PROTON AND CARBON ION DOSIMETRY ACTIVITIES AT MEDAUSTRON

Antonio Carlino, PhD

MedAustron Ion Therapy Center, Marie Curie-Straße 5, Wiener Neustadt, Austria.

Outline

- LET variation as function of different optimization approaches in proton therapy

- Gate/Geant4 as MC simulation toolkit for ion beam dosimetry

- Impact of particle energy spectra on clinical plans in carbon ion beam therapy

LET variation as function of different optimization approaches in proton therapy

Martino G[1], van Lobenstein N[2], Carlino A[1], Resch A[3,4], Palkowitsch M[1], Traneus E[5], Anson Marcos C[6], Stock M[1], Kragl G[1]

[1]MedAustron Ion Therapy Center, Medical Department, Wiener Neustadt, Austria.
[2]Delft University of Technology, Faculty of Mechanical- Maritime- and Materials Engineering, Delft, The Netherlands.
[3]Christian Doppler Laboratory for Medical Radiation Research for Radiation Oncology, Medical Radiation Research, Vienna, Austria.
[4]Medical University of Vienna- Austria, Department of Radiotherapy, Vienna, Austria.
[5]RaySearch Laboratories, Stockholm, Sweden.
[6]Hospital Universitario La Princesa, Madrid, Spain.

E-poster Nr. 58-0584:
A. Carlino et al., "Study on the LET distribution as a function of different treatment planning approaches in proton beam therapy"

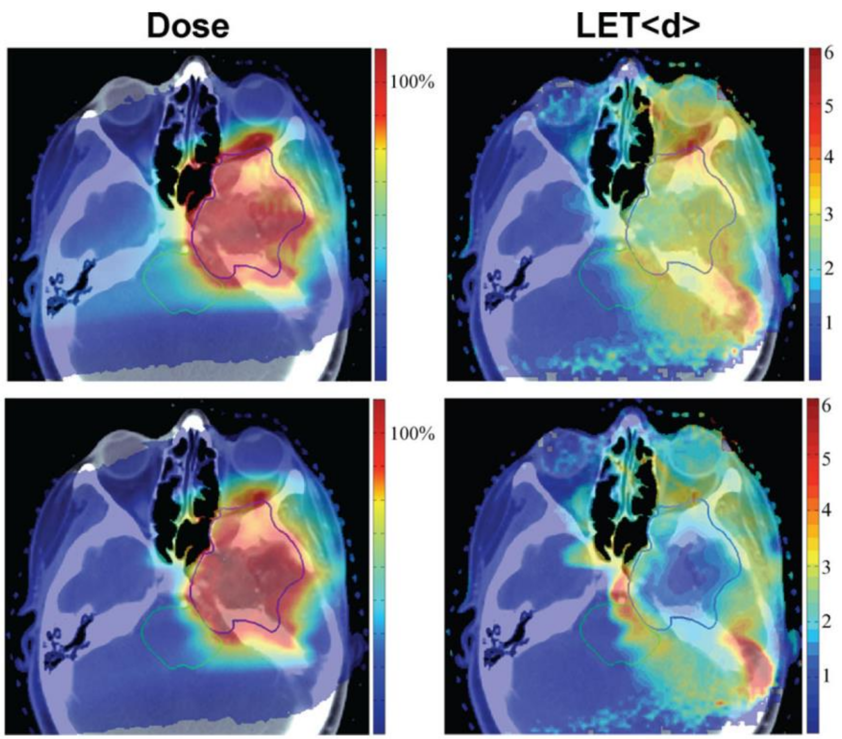
Motivation

- constant RBE of 1.1 might be good average → may not sufficiently describe biological effects in all situations

Which options do we have in clinical treatment planning to be robust against RBE-uncertainties?

$$LET_d(z) = \frac{\int_0^\infty S_{el}(E) D(E,z) dE}{\int_0^\infty D(E,z) dE}$$

- assumption that LET_d is possible quantity to correlate to biological/clinical effect without introducing any RBE models



Paganetti H, et al. AAPM TG-256 Med Phys 2019

Aim of the Study

- Benchmark RayStation LET calculation against Gate/Geant4

$$LET_T(z) = \frac{\int_0^\infty S_{el}(E)\Phi(E,z)dE}{\int_0^\infty \Phi(E,z)dE}$$

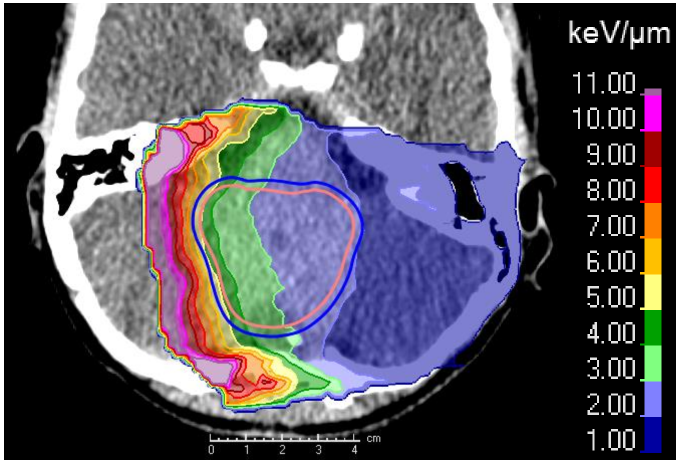
$$LET_D(z) = \frac{\int_0^\infty S_{el}^2(E)\Phi(E,z)dE}{\int_0^\infty S_{el}\Phi(E,z)dE}$$

$S_{el} \ldots$ electronic stopping power

- Use LET_d distributions to evaluate different optimization strategies for cases with critical beam incidences

www.opengatecollaboration.org

Traneus E, et al. IJROBP 2019



Materials and methods

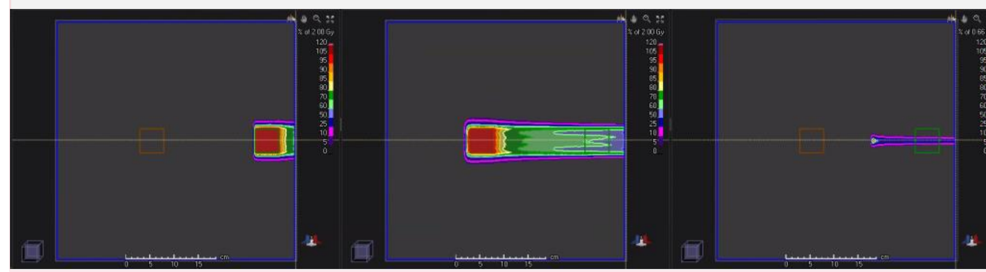
- Benchmarking of LET_d and LET_t computed in RayStation against GATE/Geant4
- Voxel size dependence
- Angular dependence (two beams)

Comparison between LET_d distributions:

- in a (5x5x5) cm^3 target
  centered at 6 and 30 cm depths in a water phantom
  using a dose grid of (0.1x0.1x0.1) cm^3

- 160 MeV pencil beam (range in water: 17.4 cm)

✓ RayStation (v5.99.50.10)
✓ Geant4 (v10.03.p01) / GATE (v8.0)



Materials and methods

- Benchmarking of LET_d and LET_t computed in RayStation against GATE/Geant4
- **Voxel size dependence**
- Angular dependence (two beams)

Cortes-Giraldo et al., A critical MC study on different scoring techniques, 2014

LET_d distributions as a function of the voxel size due to scoring artefacts?

- in a (5x5x5) cm^3 water target centered at 6 and 30 cm depths in a water phantom
- Used dose grids:
  - (0.1x0.1x0.1) cm^3
  - (0.2x0.2x0.2) cm^3
  - (0.3x0.3x0.3) cm^3

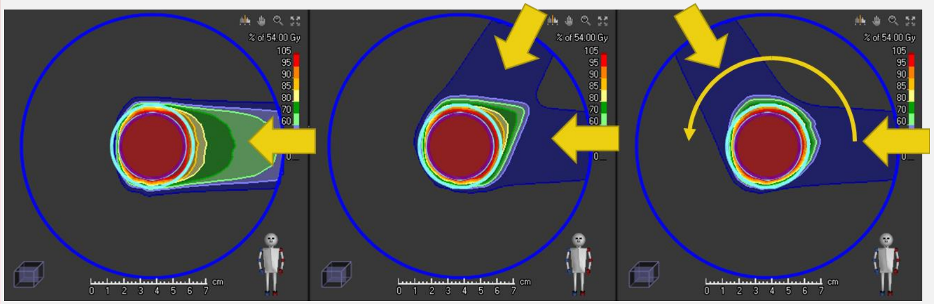
Materials and methods

- Benchmarking of LET_d and LET_t computed in RayStation against GATE/Geant4
- Voxel size dependence
- Angular dependence (two beams)

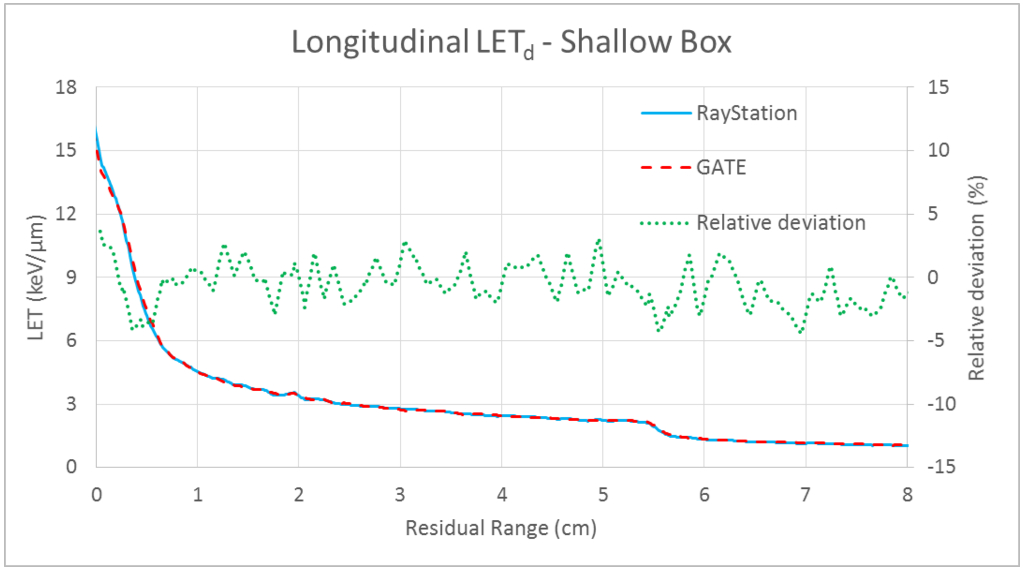
LET_d distributions as a function of the beams angles:

In a spherical target with 4 cm diameter centered in a cylindrical water phantom

- 2 SFO beams separated by 0° to 180° in steps of 10°
- DVHs and LET_dVHs analysed in concentric rings around the target



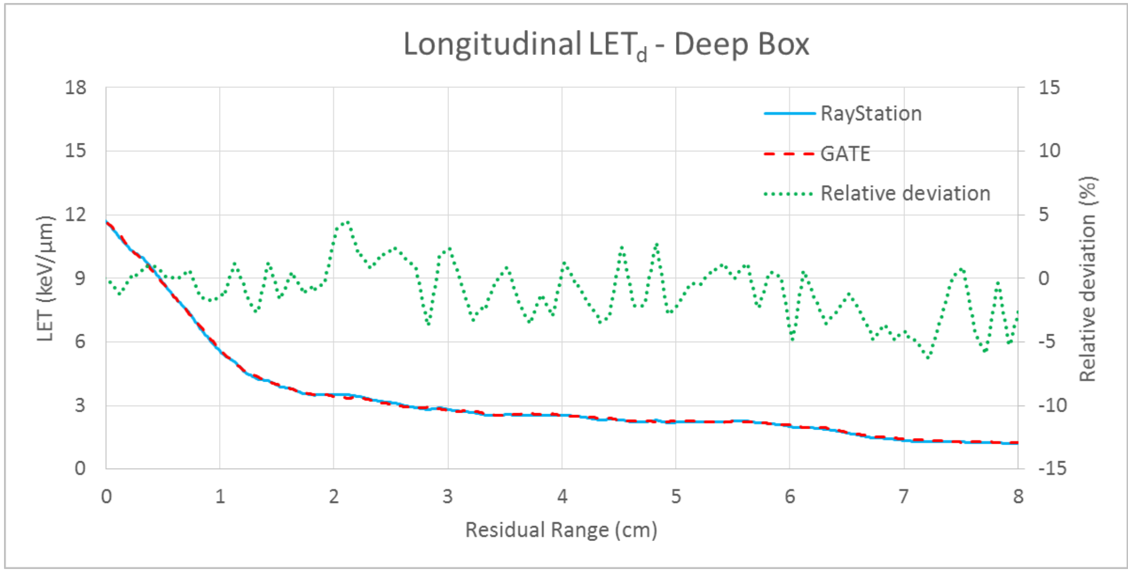
Results: Benchmarking of LET_d RayStation vs GATE/G4



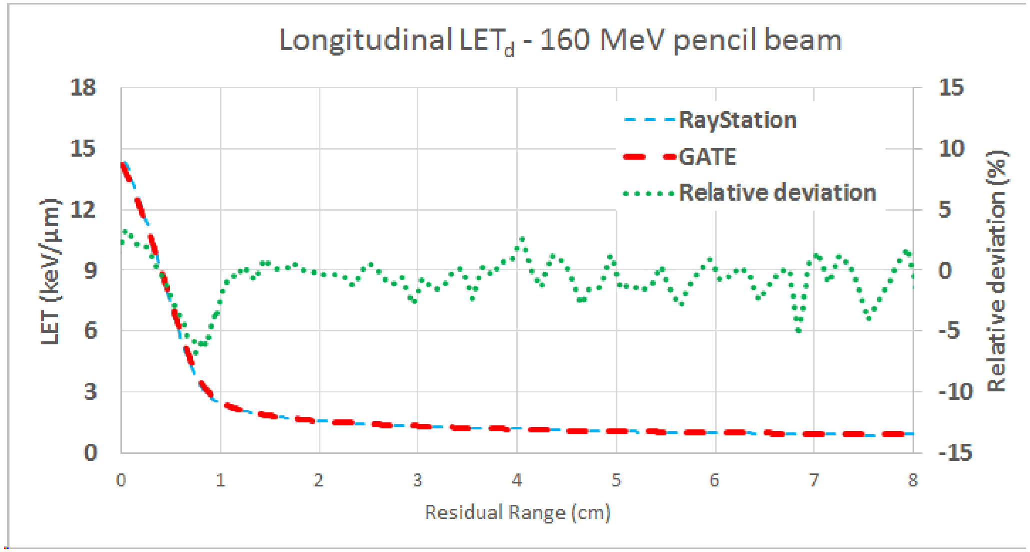
LET computation has been implemented and validated in Gate by A. Resch (PhD student MUW)

All evaluated lateral and longitudinal profiles revealed

- *Relative local deviations within ±5%. Average local deviations within ±1.5%.*
- *maximum LET_d at R10*
  - *- decreasing with depth of the target due to range straggling*

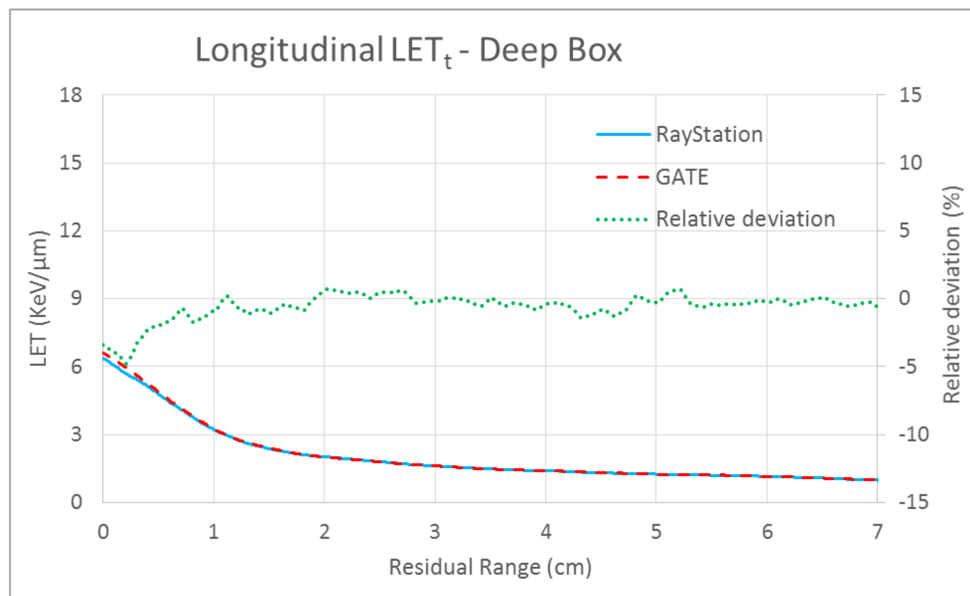


Results: Benchmarking of LET_d RayStation vs GATE/G4

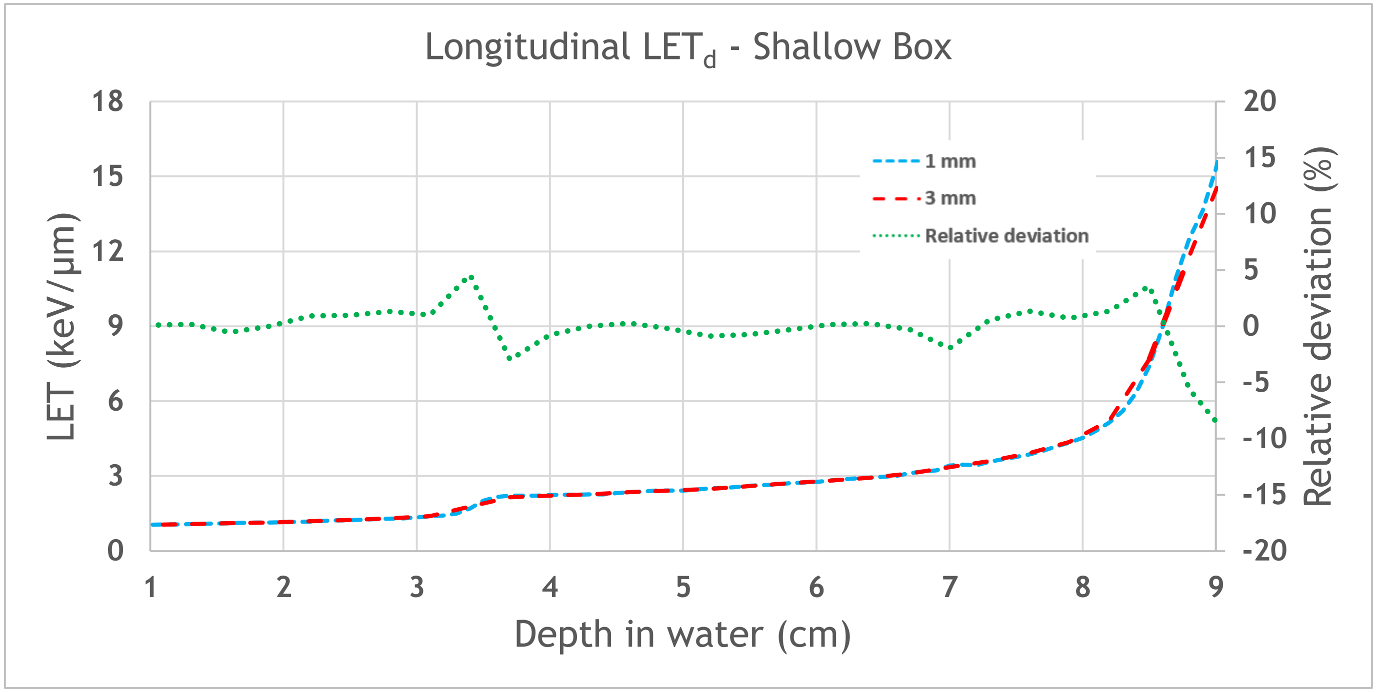


All evaluated lateral and longitudinal profiles revealed

- *Relative deviations within ±5%*
- *Smaller deviations for the track length averaged LET_t*

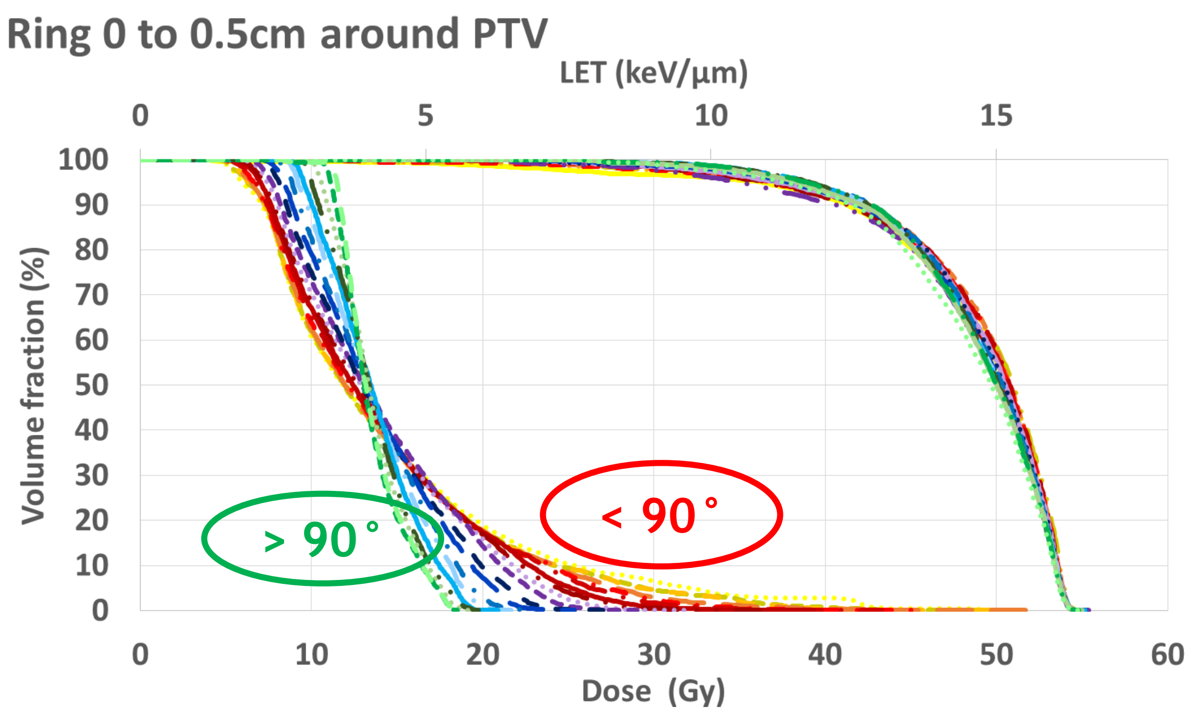


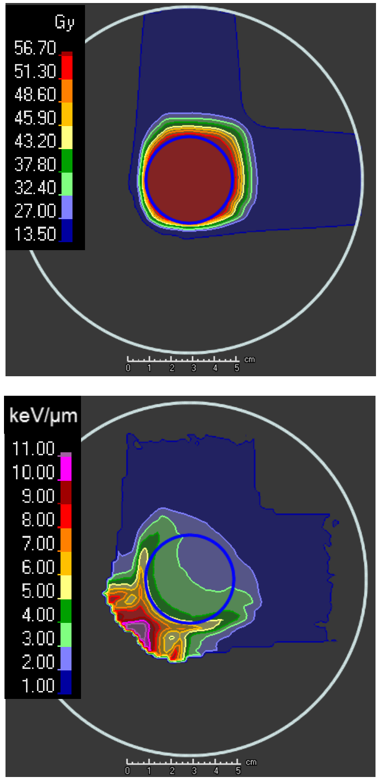
Results: Voxel size dependence in RayStation



→ No voxel size dependence was observed in RayStation as for Gate.

Results: Angular dependence





dose vs. LET_d distribution

Diff	LET_d to 2% of ring 0-0.5cm [keV/µm]
0°	12.6
90°	7.2
180°	5.4

Conclusions

- LET_d and LET_t calculated by RS in **good agreement with Gate/Geant4** - reliable tool for LET distribution display.

- No voxels size dependency in both codes (RayStation and Gate/G4)

- **Increasing number of beams** and using **orthogonal** to **contralateral** beam has highest impact on reduction of maximum LET_d.

E-poster Nr. 58-0584:
A. Carlino et al., "Study on the LET distribution as a function of different treatment planning approaches in proton beam therapy"

Gate/Geant4 as MC simulation toolkit for ion beam dosimetry

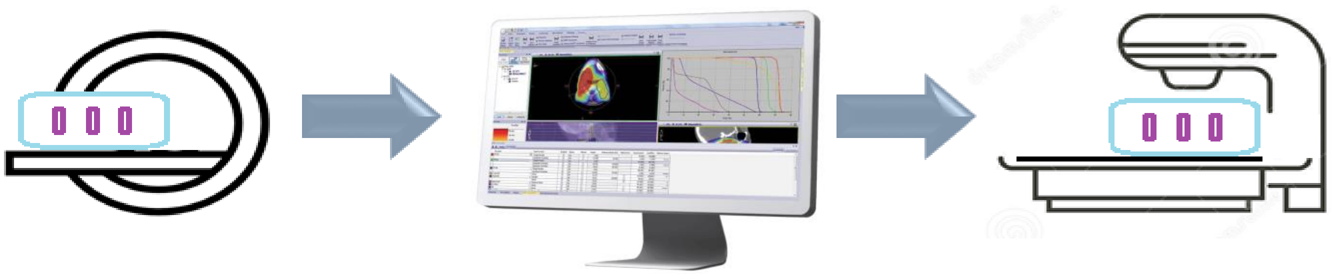
Marta Bolsa Ferruz (PhD student at MedAustron)

E-poster Nr. 58-0203*:*
M. Bolsa Ferruz et al. "Gate/Geant4 as a Monte Carlo Simulation toolkit for light ion beam dosimetry"

Motivation

End-to-end testing

- Logistic chain of RT treatment using a phantom containing dosimeters (IC and alanine)
- Alanine dosimetry performed in collaboration with the National Physics Laboratory (NPL) as a **dosimetry auditing** tool



A. Carlino et al ***Independent dosimetry audit based on end-to-end testing in proton beam therapy*** *Session Title: Quality Assurance and Verification* ***Saturday 15, 10:30***

Motivation

MedAustron

End-to-end testing

- Logistic chain of RT treatment using a phantom containing dosimeters (IC and alanine)
- Alanine dosimetry performed in collaboration with the National Physics Laboratory (NPL) as a **dosimetry auditing** tool
- Several parameters for dose calculation need to be determined

PURPOSE OF THIS WORK:

To use GATE/Geant4 as a toolkit for ion beam dosimetry

Main focus on the calculation of:

Water-to-medium stopping power ratio (SPR)

Relative effectiveness (RE) of solid-state detectors.

Relative Effectiveness

→ Dose response of solid state detectors

$$\overline{\eta}_{\text{aln}} = \frac{D_{\text{aln},{}^{60}\text{Co}}}{D_{\text{aln,X}}}$$

absorbed dose to alanine in a ^{60}Co beam

absorbed dose to alanine in a particle beam X (protons or ^{12}C ions)

(same detector response)

In case of a mixed radiation field the dose weighted average RE $\overline{\eta}$ for the field can be calculated by linear superposition of the RE of the individual components weighted by their dose contribution

$$\overline{\eta}_{\text{aln}} = \frac{\sum_{i=1}^{n_{\text{proj}}} \sum_{j=1}^{n_{\text{bin}}} \phi(E_j, Z_i) \times \left(\frac{S_{\text{el}}}{\rho}\right)_{\text{aln}} (E_j, Z_i) \times \eta_{\text{aln}}(E_j, Z_i)}{\sum_{i=1}^{n_{\text{proj}}} \sum_{j=1}^{n_{\text{bin}}} \phi(E_j, Z_i) \times \left(\frac{S_{\text{el}}}{\rho}\right)_{\text{aln}} (E_j, Z_i)}$$

Materials and methods.
RE determination in Gate

$\eta_{\mathrm{aln}}(E_j, Z_i)$ as published by R. Herrmann [PhD thesis] based on "Hansen and Olsen model"

- "GateRTion 1.0" based on GATE 8.1 and GEANT4 10.03.p03

For comparison, RE calculations also done using:

- Proton Monte Carlo dose engine of the RaySearch (RS) Treatment Planning System (TPS) (v5.99.50 evaluation version)

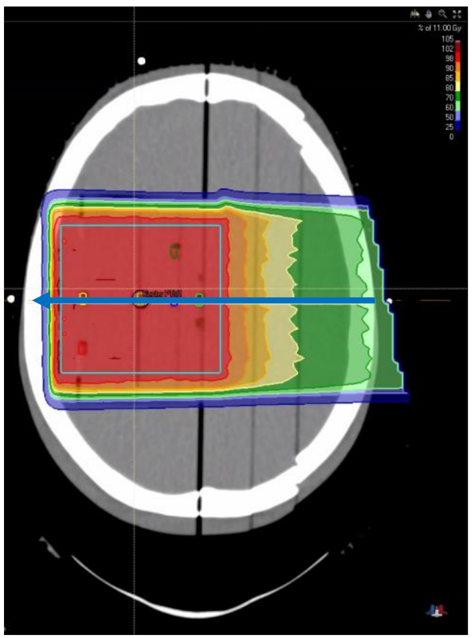
Materials and methods.

RE determination in RayStation

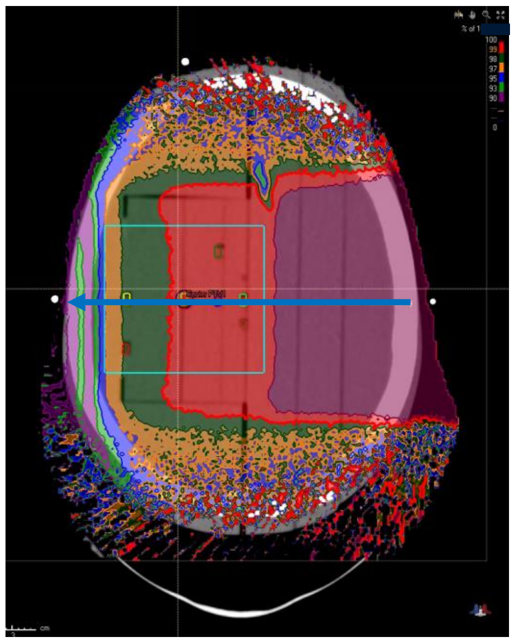
Implementation in the Monte Carlo of RayStation TPS (v5.99.50).

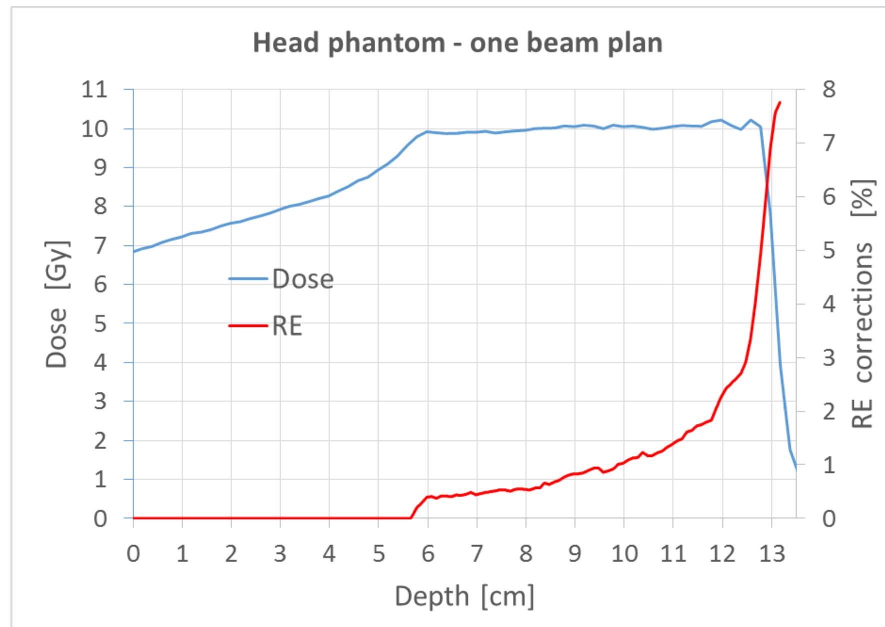
Collaboration with RaySearch Laboratories (Sweden)

3D dose distribution



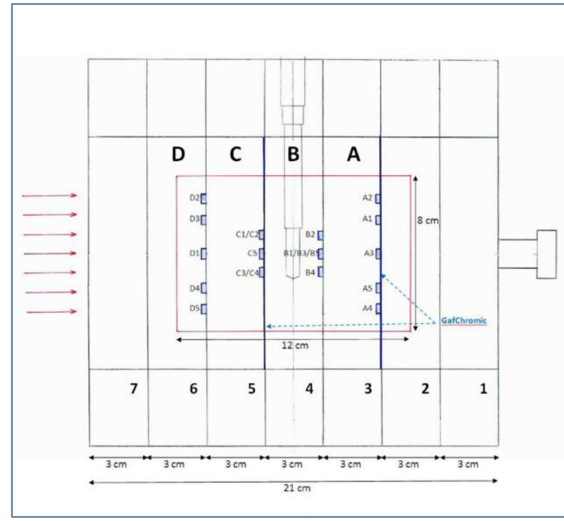
3D RE distribution



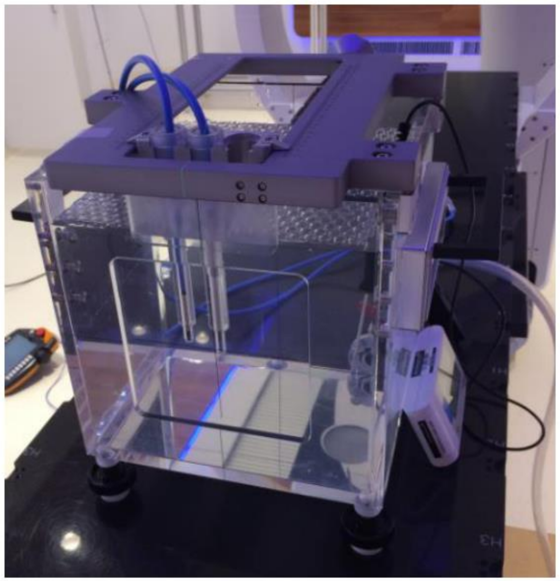


Carlino, A. et al. “**End-to-end tests using alanine dosimetry in scanned proton beams.”,** Physics in Medicine and Biology, 2018.

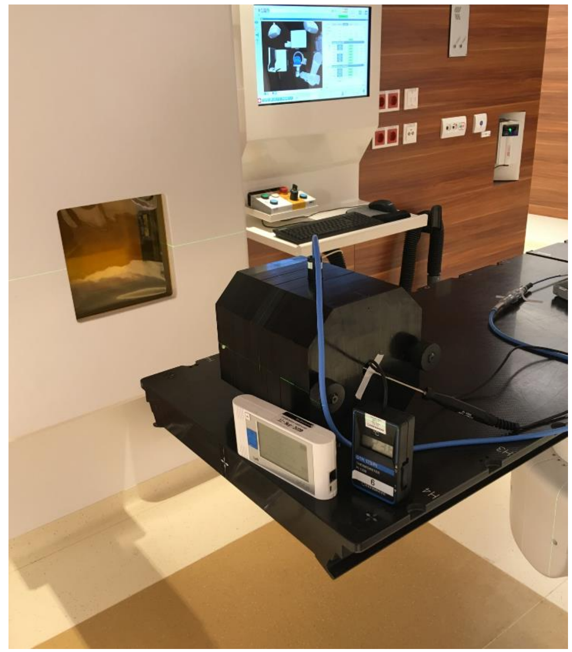
Results:
Alanine detectors (protons)



- Water phantom



- Polystyrene phantom



Experimental data from proton beam commissioning at MedAustron 2016/2017

Carlino, A., et al. PMB 63.5 (2018): 055001.
NPL Report IR 48

Results:

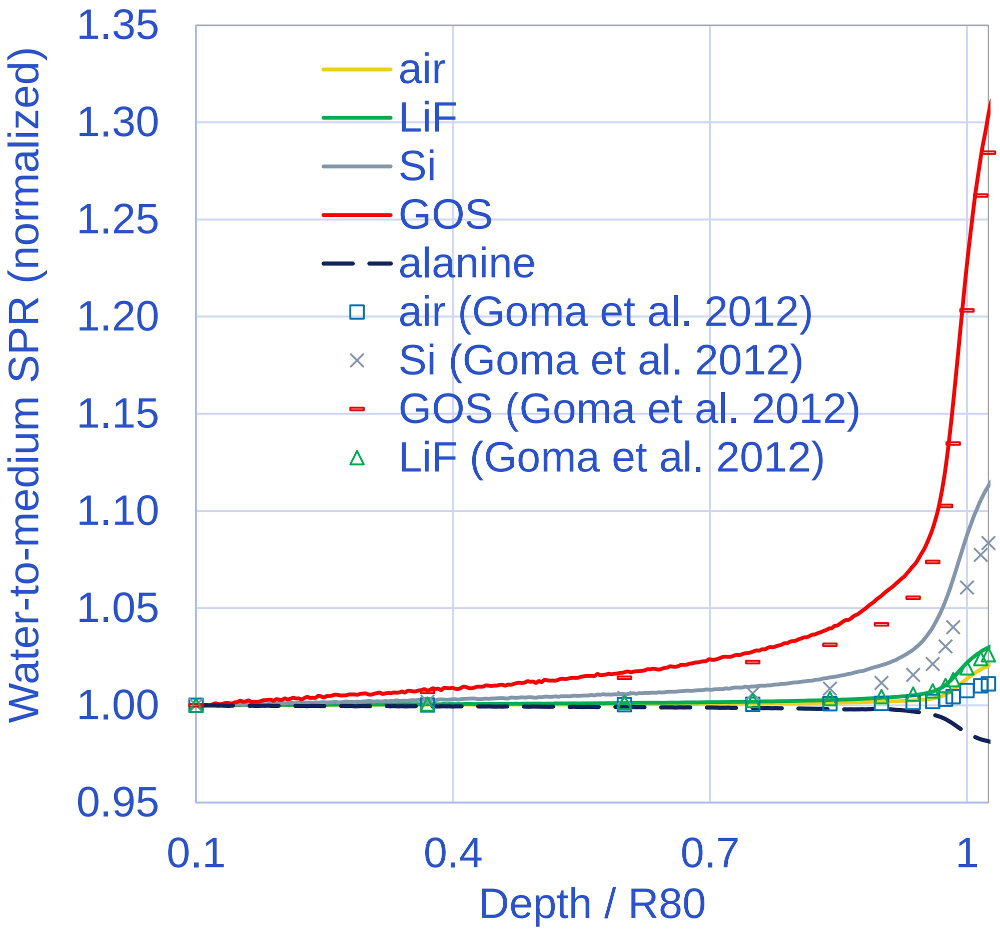
Water-to-medium SPR (protons)

MedAustron

- Comparison literature and GATE simulation

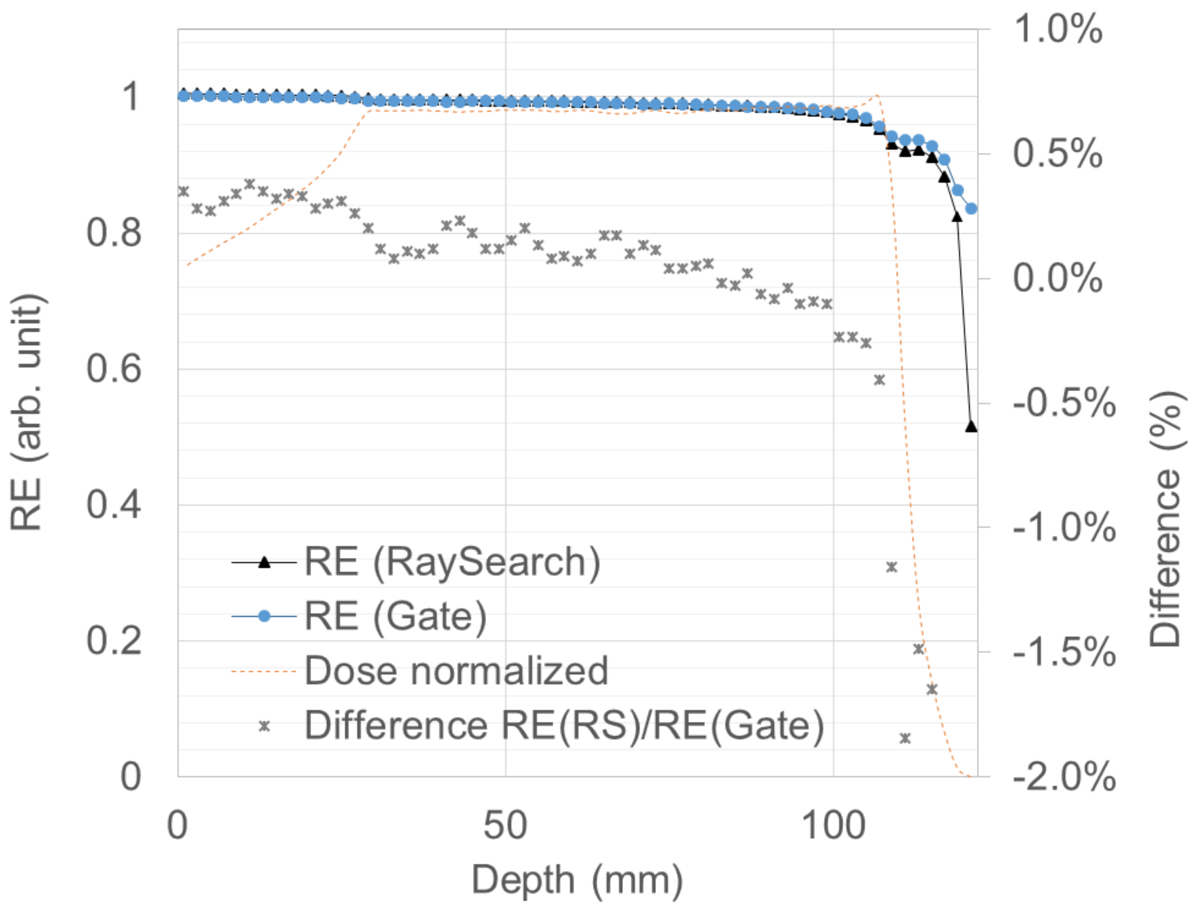
→ 150 MeV proton beam

→ 0.5-2.5% difference



MedAustron

Results:
RE benchmark RayStation vs Gate/G4 for protons in water (I)



E-poster Nr. 58-0203*:*
M. Bolsa Ferruz et al.
"Gate/Geant4 as a Monte Carlo Simulation toolkit for light ion beam dosimetry"

- The RE computed in Raystation and in Gate/G4 agreed within ±0.5% in the plateau and in the target region.
- Larger deviations in up to -2% in the distal fall-off

Results:
RE benchmark RayStation vs Gate/G4 for protons in water (II)

- Box target in a water phantom

	RE		
	RayStation	GATE	Deviation
Entrance (R_{res} = 19 cm)	1	1.0009	-0.10%
R_{res} = 4cm	0.9908	0.9891	0.18%
R_{res} = 2cm	0.9824	0.9810	0.14%

- Comparison alanine and IC dosimetry (Farmer chamber) using RE calculated with RayStation or GATE

	Deviation alanine vs Farmer chamber (RayStation)	Deviation alanine vs Farmer chamber (GATE)
Entrance	0.61%	-0.34%
R_{res} = 4cm	-0.30%	-0.42%
R_{res} = 2cm	-1.24%	-0.91%

Uncertainty on absorbed dose to water 2% with Farmer chamber (TRS398)

Uncertainty on absorbed dose to water 2.5% with alanine

MedAustron

Conclusions and perspectives

- Relative effectiveness and stopping power ratio tools were successfully implemented in Gate/G4

- Water-to-medium SPR tool for protons has been compared against literature data.

- Validation of the RE implementation based on commissioning measurements at MedAustron and comparison with RayStation was done in water and homogeneous polystyrene phantoms

- Application of these tools to carbon ion end-to-end testing is on-going

Impact of particle energy spectra on clinical plans in carbon ion beam therapy

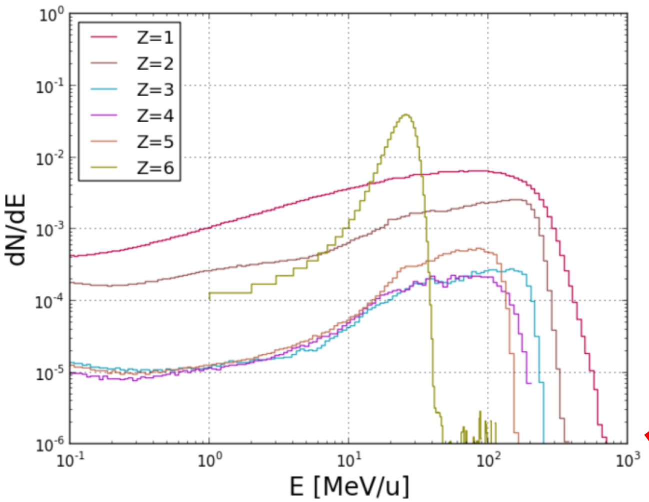
N. Lackner[1,4], A. F. Resch[2], K. Poljanc[4], A. Elia[1], D. Boersma[1], L. Grevillot[1], H. Fuchs[1,2], G. Kragl[1], S. Engdahl[3], L. Glimelius[3], T. Niessen[3], M. Stock[1], A. Carlino[1]

1 MedAustron Ion Therapy Centre, Wiener Neustadt, Austria
2 Medical University of Vienna, Department of Radiation Oncology, Austria
3 RaySearch Laboratories AB, Sveavägen 44, PO Box 3297, Stockholm, Sweden
4 Technische Universität Wien, Atominstitut, Austria

COMPUTATION OF
RBE-WEIGHTED DOSE FOR A MIXED RADIATION FIELD

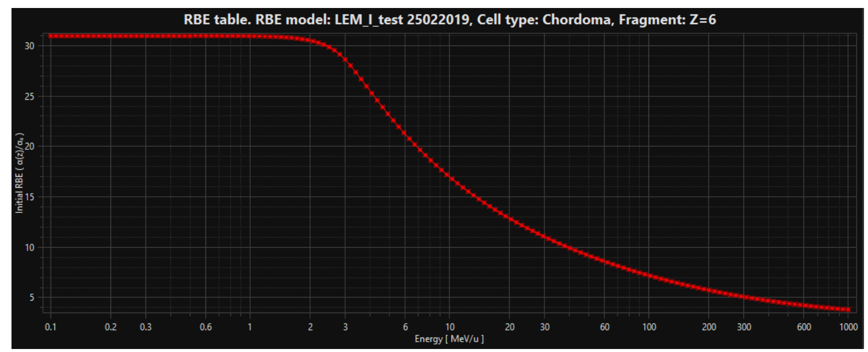
- **Local Effect Model (LEM I) [Scholz et al. 1997, Kraemer et al. 2000] implemented in the TPS (Raystation v8.1) at MedAustron**

➢ Particles spectra differential in energy (ion type Z, energy E)



Particle energy spectra (per primary particle and MeV/u) for a 300 MeV/u carbon ion beam at depth 17 cm (Bragg peak adjacent).

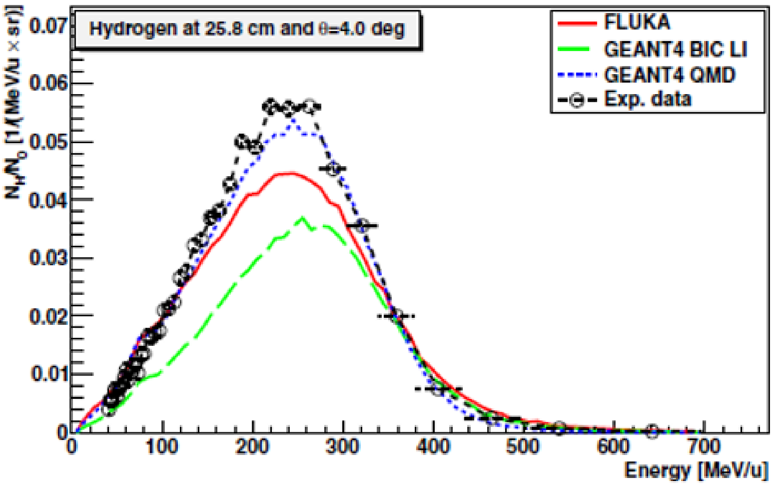
➢ Pre-computed RBE(Z,E) look-up table with LEMI implemented in RayStation



RBE table for Carbon ions (Z=6) computed in RS according to LEM I

$$D_{RBE}\,(\vec{r}) = D_{Phys}(\vec{r})\ \times RBE(\vec{r})$$

INFLUENCE PARAMETERS



Hydrogen energy spectrum for a 400 MeV/u carbon beam **[Böhlen et al. 2010]**

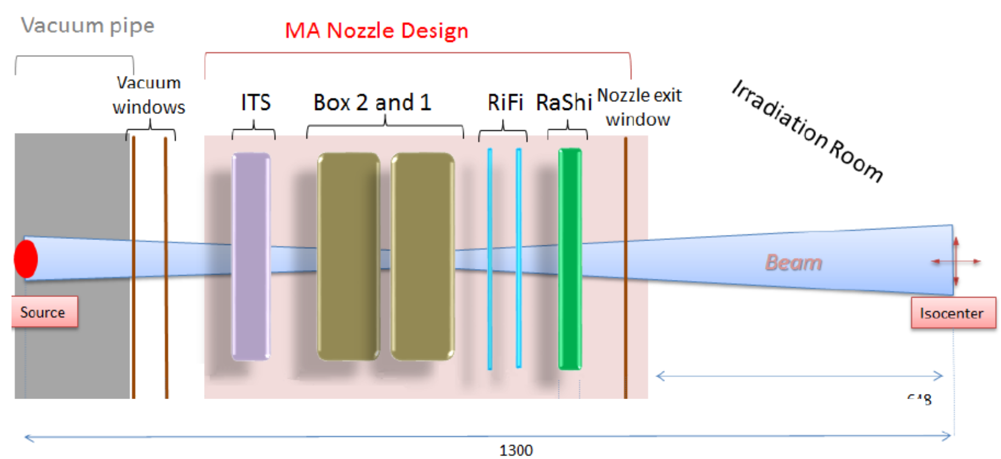
Differences in different codes

- charge changing cross-sections
- physical models within a MC code
- MC numerical settings

Also related papers: **[Lühr et al. 2012, Bolst et al. 2017]**

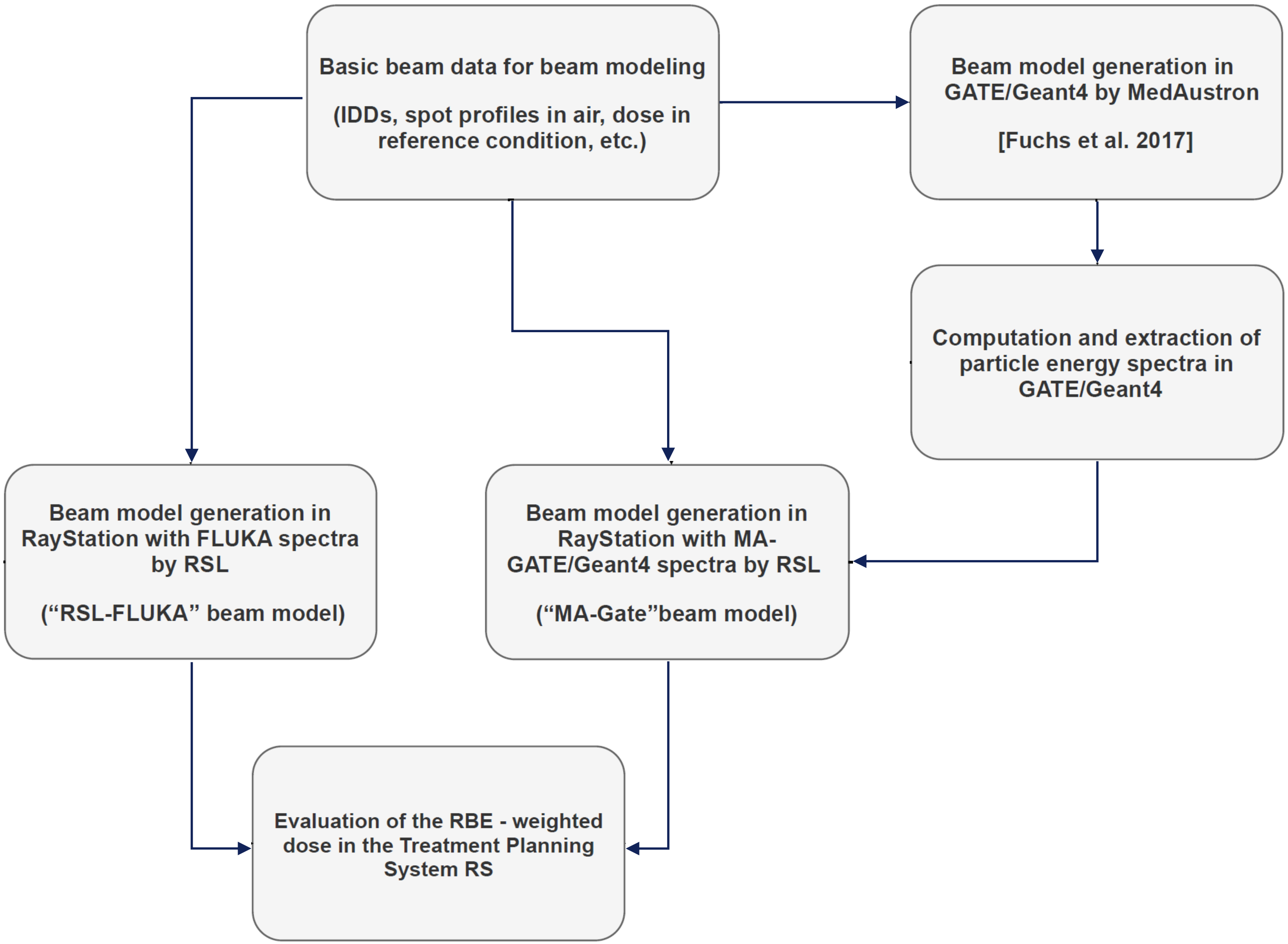
MedAustron Beamline

- Different components inside the nozzle



MedAustron Nozzle layout **[A. Elia et al. 2018]**

WORKFLOW CHART



CREATION OF THE PARTICLE ENERGY SPECTRA- MATERIALS AND METHODS

MA GATE/Geant4 **(Gate v8.2 Geant4 v10.3 patch 03 - [Grevillot et al. 2011])**

- Full nozzle geometry implementation in the MC beam model
- Developed energy spectrum actor in GATE based on track length approach **[Radiance and particle fluence – Papiez and Battista 1994]**

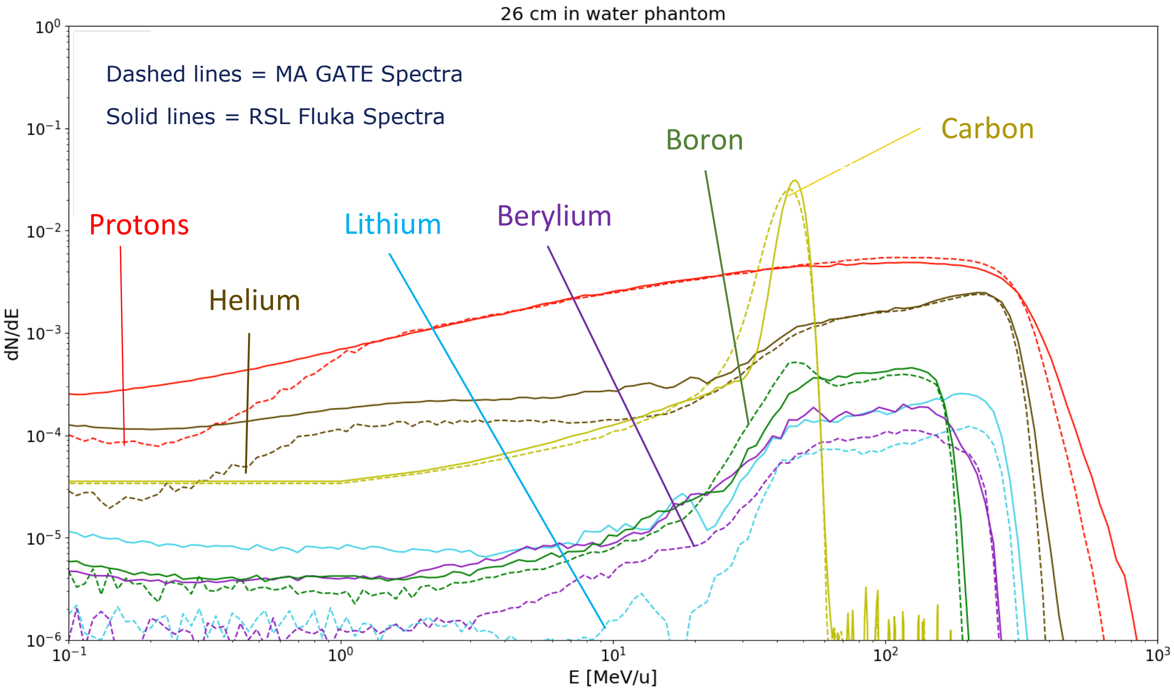
www.opengatecollaboration.org/

RSL FLUKA **[Ferrari et al. 2005]**

- Particle energy spectra in water are pre-generated with FLUKA MC code.
- mono-energetic carbon ions simulated in a water phantom (50 cm depth):
  - energies at every 5MeV/u between 50-450MeV/u (81 energies)
  - Scoring radius: 5 cm
  - Scored resolution in depth 0.1 cm

PARTICLE ENERGY SPECTRA – RESULTS: FLUKA VS GATE/G4

Particle energy spectra ~400 MeV/u



Particle energy spectra for a 400 MeV/n carbon ion beam at a specific depth of 26 cm in water.

Main deviations in the particle spectra FLUKA vs GATE/Geant4:

- Low energetic region (<1MeV/u)
- Higher energy spread of primary carbons
- Less Lithium and Berylium
- Lower maximum energy of secondary fragments in GATE

RBE-WEIGHTED DOSE EVALUATION – MATERIALS AND METHODS

Evaluation in water and in clinical cases

Targets in water:

- Box 6x6x6 cm^3,

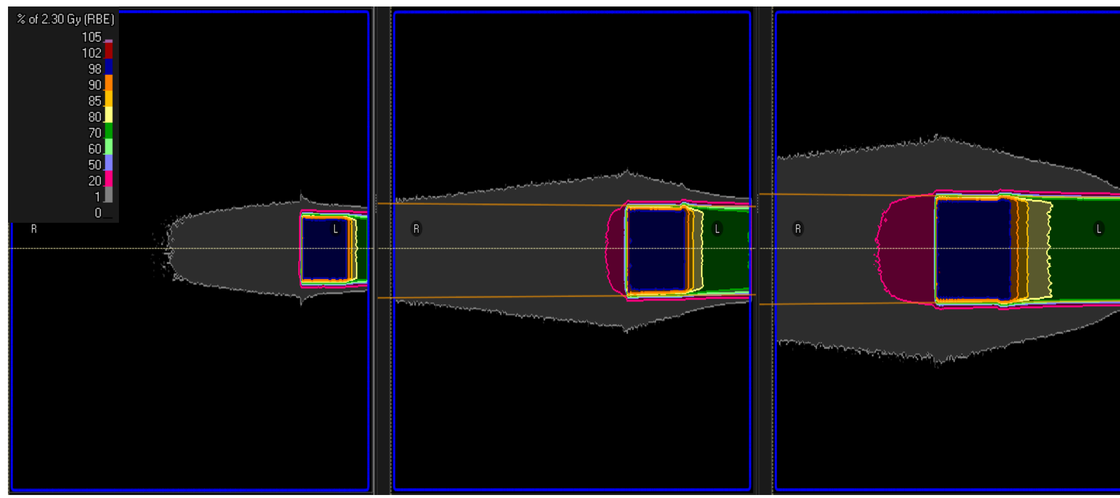
centered at 6 cm depth in water

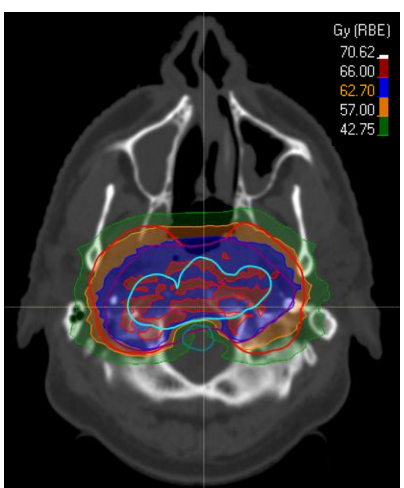
- Box 8x8x8 cm^3 ,

centered at 13 cm depth in water

- Box 10x10x10 cm^3,

centered at 21.8 cm depth in water





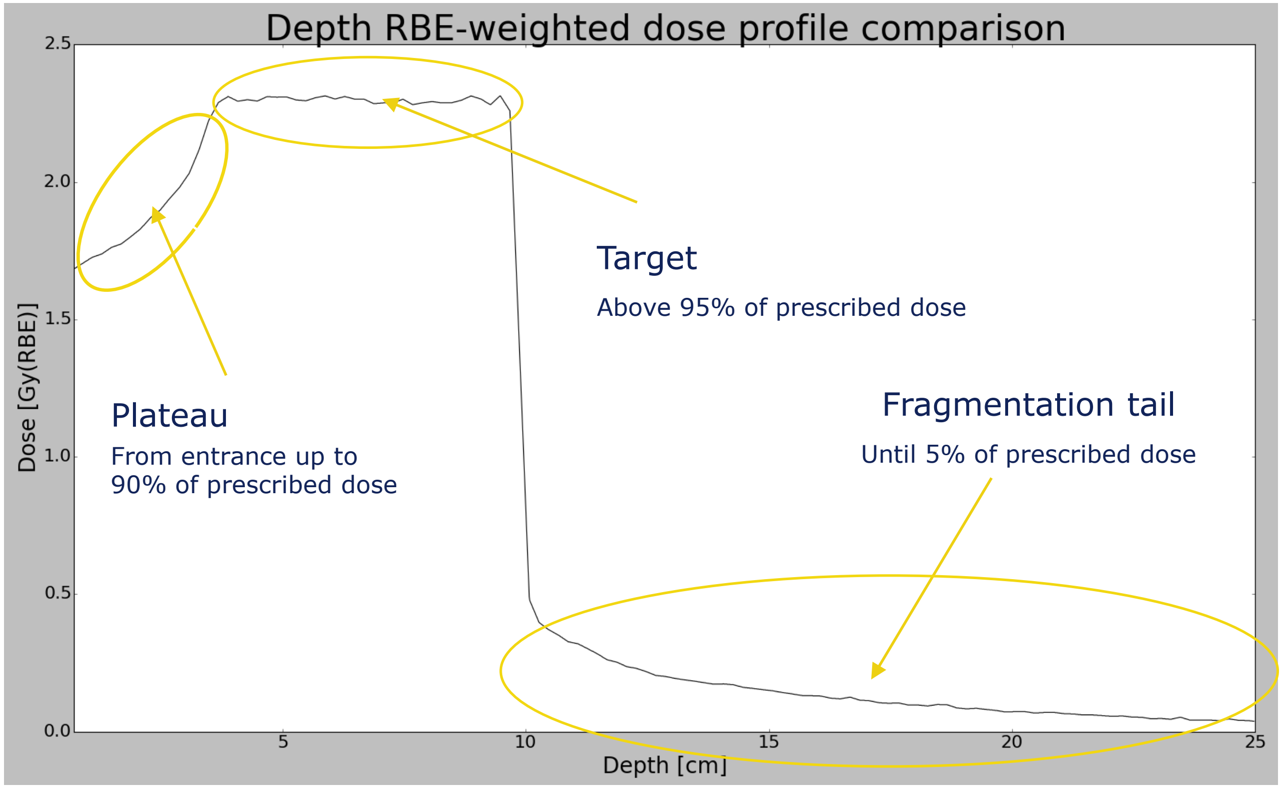
Clinical case:

- Skull base Chordoma

(PTV1 45Gy(RBE) – 15x3 Gy(RBE),
PTV2 60Gy(RBE) – 5x3 Gy(RBE),
PTV3 66Gy(RBE) – 2x3 Gy(RBE))

All plans optimized with the ‘RSL FLUKA Beam Model’ and recomputed with ‘MA GATE/G4 Beam Model’.

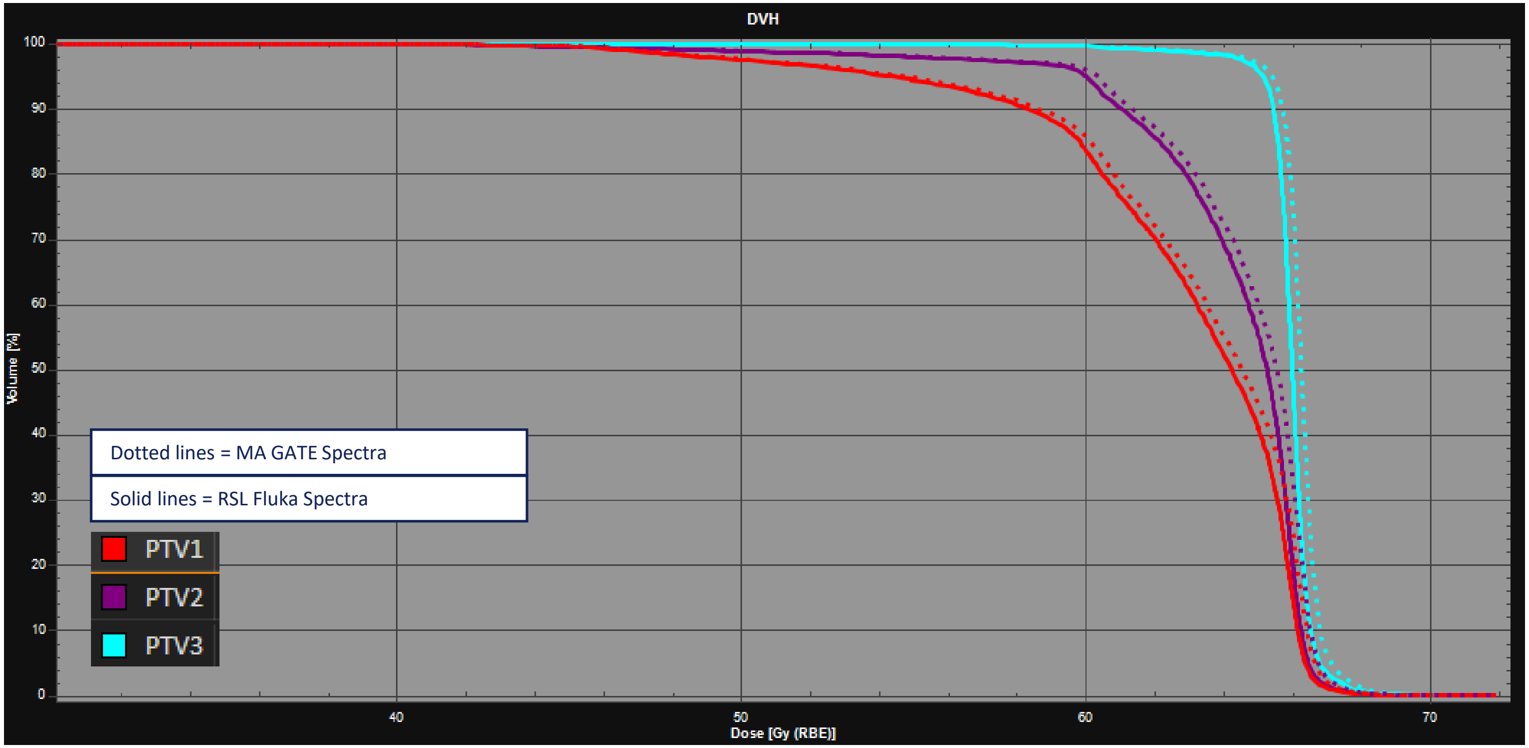
RBE-WEIGHTED DOSE EVALUATION – RESULTS IN WATER



Overview of different boxes and the mean overall deviations between the RBE-weighted dose computed with RSL-Fluka spectra and the RBE-weighted dose computed with MA-Gate spectra.

	Box 6	Box 8	Box 10
Plateau	0.4 % ± 0.3 %	0.2 % ± 0.2 %	0.1 % ± 0.2 %
Target	0.7 % ± 0.7 %	0.3 % ± 0.3 %	0.1 % ± 0.2 %
Fragmentation tail	-3.0 % ± 2.2 %	-3.3 % ± 2.6 %	-4.6 % ± 1.5 %

RBE-WEIGHTED DOSE EVALUATION – RESULTS IN CLINICAL PLAN (DVH COMPARISON) TARGET



	PTV1	PTV2	PTV3
minimum dose $D_{RBE,99\%}$	0.5%	0.3%	0.8%
median dose $D_{RBE,50\%}$	0.5%	0.4%	0.4%
maximum dose $D_{RBE,1\%}$	0.5%	0.5%	0.6%

Differences:

- Negligible RBE-weighted dose differences in the DVH for this patient case

Conclusions

- **Implementation in GATE/G4 of particle energy spectra actor based on track length approach.**
- **The RBE-weighted dose average of ‘RSL-FLUKA beam model’ and ‘MA-GATE beam model’ differ within 1% in the target region for SOBPs in water.**
- **No significant impact of the difference in particle energy spectra on RBE-weighted dose for clinical plans.**
- **Additional clinical cases at different anatomical sites under investigation.**

Acknowledgments:

➢ **MedAustron medical physics team**

➢ **RaySearch Laboratories**
- Lars Glimelius
- Erik Traneus
- Staffan Engdahl

Thank you!