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PSI


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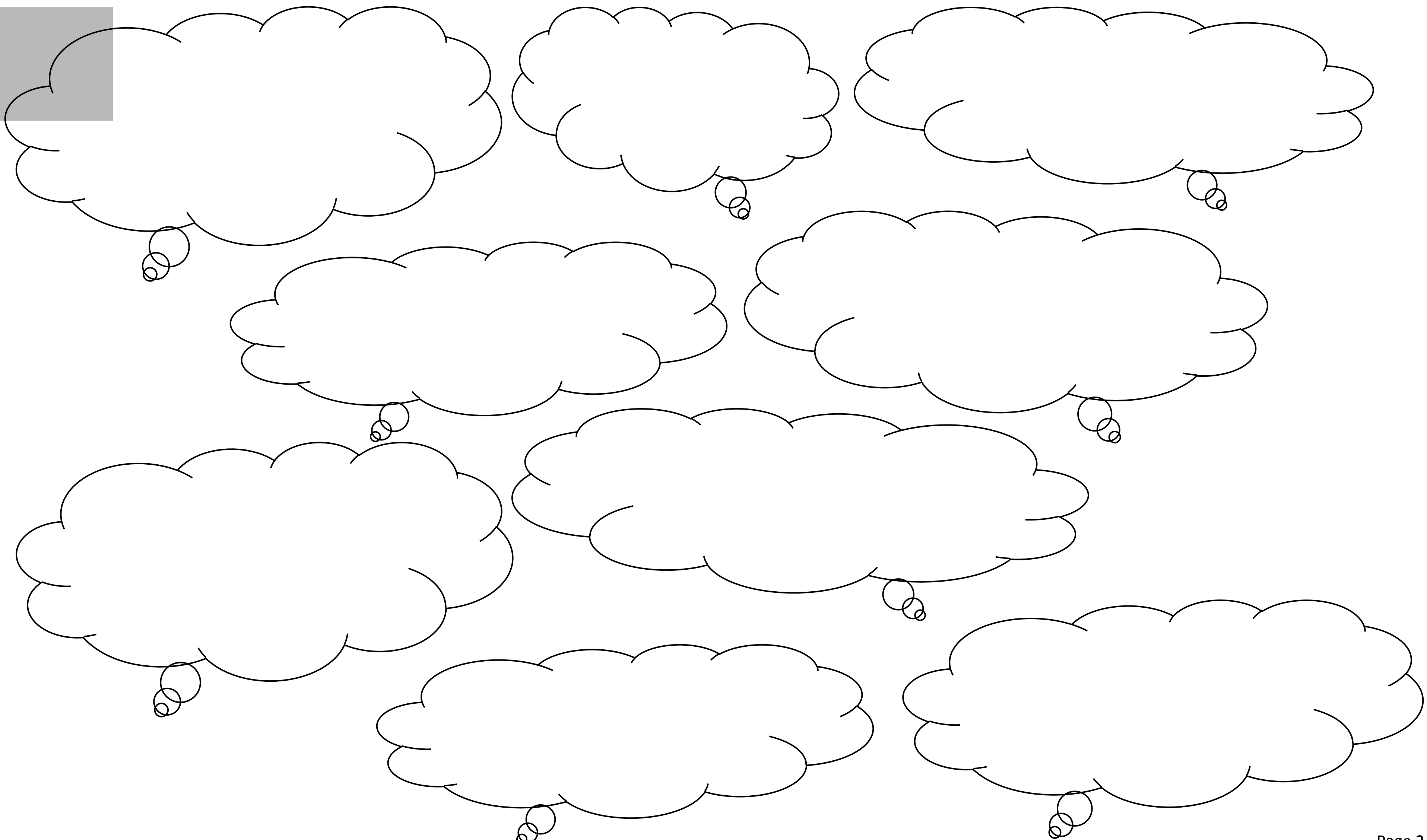
Paul Scherrer Institute, Villigen PSI, Switzerland

# State of the art in Monte Carlo studies for treatment optimization

OMA Workshop «Facility Design Optimization»
12th of March 2018

# State of the art in Monte Carlo studies for treatment optimizations



# State of the art in Monte Carlo studies for treatment optimizations

Monte Carlo for accelerator design

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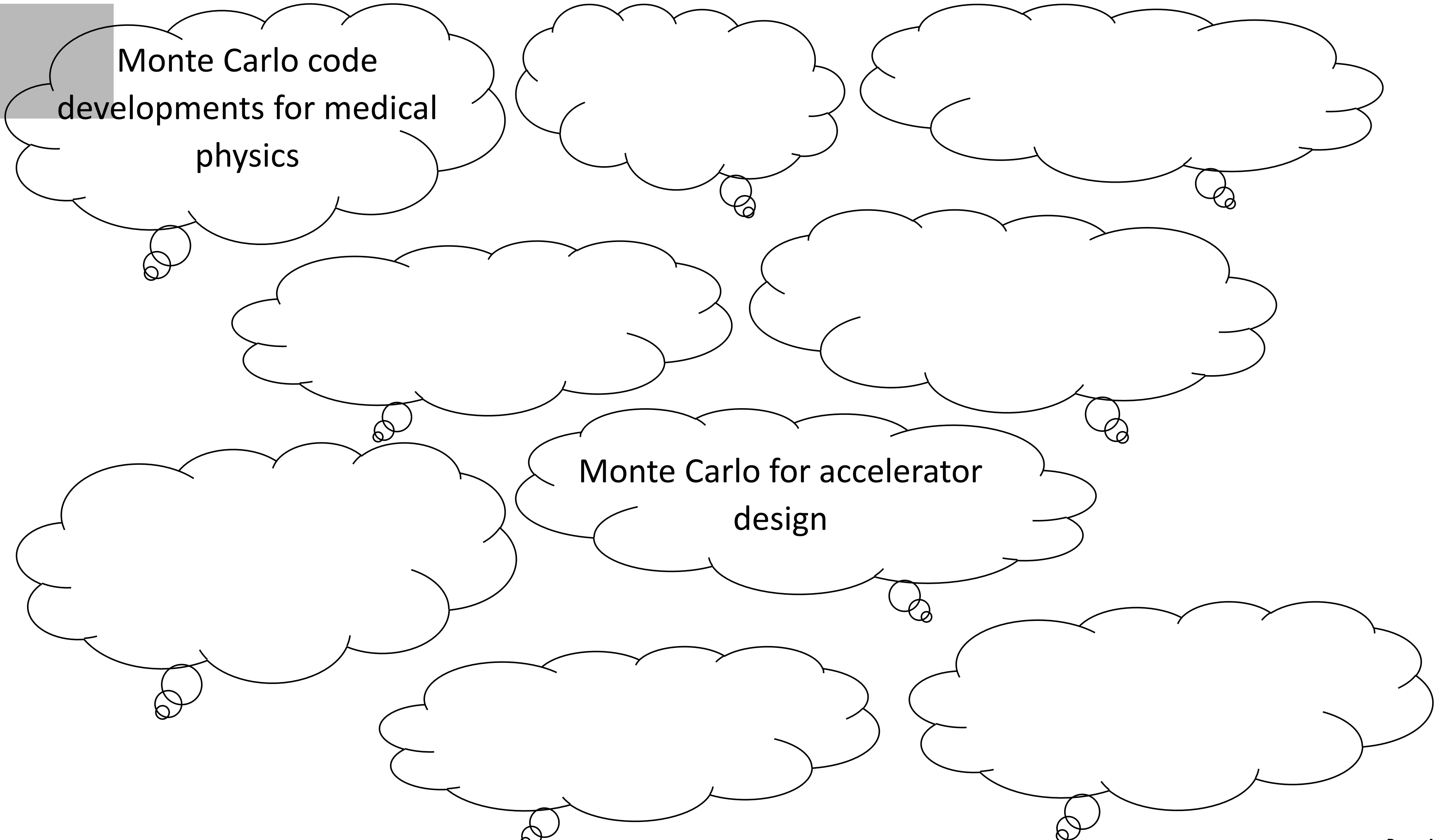

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# State of the art in Monte Carlo studies for treatment optimizations

Monte Carlo code developments for medical physics

Monte Carlo for brachytherapy

Monte Carlo for proton therapy

Monte Carlo for imaging

Monte Carlo for nuclear medicine

Monte Carlo for accelerator design

Monte Carlo for heavy ions

Monte Carlo for small beam radiotherapy

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Monte Carlo for accelerator design

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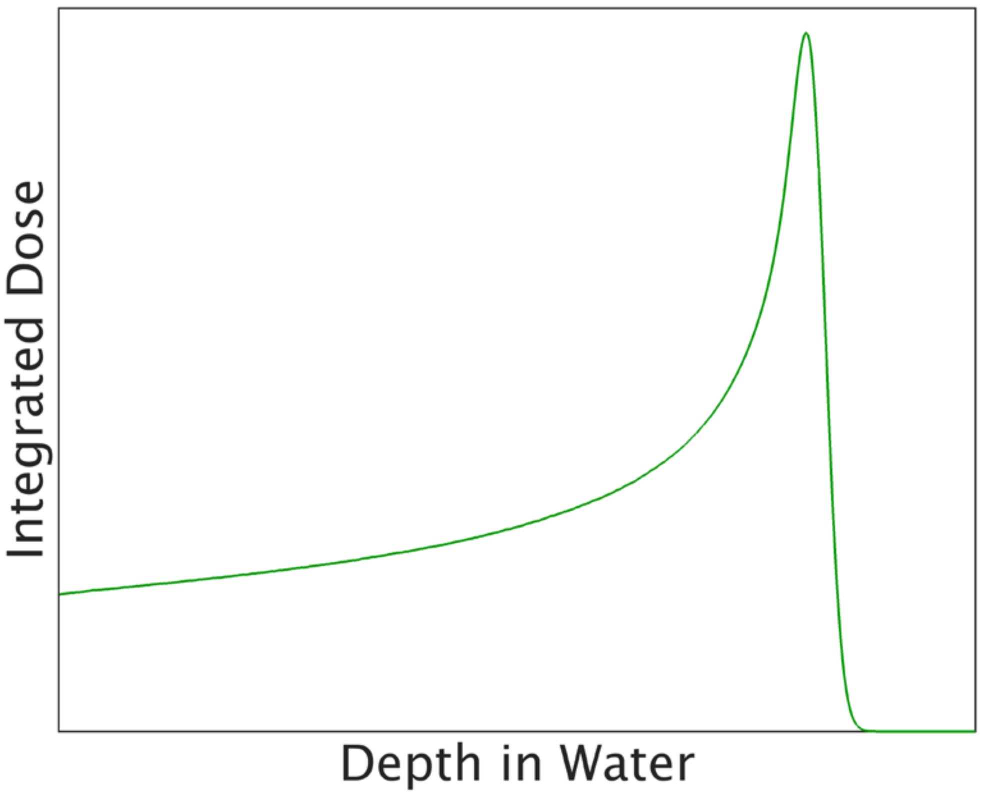
Monte Carlo for heavy ions

Monte Carlo for small beam radiotherapy

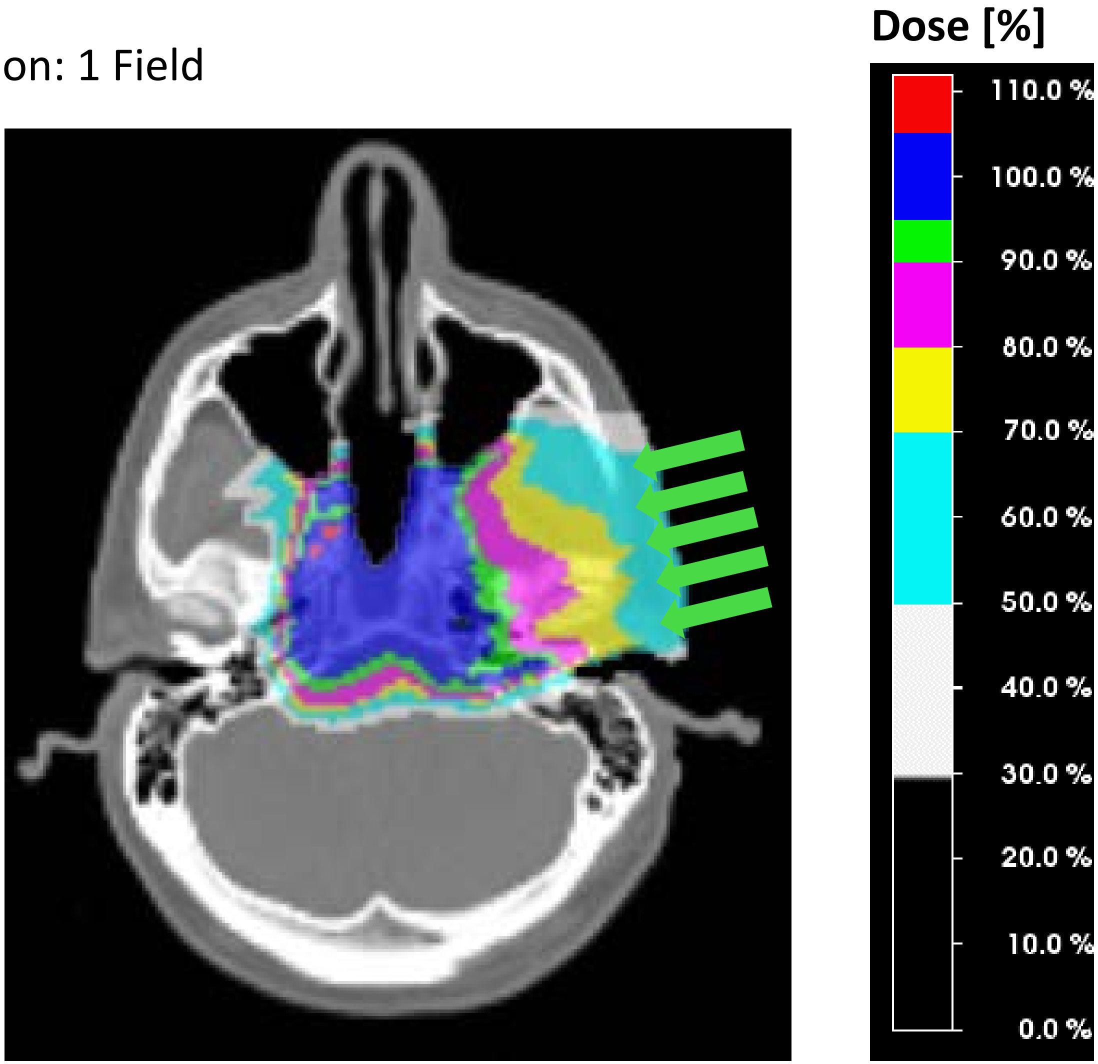
# Introduction – Proton pencil beam scanning

- Depth dose curve:
  - Protons stop
  - Most of the dose is deposited in the Bragg peak



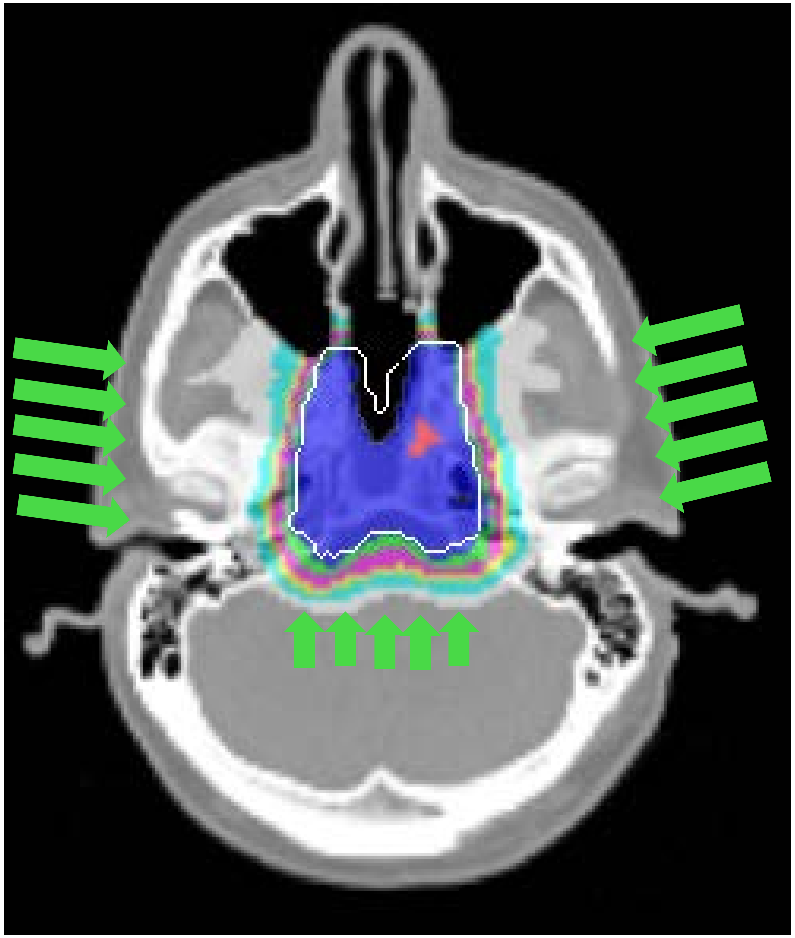
# Introduction – Proton pencil beam scanning

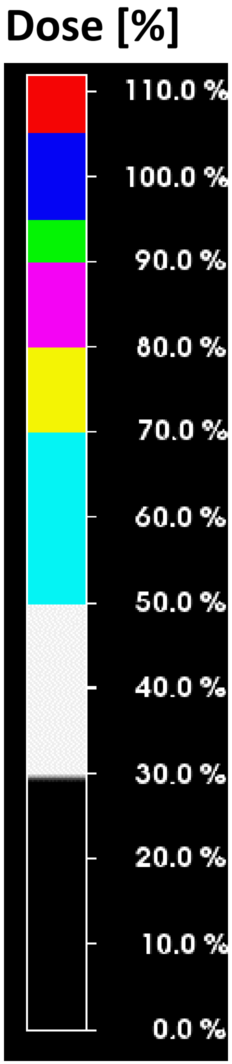
Dose distribution: 1 Field



# Introduction – Proton pencil beam scanning

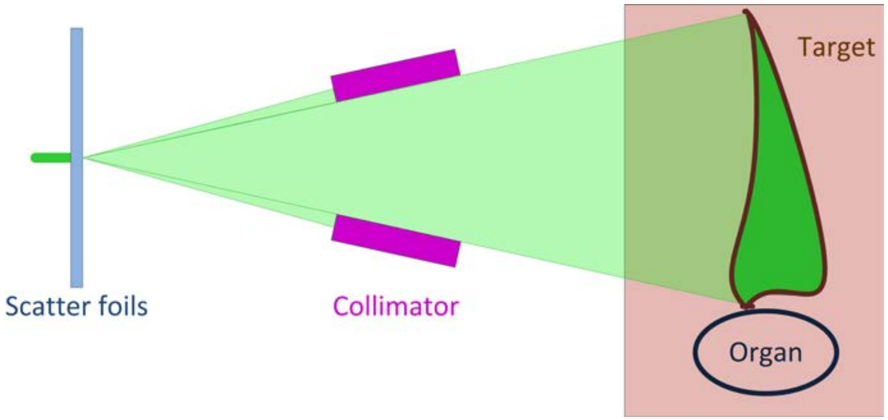
Dose distribution: 3 Field Plan



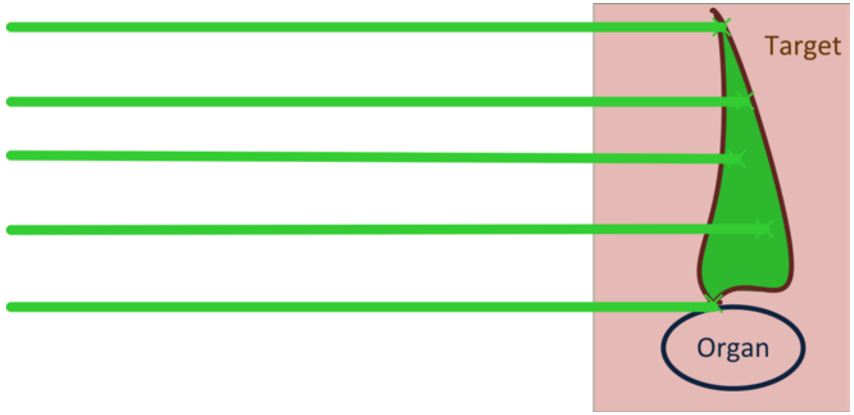


# Introduction – Proton pencil beam scanning

- 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



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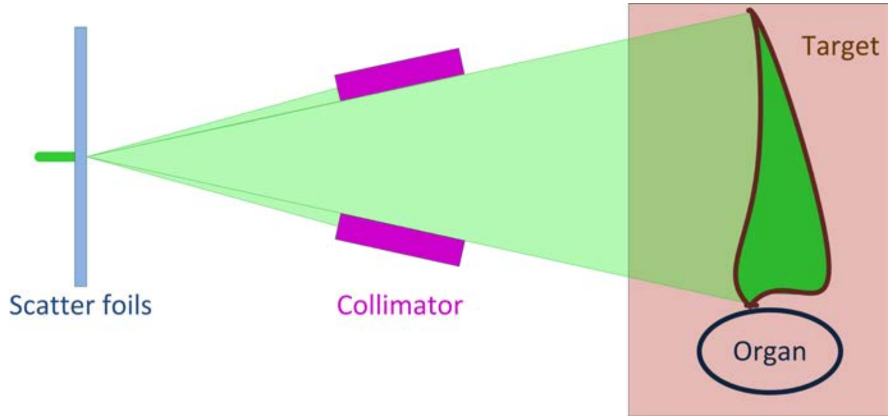


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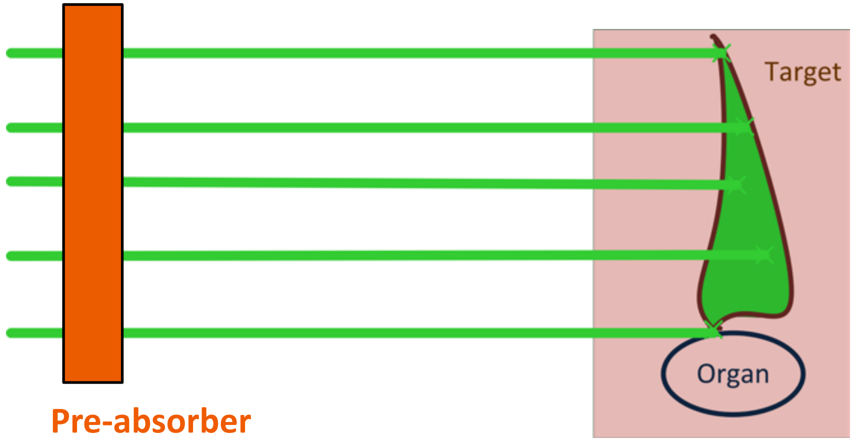

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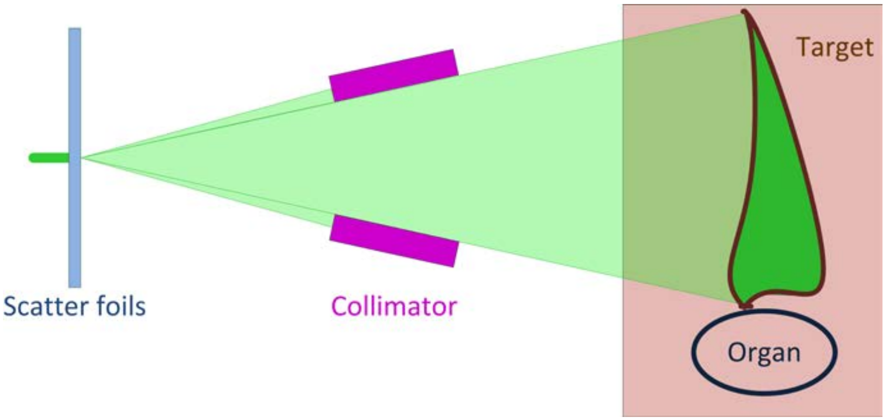


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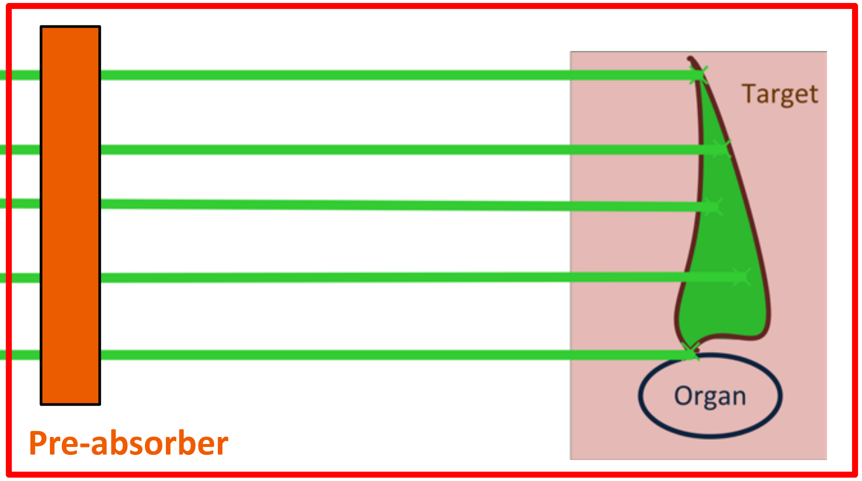


**Monte Carlo model**

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# Overview

- Setup of a Monte Carlo engine for proton pencil beam scanning

- Monte Carlo simulations for optimizing proton therapy treatement:
  - Patient specific absolute dose quality assurance in water
  - Accuracy of analytical dose calculation algorithms in the patient CT
  - Advanced beam delivery techniques.

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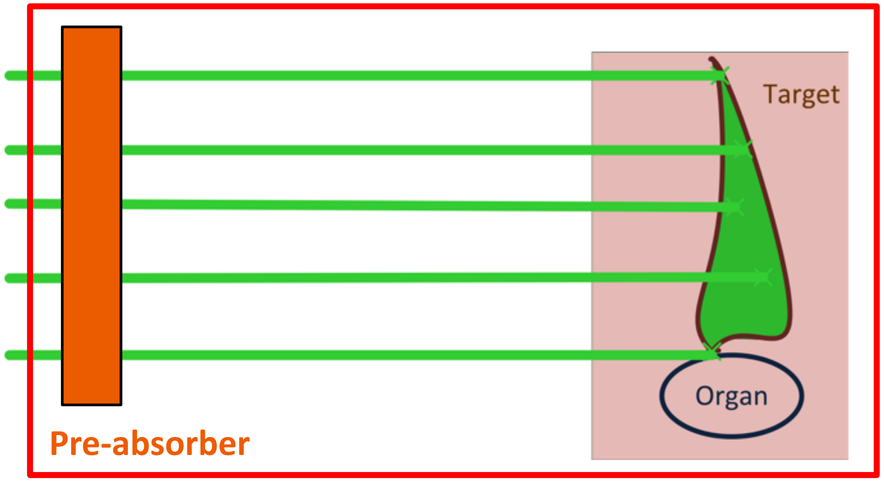
# Setup of a Monte Carlo model for proton pencil beam scanning




Monte Carlo model

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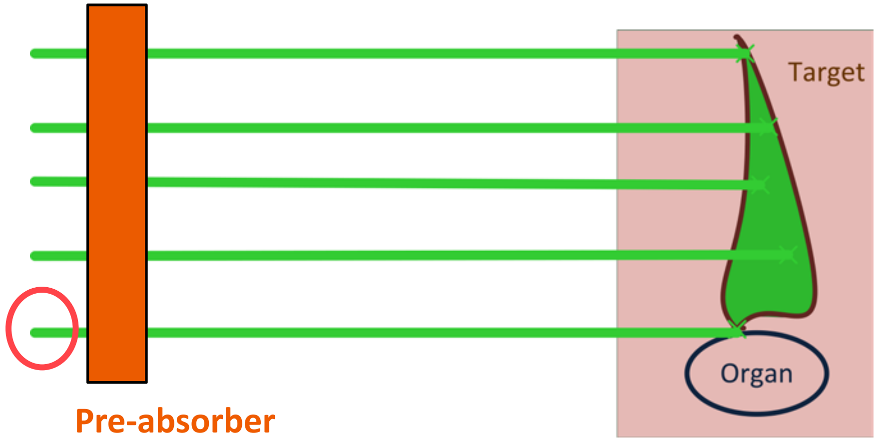
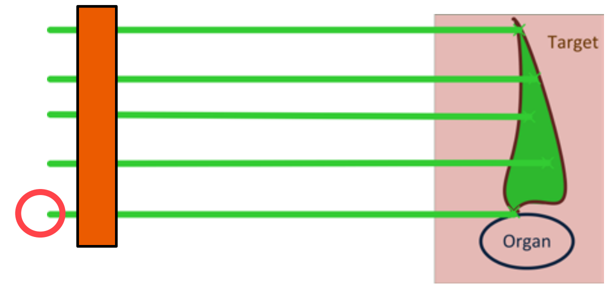
# Setup of a Monte Carlo model for proton pencil beam scanning




**Beam model at the start of the Monte Carlo simulation**

- Beam model:
  - Match lateral spot profiles in air
  - Match integral depth dose curves in water

# Setup of a Monte Carlo model for proton pencil beam scanning

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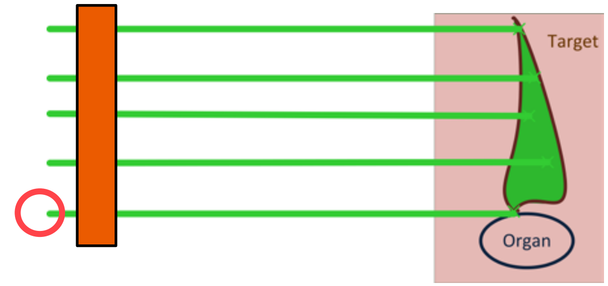


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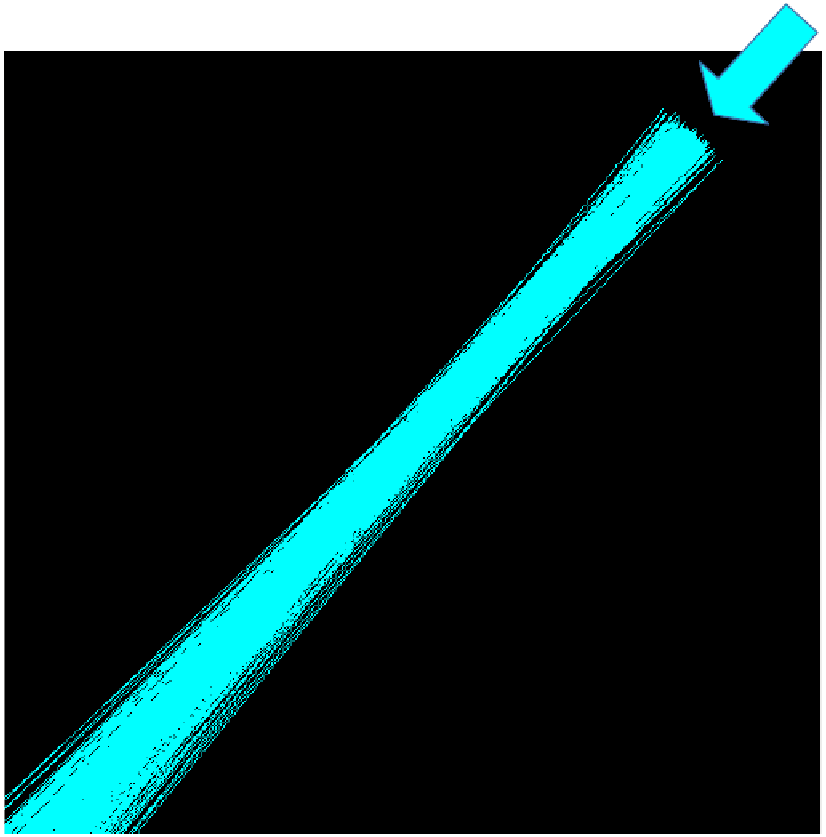
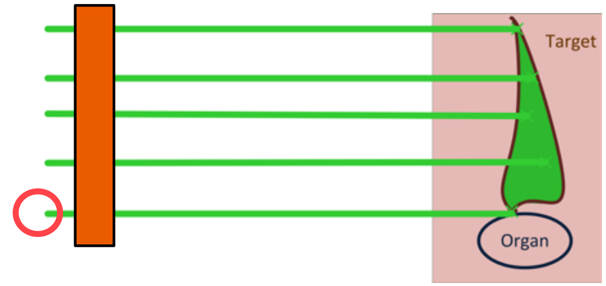
Proton beam



Tune angular and spatial distribution (3 parameters) to reproduce beam propagation in air

Setup of a Monte Carlo model for proton pencil beam scanning

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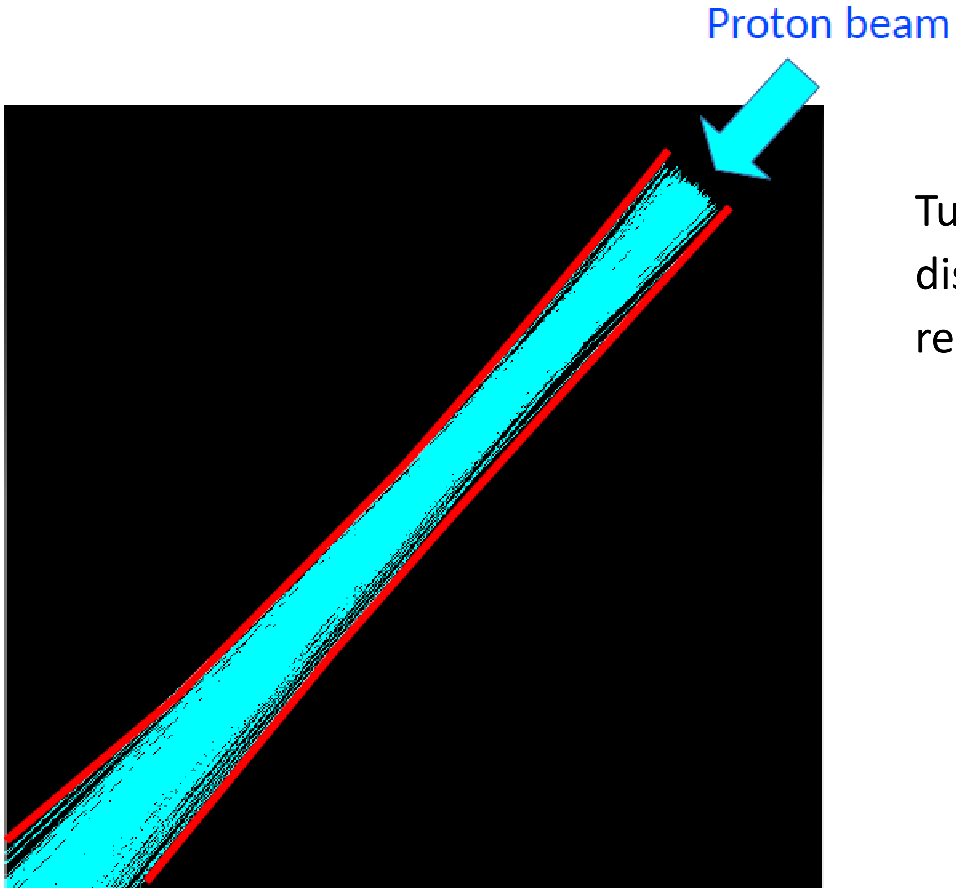
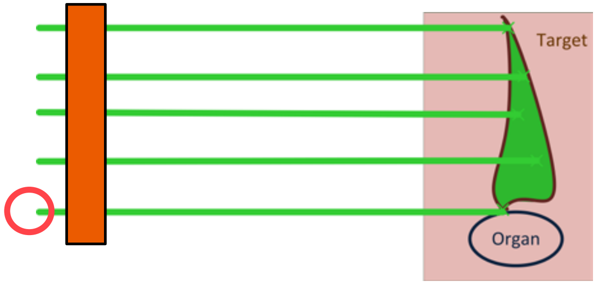
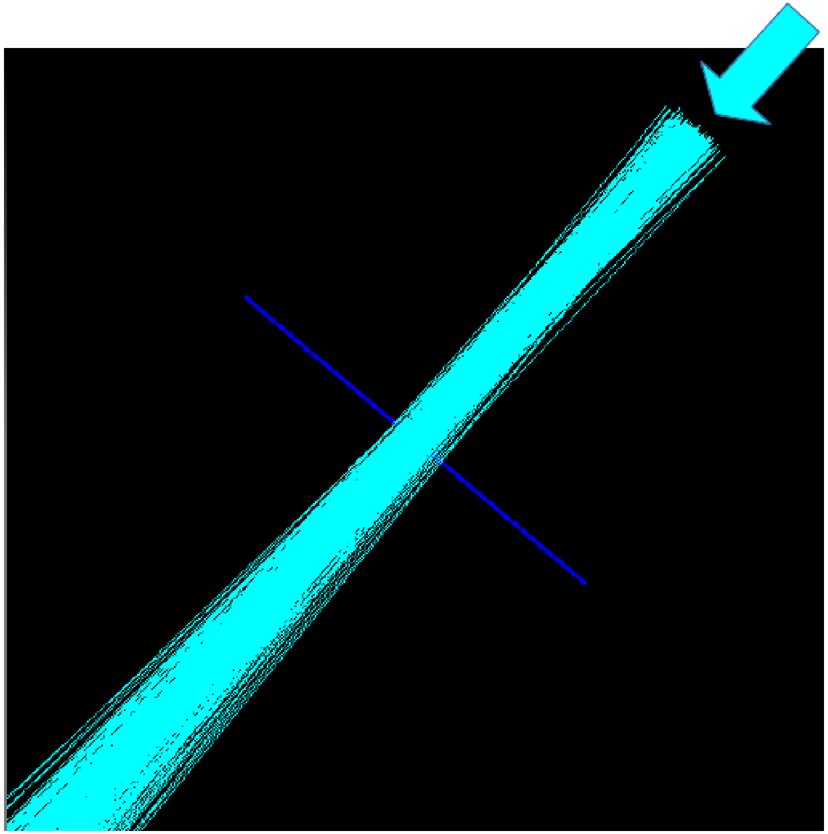


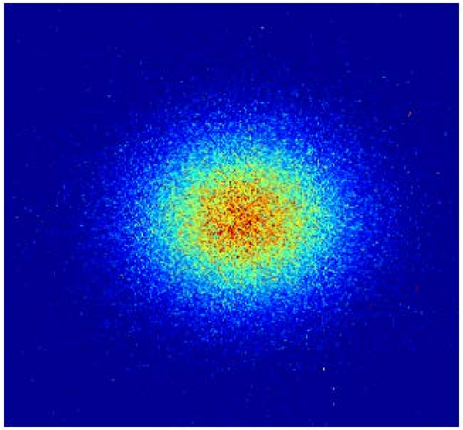

Tune angular and spatial distribution (3 parameters) to reproduce beam propagation in air

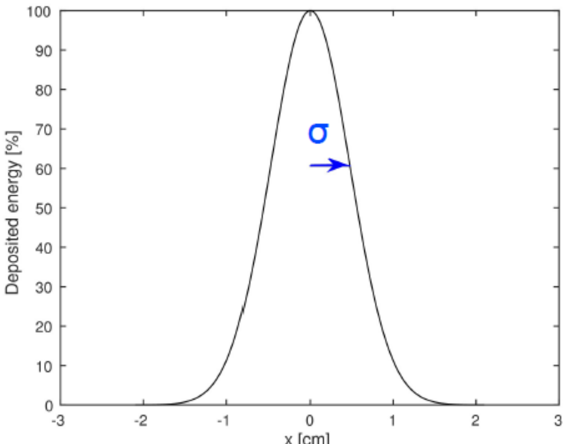
# Setup of a Monte Carlo model for proton pencil beam scanning

- Beam model:
  – Match lateral spot profiles in air:
    2D Gauss profile







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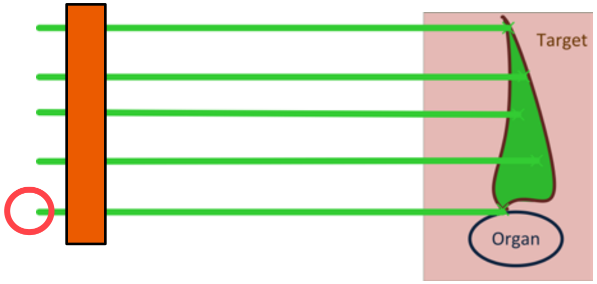


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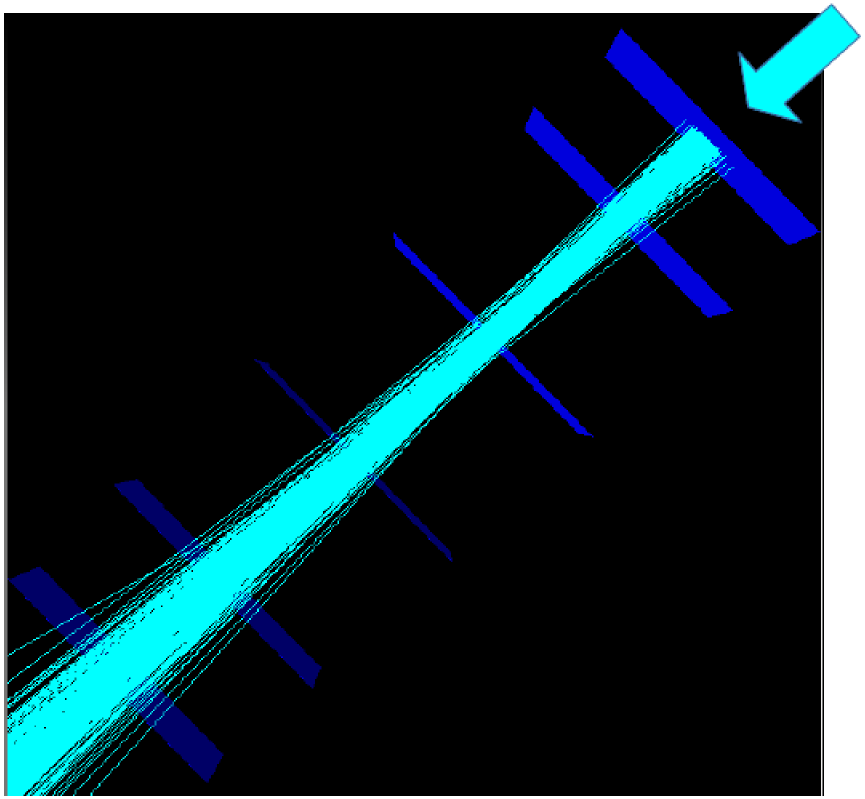

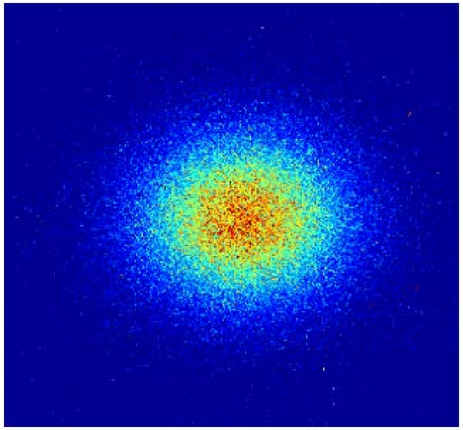

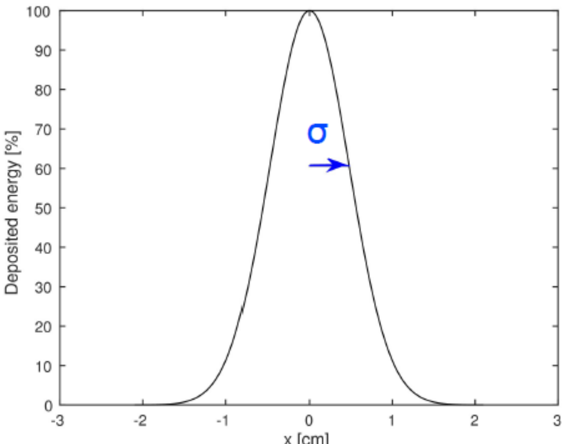

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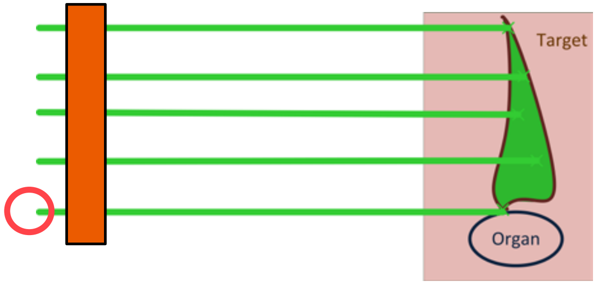


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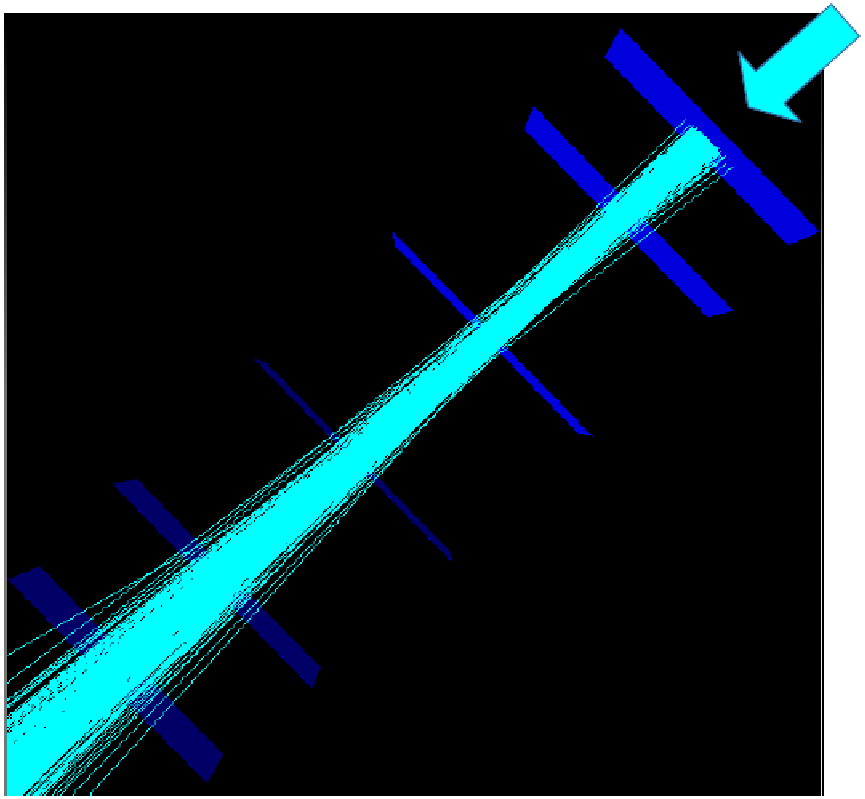

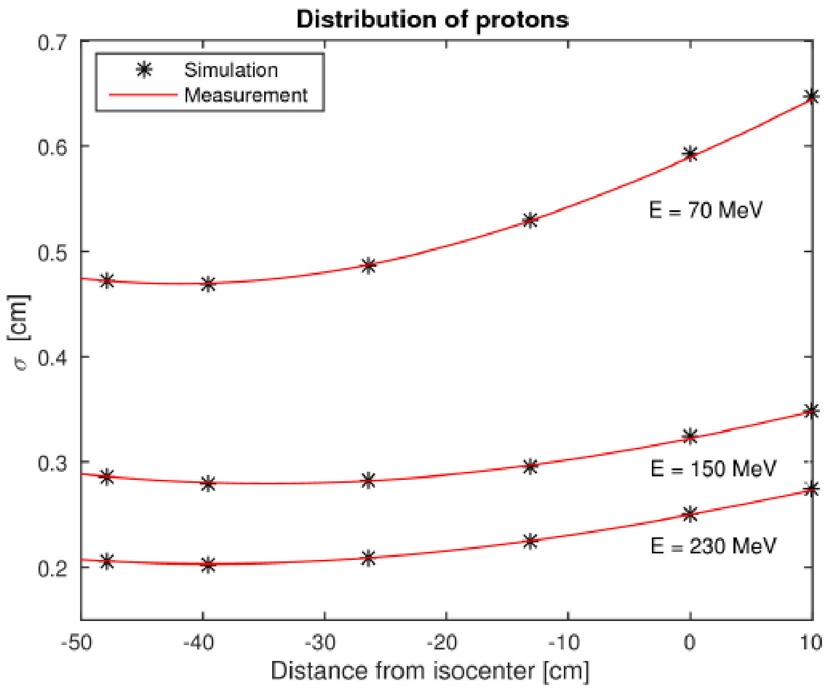

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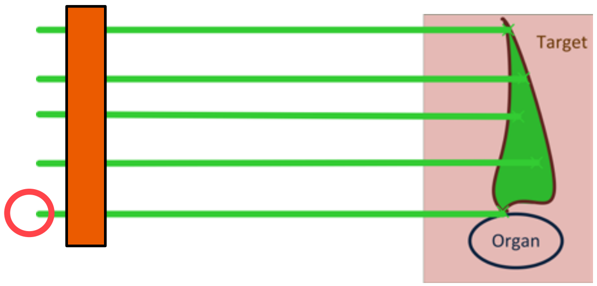
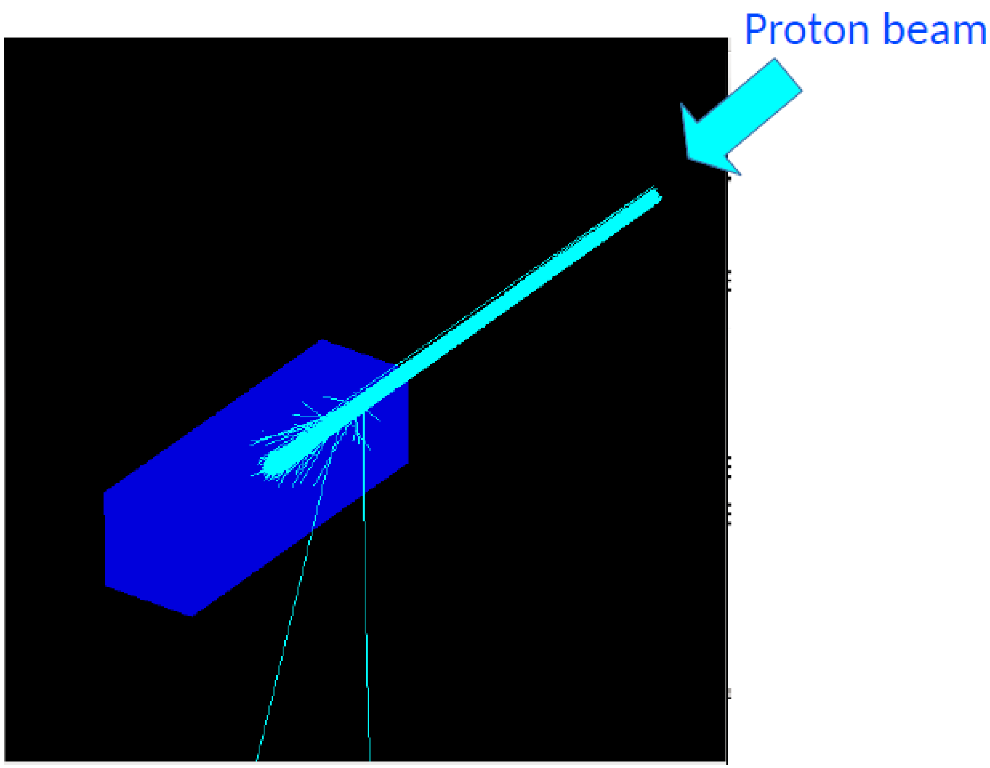



- Beam model:
  - Match integral depth dose curves in water



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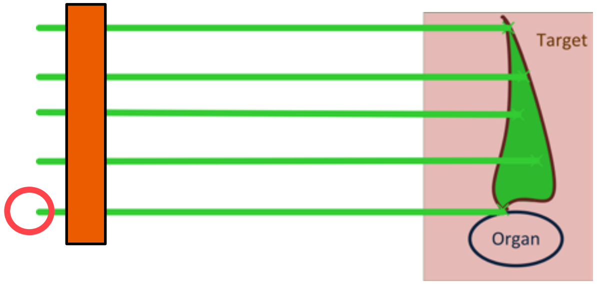


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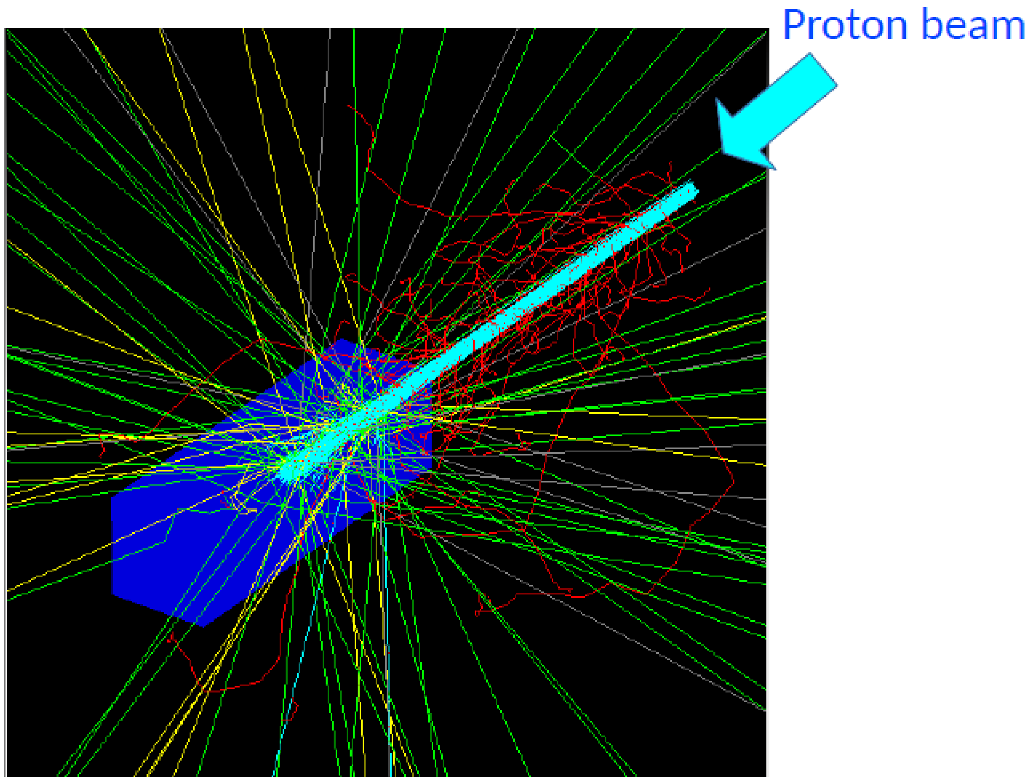

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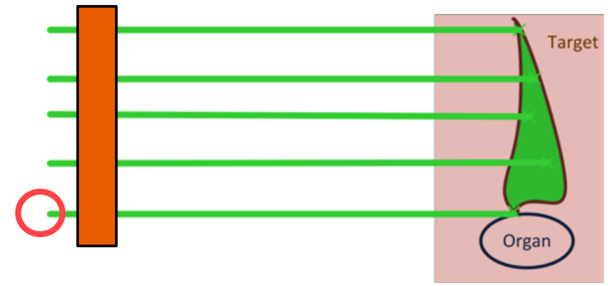


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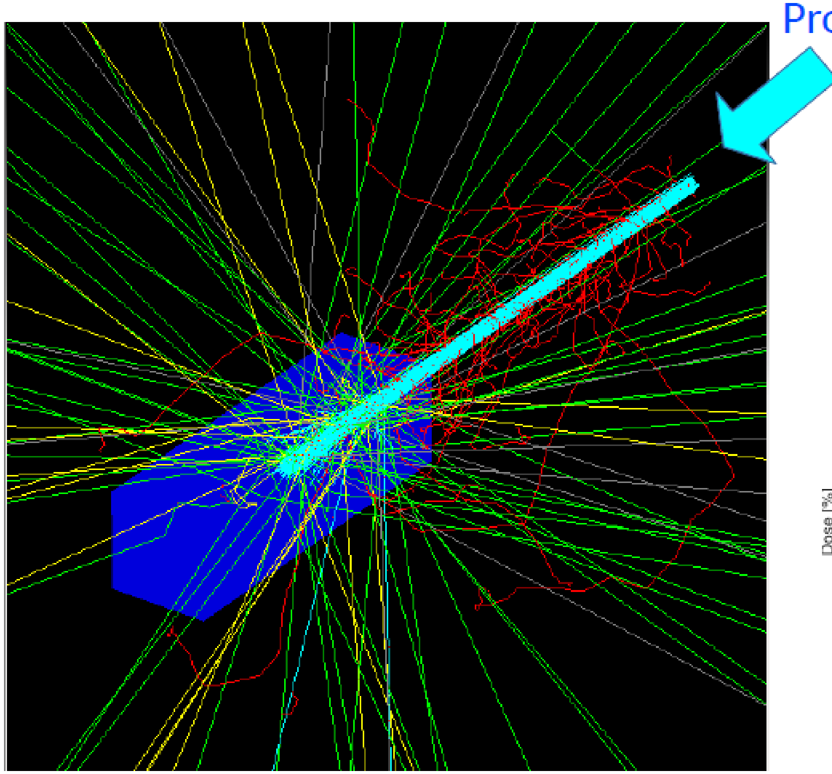
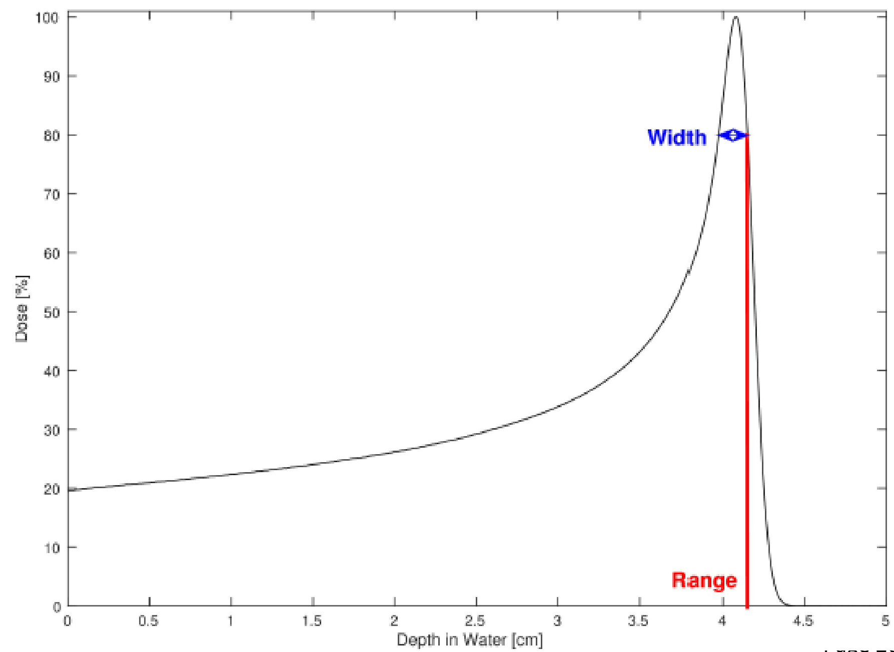
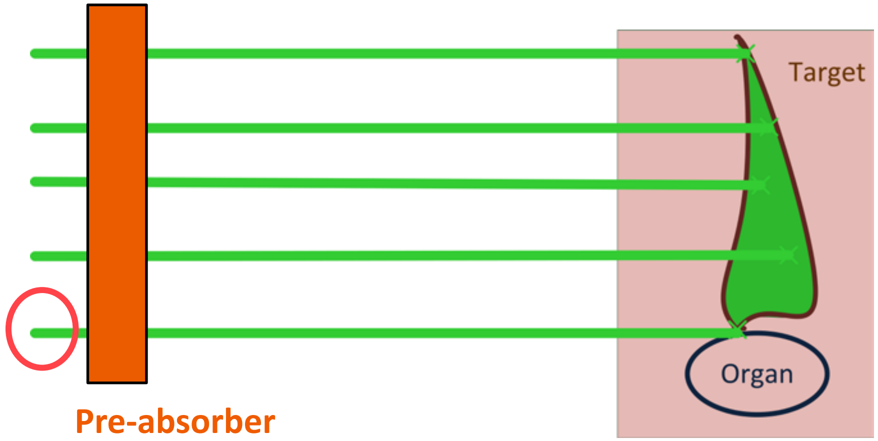



- Adjust **energy** for **range**
- Adjust **energy spread** for **width**



# Setup of a Monte Carlo model for proton pencil beam scanning

Beam model at the start of the Monte Carlo simulation

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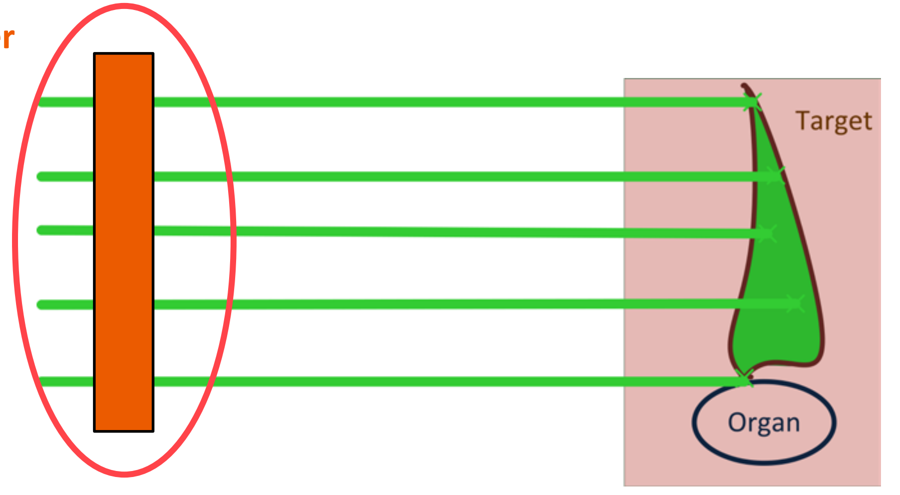
# Setup of a Monte Carlo model for proton pencil beam scanning

Pre-absorber

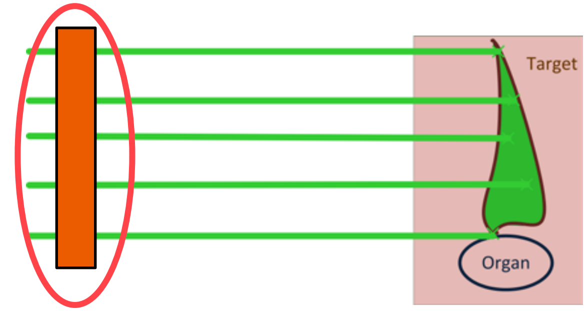
**Model physical components**

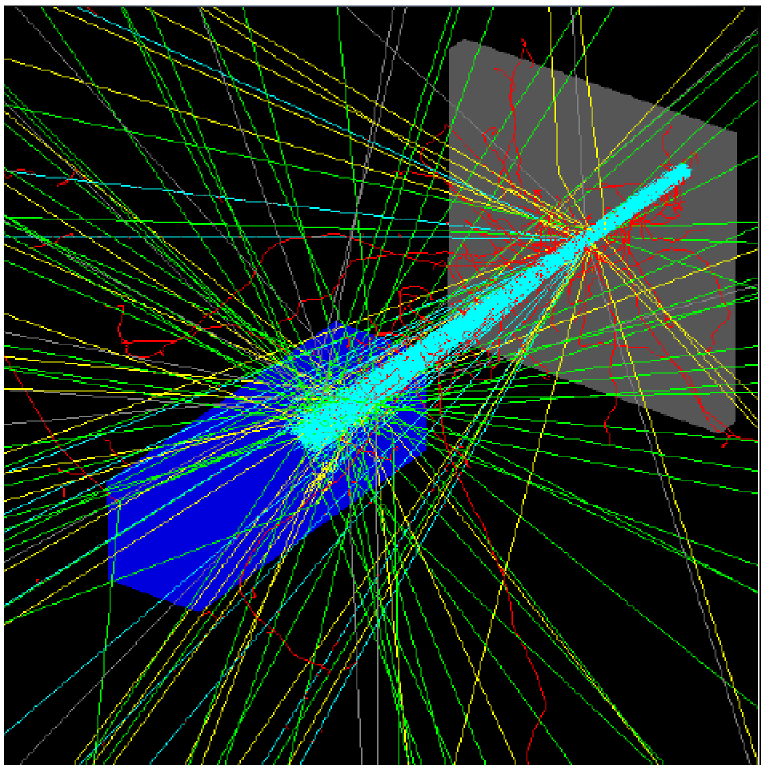



- Beam model:
  - Match lateral spot profiles in air
  - Match integral depth dose curves in water
- Include physical components:
  - Pre-absorber

# Setup of a Monte Carlo model for proton pencil beam scanning

- Include physical components: Pre-absorber



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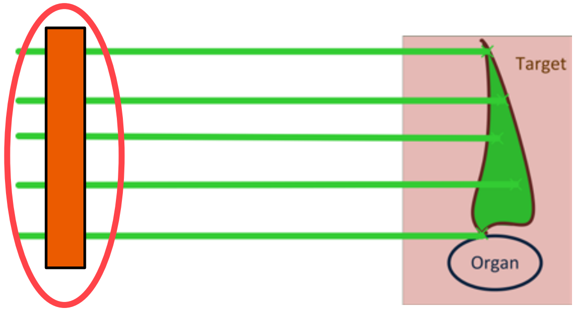


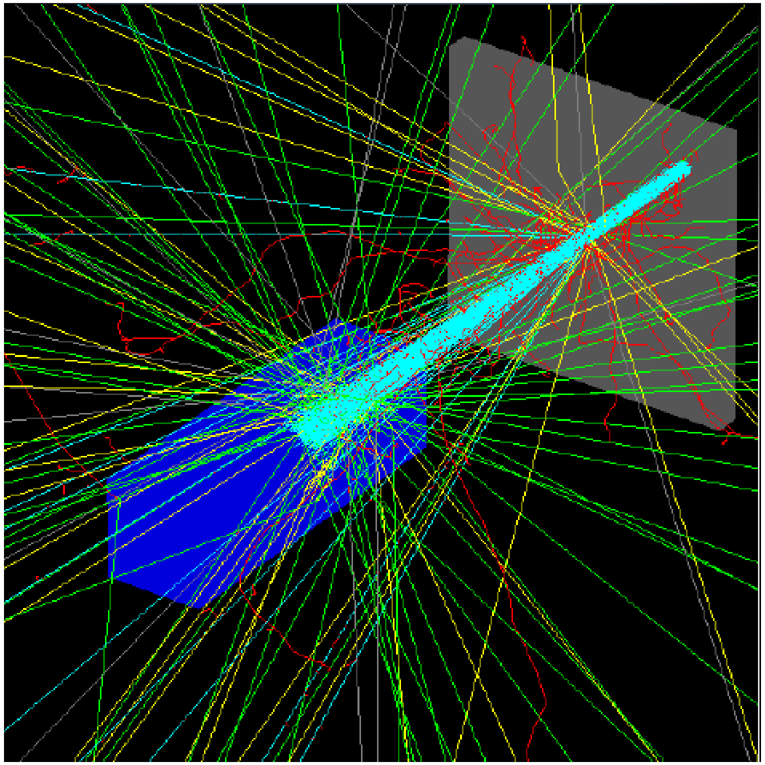

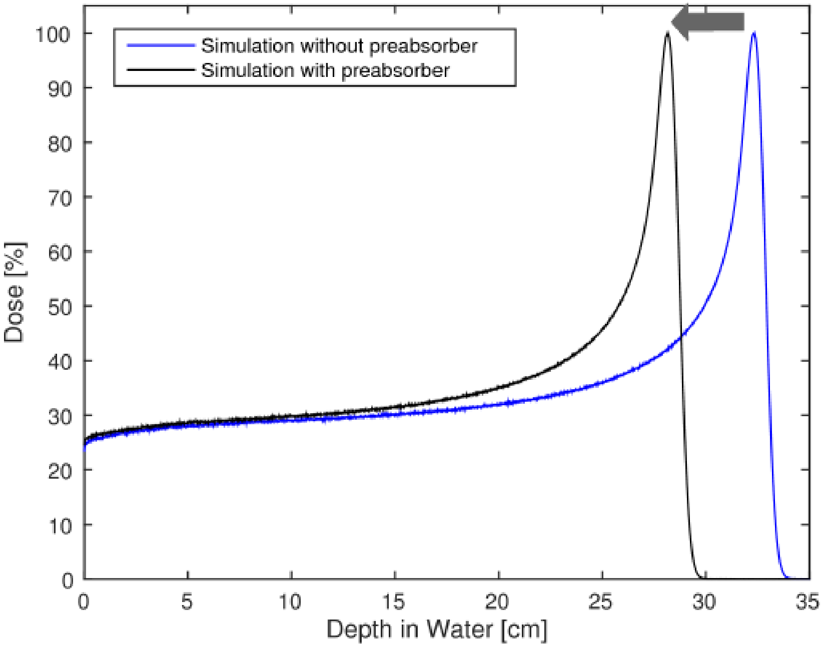

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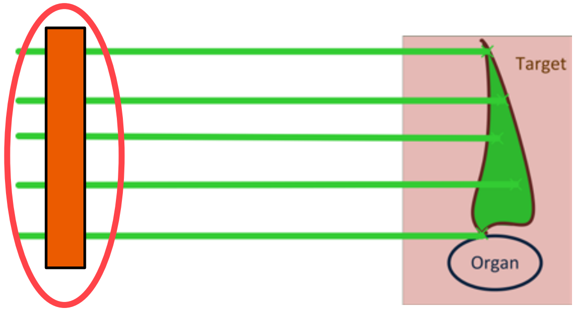


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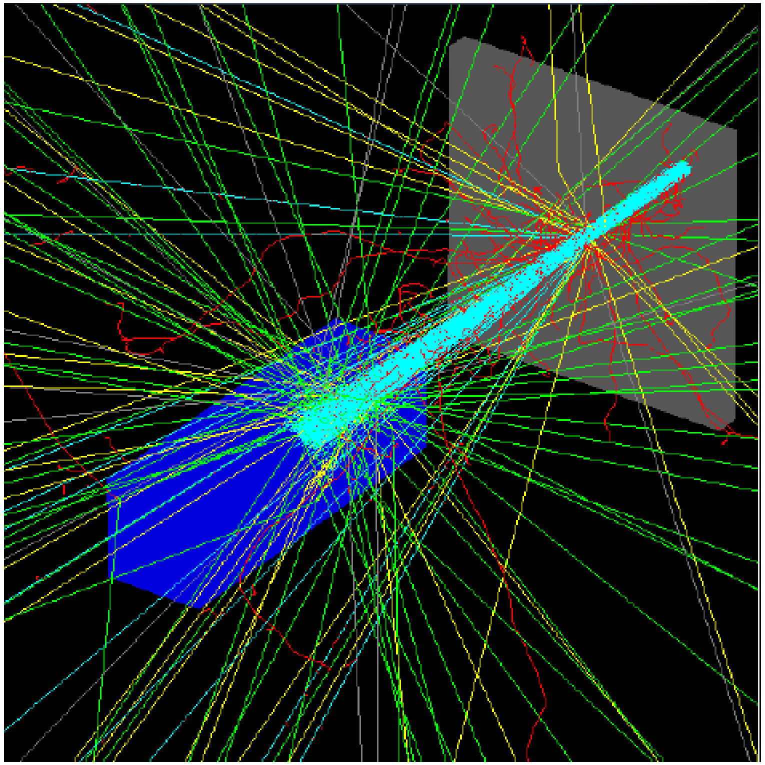
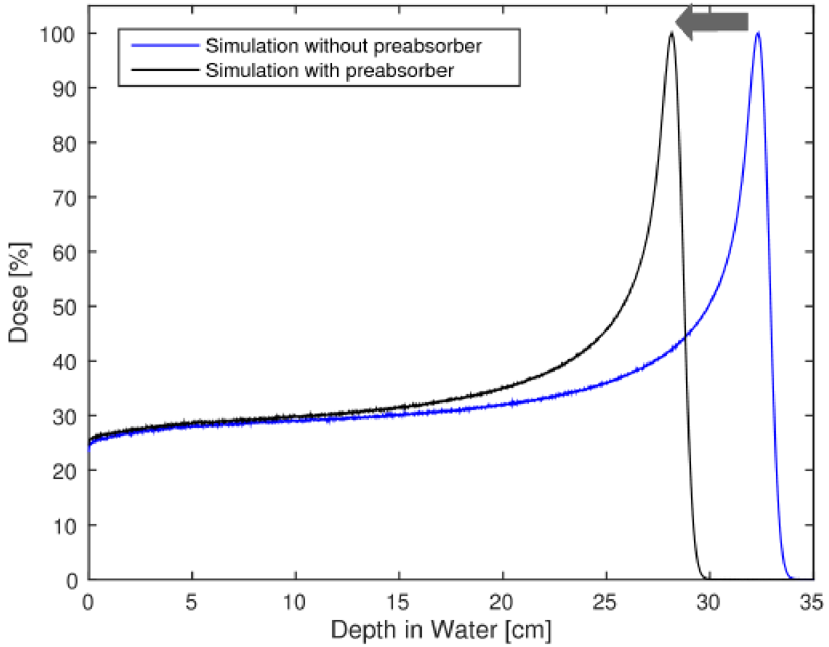
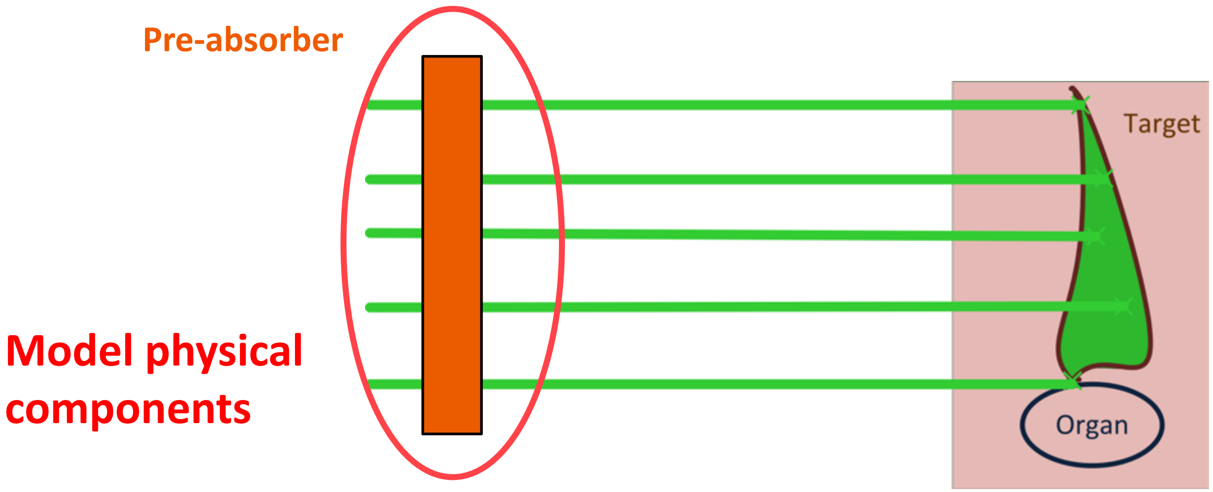





- Tune **density** to match shift of depth dose curves

# Setup of a Monte Carlo model for proton pencil beam scanning




- Beam model:
  - Match lateral spot profiles in air
  - Match integral depth dose curves in water
- Include physical components:
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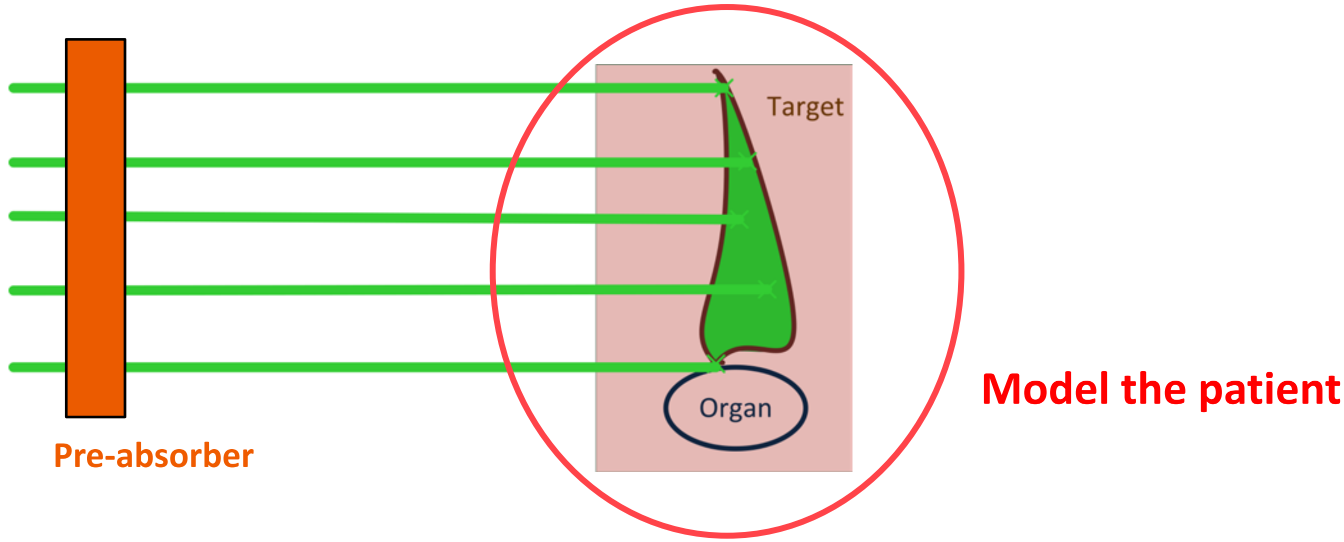


- Beam model:
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- Include physical components:
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- Patient description:

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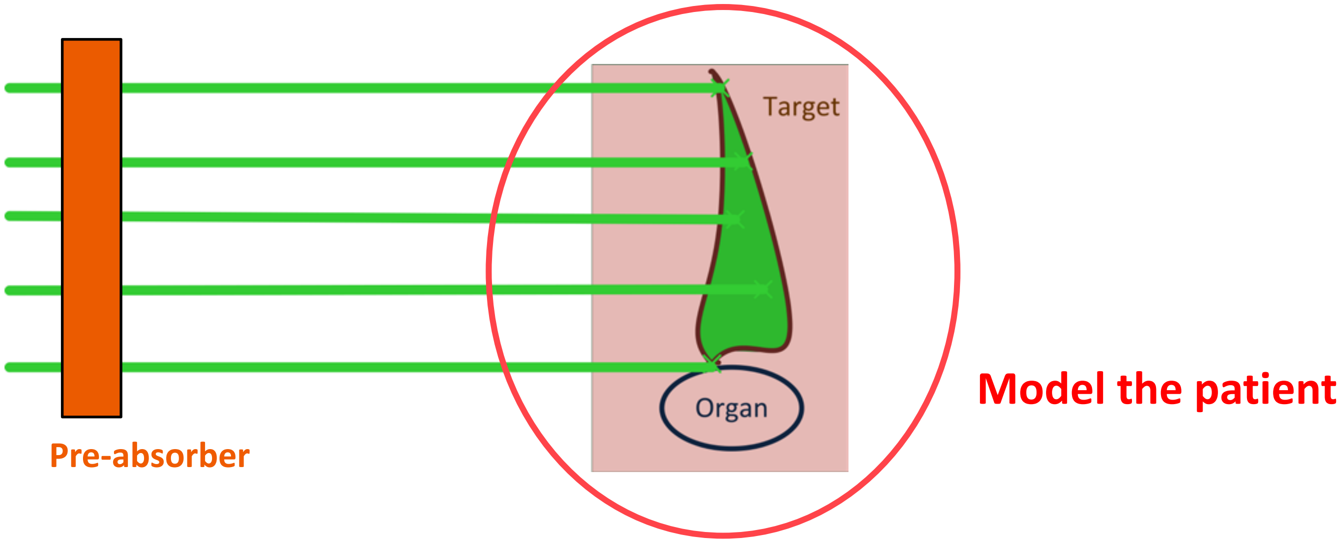
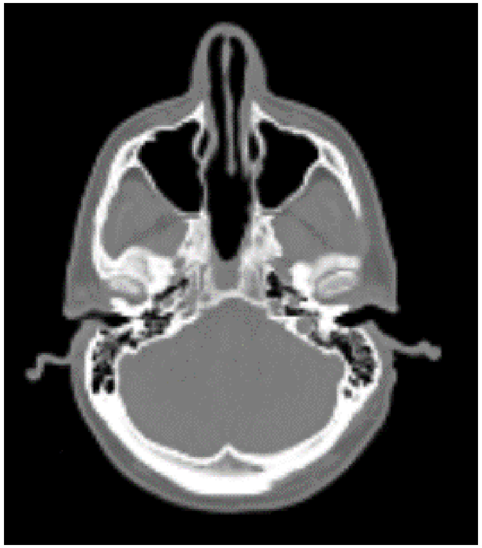



- Beam model:
  - Match lateral spot profiles in air
  - Match integral depth dose curves in water
- Include physical components:
  - Pre-absorber
- Patient description:
  - Conversion CT image to materials



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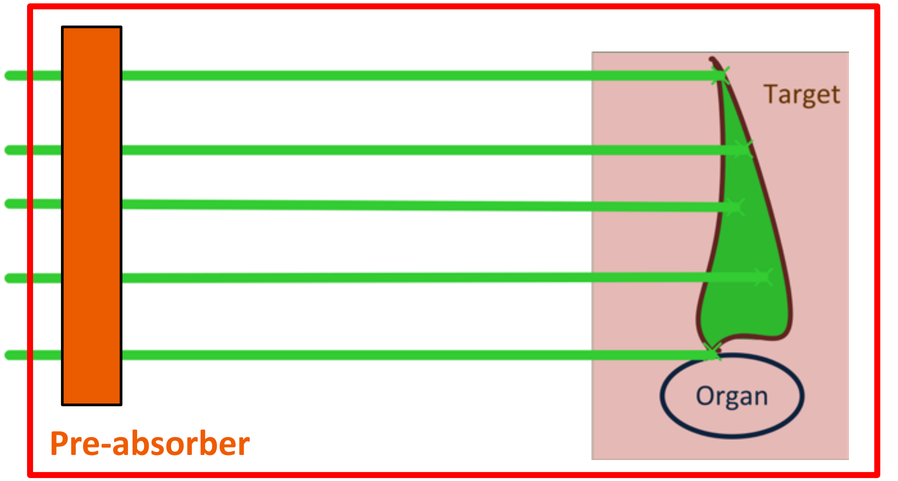


Monte Carlo model

- Beam model:
  - Match lateral spot profiles in air
  - Match integral depth dose curves in water
- Include physical components:
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- Patient description:
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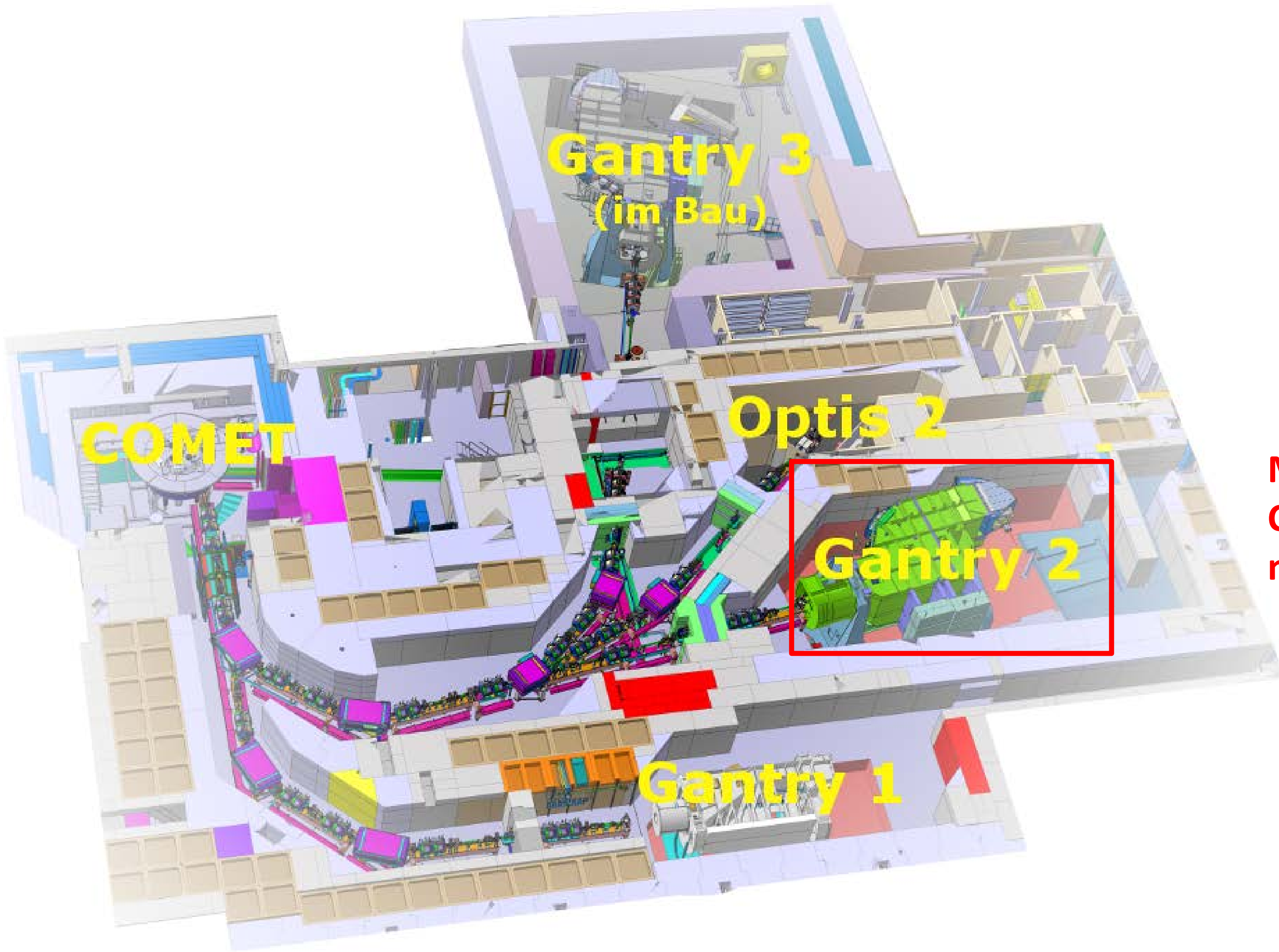
# Setup of a Monte Carlo model for proton pencil beam scanning




**Monte Carlo model**

https://www.psi.ch/protontherapy/behandlungsraeume

# Overview

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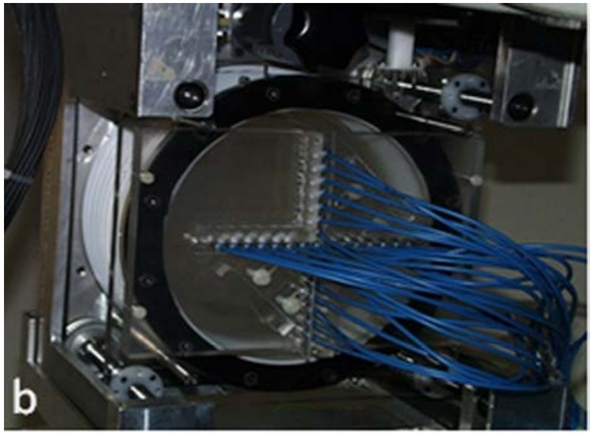
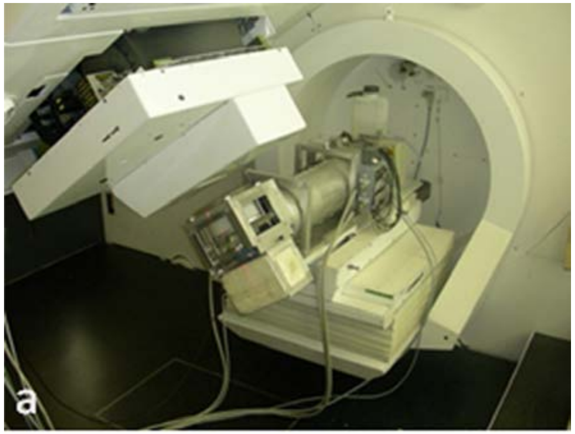
- Monte Carlo simulations for optimizing proton therapy treatement:
  - **Patient specific absolute dose quality assurance in water**
  - Accuracy of analytical dose calculation algorithms in the patient CT
  - Advanced beam delivery techniques.

# Monte Carlo for patient specific absolute dose quality assurance

**Treatment plan verification**

Measure absolute dose in a water phantom for each patient field



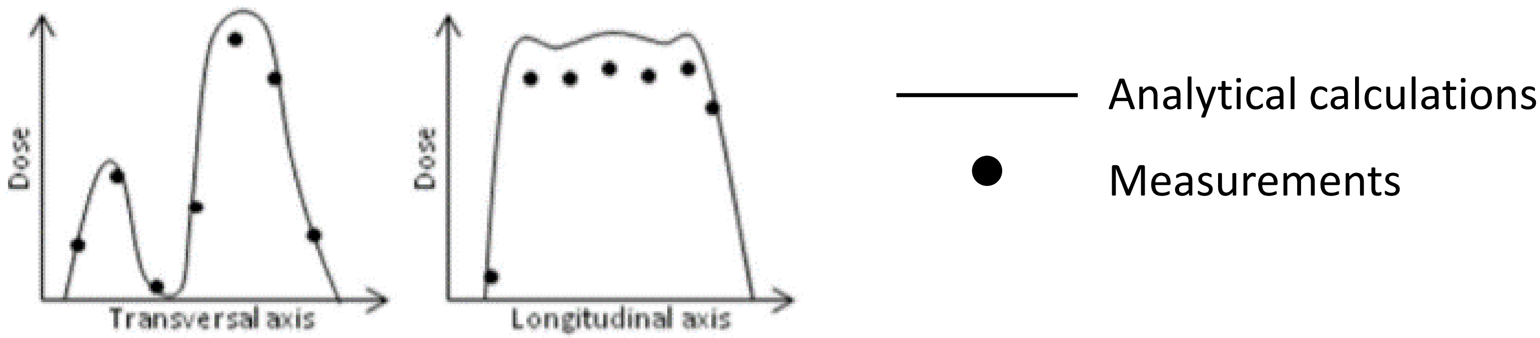




Trnkova et al 2016. Med Phys, 43, 5998.

# Monte Carlo for patient specific absolute dose quality assurance

**Treatment plan verification**

Compare analytical calculations to measurements in water:

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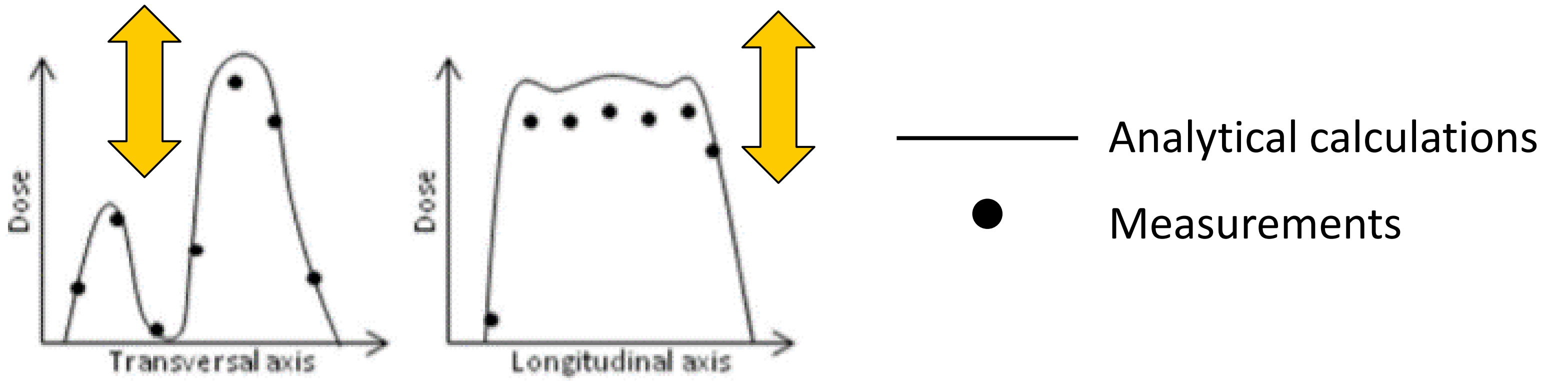


**Absolute dose offset**

Trnkova et al 2016. Med Phys, 43, 5998.

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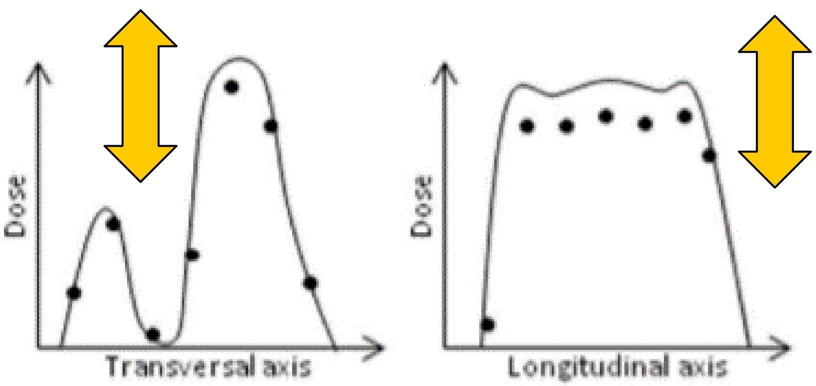
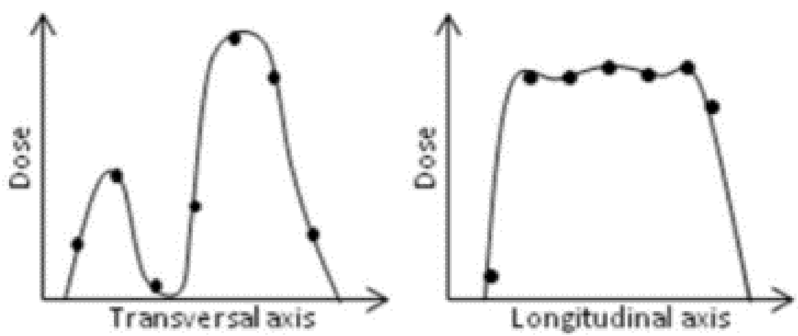



—— Analytical calculations

● Measurements

**Absolute dose offset**




**Scale with a fixed factor**

**(boosting)**

Trnkova et al 2016. Med Phys, 43, 5998.

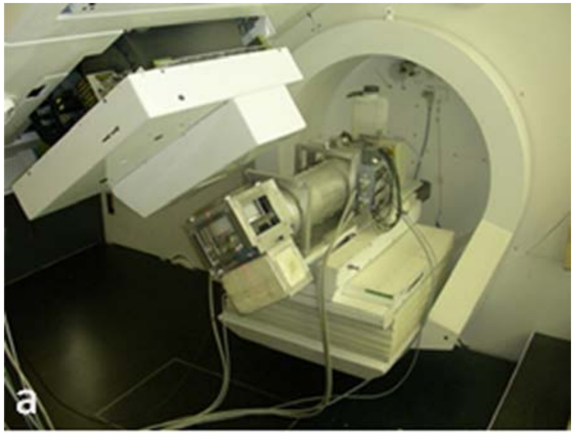
# Monte Carlo for patient specific absolute dose quality assurance

**Treatment plan verification**

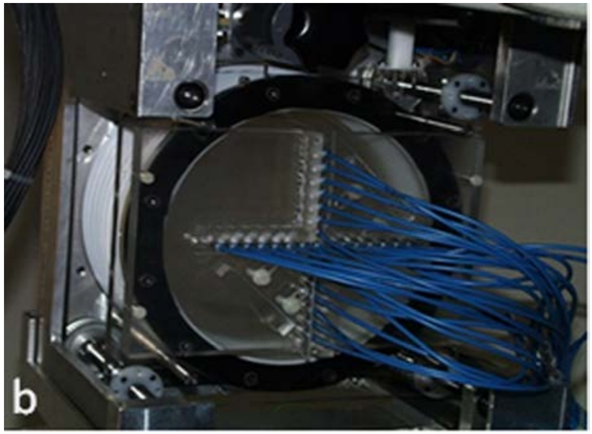
Physical measurements in a water phantom take 1-3 hours per patient.

**Monte Carlo simulations:**

– Reduce workload: Replace measurements with simulations in water.



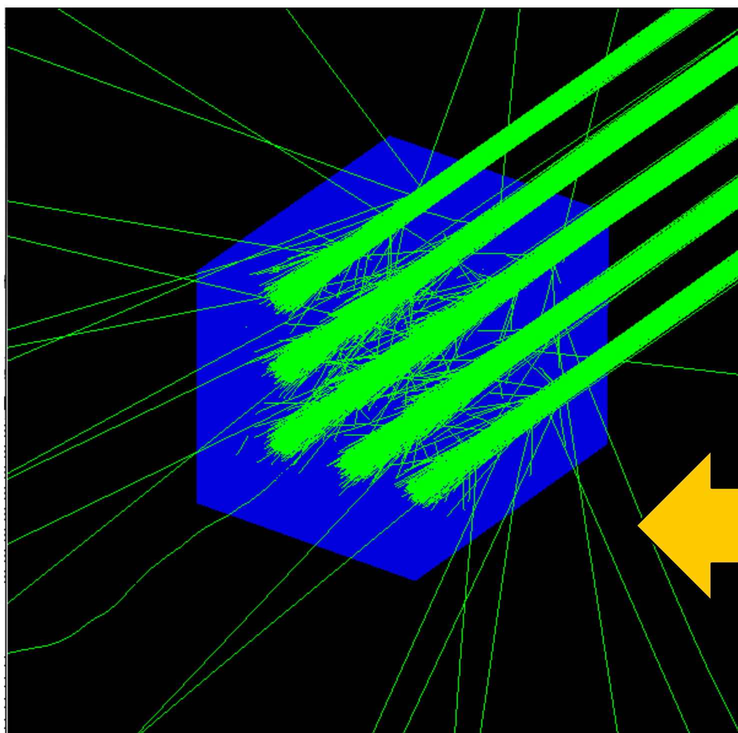

Trnkova et al 2016. Med Phys, 43, 5998.

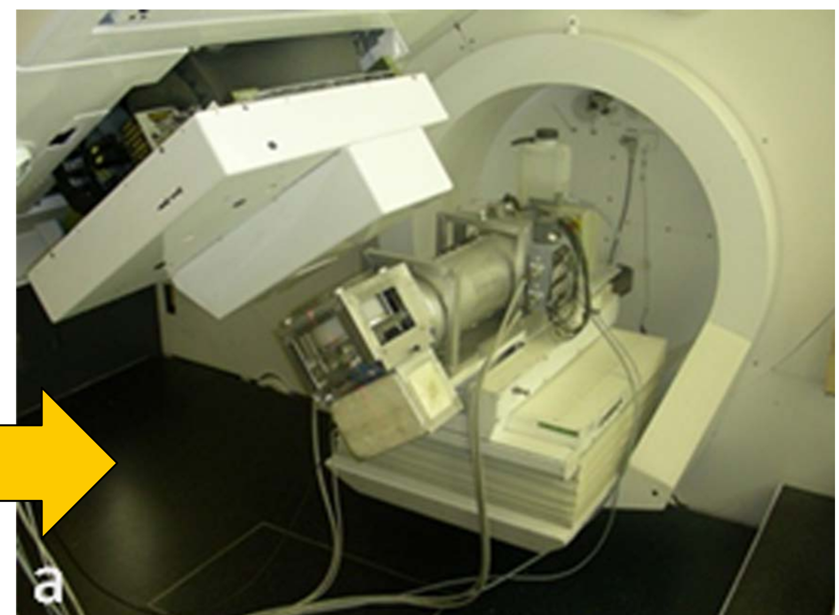


# Monte Carlo for patient specific absolute dose quality assurance

**Monte Carlo simulations:**

– Reduce workload: Replace measurements with simulations in water.





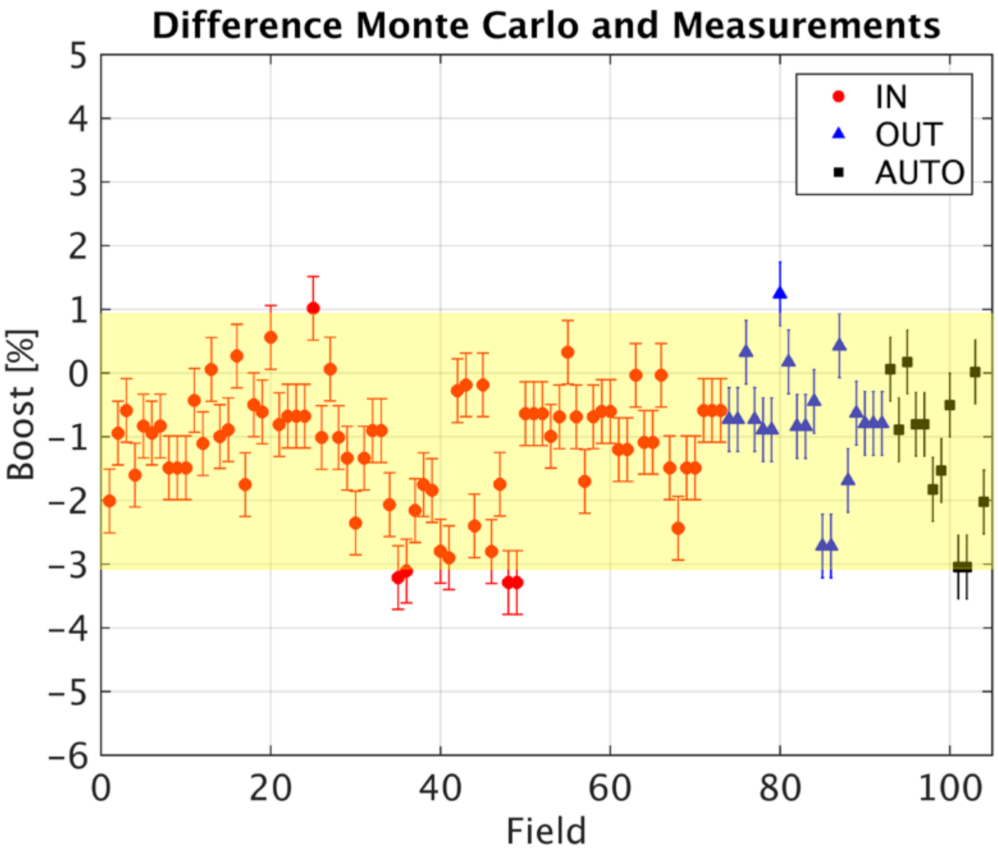

Trnkova et al 2016. Med Phys, 43, 5998.

# Monte Carlo for patient specific absolute dose quality assurance

**Monte Carlo simulations:**

– Reduce workload: Replace measurements with simulations in water.

Good agreement of Monte Carlo calculations and measurements




Comparison done by Erik Fura, Clinical Project with Alessandra Bolsi and Anna Fredh.

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# Monte Carlo for patient specific absolute dose quality assurance

**Monte Carlo simulations:**

– Reduce workload: Replace measurements with simulations in water.

**Monte Carlo simulations can be used to reduce workload without jeopardizing treatment quality**

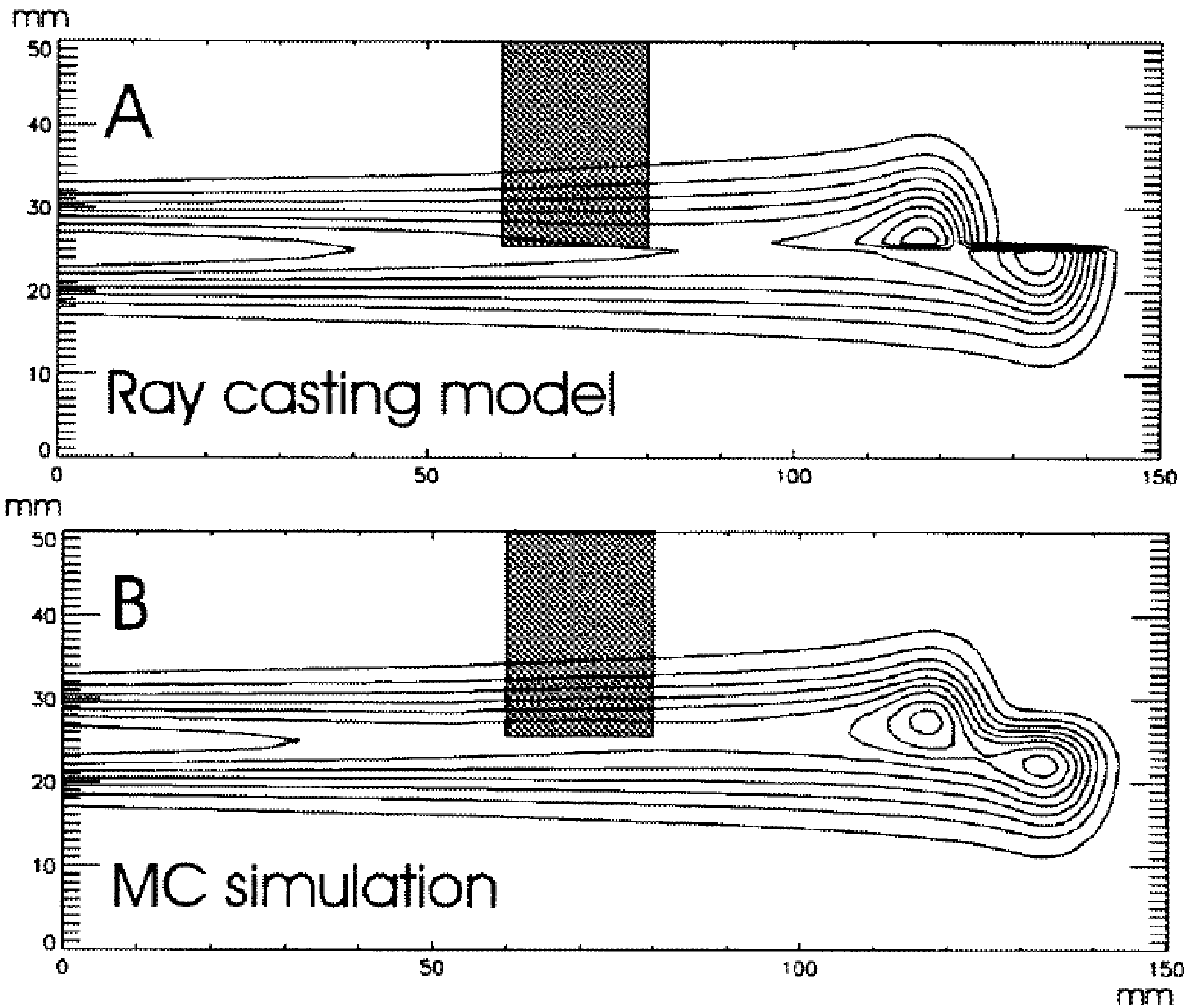
Comparison done by Erik Fura, Clinical Project with Alessandra Bolsi and Anna Fredh.

# Overview

- Setup of a Monte Carlo engine for proton pencil beam scanning

- Monte Carlo simulations for optimizing proton therapy treatement:
  - Patient specific absolute dose quality assurance in water
  - **Accuracy of analytical dose calculation algorithms in the patient CT**
  - Advanced beam delivery techniques.

# Comparison of Monte Carlo and analytical calculations



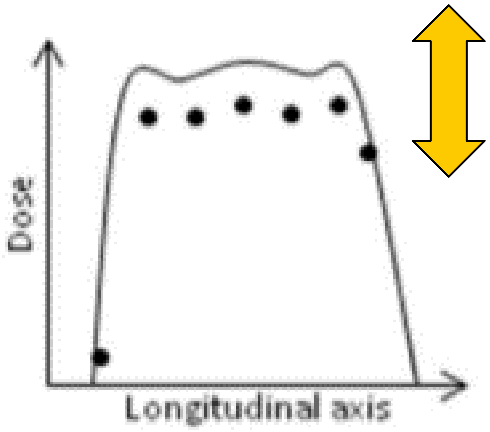

Analytical approximations.

How big is the influence on patient calculation?

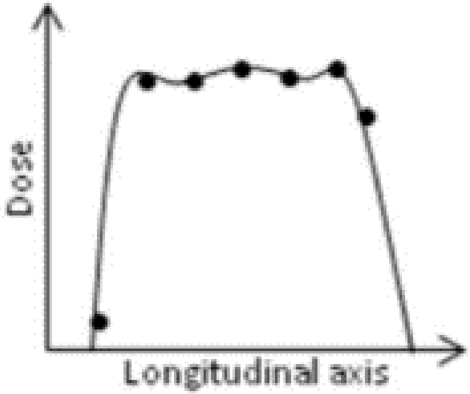
[1] SCHAFFNER, B. 1998. *Phys Med Biol,* 44**,** 27-41.

# Comparison of Monte Carlo and analytical calculations

- Absolute dose offset

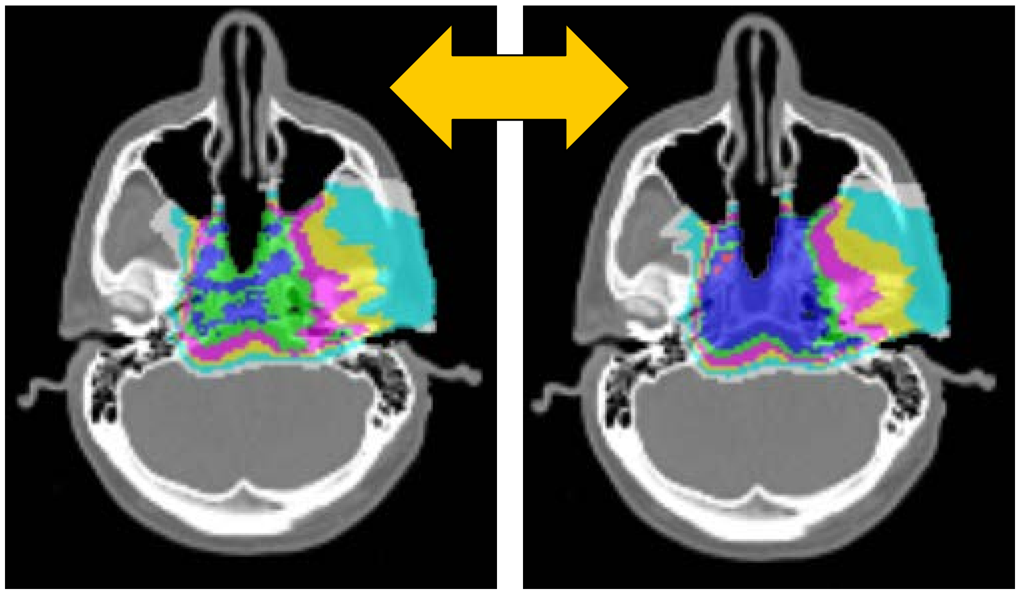



- Relative agreement (after rescaling)

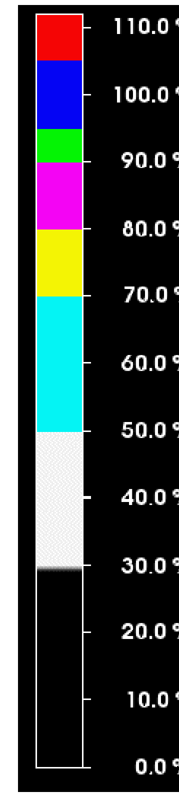



Trnkova et al 2016. Med Phys, 43, 5998.

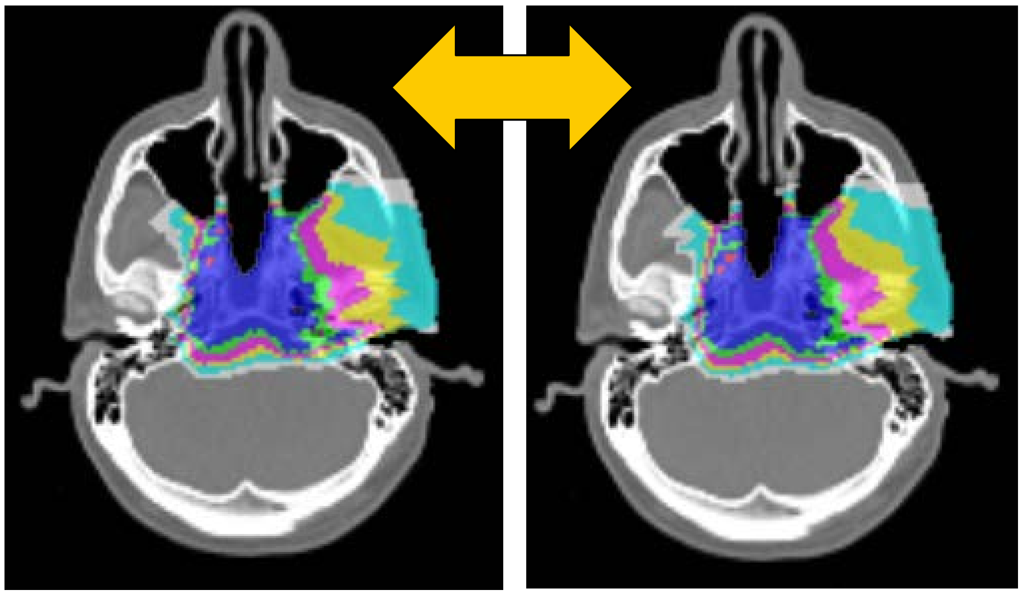
# Absolute comparison of Monte Carlo and analytical calculations



Monte Carlo Analytical

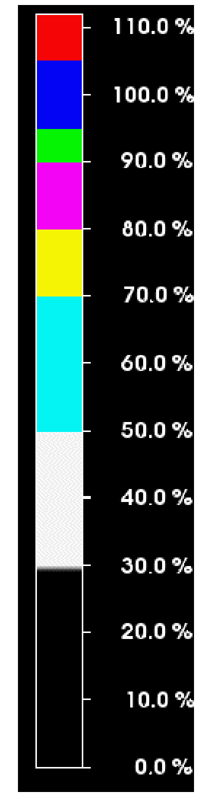


# Absolute comparison of Monte Carlo and analytical calculations



Monte Carlo
(after rescaling)

Analytical

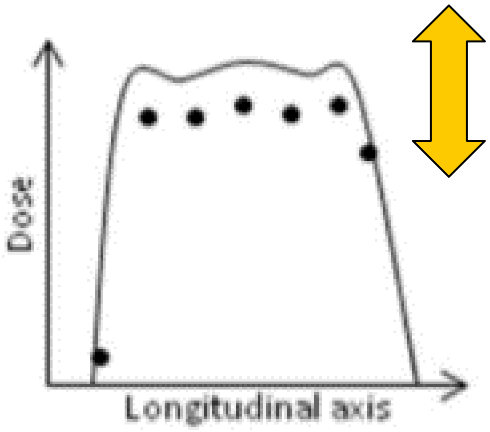



**Absolute dose offset**

**Use Monte Carlo to scale dose in the patient CT.**

# Comparison of Monte Carlo and analytical calculations

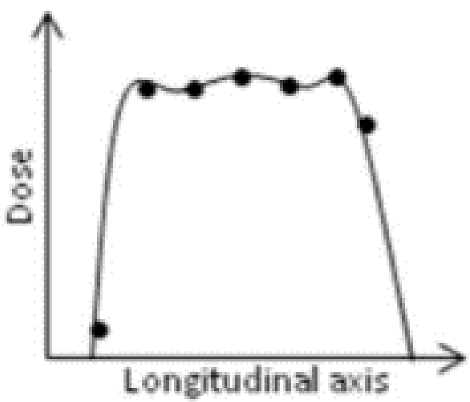
- Absolute dose offset




**Instead of water measurements/simulations:**

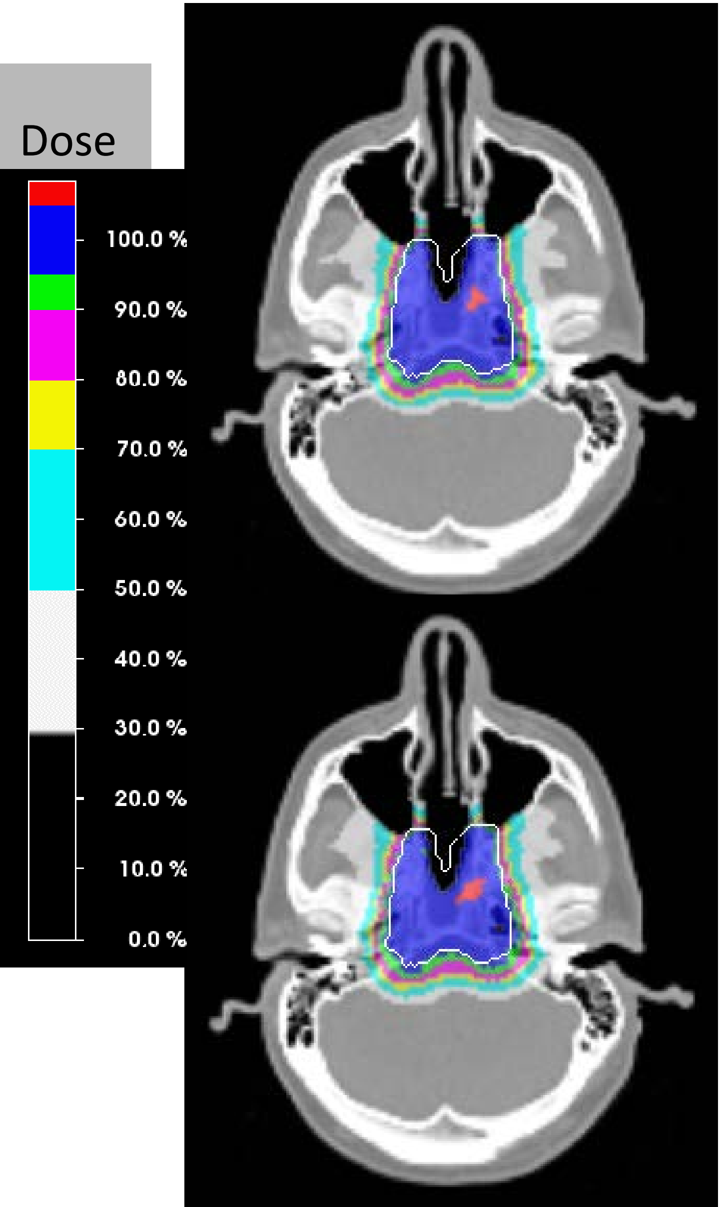
**Use Monte Carlo to scale dose in the patient CT.**

- Relative agreement




Trnkova et al 2016. Med Phys, 43, 5998.

# Relative comparison of Monte Carlo and analytical calculations

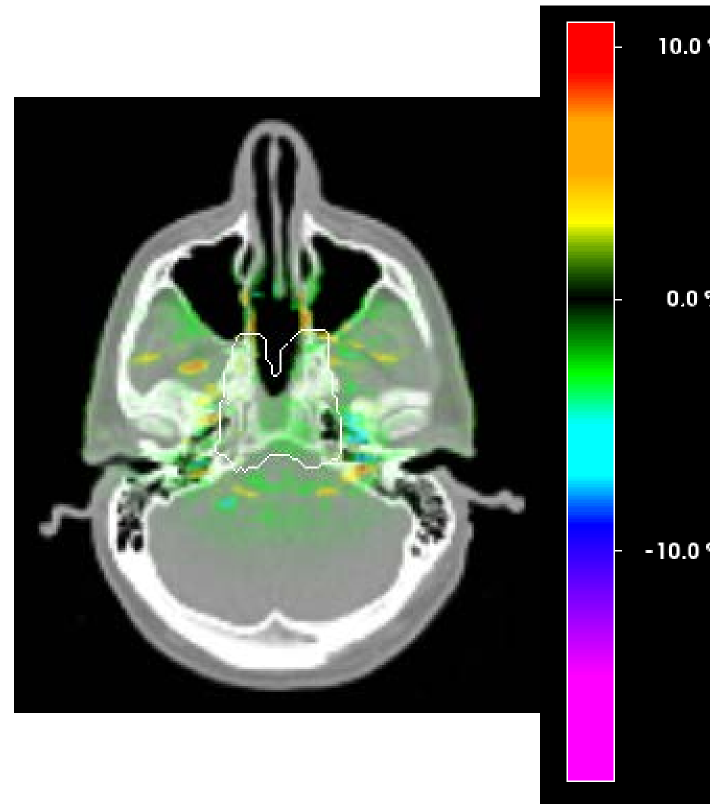



Analytical

Monte Carlo
(after rescaling)

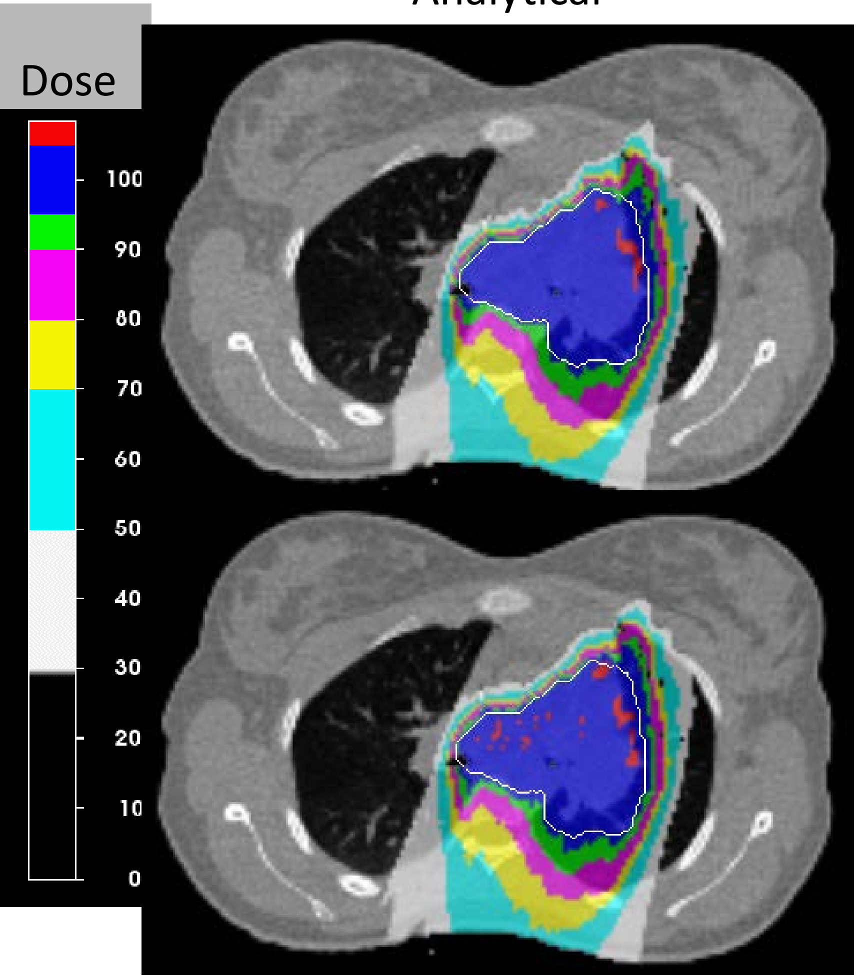
Analytical Minus
Monte Carlo

Dose
difference



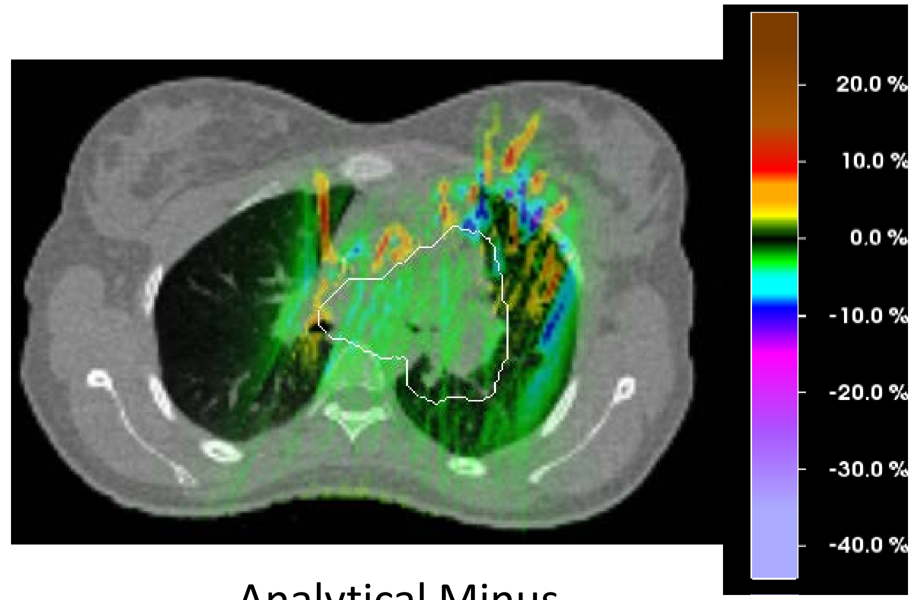
# Relative comparison of Monte Carlo and analytical calculations

Analytical



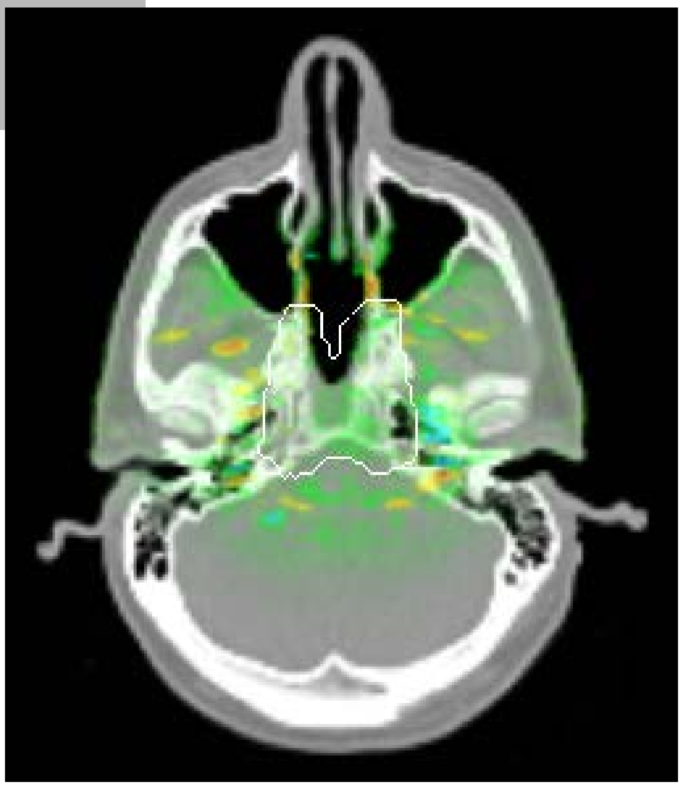

Monte Carlo
(after rescaling)

Dose
difference



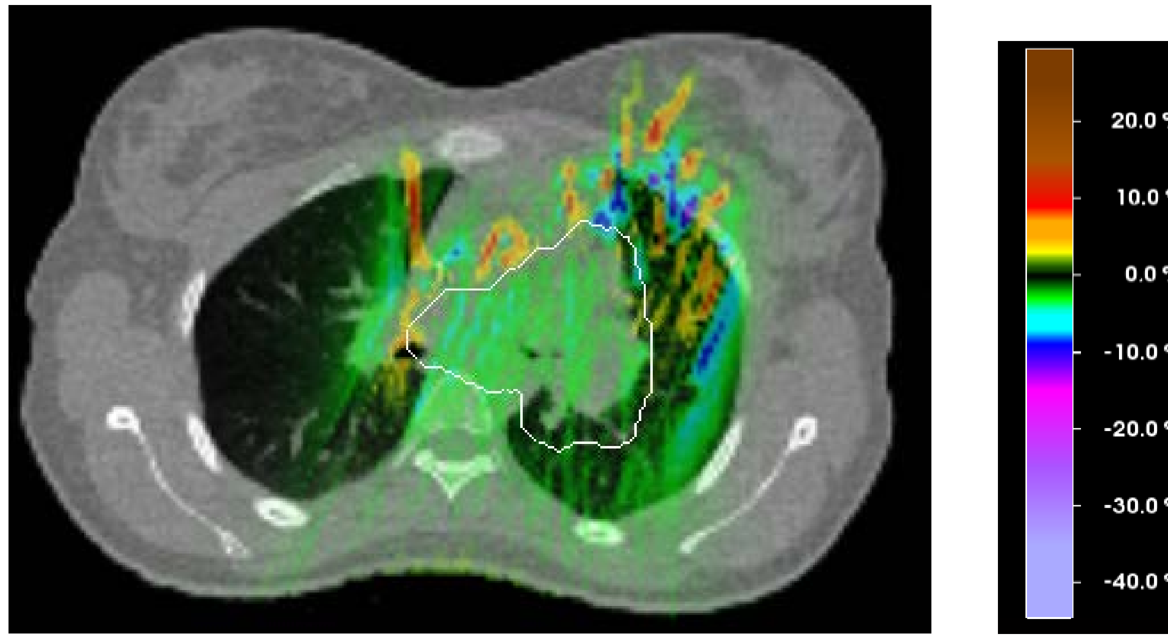

Analytical Minus
Monte Carlo

# Comparison of Monte Carlo and analytical calculations



Analytical Minus Monte Carlo

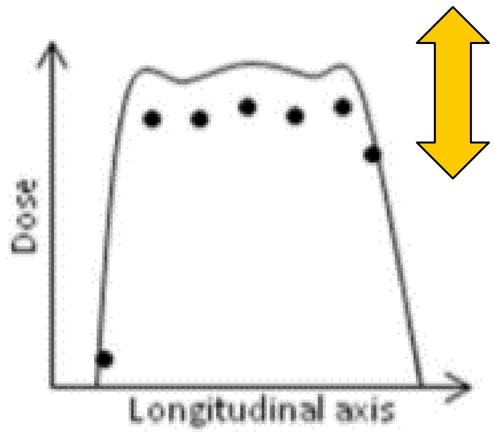
Dose difference



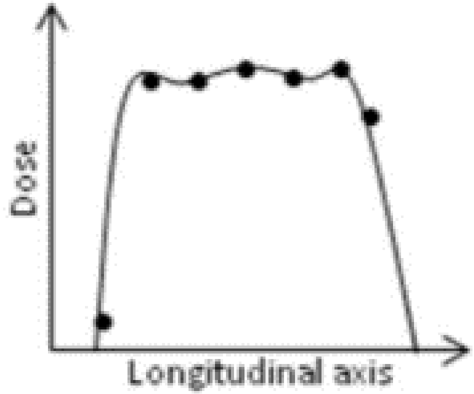

**Good relative agreement depends on treatment site and field arrangement**

# Comparison of Monte Carlo and analytical calculations

- Absolute dose offset




- Relative agreement




**Instead of water measurements/simulations:**

**Use Monte Carlo to scale dose in the patient CT.**

**Good relative agreement depends on treatment site and field arrangement**

Trnkova et al 2016. Med Phys, 43, 5998.

# Overview

- Setup of a Monte Carlo engine for proton pencil beam scanning

- Monte Carlo simulations for optimizing proton therapy treatement:
  - Patient specific absolute dose quality assurance in water
  - Accuracy of analytical dose calculation algorithms in the patient CT
  - Advanced beam delivery techniques: **Improving the lateral fall-off for proton pencil beam scanning**

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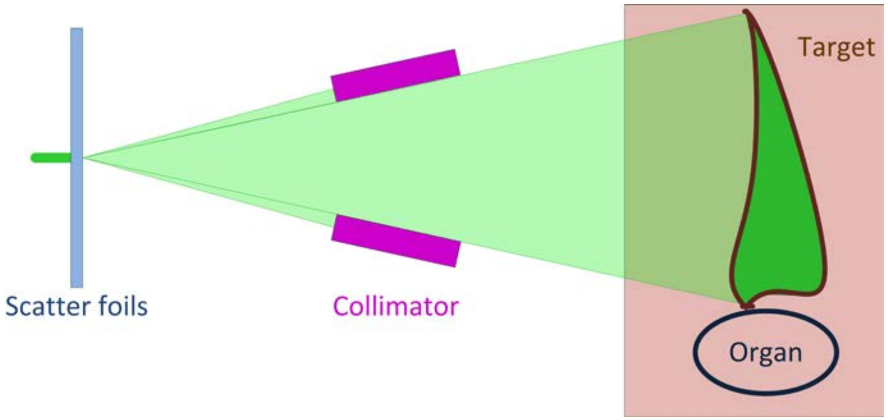
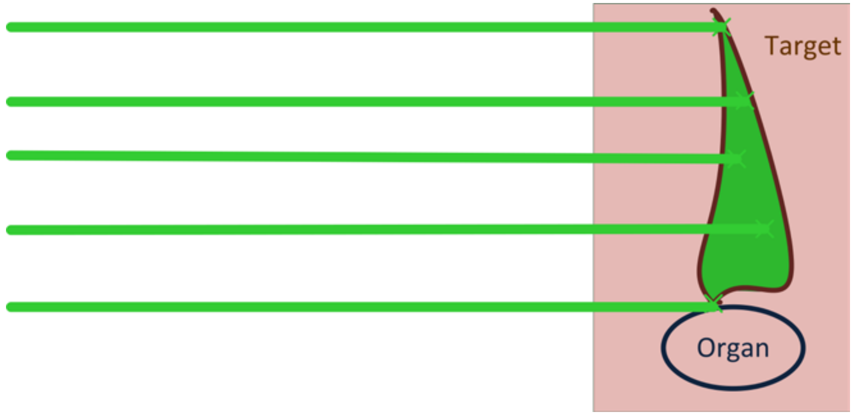
# Introduction – Proton pencil beam scanning

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



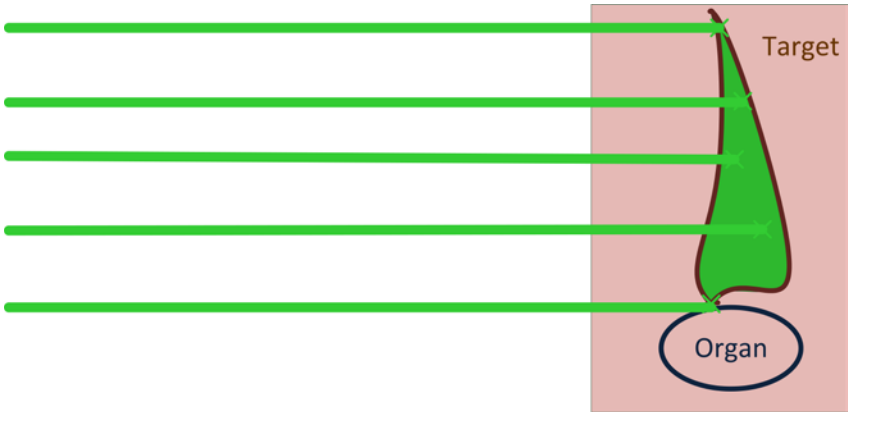

- Pencil beam scanning:
  - Small proton beams are directed into the patient
  - Depth is adjusted by energy change and pre-absorber usage



# Lateral falloff for PBS – Motivation

- 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

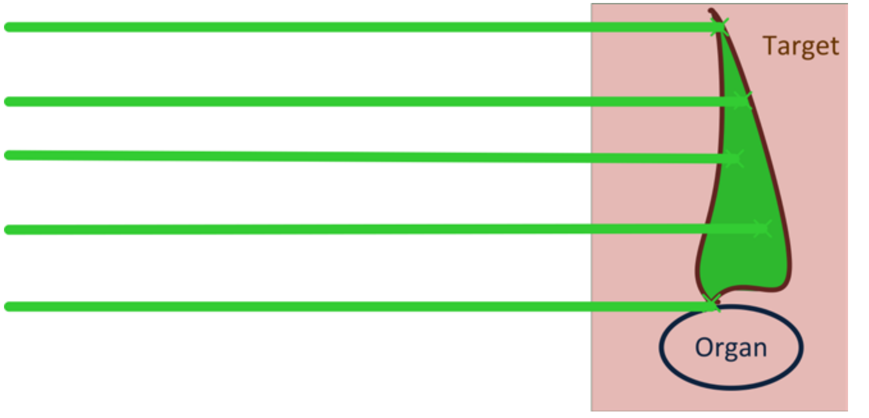



**Which are the best strategies to minimize the lateral fall-off for PBS?**

# Lateral falloff for PBS – Overview

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

- Optimization strategies:
  - Collimation
  - Edge-enhancement
  - Edge-enhanced collimation

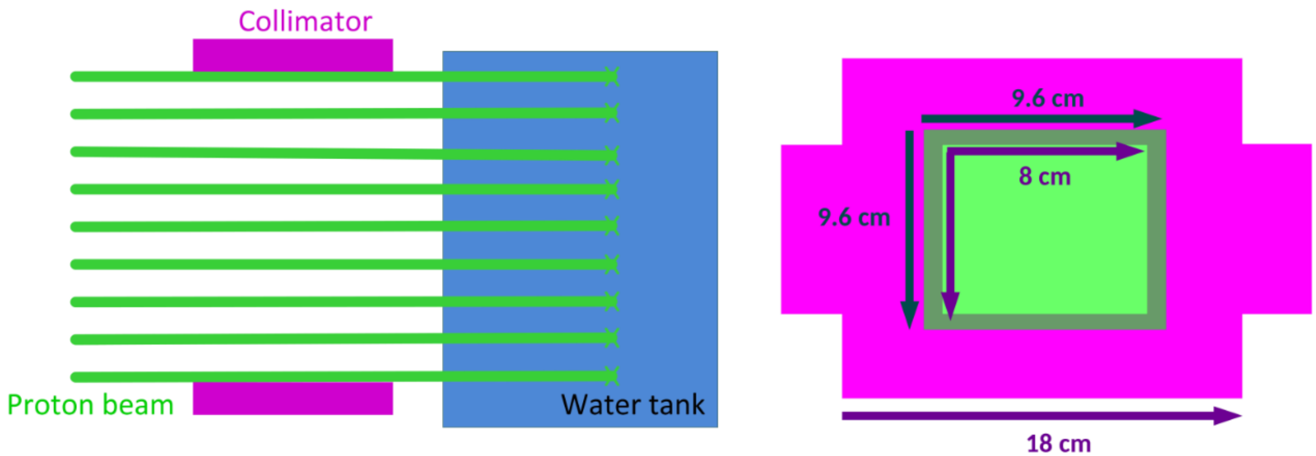


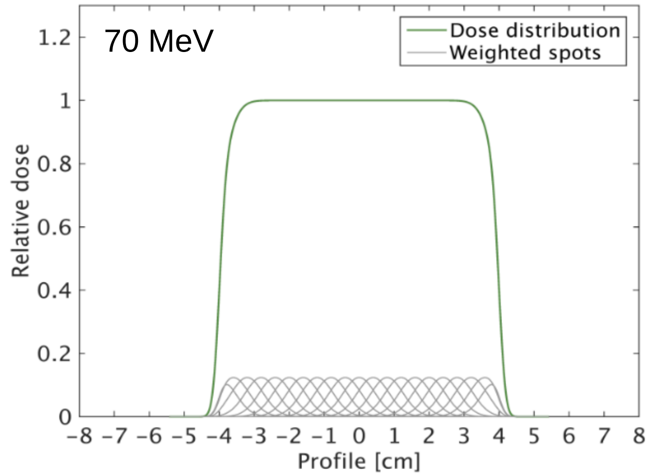

- Pre-absorber strategies:
  - Fixed pre-absorber
  - Automatic pre-absorber
  - Variable pre-absorber

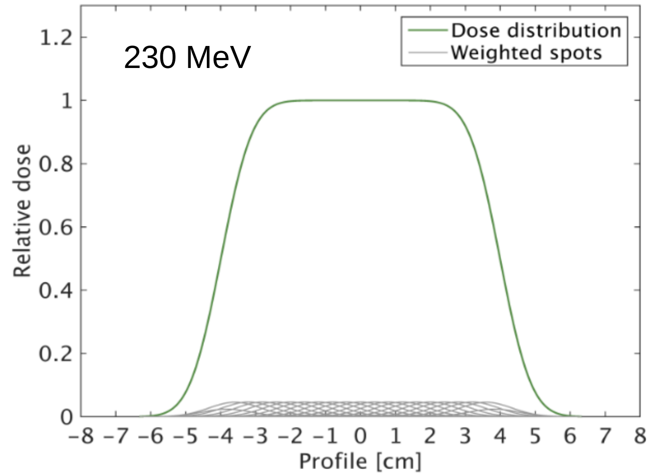
- Conclusion: Recommended settings to minimize the lateral penumbra for PBS

# Lateral falloff for PBS – Optimization approaches

**Collimation:** Uniformly weighted pencil beams are collimated



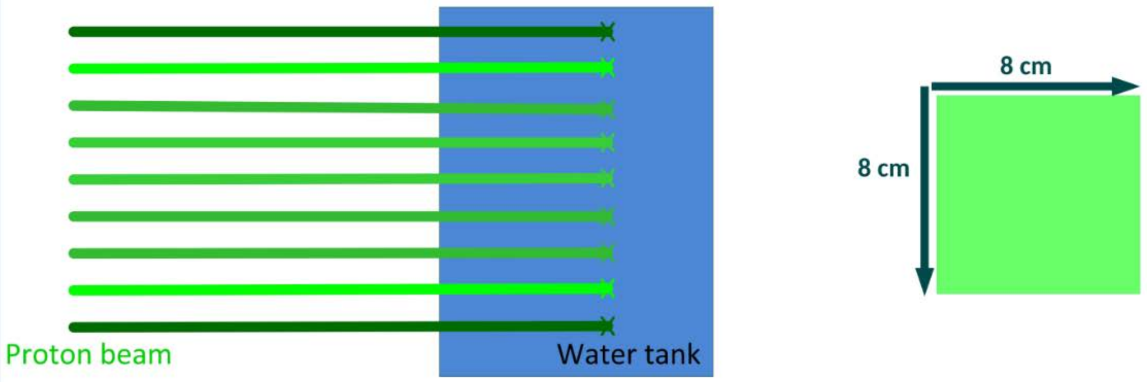



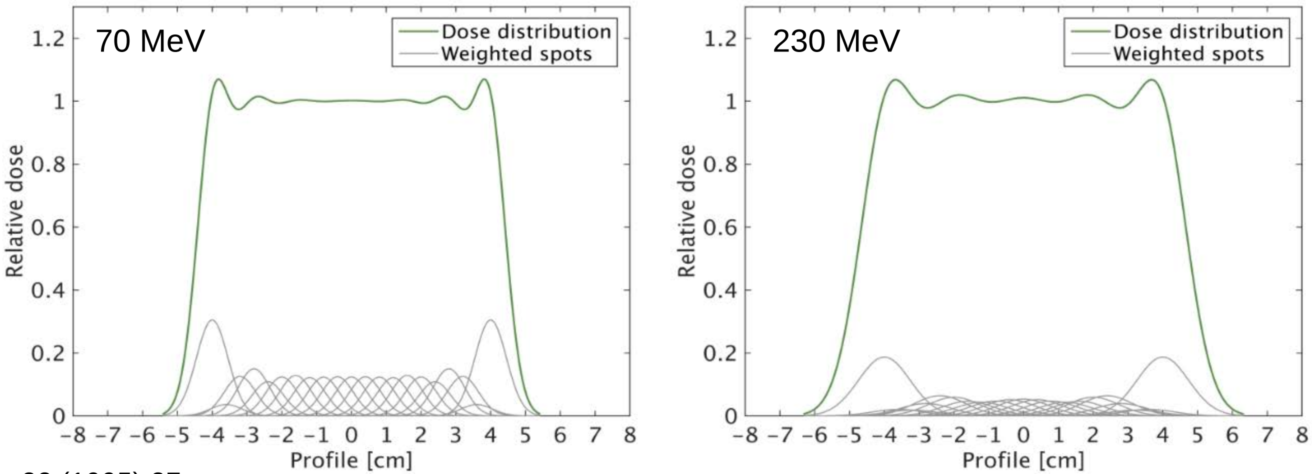




C. Winterhalter et al., *Physics in Medicine & Biology* 63.2 (2018)

# Lateral falloff for PBS – Optimization approaches

**Edge-enhancement:** The weights of *uncollimated* pencil beams are optimized



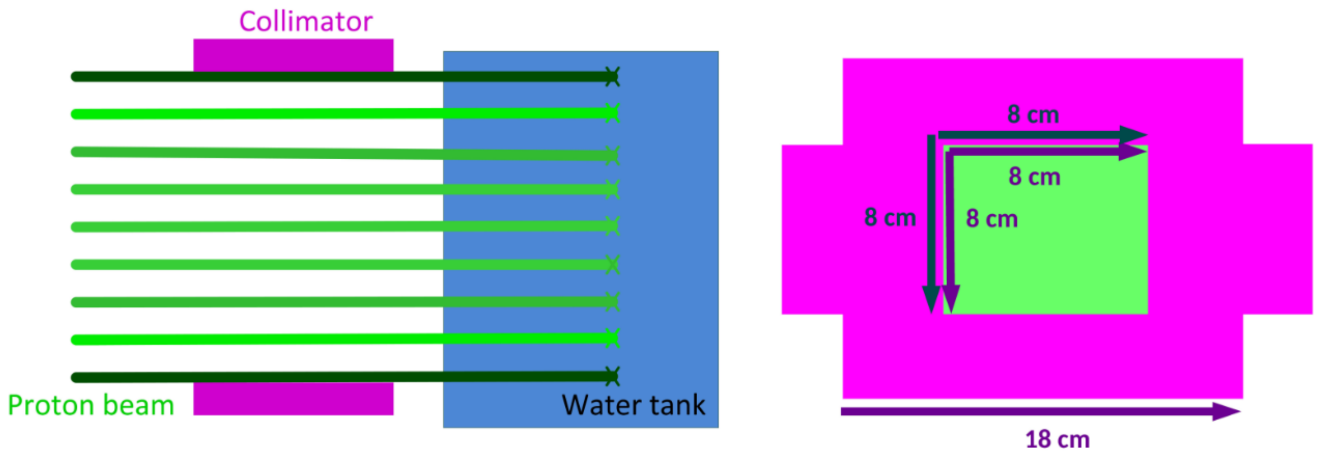



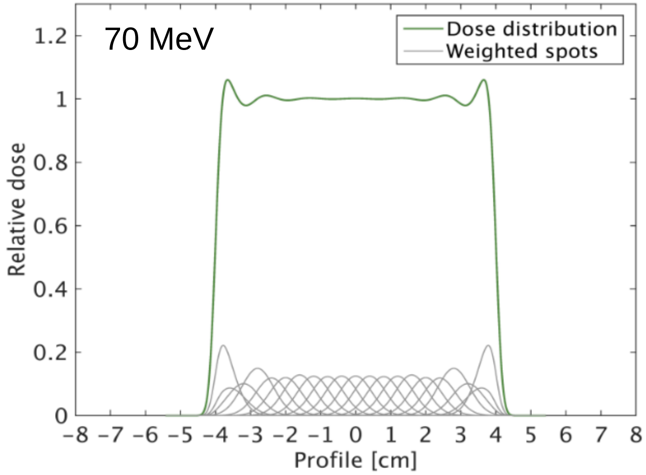


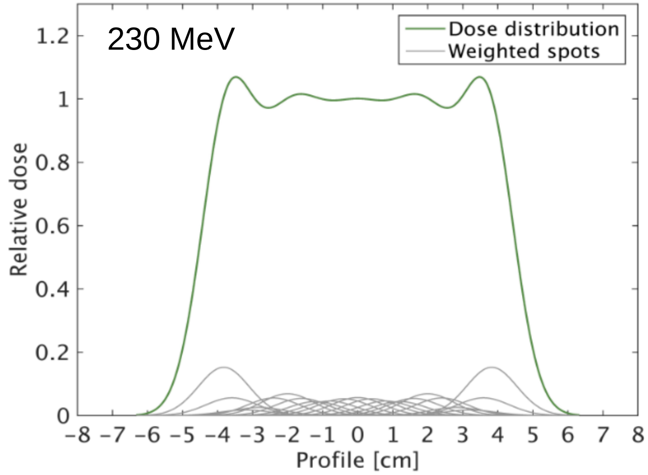
Pedroni et al. Med Phys 22 (1995):37
C. Winterhalter et al.,*Physics in Medicine & Biology* 63.2 (2018)

# Lateral falloff for PBS – Optimization approaches

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

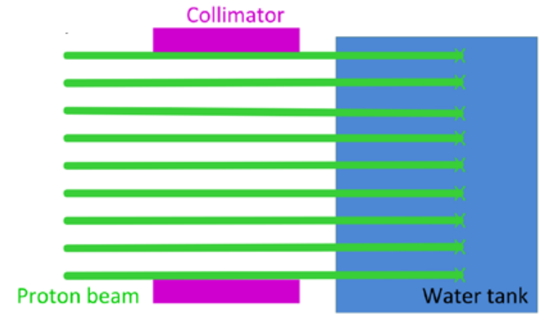


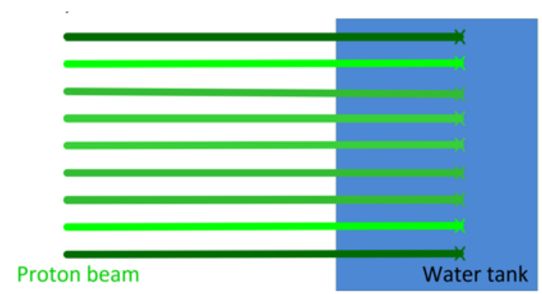




C. Winterhalter et al.,*Physics in Medicine & Biology* 63.2 (2018)

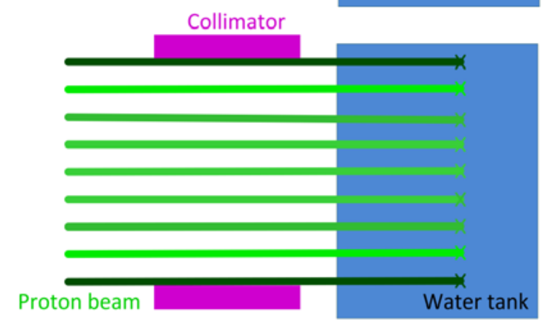
# Lateral falloff for PBS – Optimization approaches




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




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



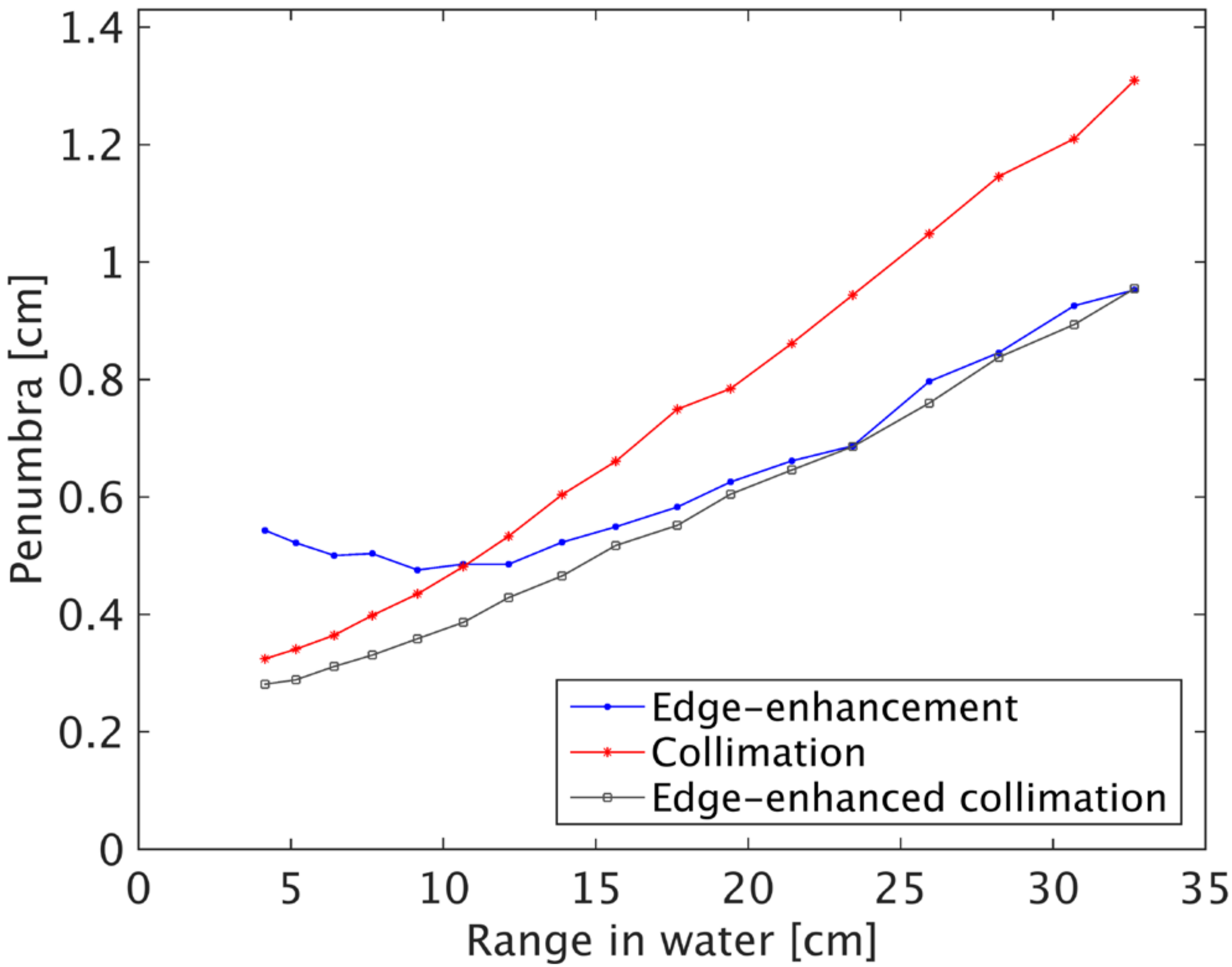

**Edge-enhanced collimation:** The weights of the collimated pencil beams are optimized

**Monte Carlo simulations** of square, monoenergetic fields

Analyse the lateral fall-off (penumbra) at the Bragg peak

C. Winterhalter et al.,*Physics in Medicine & Biology* 63.2 (2018)

# Lateral falloff for PBS (air-gap 10 cm)




C. Winterhalter et al.,*Physics in Medicine & Biology* 63.2 (2018)

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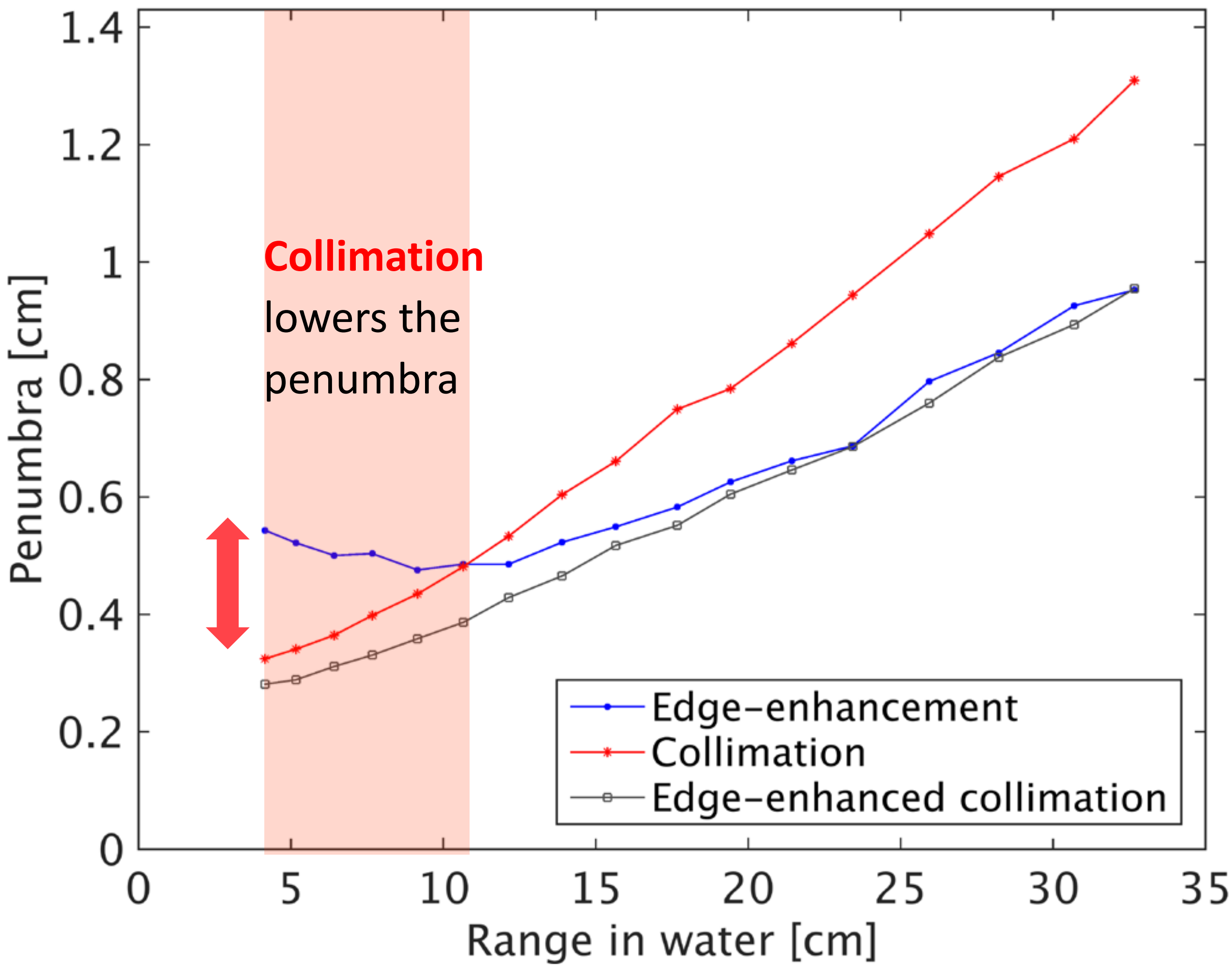


C. Winterhalter et al.,*Physics in Medicine & Biology* 63.2 (2018)

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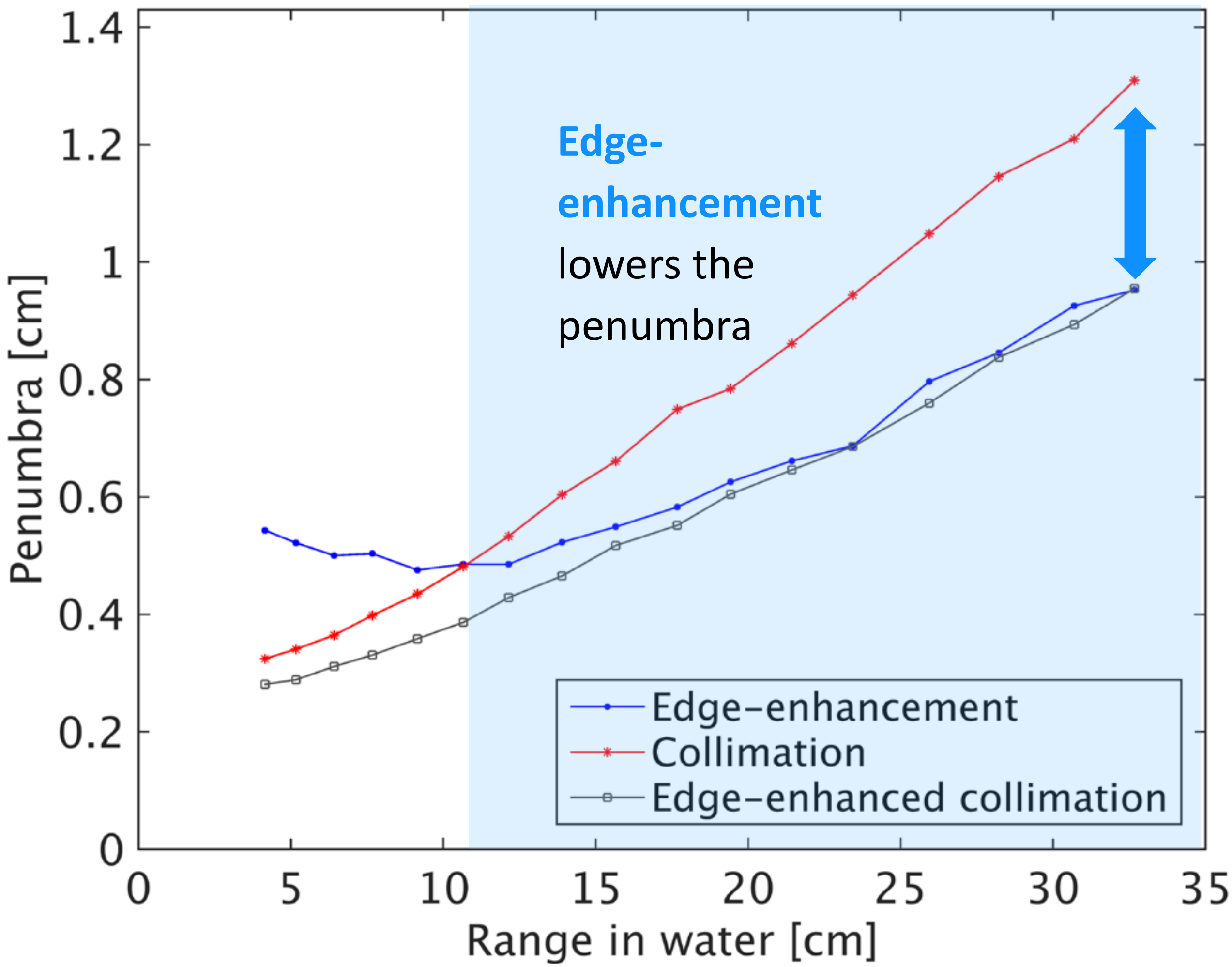
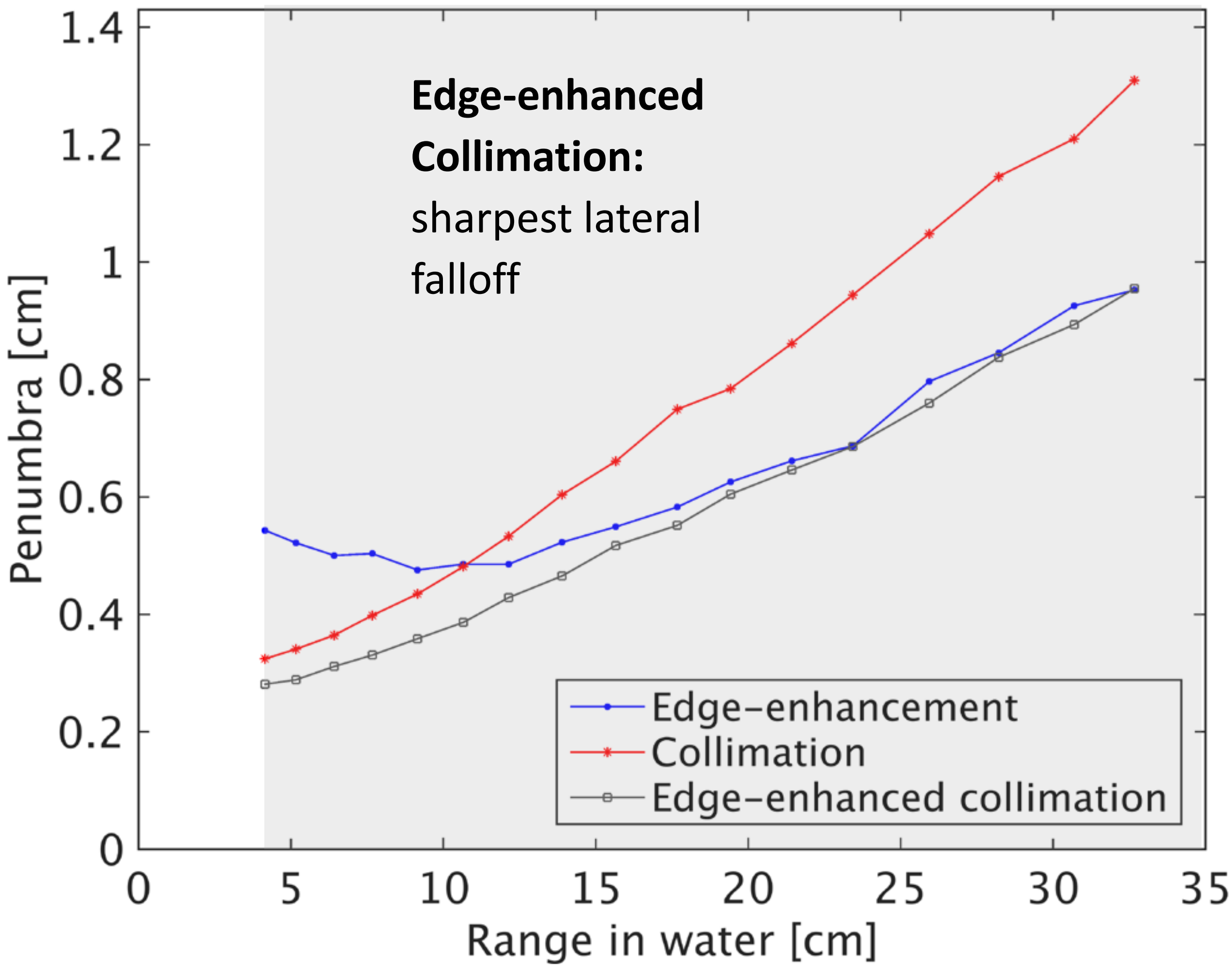


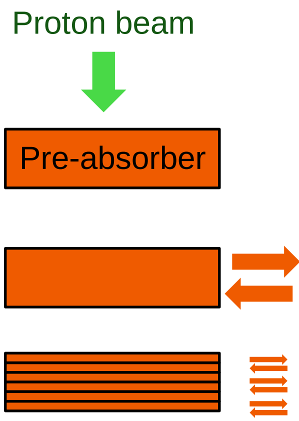

C. Winterhalter et al.,*Physics in Medicine & Biology* 63.2 (2018)

# Lateral falloff for PBS (air-gap 10 cm)



# Lateral falloff for PBS – Pre-absorber strategies

Lower limit for our gantry is 70 MeV, corresponding to a WER of 4.15 cm.
Therefore **a pre-absorber is needed** for more superficial targets.




**Fixed Pre-absorber:** All spots in the field, fixed thickness

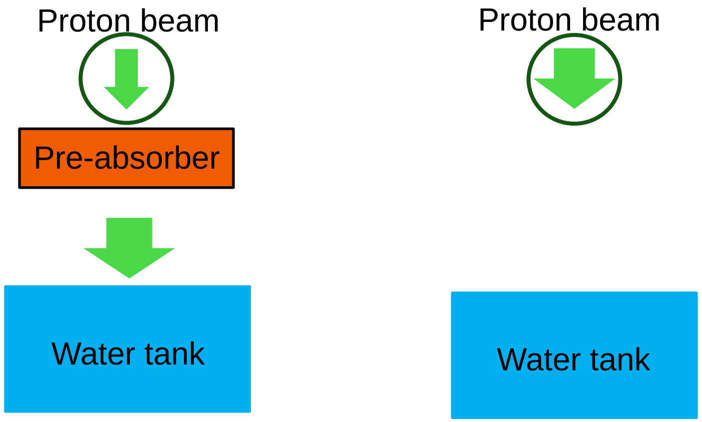
**Automatic Pre-absorber:** Low energy spots only, fixed thickness

**Variable Pre-absorber:** Low energy spots only, eight mini range shifter plates

# Lateral falloff for PBS – Pre-absorber strategies

Influence of the pre-absorber on the lateral penumbra:

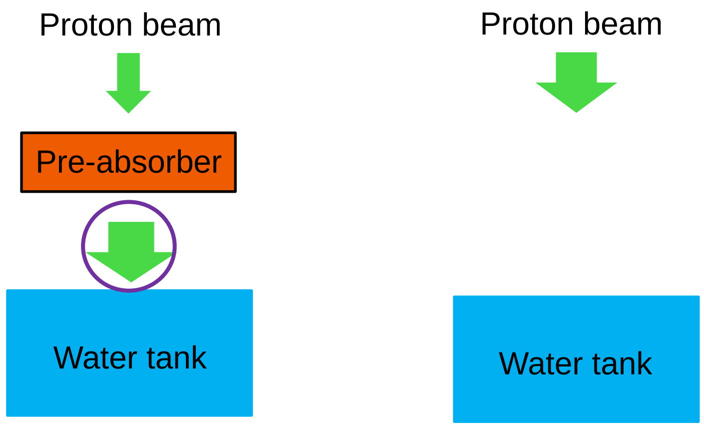
- Higher energy is transported through the gantry; less scattering and smaller initial beam size
- Scatter caused by the pre-absorber



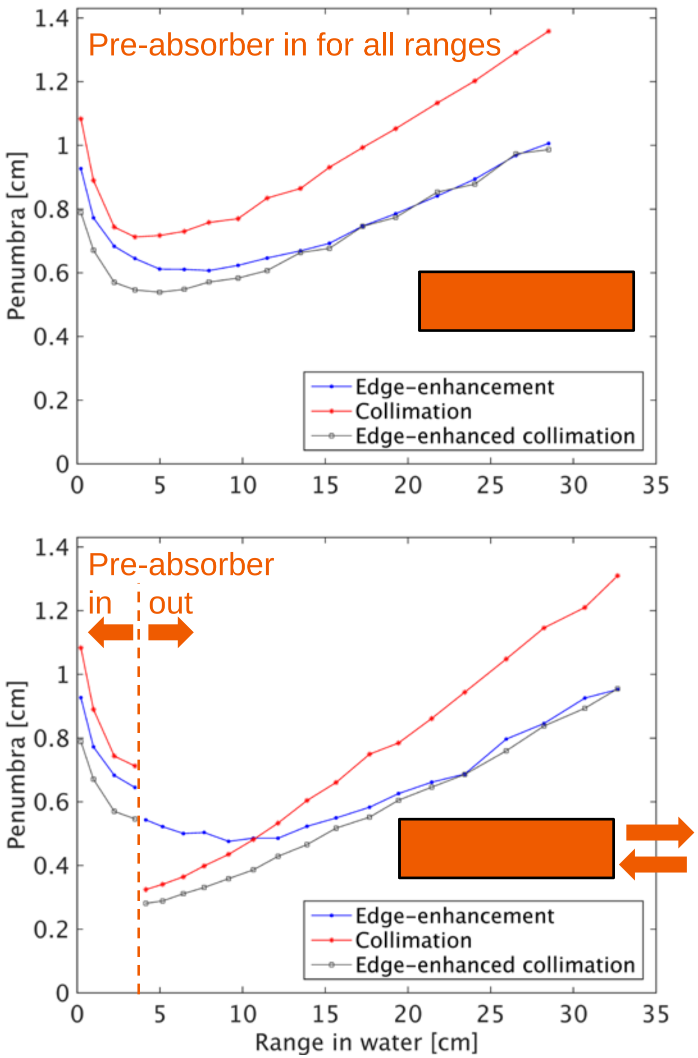
# Lateral falloff for PBS – Pre-absorber strategies

Influence of the pre-absorber on the lateral penumbra:

- Higher energy is transported through the gantry; less scattering and smaller initial beam size
- Scatter caused by the pre-absorber



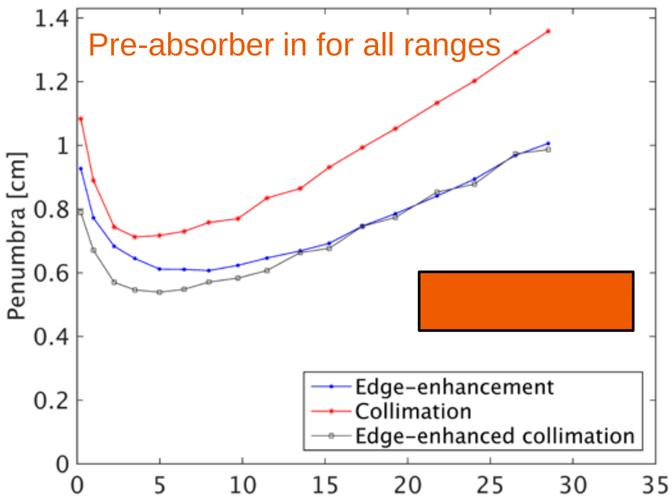
# Lateral falloff for PBS with pre-absorber



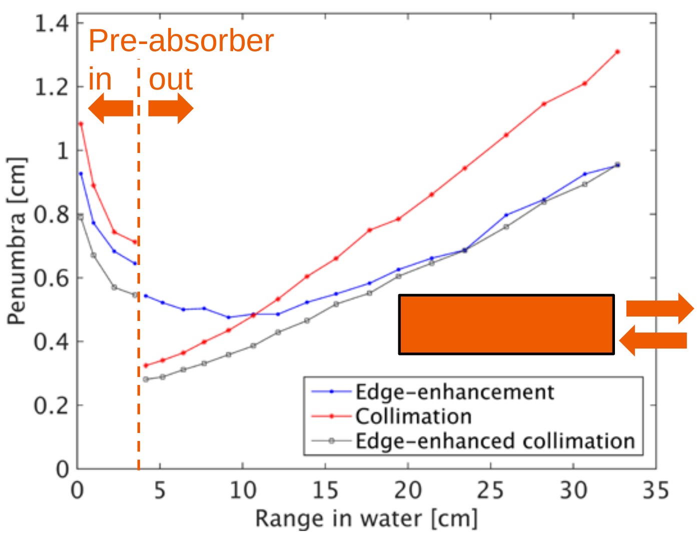

- For **edge-enhancement** and WER above 4.15 cm (airgap 10 cm), the penumbra is lowered when replacing the **fixed with the automatic pre-absorber**.

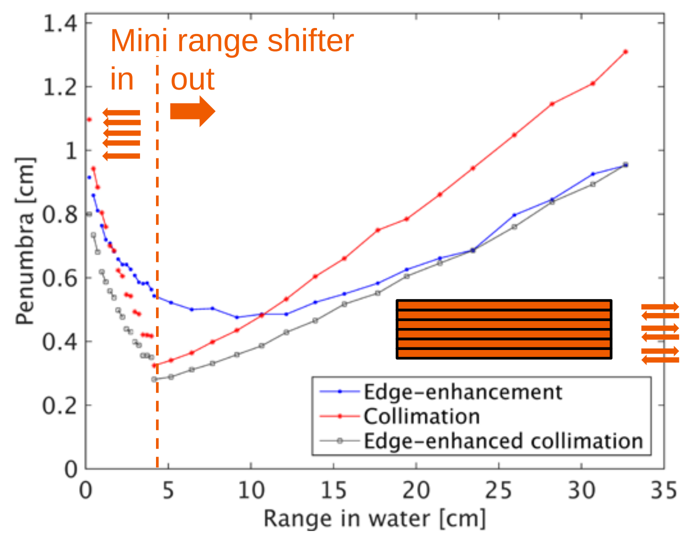
C. Winterhalter et al.,*Physics in Medicine & Biology* 63.2 (2018)

# Lateral falloff for PBS with pre-absorber

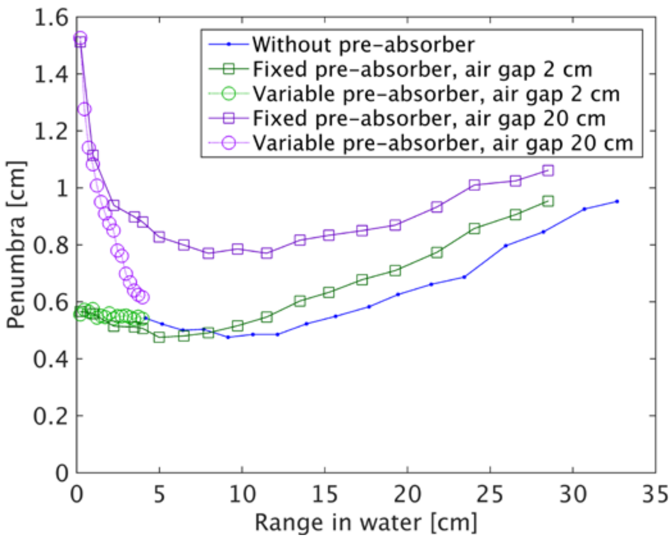


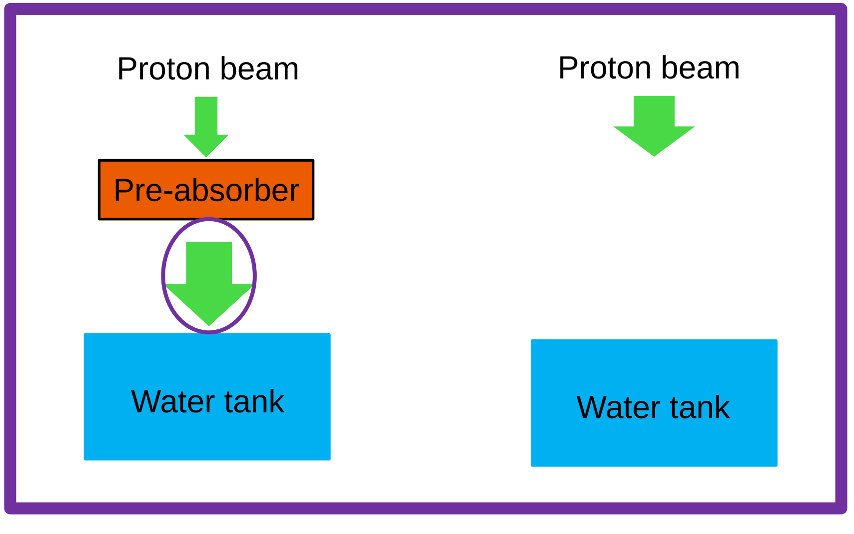

- For **edge-enhancement** and WER above 4.15 cm (airgap 10 cm), the penumbra is lowered when replacing the **fixed with the automatic pre-absorber**.
- For WER below 4.15 cm the penumbra is reduced when replacing the **automatic with the variable pre-absorber**.
- The lowest penumbra is achieved by combining **edge-enhanced collimation** with the **variable pre-absorber**.



# Lateral falloff for PBS: Effect of the airgap



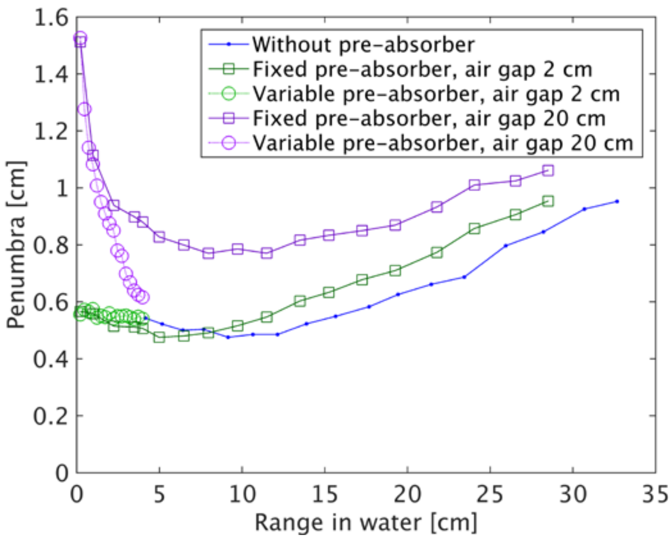




**Edge-enhancement:**

- The use of the automatic or variable, as opposed to fixed, pre-absorber has greatest effect for the **larger (20 cm) air gap**.

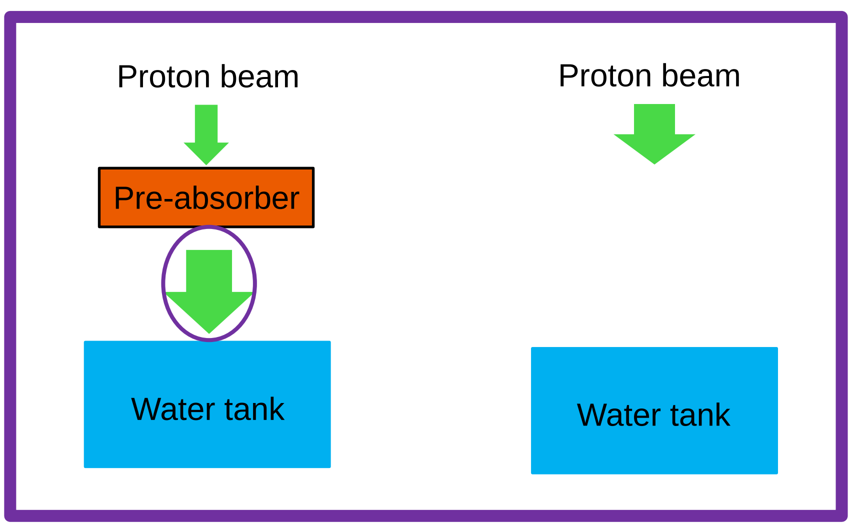
C. Winterhalter et al.,*Physics in Medicine & Biology* 63.2 (2018)

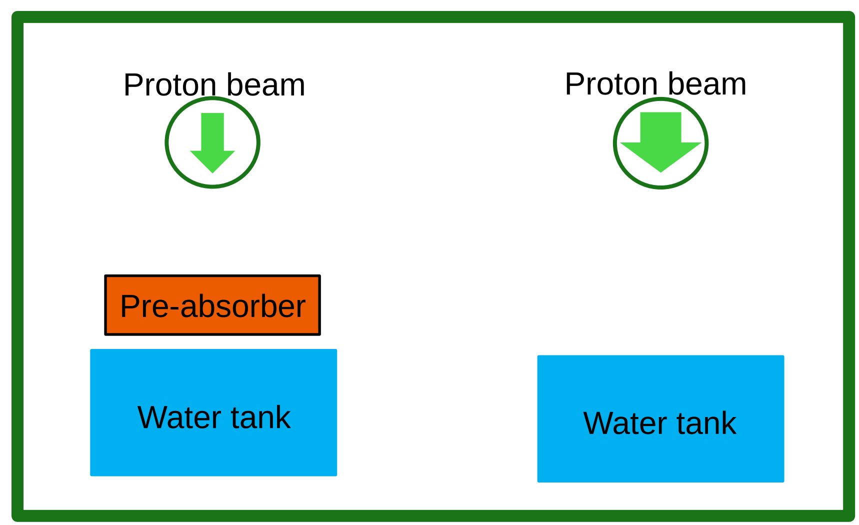
# Lateral falloff for PBS: Effect of the airgap




**Edge-enhancement:**

- The use of the automatic or variable, as opposed to fixed, pre-absorber has greatest effect for the **larger (20 cm) air gap**.
- For **air gaps smaller than 5 cm**, no benefit is obtained from the variable pre-absorber.
- For an **air gap of 2 cm**, it is favourable to use a pre-absorber for WER up to 8 cm.

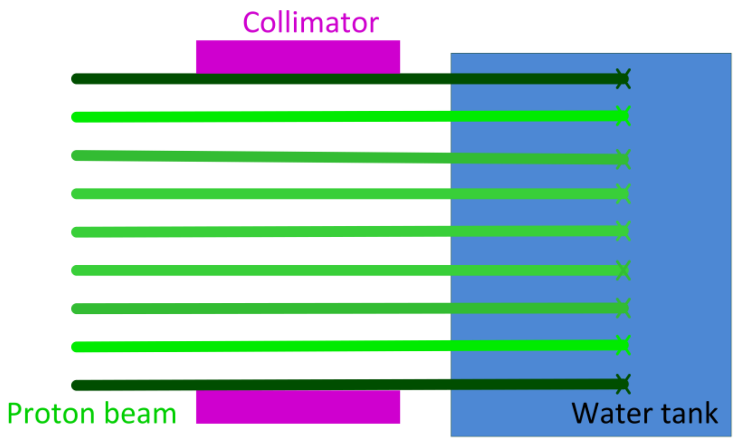



C. Winterhalter et al.,*Physics in Medicine & Biology* 63.2 (2018)

# Lateral falloff for PBS – Optimization approaches

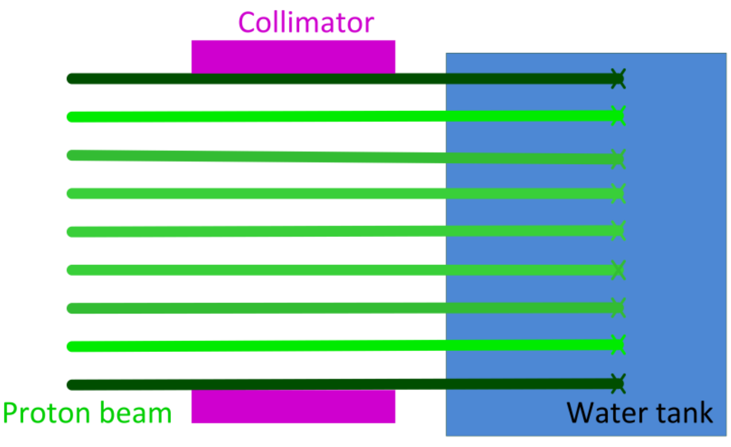
**Edge-enhanced collimation:** The weights of the collimated pencil beams are optimized




**Best penumbra in water!**

# Lateral falloff for PBS – Optimization approaches

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



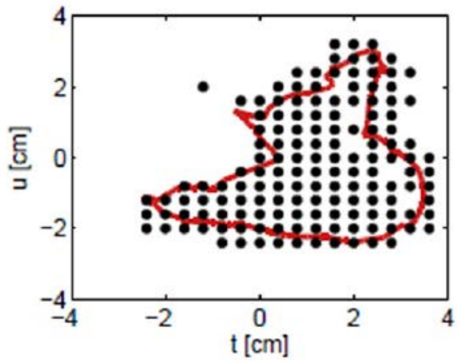

**Best penumbra in water!**

Is there an improvement for patient treatments?

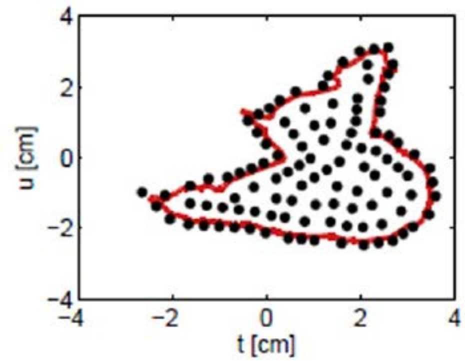
Calculate collimated fields in the patient CT!

# Penumbra improvements in patient calculations

- **Spot positioning:**




Grid scanning

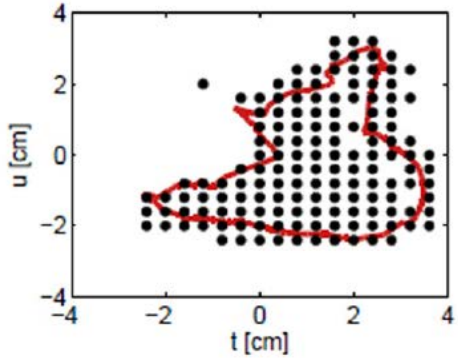



Contour scanning

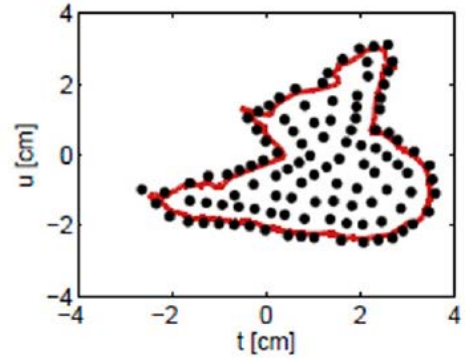
Meier, G., et al. Physics in Medicine and Biology 62.6 (2017): 2398.

# Penumbra improvements in patient calculations

- **Spot positioning:**



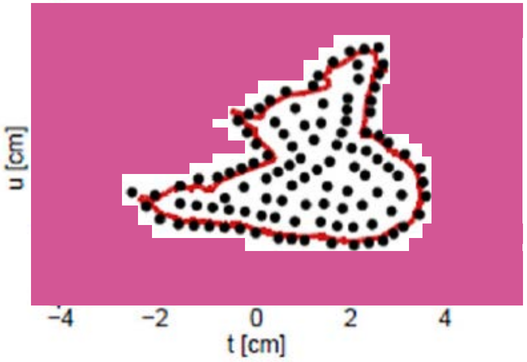

Grid scanning




Contour scanning

Meier, G., et al. Physics in Medicine and Biology 62.6 (2017): 2398.

- **Collimation:**




Without & with additional spot weight optimization

https://www.researchgate.net/figure/Varian-Millenium-120-leaf-MLC_fig1_2797570398.3.18

# Penumbra improvements in patient calculations

**Monte Carlo simulations**

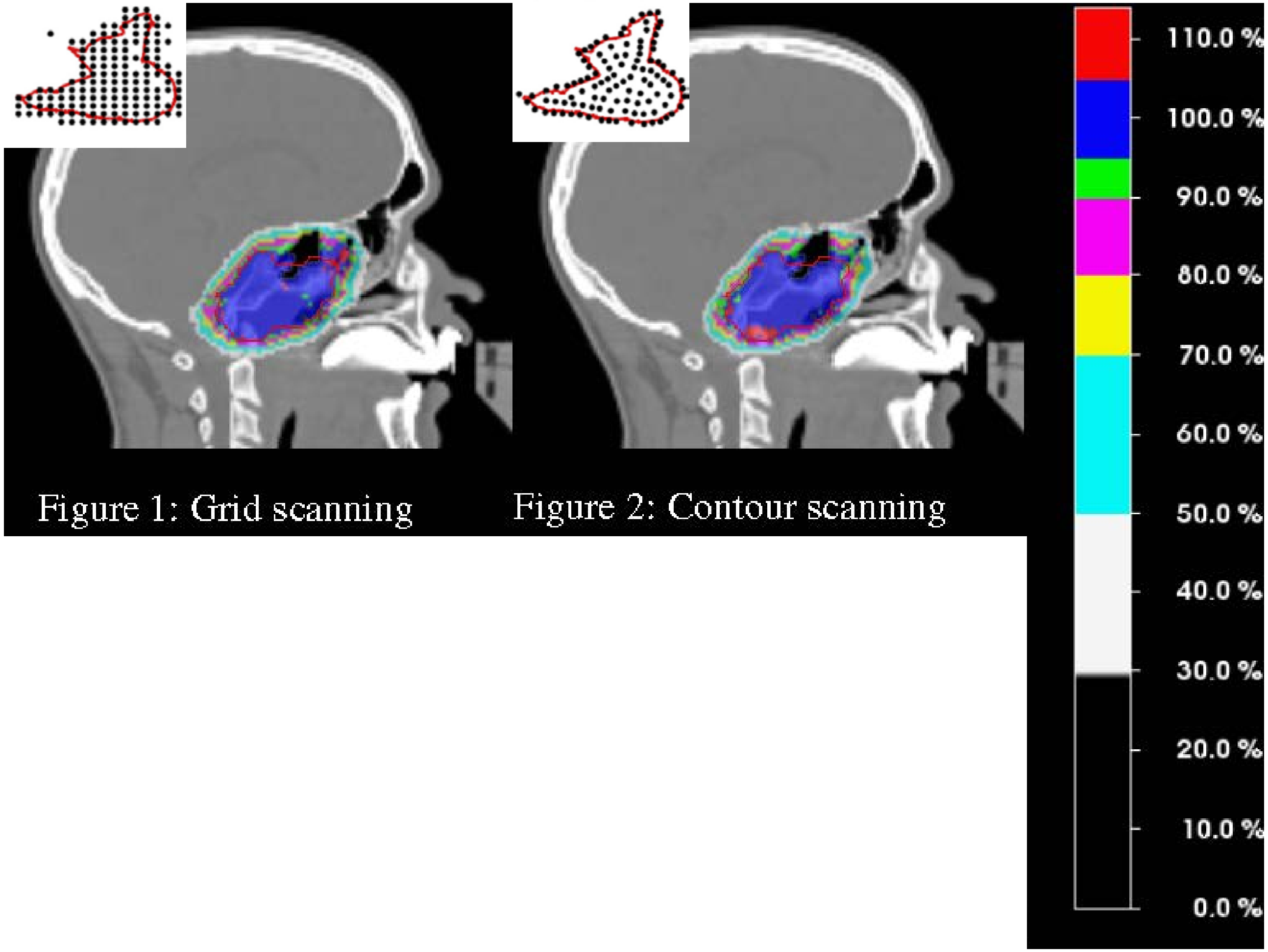
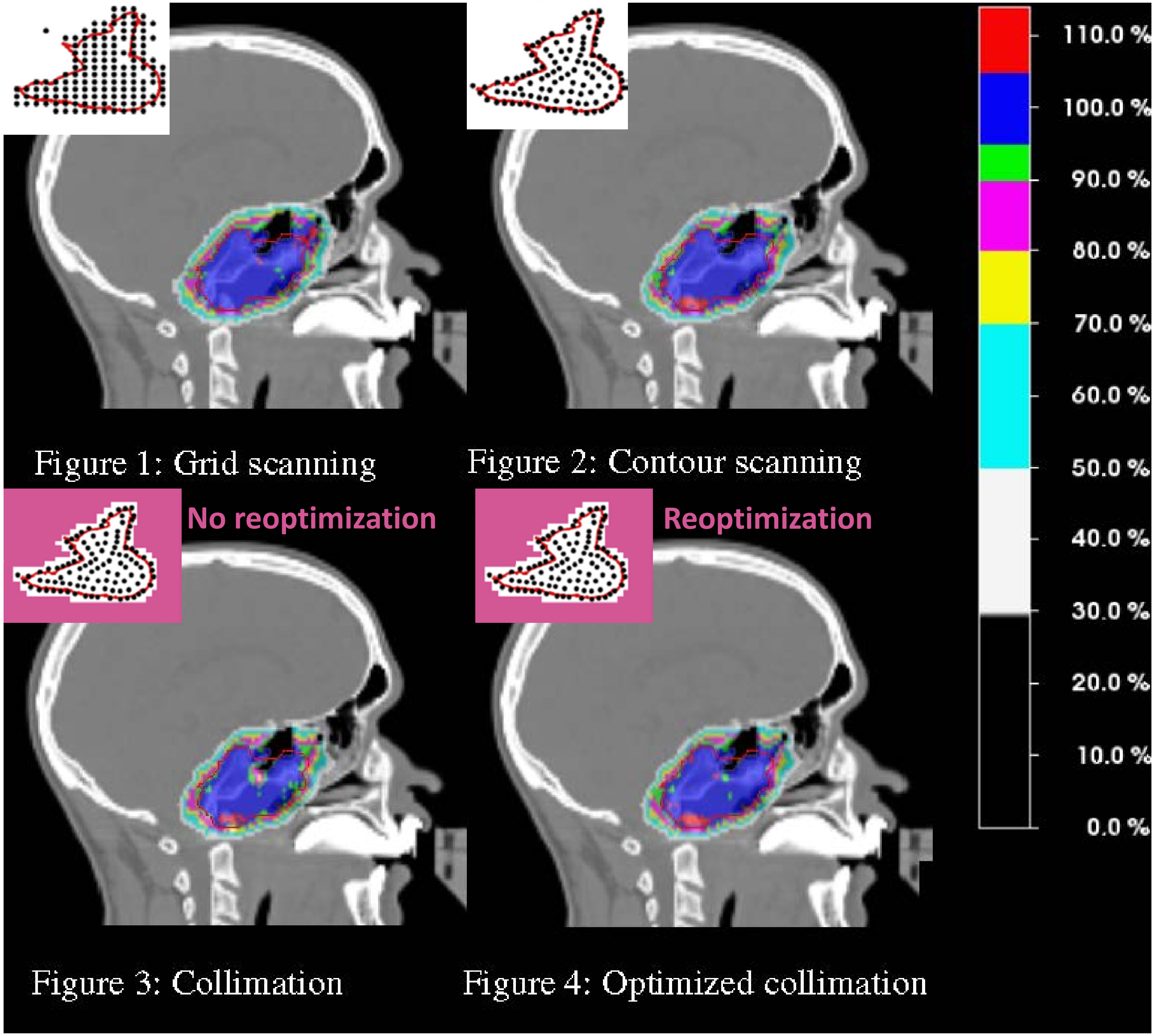



Figure 1: Grid scanning

Figure 2: Contour scanning

# Penumbra improvements in patient calculations

**Monte Carlo simulations**



# Penumbra improvements in patient calculations

**Monte Carlo simulations**

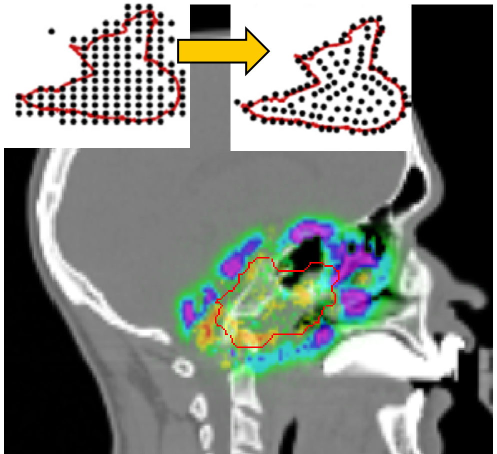
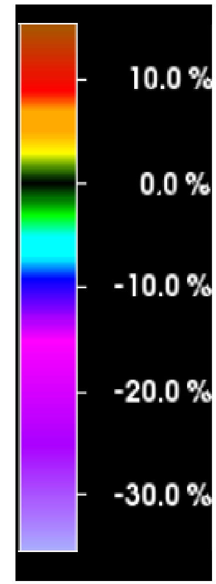
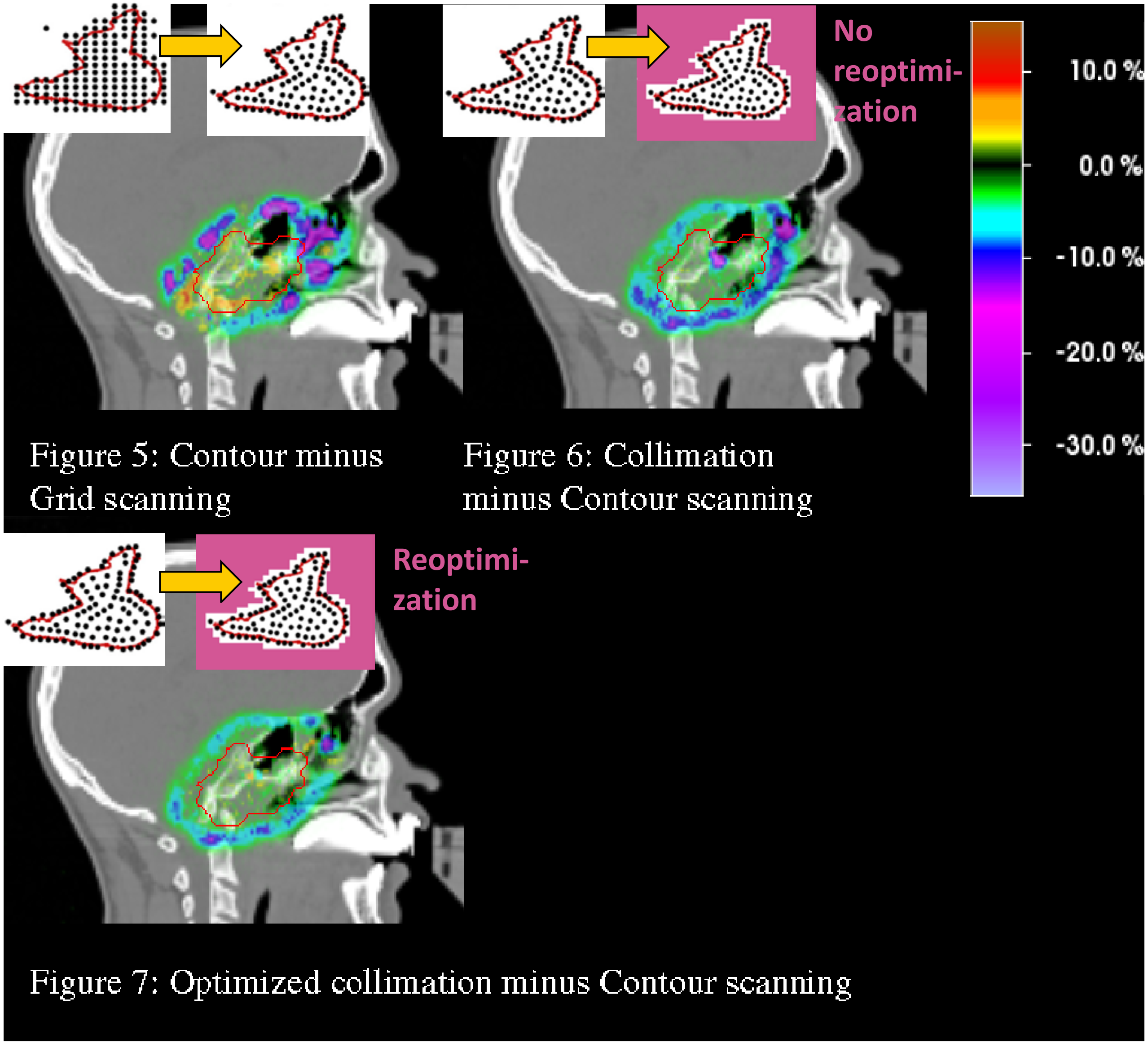


Figure 5: Contour minus Grid scanning



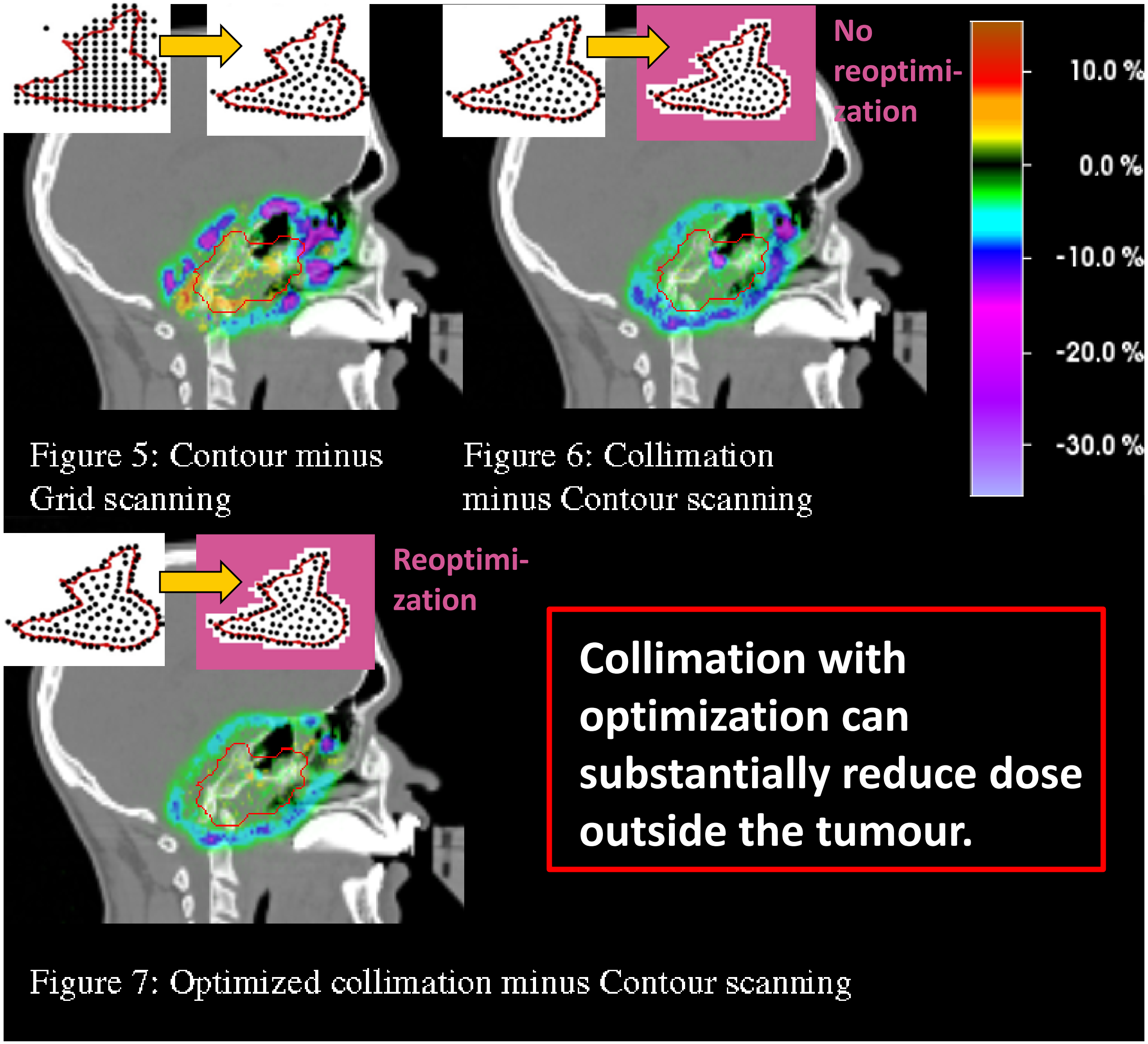
# Penumbra improvements in patient calculations

**Monte Carlo simulations**



# Penumbra improvements in patient calculations

**Monte Carlo simulations**



**Monte Carlo techniques can optimize proton therapy treatment…**

**… by reducing the workload:**
Replace patient specific absolute dose measurements with Monte Carlo simulations.

**… by increasing the accuracy:**
Validate the analytical dose calculation algorithm & scale absolute dose in the patient CT.

… **by evaluating new beam delivery techniques**:
For example collimation for proton pencil beam scanning.

# Backup