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Fluence correction factors for graphite calorimetry in clinical proton beams using Geant4

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Overview

- Background
- Formalism for dose conversion and fluence correction factor
- Monte Carlo simulations: Geant4 and TotalAbsorber
- Results
- Future work and ideas

Background

- Quantity of interest in clinical proton beams is absorbed dose to water: no primary standards currently exist
- Water calorimeters have been successfully used
- Prototype graphite calorimeters also developed & demonstrated
- Graphite calorimetry: largest uncertainty in absorbed dose-to-water determination is conversion of dose-to-graphite to dose-to-water
- Dose conversion requires accurate determination of water-to-graphite stopping power ratios and fluence correction factors.
- This work: fluence correction factors determined initially for 60 & 200 MeV monoenergetic proton beams using Geant4.

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Dose conversion and fluence correction factor

- Fluence based approach (k_{fl}, k_{fl}'):

Dose to water :
(in terms of Φ_g)

$$D_w(z_{w-eq}) = D_g(z_g)\cdot s_{w,g}(\Phi_g)\cdot k_{fl}$$

with: $$z_{w-eq} = z_g \cdot \frac{r_{0,w}}{r_{0,g}}$$

$$s_{w,g}(\Phi_g) = \frac{\sum_i \left[\int_0^{E_{\max,i}} \Phi_{E,g,i}(E)\cdot\left(\frac{S_{c,i}(E)}{\rho}\right)_w \cdot dE\right]}{\sum_i \left[\int_0^{E_{\max,i}} \Phi_{E,g,i}(E)\cdot\left(\frac{S_{c,i}(E)}{\rho}\right)_g \cdot dE\right]}$$

$$k_{fl} = \frac{\sum_i \left[\int_0^{E_{\max,i}} \Phi_{E,w,i}(E)\cdot\left(\frac{S_{c,i}(E)}{\rho}\right)_w \cdot dE\right]}{\sum_i \left[\int_0^{E_{\max,i}} \Phi_{E,g,i}(E)\cdot\left(\frac{S_{c,i}(E)}{\rho}\right)_w \cdot dE\right]}$$

Dose to water :
(in terms of Φ_w)

$$D_w(z_{w-eq}) = D_g(z_g)\cdot s_{w,g}(\Phi_w)\cdot k_{fl}'$$

- Alternatively, dose based approach (k_{fl}):

$$k_{fl} = \frac{D_w(z_{w-eq})}{D_g(z_g)\cdot s_{w,g}(\Phi_g)}$$

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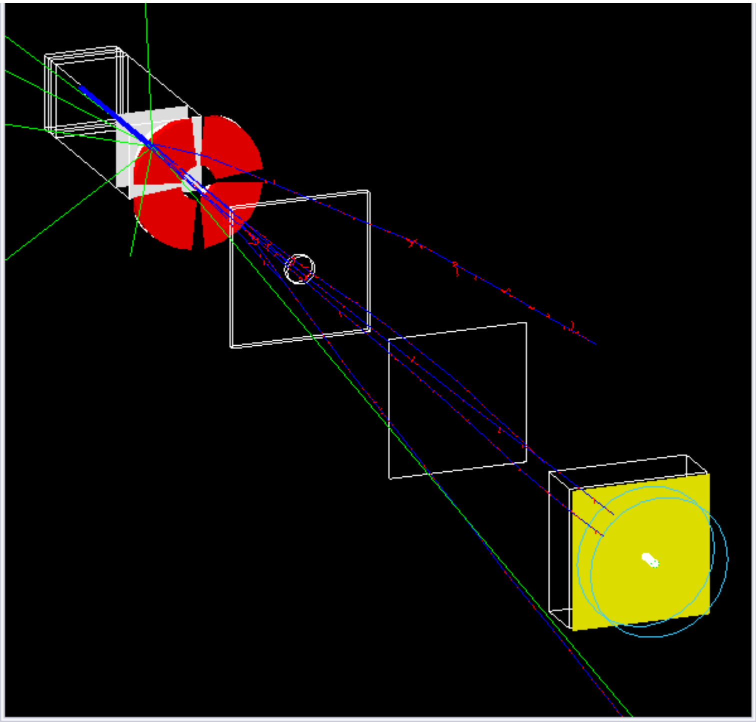
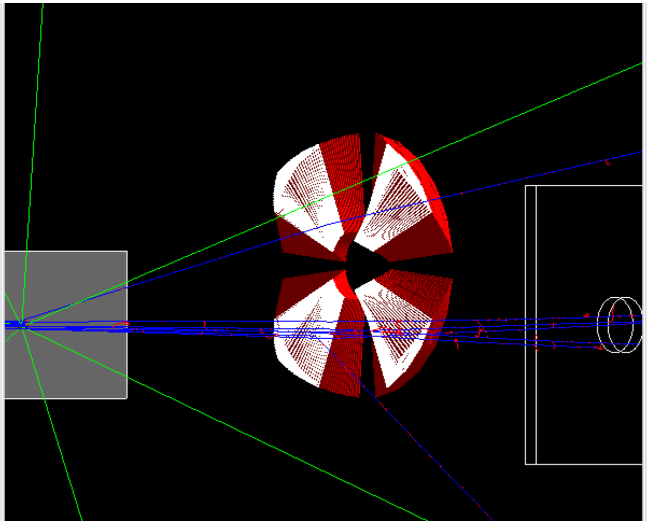
Monte Carlo simulations: TotalAbsorber

- *TotalAbsorber*: calculates depth dose and particle fluence distributions differential in energy at depths in a large slab phantom in a proton beam
- **Geometry / Beam line**
  - Cylindrical phantom with internal cylindrical-slab regions (replicated)
  - Pencil beam or full CCC passive beam line (mod wheel, range shifter etc)





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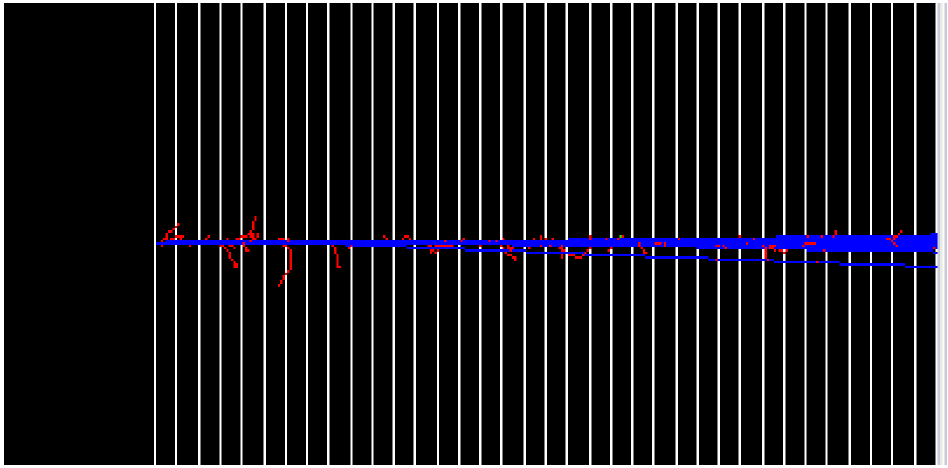
Monte Carlo simulations: TotalAbsorber

- **Physics** (based on Hadrontherapy advanced examples)
  - **G4 (v9.0)**: EM: ‘Low energy’ models, Nuclear (x3): Precompound, QGSP+BIC, QGSP+BERT
  - **G4 (v9.6.p01):** EM: emstandard_opt3, Nuclear: Binary Intranuclear Cascade (BIC)
  - ICRU49 stopping power parameterisation
  - Production cuts (EM): 0.005mm, StepMax: 0.005mm
- **Scoring/tracking**
  - Total energy deposited per step (dose)
  - Stopping power data dumped for each particle type (G4EmCalculator)
  - Particle fluence spectra differential in energy (most common particle types, fixed bins widths, every 10^{th} slab)
- **Simulations**
  - 10^6 – 10^7 initial proton events (NPL Distributed Computing Grid)
  - Post processing with Excel and/or Python scripts



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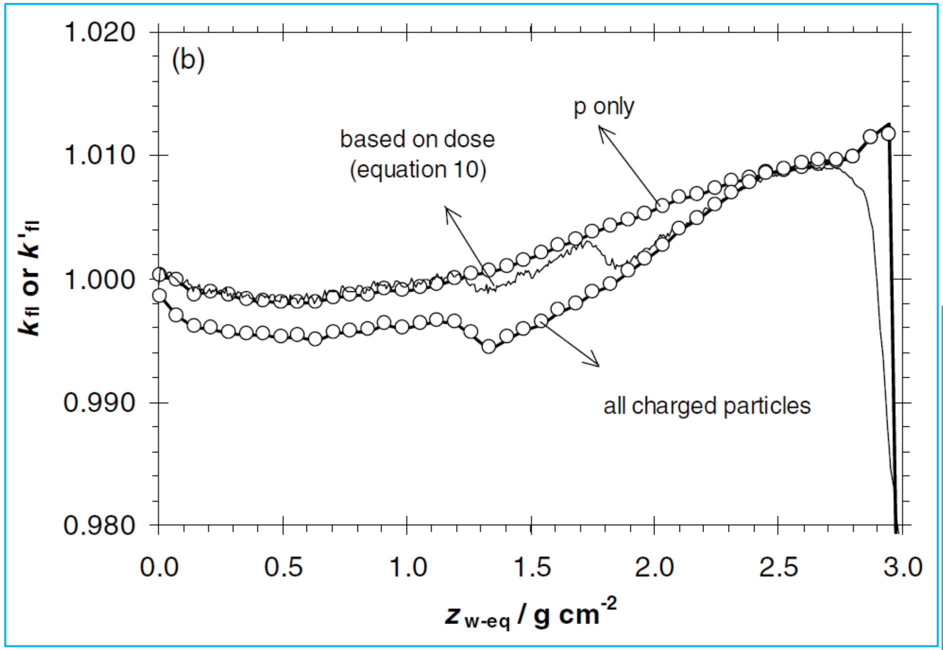
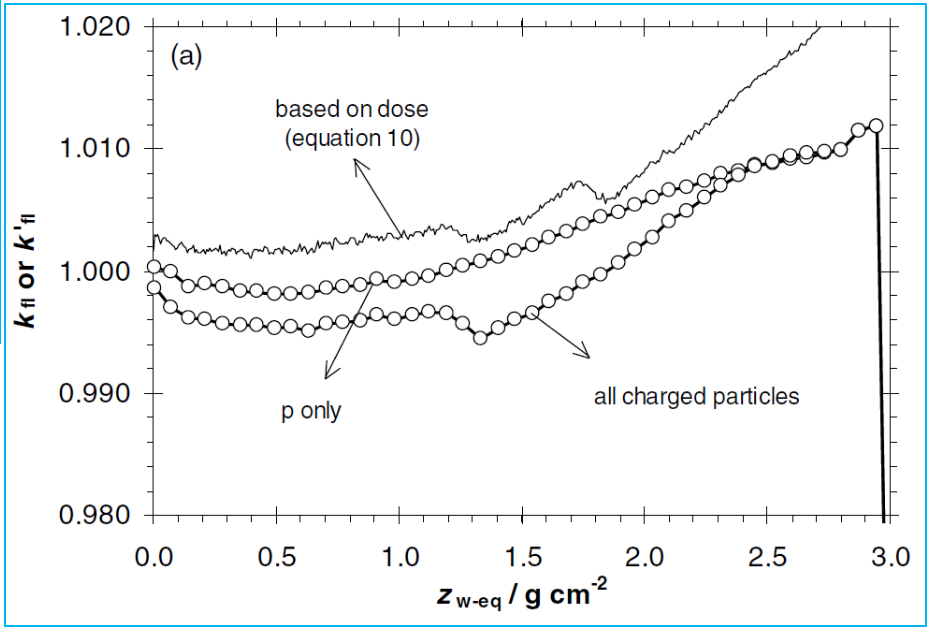
Fluence correction: 60 MeV protons (G4 v9.0)



With G4 stopping power data

With ICRU49 stopping power data



- Fluence method : k_{fl}: **thick** lines, k_{fl}': symbols
- Dose method: k_{fl} : thin line

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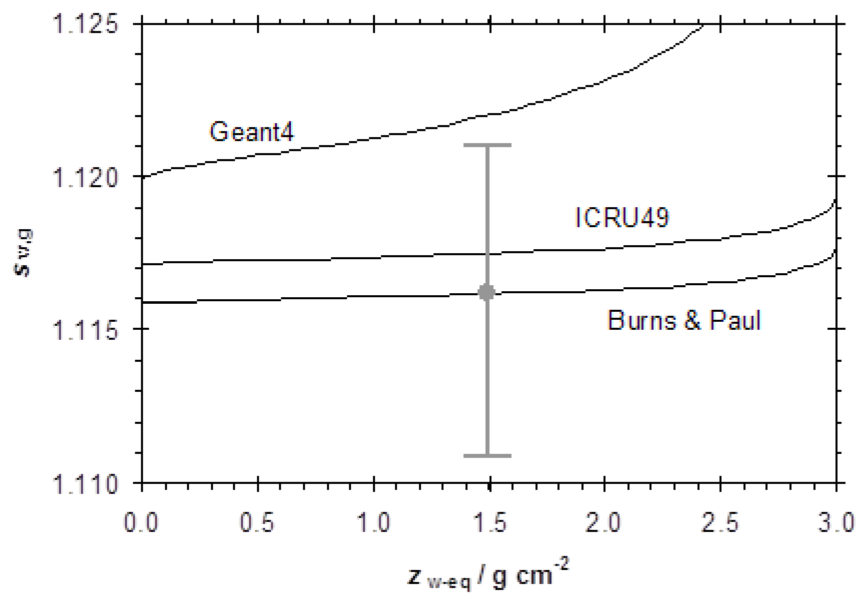
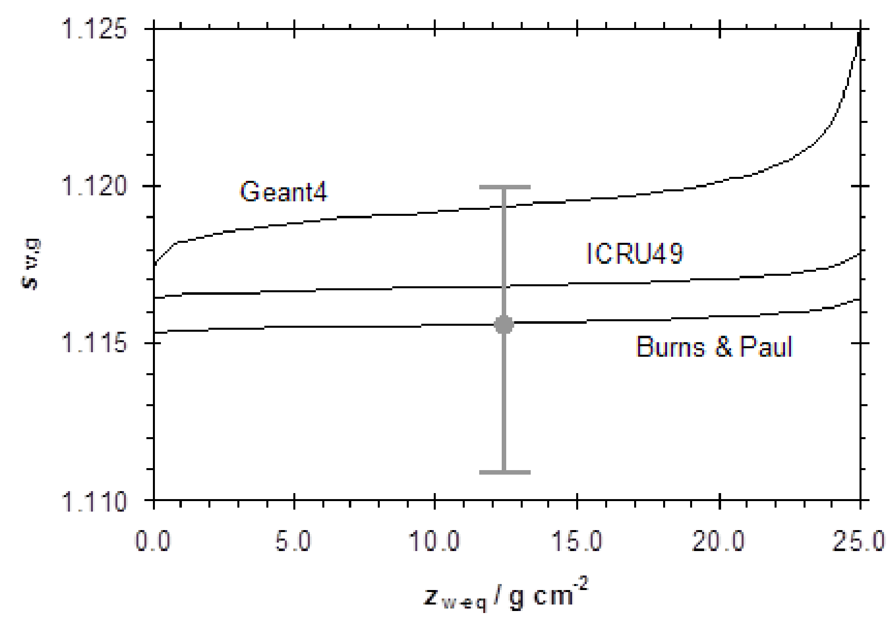
Stopping power ratios: 60, 200 MeV protons (G4 v9.0)



Water-to-graphite ratio vs depth for 60 MeV protons

Water-to-graphite ratio vs depth for 200 MeV protons



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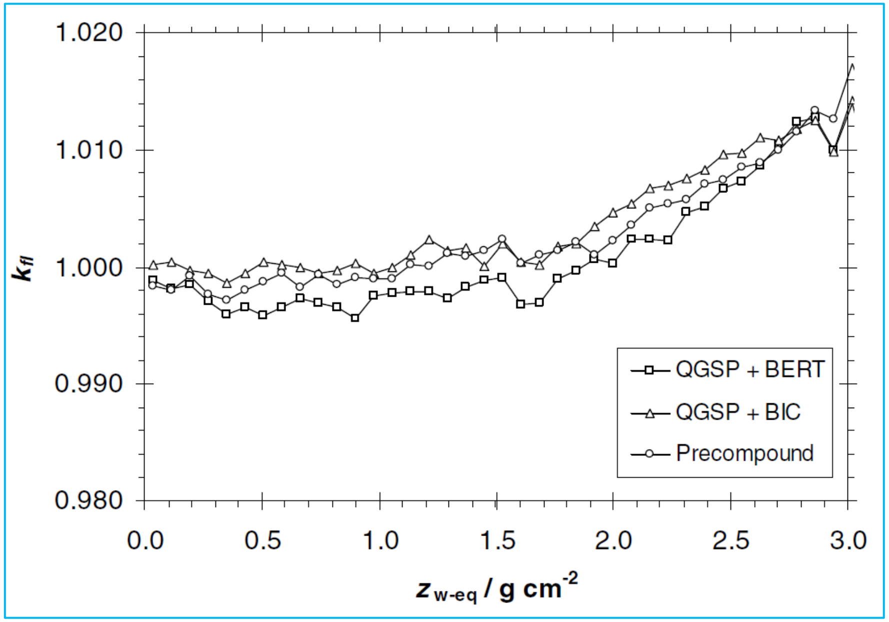
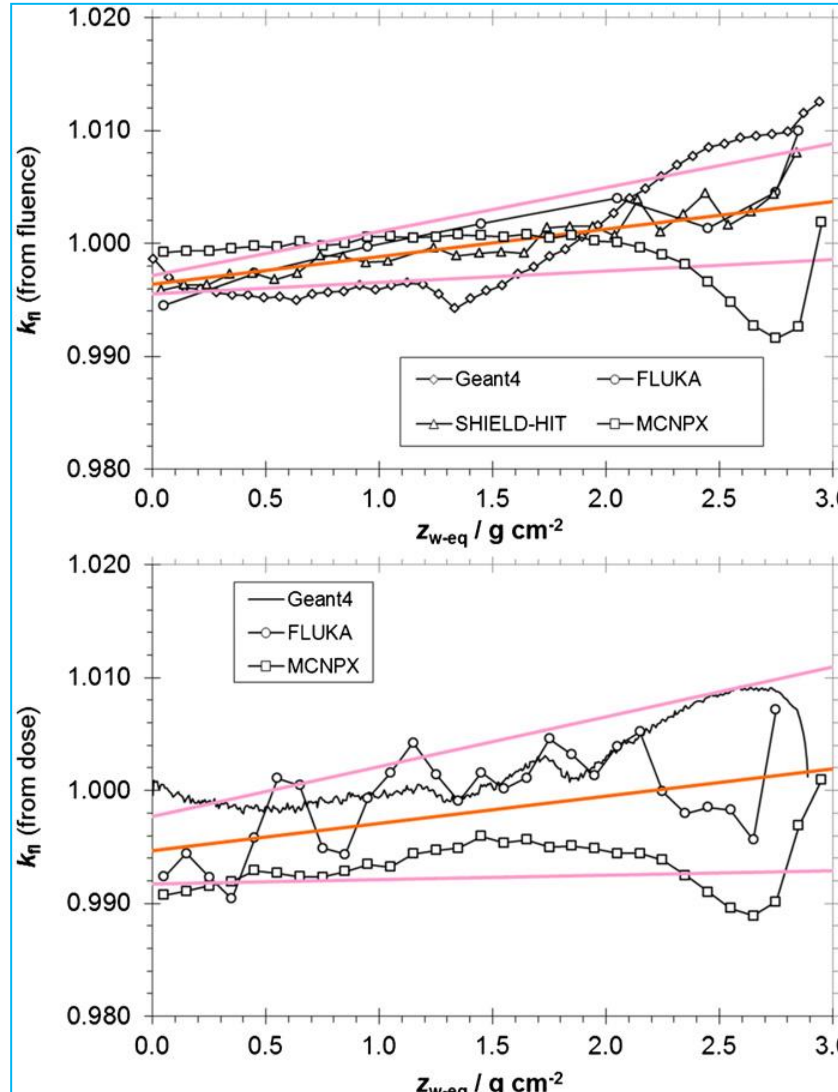
Fluence correction: 60 MeV protons (G4 v9.0)



kfl (fluence method): 3 nuclear interaction models

- Fluence: k_{fl} = **0.9964 + 0.0024 · $z_{w\text{-}eq}$**
- Dose: k_{fl} = **0.9947 + 0.0024 · $z_{w\text{-}eq}$**
- ($z_{w\text{-}eq}$ in g cm^{-2})



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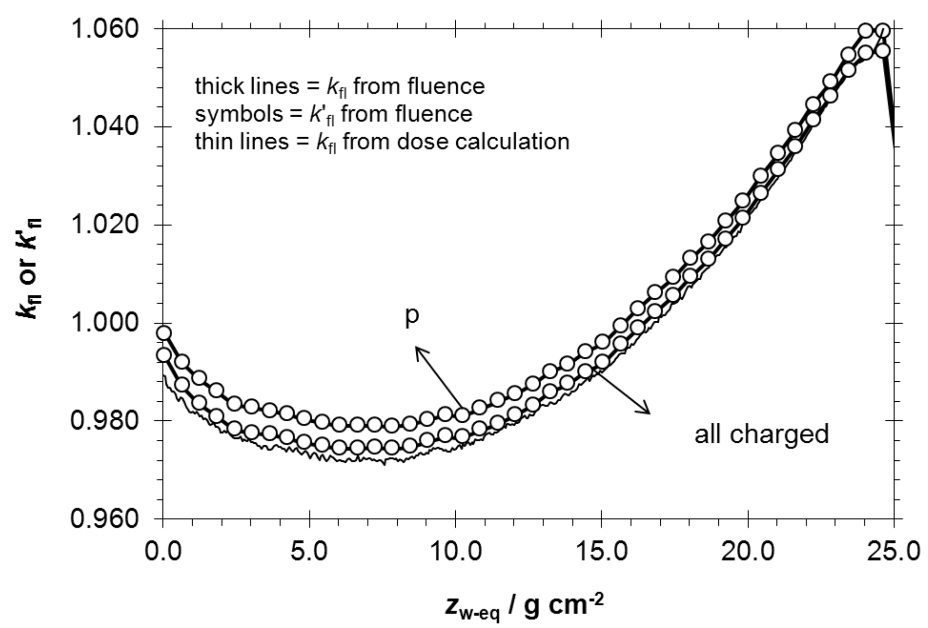
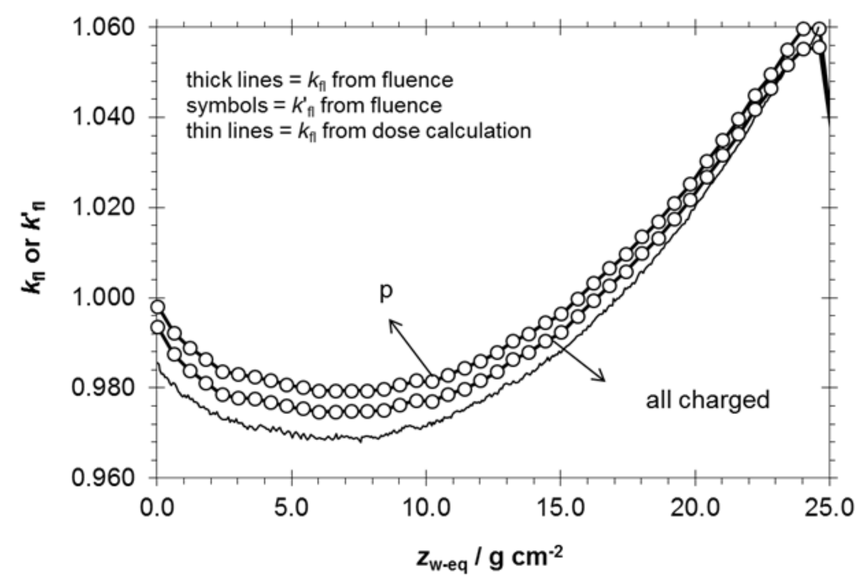
Fluence correction: 200 MeV protons (G4 v9.0)



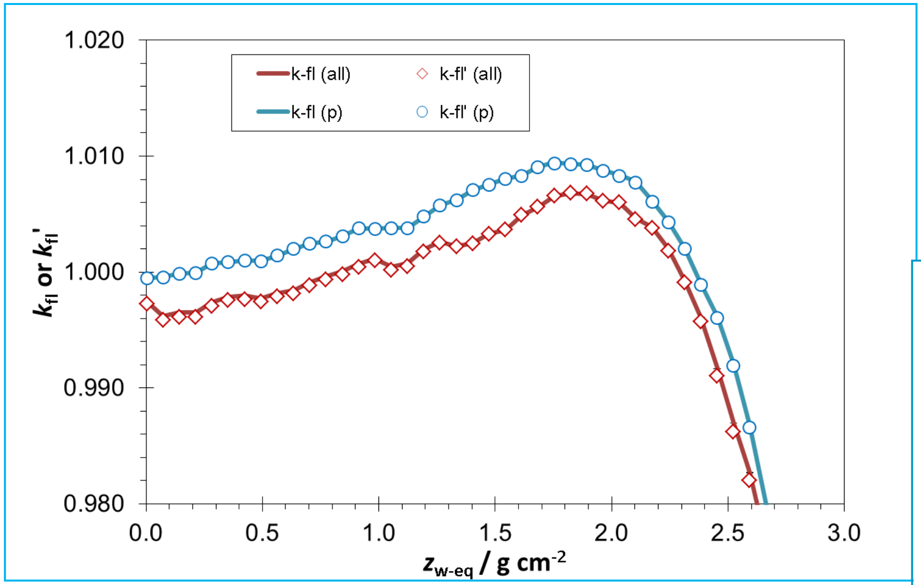
With G4 stopping power data

With ICRU49 stopping power data



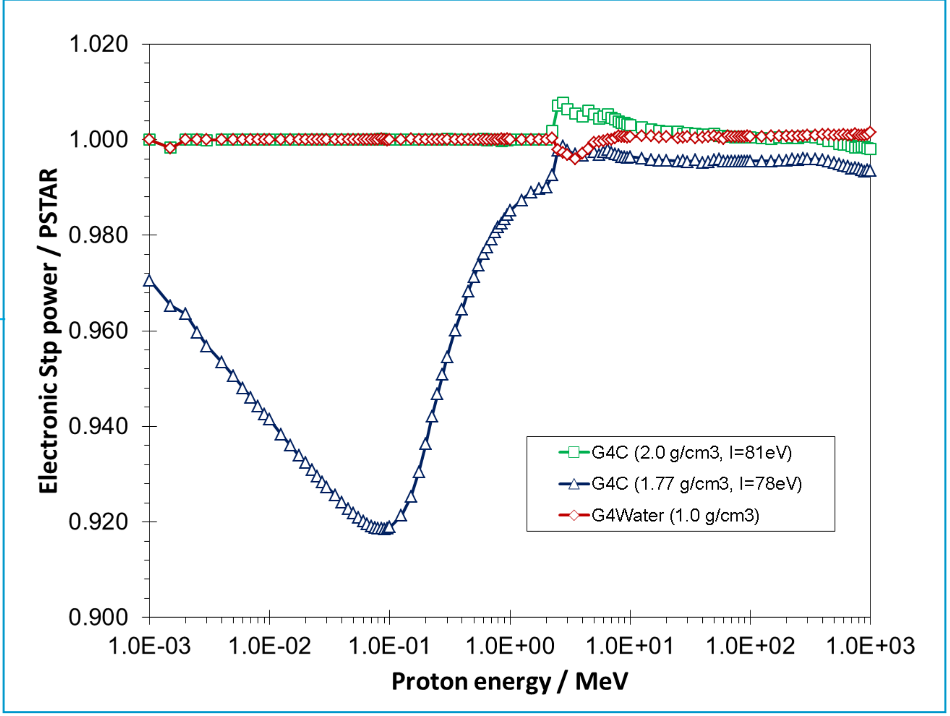
- Fluence method : k_{fl}: **thick** lines, k_{fl}': symbols
- Dose method: k_{fl} : thin line

60 MeV protons (G4 v9.6.p01): early results



kfl (fluence method): with G4 stopping power data

G4 stopping power data vs ICRU49



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Summary and Future work

- Overview of the formalism, methods and issues for determining fluence corrections using Geant4 in two monoenergetic proton beams of clinical interest:
  - k_{fl} : < unity at surface, up to 1% (60 MeV) or 6% (200 MeV) above unity near BP
  - k_{fl} and k_{fl}' (fluence method) agree (within <0.05%)
  - k_{fl} (fluence method): influence of stopping power data is small
  - dose and fluence methods consistent when using actual stopping power data used in the simulations.
  - k_{fl} (60 MeV): no significant dependence on nuclear interaction model
  - stopping power data dumped by Geant4 appears quite different to ICRU49 over certain energy ranges

- Ongoing and future work:
  - Update with new releases of Geant4 (improved stopping power data?)
  - Extend to other materials e.g. water-equivalent plastics, design study (unity k_{fl})
  - Simulate actual clinical beam lines e.g. CCC, scanned (TOPAS)

Acknowledgements

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