MONTE CARLO SIMULATION

IN SCANNED ION BEAM THERAPY

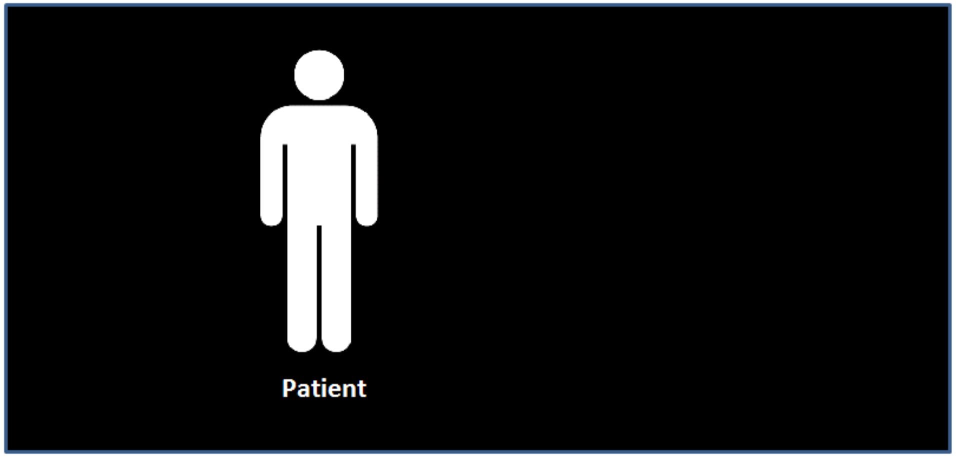
A medical physicist perspective

OMA Advanced School on Medical Accelerators and Particle Therapy
April, 2nd 2019

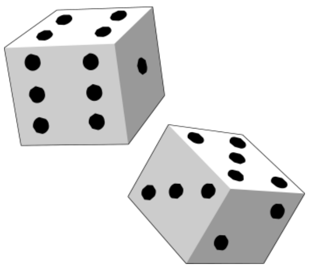
Loïc Grevillot

OUTLINE

- The Monte Carlo (MC) method
- MC Applications in Light Ion Beam Therapy (LIBT)
- MC Beam Modeling
- Treatment planning



THE MONTE CARLO METHOD



Origins of Monte Carlo

The Monte Carlo Method is a stochastic sampling method:

- To model a system by randomly sampling probability density functions (e.g. cross-sections)
- Often opposed to analytic or deterministic methods

Inventor:

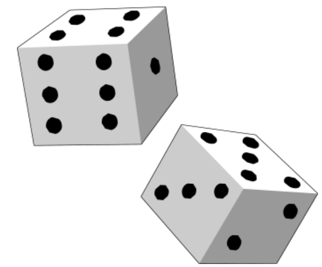
- **J. von Neumann** (in cooperation with **Ulam** and **Metropolis**) between **1940-1947**
  - working on research on atomic bomb (Los Alamos National Laboratories)
  - Coinciding with the start of the computer age
  - Name inspired by the gambling games in the casinos from the city of Monte Carlo
  - First "unclassified" paper: "The Monte Carlo Method" (Metropolis and Ulam, 1949)

First known reference:

- **Comte de Buffon (1777)**
- **first proposal of a Monte Carlo-like method**
  - He proposed to repeatedly tossing a needle on a ruled sheet of paper to determine the probability of the needle to cross one of the lines.

J Saeco and F Verhaegen, Monte Carlo Techniques in Radiation Therapy, CRC Press, November 2016

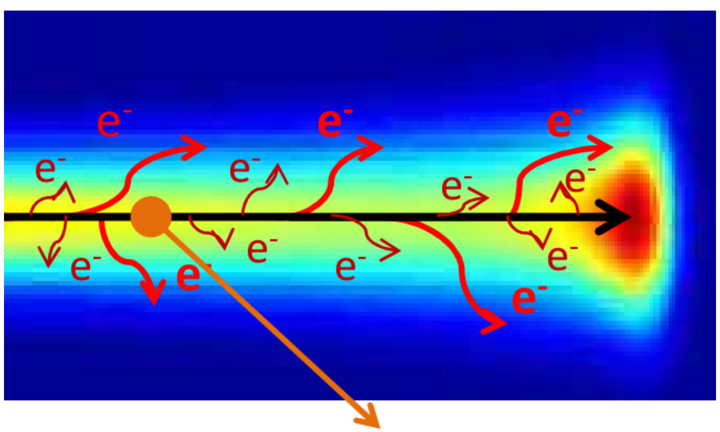
THE MONTE CARLO METHOD



Monte Carlo in practice

Monte Carlo is a step by step simulation of the physical interactions in the patient.

<u>Proton pencil beam</u>

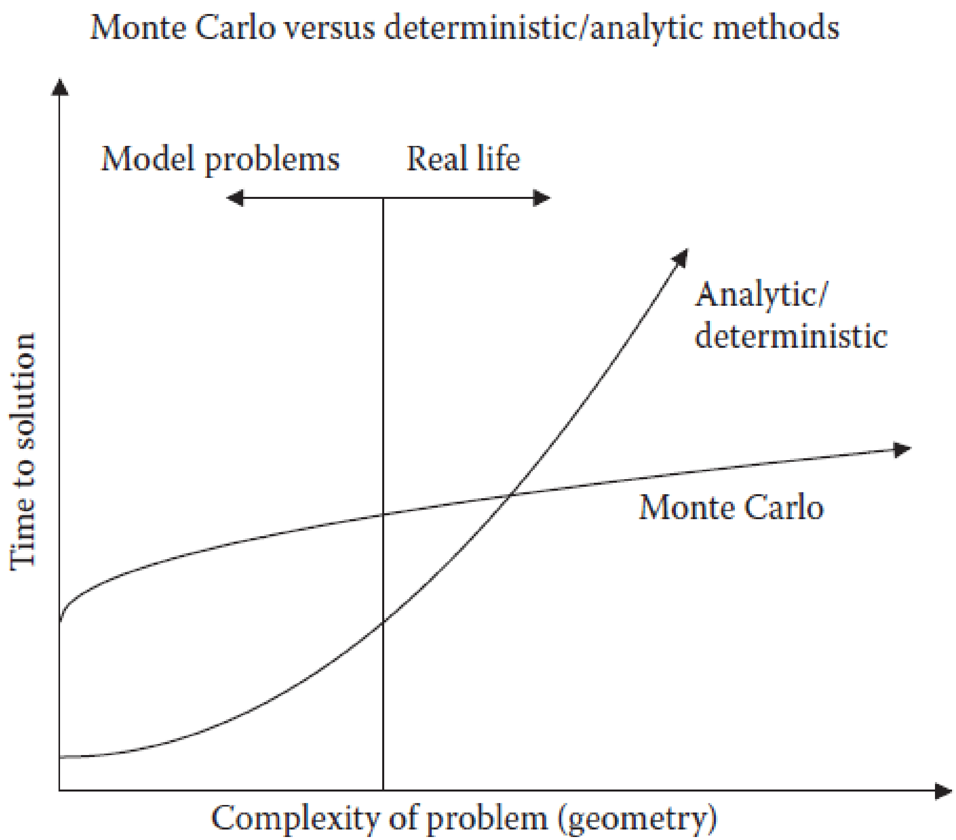


The simulation accuracy depends on:

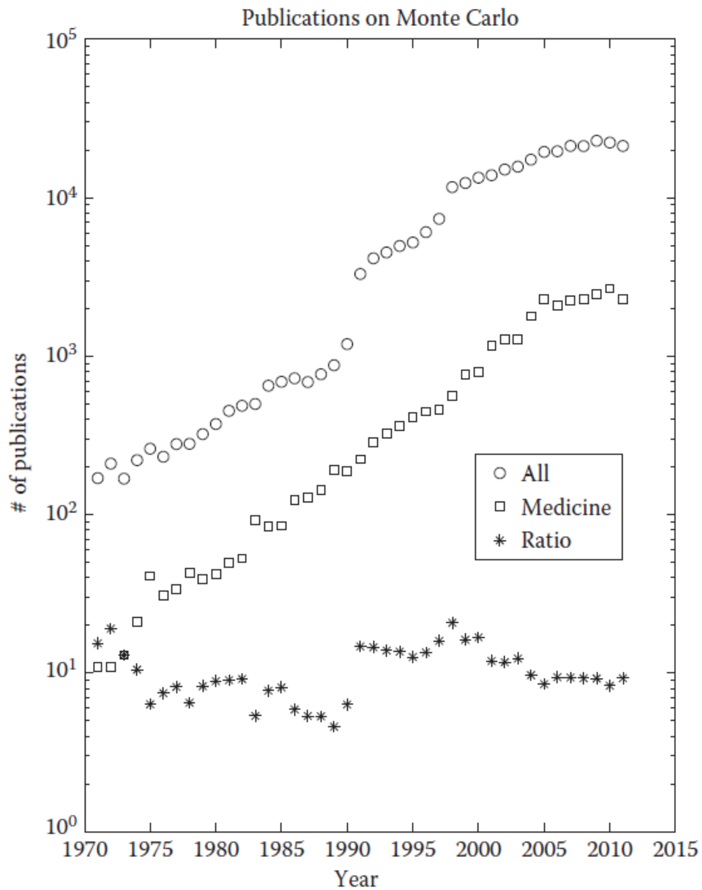
- **Random number generator**
- **Geometry and Material descriptions**
  - Water phantom
  - CT
- **Physical cross-sections / processes**
  - Stopping power / energy-loss
  - Nuclear cross-sections / fragmentation
  - …
- **Particle source description**
  - Energy spectra
  - Beam optics
- **Computation parameters settings**
  - Step size
  - Cut
  - …

THE MONTE CARLO METHOD

When to use Monte Carlo?



How much do we use it?



J Saeco and F Verhaegen, Monte Carlo Techniques in Radiation Therapy, CRC Press, November 2016

THE MONTE CARLO METHOD

MC codes in light ion beam therapy

Two main families

- **General purpose**
  - Geant4
  - Fluka
  - PHITS
  - SHIELD-HIT
  - MCNP
  - …
- **Dedicated**
  - VMCPRO
  - MCSQUARE
  - FRED
  - …

Advantages/Drawbacks:

General purpose:
- Can be used for anything
- Full physics description
- Slow

Dedicated:
- Optimized for medical application
- Restricted physics implementation
- Fast

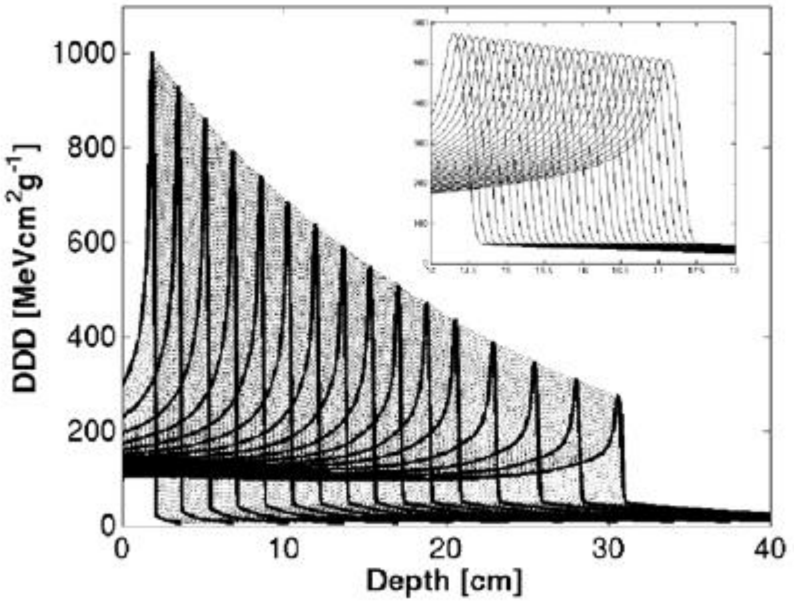
Differences:

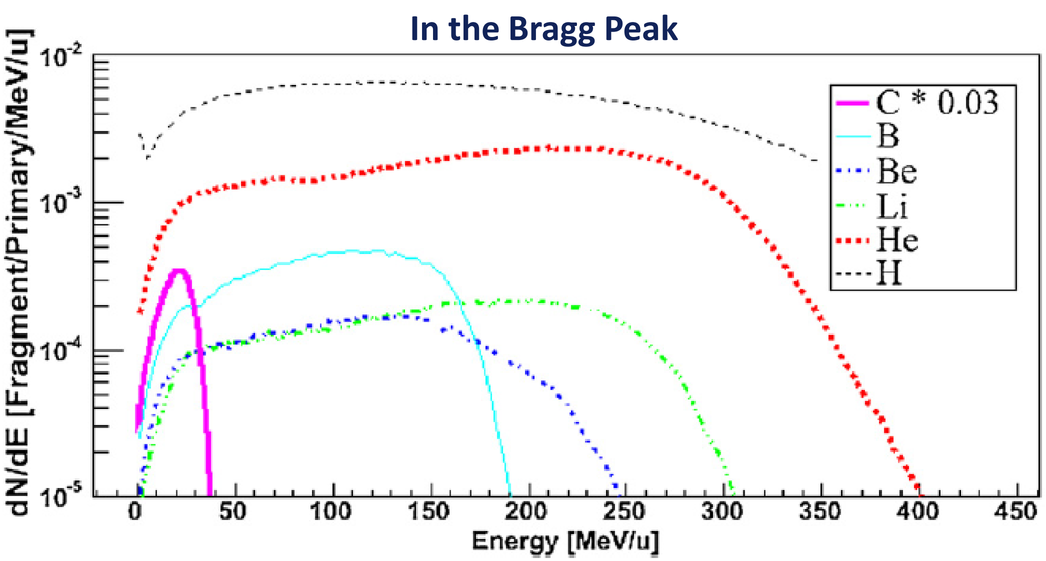
- Programming language (C++, Fortran, ….)
- Open or closed-source
- Free?
- License
- User interface
- Community of developers
- Community of users
- Performances
- …

MC APPLICATIONS IN ION BEAM THERAPY

To support start-up and commissioning of new facilities

- Generation of an accelerator library
- Depth-doses / Transverse profiles / Fragmentation spectra



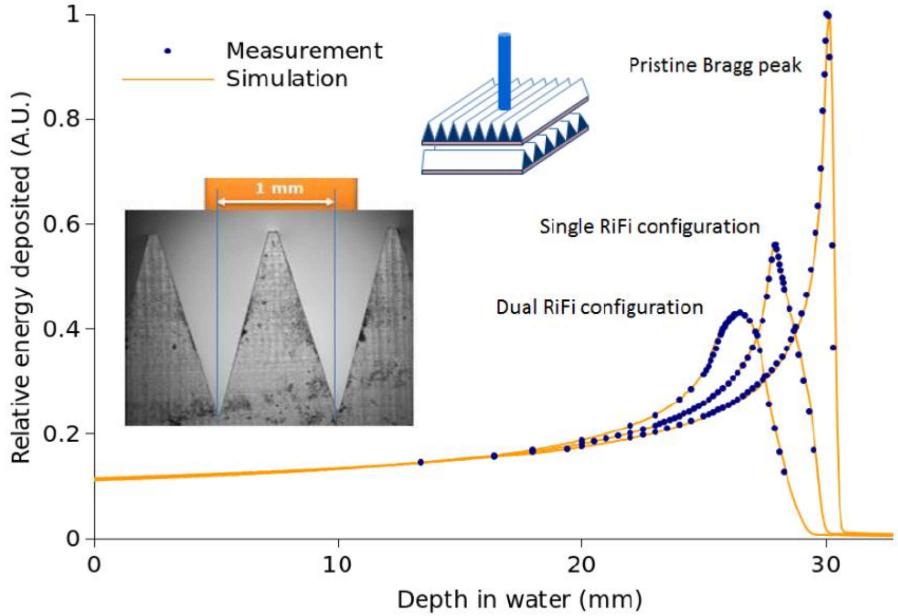


Parodi 2012, Phys. Med. Biol. 57 (2012) 3759–3784

MC APPLICATIONS IN ION BEAM THERAPY

Beam line design

- Optimization of nozzle design for clinical applications (spot size, fragmentation)
- Influence of scanning magnet fluctuations on the delivered dose
- Simulation of failure scenarios and clinical impact (risk analysis)
- Design of passive elements

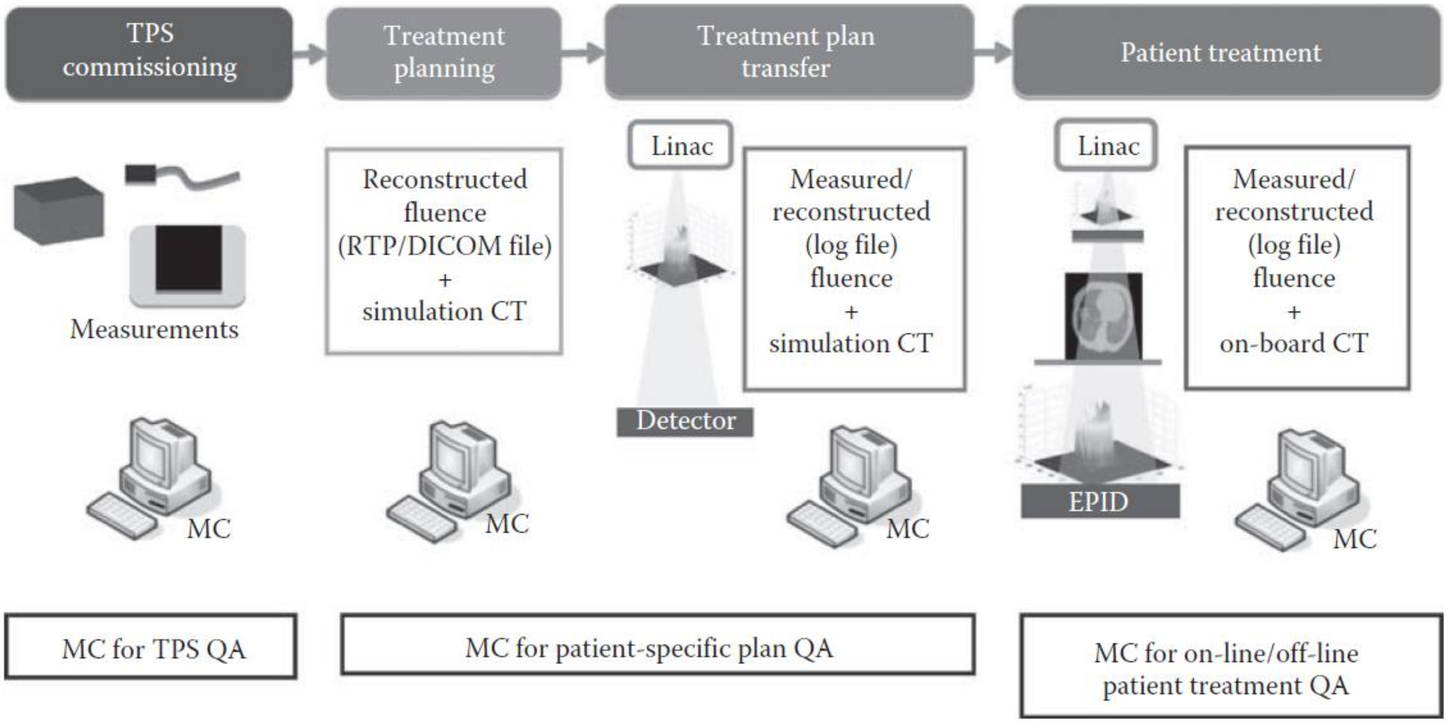


Grevillot et al., Evaluation of beam delivery and ripple filter design for non-isocentric proton and carbon ion therapy, Phys Med Biol (60) 2015

MC APPLICATIONS IN ION BEAM THERAPY

Quality Assurance (QA)

- TPS QA / Patient Specific QA / On-Line and Off-Line treatment QA

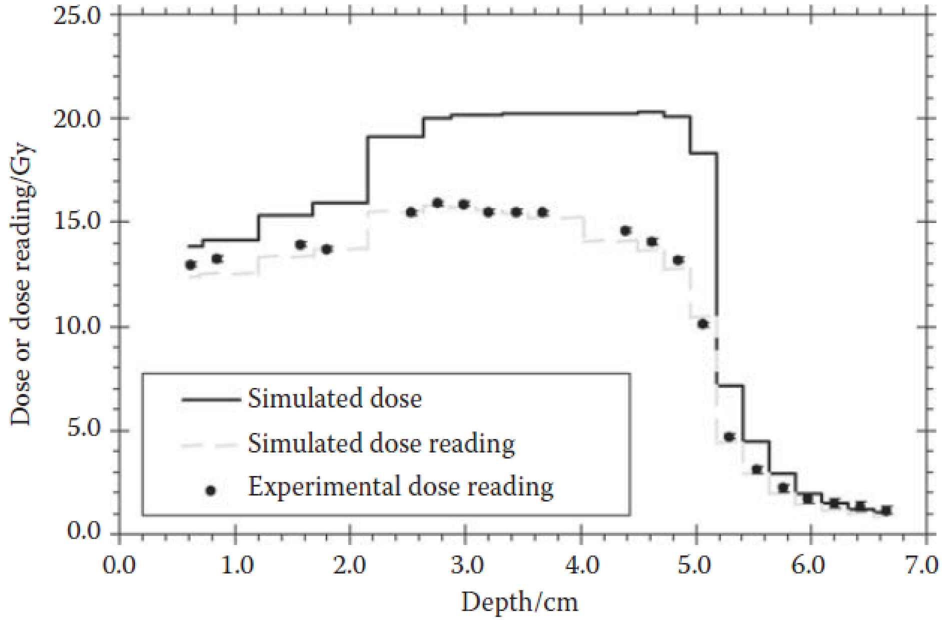


J Saeco and F Verhaegen, Monte Carlo Techniques in Radiation Therapy, CRC Press, November 2016

MC APPLICATIONS IN ION BEAM THERAPY

To support dosimetry activities

- Perturbation factors / Fluence corrections / Stopping power ratios



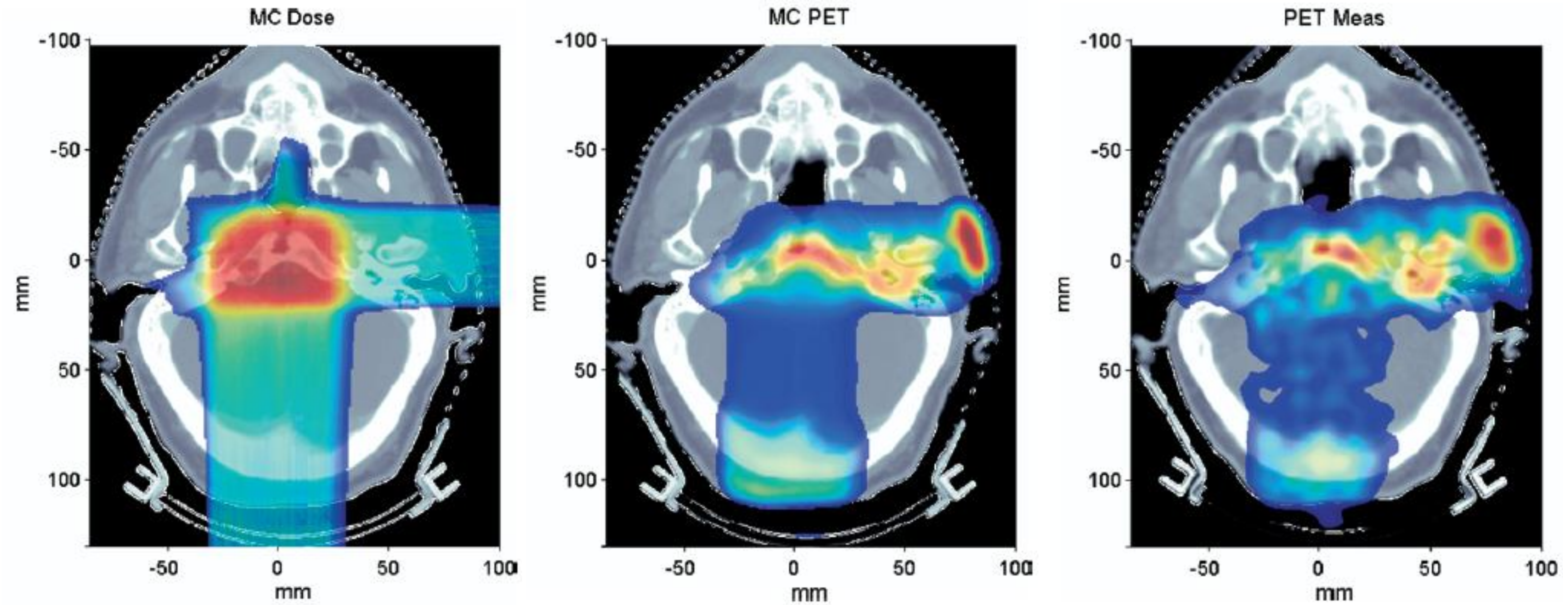
Alanine detectors in a carbon ion SOBP

J Saeco and F Verhaegen, Monte Carlo Techniques in Radiation Therapy, CRC Press, November 2016

MC APPLICATIONS IN ION BEAM THERAPY

PET-based treatment verification

- Relationship dose distribution / β+ activation images



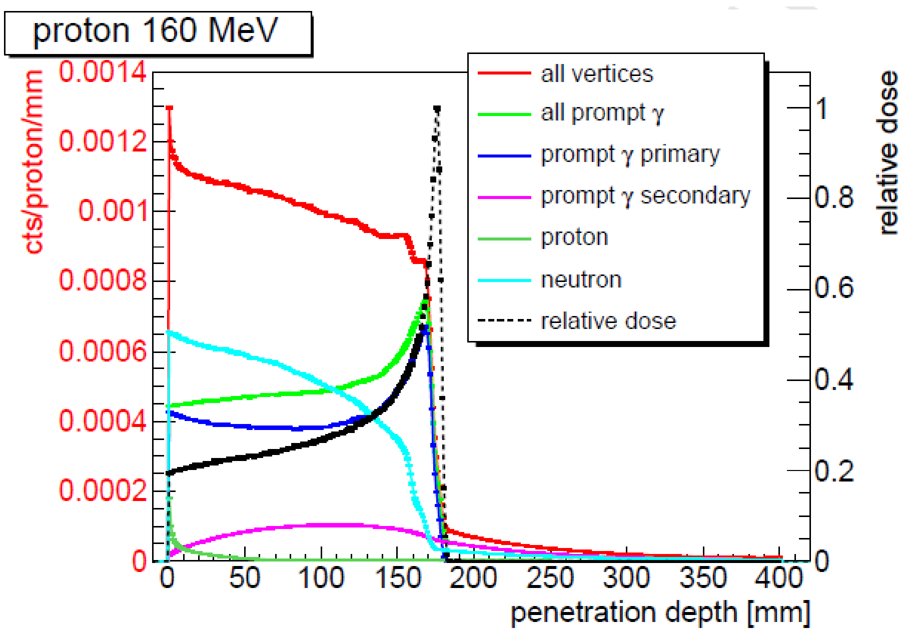
Clival chordoma proton treatment, imaged ~16-26 min after irradiation

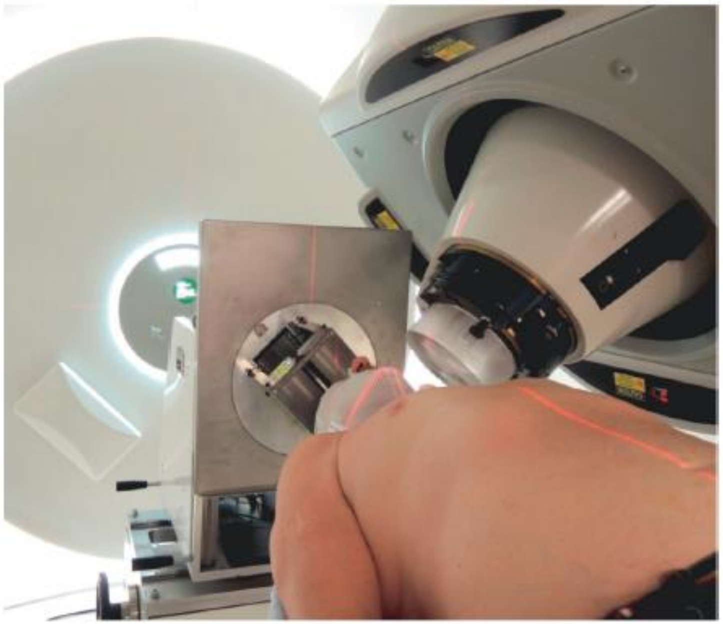
Parodi 2007, Int. J. Radiation Oncology Biol. Phys., Vol. 68, No. 3, pp. 920–934, 2007

MC APPLICATIONS IN ION BEAM THERAPY

Prompt gamma imaging (PGI)-based treatment verification

- Relationship dose distribution / PGI





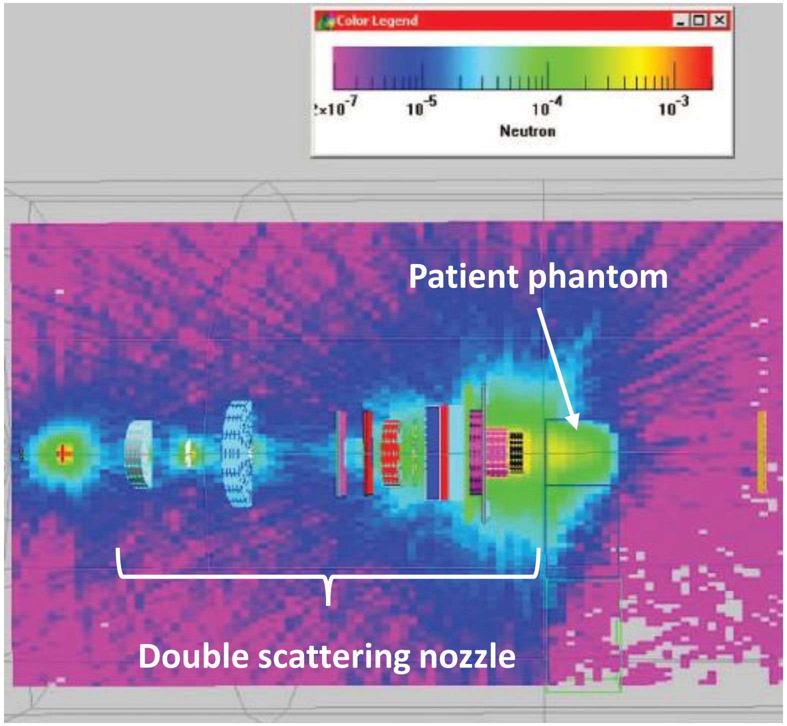
J Krimmer at al., Prompt-gamma monitoring in hadrontherapy: A review, NIM-A, July 2017

Richter et al., First clinical application of a prompt gamma based in vivo proton range verification system, Rad. Onc. 2016

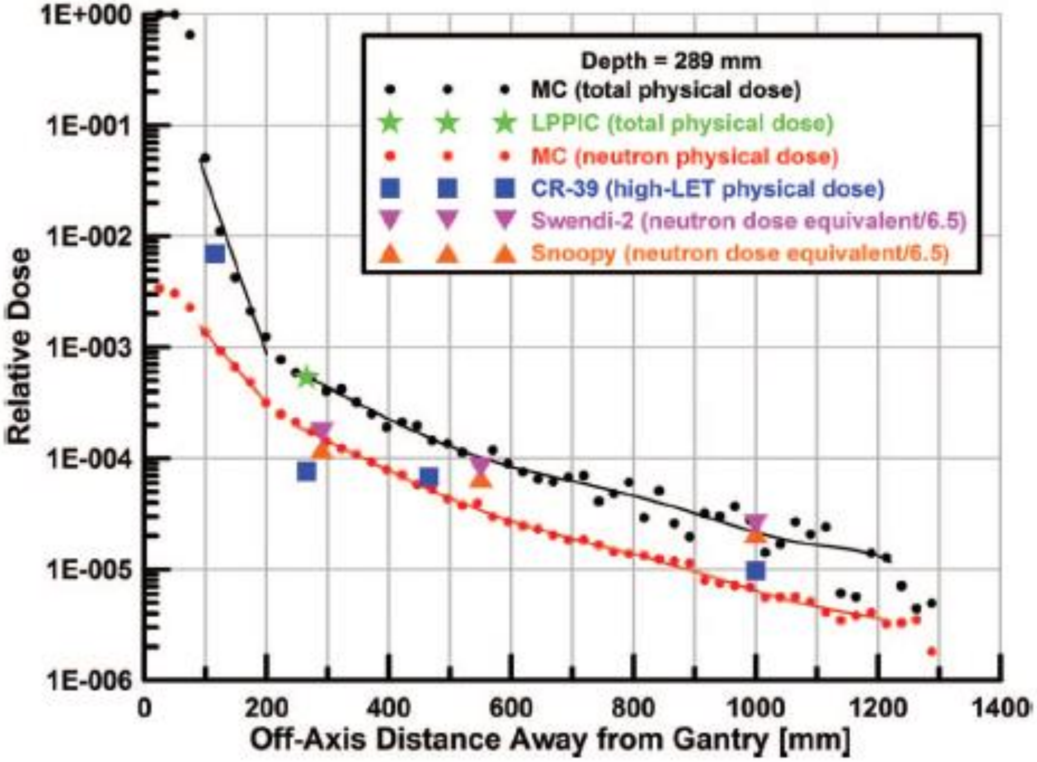
MC APPLICATIONS IN ION BEAM THERAPY

Neutron and secondary dose evaluation scattering

- Out of field equivalent dose from Loma Linda proton scattering delivery system
- MCNPX MC code



Neutron fluence with E< 10 MeV



Moyers et al., Leakage and scatter radiation from a double scattering based proton Beamline, Med Phys 35 (1), 2008

BEAM MODELING

Physics processes

Energy loss (e.g. Bethe Block equation)

- Bragg peak position (range)

Energy straggling (e.g. Landau, Vavilov equations)

- Bragg peak width

Multiple Coulomb Scattering (e.g. Moliere, Highland equations)

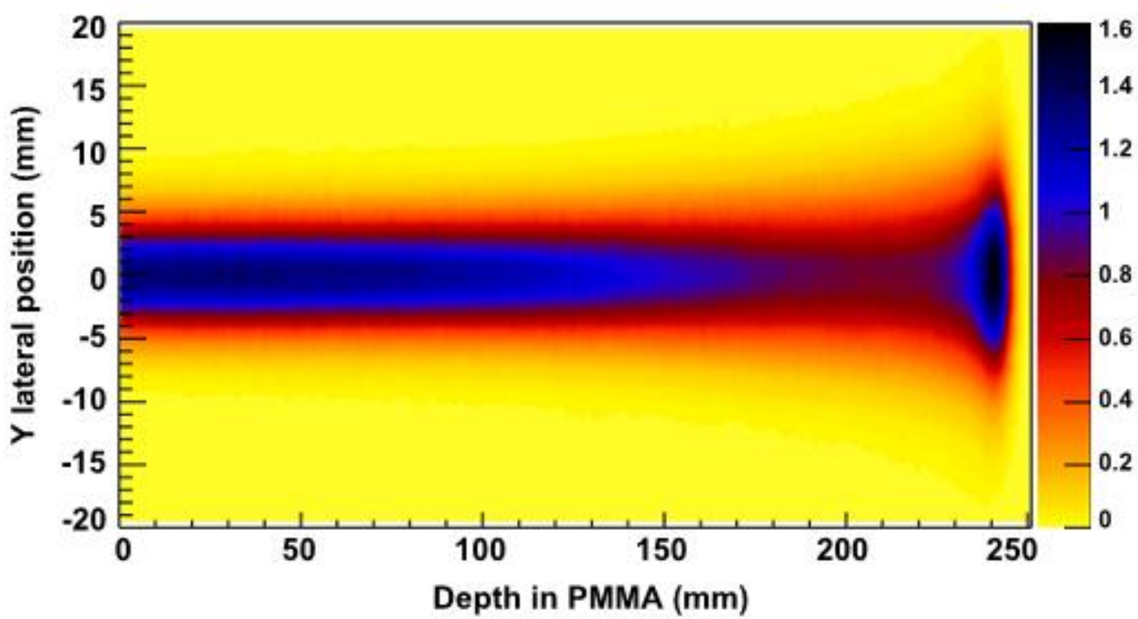
- Beam size and penumbra increase with depth (in FWHM)

Nuclear interactions (fragmentation, halo of secondaries)

- Fragmentation tail (C^{12})
- Low dose (halo) of charged secondaries away from the beam axis (protons)

BEAM MODELING

Proton depth-dose profile



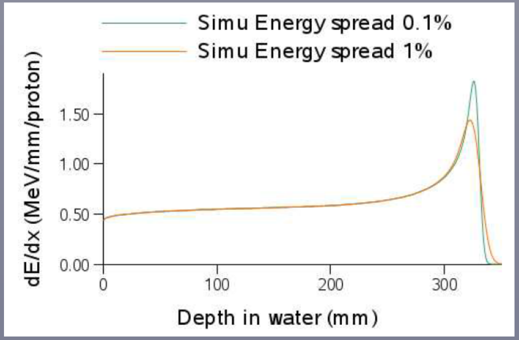
Grevillot et al, Optimization of GEANT4 settings for Proton Pencil Beam Scanning simulations using GATE, NIM-B (268) 2010

BEAM MODELING

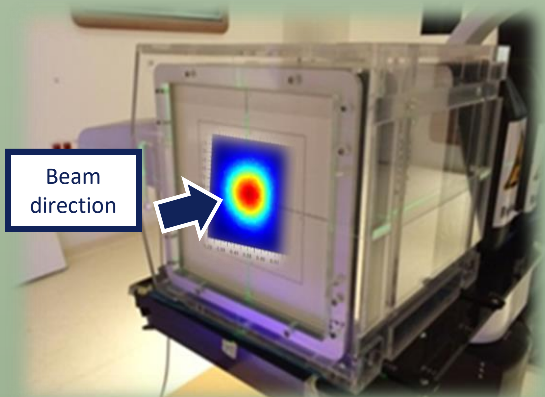
Adapted from A. Elia

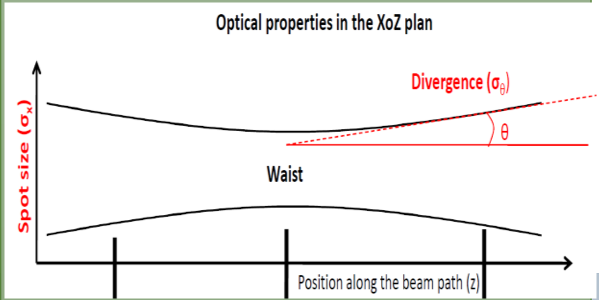
The three ingredients

Depth dose profiles in water

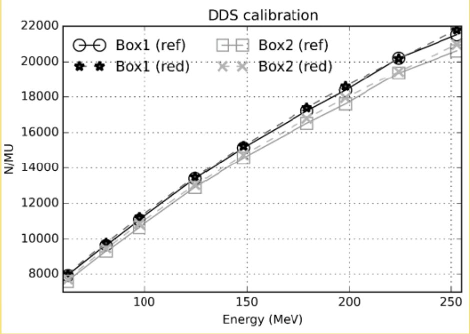


Lateral dose profiles in air





Dose in reference conditions



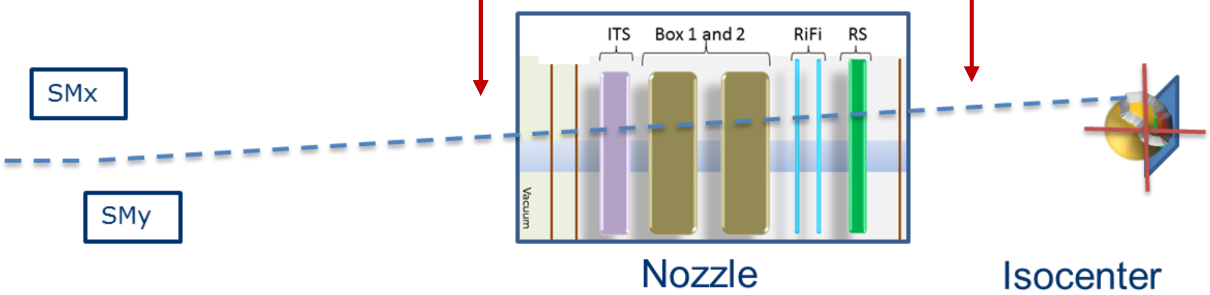
BEAM MODELING

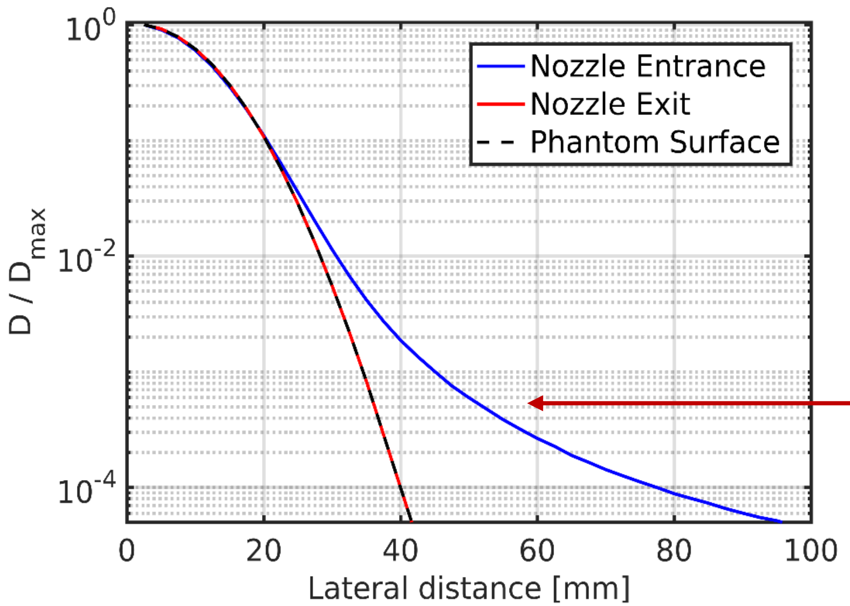
Adapted from A. Elia

Two methods

Nozzle entrance method

Nozzle exit method

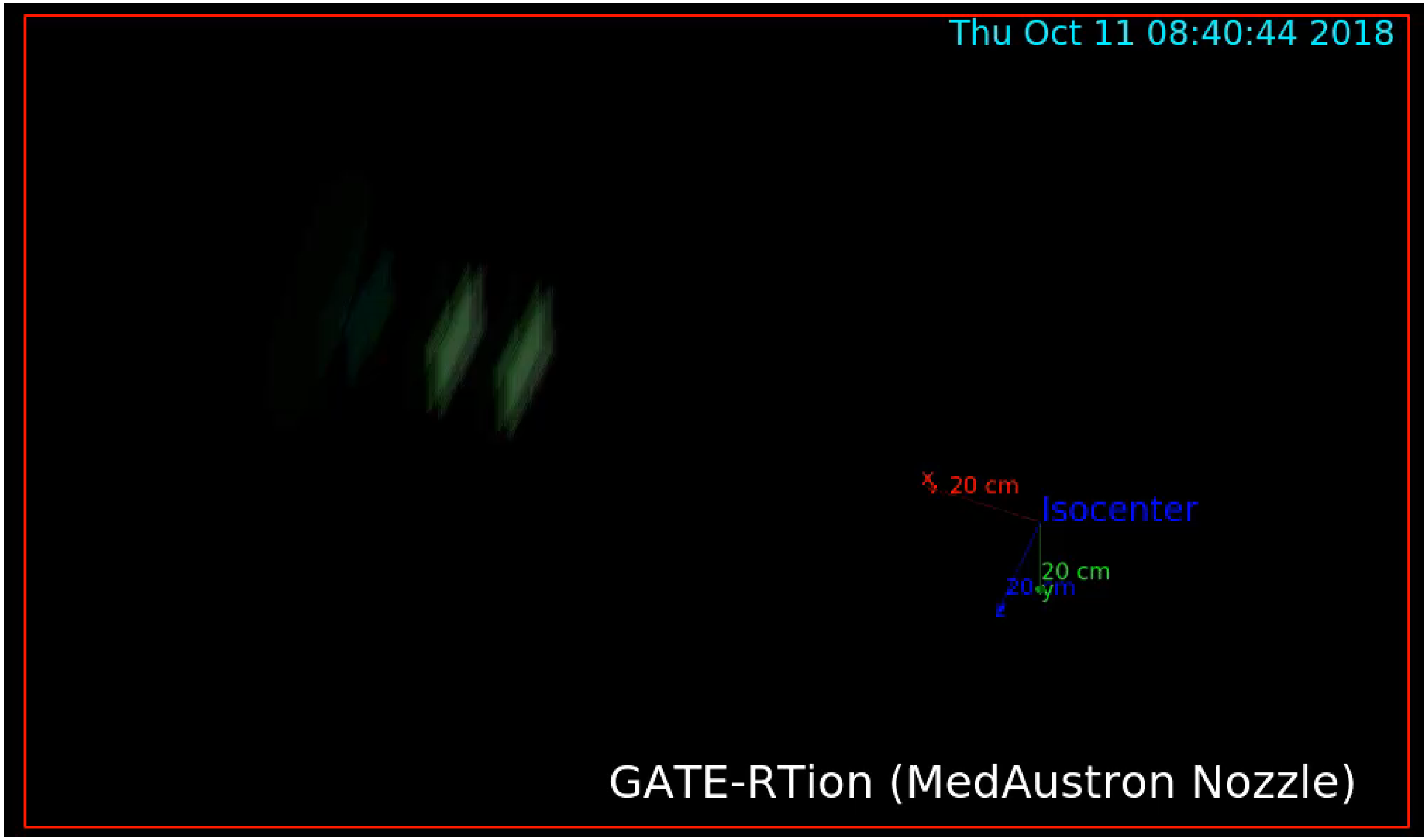




Nuclear halo

BEAM MODELING

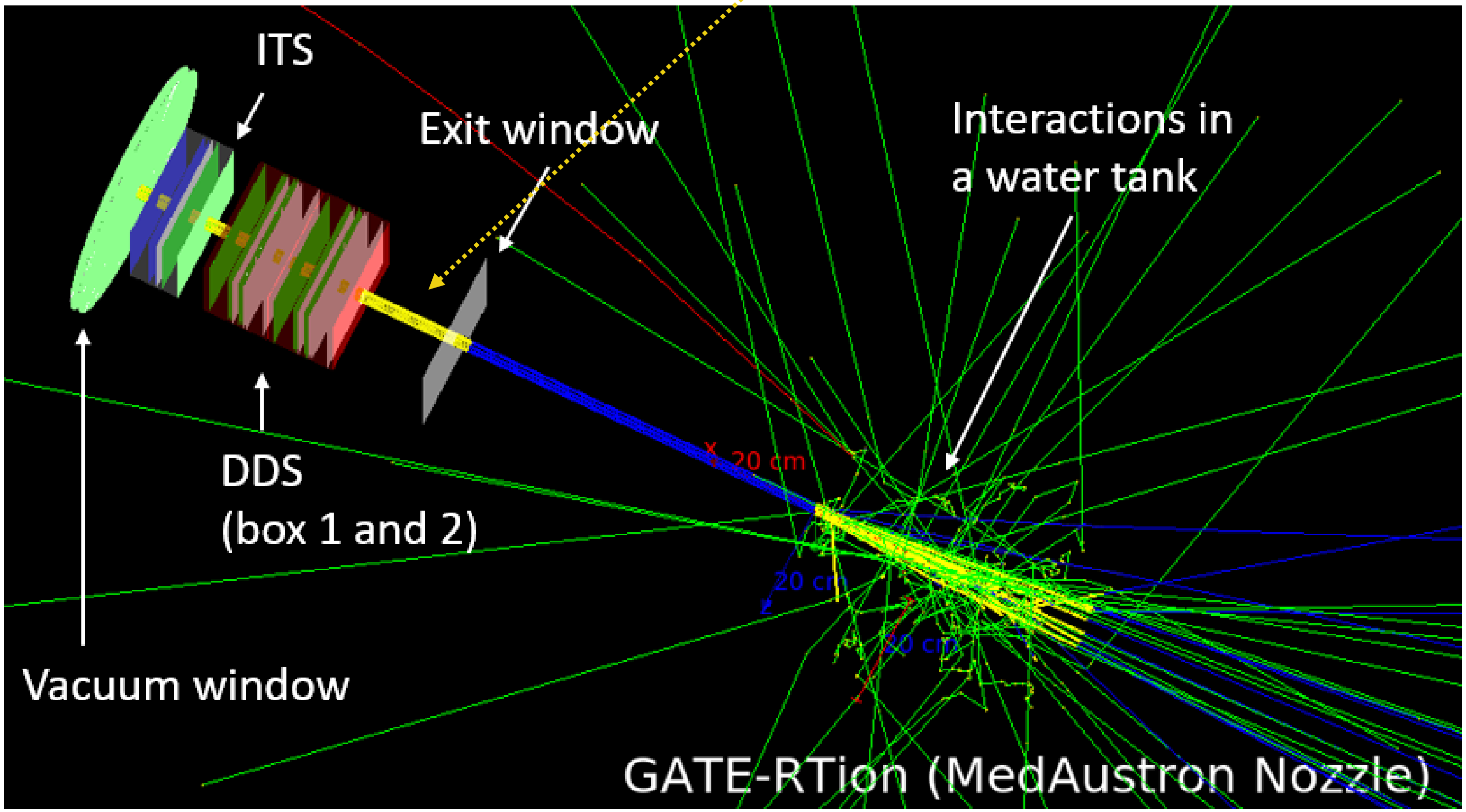
MedAustron nozzle design



BEAM MODELING

MedAustron nozzle design

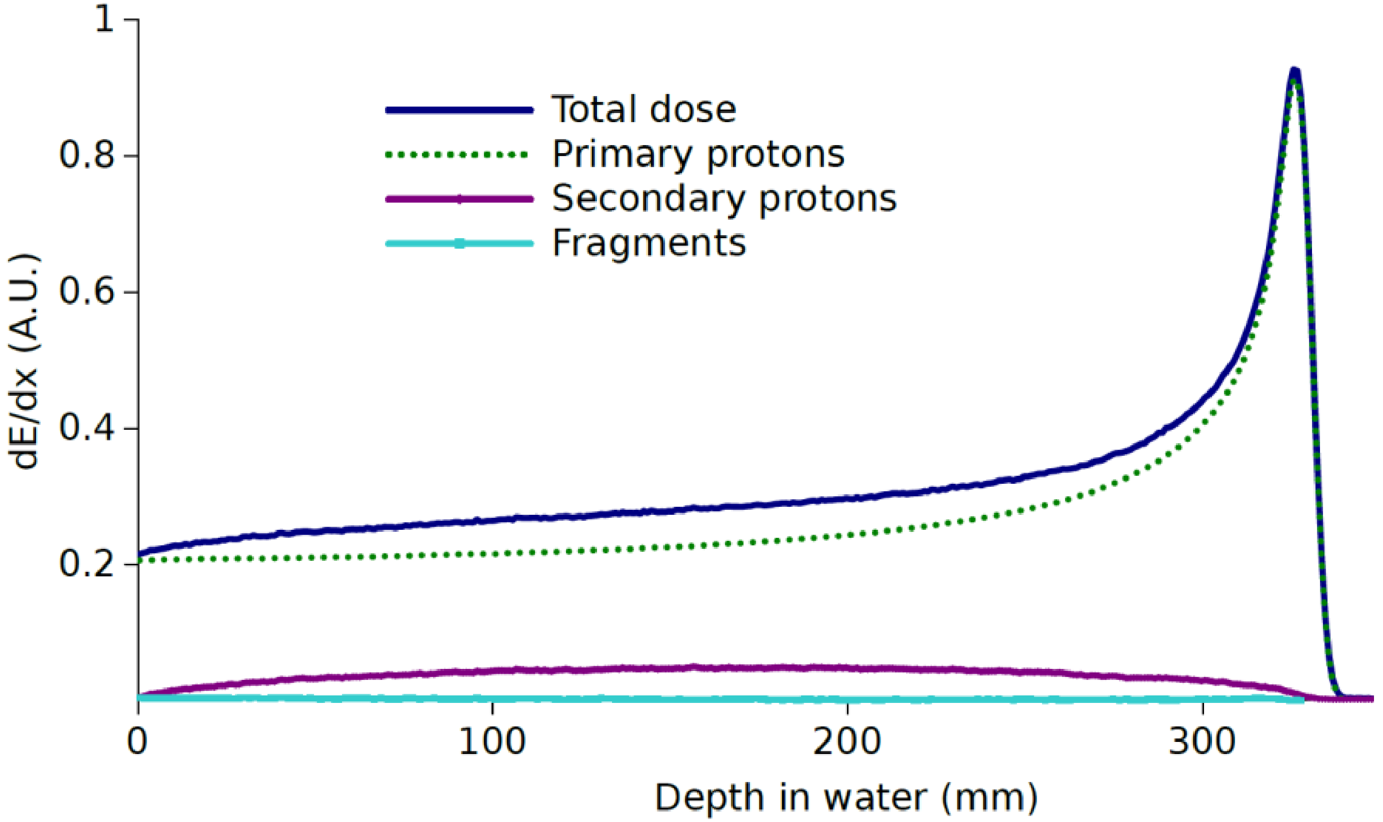
Passive elements



BEAM MODELING

Nuclear interactions for protons

Fluence reduction: about 1%/cm of water
Dose contribution: up to about 15%

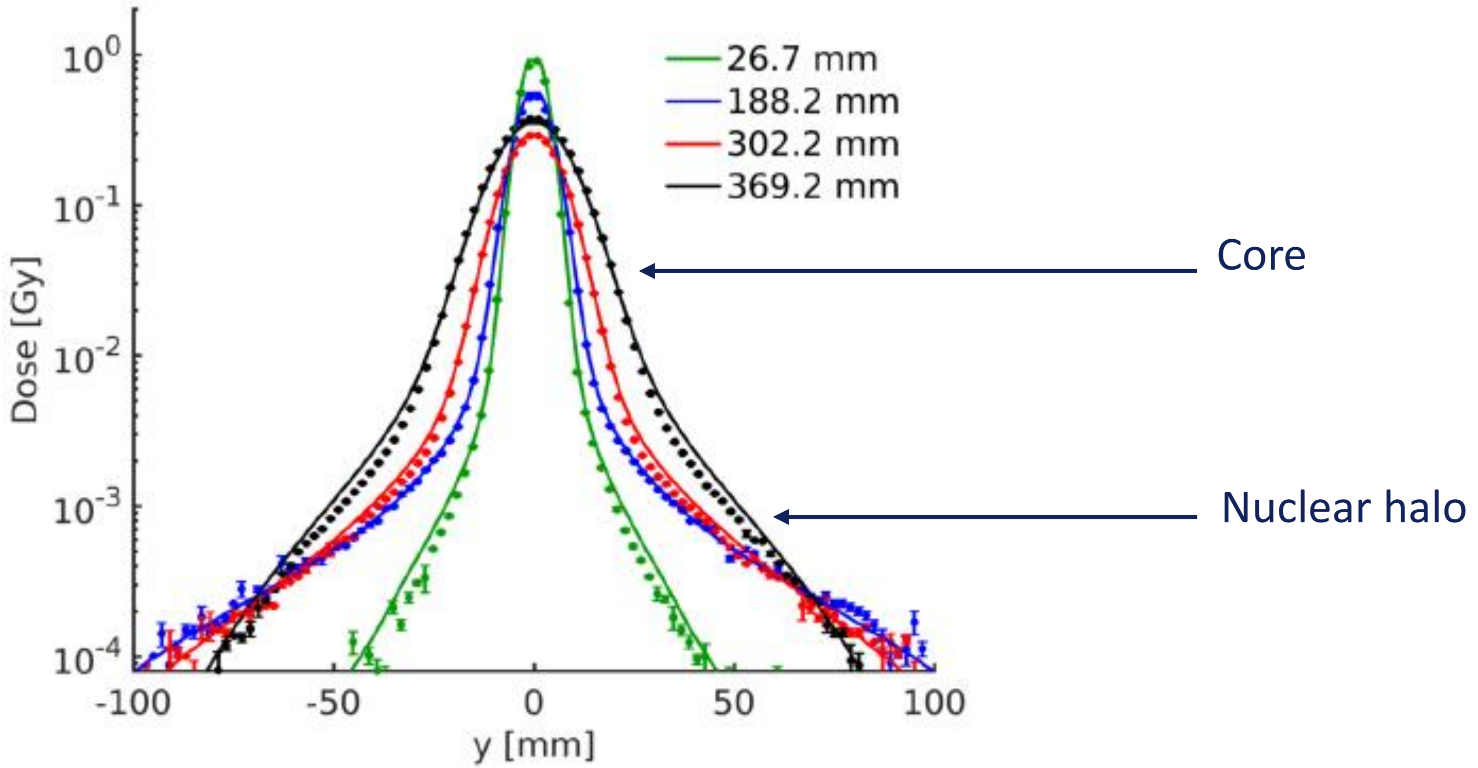


GATE/GEANT4 MC simulation of a 230 MeV proton beam.

BEAM MODELING

Nuclear interactions for protons

Nuclear halo far away from beam axis



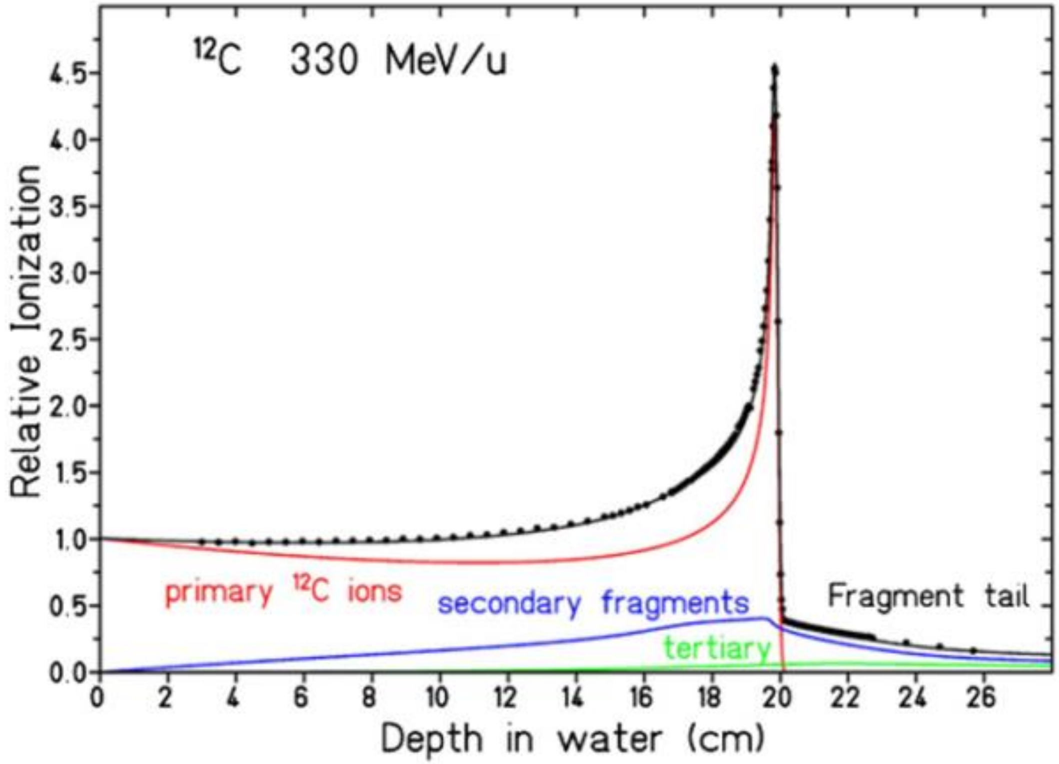
GATE/GEANT4 MC simulations vs. measurements of the transverse dose profiles of a 252.7 MeV proton beam.

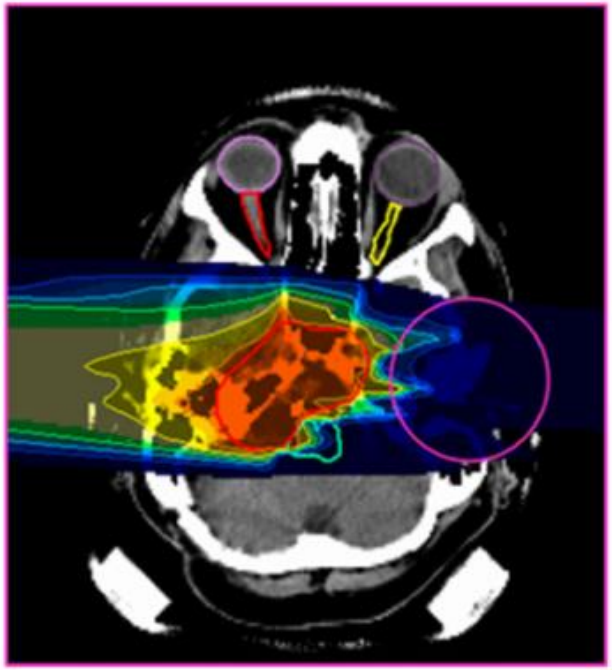
A. Resch et al., Evaluation of electromagnetic and nuclear scattering models in GATE/Geant4 for proton therapy, Med. Phys. 2019

BEAM MODELING

Nuclear interactions for carbon ions

Fluence reduction: about 4%/cm of water
Dose contribution: up to about 70%





Haettner et al, Experimental study of nuclear fragmentation of 200 and 400 MeV/u 12C ions in water for applications in particle therapy, Phys. Med. Biol., Vol. 58, 2013

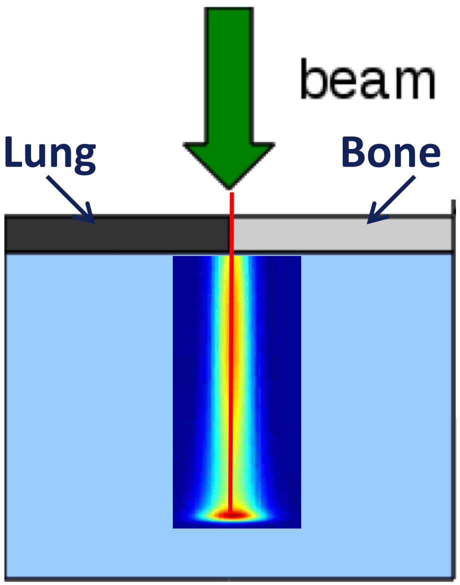
TREATMENT PLANNING

Dose computation algorithms

- **Ray tracing**
  - Fast
  - Do not properly account for lateral inhomogeneities
- **Pencil beam**
  - Compromise accuracy/speed
  - Limitation for complex heterogeneities
- **Monte Carlo**
  - Slower
  - Gold standard (detailed simulation of the physical interactions)

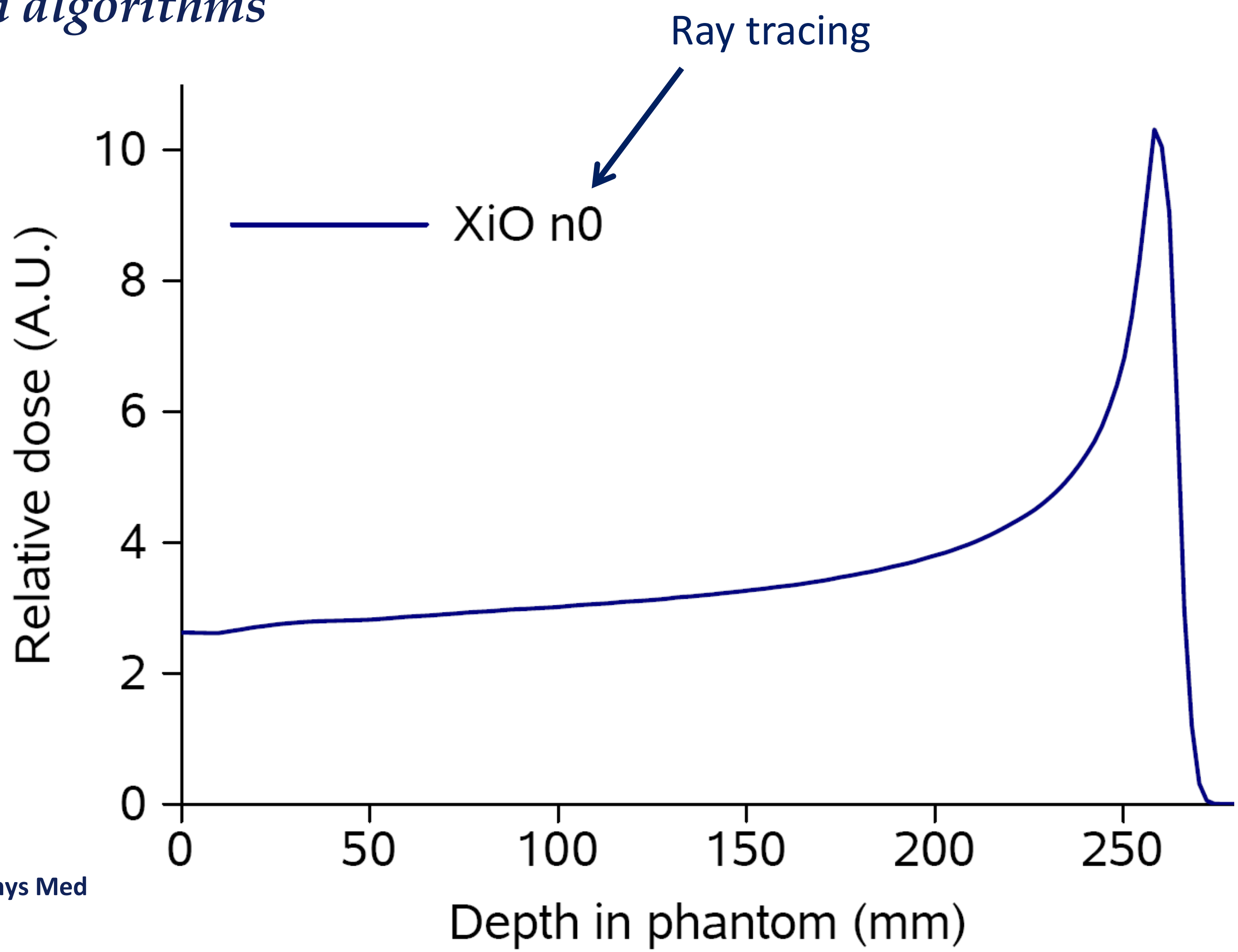
TREATMENT PLANNING

Dose computation algorithms



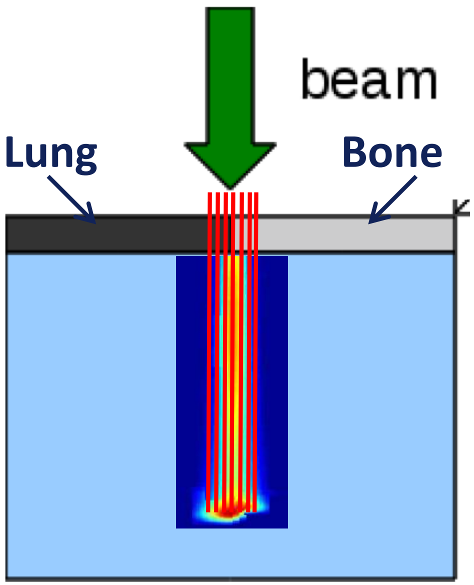
Sandwich set-up

Set-up inspired from **[Soukup et al 2005, Phys Med Biol 50(21): 5089–5104]**

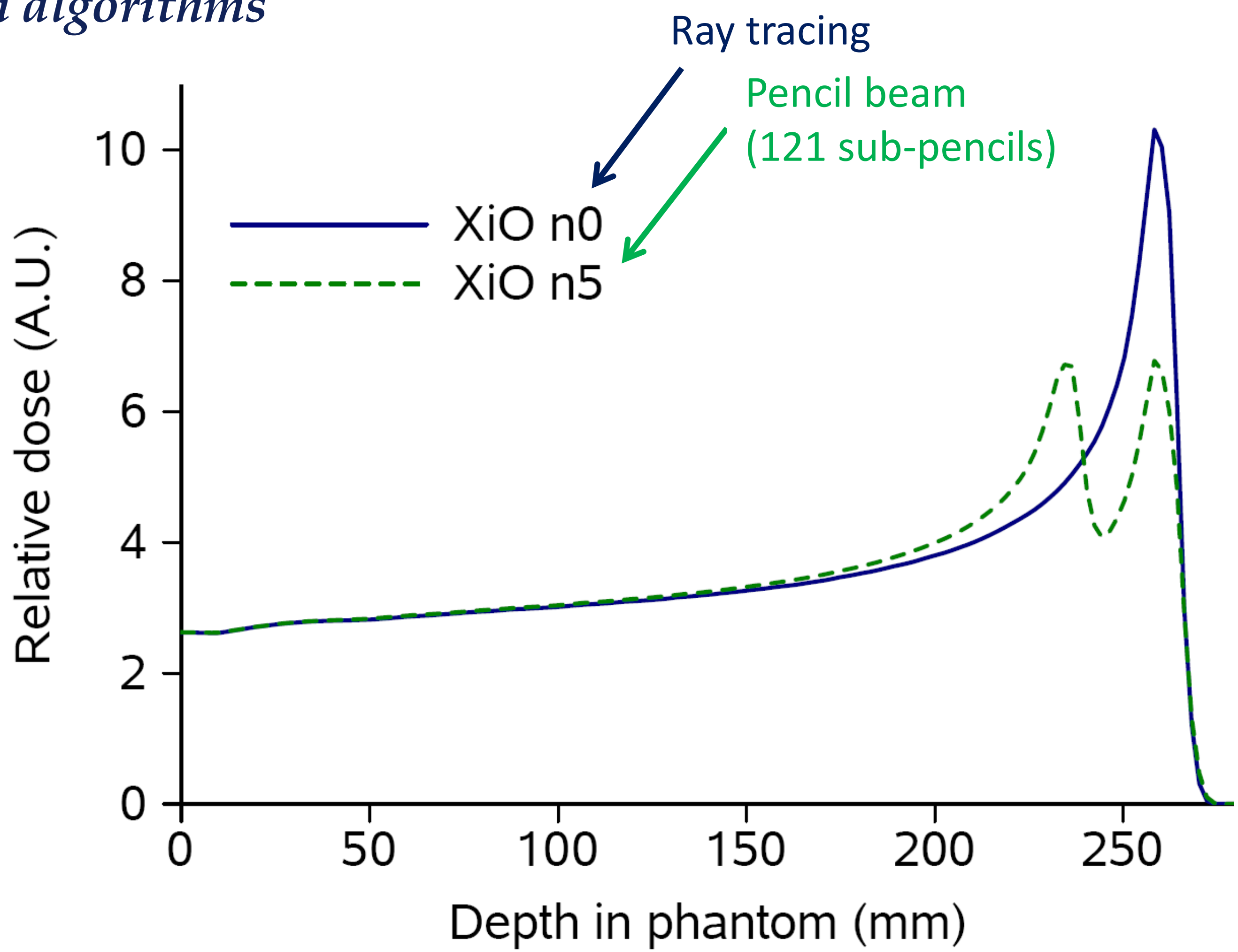


TREATMENT PLANNING

Dose computation algorithms

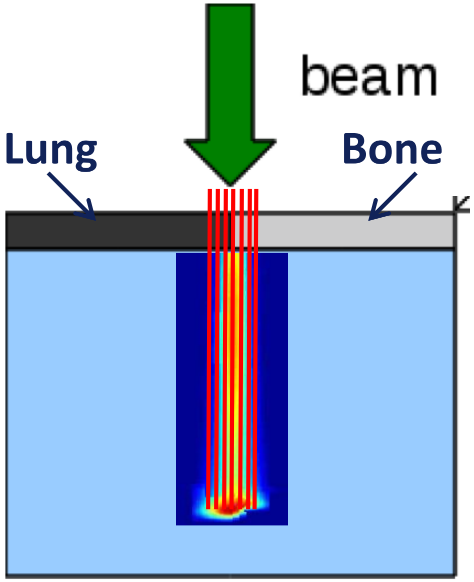


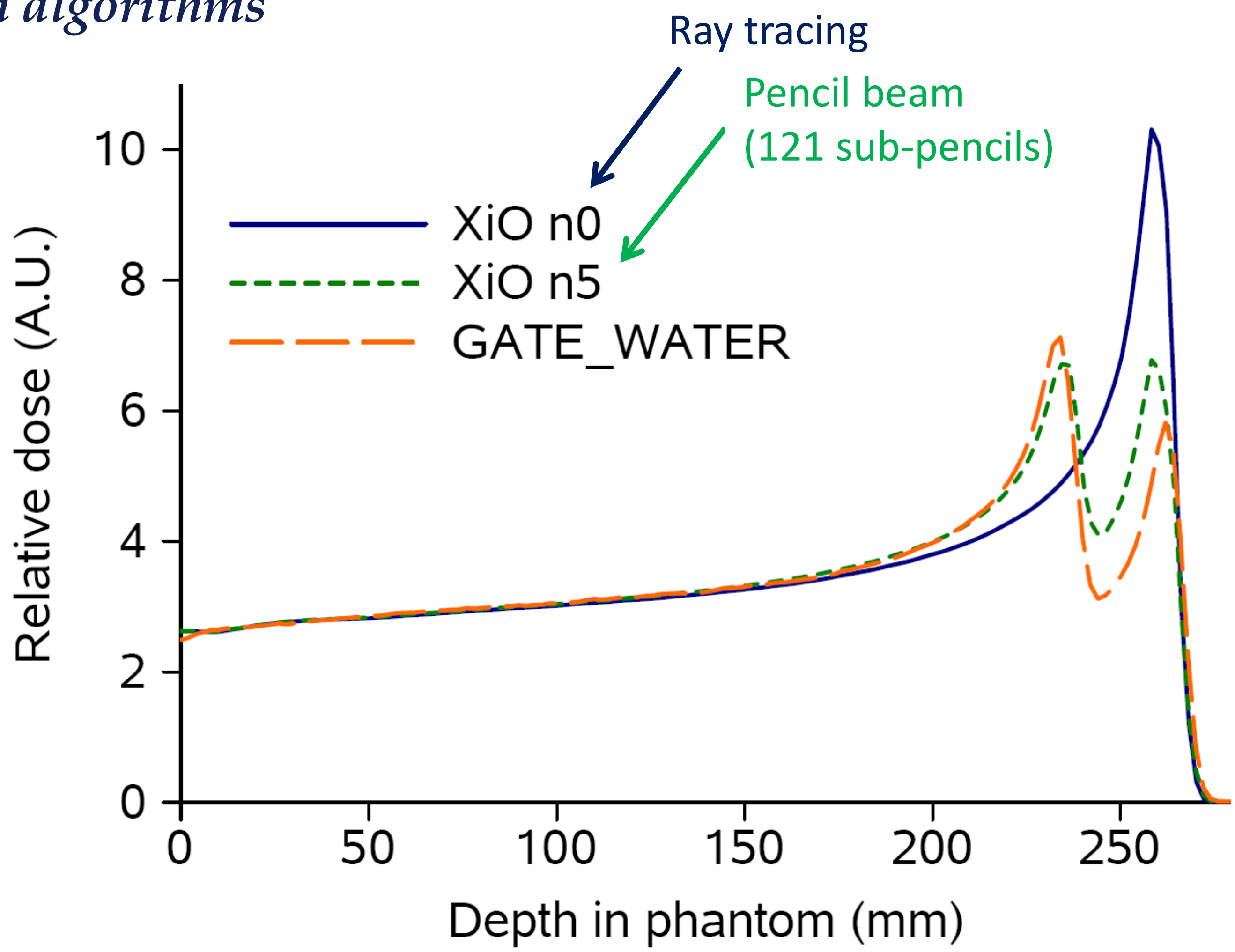
Sandwich set-up



TREATMENT PLANNING

Dose computation algorithms





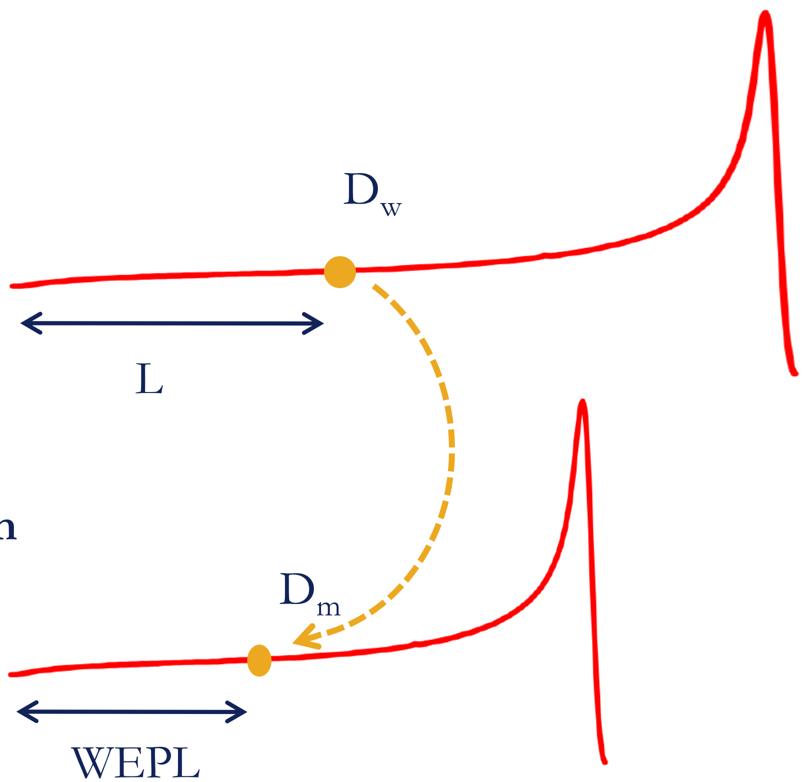
TREATMENT PLANNING

The water equivalent path length (WEPL) approximation

WEPL → same energy loss

water

medium



Proton mass stopping power in water ($MeV.cm^2.g^{-1}$)

$$D_w = \phi_w \times S_w$$

Proton fluence in water (cm^{-2})

$$D_m = \phi_m \times S_m \neq D_w$$

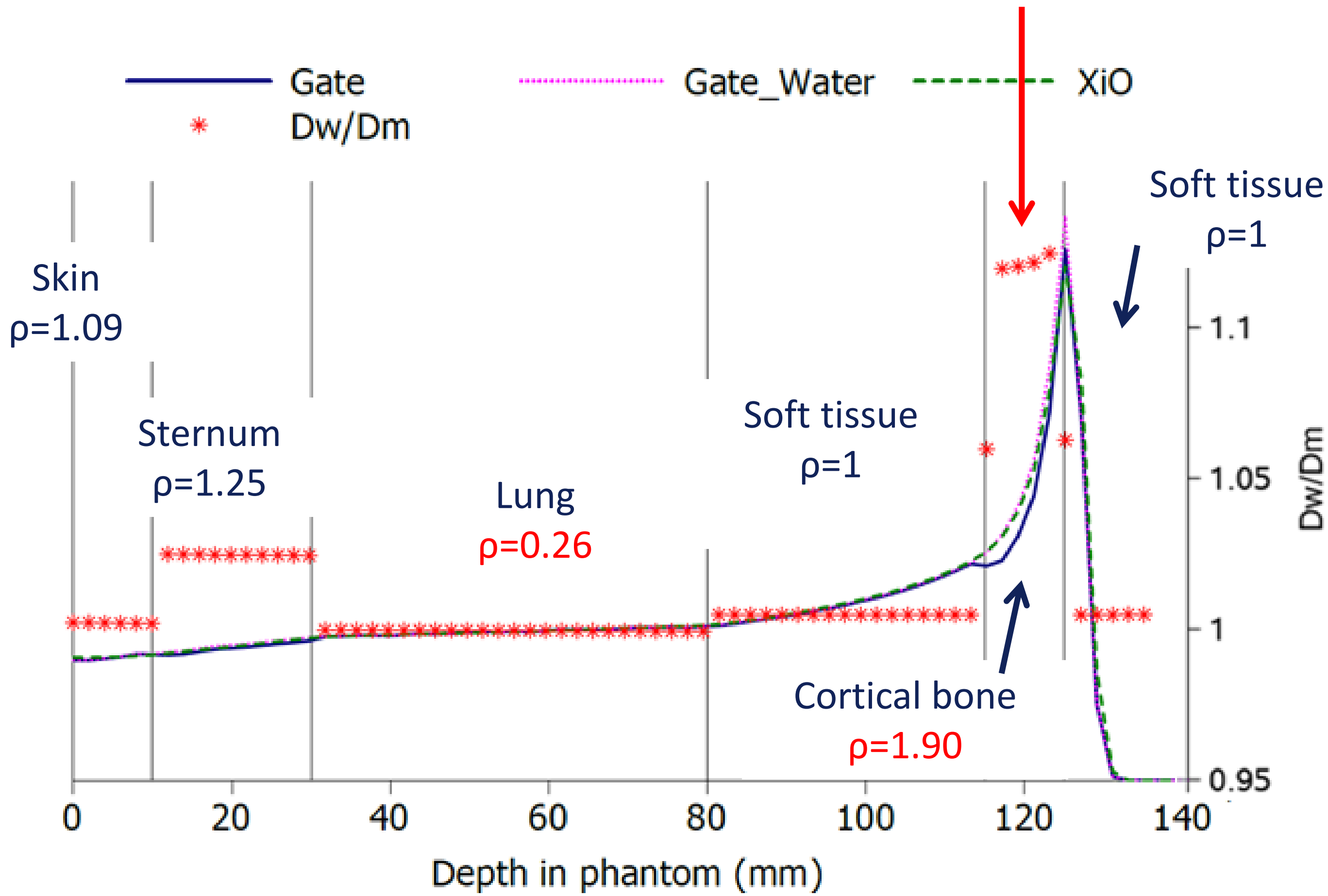
→ **TPS** gives $\mathbf{D_w}$ (historical reasons)

→ **Monte Carlo** gives $\mathbf{D_m}$

TREATMENT PLANNING

Dose to water and dose to medium

- $D_w \rightarrow$ smooth
- $D_m \rightarrow$ discontinuities
- **Difference >10% in bone**



TREATMENT PLANNING

Dose computation algorithms

Two Key advantages of Monte Carlo algorithm

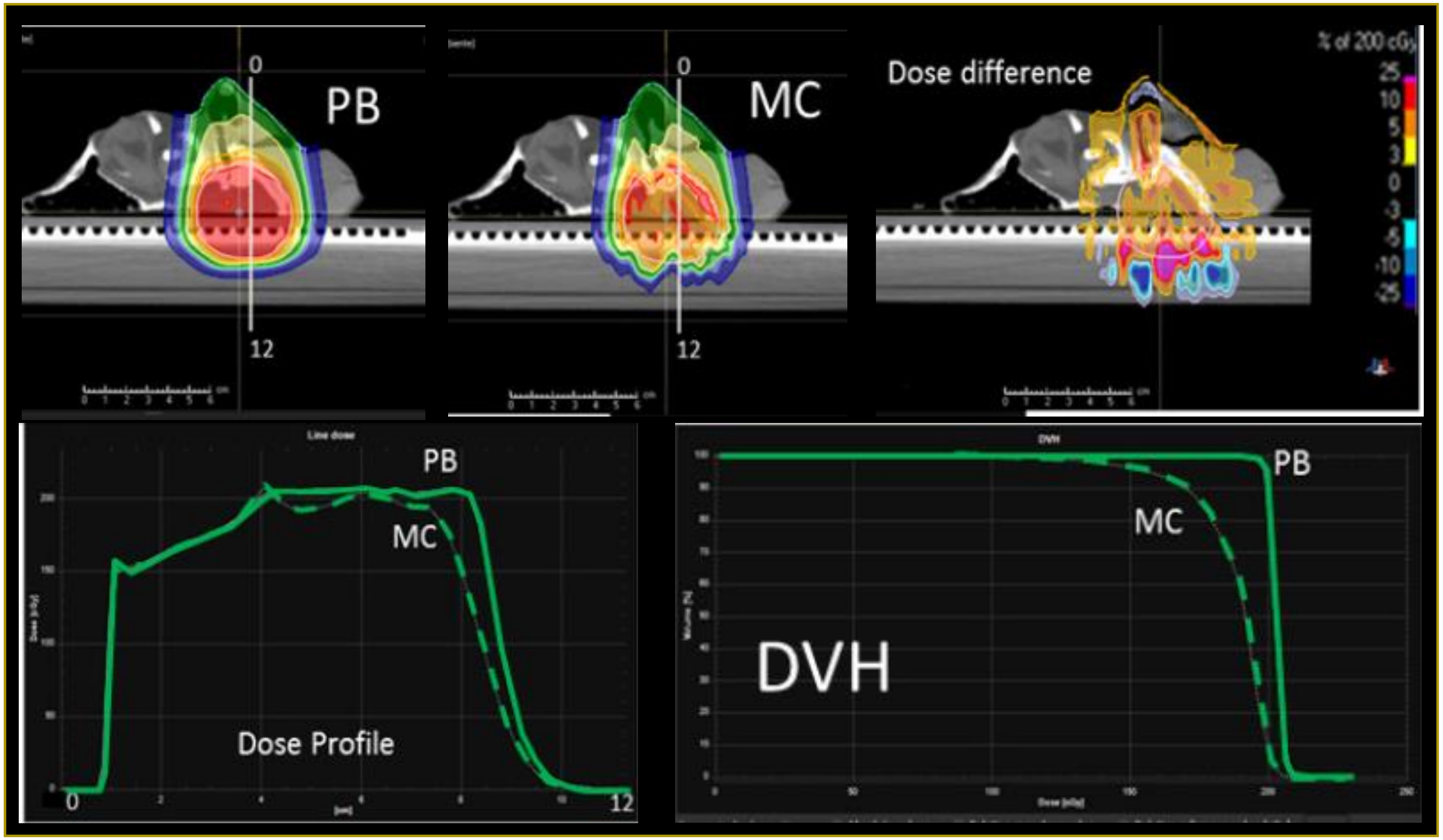
- **Transverse inhomogeneities**
  Mostly for protons! (due to multiple Coulomb scattering)

- **Transport of nuclear secondaries**
  Mostly with range shifter and large air-gaps

TREATMENT PLANNING

Dose computation algorithms

Proton irradiation of brain tissue from a lamb using a range shifter and a 20 cm air gap. Results are validated against measurements.



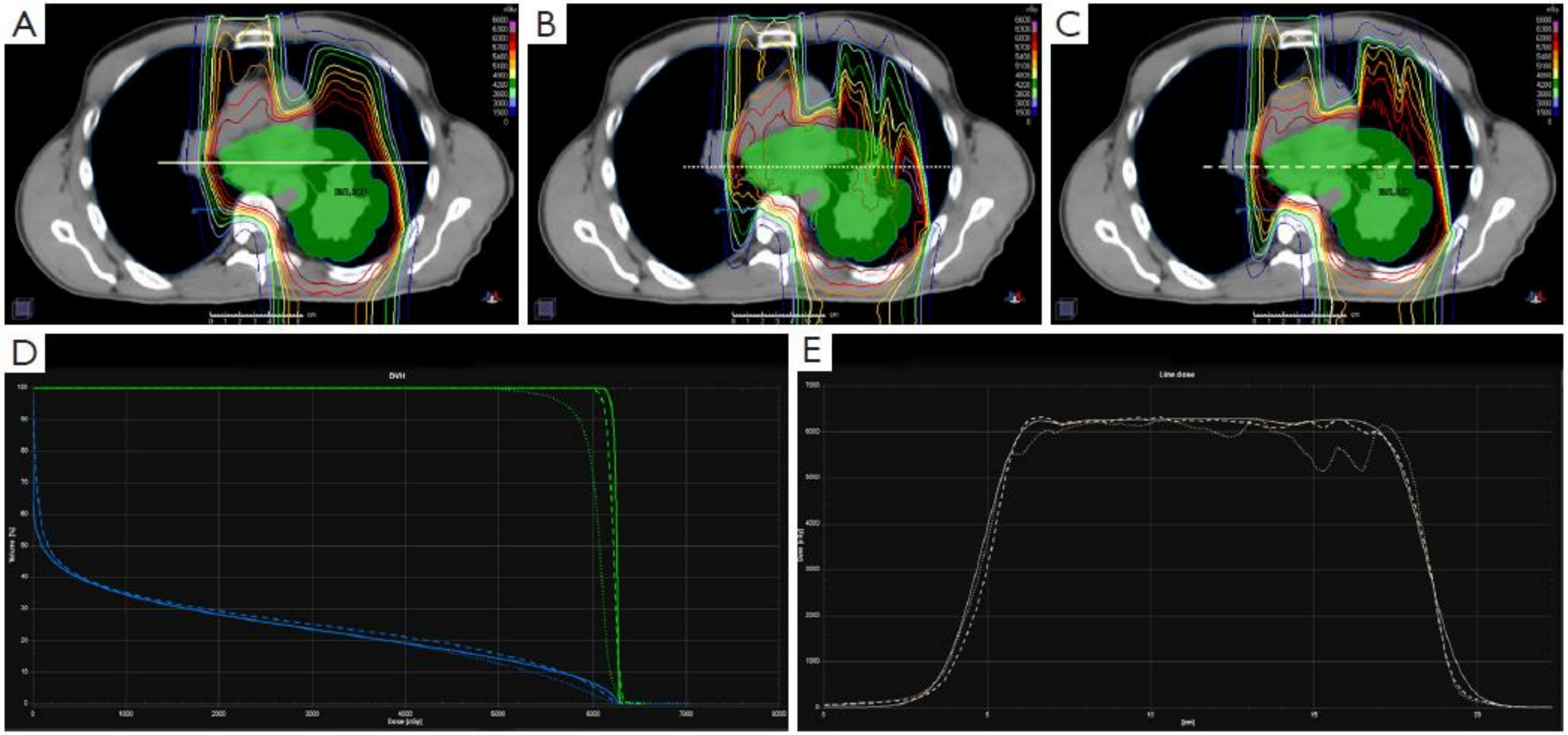
Widesott et al., Improvements in pencil beam scanning proton therapy dose calculation accuracy in brain tumor cases with a commercial Monte Carlo algorithm, *Phys. Med. Biol.* 63 (2018)

TREATMENT PLANNING

Dose computation algorithms

Proton irradiation of the lung

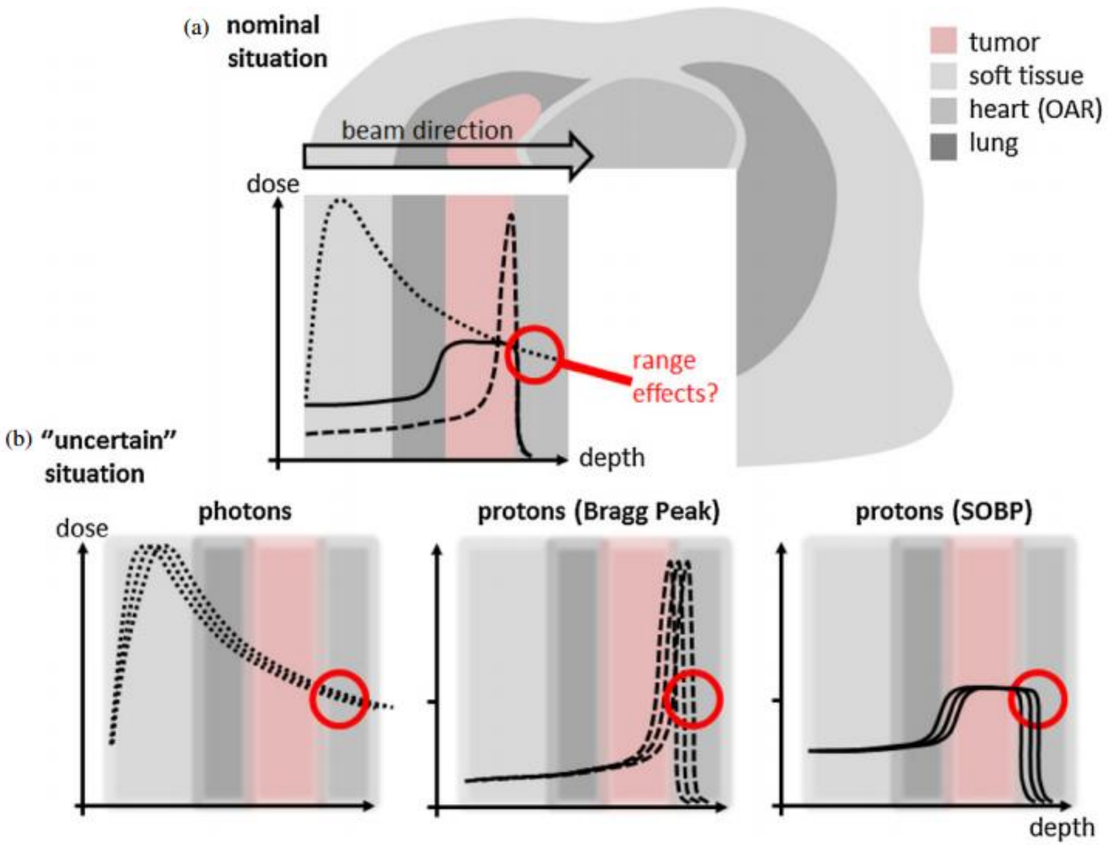
- A: PBA optimization (solid lines)
- B: A recalculated with MC (dotted lines)
- C: MC optimization (dashed lines)



Maes et al, Advanced proton beam dosimetry part II: Monte Carlo vs. pencil beam-based planning for lung cancer , Phys. Med. Biol. 63 (2018)

TREATMENT PLANNING

Range uncertainty



In vivo proton range verification: a review, A. C. Knopf and A. Lomax, Phys. Med. Biol. 2013

TREATMENT PLANNING

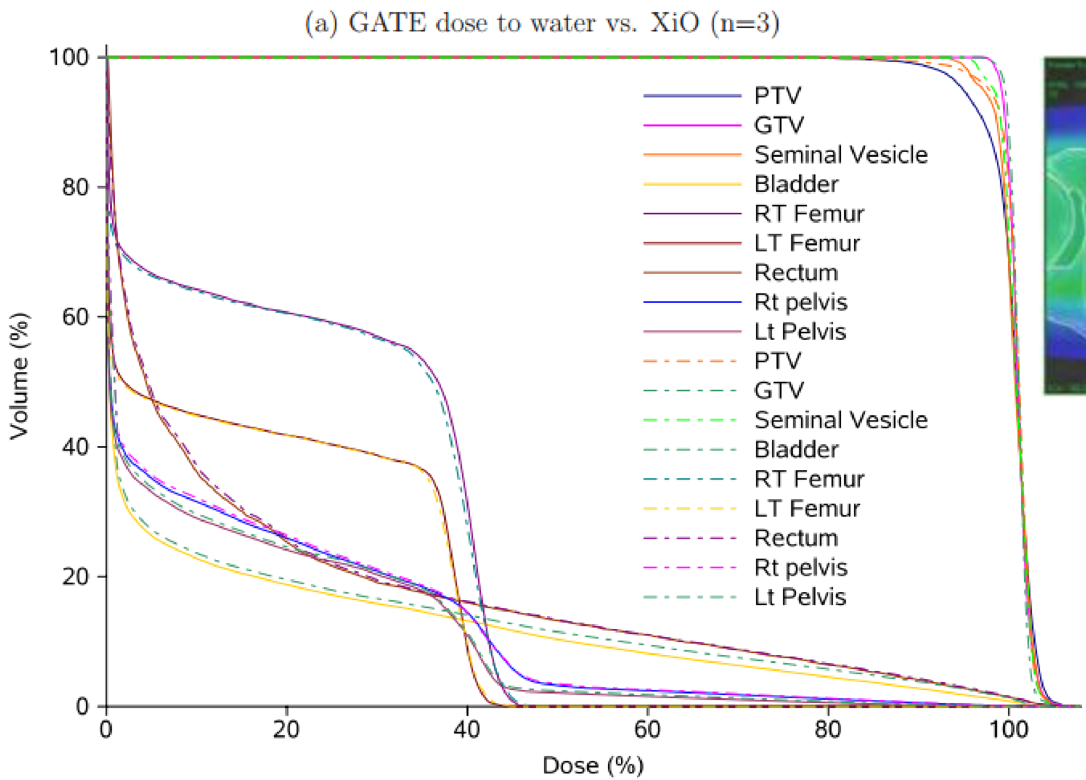
Range uncertainty

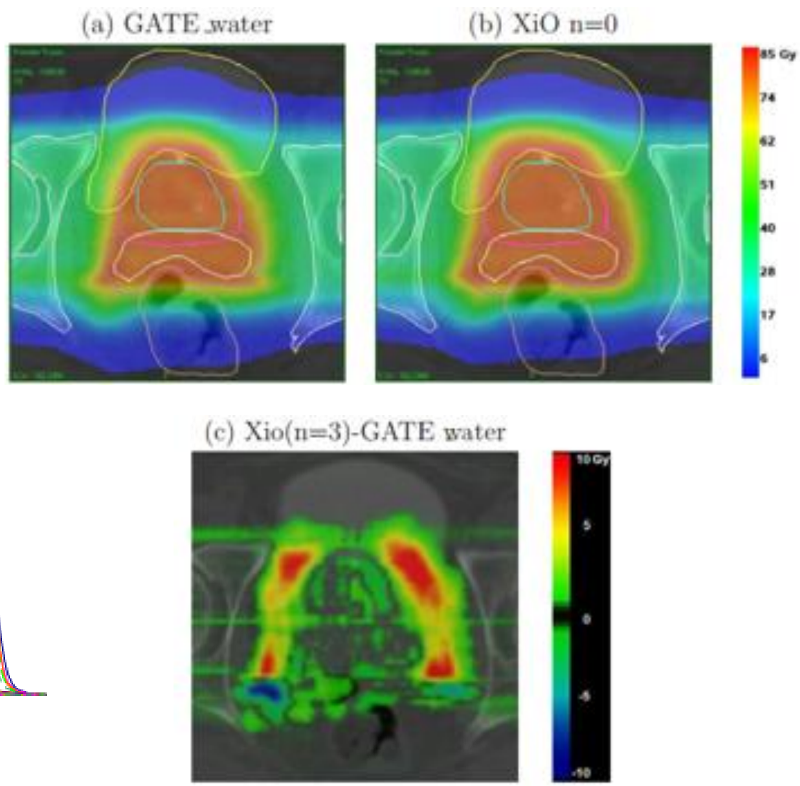
Source of range uncertainty in the patient	Range uncertainty without Monte Carlo	Range uncertainty with Monte Carlo
Independent of dose calculation		
Measurement uncertainty in water for commissioning	± 0.3 mm	± 0.3 mm
Compensator design	± 0.2 mm	± 0.2 mm
Beam reproducibility	± 0.2 mm	± 0.2 mm
Patient setup	± 0.7 mm	± 0.7 mm
Dose calculation		
Biology (always positive) ^	+ ~0.8%	+ ~0.8%
CT imaging and calibration	± 0.5%[a]	± 0.5%[a]
CT conversion to tissue (excluding I-values)	± 0.5%[b]	± 0.2%[g]
CT grid size	± 0.3%[c]	± 0.3%[c]
Mean excitation energy (I-values) in tissues	± 1.5%[d]	± 1.5%[d]
Range degradation; complex inhomogeneities	−0.7%[e]	± 0.1%
Range degradation; local lateral inhomogeneities *	± 2.5%[f]	± 0.1%
Total (excluding *, ^)	2.7% + 1.2 mm	2.4% + 1.2 mm
Total (excluding ^)	4.6% + 1.2 mm	2.4% + 1.2 mm

Paganetti et al, Range uncertainties in proton therapy and the role of Monte Carlo simulations, Phys Med Biol (57) 2012

TREATMENT PLANNING

Independent Dose Calculation

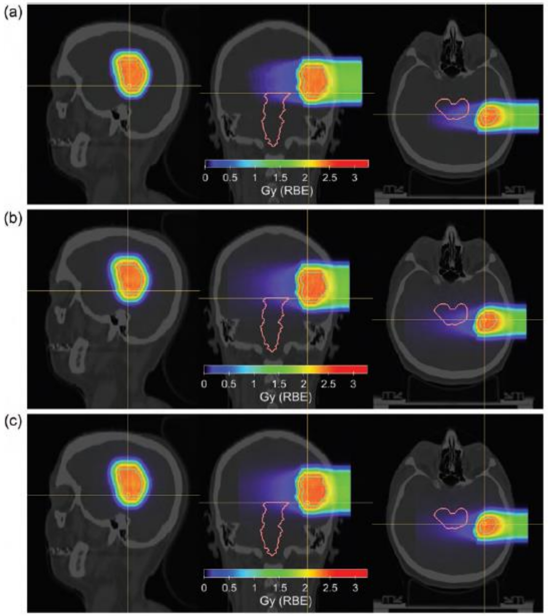




Grevillot et al, GATE as a Geant4-based Monte Carlo platform for the evaluation of proton pencil beam scanning treatment plans, Phys. Med. Biol. 57 (2012)

TREATMENT PLANNING

Independent Dose Calculation

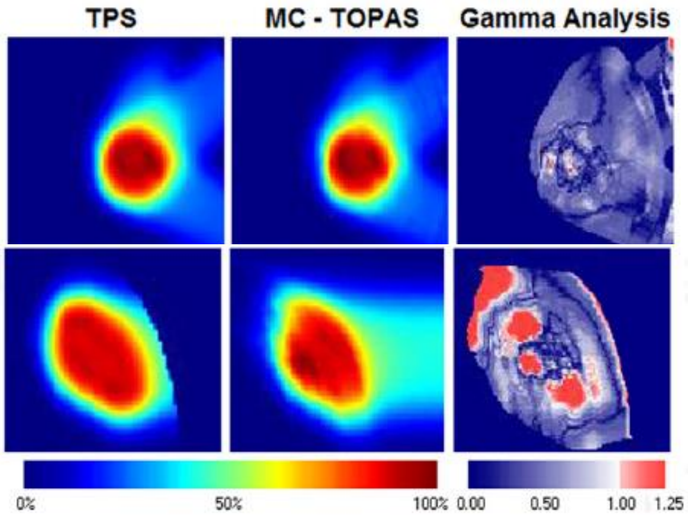


TPS optimization (PBA)

Fluka recomputation (MC)

Fluka-based re-optimized plan (MC)

Böhlen et al, A Monte Carlo-based treatment-planning tool for ion beam therapy, J. Rad. Res. 2013



Fracchiolla et al, Characterization and validation of a Monte Carlo code for independent dose calculation in proton therapy treatments with pencil beam scanning, Phys. Med. Biol. 60 (2015)

GATE

www.opengatecollaboration.org

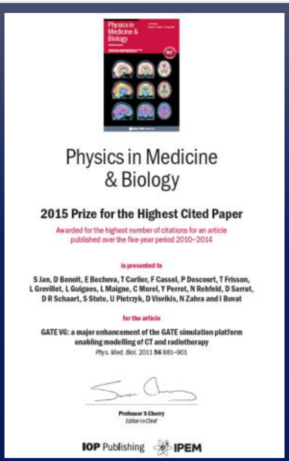
A Geant4-based MC application for medical phsyics

<u>GATE:</u>

- Free and Open source
- A very active community

  PMB citation prize 2 times: 2009 and 2015!
- Covers most fields of medical physics

  with ionizing radiations.
- Simple macro language → no C++ needed!
- A lot of capabilities!



Physics in Medicine & Biology

2015 Prize for the Highest Cited Paper

Awarded for the highest number of citations for an article published over the five-year period 2010–2014

is presented to

S Jan, D Benoit, E Becheva, T Carlier, F Cassol, P Descourt, T Frisson, L Grevillot, L Guigues, L Maigne, C Morel, Y Perrot, N Rehfeld, D Sarrut, D R Schaart, S Stute, U Pietrzyk, D Visvikis, N Zahra and I Buvat

for the article

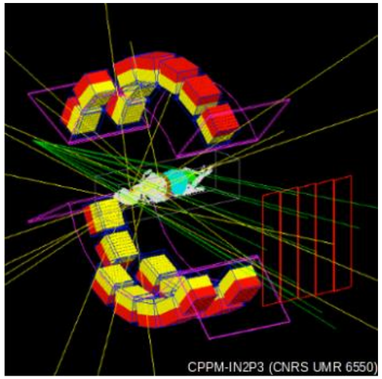
GATE V6: a major enhancement of the GATE simulation platform enabling modelling of CT and radiotherapy

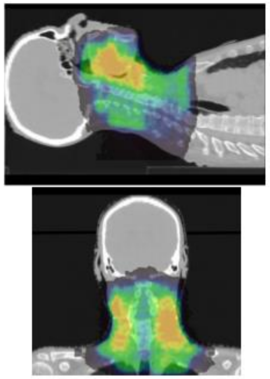
Phys. Med. Biol. 2011 **56** 881–901

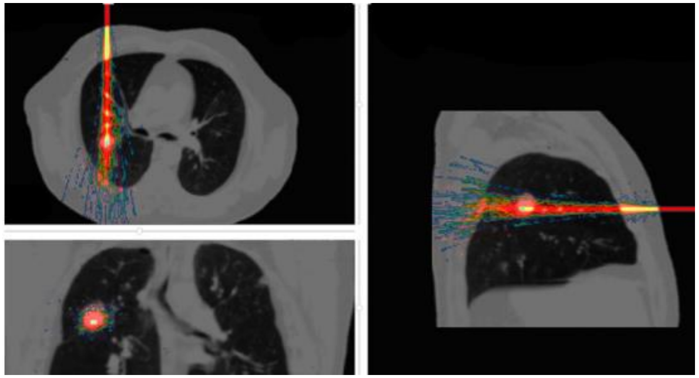
Professor S Cherry

Editor-in-Chief

IOP Publishing IPEM







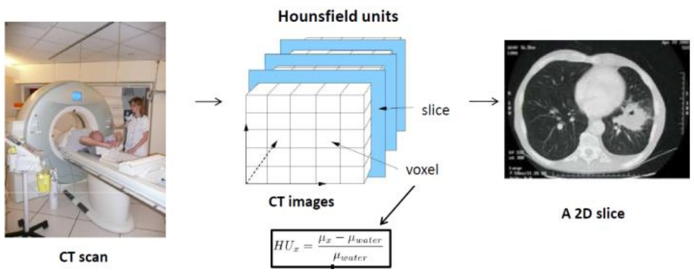
GATE-RTION

Presented at 1st ESTRO physics workshop, Nov. 2017, Glasgow.

GATE-RTion release 1.0 available!

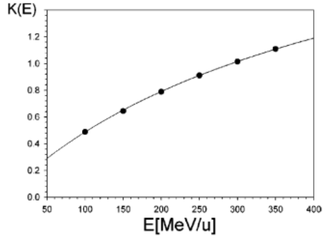
Visit our website!

http://www.opengatecollaboration.org/GateRTion



- A stable and long term GATE release, called GATE-RTion, having all necessary features for dosimetric applications in Light Ion Beam Therapy facilities equipped with the Pencil Beam Scanning delivery technique.
- Providing a collection of tools necessary for the clinical users to interface GATE with the clinical environment
- Developing guidelines for clinical users on how to implement GATE into the clinical routine using the provided tools
- Currently 6 ion therapy centers involved in Europe

In-room patient positioning



Beam monitor calibration

IDEAL

CE

Objective:
To provide a CE marked Independent DosE cALculation (IDEAL) product for scanned ion beam delivery facilities using GATE-RTion dose engine.

The project is funded within the scope of the Austrian COMET - Competence Centers for Excellent Technologies, in a collaboration between EBG MedAustron GmbH, Medical University of Vienna and ACMIT Gmbh.

Project started in February 2018 for a duration of up to 8 years.
First version planned to be available at MedAustron in 2019.

FFG Österreichische Forschungsförderungsgesellschaft

acmit AUSTRIAN CENTER FOR MEDICAL INNOVATION AND TECHNOLOGY

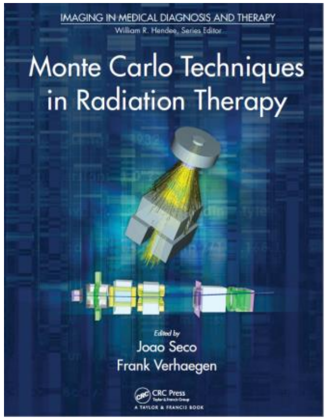
MedAustron Ion Therapy Center

MEDICAL UNIVERSITY OF VIENNA

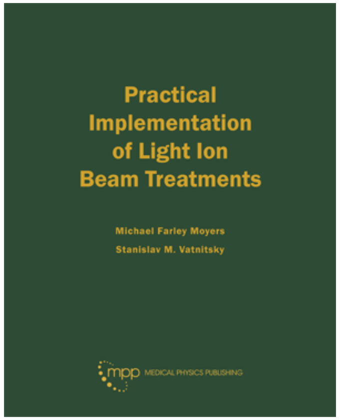
CONCLUSION

Monte Carlo is a necessary tool to support medical physics research and developments in light ion beam therapy

USEFUL BOOKS



J Saeco and F Verhaegen, Monte Carlo Techniques in Radiation Therapy, CRC Press, November 2016



M F Moyers and S M Vatnitsky, Medical Physics Publishing, December 2013

THANKS FOR YOUR ATTENTION!

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