Fano Test for Therapeutic Carbon and Helium Beams in Magnetic Fields Using Geant4/GATE

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Purpose

MR-guided ion therapy combines highly conformal dose delivery and imaging with superior soft-tissue contrast. However, magnetic fields (MFs) affect the response of air-filled ionization chambers, necessitating derivation of correction factors. In this study, the Fano test was implemented for the first time in GATE/Geant4 for clinical carbon and helium ion beams in a uniform MF to assess the transport accuracy of Monte Carlo (MC) simulations.

Material and Methods

The Fano test was conducted in GATE(v9.4)/Geant4(v11.2.2) using a three-layer cylindrical water phantom with the center being a water column with the density of air. Isotropic and uniform carbon and helium line sources (120 MeV/u, 250 MeV/u, and 400 MeV/u) were simulated along the central axis of the geometry with perpendicular MFs (0.5 T and 1 T). Baseline transport parameters were adapted from Kretschmer et al. [1] and varied systematically based on Blum et al [2]. The Q value, defined as the ratio of the simulated $E_{sim.}$ to the theoretical energy deposition E_0 in the cavity, was calculated.

$$Q = \frac{E_{sim.}}{N \cdot E_0} \cdot \left(1 + \frac{2 \cdot \rho_{water} \cdot z_{water}}{\rho_{air} \cdot z_{air}}\right) \quad (1)$$

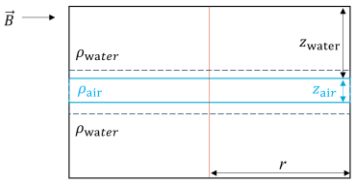

Figure 1. Schematic drawing of the setup, a box encasing the cavity was defined where tighter step parameters could be set to control boundary-crossing artefacts.

Results

Carbon ions pass the Fano test within 0.2% for most beam energy and MF combinations (Fig. 2a), with the highest deviation from unity at 1 T (Q = 0.997 ± 0.0005). Q values decrease with increasing MF strength, consistent with the proton trend reported by Blum et al. For helium ions (Fig. 2b), Q values exhibit a consistent under-response, with a maximum deviation from unity of 0.36% ± 0.04% at 0.5 T. No pronounced energy dependence was observed for either ion.

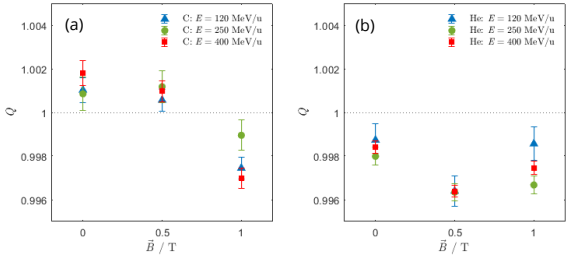

Figure 2. Q values for carbon (a) and helium (b) under varying MFs and energies.

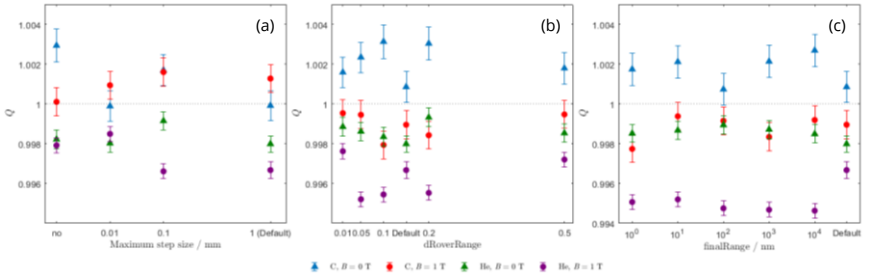

Figure 3. Q values of both ions at B = 0, 1 T for different max. step sizes (a), dRoverRanges (b), and final ranges (c).

At 250 MeV/u, reducing the maximum step size from 1 mm to 0.01 mm or omitting this restriction did not improve the results (Fig. 3a). Varying dRoverRange from 0.01 to 0.5 produced fluctuations (Fig. 3b). Similarly, no clear trend was observed when varying final range from 1 nm to 10 µm (Fig. 3c). For dRoverRange and final range, the influence of the magnetic field is evident, with the Q values at 1 T being generally lower than B = 0 T.

Conclusion

Fano test for carbon and helium ions in magnetic fields achieves agreement within 0.31% ± 0.05% and 0.36% ± 0.04%, respectively. A maximum step size of 1 mm with the default dRoverRange and final range can be used for ionization chamber simulations. Under-response of helium requires further investigation. Fano test in FLUKA is currently underway to benchmark both MC codes.

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References

1. Kretschmer J, Dulkys A, Brodbek L, Stelljes TS, Looe HK, and Poppe B: Monte Carlo simulated beam quality and perturbation correction factors for ionization chambers in monoenergetic proton beams. Med Phys. 47 (2020), S. 5890-5905.
2. Blum I, Wong JS, Padre KG, Stolzenberg J, Fuchs H, Baumann KS, Poppe B, and Looe HK: Fano cavity test and investigation of the response of the Roos chamber irradiated by proton beams in perpendicular magnetic fields up to 1 T, Phys. Med. Biol., 69 (2024).