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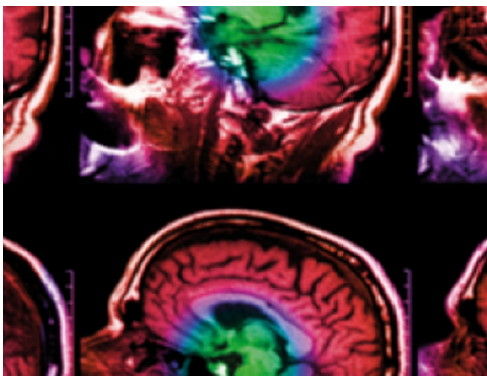
A Geant4 Fano test for novel very high energy electron beams

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PAPER

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Abstract

Objective. The boundary crossing algorithm available in Geant4 10.07-p01 general purpose Monte Carlo code has been investigated for a 12 and 200 MeV electron source by the application of a Fano cavity test. **Approach.** Fano conditions were enforced through all simulations whilst varying individual charged particle transport parameters which control particle step size, ionisation and single scattering. **Main Results.** At 12 MeV, Geant4 was found to return excellent dose consistency within 0.1% even with the default parameter configurations. The 200 MeV case, however, showed significant consistency issues when default physics parameters were employed with deviations from unity of more than 6%. The effect of the inclusion of nuclear interactions was also investigated for the 200 MeV beam and was found to return good consistency for a number of parameter configurations. **Significance.** The Fano test is a necessary investigation to ensure the consistency of charged particle transport available in Geant4 before detailed detector simulations can be conducted.

1. Introduction

The derivation of absorbed dose-to-water from the amount of charge measured in an air-filled ionisation chamber requires, among other steps, a conversion from absorbed dose to the cavity to absorbed dose-to-water. For a calibrated ionisation chamber, the change of this conversion between the calibration beam and the user beam needs to be known and this change is normally embedded in the data used in codes of practice for reference dosimetry. These strict dosimetry protocols are available for all current clinical radiotherapy treatment modalities and are described in detail in the IAEA TRS-398 Code of practice for dosimetry (IAEA 2000). Novel dosimetry techniques such as very high energy electrons (VHEEs) are growing in popularity (DesRosiers *et al* 2000), however, the same detailed reference dosimetry protocols used for clinical techniques do not currently exist.

A recent study by McManus *et al* (2020) using ultra-short pulsed 200 MeV electrons highlighted significant issues which arise in plane-parallel ion chambers due to the lack of traceable dosimetry. One of these elements is the absence of a chamber specific calibration coefficient, $N_{D,w,Q}$, which converts the charge measurement of the chamber into dose-to-water for this beam modality (McManus *et al* 2020). When deriving other ion chamber correction factors such as absolute ion recombination, from direct comparison between an ion chamber measurement and a calorimeter measurement as per the above study, incorrect determination of the calibration coefficient can lead to underestimations of the ion recombination occurring in the chamber or result in unphysical evaluations of ion collection efficiencies greater than 100% (McManus *et al* 2020).

More detailed characterisations of ion chambers must be conducted to ensure the validity of calibration coefficients for novel radiotherapy applications. Monte Carlo (MC) codes can provide accurate calculation of the beam quality correction factor, k_{Q,Q_0} , an essential component of the calibration coefficient of an ionisation chamber exposed to non-reference beams such as VHEEs with an energy of 200 MeV. As chambers are regularly used in non-reference conditions, it is necessary to apply k_{Q,Q_0} to convert between the calibration beam quality

(a beam in which the ionisation chamber has been calibrated under reference conditions), Q_0 , and the user beam quality, Q .

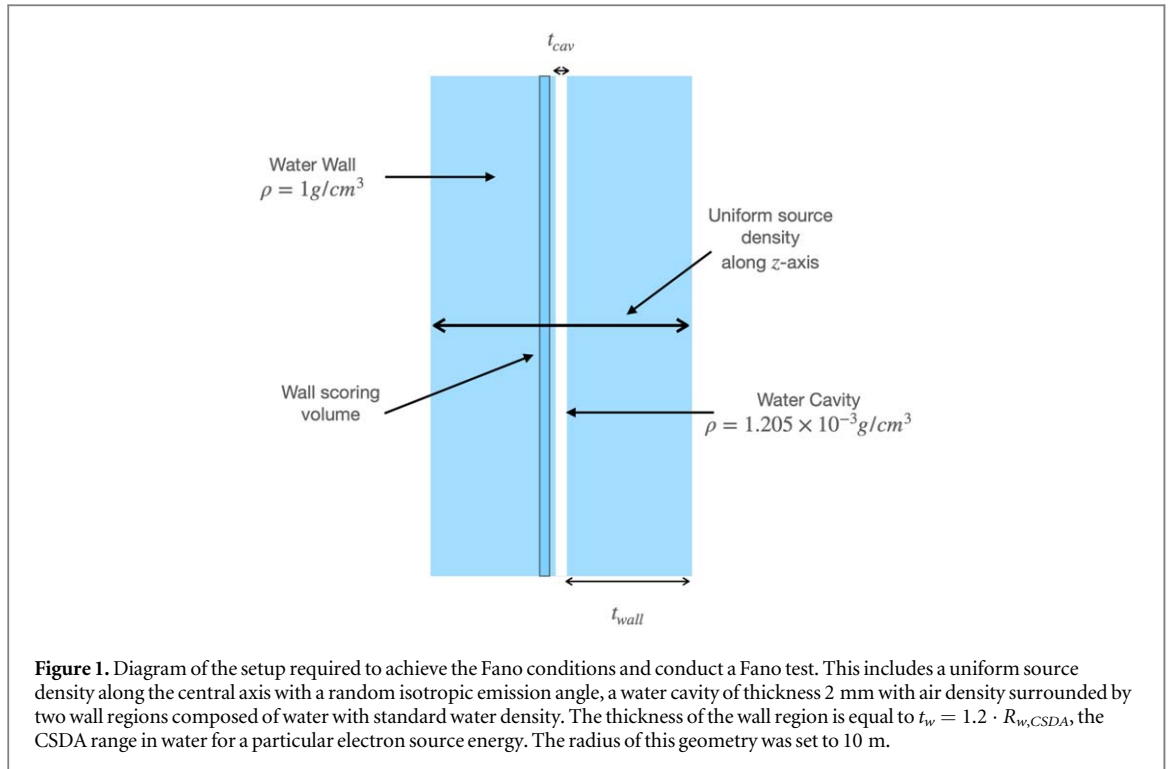
In general, the EGSnrc MC code has been ubiquitous in dosimetric calculations as this code claims greater than 0.1% accuracy in ionisation chamber calculations (Kawrakow 2000). However, EGSnrc can only simulate the electromagnetic (EM) transport of electrons, positrons and photons through matter. At the energy of interest of VHEEs, there is a non-negligible of electro-nuclear interactions, which would not be considered by EGSnrc, and may result in erroneous dose calculations. The Geant4 general purpose MC was subsequently chosen for this investigation including all relevant physical interactions, i.e. EM, hadronic and electron-/photo- nuclear processes (Agostinelli *et al* 2003, Allison *et al* 2006, 2016).

Typically, MC simulations are optimised for geometries where there are large homogeneous bodies with a limited number of boundaries between bodies. This is due to the application of the condensed history (CH) technique where multiple interactions and steps of a particle are grouped into a single averaged step. Ionisation chamber calculations, therefore, are difficult due to their small volumes, multiple boundaries and variable material densities, all of which can negatively affect a CH step. Before calculations of k_{Q,Q_0} can be conducted, the consistency of a MC code must be investigated through the application of a Fano cavity test for both the calibration and user beam quality. This test allows the user to determine the quality of the charged particle transport or if any boundary crossing artefacts are present in the simulation. The principal of the Fano cavity test is that, if the material composition and interaction properties of a medium and the charged particle source density per unit mass are constant, the dose deposited in a medium should remain the same regardless of any local density variations (Fano 1954). In order to pass the Fano test, the consistency in dose must be within 0.1% of unity at a 95% confidence level, corresponding to a $k = 2$ coverage factor assuming a normal distribution. An early Fano study of a photon-electron MC code by Smyth (1986) found up-to a 15% deficit in energy deposit for a graphite cavity exposed to a Co^{60} source (Smyth 1986). The electron transport algorithm in Geant4 has been tested with a Fano example code using a 1.25 MeV photon beam by Poon *et al* (2005), where irregularities in the boundary crossing algorithm showed up-to a 39% reduction in dose to the cavity (Poon *et al* 2005). This study was conducted for Geant4 version 4.6.2-p01, however the electron transport has been greatly improved since then (Allison *et al* 2016). Studies have found that Geant4 passed the Fano test within 0.1% when using a field of protons up-to energies of 250 MeV (Sterpin *et al* 2014, Wulff *et al* 2018). More recent studies of electron transport in Geant4 detail the effect of magnetic field on the consistency for energies up-to 10 MeV and fields of up-to 1.5 T. One study by Simiele and DeWerd (2018) found that the inclusion of magnetic fields increased the discrepancy between theory and simulation from 0.16% to 0.21% (Simiele and DeWerd 2018). In contrast, a study by O'Brien *et al* (2016) found that the Fano test in magnetic fields passed within 0.1% (O'Brien *et al* 2016). There are currently no systematic Fano test studies available for VHEEs. This work aims to investigate the quality of the charged particle transport of VHEEs available in the Geant4 general purpose MC code in order to facilitate the accurate calculation of dosimetric correction factors such as ion chamber perturbation and beam quality correction.

2. Materials and methods

The Fano test was conducted using a modified example code which is bundled with the Geant4 10.07-p01 software, named *fanoCavity2*. Simulations were run on the UCL *Myriad* high performance computer cluster. The geometry of the example is outlined in figure 1. This figure describes an 'infinite' diameter cylindrical chamber with a water cavity enclosed between two wall volumes of water. The radius of the geometry was taken arbitrarily to be 10 m as per the default implementation of the *fanoCavity2* example code. The water cavity has the equivalent thickness of the ionisation chamber of interest, $t_{cav} = 2$ mm, and has the density of air. The wall regions are composed of water with normal water density. Under Fano conditions, the thickness of the wall, t_{wall} is such that charged particle equilibrium (CPE) is achieved across and around the cavity volume for a given particle source energy, and is calculated in the *fanoCavity2* example as $1.2 \cdot R_{w,CSDA}$, the CSDA range of the particle in water. The scoring volume in which the wall dose was calculated within the CPE region was also set to have a width of 2 mm. However, the same dose would have been calculated in any volume size provided it was within the CPE region. The mono-energetic source particles were generated uniformly with respect to region density along the central axis of the geometry and were transported with random isotropic trajectory around the central axis i.e. their initial direction was sampled randomly from an isotropic angular distribution. This setup makes use of the so-called *reciprocity theorem* in which the dose to the detector geometry of figure 1 would be equivalent to that of a small detector exposed to a source of 'infinite' radius (Sempau and Andreo 2006).

The restricted stopping power energy threshold was chosen to be $\Delta = 10$ keV as this is approximately equal to a CSDA range in air of 2 mm. However, as it is not possible in Geant4 to set explicitly a threshold in terms of energy, one must apply a range cut to a particle. The default minimum particle range for secondary particle



production is 1 mm, which corresponds to threshold of approximately $\Delta = 350$ keV in water. Therefore, to achieve a $\Delta = 10$ keV restricted stopping power in both water and air, a global minimum particle range cut of $6.1 \mu\text{m}$ and a lower limit of secondary particle production of 10 keV was set.

Under the conditions of CPE, the dose in the wall material, D_{wall} , should be identical to that of the cavity, D_{cav} . The expected dose deposited can be theoretically calculated, D_{theory} , from the initial source energy in joules, E_0 , and the number of particle histories per total geometry mass, N (Sempau and Andreo 2006, Lee et al 2018):

$$D_{theory} = NE_0 . \quad (1)$$

The Geant4 code allows the user to fine tune almost every parameter relating to the transport of particles through media. These include: particle energy thresholds, fluctuations in stopping power, the use of Mott scattering as well as functions which control the step size at boundaries. There are four main parameters which can be used to affect the step size at boundaries.

- **Step Function:** The step function is a parameter in Geant4 which allows the user to define the step size of the particle at a boundary, and the fractional step size reduction per step as the particle approaches a boundary, dR/R .
- **Range Factor:** The Range Factor, f_r , is a parameter which restricts the step size of the first step a particle takes in a new volume. The step size is restricted by $f_r \cdot \max(\text{Range})$.
- **Geometry Factor:** Similarly to the Range Factor, the Geometry Factor, f_g , restricts the first step size in a new volume with respect to the distance to the next boundary, d_{geom} . The step size cannot be larger than the value of d_{geom}/f_g .
- **Skin:** The skin parameter affects the Geant4 boundary crossing algorithm which does not allow large steps to occur immediately before and after a boundary. Moreover, single scattering is employed within a defined volume around a boundary.

Another part of the *Step Function* parameters is the *finalRange* which controls the step size at a boundary, however reducing this value from its default $10 \mu\text{m}$ resulted in significantly longer simulation time and as a result was not varied throughout this investigation. More detailed information can be found in the Geant4 Physics Reference Manual (Geant4 Collaboration 2020).

Geant4 has implemented a number of default EM physics transport codes which have varying degrees of complexity. A recent and advanced code, designed to achieve error free boundary crossing, is the *G4EmStandardPhysics-Option4* physics list. This physics list has defaults for the above parameters of, $dR/R = 0.2$, $f_r = 0.08$, $f_g = 2.5$ and $skin = 3$.

The multiple scattering (MSC) and ionisation models implemented in the option-4 physics list are also important parameters to consider when testing the charged particle transport of a MC code. There are a number of default ionisation models tailored to defined energy ranges. In the option-4 EM physics list, the default ionisation models for electrons are the *Livermore* (LIV) ionisation model for energies below 0.1 MeV and the *Möller-Bhabha* (MB) model for all other energies. Default MSC models include the *Goudsmit-Saunderson* (GS) model for energies below 100 MeV and the *Wentzel VI* (WVI) model for all larger energies. The GS model is applicable to electron and positron transport with highest consistency for electrons below 100 MeV, whilst the WVI model is applied to all charged particles with energies above 100 MeV.

Caveats to the Fano test are that the density effect associated with the calculation of mass stopping power must be removed such that the mass stopping power is unchanged between the cavity and the wall (which was confirmed at the beginning of each simulation through commands within the Geant4 source code), and also radiative interactions such as bremsstrahlung must be turned off. These restrictions were applied to both ionisation models.

For this study the calibration beam energy was 12 MeV, with a VHEE user beam energy of 200 MeV, as was employed in the absolute dosimetry study by McManus *et al* (2020). Electron-nuclear interactions were considered for the VHEE case as there is a probability for these high energy particles to produce other heavy charged particles such as protons. For this the Geant4 *QBBC* reference physics list was used. This list is recommended for medical and space physics applications and implements the Binary Cascade Model for proton energies between 0 and 1.5 GeV. Photo-nuclear interactions are controlled by the Bertini Cascade Model below 6 GeV with the nuclear interaction of electrons and positrons being mediated by a virtual photon.

3. Results

Figure 2 shows the Fano test results for the cavity-wall, D_{cav}/D_{wall} dose ratio of the 12 MeV calibration beam for varying transport parameters, with the default parameter configuration shown as the red crosses. The wall thickness was calculated to be $t_{wall} = 6.859$ cm to ensure CPE was present around the cavity and wall scoring volume. The implementation of both *Möller-Bhabha* and *Livermore* ionisation models returned a restricted mass stopping power (RSP) at 12 MeV of approximately $L(E, \Delta) = 1.6845 \text{ MeV cm}^2 \text{ g}^{-1}$ with $\Delta = 10$ keV.

Figure 2(a) shows the variations of the dose ratio with f_r . With decreasing f_r , the step size of the initial step in the cavity volume decreased. Uncertainties are shown with a $k = 2$ coverage factor (95% confidence level) with an approximate relative uncertainty of 0.12%. All ratios passed the Fano test within 0.1% of unity, however, due to the lack of statistical significance, it was difficult to distinguish the effect of f_r on the dose ratio.

The variation of the cavity-wall dose ratio with geometry factor, f_g , can be seen in figure 2(b). Increasing from the default value to $f_g = 3$ also returned good consistency and passed at $k = 2$. The ratio at $f_g = 3.2$ showed a mean dose ratio outside of 0.1% of unity and therefore did not pass (DNP) despite uncertainties covering unity at $k = 2$ coverage. Similarly, $f_g = 3.5$ and 4 DNP the Fano test.

Figure 2(c) shows the *skin* parameter effect on the cavity-wall dose ratio. Values of *skin* = 1, 3 and 5 returned excellent agreement at $k = 2$ and passed the Fano test. The *skin* = 3.5 consistency, however, DNP the Fano test within uncertainties and showed almost 0.2% deviation from unity.

Finally, the dR/R parameter is considered in figure 2(d). Increasing dR/R increases the fractional step size reduction per step as a particle approaches a boundary. All values of dR/R investigated passed the Fano test within uncertainties at $k = 2$, except for $dR/R = 0.1$ which DNP the Fano test.

Plots in figure 3 show the 12 MeV cavity-theoretical dose ratio, D_{cav}/D_{theory} , as described by figure 1. In order for a particular set of transport parameters to pass the Fano test, both the cavity-wall and cavity-theoretical dose ratios must provide a ratio within 0.1% of unity with uncertainties at $k = 2$ coverage, where the relative uncertainty on the dose ratio was approximately 0.12%.

Generally, the cavity-theoretical dose ratio followed a similar trend to that of the cavity-wall dose ratios. Passing configurations included all values of $f_r, f_g = 3, skin = 1, 5$ and $dR/R = 0.4, 0.8, 1$. A summary of the transport parameters which passed the Fano test overall can be found in table 1 along with their associated uncertainty at a $k = 2$ coverage.

For the 200 MeV case, the restricted stopping power was calculated to be $L(E, \Delta) = 2.1544 \text{ MeV cm}^2 \text{ g}^{-1}$ with the wall thickness being calculated as $t_{wall} = 88.747$ cm. As described previously, the default energy boundary between the GS and WVI MSC models is 100 MeV. However, Fano tests using this default energy resulted in a greater than 6% deviation from unity for both the cavity-wall and cavity-theoretical dose ratios regardless of transport parameter configuration. As the GS model is considered more accurate for the transport of electrons, the energy boundary was increased to 175 MeV, whereby only the highest of particle energies were treated by the WVI model which is used for large angle scattering. This resulted in more consistent dose results similar to that of the 12 MeV case. Plots in figures 4 and 5 show again the default parameter configuration as the

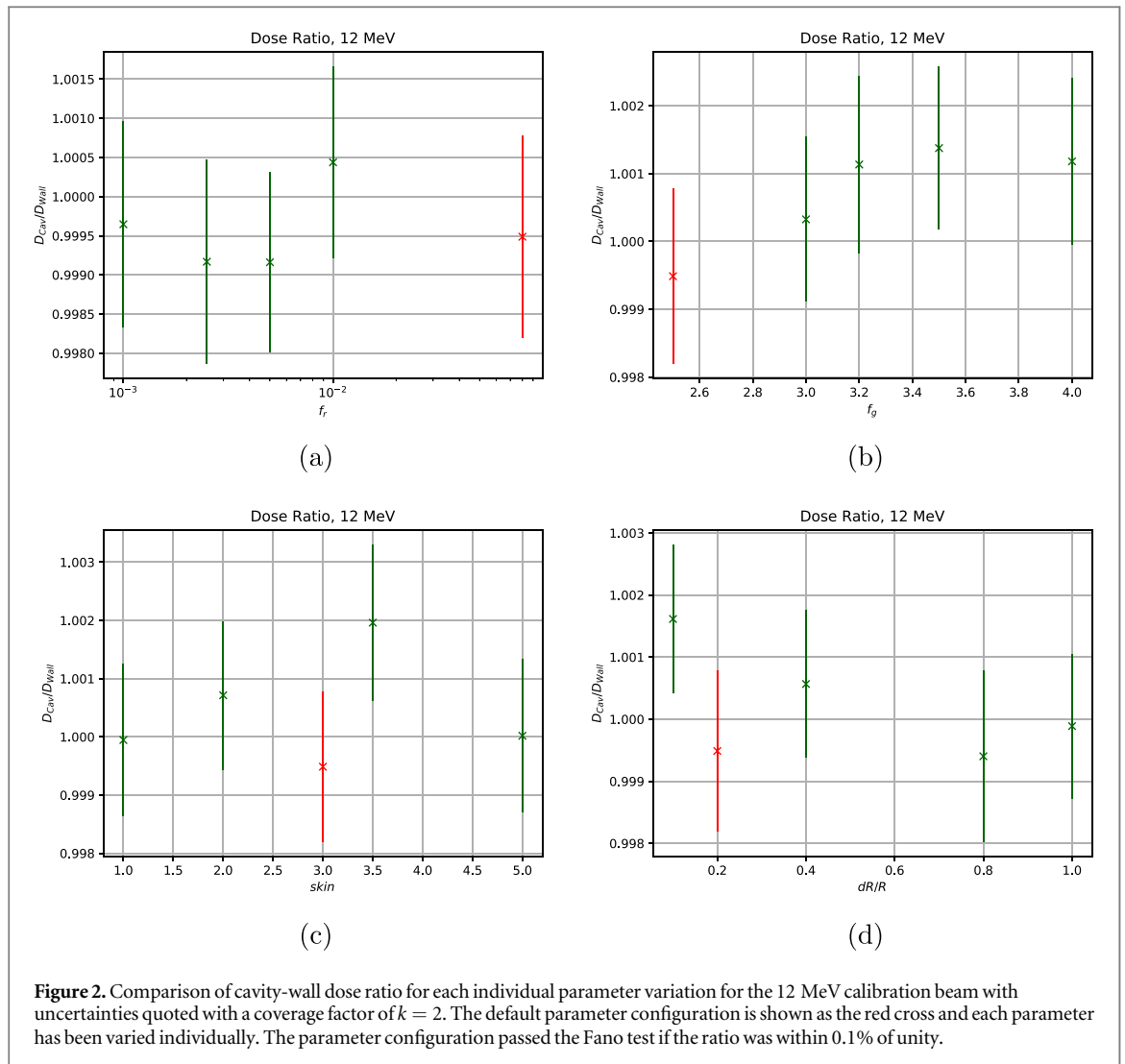


Figure 2. Comparison of cavity-wall dose ratio for each individual parameter variation for the 12 MeV calibration beam with uncertainties quoted with a coverage factor of $k = 2$. The default parameter configuration is shown as the red cross and each parameter has been varied individually. The parameter configuration passed the Fano test if the ratio was within 0.1% of unity.

red crosses, however the default is now considered to include the MSC energy boundary of 175 MeV. The orange crosses represent the dose ratios where nuclear interactions were included with the *QBBC* reference physics list. Again, all relative uncertainty values in figures 4 and 5 are given at a $k = 2$ coverage.

The cavity-wall dose ratio for the 200 MeV case can be seen in figure 4. Considering first the EM physics implementation only (red and green crosses), the default configuration with the 175 MeV MSC boundary DNP the Fano test within 0.1%. Decreasing f_r , shown in figure 4(a), to 0.01 resulted in an increase in the cavity dose compared to the wall dose such that this configuration passed. Unexpectedly, $f_r = 0.005$ showed a large deviation from unity of approximately 2.5%, however, reducing f_r further to 0.0025, dose consistency was restored and the Fano test passed.

The variation of f_g is shown in figure 4(b). Reducing f_g to 2 resulted in a configuration which DNP within 0.1%, however $f_g = 1$ passed the Fano test within uncertainties at $k = 2$. Increasing to $f_g = 3$ also returned a passing dose ratio within uncertainties.

For the *skin* parameter, figure 4(c), the only configurations which were found to pass within 0.1% at a $k = 2$ coverage were $skin = 4$ and 5.

The dR/R parameter can be seen in figure 4(d). Minimal variation from unity in the dose ratio was observed for values of $dR/R = 0.1$ and 0.4, both of which passed the Fano test at $k = 2$. However, $dR/R = 0.8$ showed a larger cavity dose contribution leading to a ratio which DNP within 0.1% of unity.

When implementing the *QBBC* nuclear physics list alongside the the EM option-4 list (orange crosses) the cavity-wall dose ratio consistency showed less fluctuation and, in general, less deviation from unity in comparison to the same parameter configuration with only the EM physics list. With the exception of $dR/R = 0.8$, all parameter configurations were found to pass the Fano test within 0.1% at a coverage of $k = 2$.

The cavity-theoretical dose ratios can be seen in figure 5. Again, theoretical dose ratios followed a similar trend to the cavity-wall case showing only minimal (around 0.05%) variations in the average cavity-theoretical

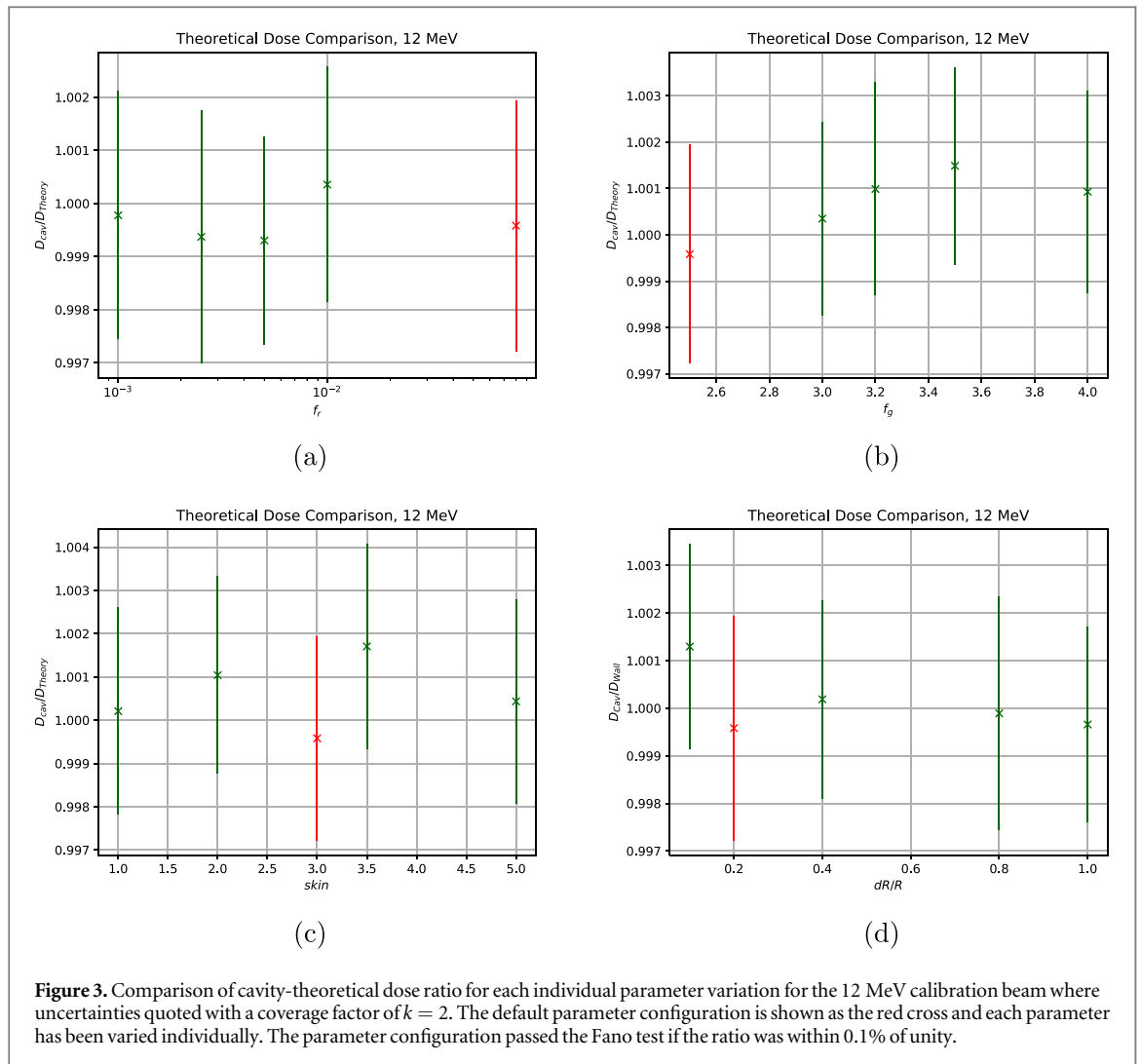


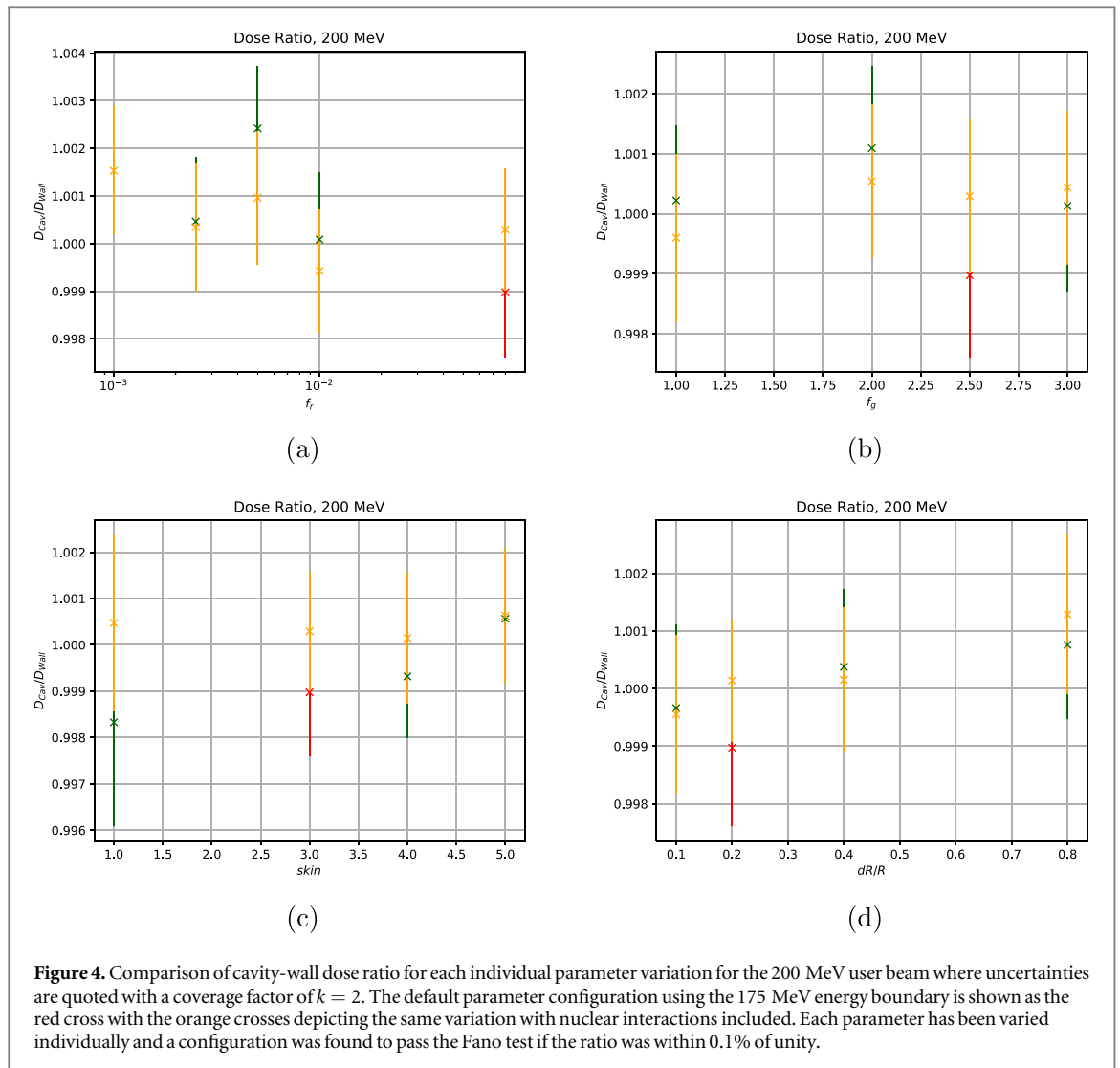
Figure 3. Comparison of cavity-theoretical dose ratio for each individual parameter variation for the 12 MeV calibration beam where uncertainties quoted with a coverage factor of $k = 2$. The default parameter configuration is shown as the red cross and each parameter has been varied individually. The parameter configuration passed the Fano test if the ratio was within 0.1% of unity.

Table 1. All configurations for the 12 MeV calibration beam which passed the Fano test within 0.1% of unity with a coverage factor of $k = 2$. Relative uncertainties are quoted here in brackets at the $k = 2$ coverage level.

12 MeV Fano test		
Transport parameter	D_{cav}/D_{wall}	D_{cav}/D_{theory}
Default	0.9995 (0.13%)	0.9996 (0.12%)
$f_r = 0.01$	1.0004 (0.12%)	1.0004 (0.11%)
$f_r = 0.005$	0.9992 (0.12%)	0.9993 (0.10%)
$f_r = 0.0025$	0.9992 (0.13%)	0.9994 (0.12%)
$f_r = 0.001$	0.9996 (0.13%)	0.9998 (0.12%)
$f_g = 3$	1.0003 (0.12%)	1.0004 (0.10%)
$skin = 1$	0.9999 (0.13%)	1.0002 (0.12%)
$skin = 5$	1.0000 (0.13%)	1.0004 (0.12%)
$dR/R = 0.4$	1.0006 (0.12%)	1.0002 (0.10%)
$dR/R = 0.8$	0.9994 (0.13%)	0.9999 (0.12%)
$dR/R = 1$	0.9999 (0.12%)	0.9997 (0.10%)

dose ratio compared to the cavity-wall. Unlike the cavity-wall case, all parameter configurations, with nuclear interactions included, passed the Fano test within 0.1% of unity.

All passing configurations of the 200 MeV VHEE beam, with and without nuclear interactions included, are shown in table 2. This table also shows configurations which DNP. This allows one to compare cases where the inclusion of nuclear interactions resulted in a passing Fano test, whilst the use of EM physics only did not.



Moreover, in cases such as $f_g = 2$ and $dR/R = 0.8$, where the cavity-wall dose ratio DNP within 0.1% but the cavity-theoretical ratio did pass, the overall Fano test result was considered not to pass.

The calculation of D_{cav} and D_{wall} were obtained from separate simulations, each with 10^6 histories, spread over 1000 parallel processes, resulting in a total of 10^9 histories. The total computational simulation time for the 12 MeV beam was approximately 248 CPU hours per dose calculation, with the 200 MeV case using approximately 3000 CPU hours per dose calculation.

4. Discussion and conclusions

A detailed Fano test of both a 12 MeV calibration beam and a novel 200 MeV VHEE source has been conducted in the Geant4 MC code. Several parameters integral to the charged particle transport were varied and the most consistent parameter configurations determined. Geant4 has been shown to deliver excellent dose consistency across geometry boundaries of varying density for a number of EM transport parameter configurations at both clinical and novel VHEE energies. Each transport parameter was varied individually from default such that their impact on the dose consistency could be determined. Doubtless, various other combinations of transport parameters would also pass the Fano test, however, their individual impact on the Fano test result would be more difficult to identify. This study has shown that there are a variety of parameter configurations one can use in order to conduct an accurate ion chamber simulation using Geant4 at both 12 and 200 MeV.

For the clinical 12 MeV beam energy, the current default option-4 EM physics list showed good consistency and passed the Fano test within 0.1% of unity for both the cavity-wall and cavity-theoretical dose ratios. The Range Factor, f_r , showed the least effect on the dose ratio at 12 MeV, where at a $k = 2$ coverage level, it became difficult to distinguish between values. The remaining parameters showed larger deviations, greater than 0.1%, from unity for a number of parameter values. Within $k = 2$ uncertainties, all theoretical dose ratios calculated for

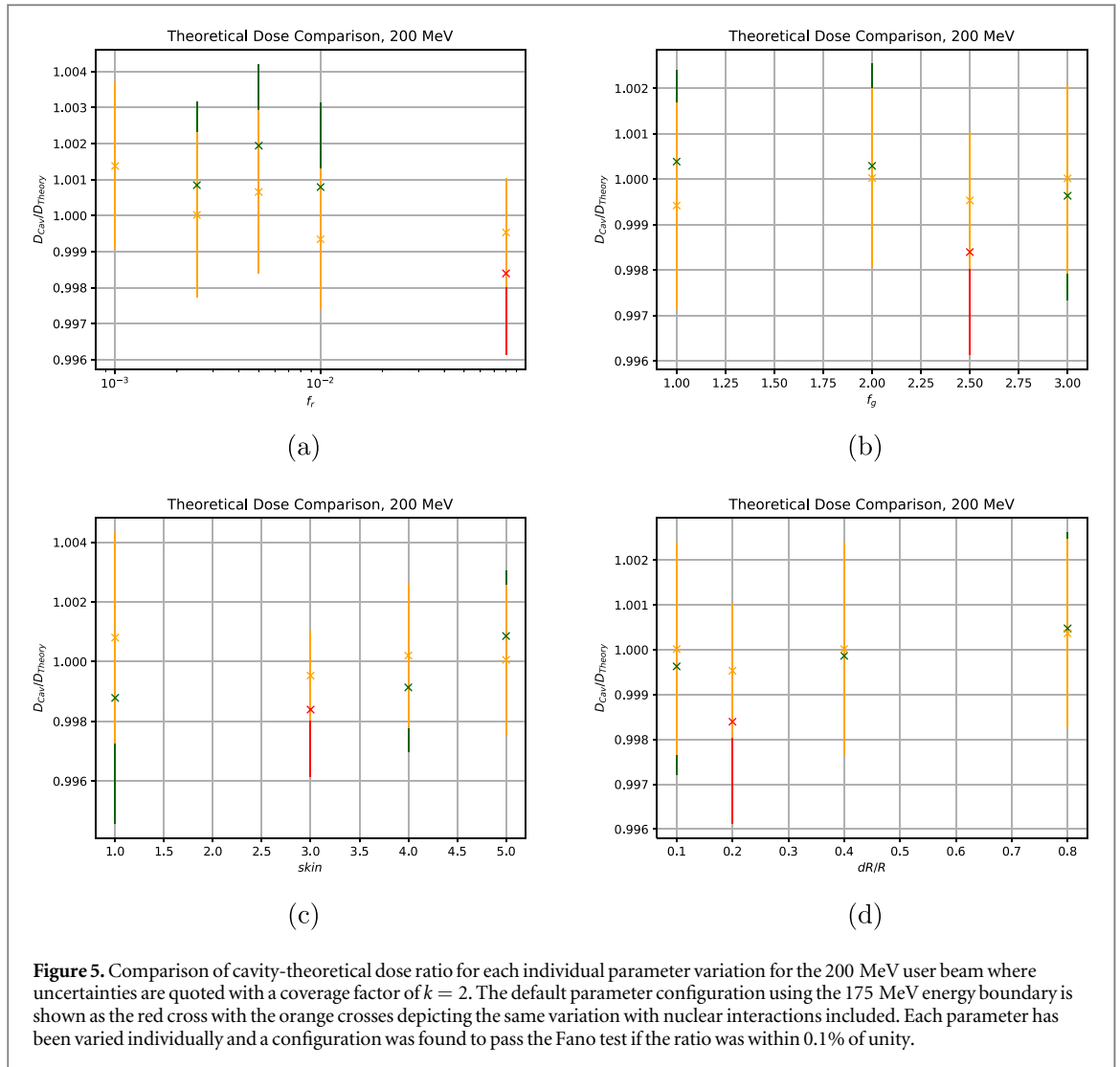


Figure 5. Comparison of cavity-theoretical dose ratio for each individual parameter variation for the 200 MeV user beam where uncertainties are quoted with a coverage factor of $k = 2$. The default parameter configuration using the 175 MeV energy boundary is shown as the red cross with the orange crosses depicting the same variation with nuclear interactions included. Each parameter has been varied individually and a configuration was found to pass the Fano test if the ratio was within 0.1% of unity.

Table 2. All configurations for the 200 MeV user beam which passed the Fano test within 0.1% of unity with a coverage factor of $k = 2$, with and without nuclear interactions included. Relative uncertainties are quoted here in brackets at the $k = 2$ coverage level.

Transport parameter	200 MeV Fano test			
	No nuclear interactions		Nuclear interactions included	
	D_{cav}/D_{wall}	D_{cav}/D_{theory}	D_{cav}/D_{wall}	D_{cav}/D_{theory}
Default	DNP	DNP	1.000 29 (0.12%)	0.999 53 (0.08%)
$f_r = 0.01$	1.000 09 (0.13%)	1.000 79 (0.12%)	0.999 40 (0.13%)	0.999 34 (0.10%)
$f_r = 0.005$	DNP	DNP	1.000 97 (0.14%)	1.000 65 (0.13%)
$f_r = 0.0025$	1.000 46 (0.14%)	1.000 85 (0.12%)	1.000 35 (0.13%)	1.000 02 (0.11%)
$f_g = 1$	1.000 22 (0.12%)	1.000 39 (0.10%)	0.999 60 (0.14%)	0.999 42 (0.11%)
$f_g = 2$	DNP	1.000 29 (0.11%)	1.000 54 (0.13%)	1.00003 (0.10%)
$f_g = 3$	1.000 13 (0.14%)	0.999 64 (0.11%)	1.000 44 (0.13%)	1.000 02 (0.10%)
$skin = 1$	DNP	DNP	1.000 47 (0.19%)	1.000 81 (0.18%)
$skin = 4$	0.999 32 (0.12%)	0.999 14 (0.11%)	1.000 15 (0.14%)	1.000 20 (0.12%)
$skin = 5$	1.000 56 (0.13%)	1.000 86 (0.11%)	1.000 63 (0.15%)	1.000 06 (0.13%)
$dR/R = 0.1$	0.999 66 (0.15%)	0.999 63 (0.12%)	0.999 55 (0.14%)	1.000 02 (0.12%)
$dR/R = 0.4$	1.000 38 (0.13%)	0.999 87 (0.11%)	1.000 15 (0.13%)	1.000 02 (0.12%)
$dR/R = 0.8$	1.000 76 (0.13%)	1.000 48 (0.11%)	DNP	1.000 37 (0.11%)

the 12 MeV case showed almost the same average dose ratios as the cavity-wall dose ratio. Regardless of whether the configuration passed the Fano test, this provided confidence that Geant4 was calculating the expected dose accurately between geometries of varying density.

For the 200 MeV VHEE user beam, the option-4 EM physics list in its default form, with a 100 MeV MSC energy boundary, was shown to cause significant consistency issues with dose ratios of greater than 6% deviation from unity. Preliminary investigations found that increasing this MSC energy boundary to 175 MeV improved consistency greatly, however, the use of the remaining default parameters did not result in a passing configuration. Using the EM physics list only showed increased dose ratio variation, with four configurations found not to pass within 0.1%, in comparison to the inclusion of the nuclear physics list, which resulted in all but one configuration passing within 0.1%. The observed increase in consistency when nuclear interactions were included may result from the fact that the artefacts which cause particles not pass the Fano conditions will have smaller effect for ions than for electrons because of the much larger ionisation density and the much smaller angular deflections they experience. Thus, if the fraction of dose deposited by ions becomes larger, the deviations from Fano conditions becomes smaller.

In the case of $f_g = 2$ and $dR/R = 0.8$, the Fano test was found to pass only for the cavity-theoretical ratio and not the cavity-wall ratio. This indicates that whilst the calculation of the cavity dose in Geant4 was accurate, the boundary crossing between regions of different density was not correct for those particular parameters to achieve a passing ratio.

With the more regular development and availability of novel and non-reference beam qualities for radiation therapy applications, Geant4 could provide accurate particle transport for applications outside the scope of other MC codes such as EGSnrc. From the success of the Fano test of Geant4 for both the clinical and VHEE source energies, it is now possible to continue to the calculation of ion chamber perturbation and beam quality correction factors, using the above passing parameter configurations, such that the development of traceable dosimetry for VHEEs can accelerate its translation to the clinical setting.

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References

- Allison J et al 2016 Recent developments in Geant4 *Nucl. Instrum. Methods Phys. Res. A* **835** 186–225
- Agostinelli S et al 2003 Geant4a simulation toolkit *Nucl. Instrum. Methods Phys. Res. A* **506** 250–303
- Allison J et al 2006 Geant4 developments and applications *IEEE Trans. Nucl. Sci.* **53** 270–8
- DesRosiers C, Moskvina V, Bielajew A F and Papiez L 2000 150–250 MeV electron beams in radiation therapy *Phys. Med. Biol.* **45** 1781
- Fano U 1954 Note on the Bragg–Gray cavity principle for measuring energy dissipation *Radiat. Res.* **1** 237–40
- Geant4 Collaboration 2020 Physics Reference Manual, Release 10.7, Rev5.0
- IAEA 2000 *Absorbed dose determination in external beam radiotherapy* Technical Reports Series No. 398
- Kawrakow I 2000 Accurate condensed history Monte Carlo simulation of electron transport: I. EGSnrc, the new EGS4 version *Med. Phys.* **27** 485–98
- Lee J, Lee J, Ryu D, Lee H and Ye S-J 2018 Fano cavity test for electron Monte Carlo transport algorithms in magnetic fields: comparison between EGSnrc, PENELOPE, MCNP6 and Geant4 *Phys. Med. Biol.* **63** 195013
- McManus M, Romano F, Lee N D, Farabolini W, Gilardi A, Royle G, Palmans H and Subiel A 2020 The challenge of ionisation chamber dosimetry in ultra-short pulsed high dose-rate very high energy electron beams *Sci. Rep.* **10** 1–11
- O'Brien D J, Roberts D A, Ibbott G S and Sawakuchi G O 2016 Reference dosimetry in magnetic fields: formalism and ionization chamber correction factors *Med Phys* **43** 4915–27
- Poon E, Seuntjens J and Verhaegen F 2005 Consistency test of the electron transport algorithm in the GEANT4 Monte Carlo code *Phys. Med. Biol.* **50** 681
- Smyth V G 1986 Interface effects in the Monte Carlo simulation of electron tracks *Med. Phys.* **13** 196–200
- Simiele E and DeWerd L 2018 On the accuracy and efficiency of condensed history transport in magnetic fields in GEANT4 *Phys. Med. Biol.* **63** 235012
- Sterpin E, Sorriaux J, Souris K, Vynckier S and Bouchard H 2014 A Fano cavity test for Monte Carlo proton transport algorithms *Med. Phys.* **41** 011706

- Sempau J and Andreo P 2006 Configuration of the electron transport algorithm of PENELOPE to simulate ion chambers *Phys. Med. Biol.* **51** 3533–48
- Wulff J, Baumann K-S, Verbeek N, Bäumer C, Timmermann B and Zink K 2018 TOPAS/Geant4 configuration for ionization chamber calculations in proton beams *Phys. Med. Biol.* **63** 115013