Benchmarking GATE/Geant4 and RayStation MC for pencil beam scanning light ion beams in combination with a passive beam collimation

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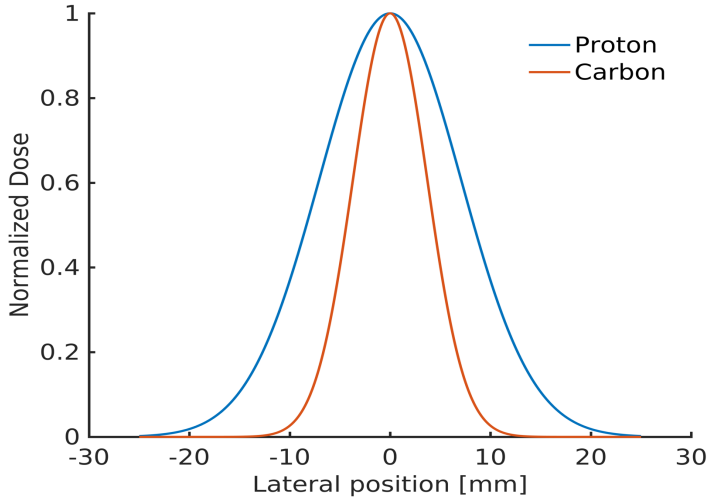
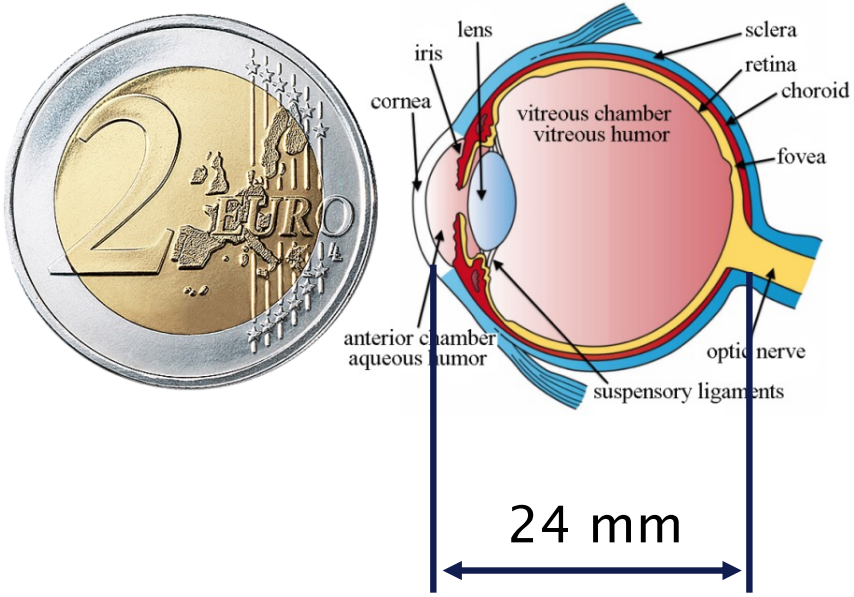
Motivation

- Pencil beam (PB) scanning
  - Available initial proton energies
    - Active: ~ 60 – 250 MeV
    - Passive energy degradation (range shifters) to generate lower energies
      - ➔ broadens the PB profile due to MCS
- Passive beam collimation
  - Collimators can improve the lateral dose fall-off

➔ Combine collimator and PB scanning to create small fields with sharp edges

➔ Possible applications: Ocular tumors, small animal irradiation





Purpose

- **Validate the Monte Carlo dose engine of the commercial treatment planning system (TPS) RayStation**

  … against GATE/Geant4 simulations

  … against experimental data

- **Validate dose calculation accuracy of GATE/Geant4**

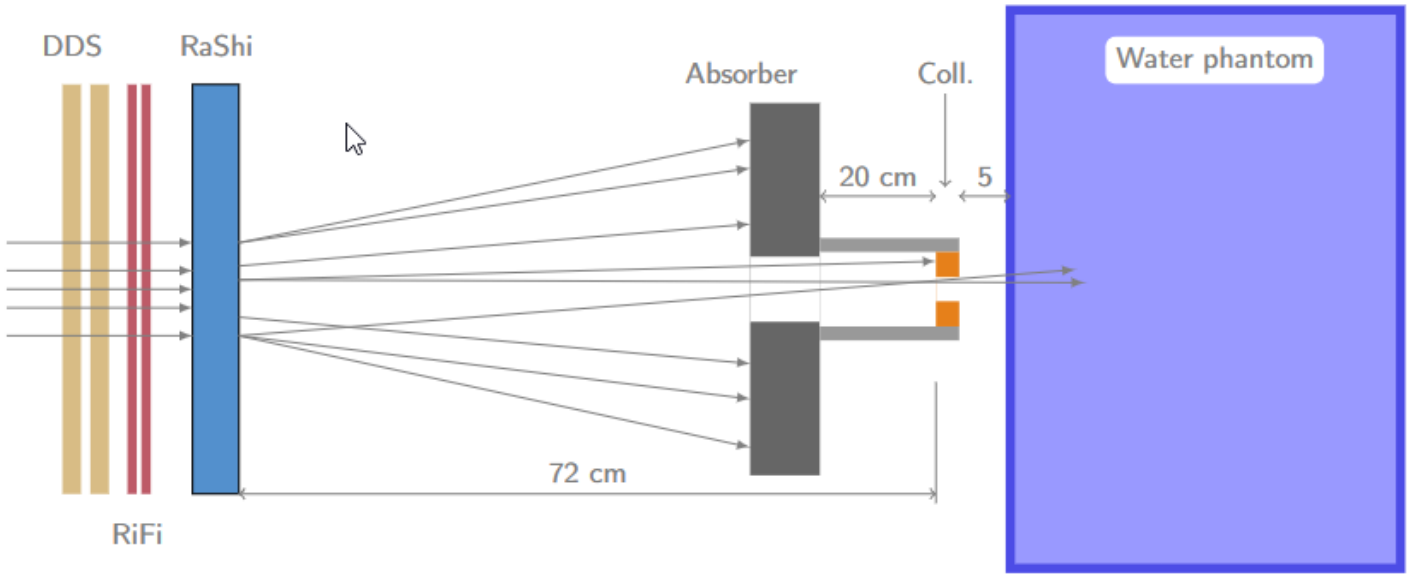
  … using experimental data

- **Acquire experimental data**

Beamline setup

- **Beam**
  - Active scanned proton pencil beams
  - Mono energetic ~ 69 – 97 MeV
- **Clinical nozzle**
  - Range shifter (30 mm PMMA) 72 cm upstream of isocenter
- **Passive beam modifier**
  - Plastic off-axis absorber (35.5 mm aperture)

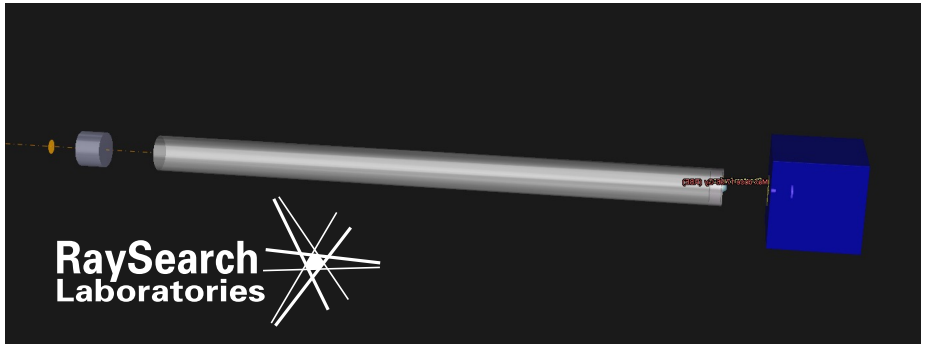
    ➔ Narrower aperture than downstream element: “Taper”
  - Steel pipe (38 mm aperture)
  - Brass collimator 5 cm from surface
    - Aperture diameter: 5 – 34 mm



Simulation setup

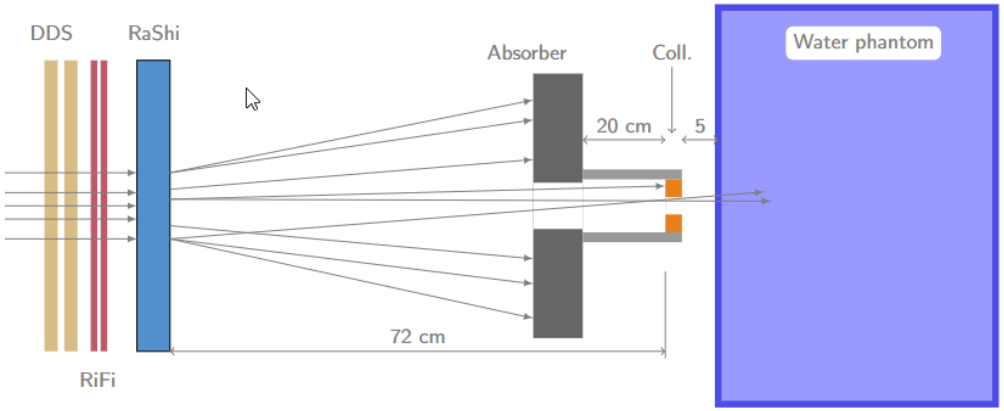
Treatment planning system

- RayStation 11B, RaySearch laboratories
  - Dose algorithm: Monte Carlo
  - Off-axis absorber and pipe not included
  - MCS threshold varied: 5, 15, 30 MeV
- Beam model
  - Based on open beam data only



GATE 9.1/Geant4 10.6

- Scoring
  - Dose to water, beam quality correction factors
- Extensively validated beam model
  - Elia et al. 2019, Resch et al. 2019
- Full description of geometry
  - Nozzle elements
  - Passive absorbers, collimator, pipe



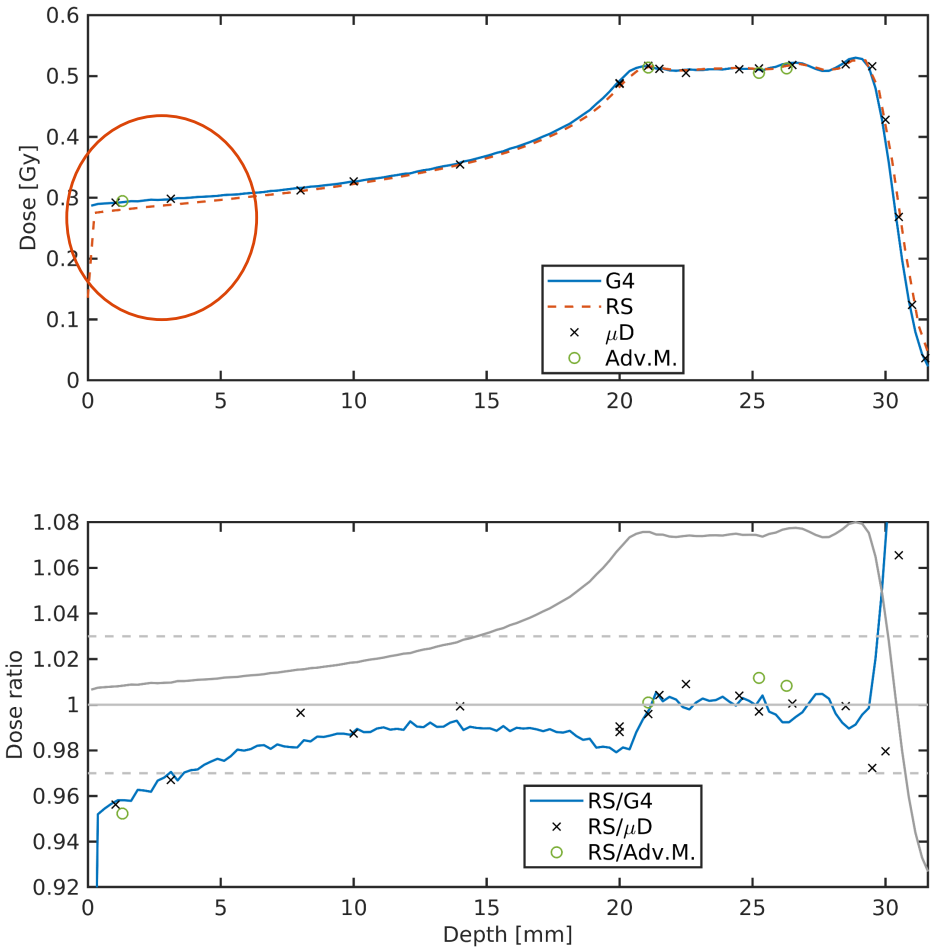
Measurement overview

- Beams
  - Mono energetic beams
  - Spread out Bragg peaks
    - Range in water: 3, 5, 10, 30 mm
    - Modulation width: 3, 5, 10, 30 mm
- Collimator apertures
  - 5 aperture diameters: 5, 8, 10, 15, 34 mm
- Evaluation quantities:
  - Absorbed dose to water
- Measurement devices
  - Water phantom MP3-P, PTW
    - Detector – beam alignment accuracy < 0.2 mm (measured)
  - Depth dose profiles
    - Advanced Markus IC, T34045, PTW, Germany
    - MicroDiamond (MD), T6019, PTW, Germany
  - Lateral profiles
    - GAFchromic EBT3 films, Ashland
    - Resolution: 300 dpi (0.08 mm pixel length)

Results: Depth dose profiles
Deep targets

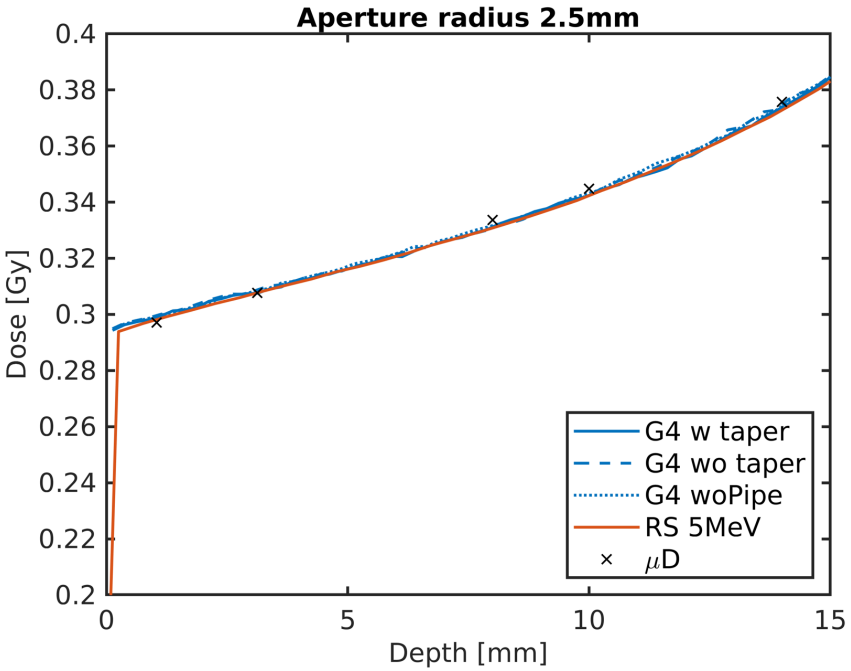
Aperture diameter: 15 mm

- SOBP:
  - Less than 1% dose deviation in SOBP
- Entrance region (depth < 5 mm)
  - Up to 5% dose deviation

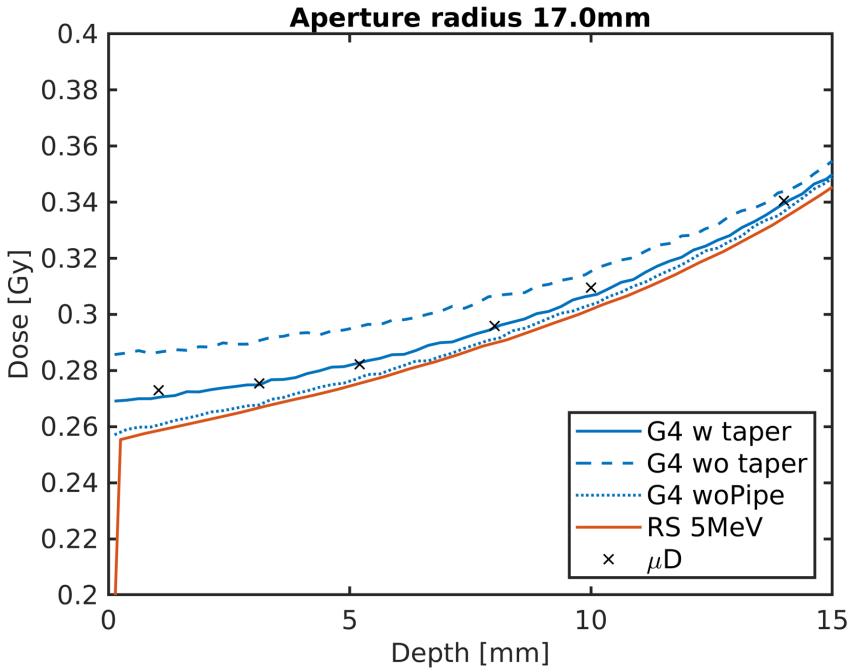


Results: Depth dose profiles
Deep targets – entrance region aperture dependence

Aperture diameter: 5 mm



Aperture diameter: 34 mm

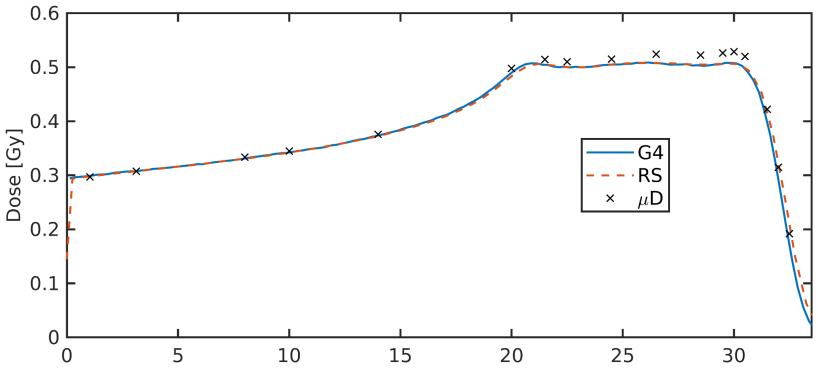


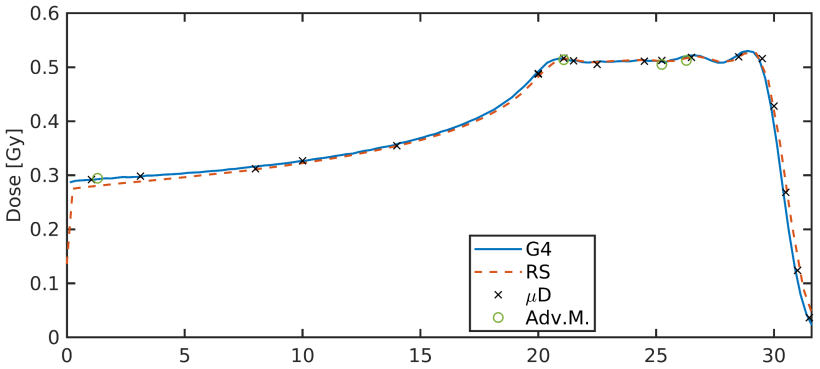
Deviations in entrance channel:

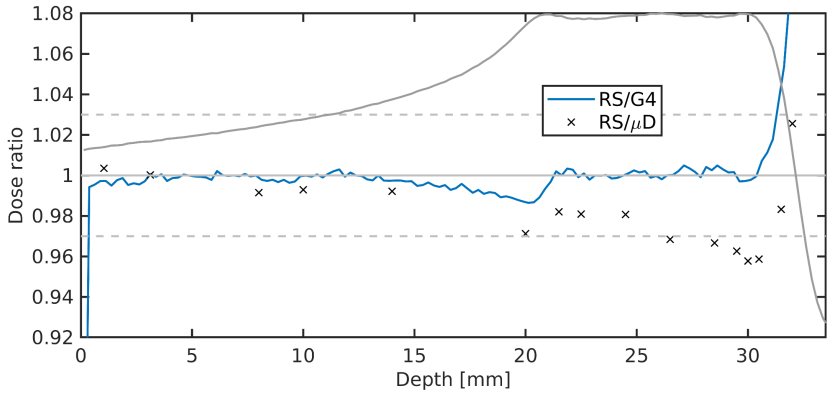
- Origin in scatter from pipe

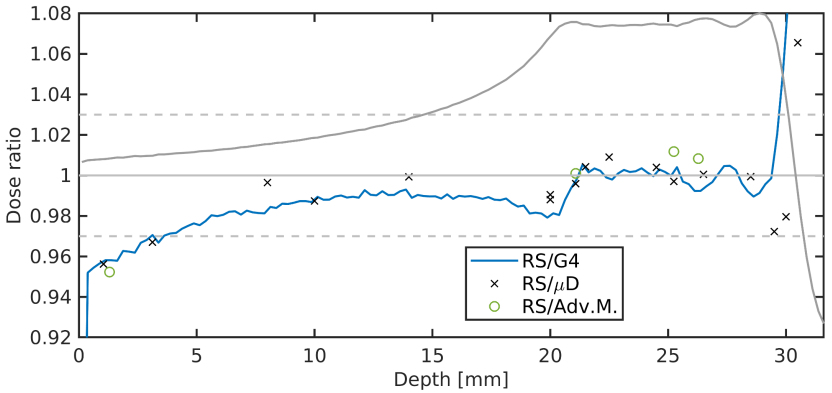
  ➔ increasing with increasing aperture
- Reduced by applying tapering

Results: Depth dose profiles
Smallest possible aperture?









Aperture diameter: 5 mm

- GATE/Geant4 and RayStation agree well
- Measurements deviate up to 5%

Aperture diameter: 8 mm

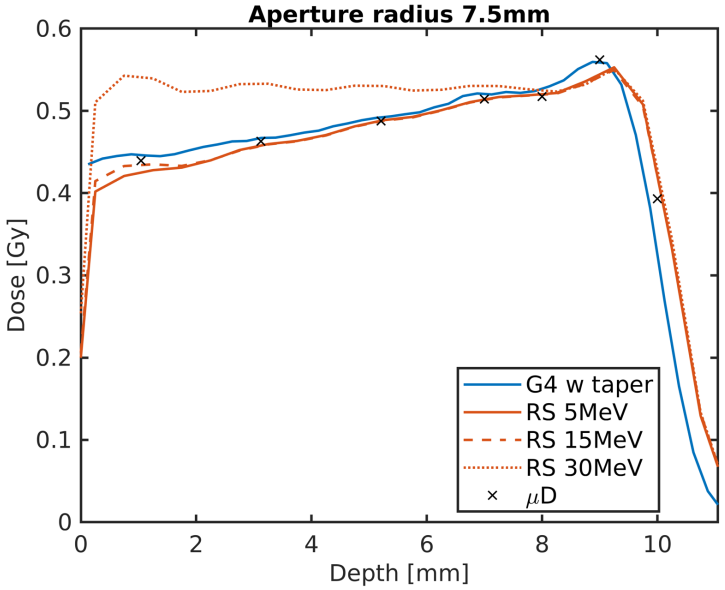
- GATE/Geant4, RayStation and measurements agree

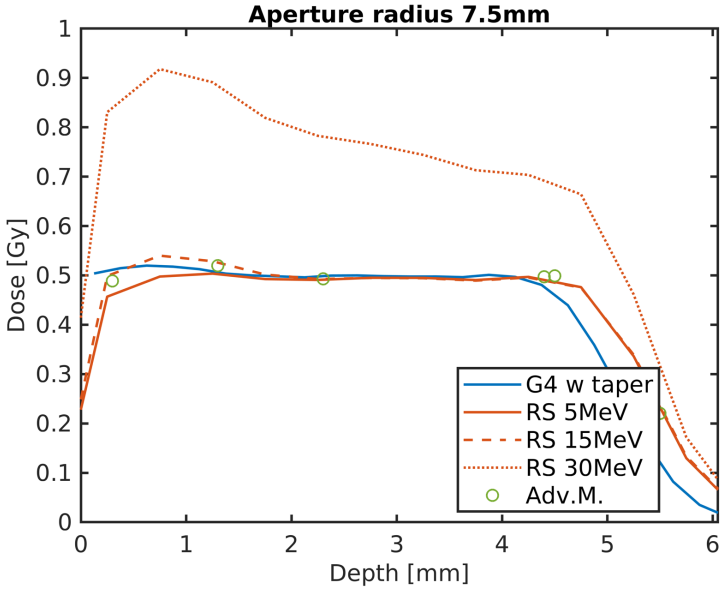
➔ **Define 8 mm diameter as lower limit**

Results: Depth dose profiles
Shallow targets

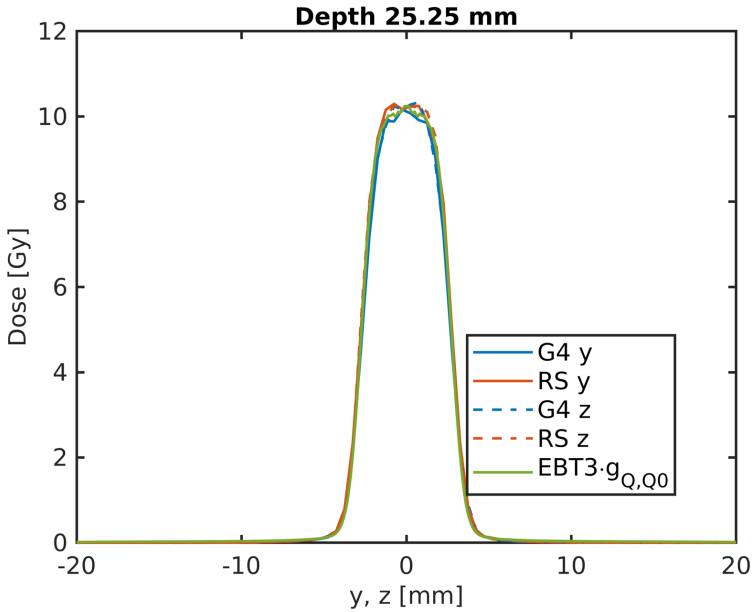
- SOBP ranges < 10 mm depth (water)
- Strong dependence on Multiple Coulomb Scattering threshold
  - Default (30 MeV) not acceptable for shallow targets with **Ocular setup**
  - Energy threshold < 15 MeV sufficient for targets SOBP ranges > 5 mm
  - MCS threshold in range shifter = 5 MeV in RayStation 12A

E [MeV]	CSDA range [mm]
5	0.4
15	2.5
30	8.8

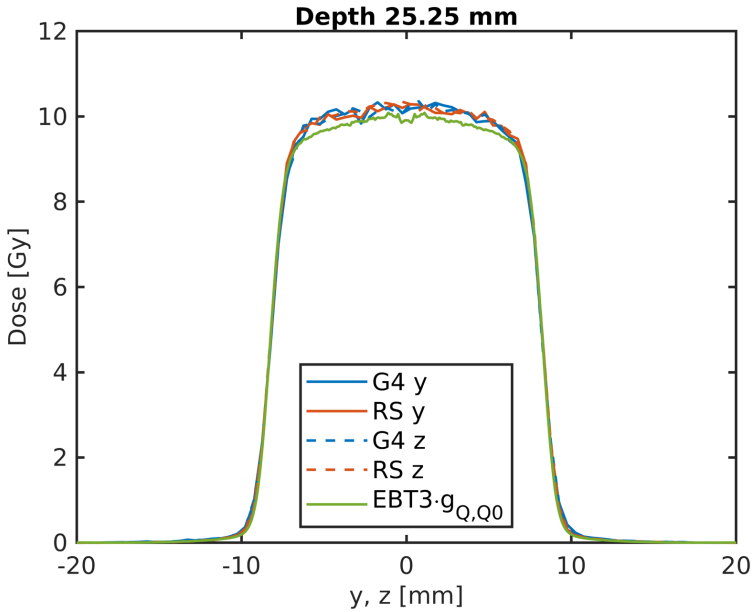




Results: Lateral dose profiles
Center of SOBP



Aperture diameter: 5 mm



Aperture diameter: 15 mm

Good agreement between treatment planning system (RS) and

- GATE/Geant4
- Measurements (EBT3 films)

For

- Both directions (x, y)
- At all depths
- All apertures

Summary & Conclusions

- Dose calculation of **PB scanning** in combination with a **collimator** successfully validated for
  - RayStation 11B with option for reduction of MCS threshold
  - GATE/Geant4 10.6
- Valid for
  - SOBP range in water: 5 mm < depth < 35 mm
  - Aperture: 8 mm < diameter < 34 mm

➔ Commercial TPS dedicated for pencil beam scanning can be used clinically, but MCS threshold (upstream the patient) must be reduced

➔ Threshold updated in RayStation 12A

➔ GATE/Geant4 dose calculation accuracy sufficient

Acknowledgment

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Thank you for your attention!