Benchmarking LET_d calculation of a commercial treatment planning system and GATE/Geant4 for carbon ion beams

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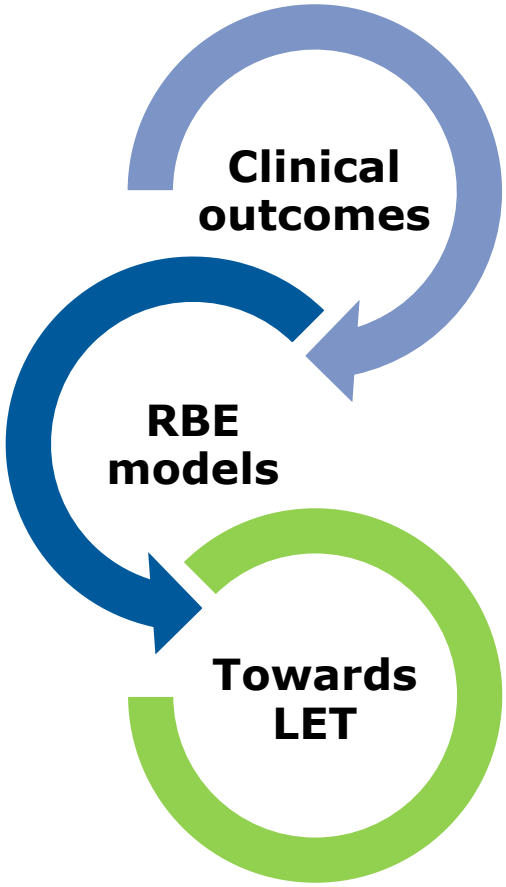
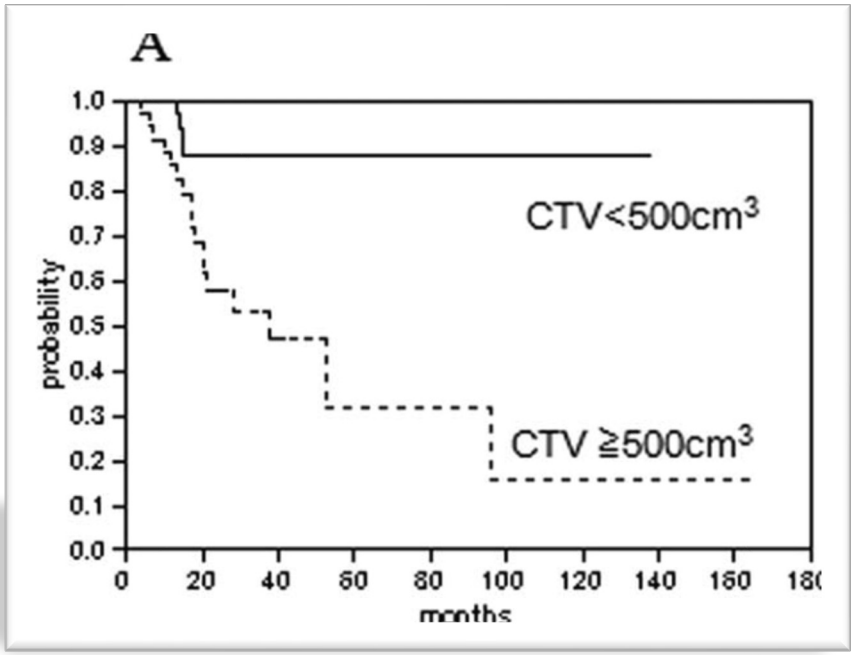
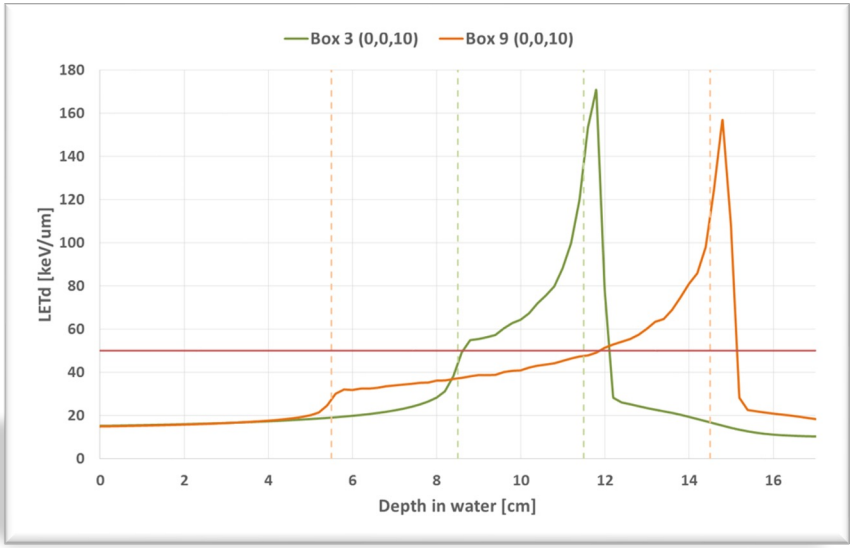
Motivation





Matsunobo et al. 2012



Overview

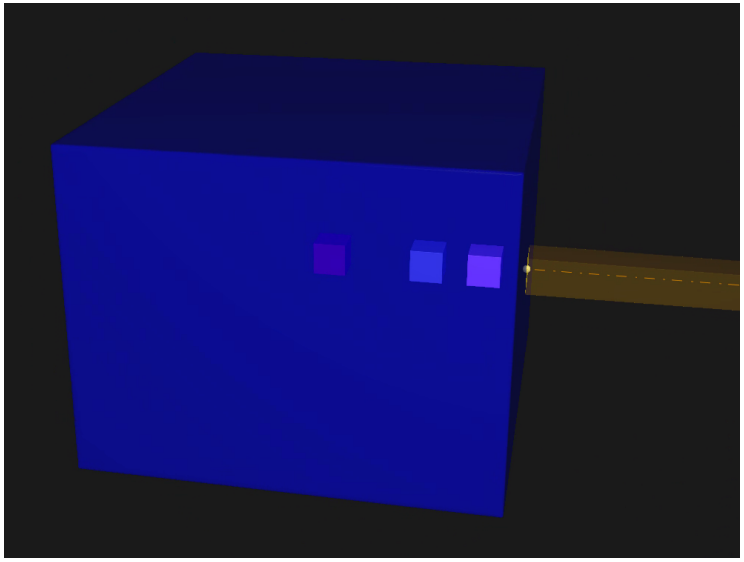
RaySearch Laboratories

GATE

GEANT4 A SIMULATION TOOLKIT

- **Dose average LET (LET_d)**
- **Filtered dose**
  - $D_{<100\ keV/\mu m}$
  - $D_{\geq 100\ keV/\mu m}$

- **Spread-out Bragg peak**
  - Homogeneous (water)
  - Heterogeneous medium
- **Monoenergetic layers**



Materials & Methods: RayStation 9A-IonPG

- **Dose computation**
  - Pencil beam dose calculation algorithm (PB)
    - Pre-generated FLUKA particle energy spectra in water

- **LET_d scoring**
    - Parametrized stopping power tables from FLUKA
    - Average all particles $z \leq 6$

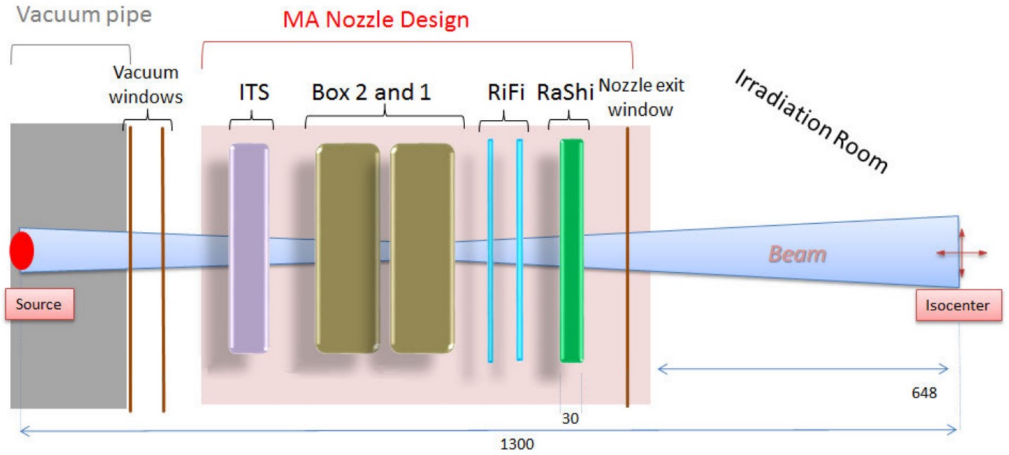
$$LET_d = \frac{\sum_z^Z \sum_i^N L_z^2(E_i)\, \Phi_z(E_i)}{\sum_z^Z \sum_i^N L_z(E_i)\, \Phi_z(E_i)}$$

$$= \frac{\sum_z^Z \sum_i^N d_z(E_i)\, L_z(E_i)}{\sum_z^Z \sum_i^N d_z(E_i)}$$

L: unrestricted linear energy transfer; Φ: fluence differential in energy; d: dose;
z: charged particle type;
E: energy;
Z: total number of energy bins (PB) / number of steps in the voxel (MC);
N: highest atomic number of the included ion types

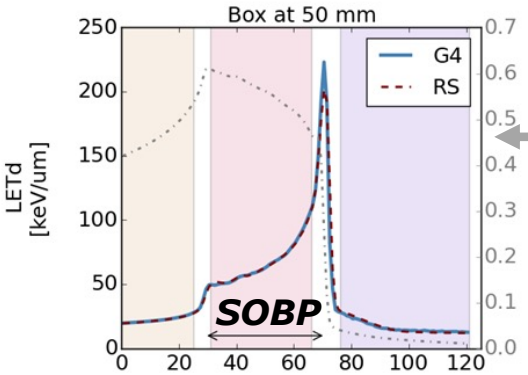
Materials & Methods: GATE /Geant 4

- **Settings**
  - Gate v9.1 / Geant4 10.6.p01
  - Beam model: detailed geometric description of nozzle elements and beam properties
  - Physics list: FTFP_INCLXX_EMZ
  - Simulated source ions: 10^8
  - Maximum step size: 0.1 mm
  - Scoring volumes: corresponding to RS scoring grid



- **LET_d scoring**
  - Using Gate LET Actor
    - With default scoring options
      - Electronic Stopping power from G4EMCalculator
    - Using particle filters for separate scoring

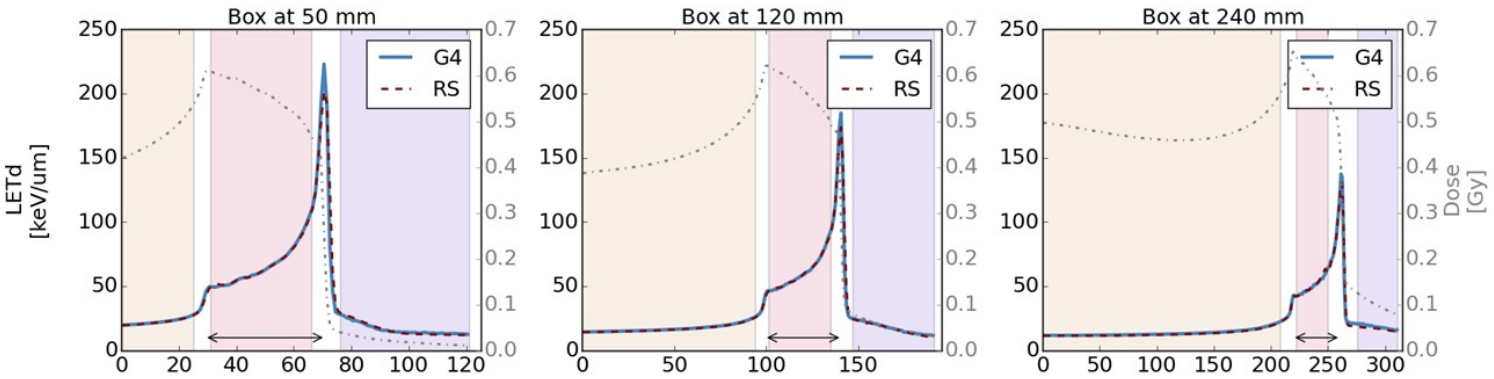
Results: LET_d / longitudinal profile



physical dose

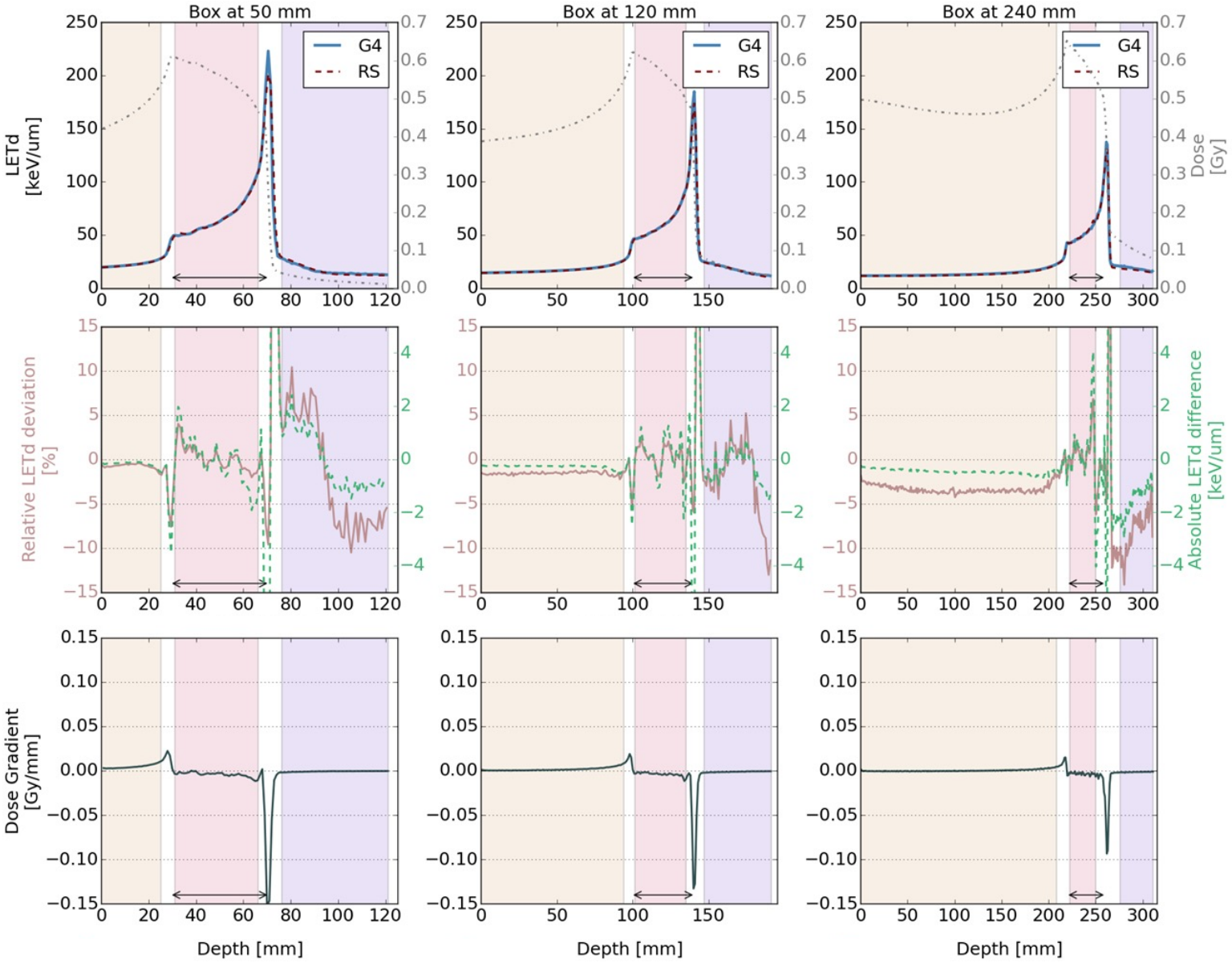
Prescribed RBE-weighted dose: D_{RBE}=2.3 Gy(RBE)

Results: LET_d / longitudinal profile



Shallow ***Deep***

Results: LET_d / longitudinal profile



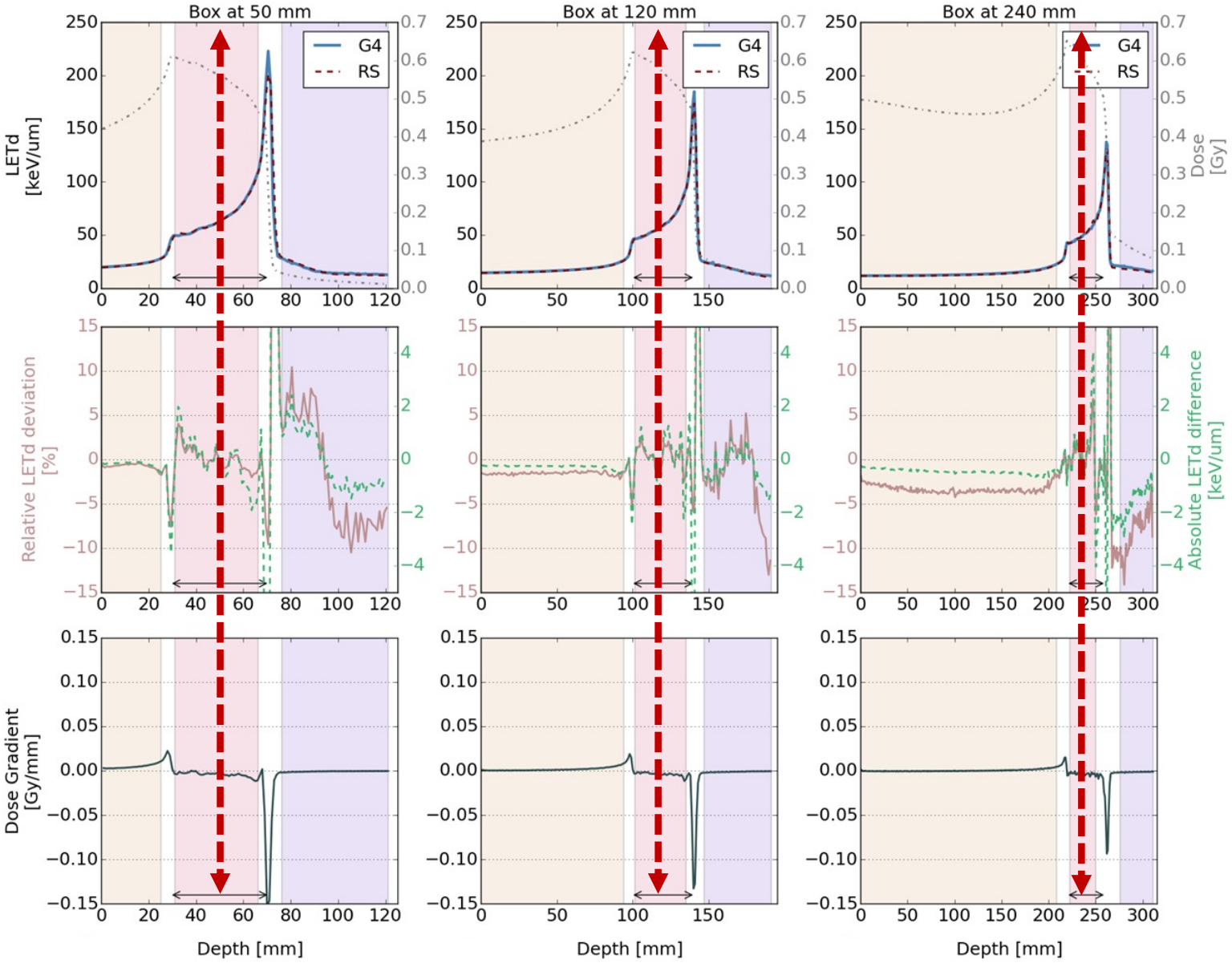
Plateau & Target:

- $\bar{\delta}$ <1 keV/um
- δ_{max}= 4 keV/um
- $\bar{\Delta}$ <3.5%

Fragmentation tail:

- $\bar{\delta}$ <2 keV/um
- δ_{max}= 6 keV/um
- $\bar{\Delta}$ <8.3%

Results: LET_d / longitudinal profile



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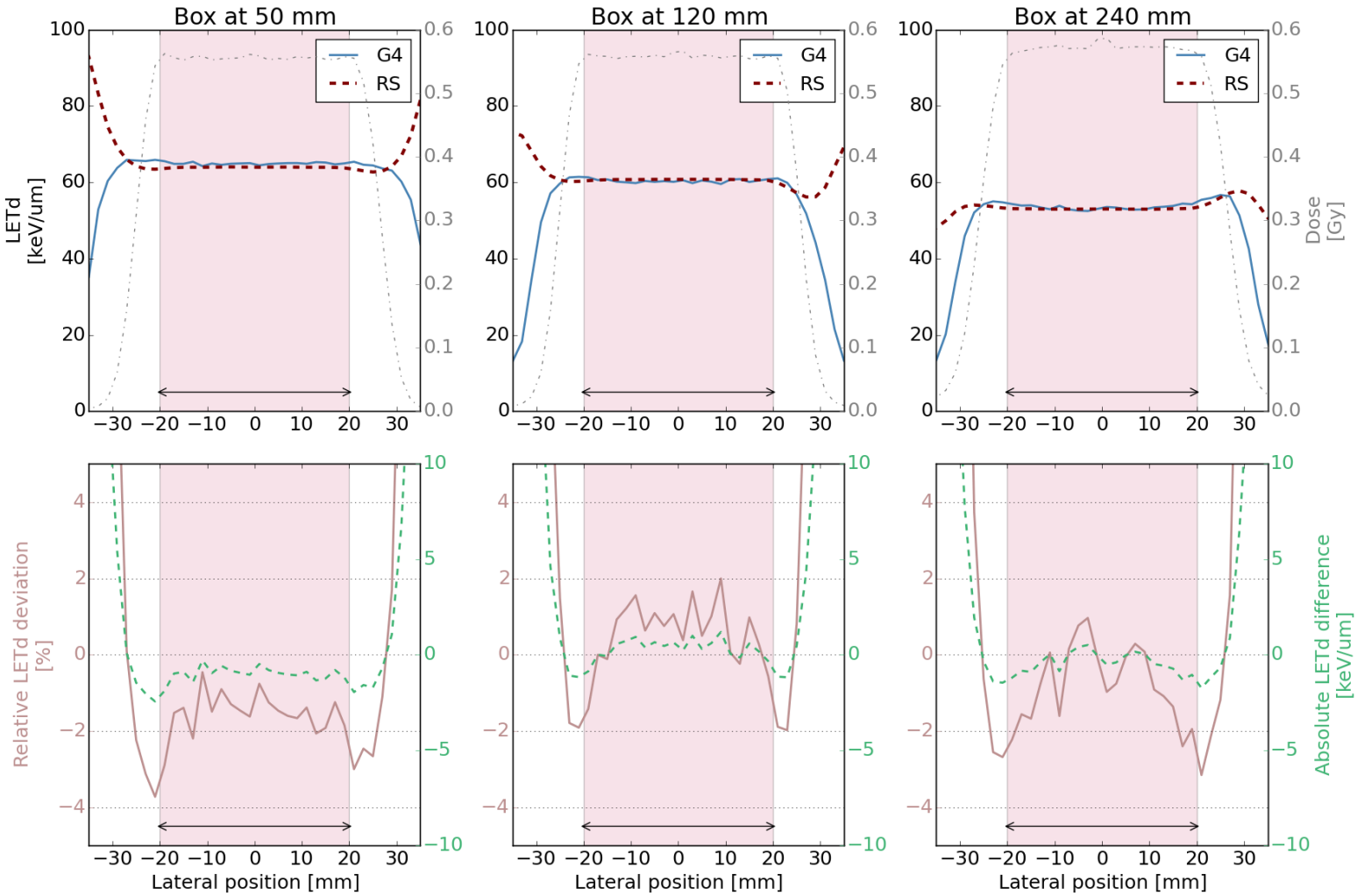
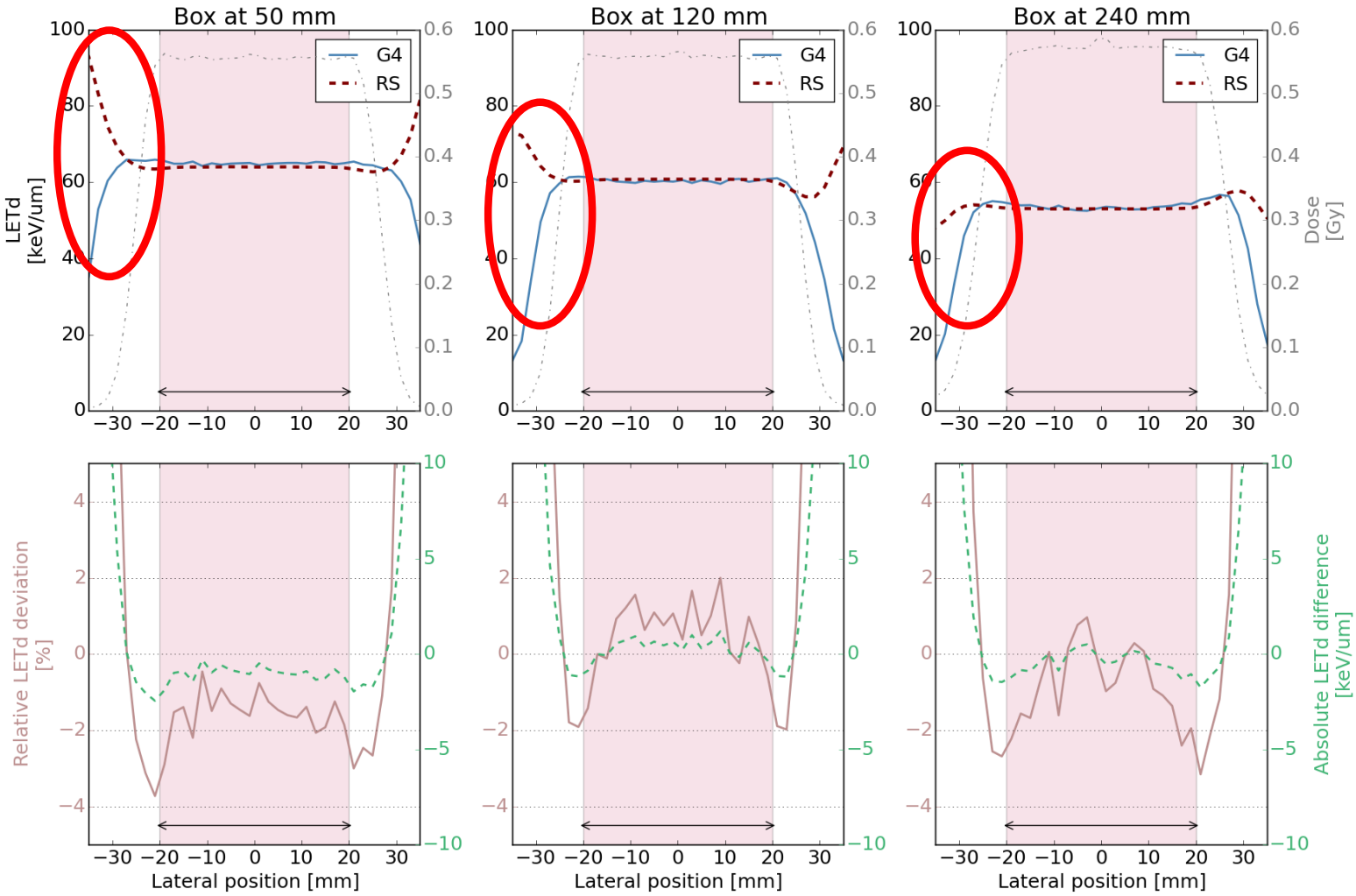
Results: LET_d / transversal profile



Target:

- $\bar{\delta} \leq 1$ keV/um
- $\bar{\Delta} \leq 1.5\%$

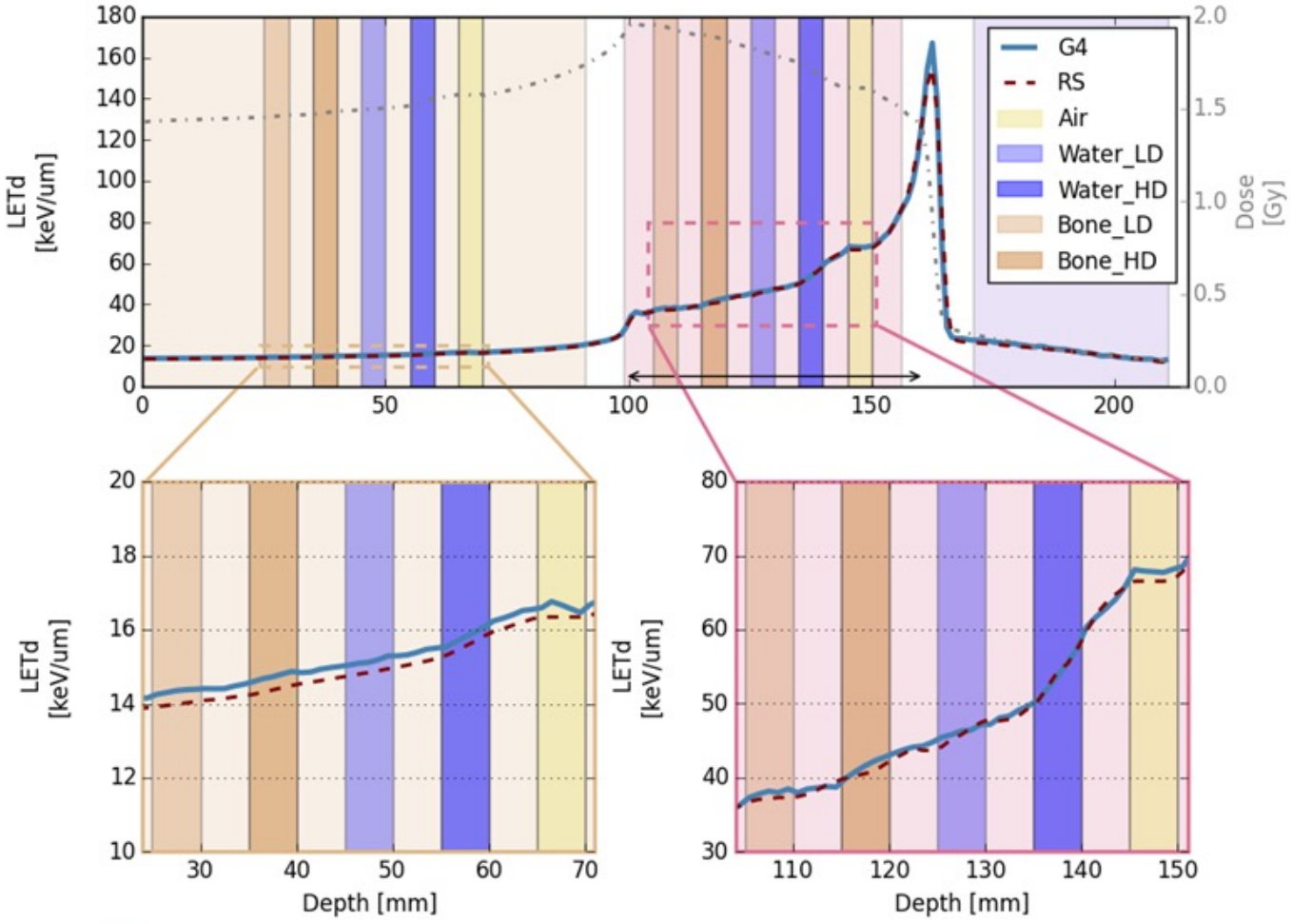
Results: LET_d / transversal profile



Target:

- $\bar{\delta} \leq 1$ keV/um
- $\bar{\Delta} \leq 1.5\%$

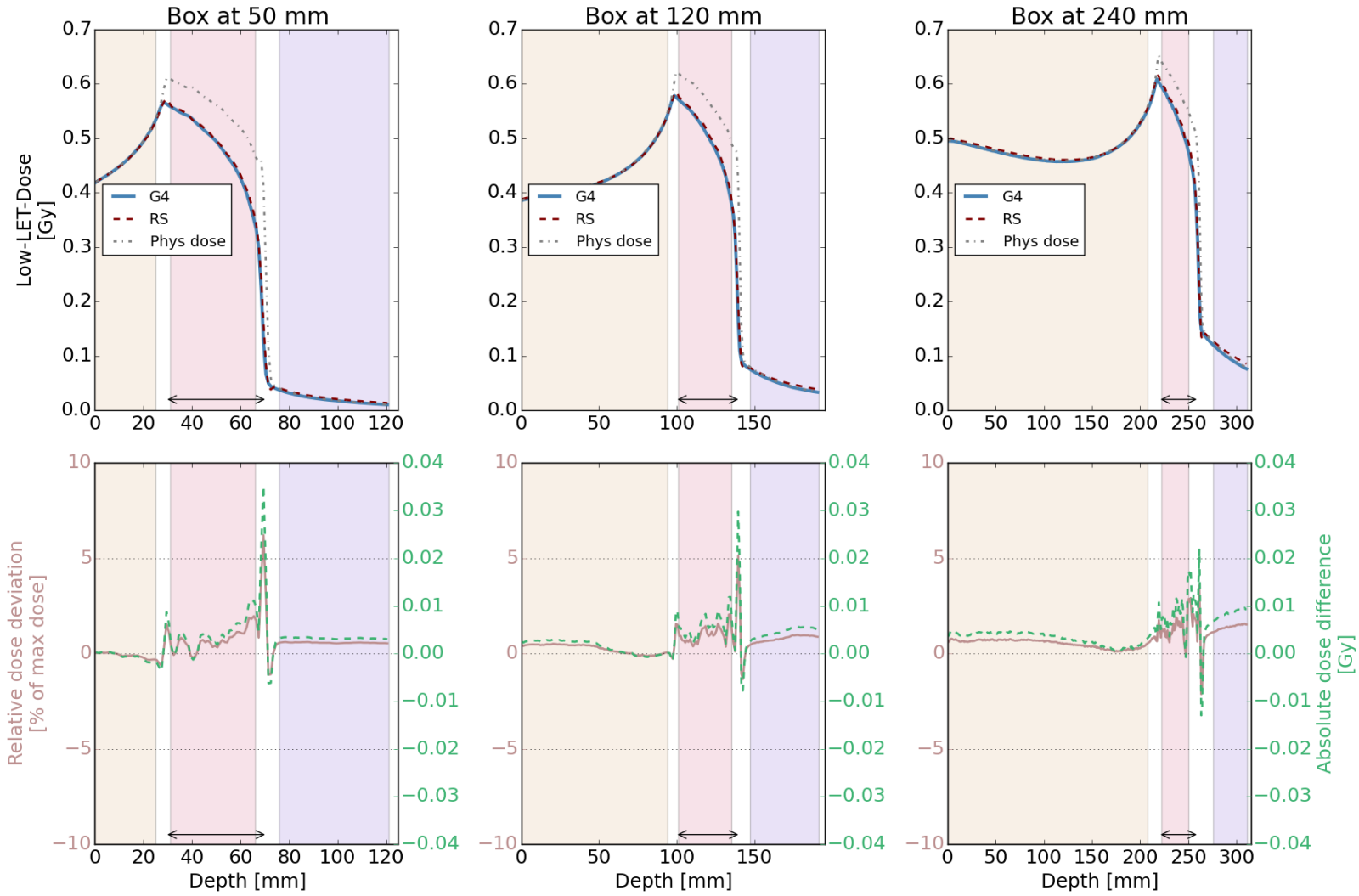
Results: LET_d / setup with heterogeneity



All three regions:

- $\bar{\delta}$ <0.5 keV/um
- δ_{max}= 3.3 keV/um
- $\bar{\Delta}$ <2.5%

Results: LET–based (phys.) dose filtration

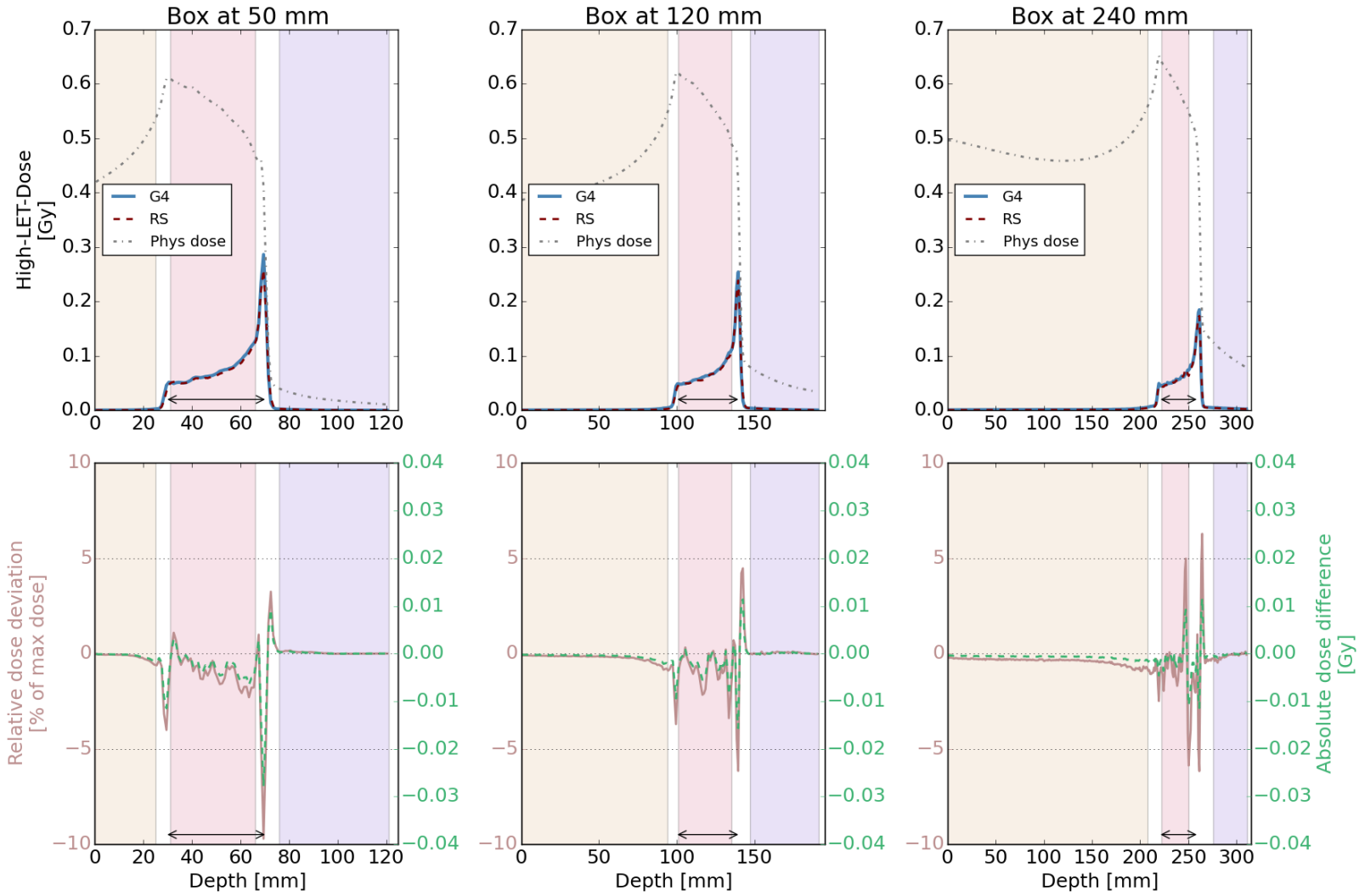


All three regions:

- $\bar{\delta}$ <1 cGy
- δ_{max}= 2 cGy
- $\bar{\Delta}$ <1.5%

***Low*-LET-Dose ($LET_{<100\ keV/\mu m}$)**

Results: LET–based (phys.) dose filtration



All three regions:

- $\bar{\delta}$ <1 cGy
- δ_{max} = 2 cGy
- $\bar{\Delta}$ <1.5%

***High*-LET-Dose ($LET_{\geq 100\ keV/\mu m}$)**

Conclusion

- **LET_d profiles**
  - *Longitudinal:*
    - *Target: agreement within our tolerances ($\bar{\Delta}$ <3.5%)*
    - *Fragmentation tail: deviations increasing with increasing energies*
  - *Transversal:*
    - *Target: good agreement ($\bar{\Delta}$ ≤1.5%)*
    - *Out of field: wrong*
  - *Heterogeneous: LET_d to water conversion consistently implemented*

- **LET filtered dose**
  - *All three regions: good agreement ($\bar{\Delta}$ <1.5%)*

◇ *Independent LET implementation*

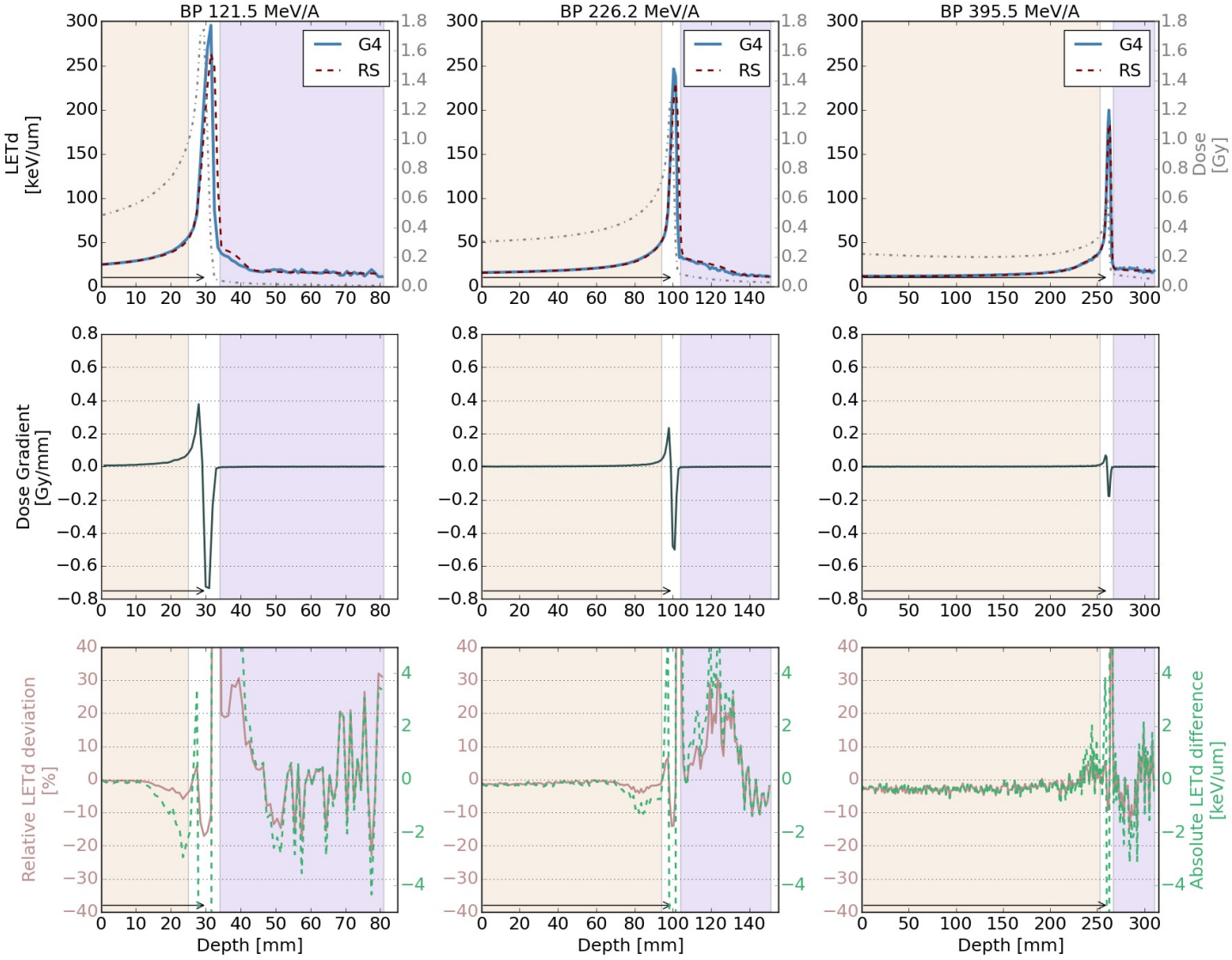
◇ *Different scoring algorithms (PB + FLUKA vs. GATE/Geant4 MC)*

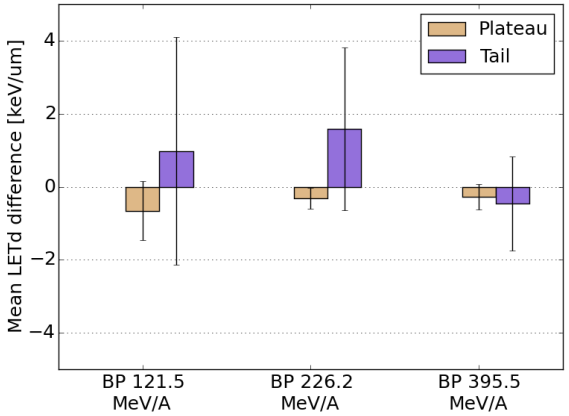
→ *Satisfying agreement*

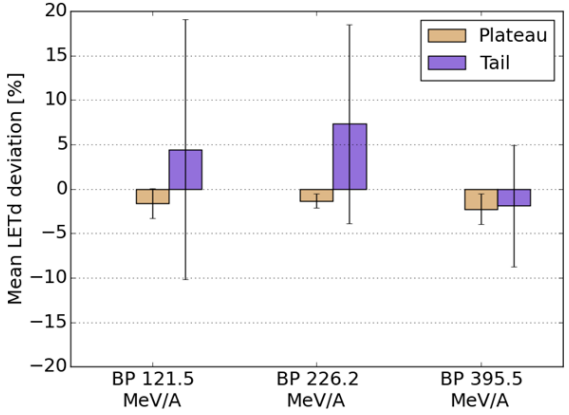
→ *The LET-based functionalities provided in RS can be used for future studies*

Thank you for your attention !

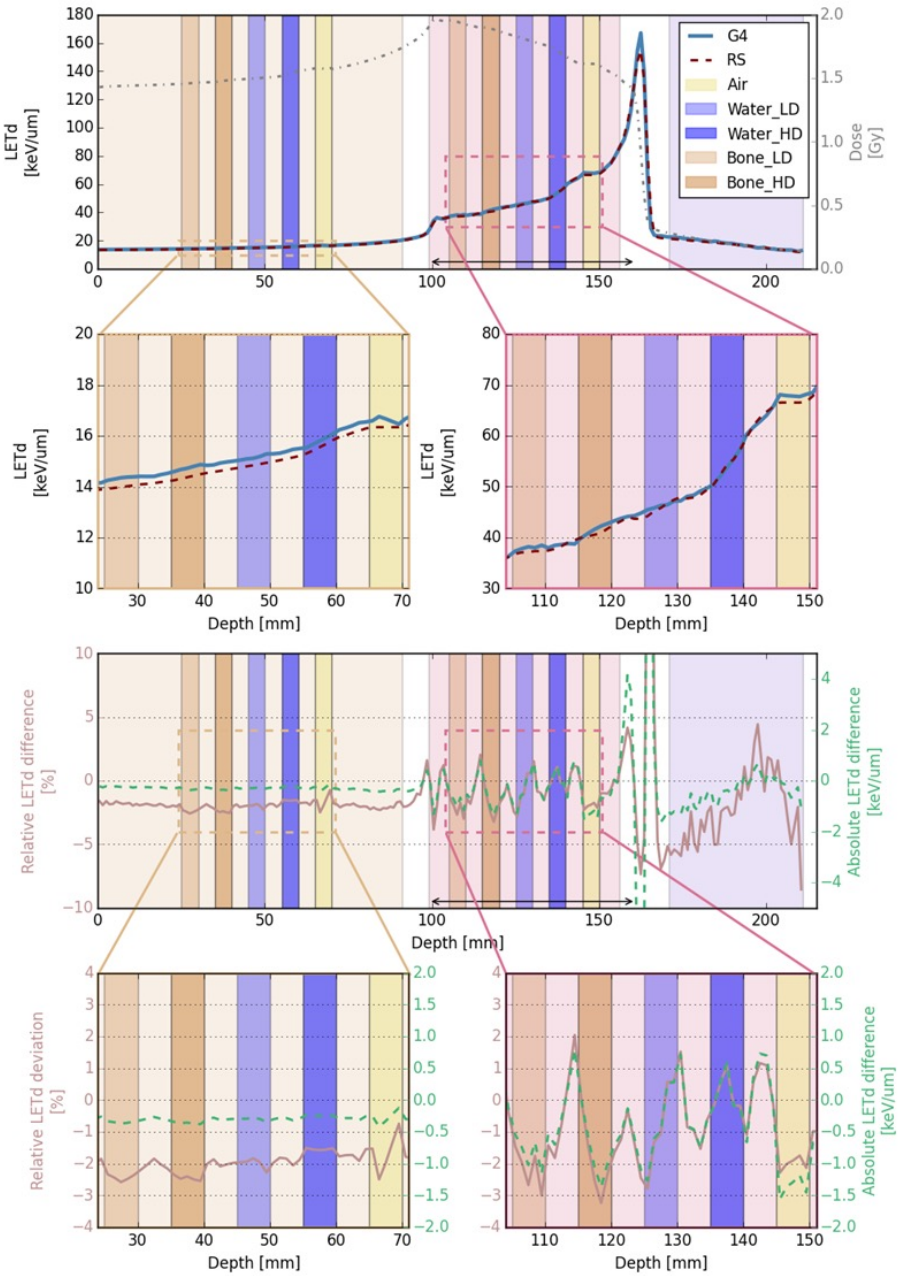
Results: LET_d / BP in water

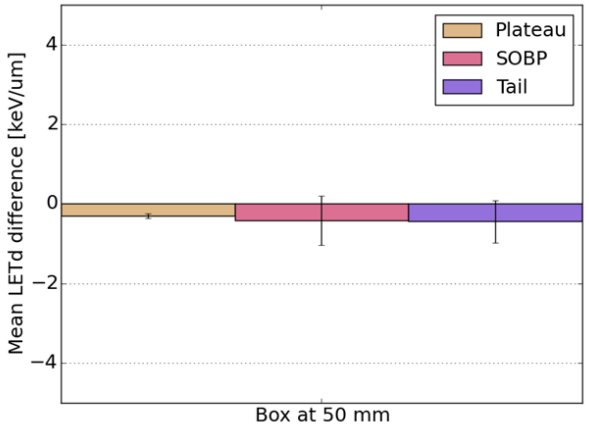


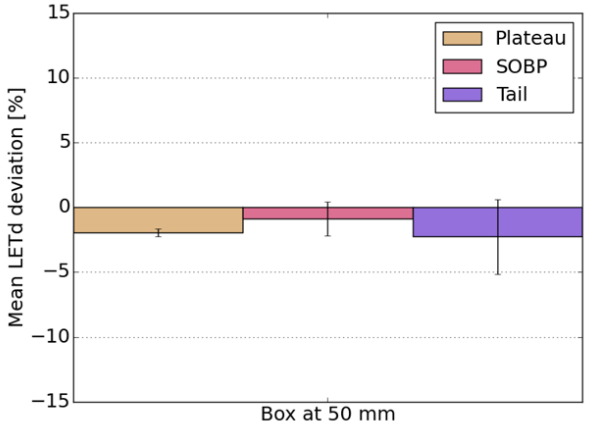




Results: LET_d / SOBP in water + heterogeneity







Results: LET_d per ion type