Accelerated Monte Carlo for treatment planning

Human Care Makes the Future Possible

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Disclosures

- Employee of Elekta

Accelerated Monte Carlo for treatment planning

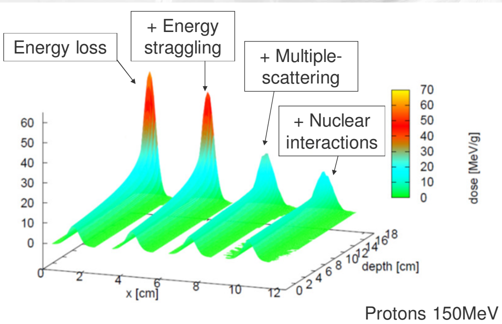
- Dose algorithms for treatment planning purposes should:
  - Calculate dose as accurate as possible …
  - … but respect the practical constraints (time)
- Solutions:
  - Increase accuracy of analytical algorithms
  - Decrease calculation time of Monte Carlo algorithms

Accelerated Monte Carlo for treatment planning

Accelerating approaches (from user's perspective):

- Hardware
  - Multicore CPU, GPU …
- Software
  - Efficient code (language, voxel transport, random number generator etc)
  - Variance reduction methods
  - Reasonable physics approximation

Physics - Overview



Kohno et al, Jpn. J. Appl. Phys. Vol. 41 (2002)

- Energy loss from measured broad beam depth dose in water (covers everything including stopping power, energy straggling, contribution of secondaries)
- Voxels with waterequivalent thickness
- MCS with small angle Gaussian approach

Tourovsky et al, Phys. Med. Biol. 50 (2005)

- Water equivalent stopping powers, Gaussian energy straggling as additional initial energy spread
- MCS with small angle Gaussian approach
- No transport of secondary particles (dose due to nuclear secondaries deposited along the path of primary protons)

Li et al, Phys. Med. Biol. 50 (2005)

Track repeating algorithm

- Pregenerated 250 MeV proton tracks in water with Geant3 (using primary and secondary protons only)
- Scale step length with material (using stopping power for bone, density for all others)
- Adjust scattering angle with material (only for bone, ignore energy dependence)

Yepes et al

Yepes et al, Nucl Technol. (2009)

- Extend the step and angle scaling with material using Geant4 simulated stopping power ratios (range ratios) to >42 materials

Yepes et al, Phys. Med. Biol. 55 (2010)

- Implement on GPU

Fippel, Soukup, Med. Phys. 31 (2004)

VMCpro

- Class II condensed history algorithm with continuous energy loss, ionization, multiple scattering, δ electron transport, nuclear elastic proton scattering and inelastic proton nucleus reactions, secondary proton transport

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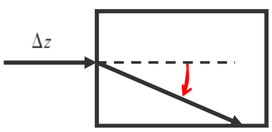
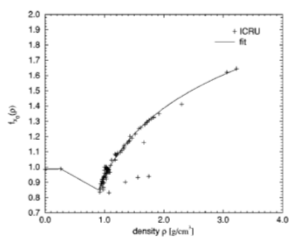
VMCpro - Multiple Coulomb Scattering



Rossi: $\theta_0^2 = \left(\frac{E_s}{\beta p}\right)^2 \frac{\Delta z}{X_0(\rho)}$

Radiation length

$f_{X_0}(\rho) = \frac{\rho_w}{\rho} \frac{X_w}{X_0(\rho)}$



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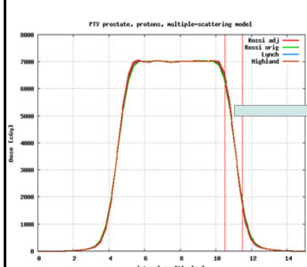
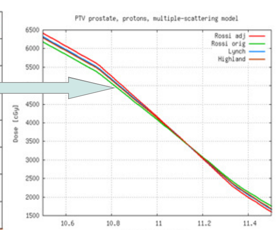
Multiple Coulomb Scattering model





Prostate plan (PB, SFUD)

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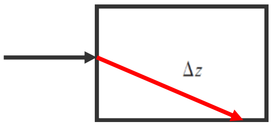
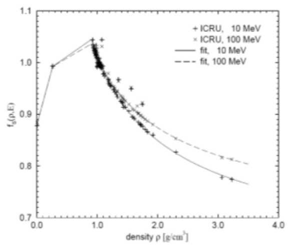
VMCpro - Energy loss



stopping power ratio

$$f_S(\rho,T_p)=\frac{\rho_w}{\rho}\frac{S(\rho,T_p)}{S_w(T_p)}$$



$$\Delta z_w=f_S(\rho,T_p)\frac{\rho}{\rho_w}\Delta z$$

Total stopping power in water tabulated (ICRU 49)

Mean Energy loss

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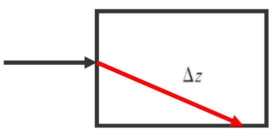
VMCpro – energy straggling



- Energy straggling – sample from a Gaussian distribution with variance

$$\Omega^2=2\pi r_e^2 m_e n_e \Delta z\,\frac{\min(T_e^{\min},T_e^{\max})}{\beta^2}\left(1-\frac{\beta^2}{2}\right)$$

- Delta electrons transport (CSDA) – discrete interactions

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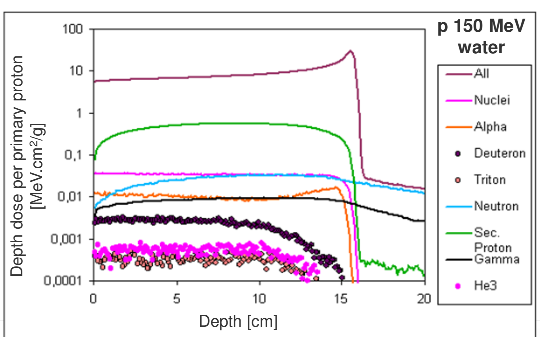
Dose due to products of nuclear interactions



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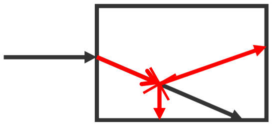
VMCpro - nuclear interactions



- Tabulated + fitted cross sections in water
  - Elastic proton – proton interactions
  - Elastic proton – oxygen interactions
  - Non-elastic proton – oxygen interactions
  - Transport primary and secondary protons

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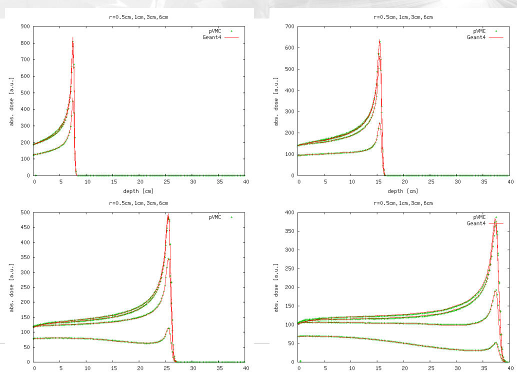
Geant4 as validation tool



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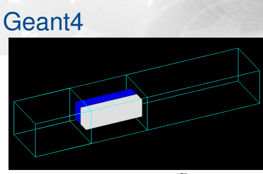
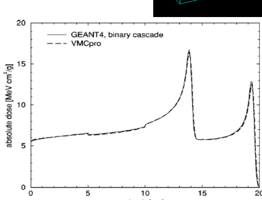
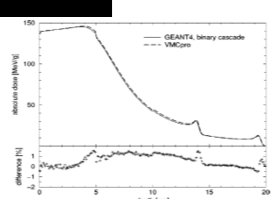
Validation: Geant4





Integrated depth dose



Central axis depth dose

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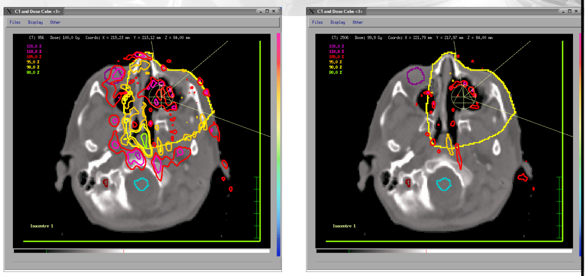
Comparison with pencil beam algorithm



1 sub-spot — Nuclear correction

121 sub-spots — Nuclear correction

Implementation for spot scanning

- Beam model
- Dose to water/tissue
- Uncertainties
- CT calibration: HU to mass density for human tissues

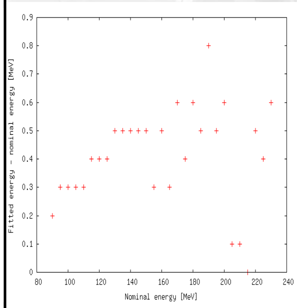
MC beam model scanning

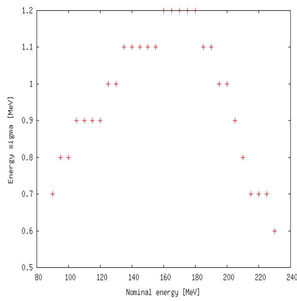
Initial spot properties

- Spot size (2D Gaussian)
- Spot direction – given by distance to lateral deflection magnets
- Divergence
- Possibly also range shifting devices and aperture – geometry and material information
- Energy spectrum – fit depth dose curves
- MU Calibration

MC specific

Mean energy / Energy sigma





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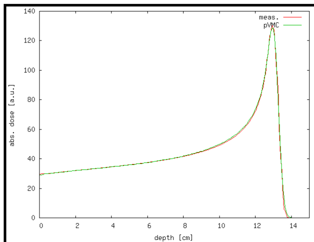
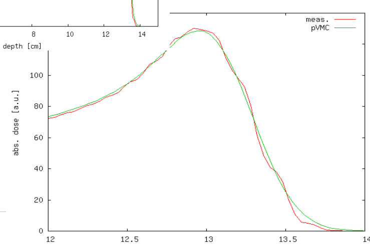


- Measurement quality?
- Fit manually adjusted for two energies



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Uncertainty – stopping criteria

- Number of protons per spot – time
- Low uncertainty per spot necessary for IMPT optimization
- Specifics – air
- Definition of stopping criteria: maximum relative uncertainty (or Mean Relative Statistical Uncertainty), maximum number of particles

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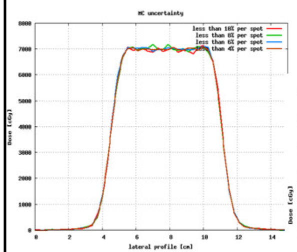
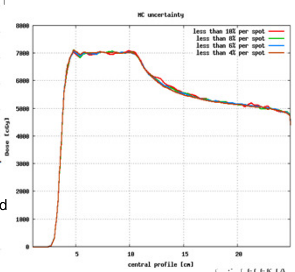
Monte Carlo – Select Uncertainty





Proton prostate plan (SFUD) with MC and maximal relative uncertainty of 4%, recalculated with less accuracy

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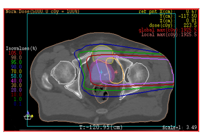
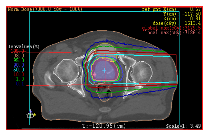
MC for IMPT - Workflow example*

1 Dose calc

PB



2 Optimize

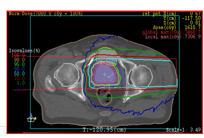


Calculate all spots

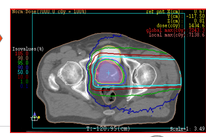
3 Dose calc

MC

<5% /spot
total: 125 s
<3% /spot
total: 315 s
(8 cores)



4 Optimize



Calculate active spots only

*Works-in-progress

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Conclusions

- Calculation times acceptable ...
- Accuracy comparable with multipurpose MC ...
- Accelerated MC in photon/electron world becoming routine …
- … no reason why not for protons

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