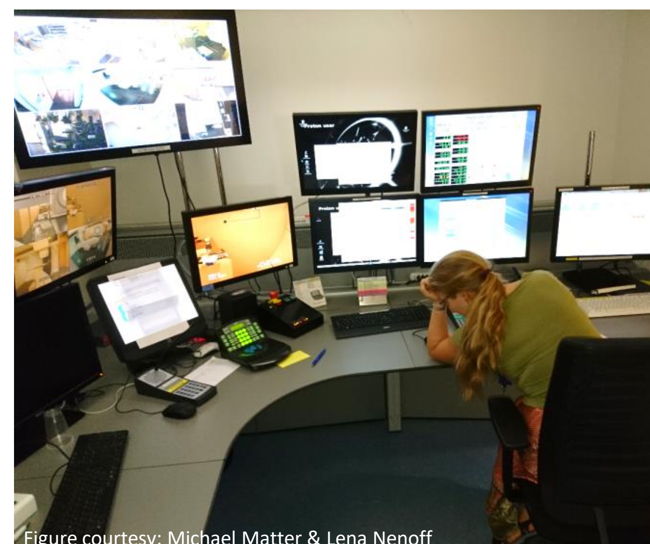
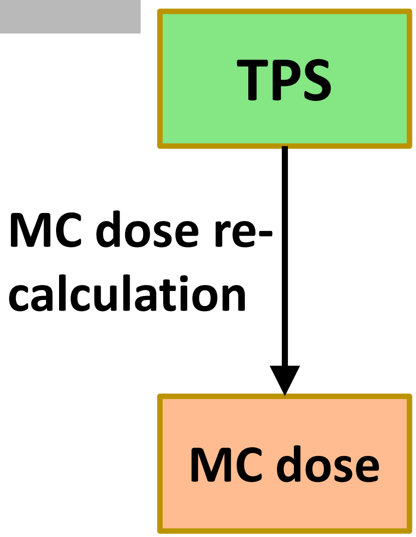


Figure courtesy: Michael Matter & Lena Nenoff

4) What is the combined error of calculation and delivery?



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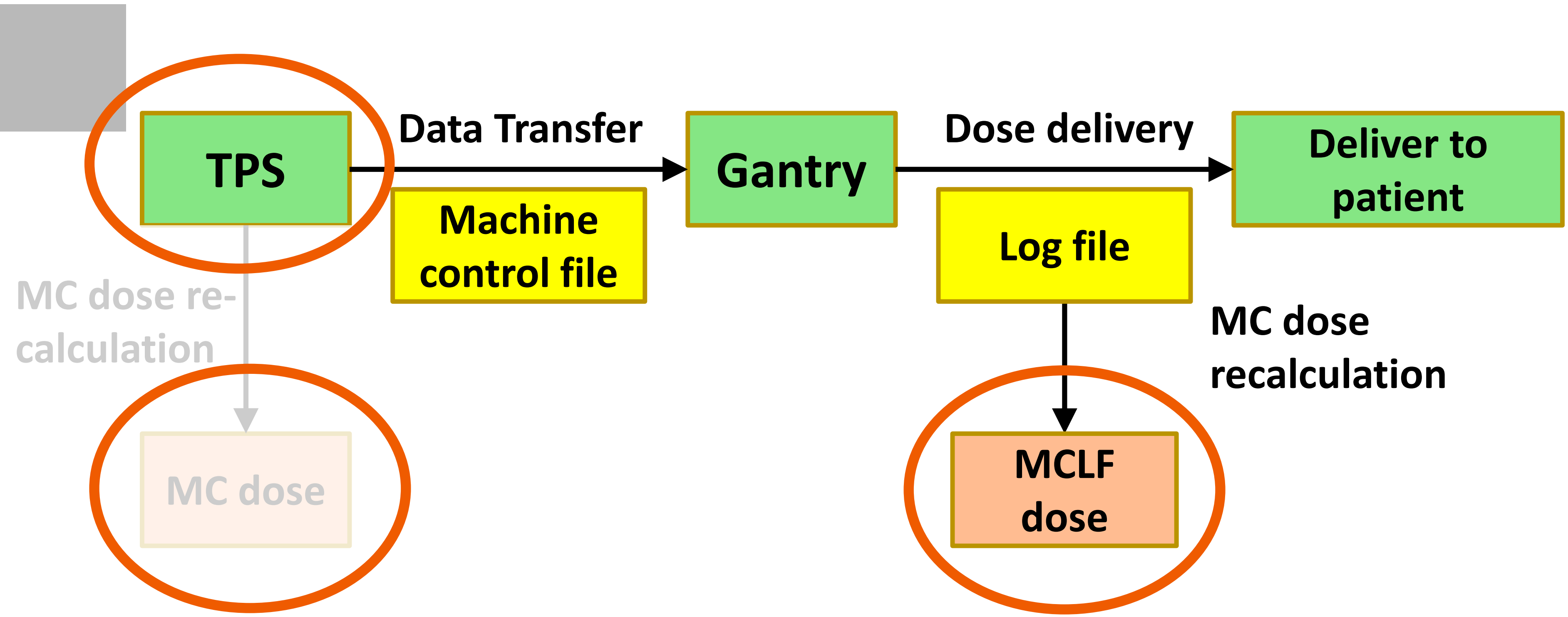
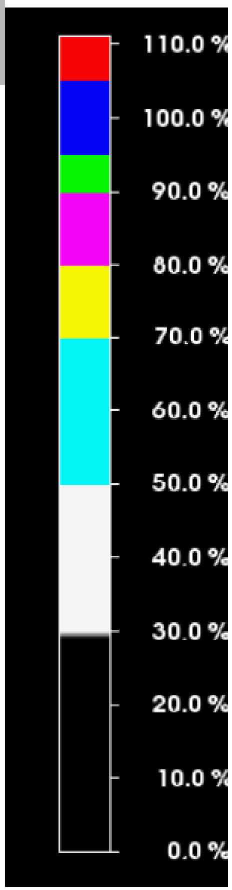
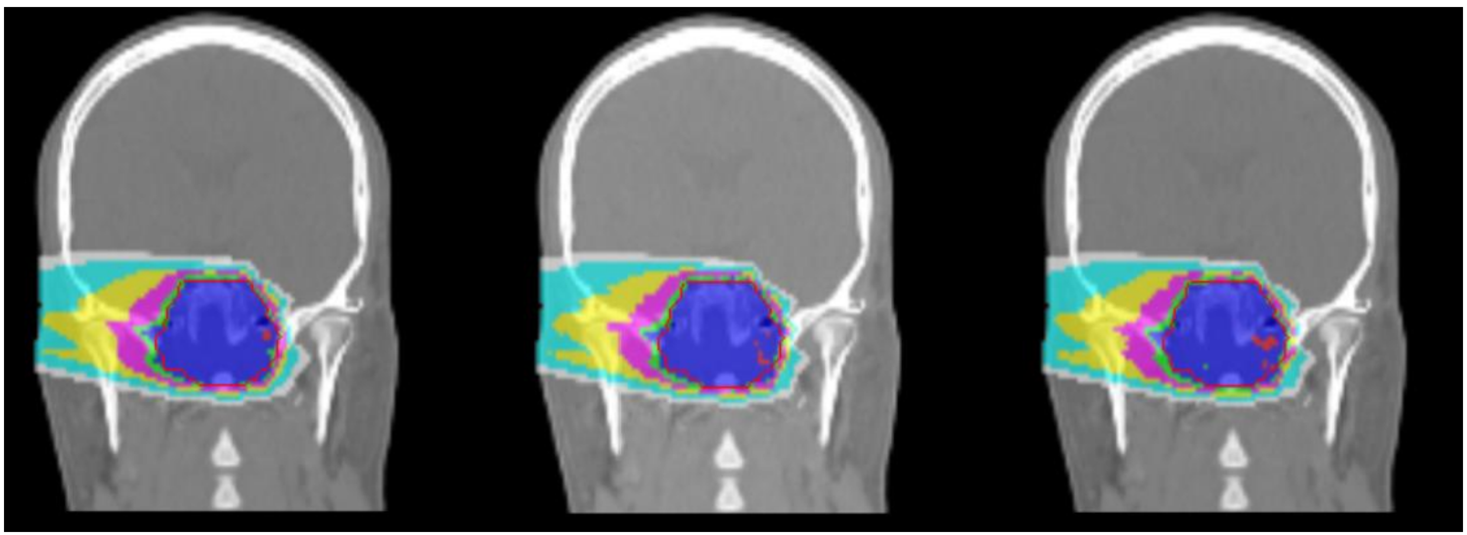


Winterhalter et al. (2019c), Phys. Med. Biol.64 035014

4) What is the combined error of calculation and delivery?



Treatment planning system (TPS) | **Monte Carlo (MC)** | **Monte Carlo from Log File (MCLF)**



Winterhalter et al. (2019c), Phys. Med. Biol.64 035014

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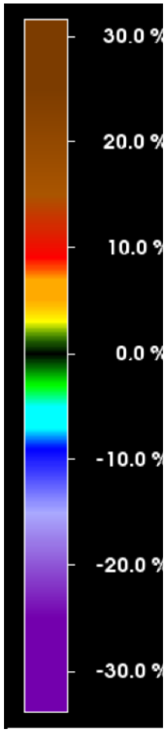
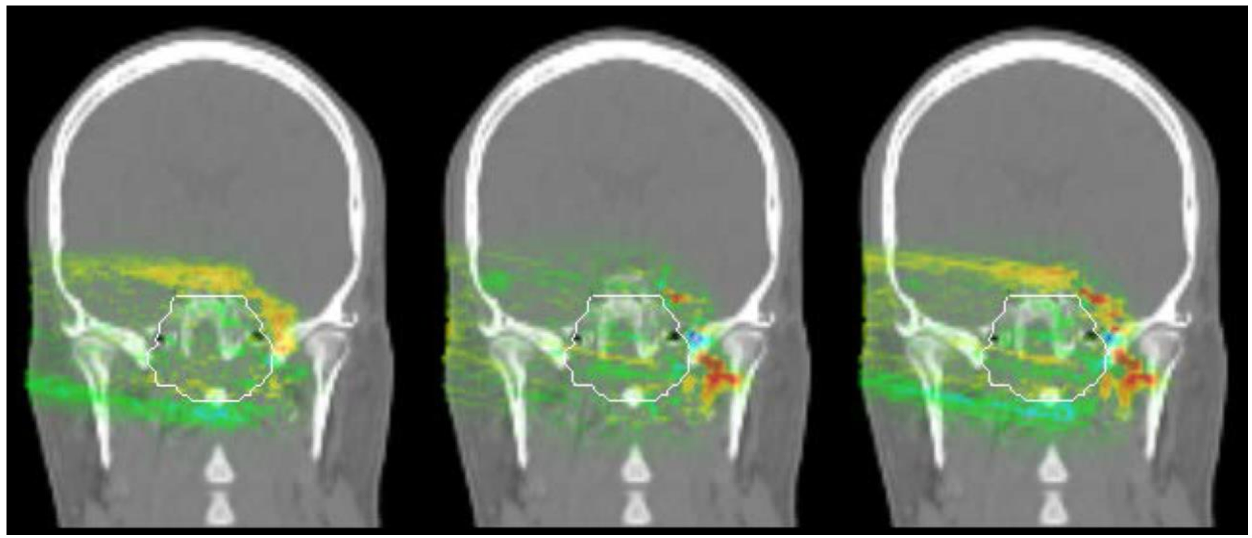


Delivery | Calculation | Combination



MC – MCLF | TPS – MC | TPS - MCLF

Monte Carlo from log-files:

… checks dose calculation accuracy

… checks data transformation & dose delivery

and could be used to reduce/replace patient specific quality assurance measurements.

Winterhalter et al. (2019c), Phys. Med. Biol.64 035014

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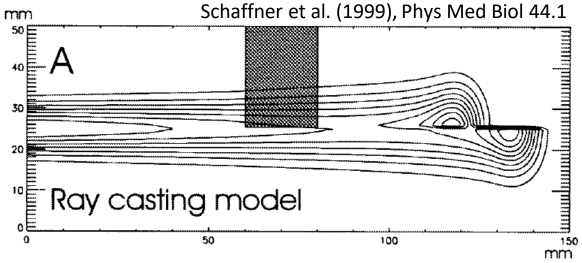
Summary 2: Implementing Monte Carlo Techniques for Proton Therapy

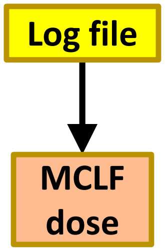
Schaffner et al. (1999), Phys Med Biol 44.1



3) How accurate are analytical dose calculations?

- Clinical dosimetric indices: agreement within ±5%
- No substantial dependence on the algorithm

Winterhalter et al. (2019b), Phys. Med. Biol.64 065021



4) What is the combined error of calculation and delivery?

- Monte Carlo from log-files could be used to replace patient specific quality assurance measurements.

Winterhalter et al. (2019c), Phys. Med. Biol.64 035014

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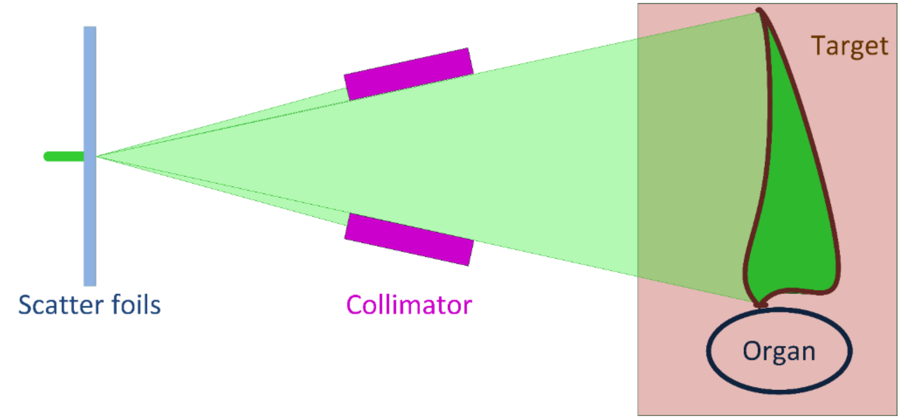
Applying Monte Carlo Techniques for Proton Therapy

5) How does collimation improve the lateral fall-off in water?

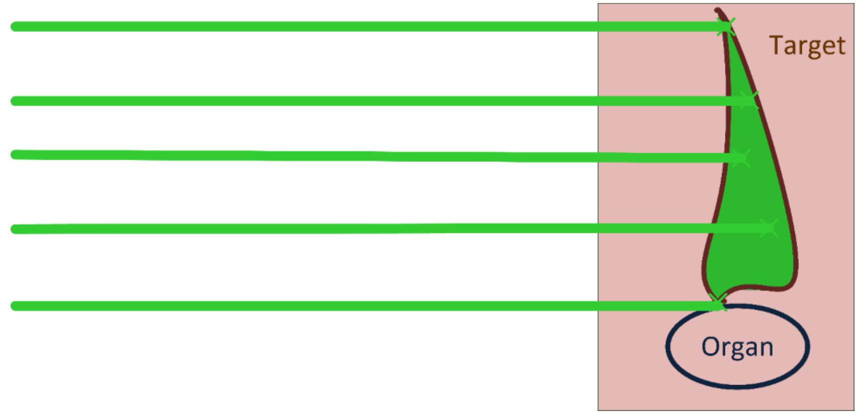
6) How does collimation improve the dose in the patient?

5) How does collimation improve the lateral fall-off in water?

- Passive scattering:
  - Broad beam
  - Lateral conformation: collimator



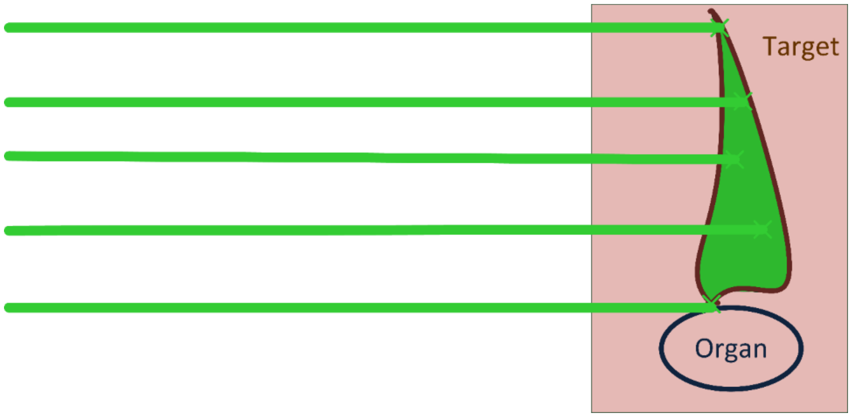
- Pencil beam scanning:
  - Small proton beams are directed into the patient



5) How does collimation improve the lateral fall-off in water?

- Shallow targets: Lateral fall-off (penumbra) of a collimated broad divergent beam is superior to the one of a scanned pencil beam (Safai et al., Physics in Medicine and Biology 53.6 (2008):1729)

- Sharp distal falloff is rarely employed to spare critical organs



Which are the best strategies to minimize the lateral fall-off for PBS?

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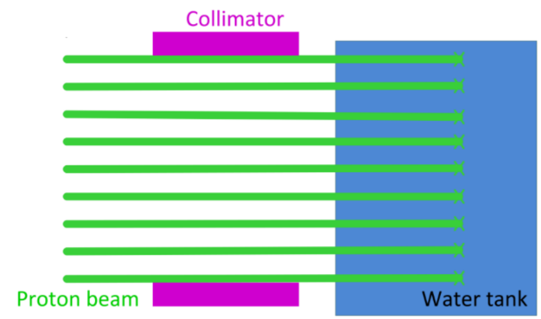
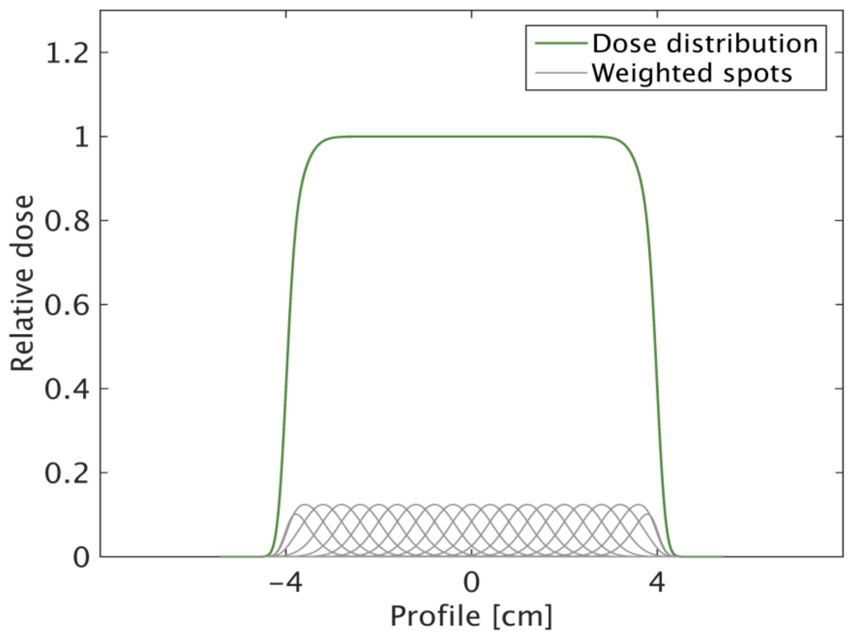
5) How does collimation improve the lateral fall-off in water?

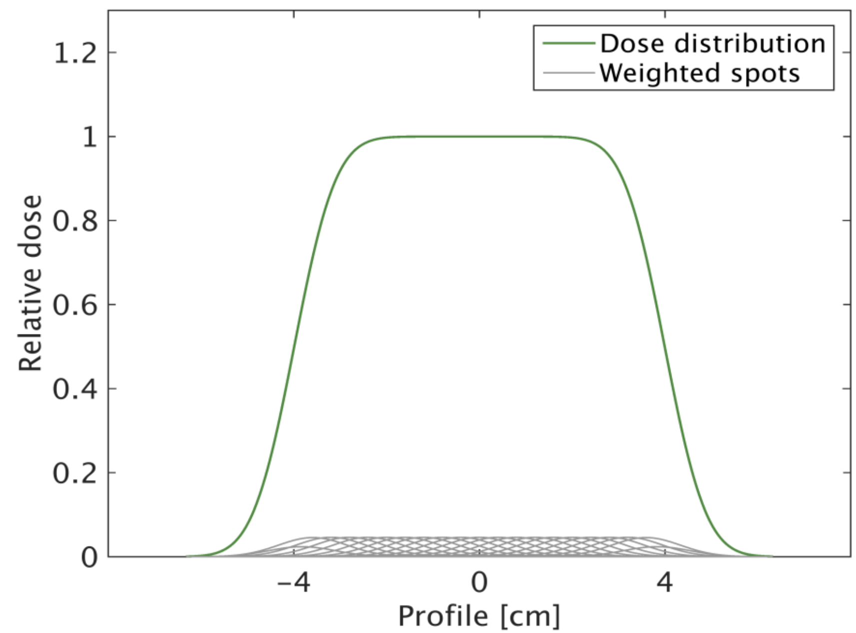


Collimation: Uniformly weighted pencil beams are collimated *(Passive scattering)*

E = 70 MeV



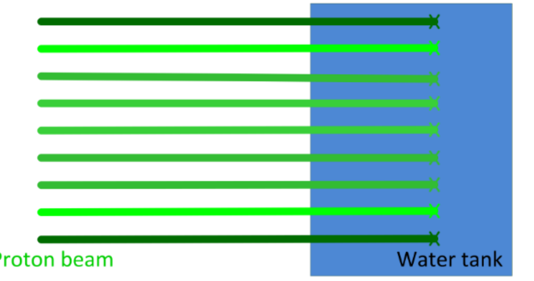
E = 230 MeV



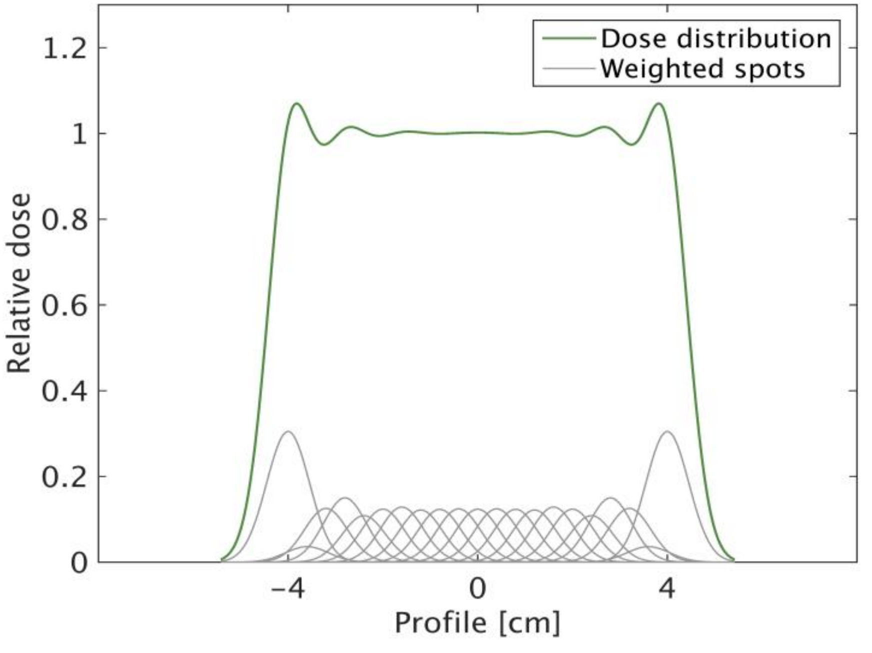
Winterhalter et al. (2018b), Phys Med Biol 63.2
Winterhalter et al. (2018c), Phys Med Biol 63.20

5) How does collimation improve the lateral fall-off in water?

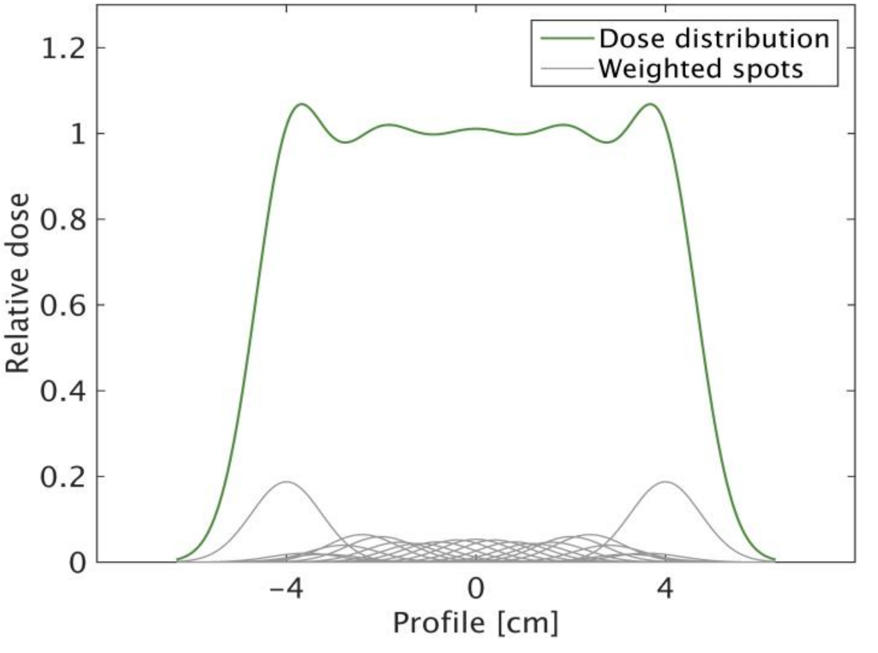
Edge-enhancement: The weights of the uncollimated pencil beams are optimized *(Pencil beam scanning)*



E = 70 MeV



E = 230 MeV



Winterhalter et al. (2018b), Phys Med Biol 63.2
Winterhalter et al. (2018c), Phys Med Biol 63.20

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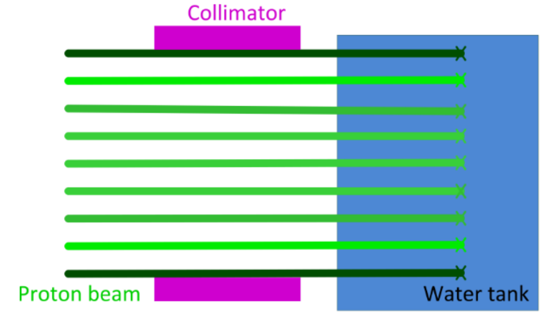
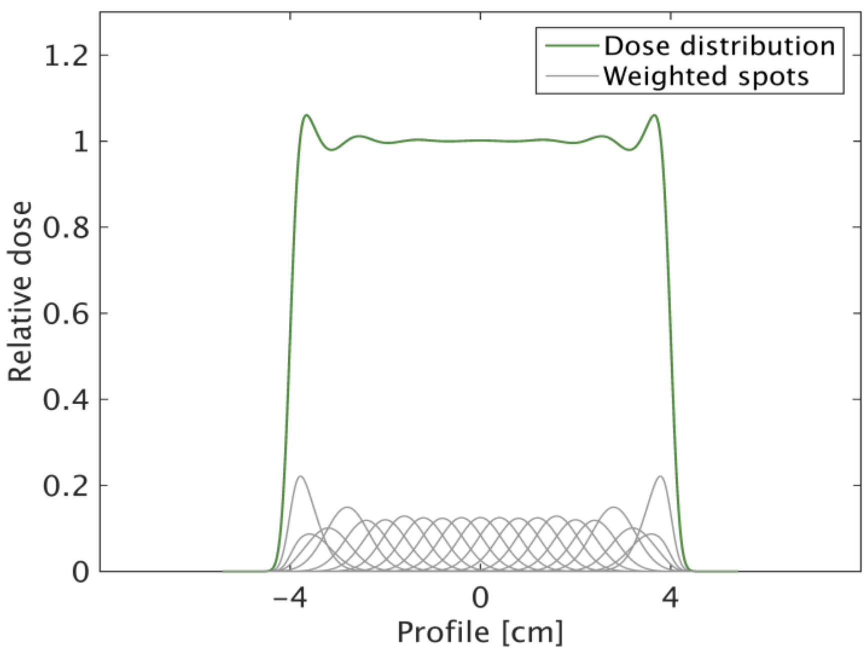
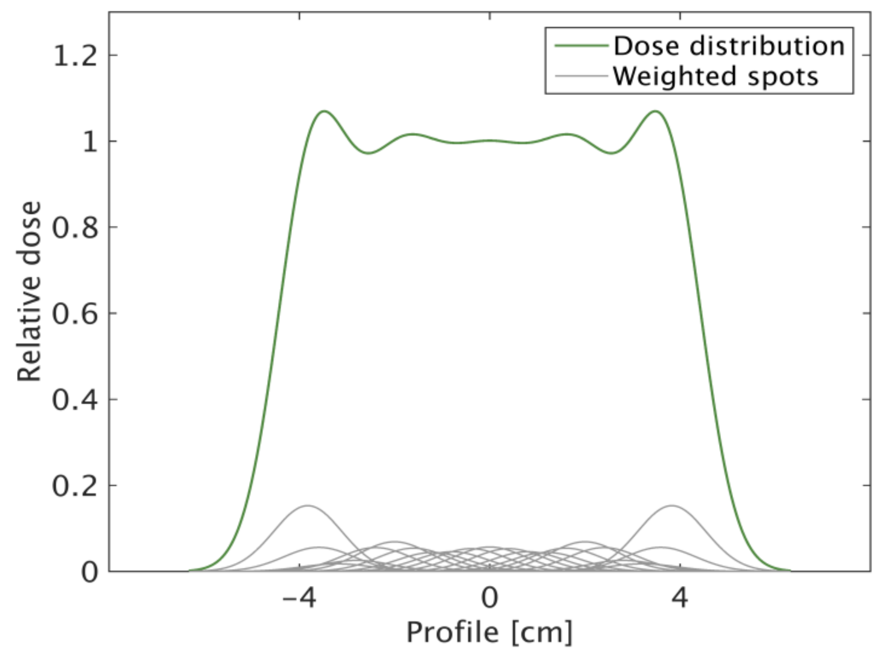


Edge-enhanced collimation: The weights of the collimated pencil beams are optimized

E = 70 MeV



E = 230 MeV



Winterhalter et al. (2018b), Phys Med Biol 63.2
Winterhalter et al. (2018c), Phys Med Biol 63.20

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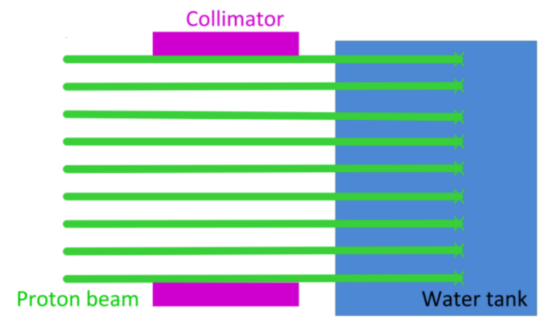
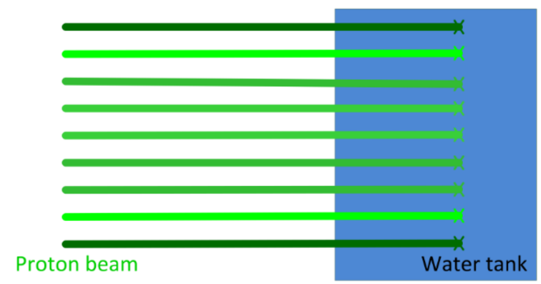
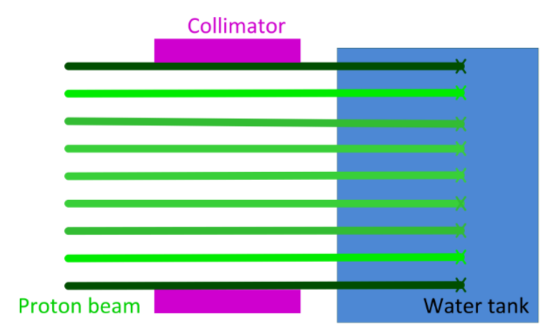
Collimation: Uniformly weighted pencil beams are collimated *(Passive scattering)*



Edge-enhancement: The weights of the uncollimated pencil beams are optimized *(Pencil beam scanning)*

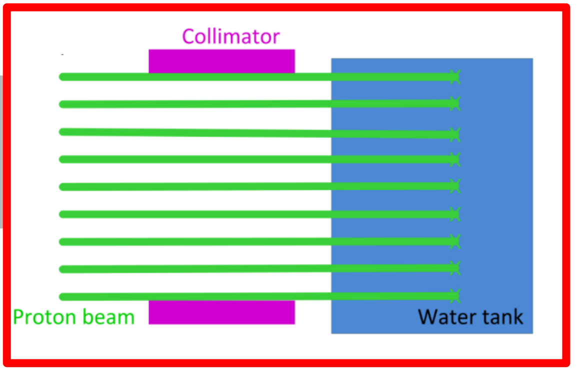


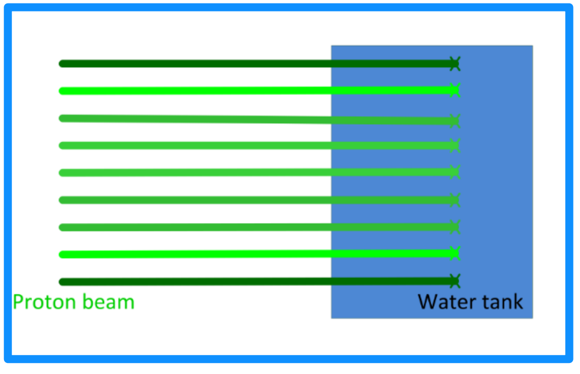
Edge-enhanced collimation: The weights of the collimated pencil beams are optimized

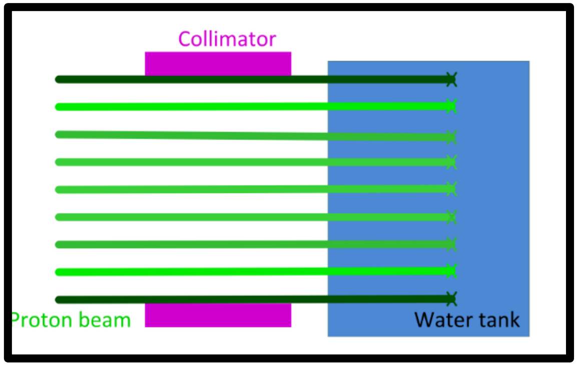


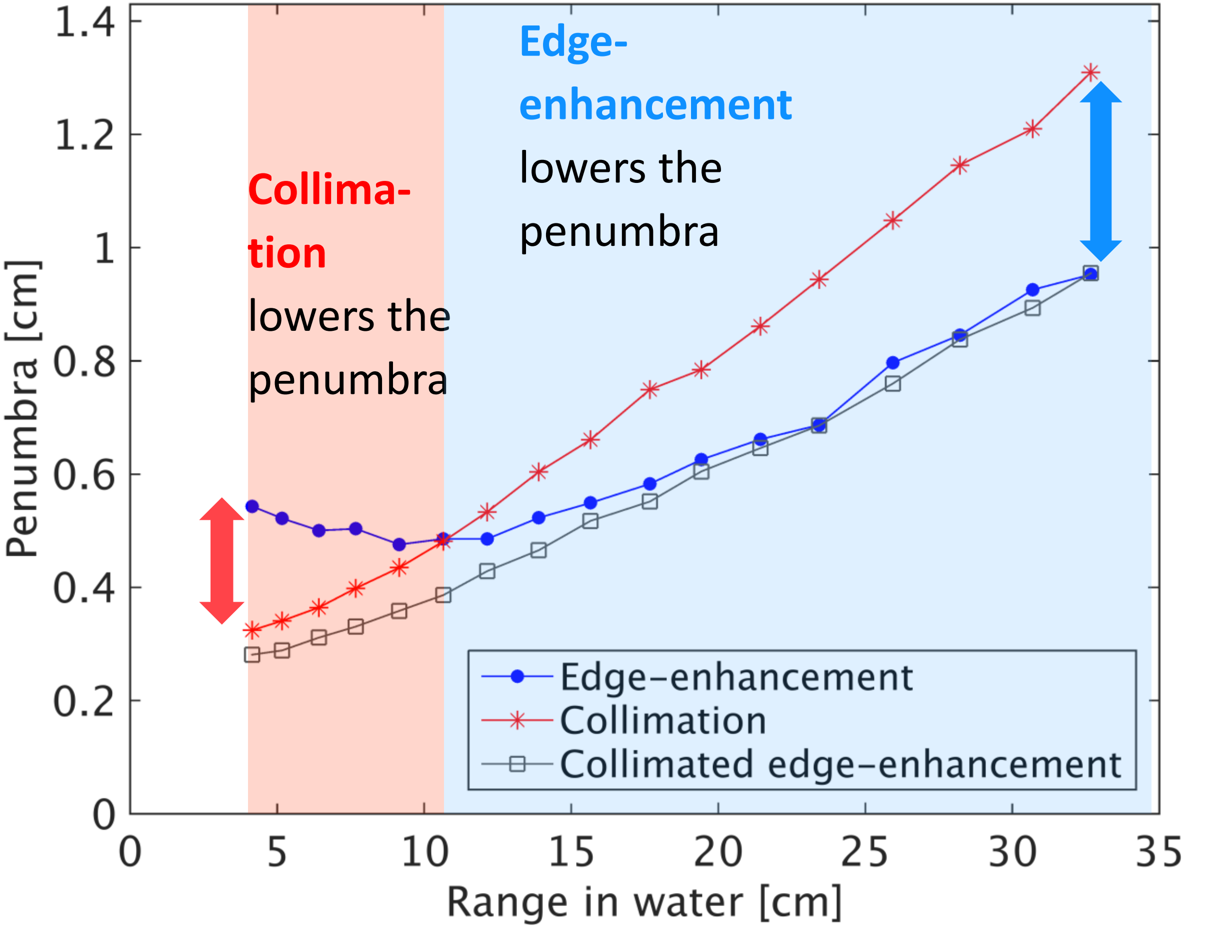
Winterhalter et al. (2018b), Phys Med Biol 63.2
Winterhalter et al. (2018c), Phys Med Biol 63.20

5) How does collimation improve the lateral fall-off in water?









Winterhalter et al. (2018b), Phys Med Biol 63.2; Winterhalter et al. (2018c), Phys Med Biol 63.20

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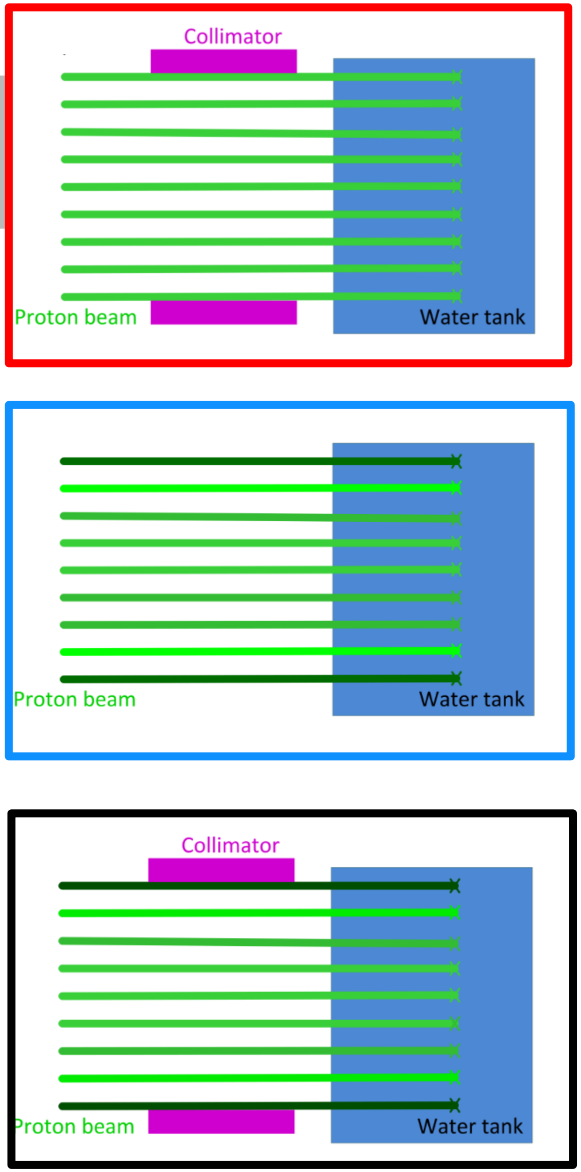
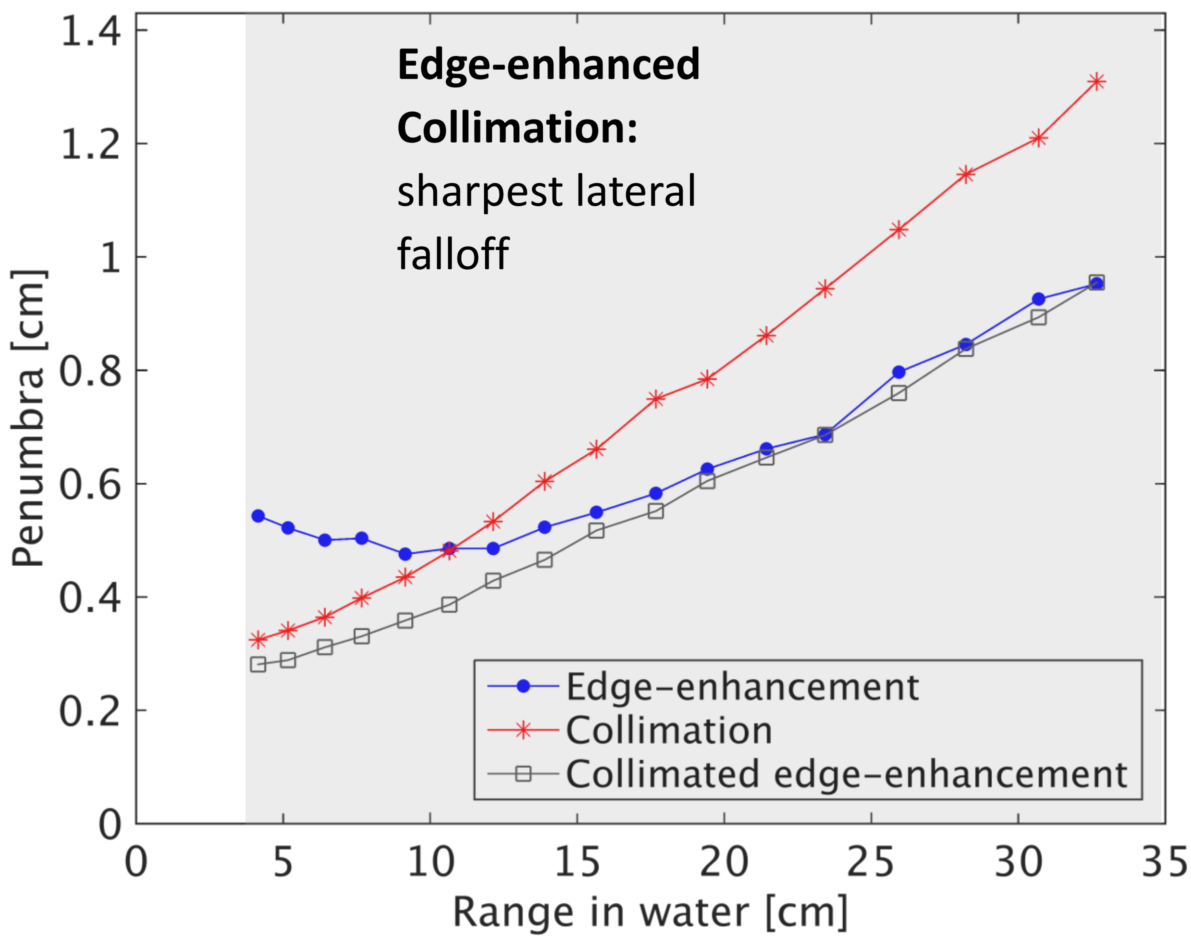
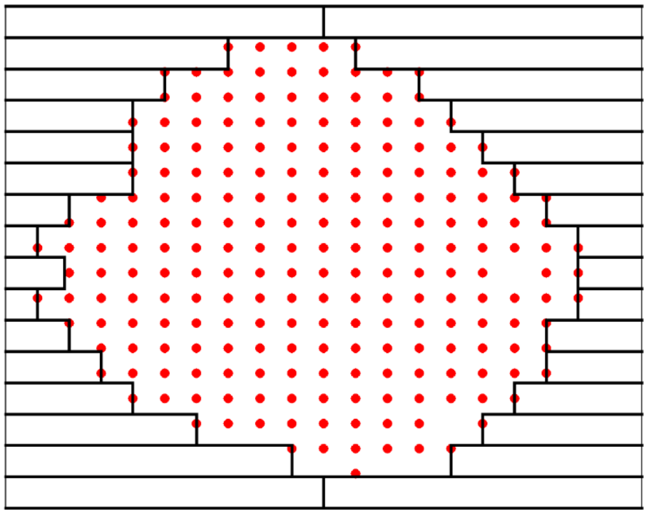


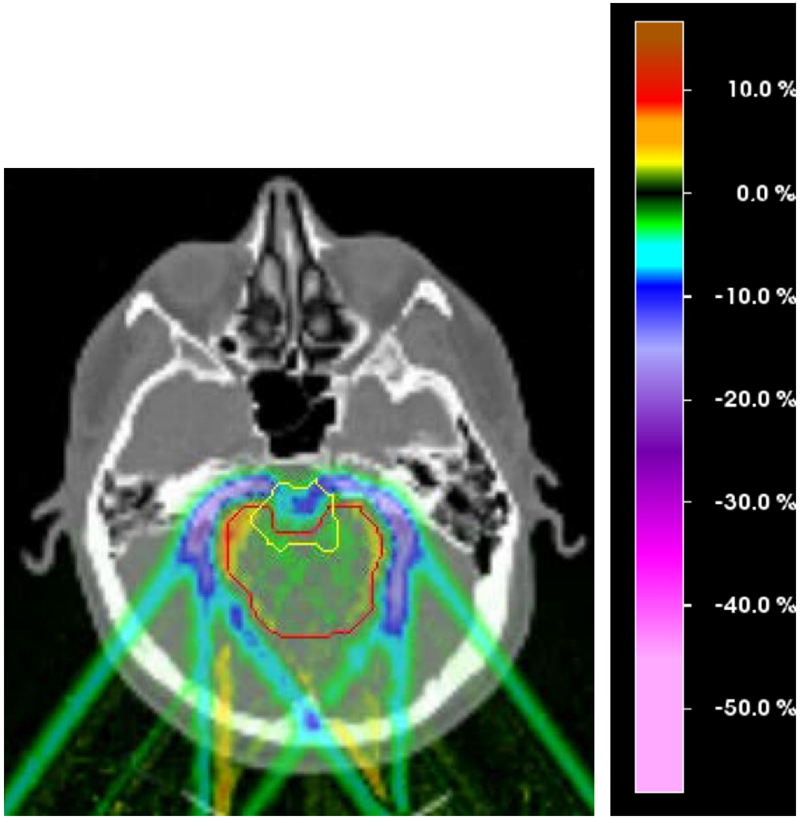


Winterhalter et al. (2018b), Phys Med Biol 63.2; Winterhalter et al. (2018c), Phys Med Biol 63.20

6) How does collimation improve the dose in the patient?



Optimized, energy layer specific collimation

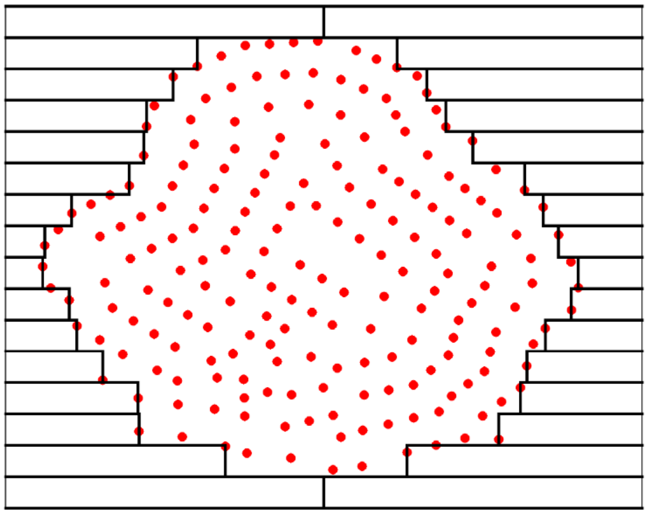


Normal tissue (V30%) dose reduction: 20%

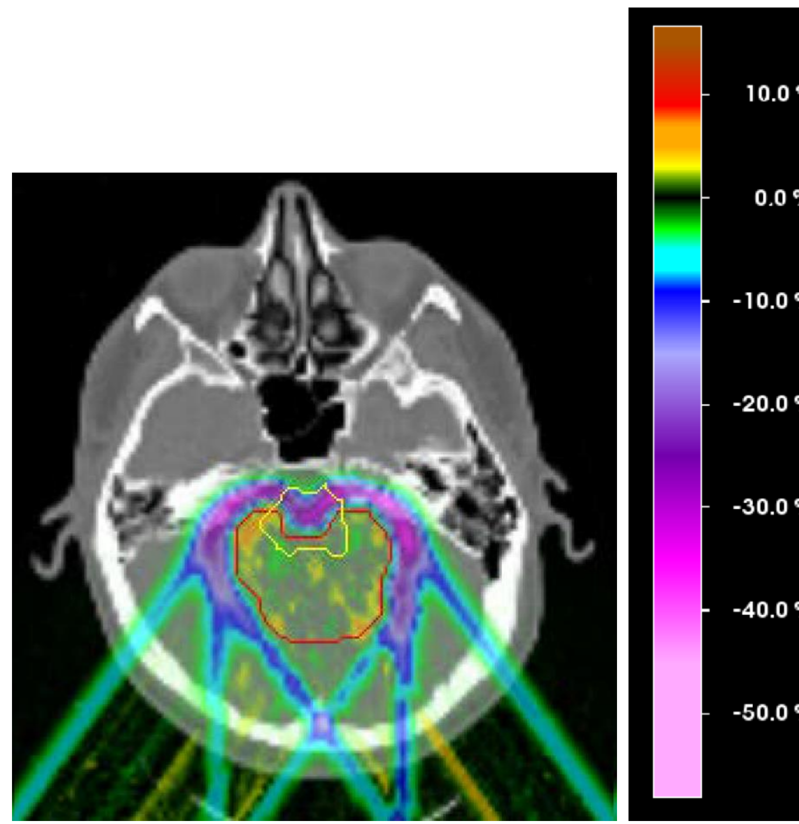
Mean dose to brainstem reduction: 7%

Winterhalter et al. (2018d), Phys. Med. Biol.64 015002

6) How does collimation improve the dose in the patient?



Optimized energy layer specific collimation AND **spots following the target contour** (*Meier et al 2017, Phys Med Biol, 62(6)*)



Normal tissue (V30%) dose reduction: 25%

Mean dose to brainstem reduction: 13%

Winterhalter et al. (2018d), Phys. Med. Biol.64 015002

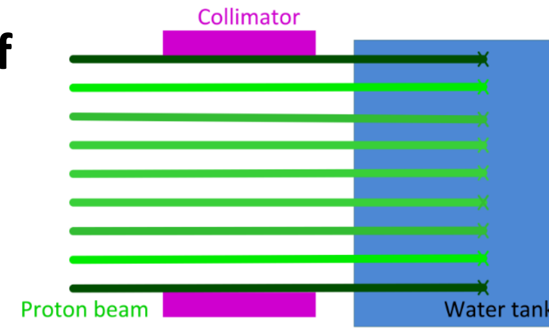
Summary 3: Applying Monte Carlo Techniques for Proton Therapy

5) How does collimation improve the lateral fall-off water?

- Penumbra improvement for ranges up to 15cm

Winterhalter et al. (2018b), Phys Med Biol 63.2

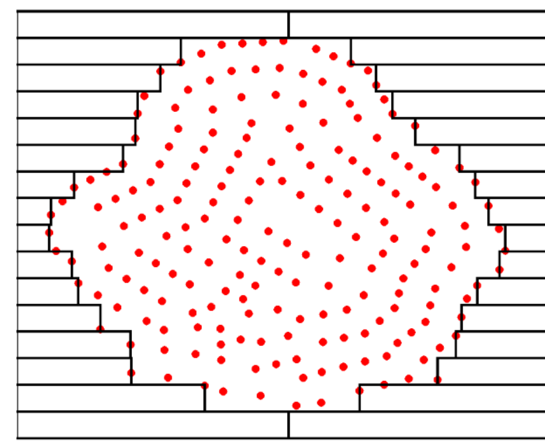
Winterhalter et al. (2018c), Phys Med Biol 63.20



6) How does collimation improve the dose in the patient?

- Reduced dose to normal tissue, acceptable target coverage

Winterhalter et al. (2018d), Phys. Med. Biol. 64 015002



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Validating, implementing and **applying** Monte Carlo Techniques for Proton Therapy

What is next?

Monte Carlo simulations for patient calculations

- Clinical commissioning
  - Measurements in geometric phantoms
  - Measurements in anthropomorphic phantoms

- Reduce/replace patient specific quality assurance measurements
  - Increase patient throughput
  - Verifications directly in the patient CT

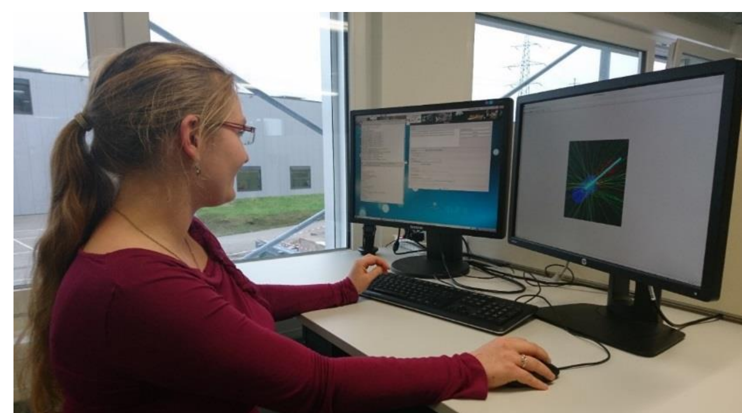
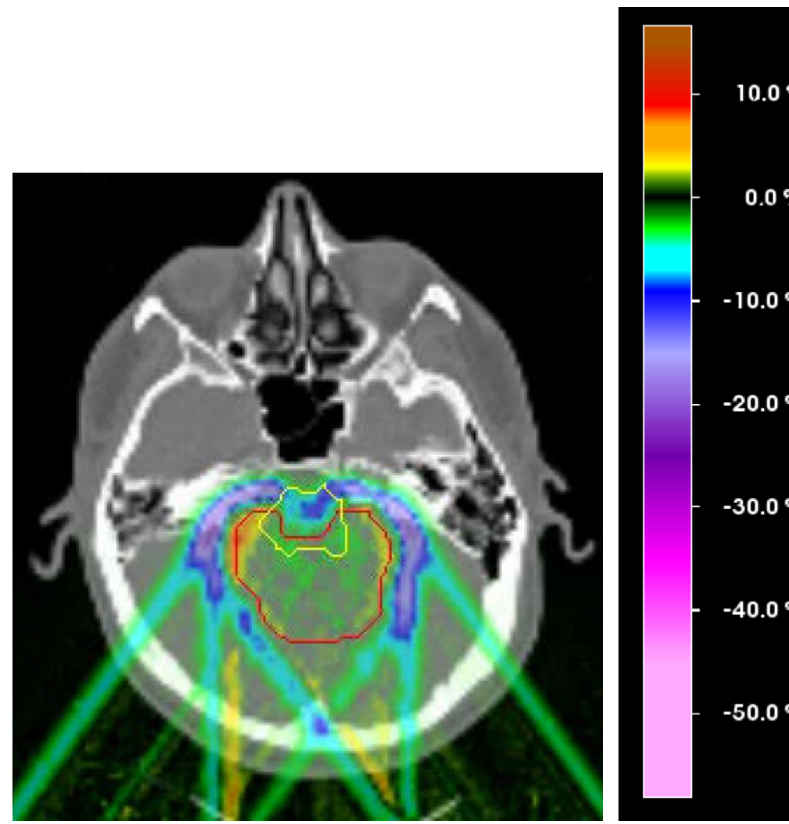


Figure courtesy: Lena Nenoff

Collimation for proton pencil beam scanning

- Experimental validation
- Improvements in the analytical & Monte Carlo model
- Collimator design
  - Choice of material
  - Light design
  - Fast adjustment of leafs



Winterhalter et al. (2018d), Phys. Med. Biol.64 015002

My thanks go to…

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- Clemens Grassberger & TOPAS User Forum
- Varian Medical Systems Particle Therapy, Germany

- Joël Mesot, Håkan Nyström, Gian Michele Graf

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Setup and validation of a Monte Carlo system…

… for dose calculation in the patient geometry.

… to replace/reduce patient specific quality assurance measurements.

First steps to improve penumbra for proton therapy.

C. Winterhalter et al 2019a, «Comparison of two Monte Carlo calculation engines for proton pencil beam scanning.», *submitted to Medical Physics.*

C. Winterhalter et al 2018a, «Validating a Monte Carlo approach to absolute dose quality assurance for proton pencil beam scanning» *Phys Med Biol 63.17 (2018): 175001.*

C. Winterhalter et al 2019b, «Evaluation of the ray-casting analytical algorithm for pencil beam scanning proton therapy.» *Phys Med Biol 64 (2019): 065021*

C. Winterhalter et al 2019c, «Log file based Monte Carlo calculations for proton pencil beam scanning therapy.» *Phys Med Biol 64 (2019): 035014*

C. Winterhalter et al 2018b, «A study of lateral fall-off (penumbra) optimisation for pencil beam scanning (PBS) proton therapy.» *Phys Med Biol 63.2 (2018): 025022.*

Varian Recognition Award (Swiss Society of Radiobiology and Medical Physics).

C. Winterhalter et al 2018c, «Comment on `Collimated proton pencil-beam scanning for superficial targets: impact of the order of range shifter and aperture'» *Phys Med Biol, 63.20 (2018): 208001*

C. Winterhalter et al 2018d, «Contour scanning, multi-leaf collimation and the combination thereof for proton pencil beam scanning.» *Phys Med Biol 64 (2018): 015002*

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