PAUL SCHERRER INSTITUT PSI

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[1]Paul Scherrer Institute, Villigen, Switzerland [2]Funded by a research grant of Varian Medical Systems Particle Therapy GmbH, Germany [3]The Christie NHS Foundation Trust, Manchester, UK

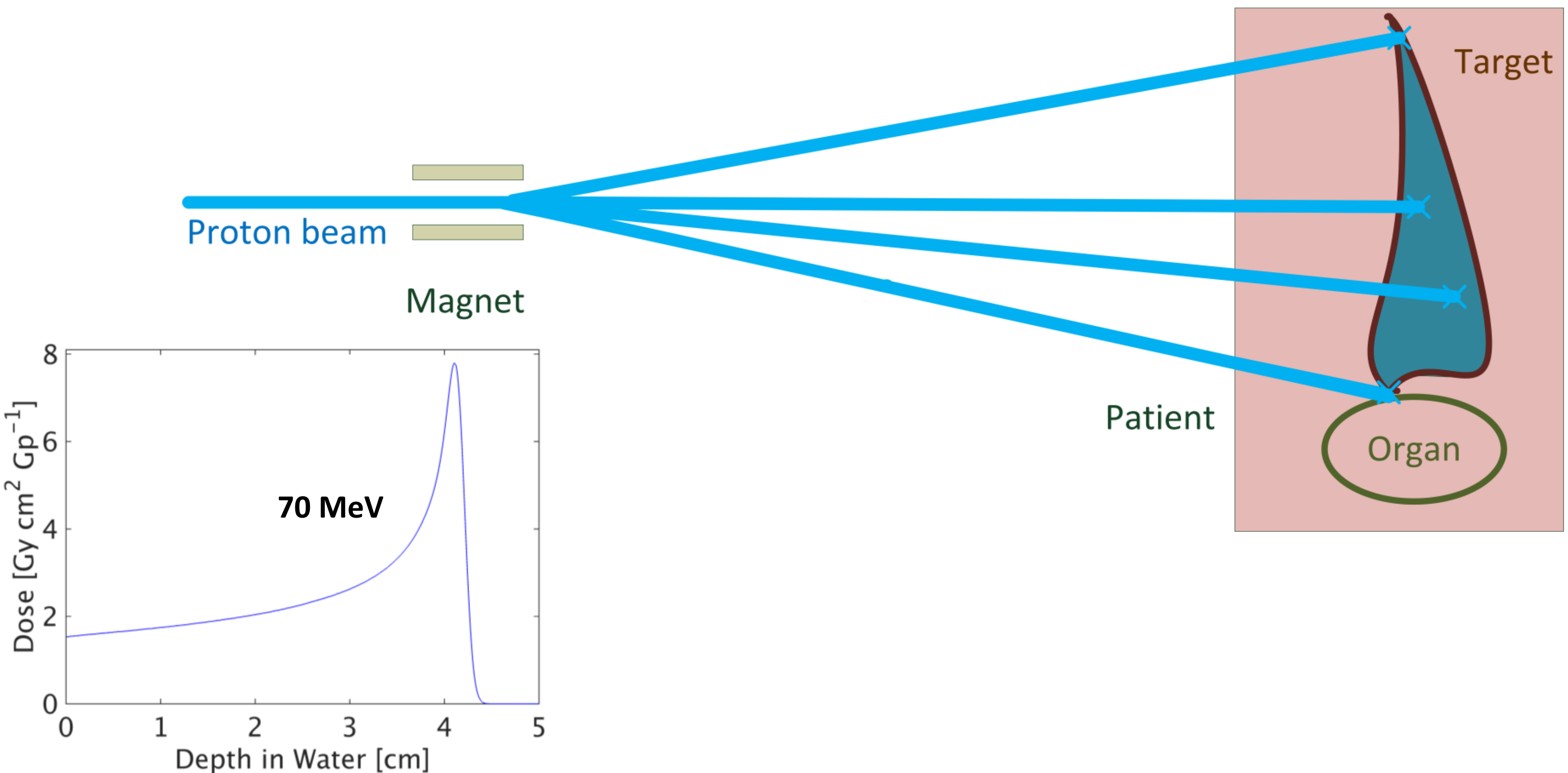
Comparison of two Monte Carlo calculation engines for proton pencil beam scanning

International Conference on Monte Carlo Techniques for Medical Applications
16th of October 2017

Introduction – Proton pencil beam scanning

Pencil beam scanning:

- Small proton beams (spots) are directed into the target
- Depth is adjusted by energy change (70 MeV to 230 MeV) and pre-absorber usage



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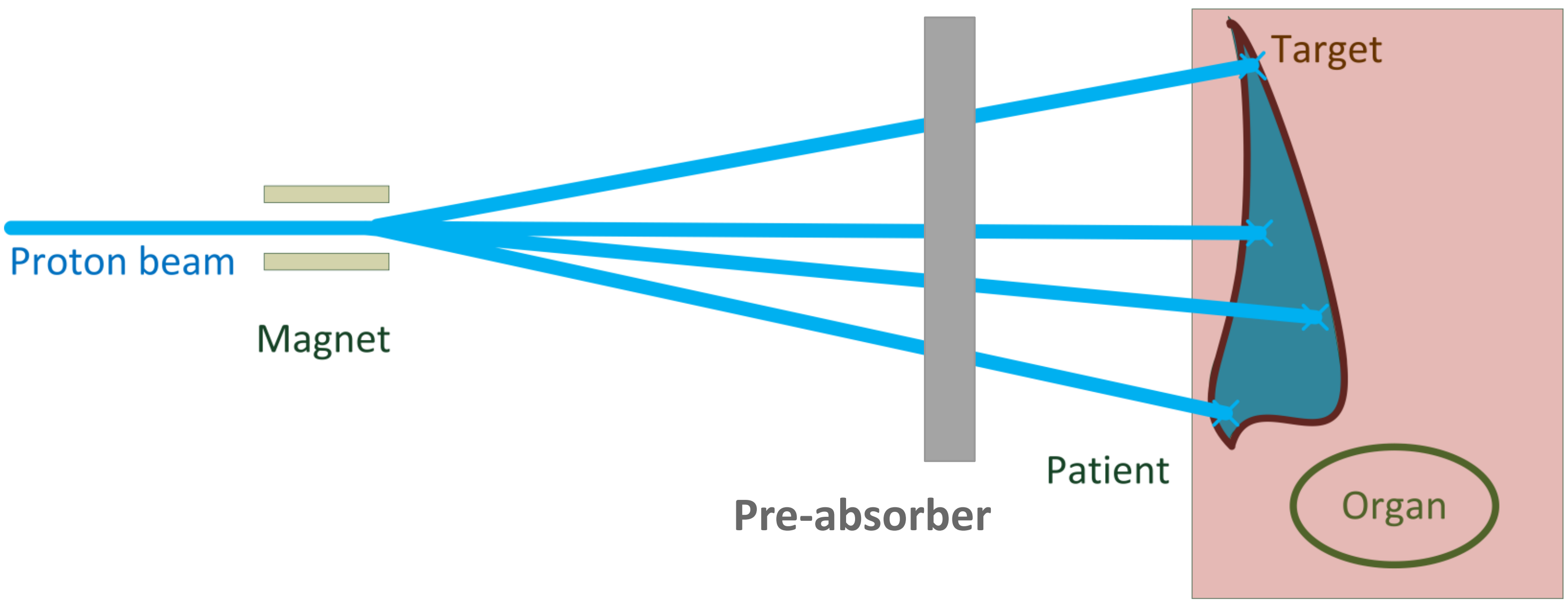
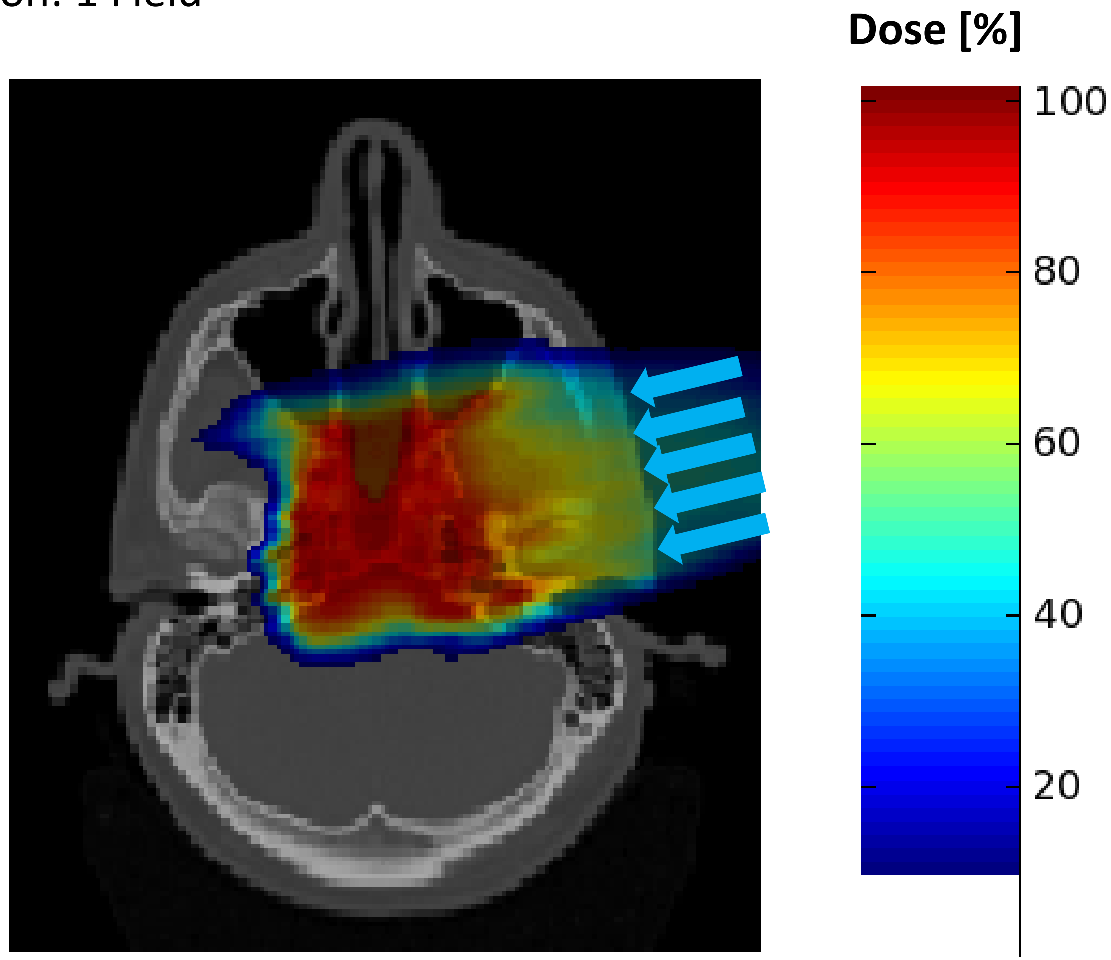


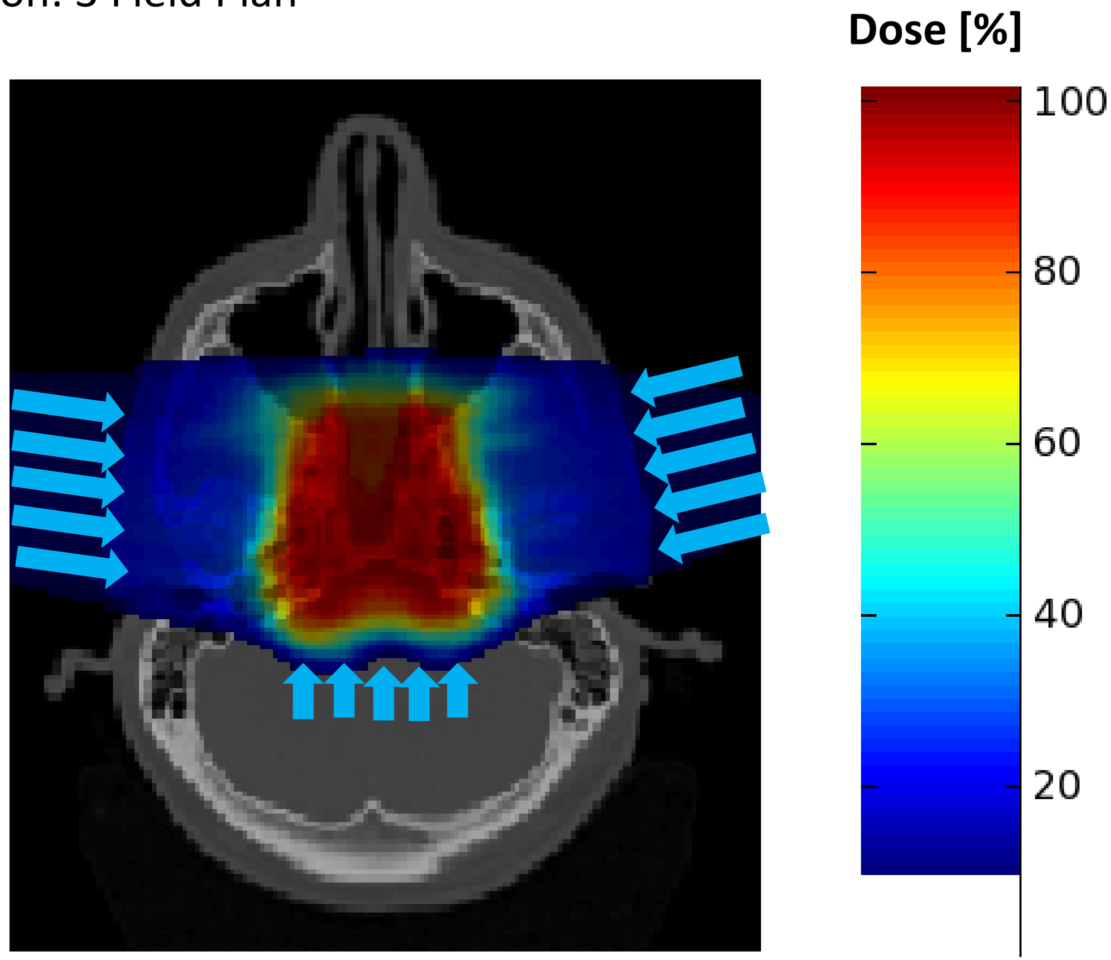
Introduction – Proton pencil beam scanning

Dose distribution: 1 Field



Introduction – Proton pencil beam scanning

Dose distribution: 3 Field Plan



Monte Carlo for proton pencil beam scanning

Monte Carlo simulation models for proton pencil beam scanning are not an off-the shelf tool.

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

Comissioning data PSI Gantry 2

Comparison of two Monte Carlo engines for proton pencil beam scanning

Comissioning data PSI Gantry 2

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

Comparison of two Monte Carlo engines for proton pencil beam scanning

Comissioning 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

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Compare dose results in simple geometric setups and in patient geometries

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

Overview

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

- Setup of the two Monte Carlo systems

- Comparison of the doses calculated with the two Monte Carlo systems in simple geometries & patient geometries
  - Without pre-absorber
  - With pre-absorber

- Discussion
  - Which factors are critical when setting up the Monte Carlo system?
  - How big are the remaining differences?

Setup of the two Monte Carlo systems

Setup Monte Carlo model for proton pencil beam scanning

- Choose Monte Carlo code, toolkit and physics

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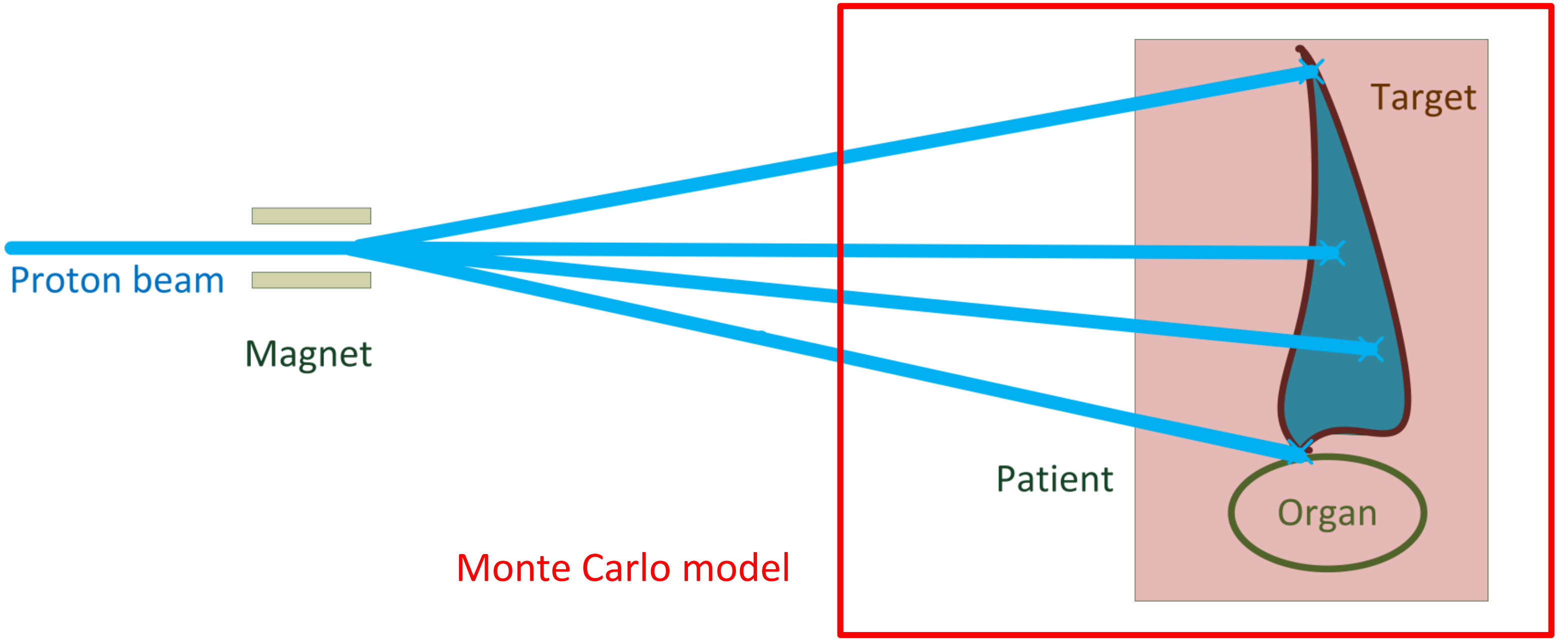

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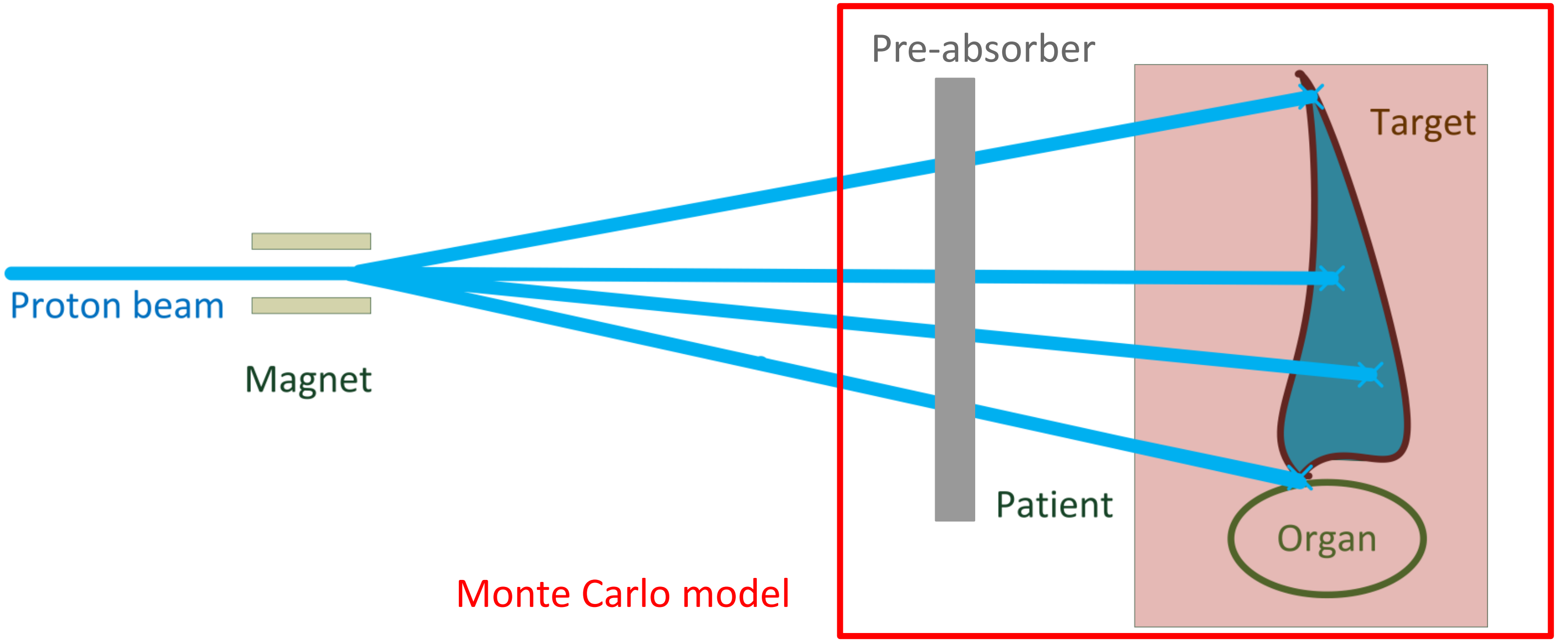

[1] GRASSBERGER, C., et al. 2015. *Phys Med Biol,* 60**,** 633-45.
[2] GREVILLOT, et al. 2011. *Phys Med Biol,* 56**,** 5203-19.
[3] FRACCHIOLLA, F., et al. 2015. *Phys Med Biol,* 60**,** 8601-19.

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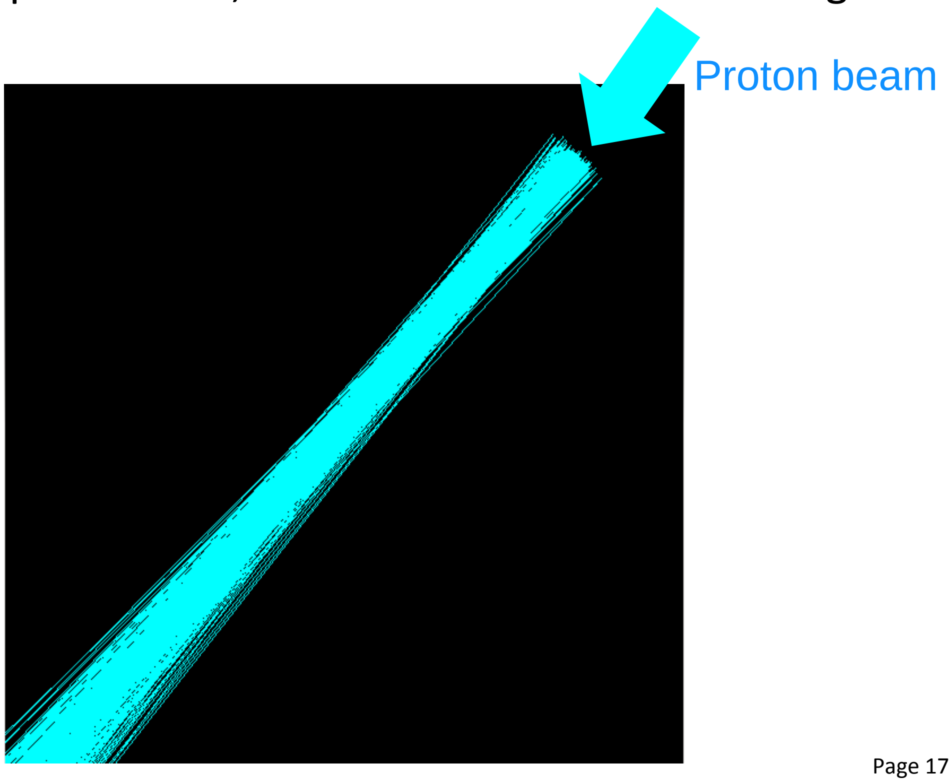

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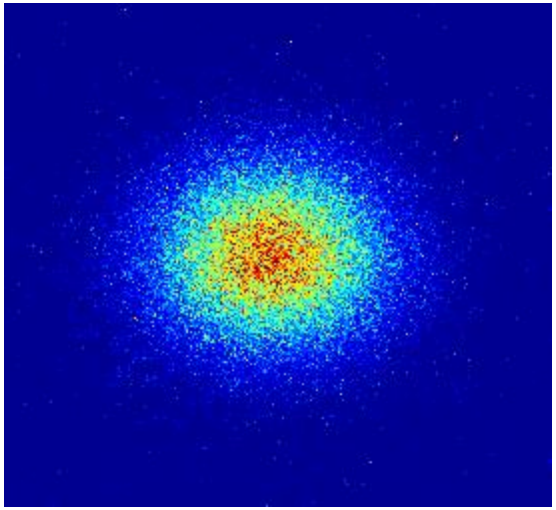

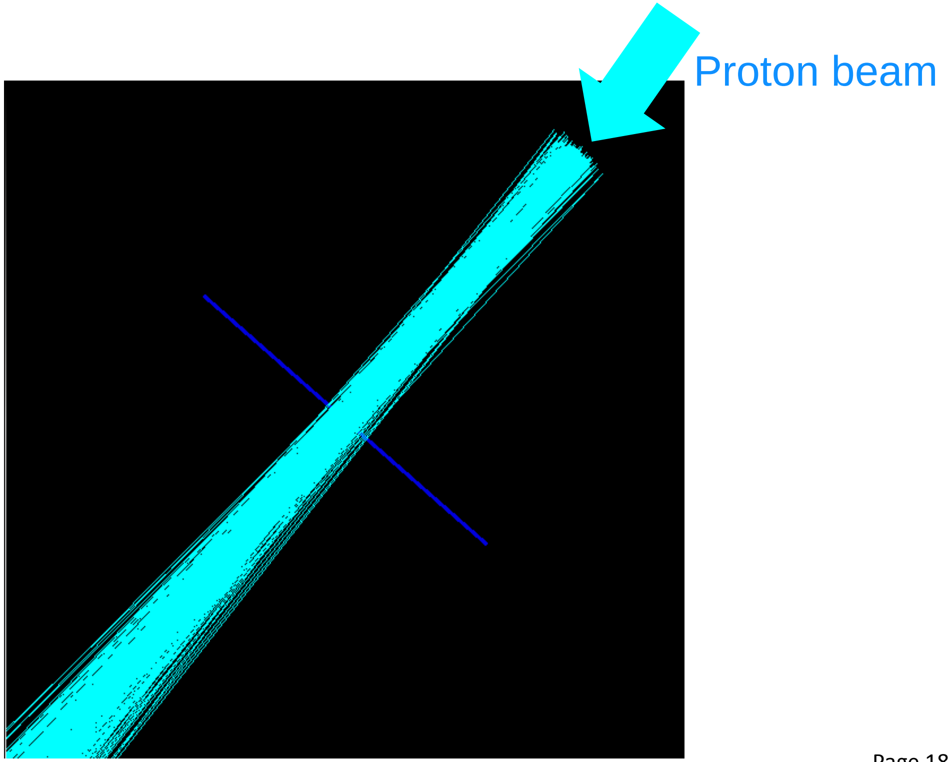

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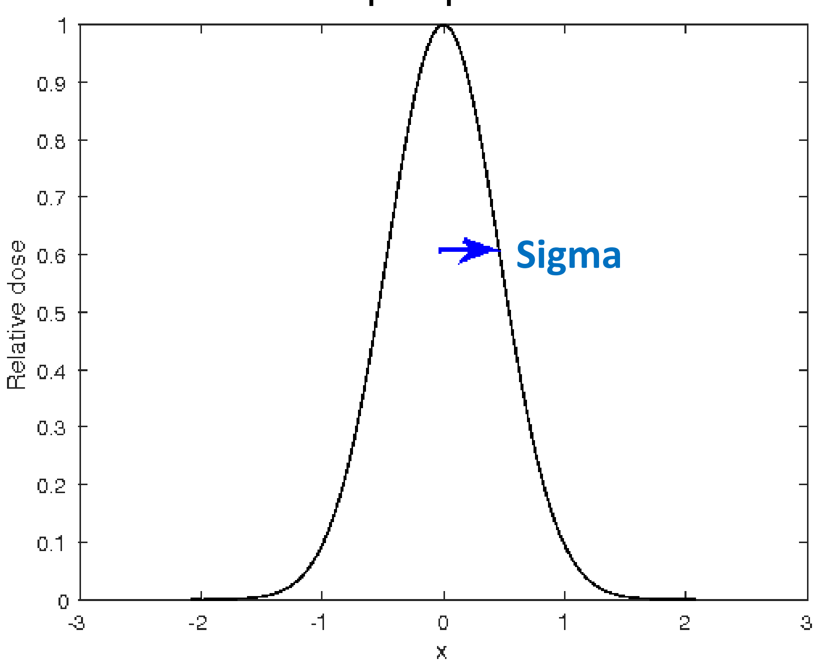

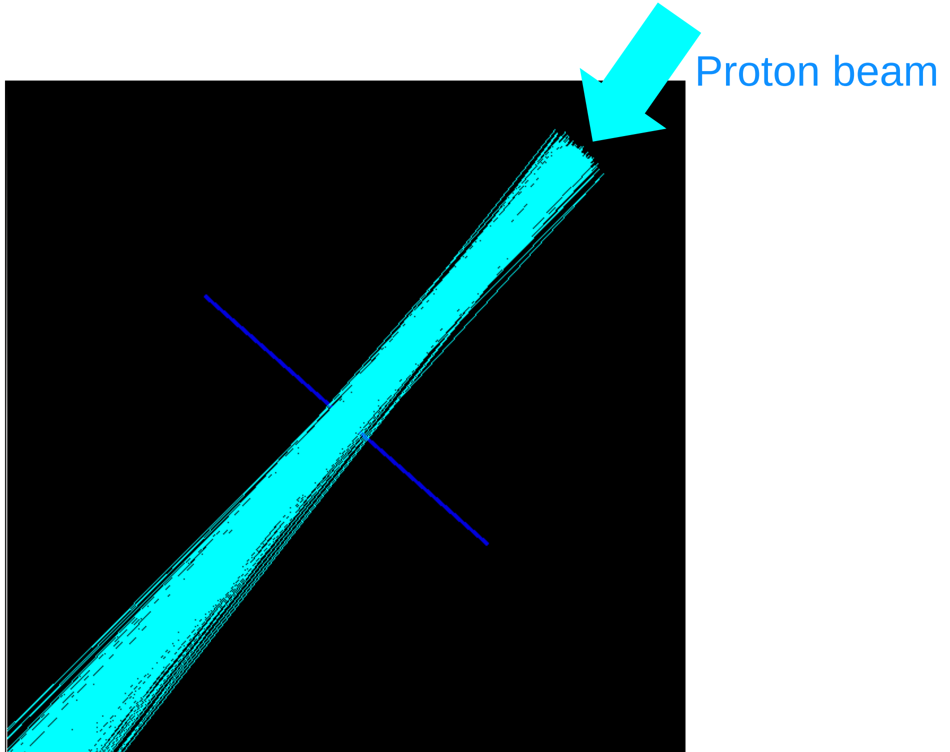

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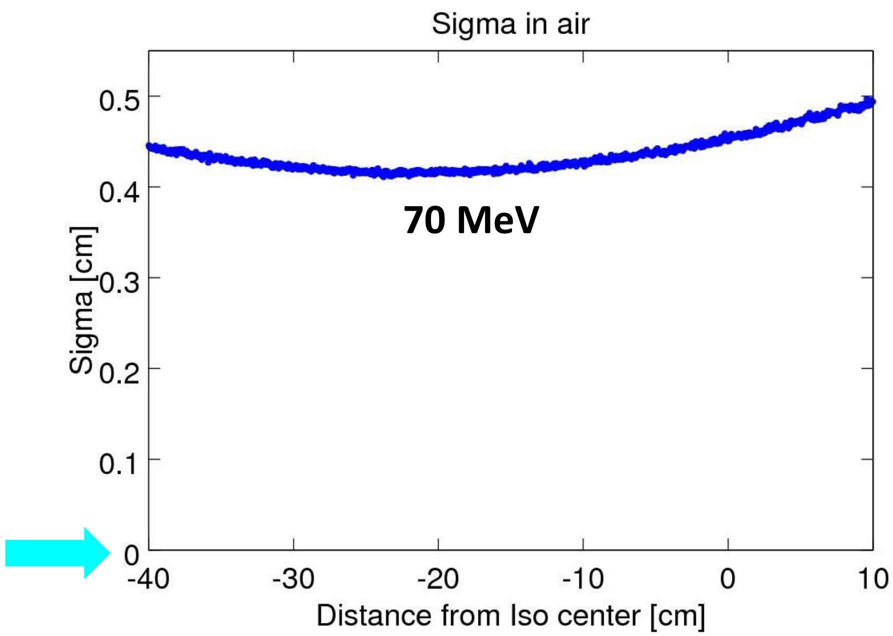

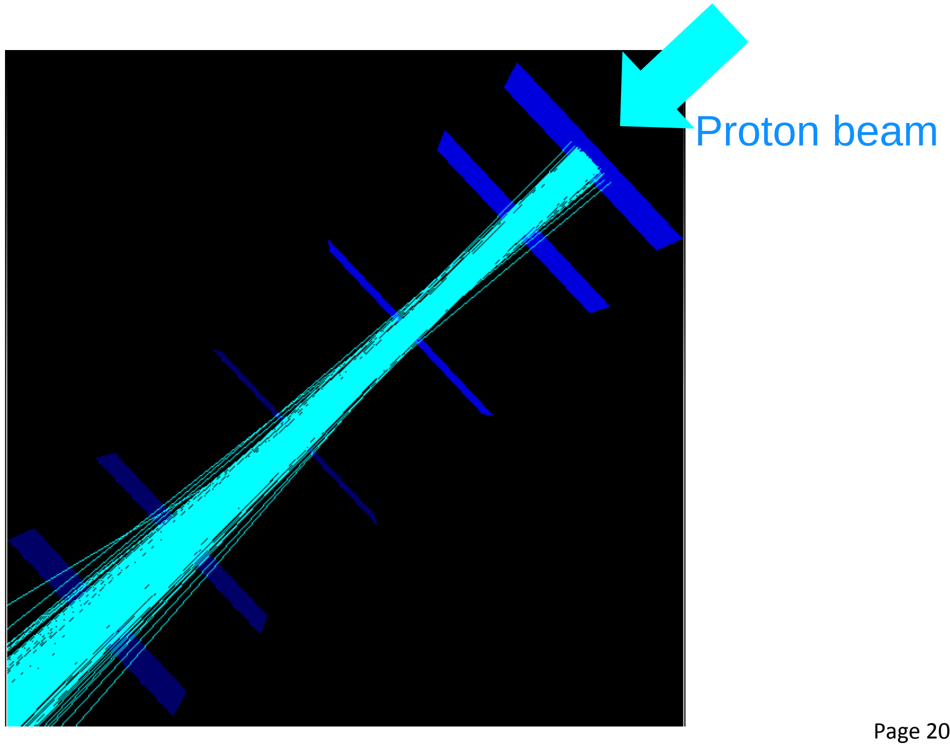

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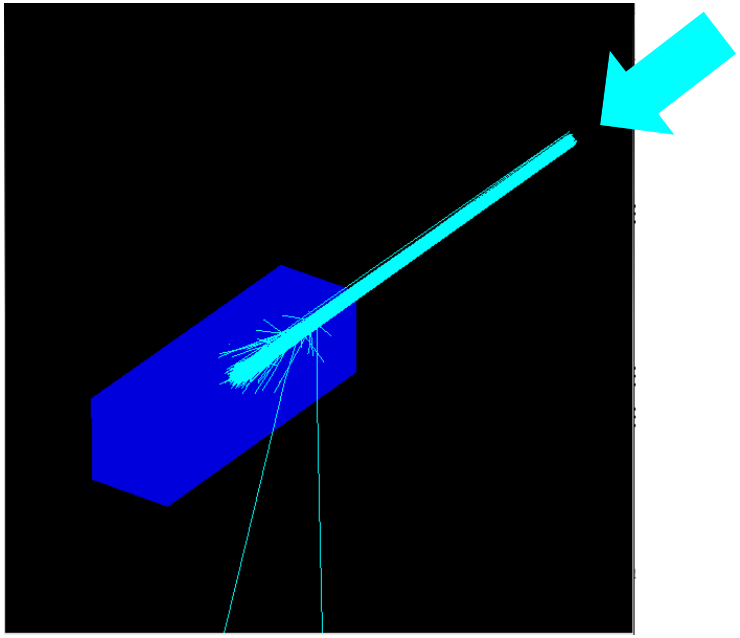

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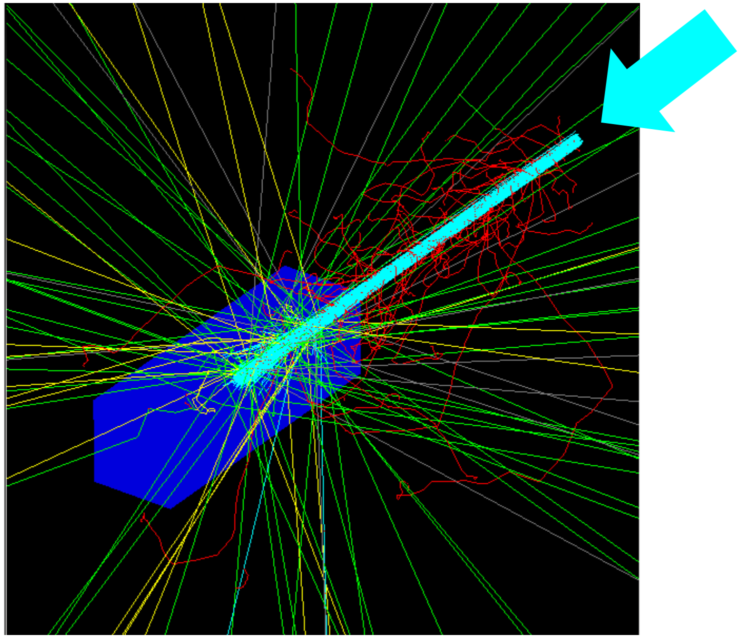

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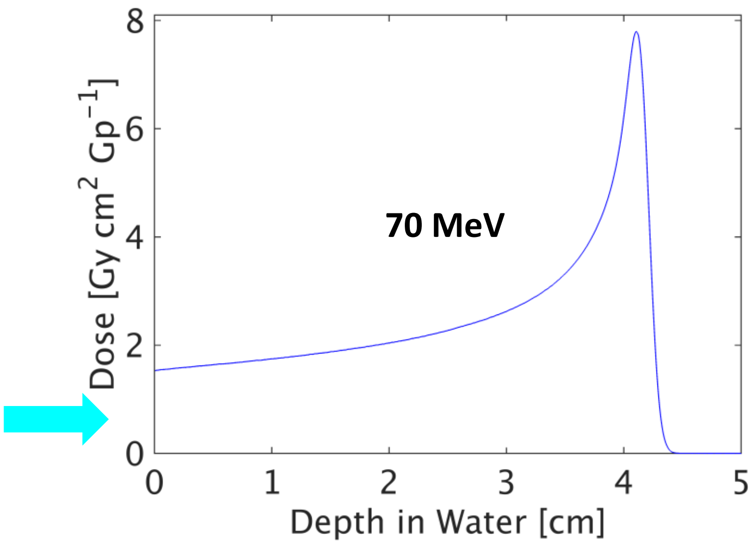

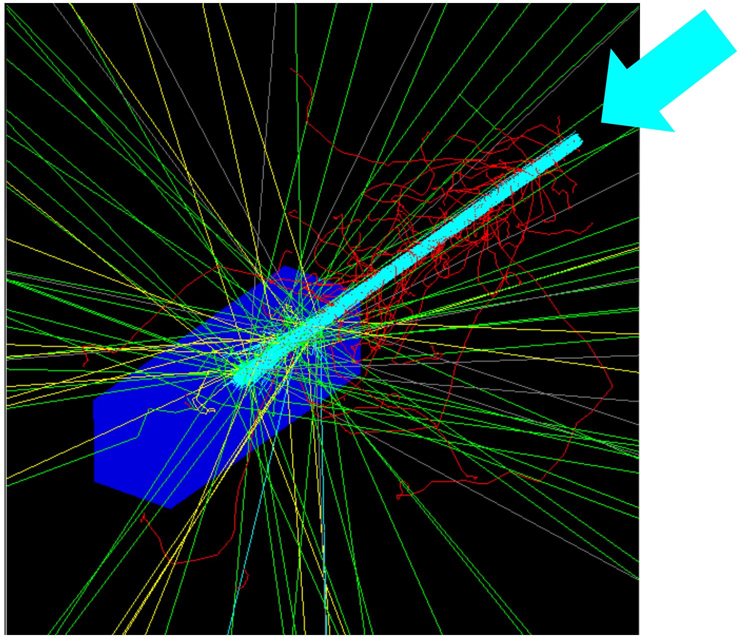

Setup of the two Monte Carlo models

PSI model

The Christie model

Monte Carlo: *Which Monte Carlo code, toolkit and physics?*
Physics:

Geometry: *Decide where to start the model & which components to include*
Pre-absorber:

Beam model: *Fine tune beam input parameters, such that simulation results agree with*
CT calibration: *comissioning data*

Setup of the two Monte Carlo models

	PSI model	**The Christie model**
Monte Carlo:	TOPAS, GEANT4 10.02.p01	Gate, GEANT4 10.02.p01
Physics:	Topas default list [1]	QGSP_BIC

[1] JARLSKOG, C. Z. & PAGANETTI, H. 2008. *IEEE Transactions on nuclear science,* 55**,** 1018-1025.

Setup of the two Monte Carlo models

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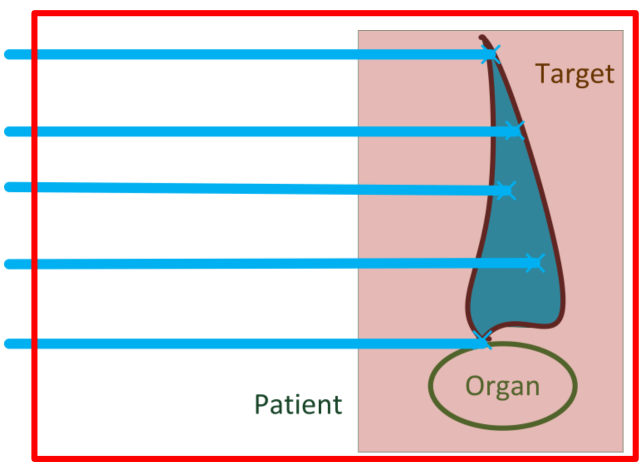
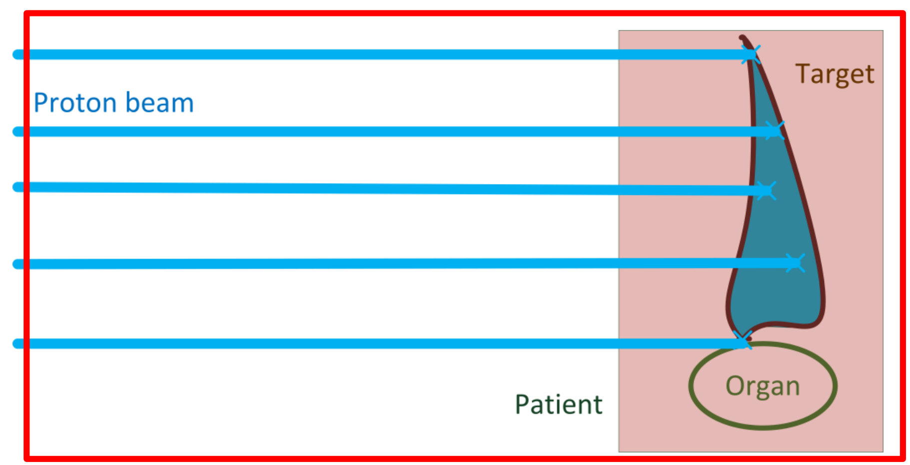


PSI model



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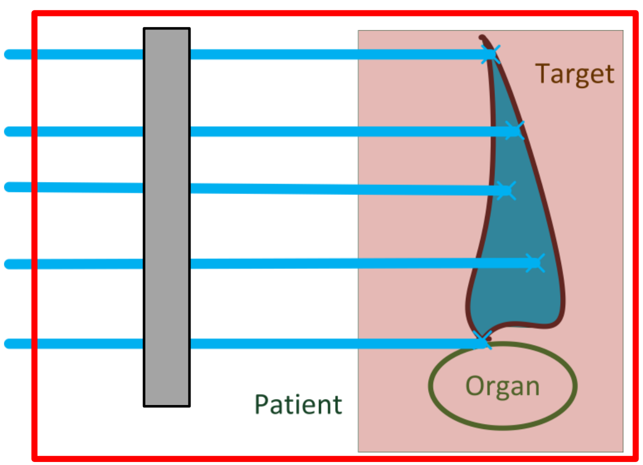

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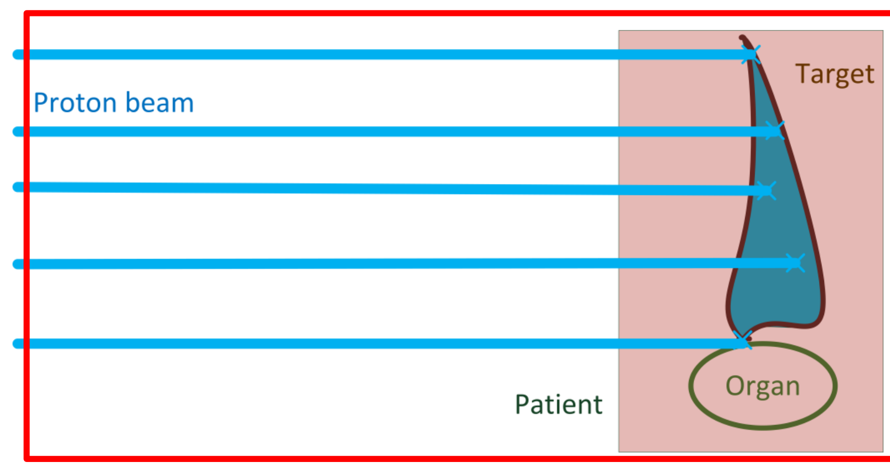

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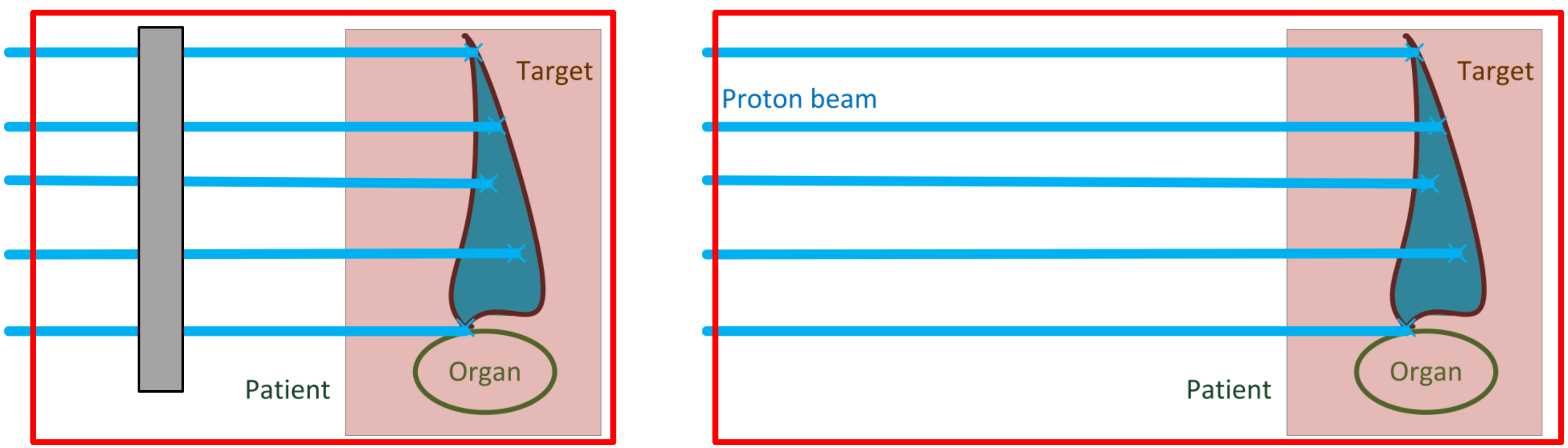

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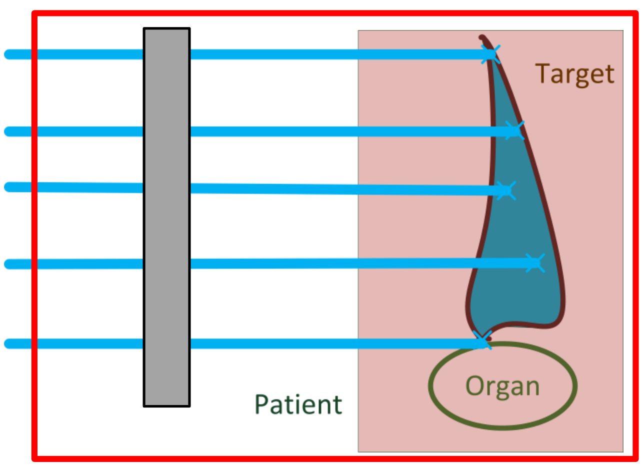
Pre-absorber:	Physical object in the beam	Modify beam optics
Beam model:	Independently tuned such that each system matches same commissioning data	
CT calibration:	Matched in each system	



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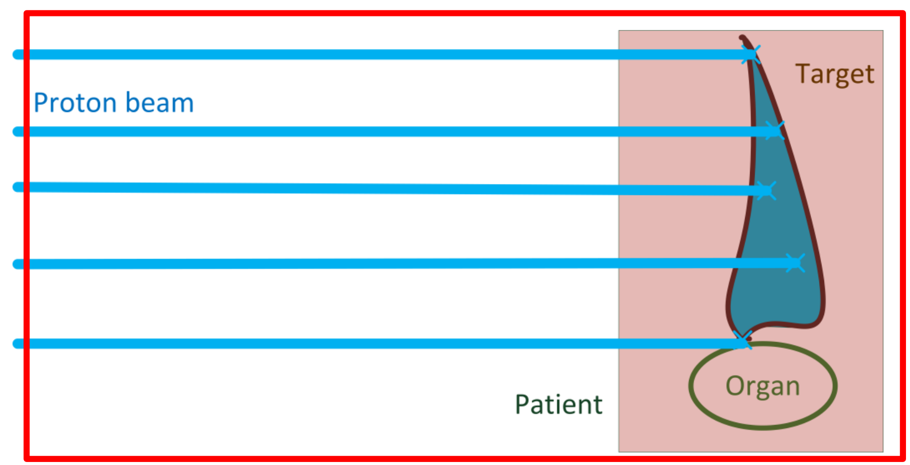
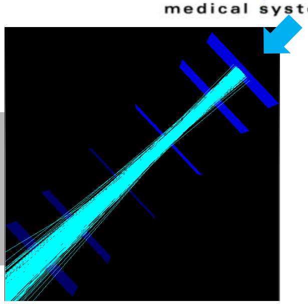


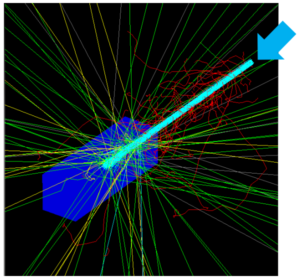
The Christie model

Comparison of the two Monte Carlo systems

Comparison of the two Monte Carlo models



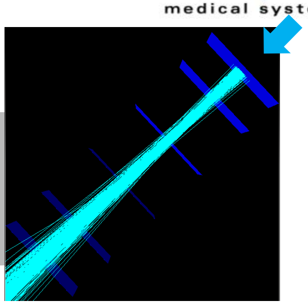
Single spots air



Single spots in water

Check the tuning of the two models

Comparison of the two Monte Carlo models



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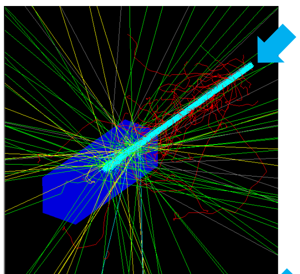
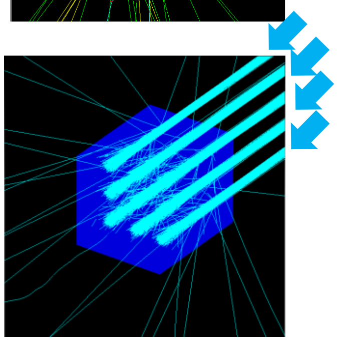


Single spots in water

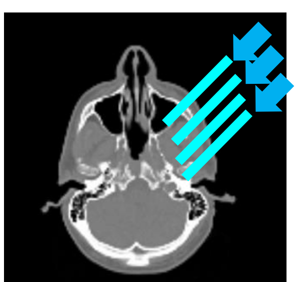
Check the tuning of the two models

Single spots in bone & brain



Patient fields in water

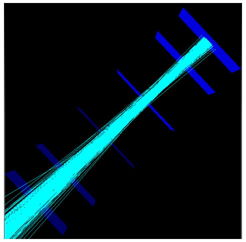
Compare the two models

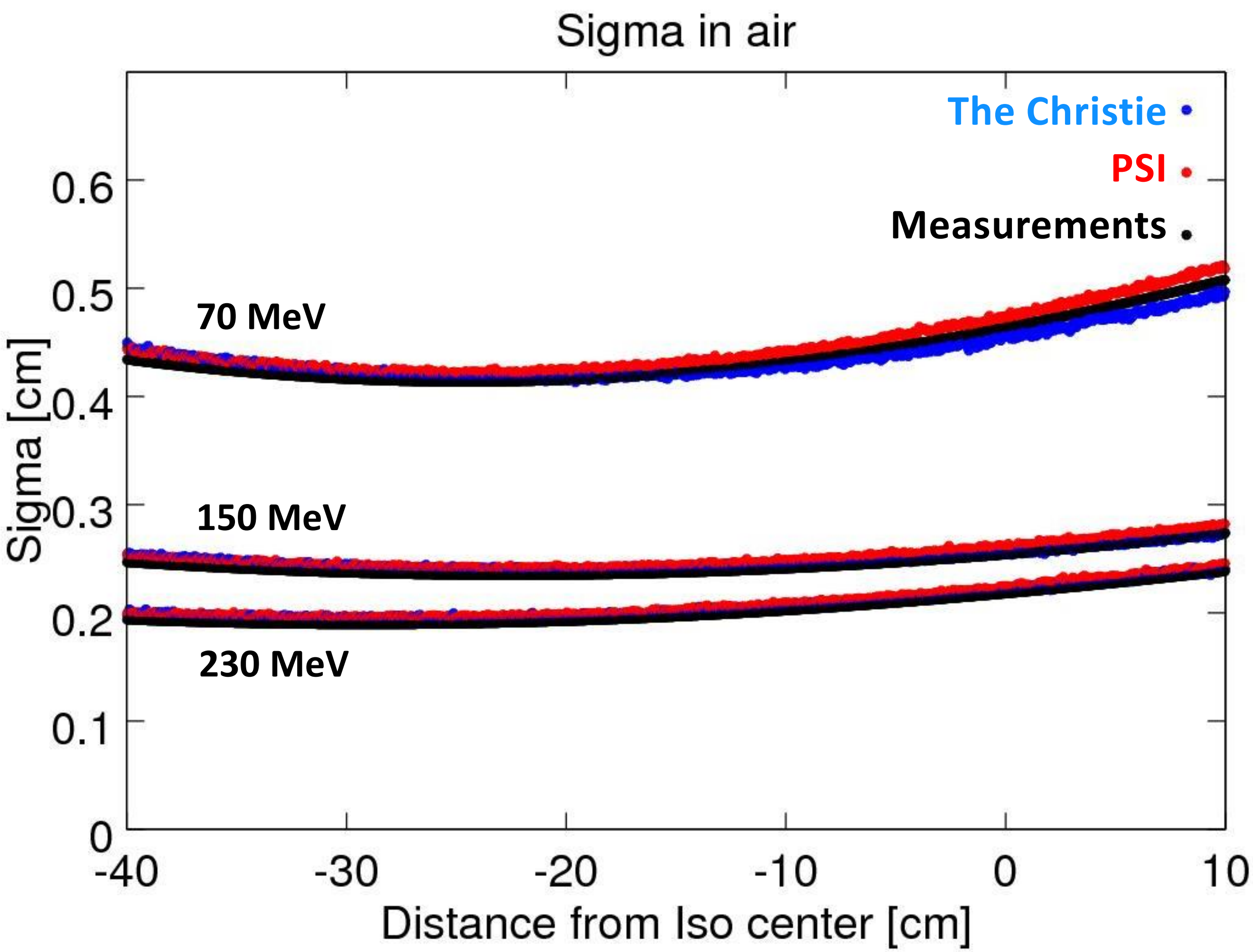


Patient fields in the CT

Results without pre-absorber

Tuning: Spot sizes in air





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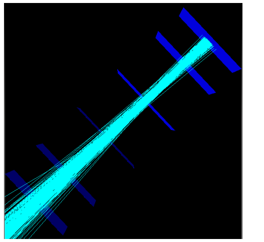
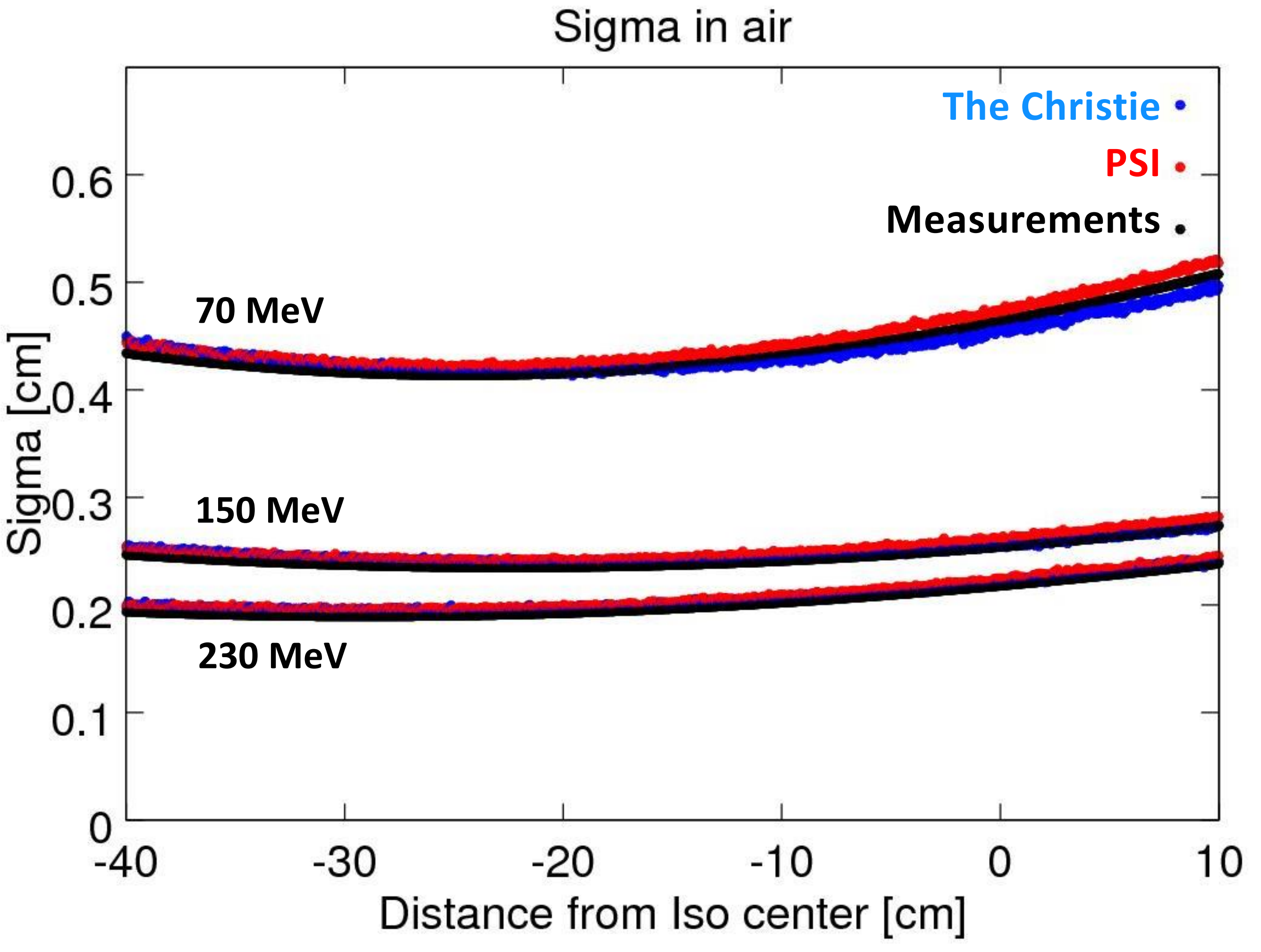
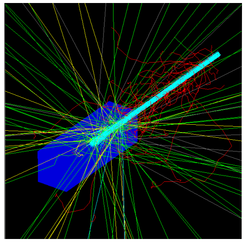
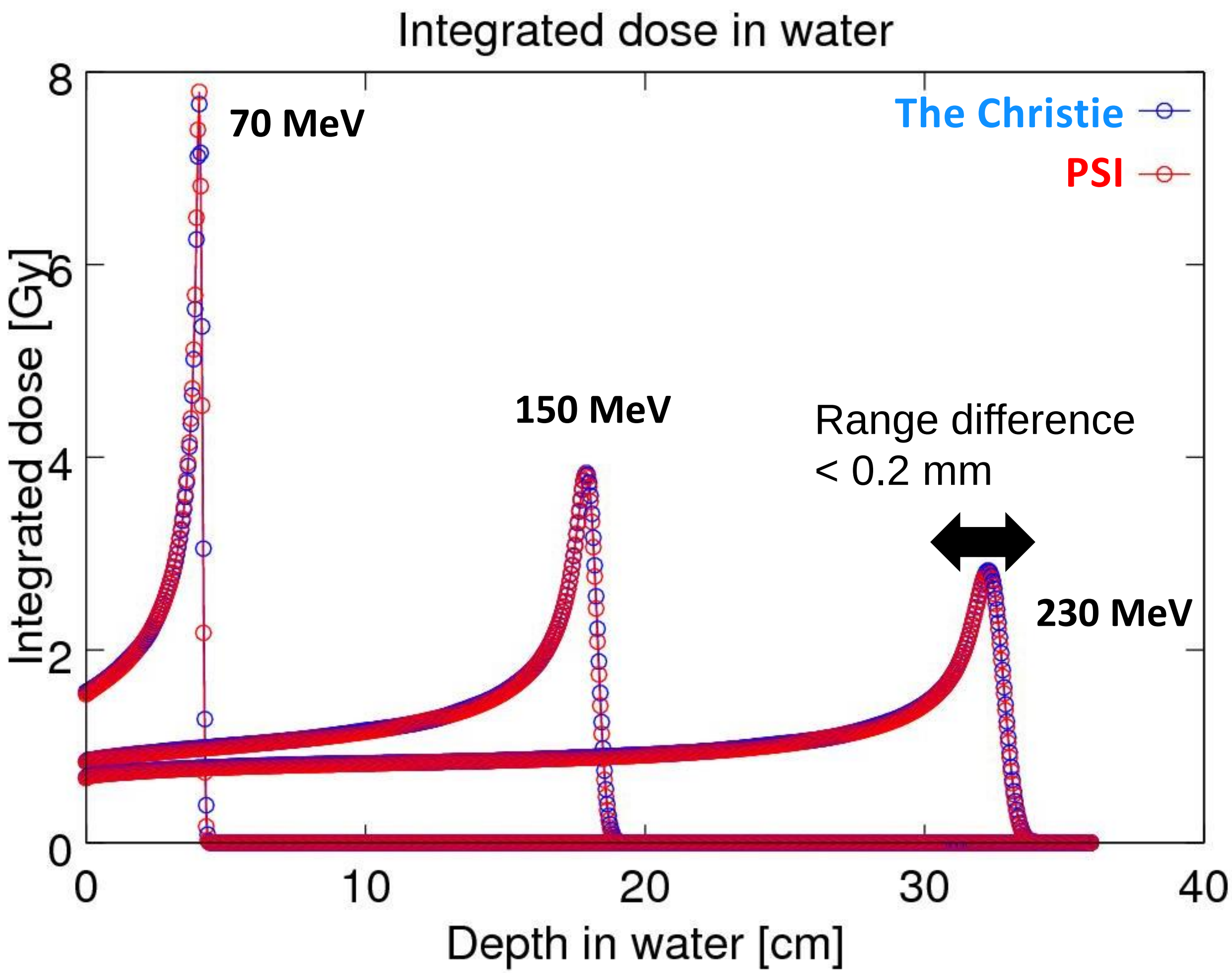




Good agreement between both Monte Carlo engines and measurements (0.2 mm)

Tuning: Range in water





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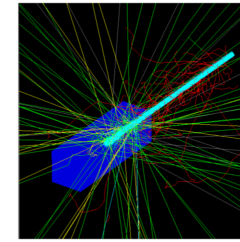
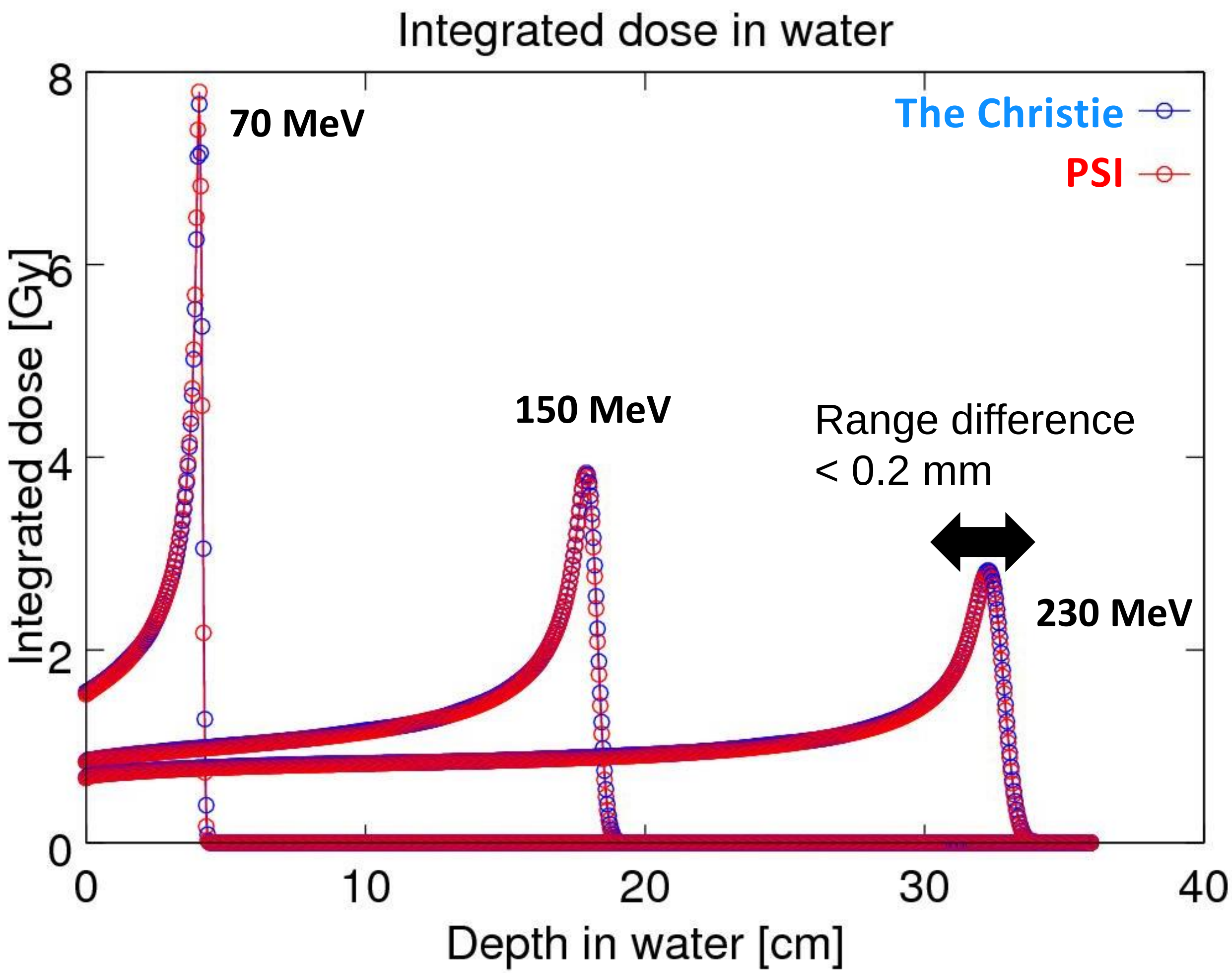
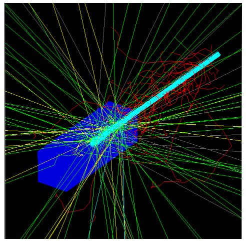


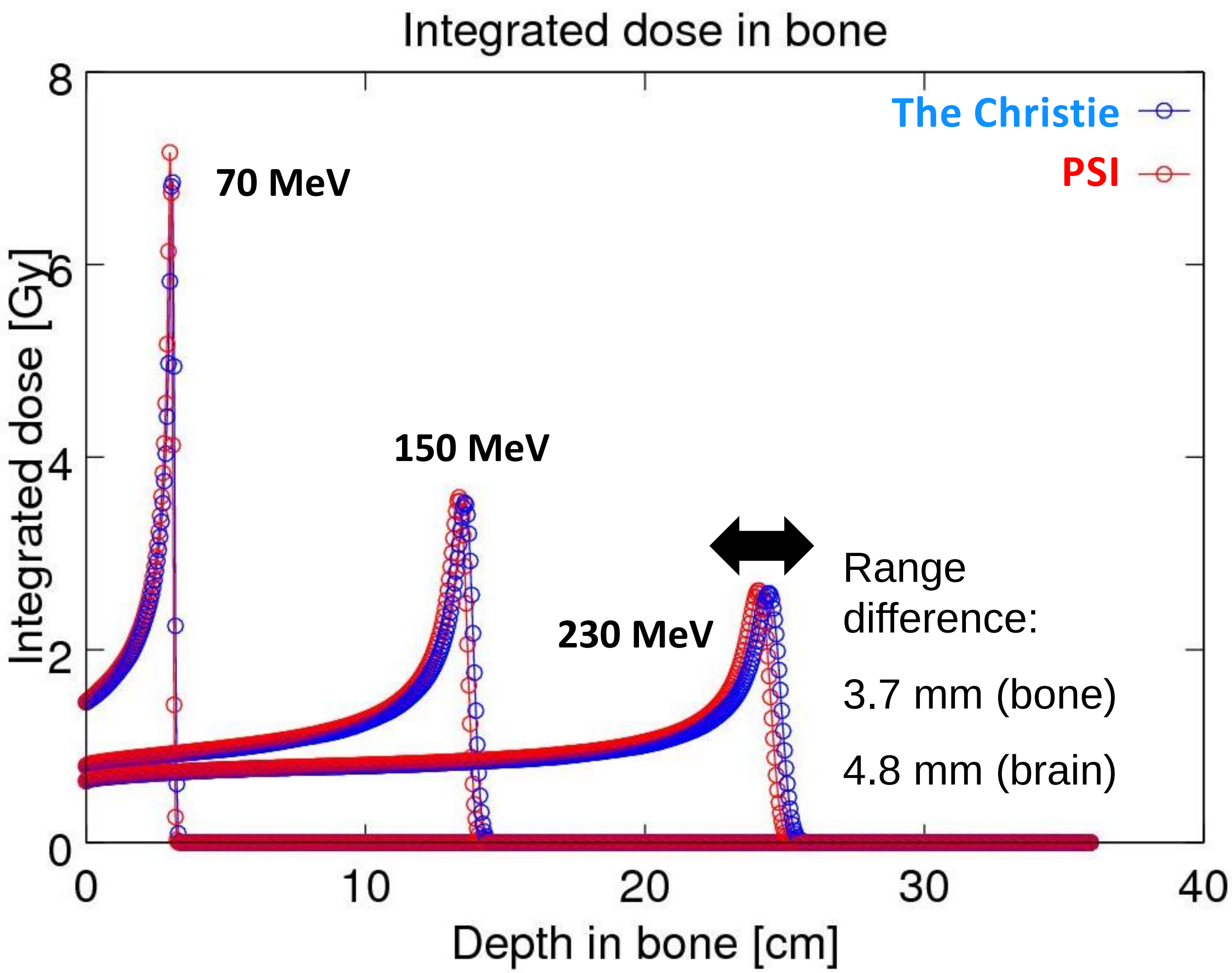


Ranges match in water, the material we used for the tuning of the two systems

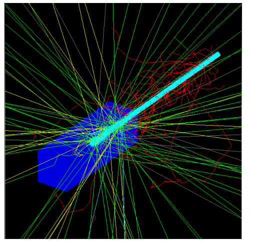
✓

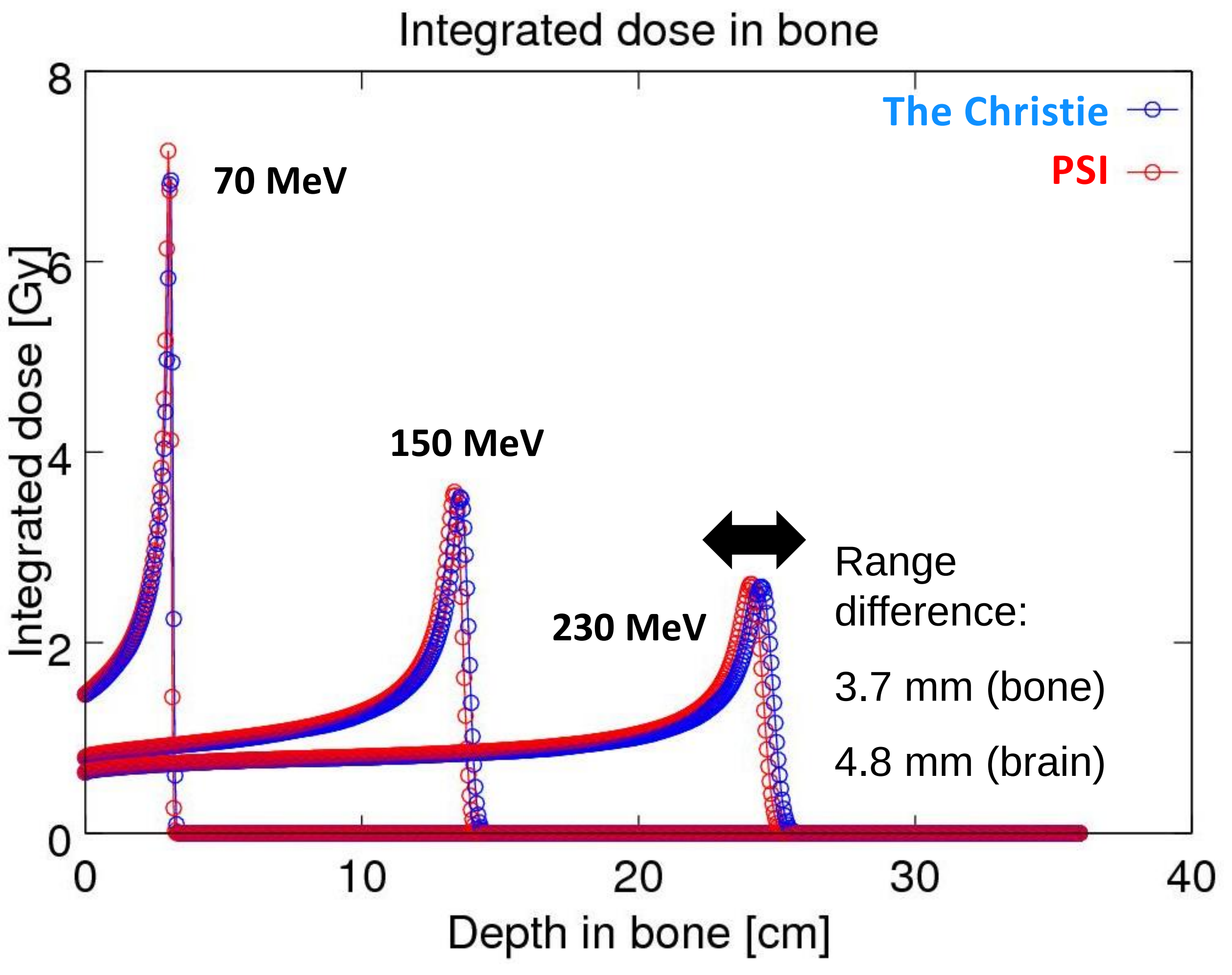
Range in bone & brain





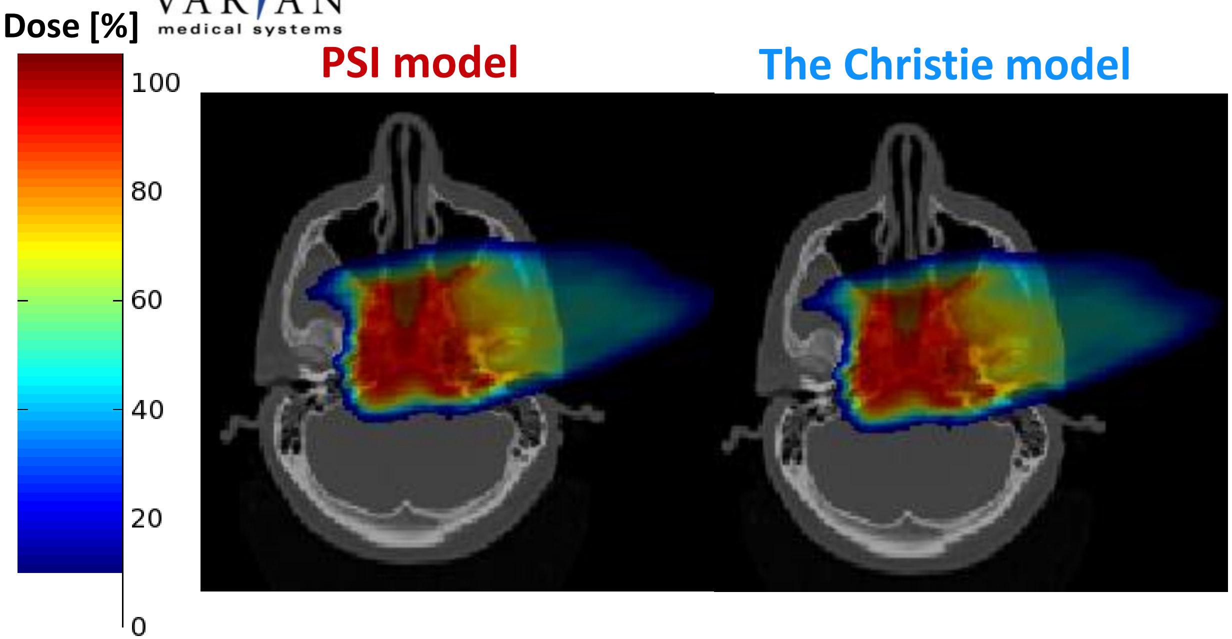
Range in bone & brain





Ranges do not match in other materials than water.

Patient fields in the CT



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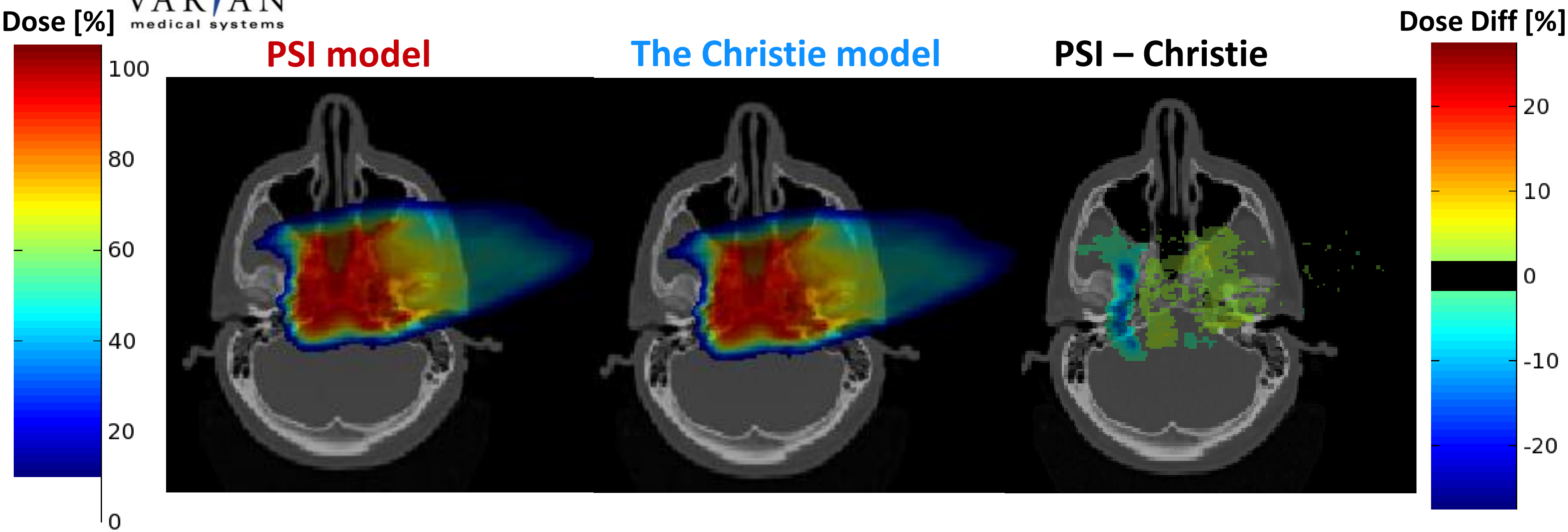

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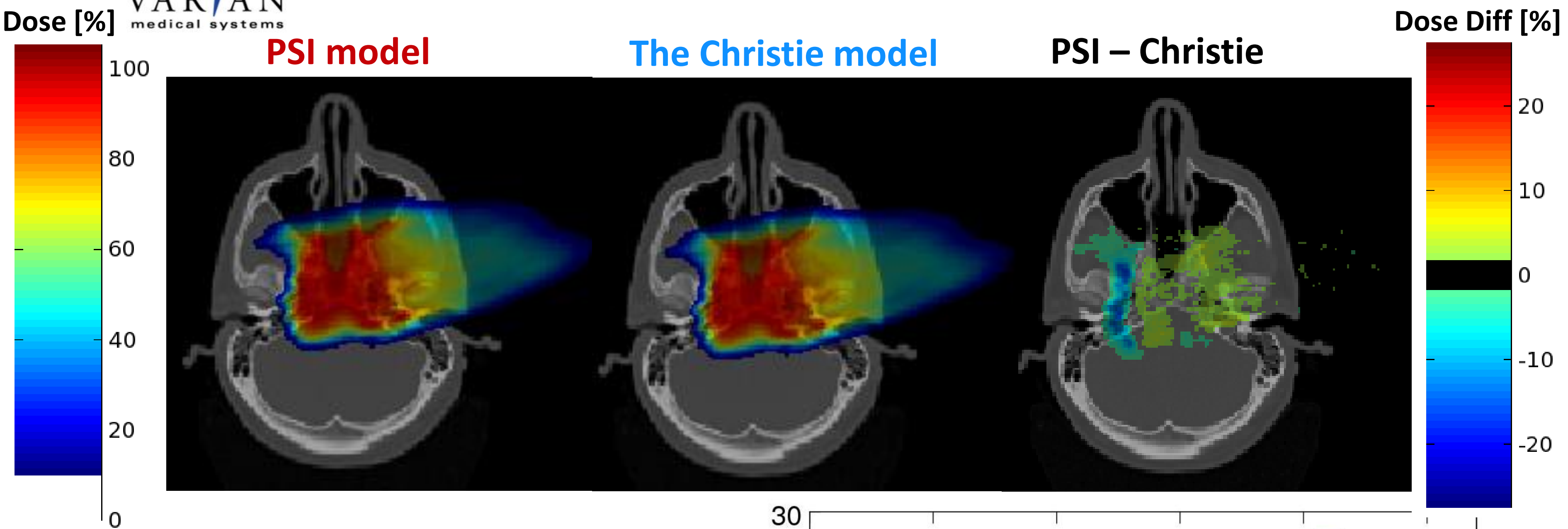

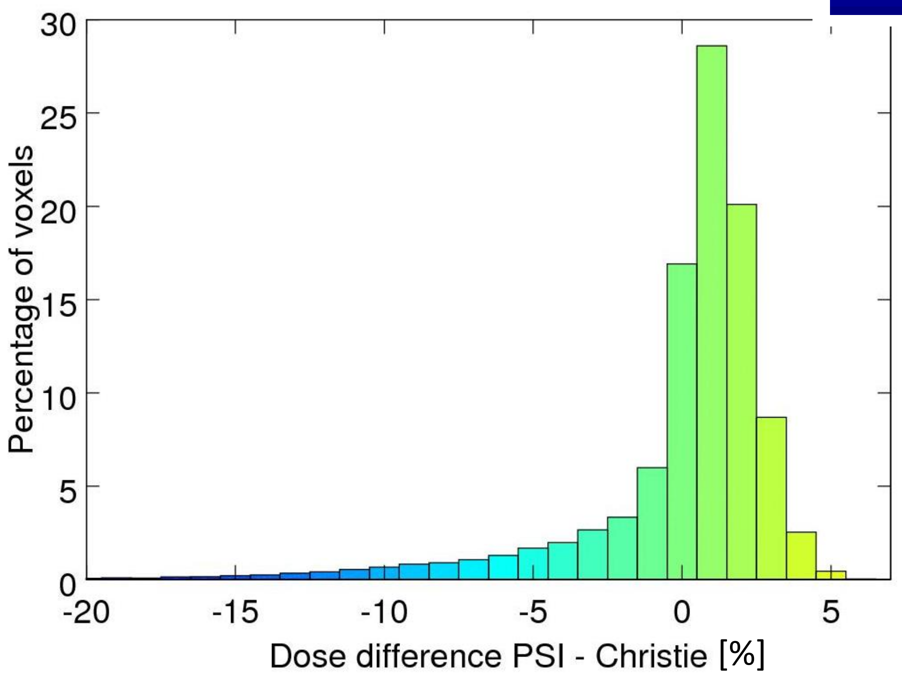

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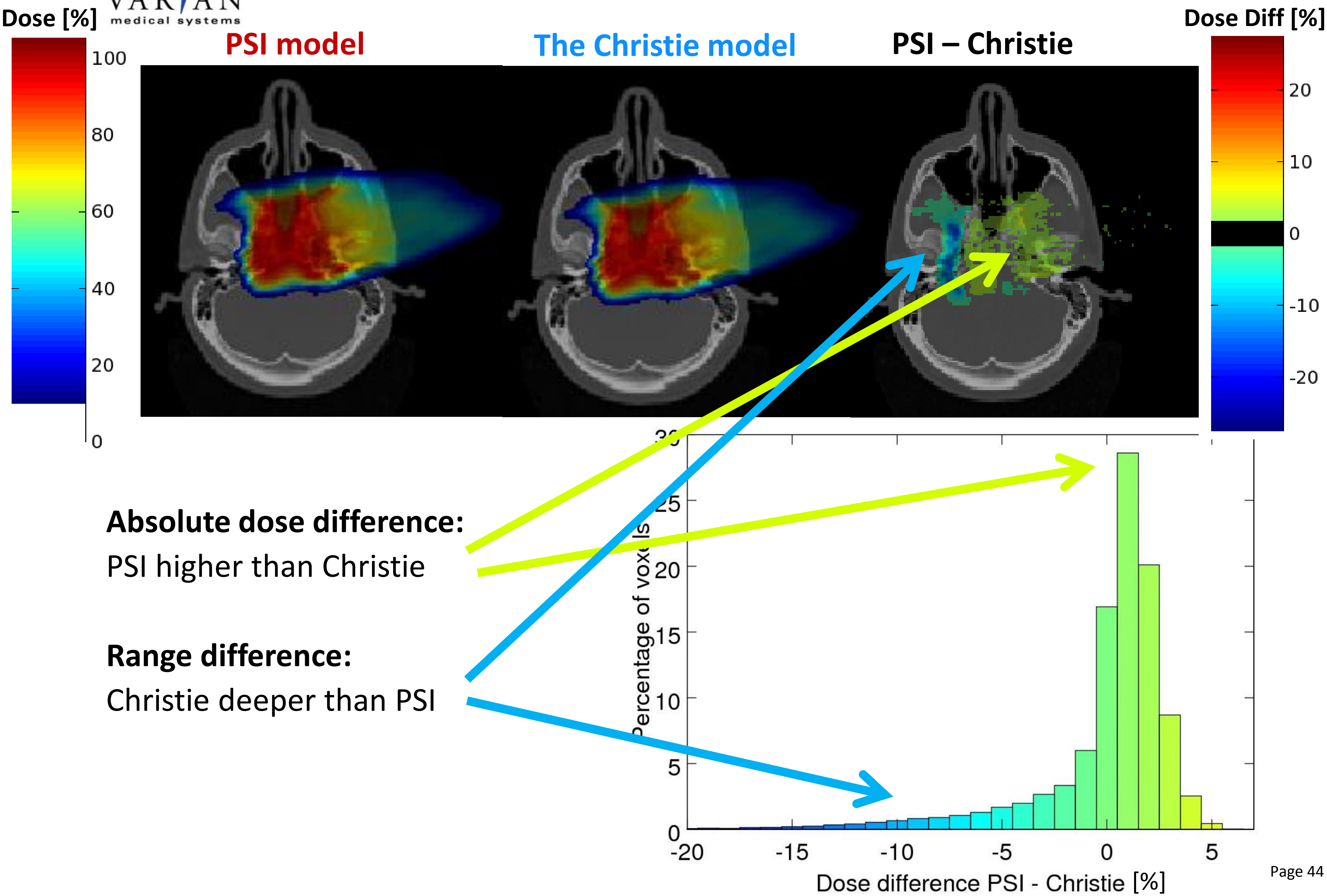

Absolute dose difference:

PSI higher than Christie

Range difference:

Christie deeper than PSI

Ionisation potentials

- Difference due to **different default ionisation potentials of water.**
- **Ionisation potential**: Energy needed to remove one electron from the atom.

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- **The Christie system**:
  - Water is defined using its elemental composition
  - Resulting ionisation potential: **I = 69 eV**
- **PSI system**:
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This would have never been found by comparing simulations to measurements in water!

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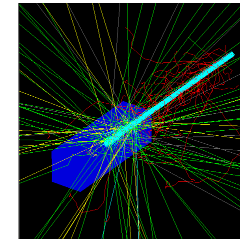
How much do Monte Carlo simulated doses depend on the model setup?

Pay close attention to ionisation potentials!

Results without pre-absorber
After retuning The Christie system with I = 78 eV

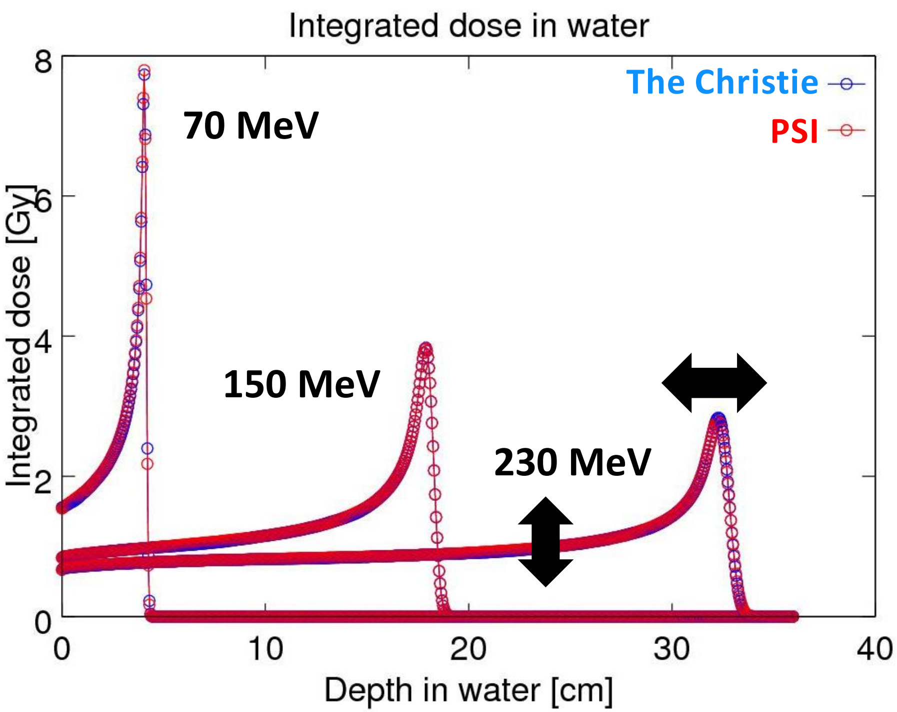
Tuning: Spots in water & bone & brain

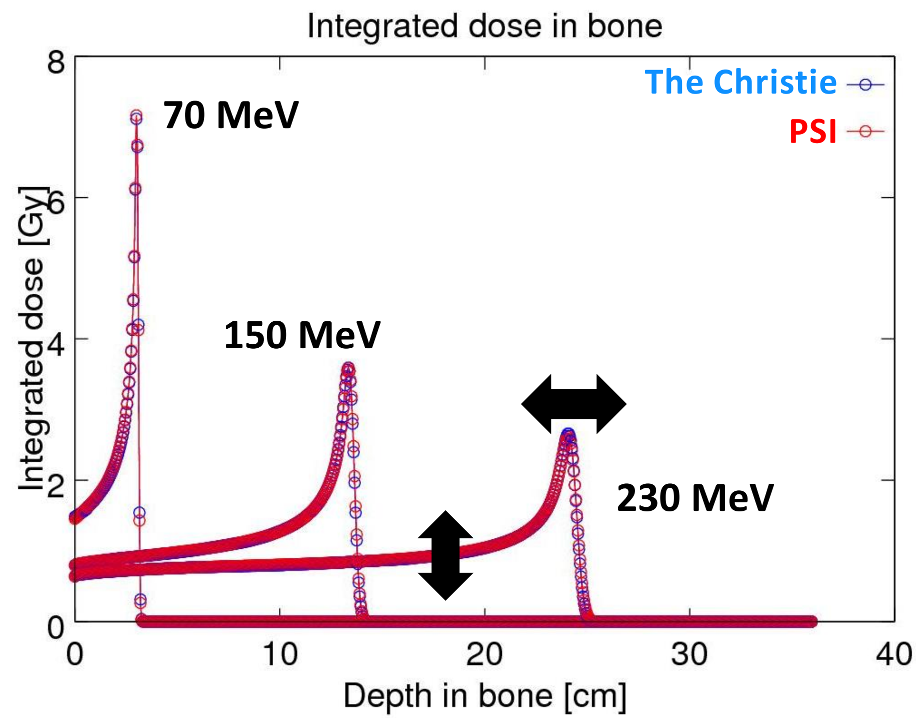


After retuning The Christie system with I = 78 eV:

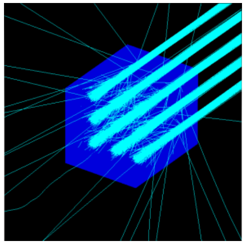
Ranges agree within 0.15 mm for all materials

Absolute doses agree within 0.25%

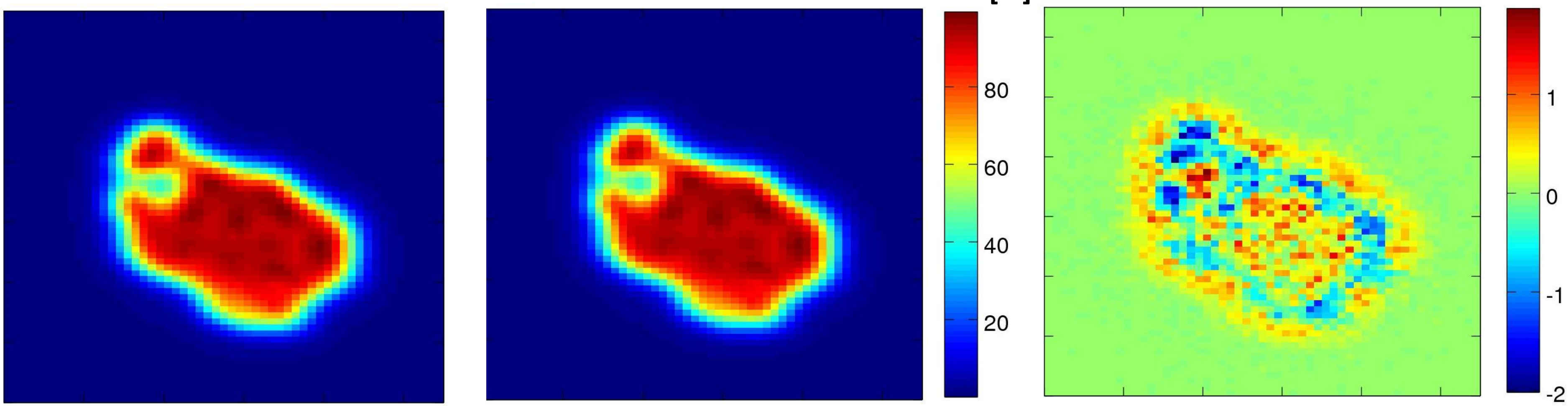




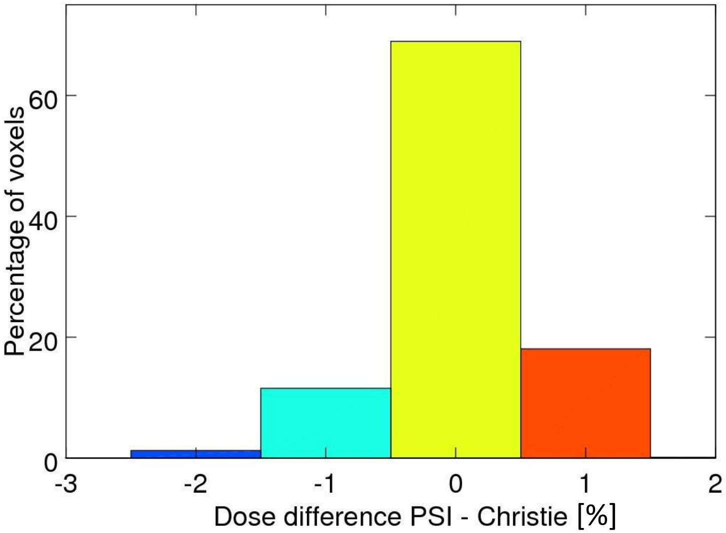
Patient fields in the water tank



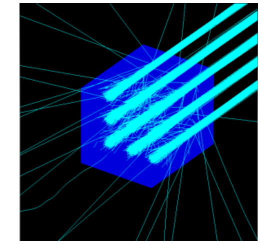
PSI model | **The Christie model** | **PSI – Christie**

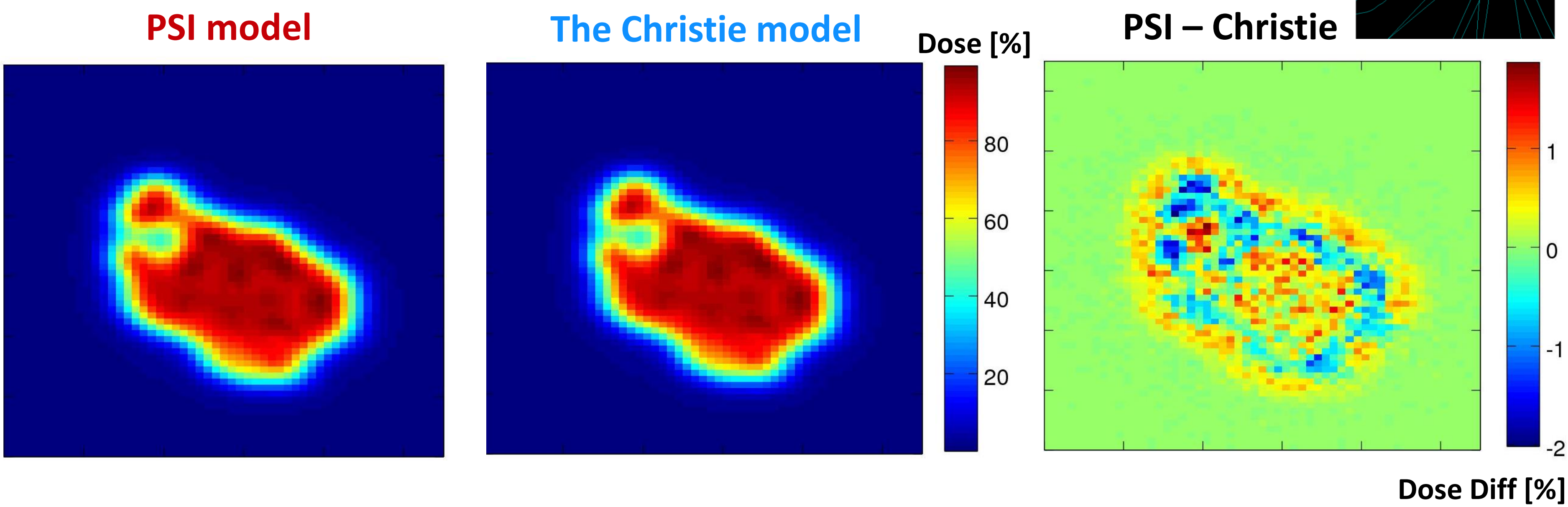


Christie model versus PSI model:
Gamma analysis: 100% (2%,2mm); ≥ 99.6% (1%,1mm)
98% of the voxels agree within 1.5%



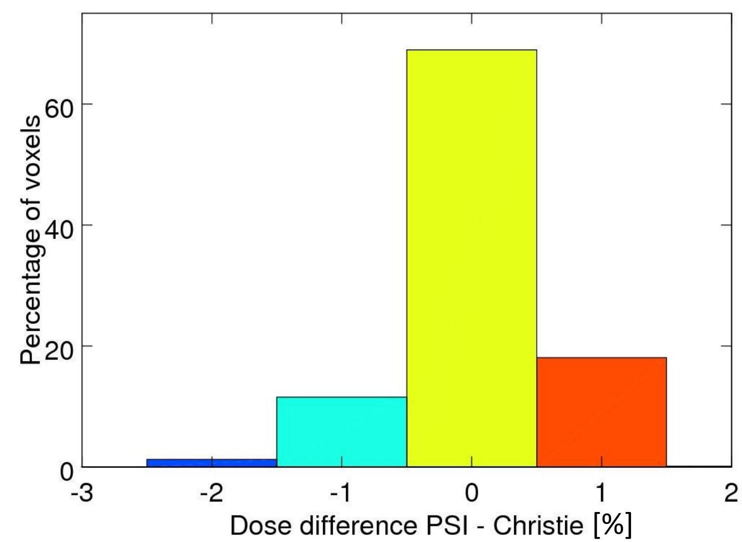
Patient fields in the water tank



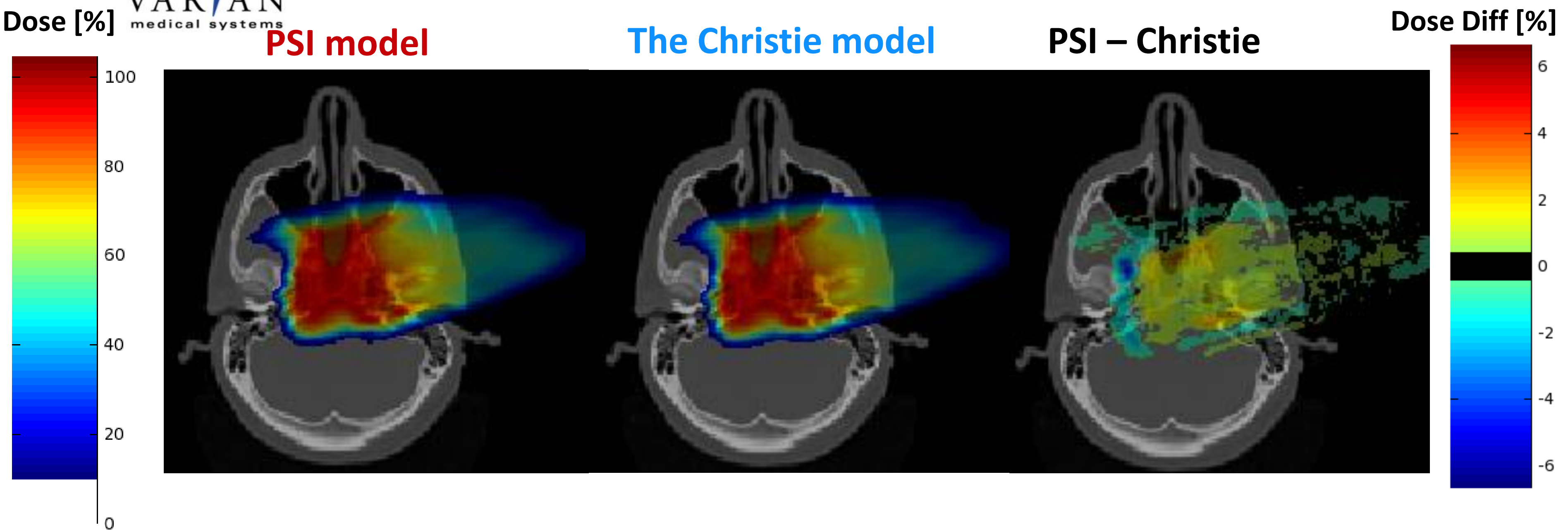


Christie model versus PSI model:
Gamma analysis: 100% (2%,2mm); ≥ 99.6% (1%,1mm)
98% of the voxels agree within 1.5%

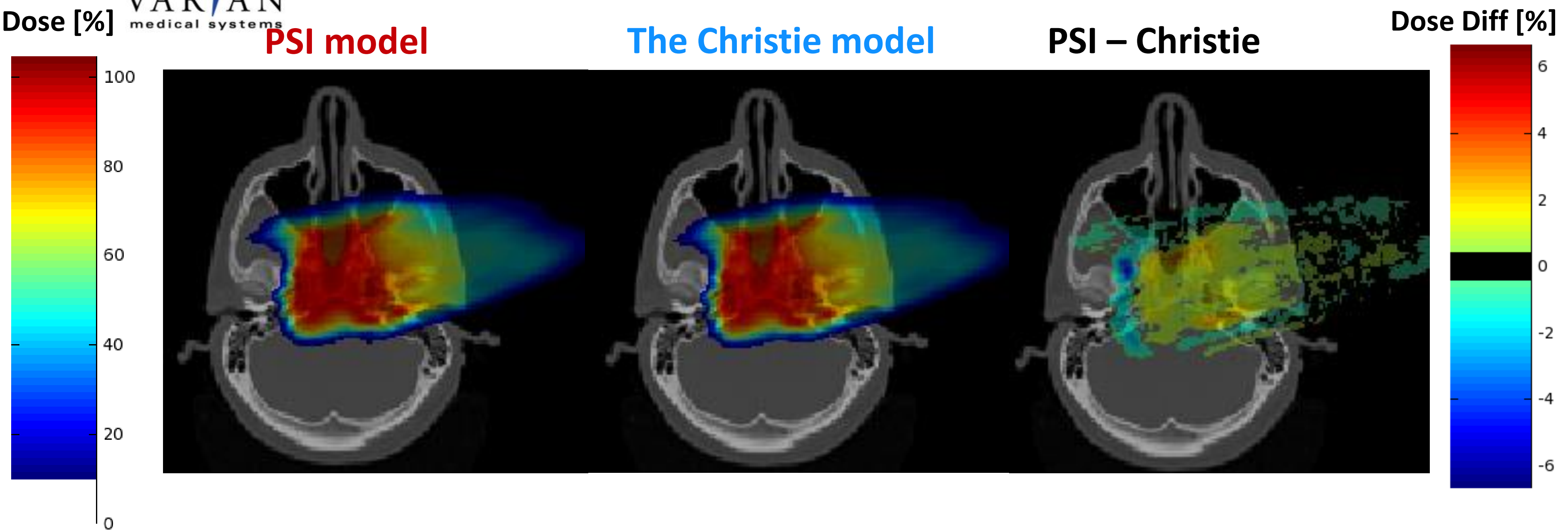
Measurement versus PSI & Christie model:
- Relative doses: fullfill clinical criteria 100 % (3%,3mm)
- Absolute dose: Both models are 1%-3% lower than measurements



Patient fields in the CT



Patient fields in the CT



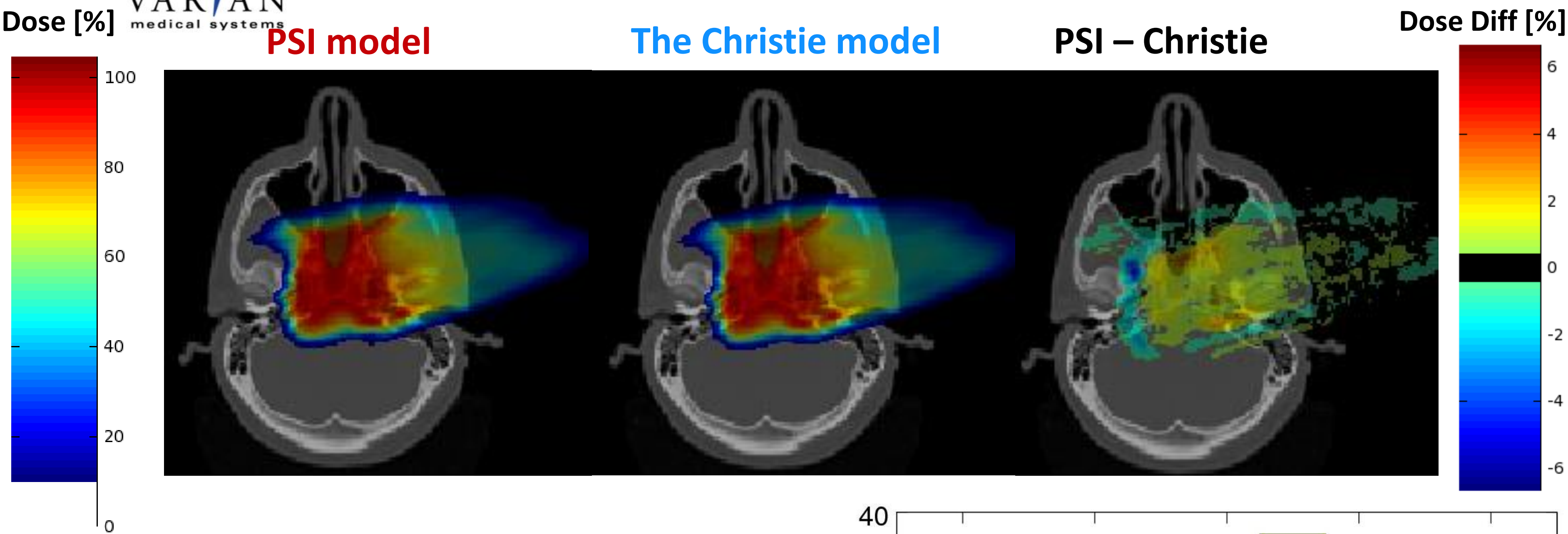
How much do our results depend on the model setup?

Excellent clinical agreement:

Gamma analysis:

99.9% (2%,2mm); 94% - 98% (1%,1mm)

Patient fields in the CT



How much do our results depend on the model setup?

Excellent clinical agreement:

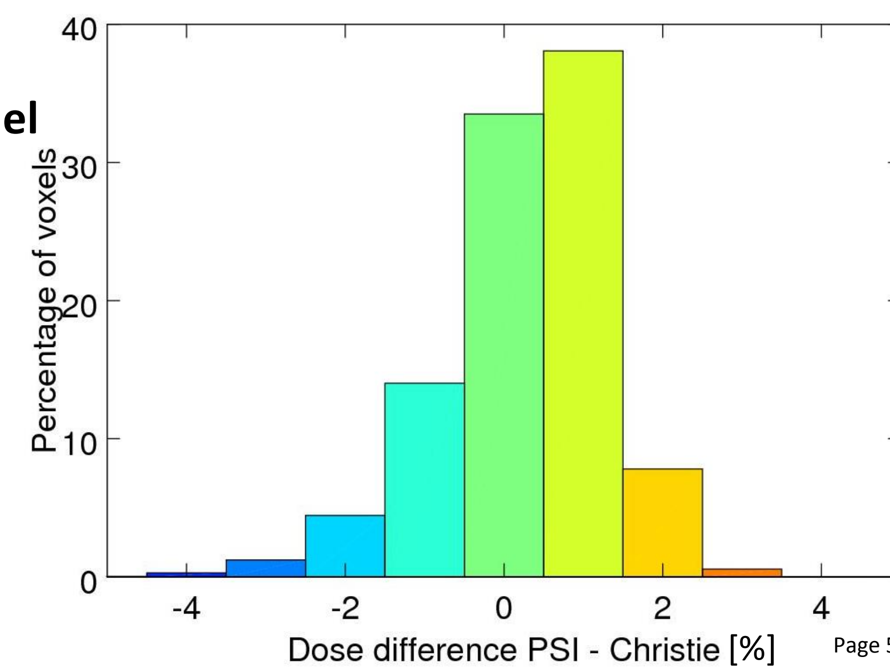
Gamma analysis:

99.9% (2%,2mm); 94% - 98% (1%,1mm)

Remaining dose difference:

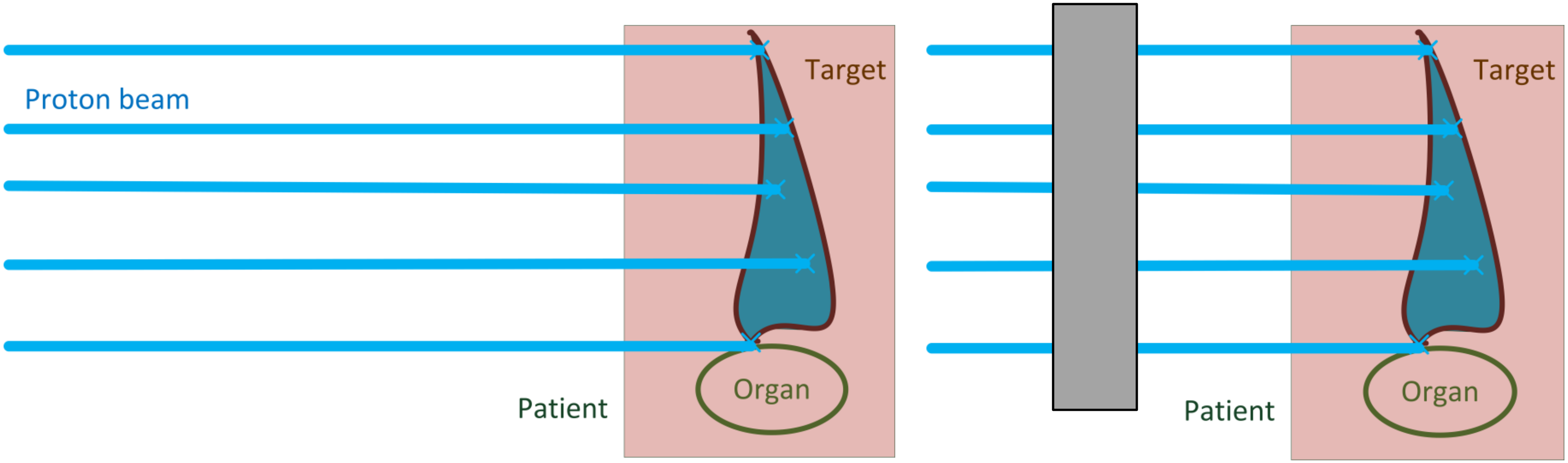
86% of the voxels agree within 1.5%

98 % of the voxels agree within 2.5%

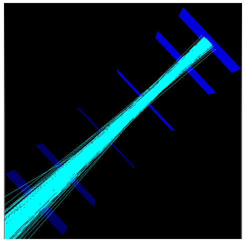


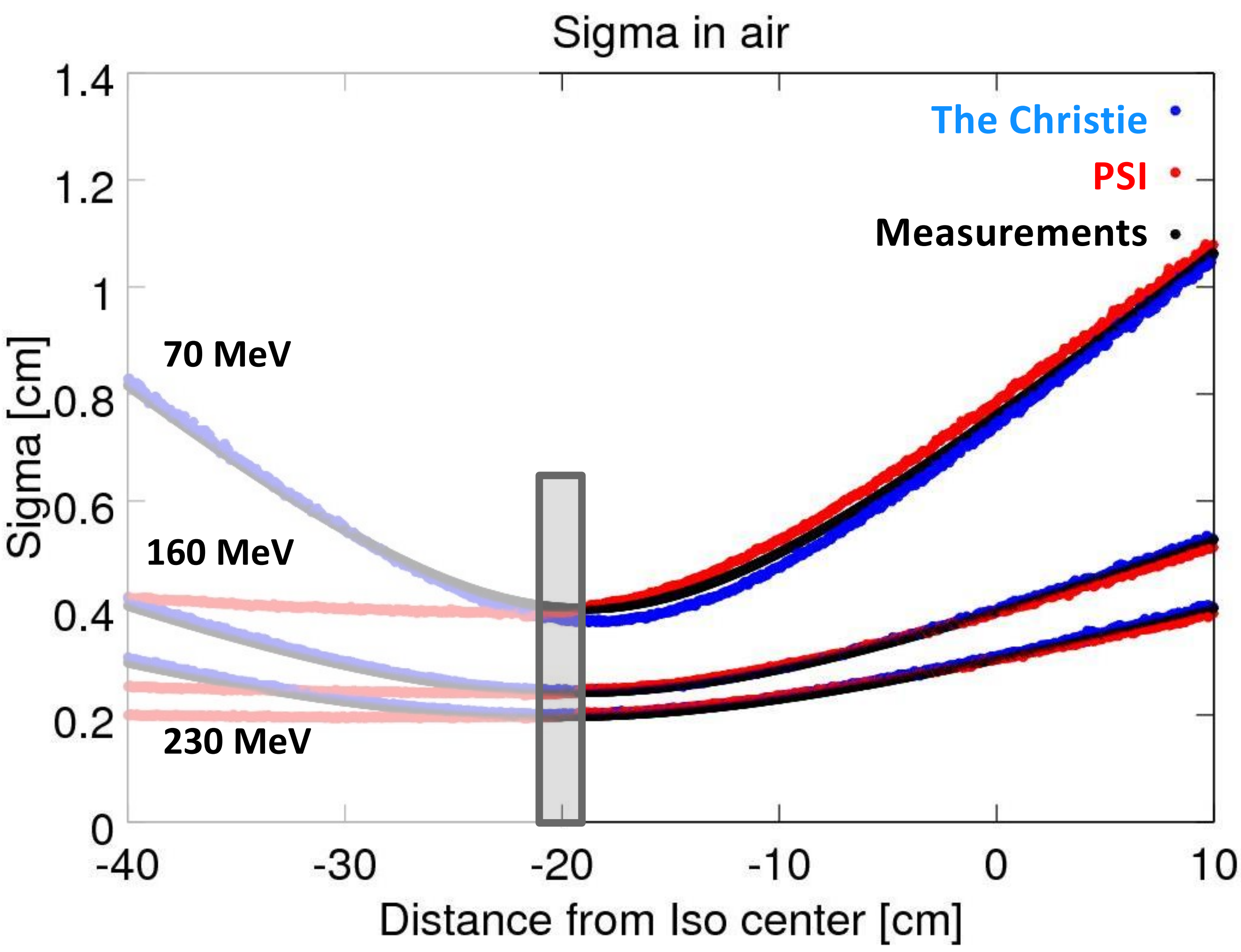
Results with pre-absorber

The Christie system | **PSI system**:



Spot sizes in air with pre-absorber

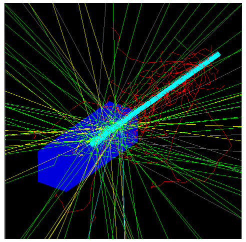




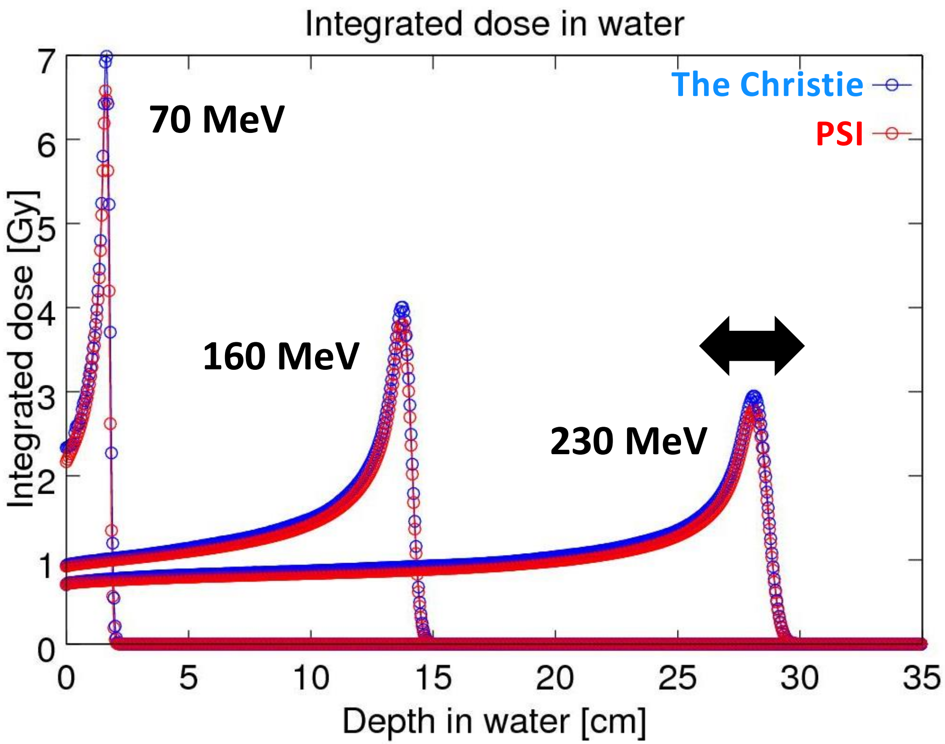
Good agreement between both Monte Carlo engines and measurements (0.35 mm)

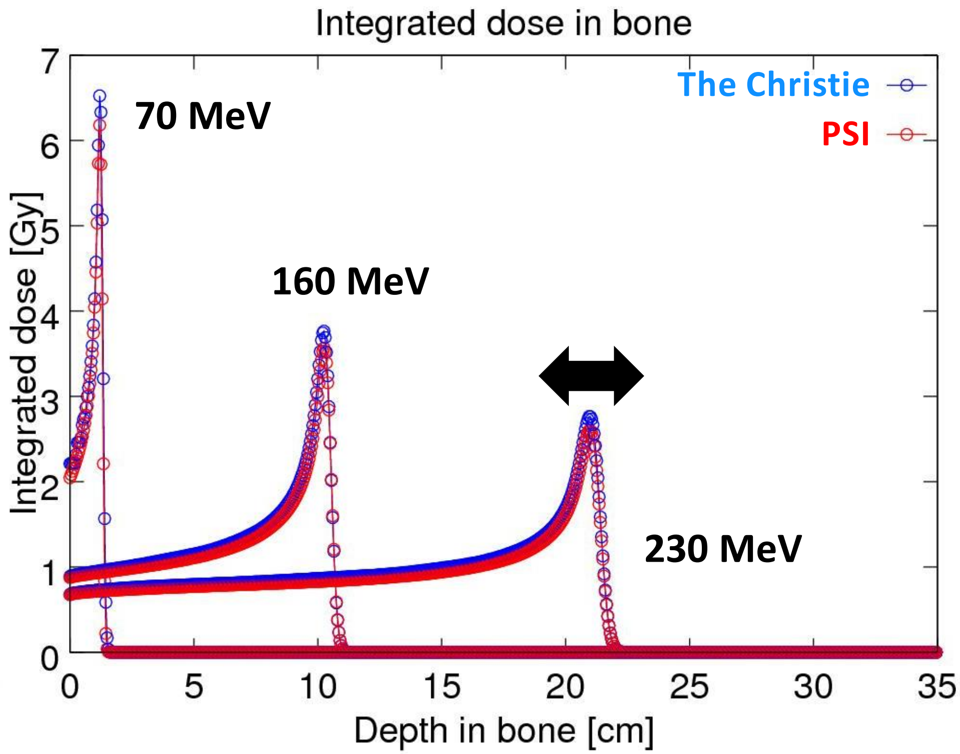
✓

Range in water & bone & brain with pre-absorber

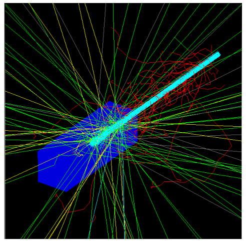


Ranges agree within 0.22 mm for all materials



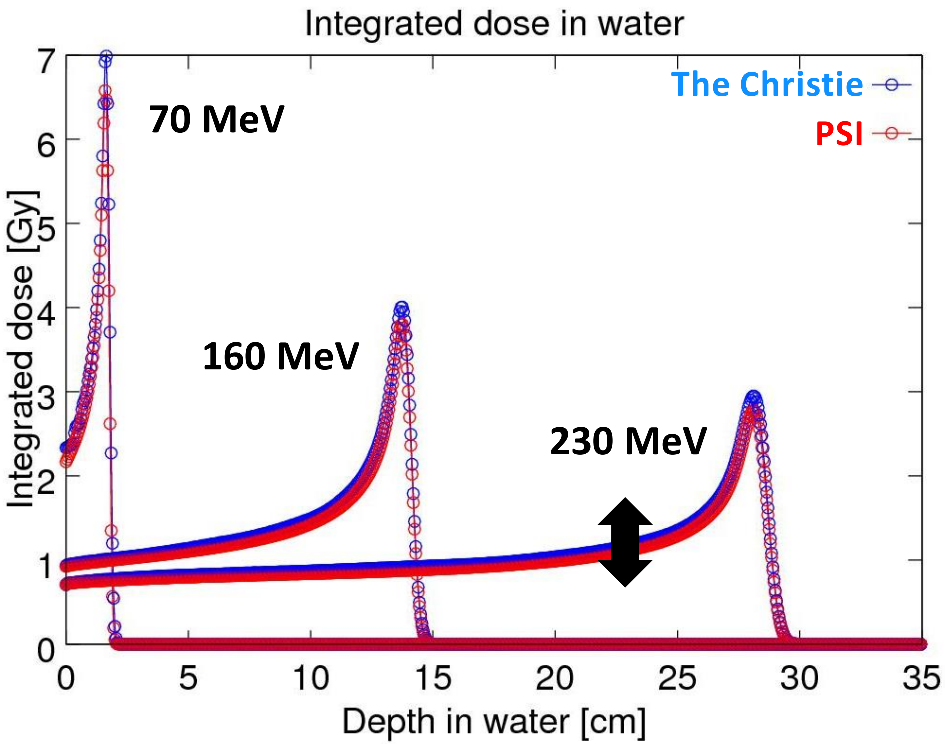


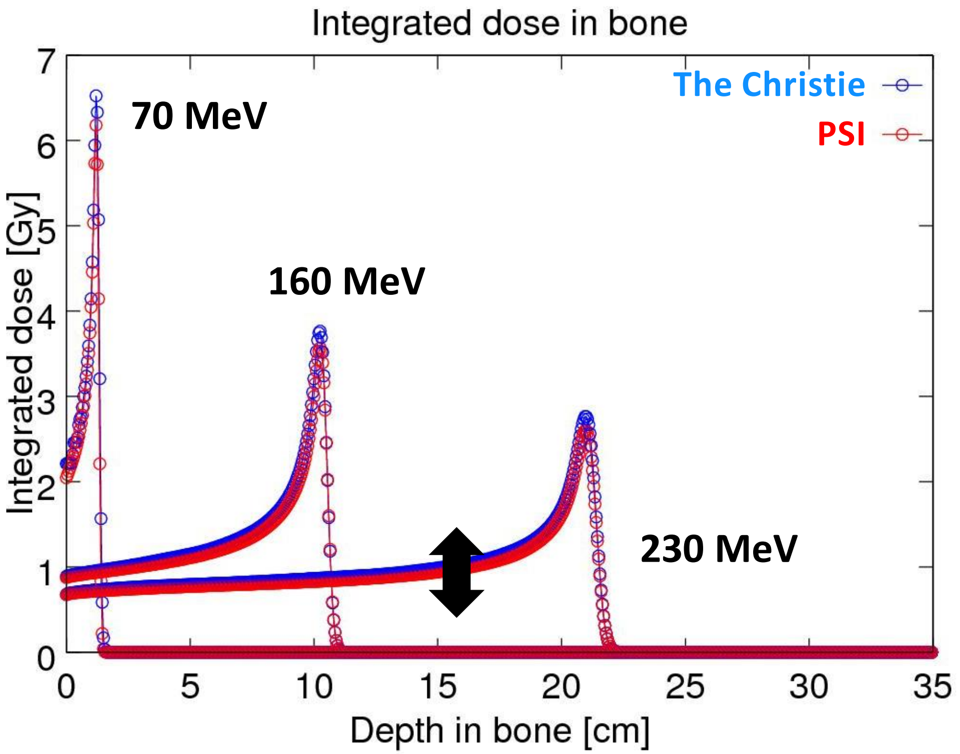
Range in water & bone & brain with pre-absorber



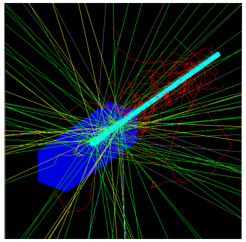
Systematic **absolute dose differences** of 4% - 7%

The **Christie model** predicts higher dose than the **PSI model**





Range in water & bone & brain with pre-absorber

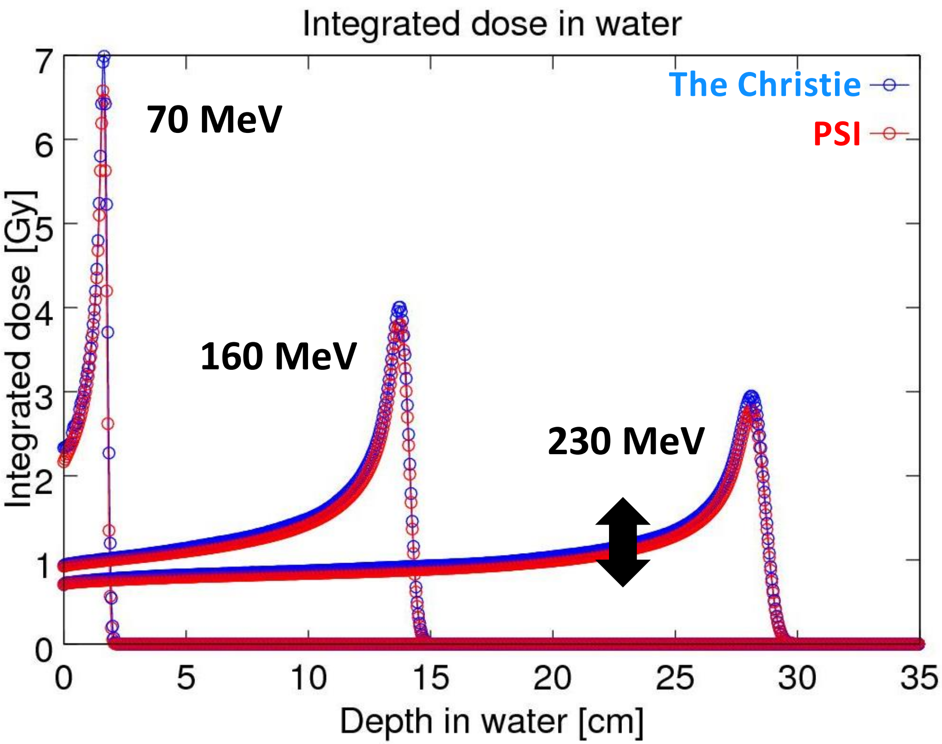


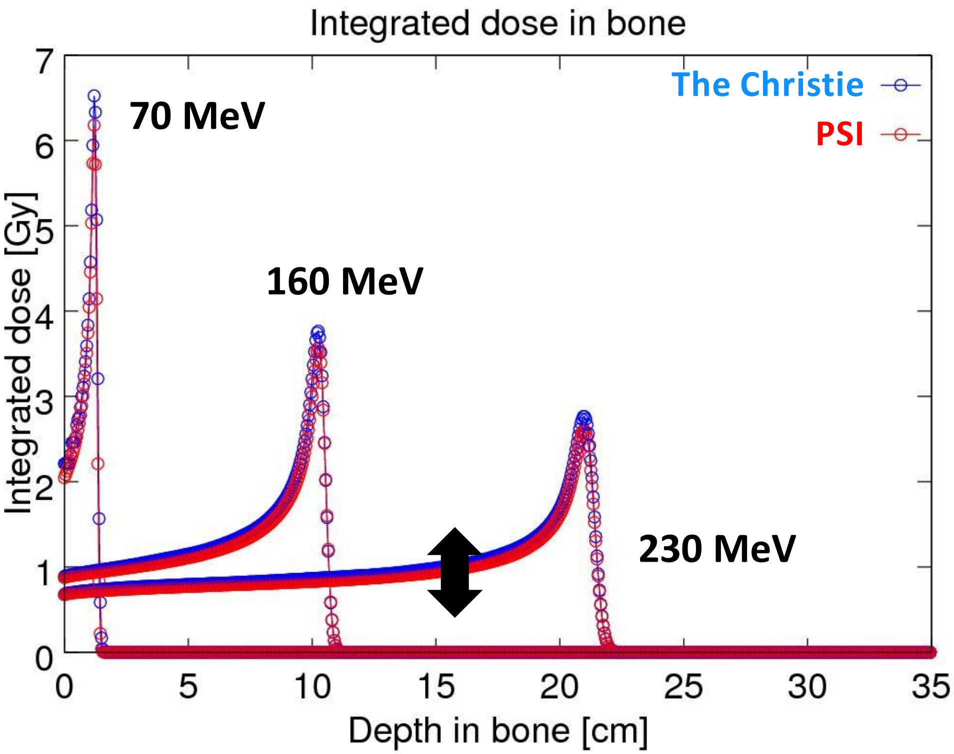
Systematic **absolute dose differences** of 4% - 7%

The **Christie model** predicts higher dose than the **PSI model**

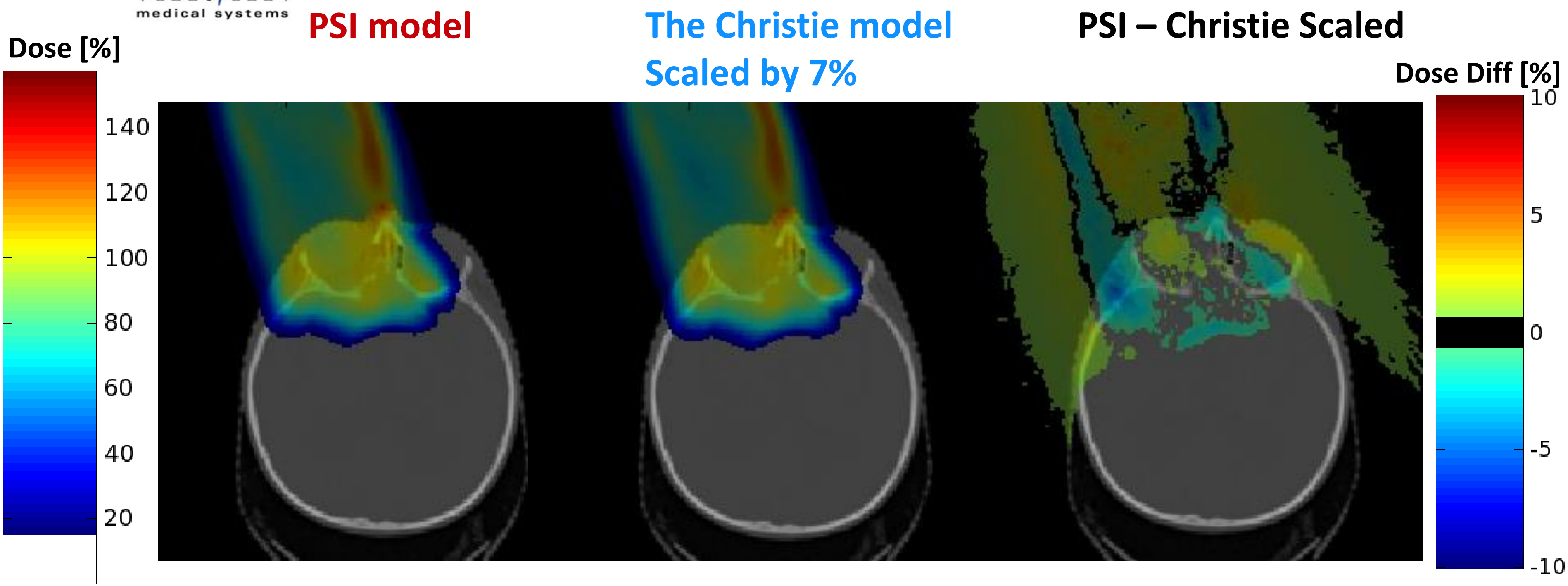
Water tank measurement versus PSI & Christie model:

PSI model is 1%-2% lower; Christie model is 5%-7% higher than measurements



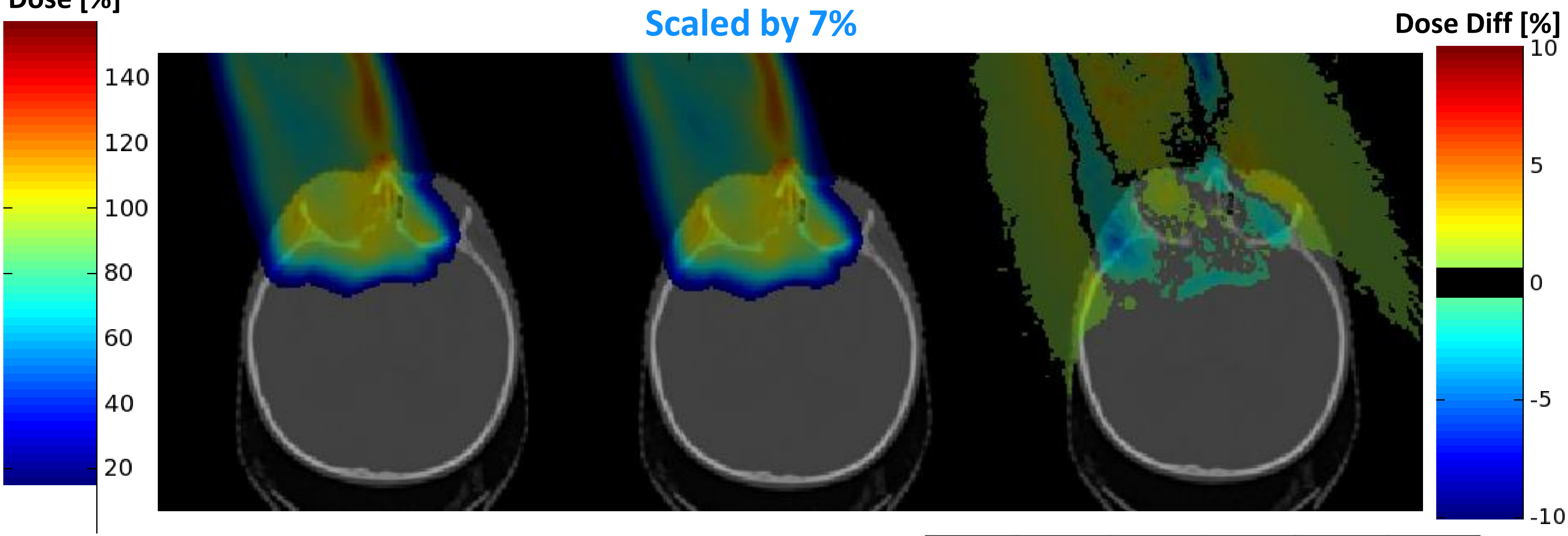


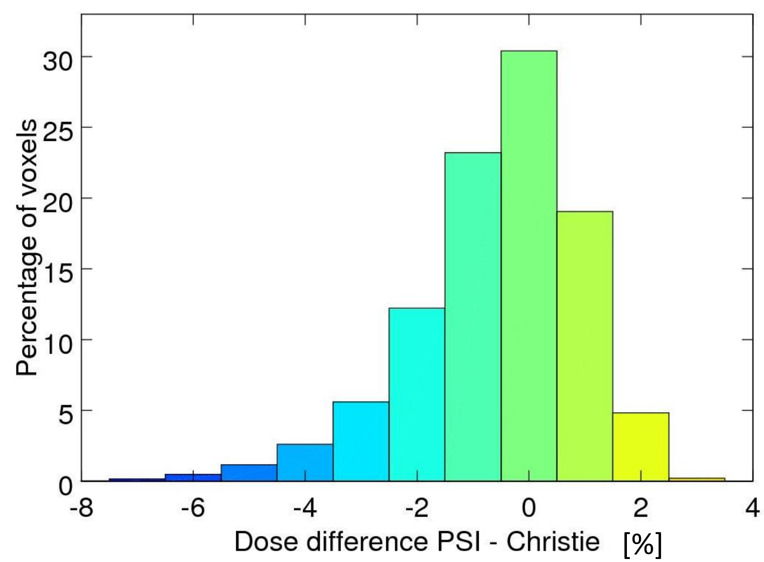
Patient fields in the CT



Patient fields in the CT

PSI model | **The Christie model Scaled by 7%** | **PSI – Christie Scaled**





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

With different pre-absorber models:

- Excellent clinical agreement for relative doses: 99.6% (2%,2mm); 94% - 99% (1%,1mm)
- Absolute doses do not agree – proton loss due to the pre-absorber

Key messages

Summary

Monte Carlo simulations for proton pencil beam scanning is not an off-the shelf tool.

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

Summary

Monte Carlo simulations for proton pencil beam scanning is not an off-the shelf tool.

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

- A tuned system is only reliable within the bounds of its tuning
  - Pay close attention to ionisation potentials
  - Be careful when not modelling physical objects

- How accurate can we be?
  - Excellent agreement in water and in patient CT
  - Remaining dose differences of up to 2.5%

Outlook

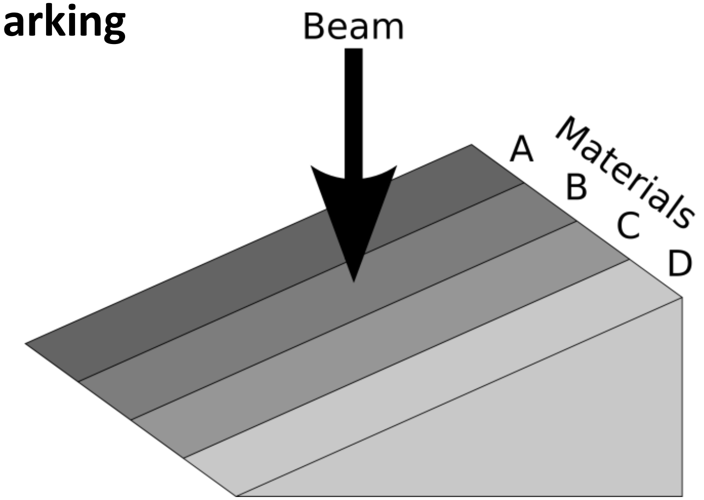
- Global Challenge Network+ in Advanced Radiotherapy (https://www.advanced-radiotherapy.ac.uk)
  – Multi-Scale Monte Carlo Modelling for Radiotherapy Sandpit
  – March 2017, Manchester, UK

- Two related projects:
  – Aitkenhead A. et al: Physical and software phantoms for proton therapy
  – Nixon. A. et al: Sensitivity TEsting and Analysis using Monte CArlo for RadioTherapy (STEAMCART)

Physical and software phantoms for proton therapy

- Need to verify Monte Carlo simulations not only in water but also in additional materials:
  - Dose distributions simulated in the water used for the tuning will always fit measurements in water
  - Need additional benchmarking in non-water materials

Aim: Standard phantom design for MC benchmarking



Picture courtesy: Adam Aitkenhead

Sensitivity TEsting and Analysis using Monte CArlo for RadioTherapy (STEAMCART)

- What is the influence of ionisation potentials used within the CT?
  - Even for elements, ionisation potentials reported in literature are subject to high fluctuations [1]
  - How much does this influence patient calculations?

- Which other values could be important?

Aim: Produce a tool which can be used to perform sensitivity testing on TOPAS & GATE to identify physical parameters contributing to uncertainty in dose.

[1] DOOLAN, P. J. et al. 2016. *Phys Med Biol,* 61**,** 8085 – 8104.

Two Monte Carlo models for the same spot scanning Gantry have been set up, showing …

- That a tuned system is only reliable within the bounds of its tuning. Pay attention to ionisation potentials and physical objects.
- Excellent agreement between the simulated dose distributions and measurements.