



Towards analytic dose calculation for MR guided particle beam therapy

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Visit <http://www.meduniwien.ac.at/hp/radonc/>



and many others

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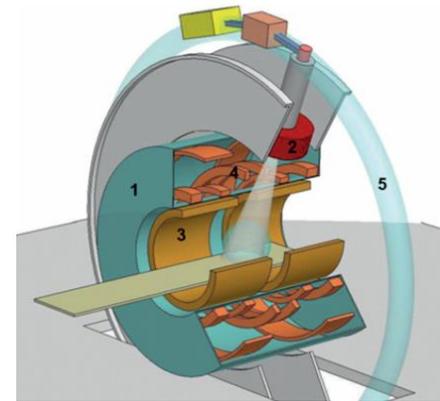


Content

- Motivation
- Effects at Bragg peak area
- Beam deflection
- Effects at tissue interfaces

Motivation - MR guided radiotherapy

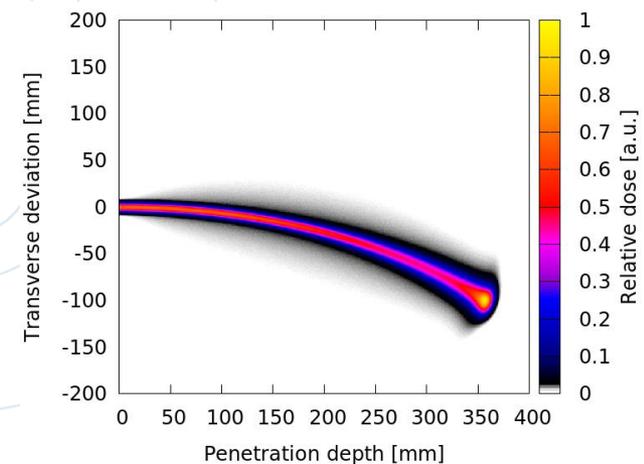
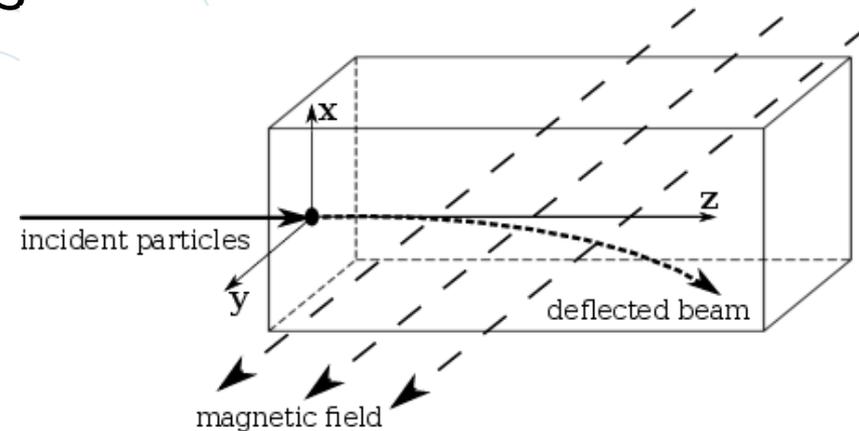
- Advantages of MR guided radiotherapy
 - High soft-tissue contrast, no additional dose
 - Real-time imaging
 - Organ motion and anatomy changes
- Co-60 MR already in clinical use (ViewRay)
- First MR-Linac in Utrecht (Elekta, Philips)
- Challenges
 - Magnetic field influences charged particles
 - MRI and beam delivery system need to work simultaneously at high precision



Utrecht MR-Linac: cylindrical 1.5T closed-bore MRI, 6 MV Linac on accelerator ring

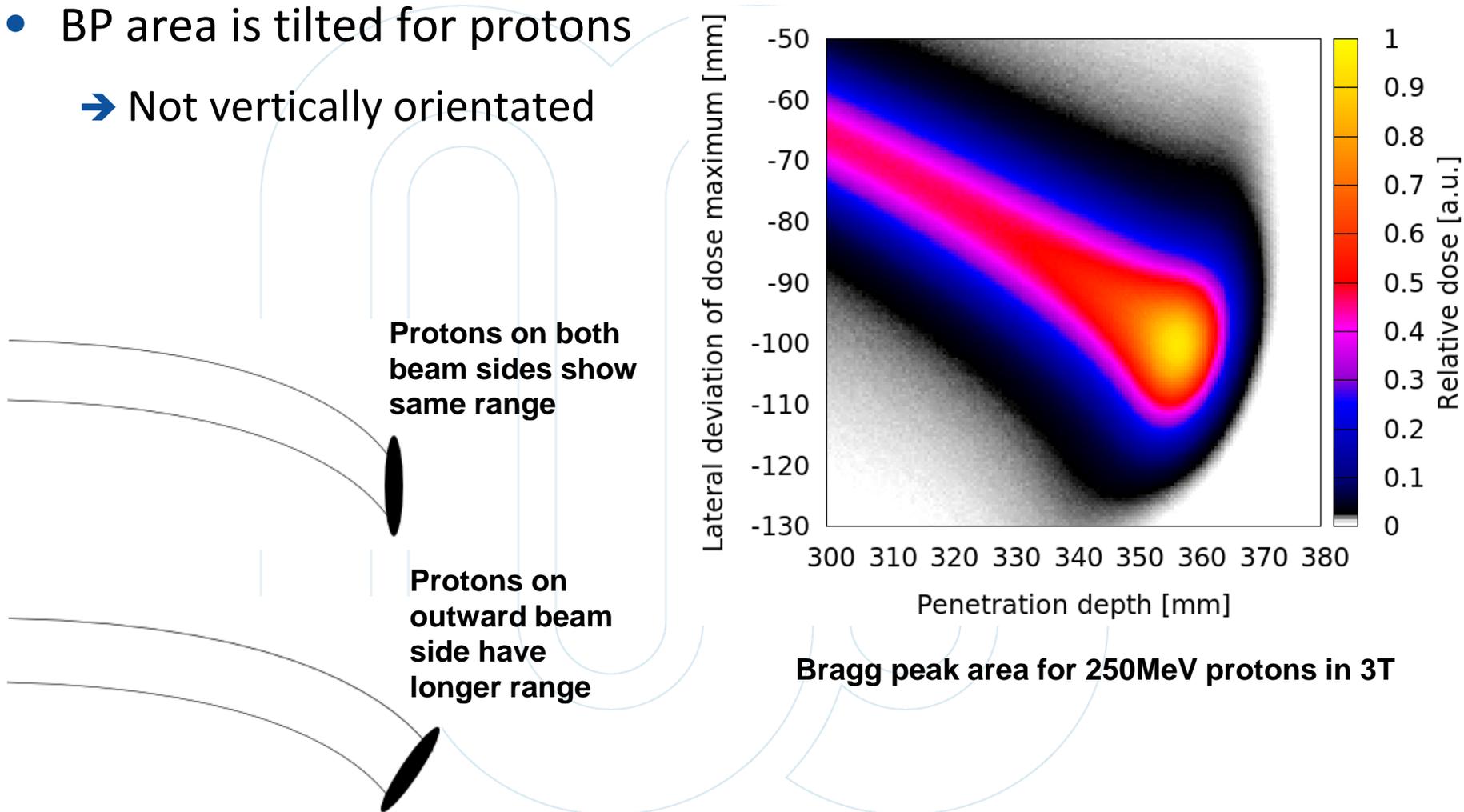
Set-up

- Simulated proton and carbon ion beams in magnetic fields using GATE 7.0 alongside Geant4.10.0.p3
- Clinical energies at MedAustron
 - Protons: 60, 150, and 250 MeV
 - C12: 120, 250, and 400 MeV/u
- Magnetic fields: 0.35 T, 1 T, 3 T
 - perpendicular to initial beam direction
 - Lorentz force induces lateral deflection



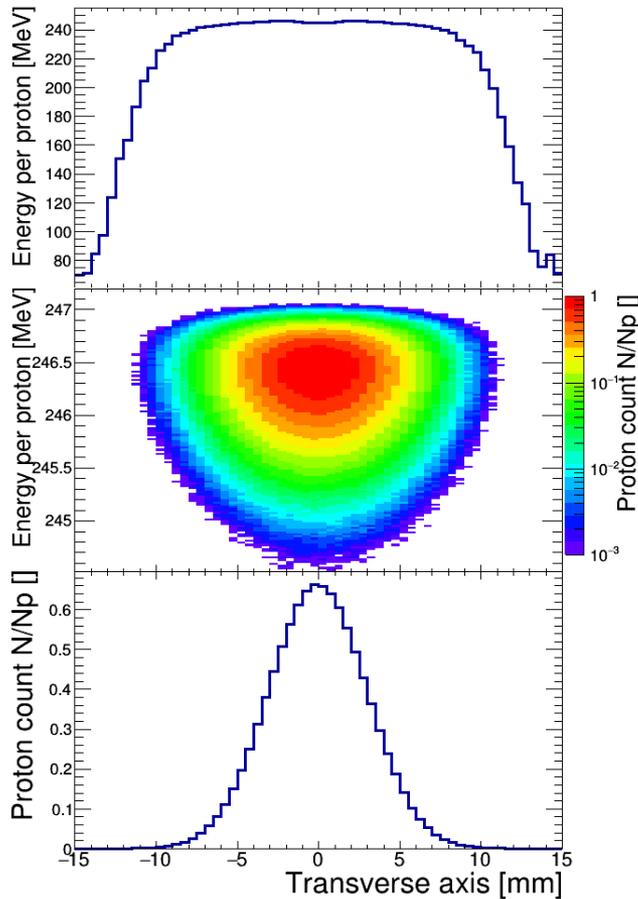
Bragg peak (BP) area

- BP area is tilted for protons
 - Not vertically orientated

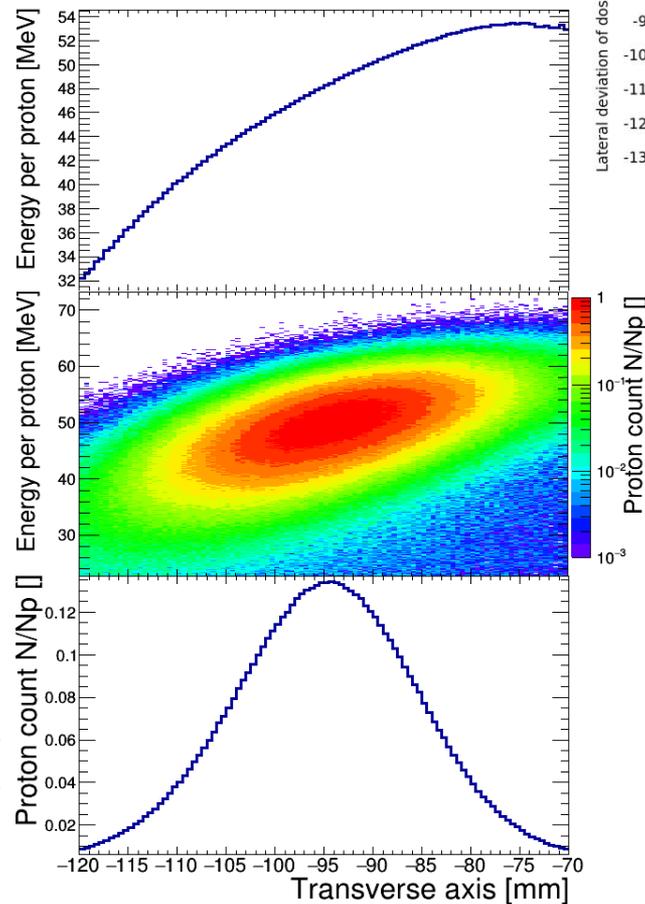


Spectral analysis of the Bragg peak area

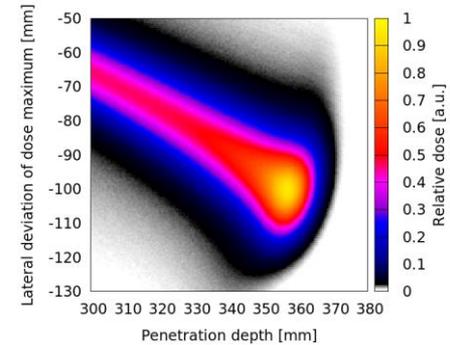
Protons



depth = 10 mm



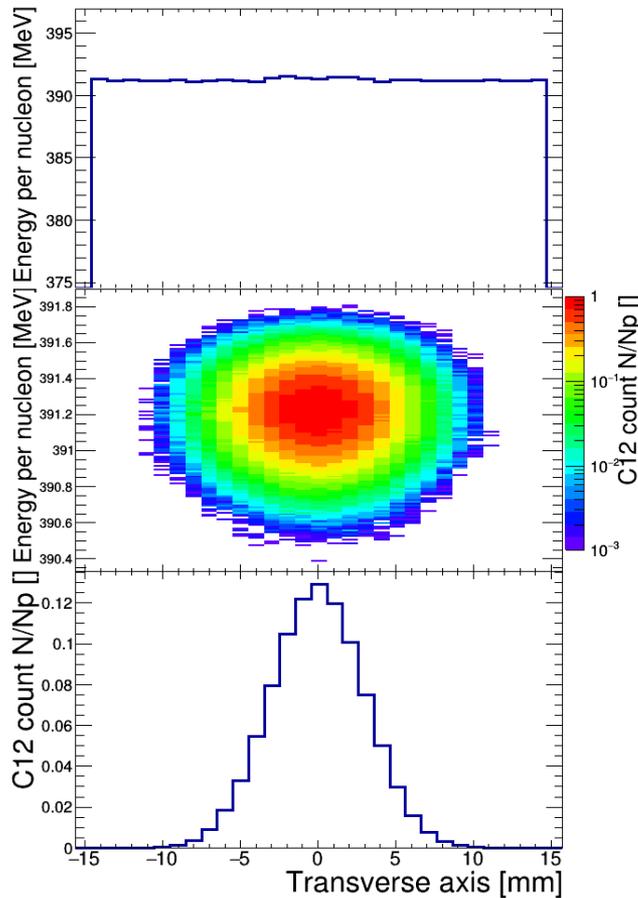
depth = 350 mm



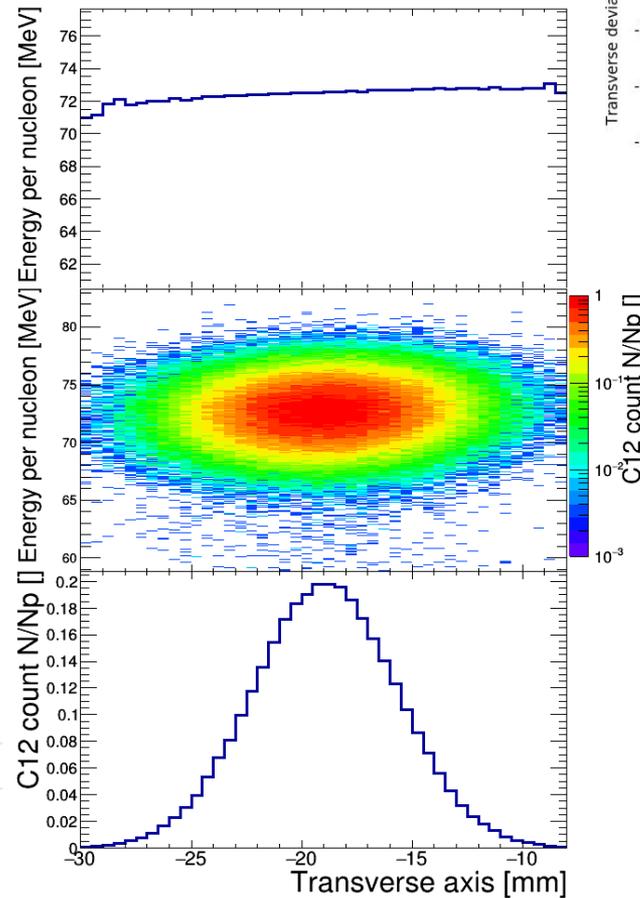
250 MeV protons @ 3T

Spectral analysis of the Bragg peak area

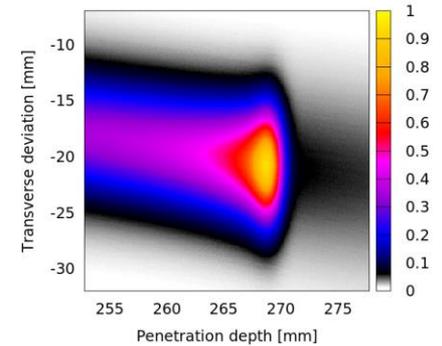
C12



depth = 10 mm



depth = 260 mm



400 MeV/u C12 @ 3T

Beam deflection

- Pronounced deflection at higher particle energies and magnetic fields

→ Compensation required

	250 MeV Protons	400 MeV/u C12
0.35 T	11.8 mm	2.4 mm
1 T	32.8 mm	6.9 mm
3 T	98.9 mm	20.7 mm

- Less deflection for C12 due to lower charge to mass ratio
- Reduced penetration depth in magnetic fields
 - Up to 18 mm for 250 MeV protons in 3 T

Numerical calculation of beam deflection

- Monte Carlo simulations time consuming
- Solving relativistic Lorentz equation

$$\frac{d}{dt} (\gamma m_0 \vec{v}) = q (\vec{v} \times \vec{B}) \quad \gamma = \left(1 - \frac{|\vec{v}|^2}{c^2}\right)^{-\frac{1}{2}}$$

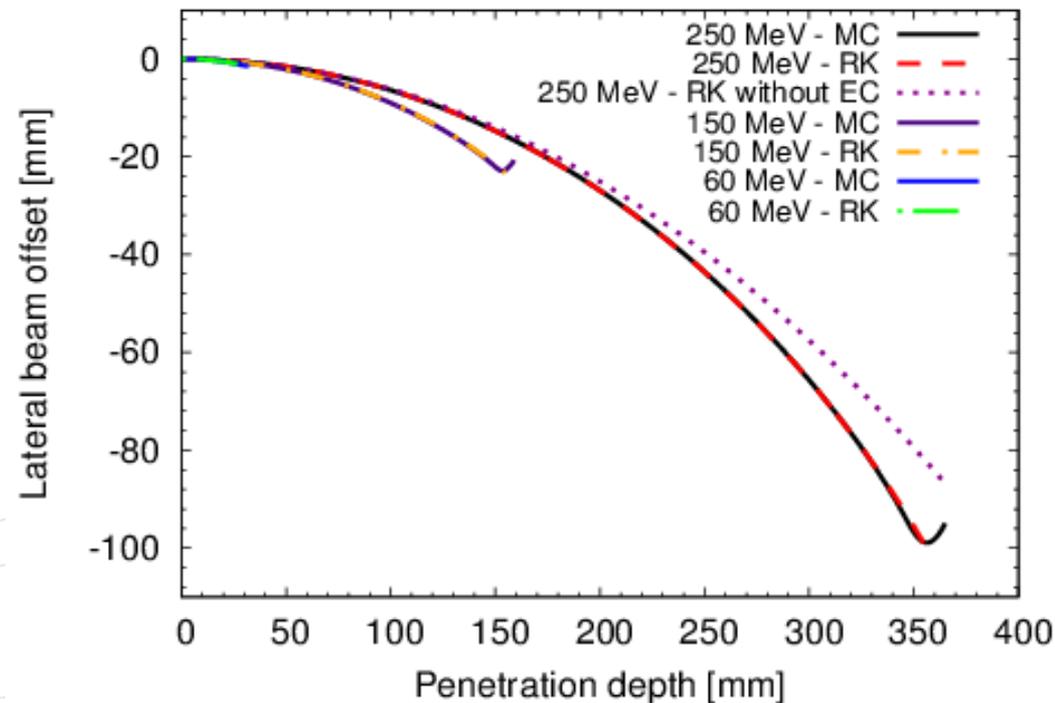
- Particles slowing down -> energy correction

$$\gamma' = \gamma_{\text{old}} - \frac{1}{m_0} \int_0^d \frac{dE}{ds} ds$$

- Runge-Kutta method for numerical calculation

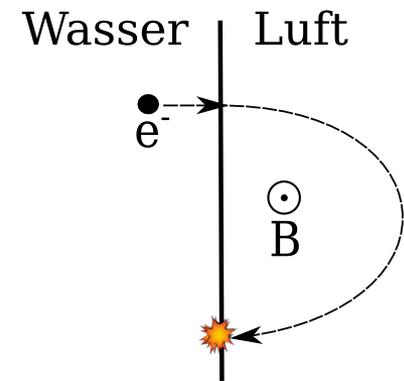
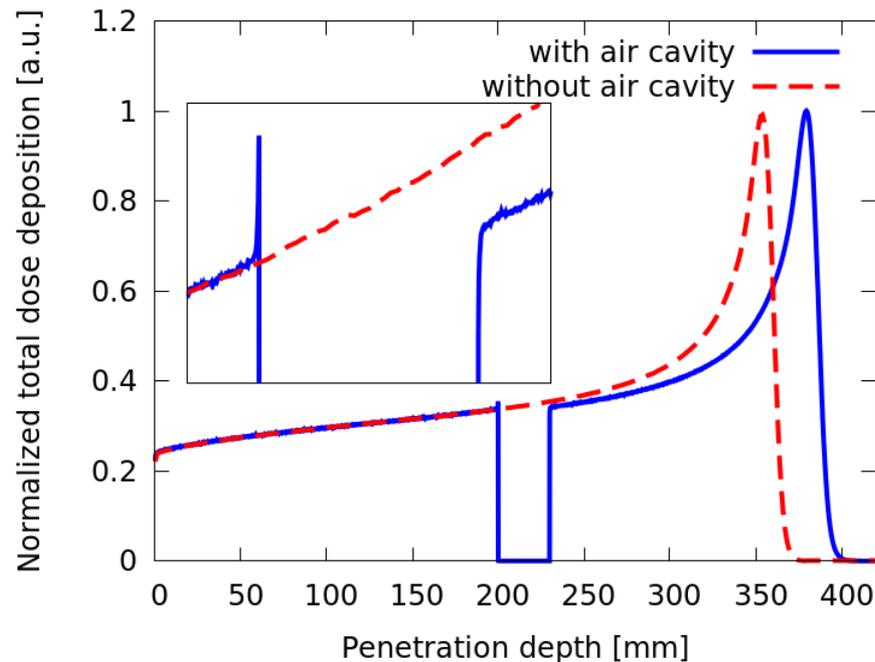
Numerical calculation of beam deflection II

- Changes in magnetic field could be taken into account at each step
- Dose calculation algorithm implementation foreseen
 - Fast < 5 ms
 - < 1.8% maximum deviation
- Rise at end of beam due to multi-particle effect



Effects at tissue interfaces

- 250 MeV proton beam in 3 T field
 - Heterogeneous geometry: Water – Air – Water
- Electron Return Effect (ERE): up to 6% dose increase
- Small compared to Photon beams (factor of 7 larger) [1]



ERE: Secondary electrons move on circular path in air and deposit energy a tissue interface

[1] Raaijmakers *et al.*, PMB, 2008

Summary and Outlook

- Beam deflection up to 9.9 cm for protons
 - Smaller beam deflection for C12 (up to 2.0 cm)
 - Numerical algorithm precisely models deflection (<1.8% difference)
- Range straggling effect in magnetic fields
 - Tilted Bragg peak area for protons, not for C12
- Tissue interfaces effects small (<2% in single voxel)
- Work in progress: Implementation into dose calculation algorithm

Thank you for your attention!



Appendix: Lateral deviations

- Bragg Peak position: Depth [mm] / lateral deviation [mm]

Protonen	0 T	0.35 T	1 T	3 T
60 MeV	0 / 30.55	0.21 / 30.55	0.5 / 30.55	1.4 / 30.45
150 MeV	0 / 156.5	2.45 / 156	7.25 / 155	22.75 / 153
250 MeV	0 / 376.5	11.75 / 375.3	32.75 / 373	98.75 / 356

Carbon ions	0 T	0.35 T	1 T	3 T
120 MeV/u	0 / 34.9	0.08 / 34.9	0.21 / 34.9	0.65 / 34.8
250 MeV/u	0 / 124.5	0.65 / 124.4	1.85 / 124.3	5.65 / 124.1
400 MeV/u	0 / 270.1	2.35 / 269.9	6.85 / 269.4	20.65 / 269.2

