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Original paper

Monte Carlo calculated ionization chamber correction factors in clinical proton beams – deriving uncertainties from published data

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ABSTRACT

For the update of the IAEA TRS-398 Code of Practice (CoP), global ionization chamber factors (f_Q) and beam quality correction factors (k_Q) for air-filled ionization chambers in clinical proton beams have been calculated with different Monte Carlo codes. In this study, average Monte Carlo calculated f_Q and k_Q factors are provided and the uncertainty of these factors is estimated.

Average f_Q factors in monoenergetic proton beams with energies between 60 MeV and 250 MeV were derived from Monte Carlo calculated f_Q factors published in the literature. Altogether, 195 f_Q factors for six plane-parallel and three cylindrical ionization chambers calculated with PENH, FLUKA and GEANT4 were incorporated. Additionally, a weighted standard deviation of f_Q factors was calculated, where the same weight was assigned to each Monte Carlo code.

From average f_Q factors, k_Q factors were derived and compared to the values from the IAEA TRS-398 CoP published in 2000 as well as to the values of the upcoming version.

Average Monte Carlo calculated f_Q factors are constant within 0.6% over the energy range investigated. In general, the different Monte Carlo codes agree within 1% for low energies and show larger differences up to 2% for high energies. As a result, the standard deviation of f_Q factors increases with energy and is ~0.3% for low energies and ~0.8% for high energies.

k_Q factors derived from average Monte Carlo calculated f_Q factors differ from the values presented in the IAEA TRS-398 CoP by up to 2.4%. The overall estimated uncertainty of Monte Carlo calculated k_Q factors is ~0.5%–1% smaller than the uncertainties estimated in IAEA TRS-398 CoP since the individual ionization chamber characteristics (e.g. fluence perturbations) are considered in detail in Monte Carlo calculations. The agreement between Monte Carlo calculated k_Q factors and the values of the upcoming version of IAEA TRS-398 CoP is better with deviations smaller than 1%.

1. Introduction

Currently, the IAEA TRS-398 Code of Practice (CoP) [1] is being updated [2,3]. In the upcoming version, Monte Carlo calculated global ionization chamber factors (f_Q) and beam quality correction factors (k_Q)[1] for various air-filled ionization chambers and beam qualities will be taken into account to provide recommended k_Q factors [4]. In recent studies [5–10], f_Q as well as k_Q factors in clinical proton beams have been calculated with the use of the Monte Carlo codes PENH [11], GEANT4 [12] and FLUKA [13–15]. It has been shown that all three Monte Carlo codes are able to calculate k_Q factors in clinical proton beams in agreement with experimental values within 1.5%. In general, the agreement between the individual Monte Carlo codes is better for low energies, whereas a larger divergence can be observed for high energies.

In this study, we provide average Monte Carlo calculated f_Q factors derived from already published data and estimate the uncertainty of

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[1] Note that the beam quality correction factor is typically denoted as k_{Q,Q_0}. However, when ^{60}Co radiation is used for calibration – which is the case for all factors investigated in this study – the subscript Q_0 can be omitted.

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these average factors. The main goal is to investigate the overall uncertainty of Monte Carlo calculated f_Q factors and the contribution of type-A and type-B uncertainties. Furthermore, k_Q factors are calculated from average Monte Carlo calculated f_Q factors and compared to the values presented in the IAEA TRS-398 CoP published in 2000 as well as the values recently published by Palmans et al. [4]. Palmans et al. [4] derived k_Q factors in clinical proton beams from experimentally determined and Monte Carlo calculated factors published in the literature that will be included in the upcoming version of the IAEA TRS-398 CoP. However, the authors used a different approach as presented in this study.

2. Materials and methods

2.1. Description of the studies included in the data analysis

The studies by Wulff et al. [6], Gomà and Sterpin [7], Baumann et al. [8], Kretschmer et al. [9] and Baumann et al. [10] were included for the calculation of average f_Q factors in clinical proton beams.

Wulff et al. [6] used the toolkit TOPAS [16] based on the Monte Carlo code GEANT4 version 10.03.p1 to calculate f_Q factors for the air-filled ionization chambers IBA NACP-02 and NE 2571 at proton energies between 70 MeV and 250 MeV. The authors compared two different hadronic interaction models (binary cascade and Bertini cascade [17,18]) with resulting differences of 0.3% at maximum. For the determination of average f_Q factors, we used the f_Q factors calculated with the default binary cascade model since this is the model applied in the other GEANT4-based studies.

Gomà and Sterpin [7] employed PENH, an extension of the Monte Carlo code PENELOPE [19], that includes the transport of protons to calculate f_Q (and k_Q) factors for ten plane-parallel and five cylindrical ionization chambers for monoenergetic proton beams at energies between 60 MeV and 250 MeV. The simulation of proton nuclear interactions and prompt-gamma emission for all ICRU 63 isotopes (^{1}H, ^{12}C, ^{14}N, ^{16}O, ^{27}Al, ^{28}Si, ^{31}P, ^{40}Ca, ^{56}Fe, ^{63}Cu, ^{184}W, ^{208}Pb) was included in that study. Secondary particles heavier than protons were treated as protons with a range equal to that of the original secondary particle, while neutrons were not transported. This latter limitation of the code, however, is assumed to have a negligible effect on the calculation of f_Q factors, since the contribution of neutrons to the physical dose is less than 0.1% in proton pencil beam delivery systems [20].

Both Baumann et al. [8] and Kretschmer et al. [9] applied the Monte Carlo code GEANT4 version 10.03.p1 and version 10.04.p1, respectively, to calculate f_Q (and k_Q) factors for various ionization chambers in clinical proton beams of energies between 60 MeV and 250 MeV. In both studies, the default binary cascade model for hadronic interactions was used. Baumann et al. [8] used the toolkit TOPAS and Kretschmer et al. [9] used the toolkit GATE [21,22].

More recently, Baumann et al. [10] calculated f_Q (and k_Q) factors for six plane-parallel and four cylindrical ionization chambers at energies between 60 MeV and 250 MeV using the Monte Carlo code FLUKA version FLUKA2020.0.beta.1. A full consideration of hadronic interactions was activated: for the simulation of hadron–nucleus collisions, the PEANUT model was used whereas nucleus–nucleus interactions were treated via the BME model for kinetic energies below 125 MeV/u and via the RQMD model for higher energies [23,24].

It was shown that all three Monte Carlo codes employed for the calculation of f_Q factors in clinical proton beams pass the Fano test within 0.15% or better [6,25–27]. Furthermore, it was demonstrated that all three codes show a good agreement with experimental values of k_Q at the 1.5% level. All studies made use of the latest recommendations of the ICRU 90 report [28] concerning the mean ionization potentials (I) used to calculate the electronic stopping powers for water, air and graphite. For a detailed overview of transport parameters and cross sections used for the simulations, please refer to the individual studies.

Note that Gomà et al. [5] also calculated f_Q (and k_Q) factors in clinical proton beams by using a combination of the Monte Carlo codes GEANT4 and PENH. Since the version of PENH employed in that study was not capable of simulating proton nuclear interactions, GEANT4 was used to simulate the proton transport in water in front of the ionization chamber geometry accounting for nuclear interactions. A phase space file was scored and subsequently used in PENH to calculate the dose absorbed in air in the sensitive volume of the ionization chambers, however, without regarding nuclear interactions in the ionization chamber geometry. Since nuclear interactions should be included in the Monte Carlo simulation of k_Q factors [7], we decided to exclude those f_Q factors published by Gomà et al. [5] from this study.

2.2. Simulation geometries

All considered studies applied a uniform and parallel beam of 10×10 cm^2 impinging perpendicular on a water phantom surface as proton source. f_Q factors were calculated as:

$$f_Q = \frac{D_w}{\bar{D}_{air}} \quad (1)$$

where D_w is the absorbed dose-to-water at the reference point when the chamber is absent and $\bar{D}_{air}$ is the average absorbed dose-to-air in the cavity of the air-filled ionization chamber [29]. For the calculation of $\bar{D}_{air}$, ionization chambers were positioned with their reference points at reference depths of 1 g cm^{-2} for low proton energies ($E < 80$ MeV) and 2 g cm^{-2} for higher energies. The only exception is that Kretschmer et al. [9] used a depth of 2 g cm^{-2} for all proton energies. Following the IAEA TRS-398 CoP, the reference point for plane-parallel chambers is positioned at the centre of the inner surface of the chamber's entrance window. For cylindrical chambers, the reference point corresponds to the centre of the cavity on the symmetry axis. D_w was calculated in a disc that was centred at the reference depth. The height of the disc was 250 μm in each study while the radius varied between 5 to 10 mm.

Concerning the modelling of the ionization chamber geometries in the different studies, all authors mainly relied on blueprints provided by the corresponding manufacturers. The ionization chamber models used by Wulff et al. [6], Baumann et al. [8] (GEANT4) and Baumann et al. [10] (FLUKA) were exactly the same and modelled independently from Gomà and Sterpin [7] (PENH) and Kretschmer et al. [9] (GEANT4).[2] For the plane-parallel ionization chambers, the dimensions of the sensitive volumes (radius of the cavity and electrode spacing) were the same for all studies, with one exception: The radius of the sensitive volume of the PTW Roos chamber was set to 7.8 mm in the studies by Gomà and Sterpin [7] and Kretschmer et al. [9], whereas a radius of 7.5 mm was used in the residual studies. Tables 1 and 2 summarize the dimensions and materials of the entrance windows and collecting electrodes for the plane-parallel ionization chambers as used in the various studies. Small differences in the dimensions and used materials between the different studies can be observed, especially for the collecting electrodes. For the cylindrical ionization chambers, no detailed geometry descriptions were provided by the authors. The ionization chambers PTW 30013 and IBA FC65-G were modelled using blueprints from the manufacturers. For the modelling of the NE 2571, Wulff et al. [6], Baumann et al. [8], Kretschmer et al. [9] and Baumann et al. [10] used the geometry and material descriptions from the original publication [30], whereas Gomà and Sterpin [7] employed this publication only for the material description but modelled the chamber geometry following blueprints from the manufacturer.

[2] Note that the modelling of the plane-parallel ionization chamber IBA NACP-02 used by Wulff et al. [6] was adopted by Kretschmer et al. [9] and not modelled independently.

Table 1
Dimensions and materials of the entrance windows of the plane-parallel ionization chambers as used in the different studies. The mass density of each material is given in brackets. The abbreviations used are: PET for Polyethylene terephthalate, PMMA for Polyether methacrylate, and PE for Polyethylene.

Ionization chamber	Wulff et al. [6] Baumann et al. [8] Baumann et al. [10]	Gomà and Sterpin [7]	Kretschmer et al. [9]
PTW			
Roos	1.1 mm PMMA (1.19 g/cm^3) 20 μm graphite (0.82 g/cm^3)	1.11 mm PMMA (1.19 g/cm^3) 20 μm graphite (0.82 g/cm^3)	1.01 mm PMMA (1.19 g/cm^3) 20 μm graphite (0.82 g/cm^3) 0.1 mm PMMA (1.19 g/cm^3)
Markus	0.87 mm PMMA (1.19 g/cm^3) 0.4 mm Air (1.20 mg/cm^3) 30 μm PE (0.93 g/cm^3)	0.87 mm PMMA (1.19 g/cm^3) 0.4 mm Air (1.20 mg/cm^3) 30 μm PE (0.94 g/cm^3)	0.87 mm PMMA (1.19 g/cm^3) 0.4 mm Air (1.20 mg/cm^3) 30 μm PE (0.92 g/cm^3)
Advanced Markus	0.87 mm PMMA (1.19 g/cm^3) 0.4 mm Air (1.20 mg/cm^3) 30 μm PE (0.93 g/cm^3)	0.87 mm PMMA (1.19 g/cm^3) 0.4 mm Air (1.20 mg/cm^3) 30 μm PE (0.94 g/cm^3)	0.87 mm PMMA (1.19 g/cm^3) 0.4 mm Air (1.20 mg/cm^3) 30 μm PE (0.92 g/cm^3)
IBA			
NACP-02	0.1 mm PET/Mylar (1.4 g/cm^3) 0.5 mm grahpite (1.82 g/cm^3)	0.1 mm PET/Mylar (1.4 g/cm^3) 0.5 mm graphite (1.80 g/cm^3)	0.1 mm PET/Mylar (1.39 g/cm^3) 0.5 mm graphite (1.85 g/cm^3)
PPC-05	0.95 mm C552 (1.76 g/cm^3) 50 μm graphite (1.82 g/cm^3)	0.95 mm C552 (1.76 g/cm^3) 50 μm graphite (1.80 g/cm^3)	
PPC-40	0.9 mm PMMA (1.19 g/cm^3) 100 μm graphite (0.93 g/cm^3)	0.95 mm PMMA (1.19 g/cm^3) 50 μm graphite (1.80 g/cm^3)	

Table 2
Dimensions and materials of the collecting electrodes of the plane-parallel ionization chambers as used in the different studies. The mass density of each material is given in brackets. The abbreviations used are: PE for Polyethylene, PMMA for Polyether methacrylate, PPE for Polyphenyl ether, and PEEK for Polyether ether ketone.

Ionization chamber	Wulff et al. [6] Baumann et al. [8] Baumann et al. [10]	Gomà and Sterpin [7]	Kretschmer et al. [9]
PTW			
Roos	20 μm graphite (0.82 g/cm^3)	20 μm graphite (0.82 g/cm^3)	30 μm graphite (0.44 g/cm^3)
Markus	20 μm graphite (1.72 g/cm^3)	20 μm graphite (0.82 g/cm^3)	30 μm graphite (0.44 g/cm^3)
Advanced Markus	20 μm graphite (0.82 g/cm^3)	20 μm graphite (0.82 g/cm^3)	30 μm graphite (0.44 g/cm^3)
IBA			
NACP-02	50 μm graphite (0.92 g/cm^3) 0.25 mm Rexolite (1.05 g/cm^3)	50 μm graphite (1.80 g/cm^3) 0.3 mm PE (0.94 g/cm^3)	50 μm graphite (0.92 g/cm^3) 0.25 mm Rexolite (1.05 g/cm^3)
PPC-05	50 μm graphite (1.82 g/cm^3) 0.45 mm PPE (1.06 g/cm^3)	50 μm graphite (1.80 g/cm^3) 0.5 mm PEEK (1.32 g/cm^3)	
PPC-40	100 μm graphite (0.93 g/cm^3) 1 mm PMMA (1.19 g/cm^3)	50 μm graphite (1.80 g/cm^3)	

2.3. Data analysis

From the f_Q factors published in the studies described in Section 2.1, average Monte Carlo calculated f_Q factors ($\bar{f}_Q(E)$) as a function of initial proton energy E were calculated as follows:

$$\bar{f}_Q(E) = \frac{f_Q^{\mathrm{PENH}}(E) + f_Q^{\mathrm{FLUKA}}(E) + \frac{1}{N}\sum_{i=1}^{N}\left(f_Q^{\mathrm{GEANT4}}\right)_i(E)}{3} \quad (2)$$

where $f_Q^{\mathrm{PENH}}(E)$, $f_Q^{\mathrm{FLUKA}}(E)$ and $f_Q^{\mathrm{GEANT4}}(E)$ are the f_Q factors calculated with the different Monte Carlo codes. For PENH and FLUKA only one value is available for each ionization chamber model and proton energy. For GEANT4 there are up to three values available in the literature. To avoid a bias in the calculation of $\bar{f}_Q(E)$, the weighting by $1/N$ was applied, where N is the number of available values for f_Q factors calculated with GEANT4. Hence, the weight for each of the three Monte Carlo codes is 1/3 independent on the number of publications that use a specific Monte Carlo code. Using this weighting approach, a larger impact of a more commonly used Monte Carlo code is avoided.

We decided not to weight the individual f_Q factors by their reported statistical uncertainty (e.g. larger weight for smaller statistical uncertainty) since the statistical uncertainty does not define the validity of a Monte Carlo code. Furthermore, the statistical uncertainties of f_Q factors calculated with FLUKA are in general larger compared to PENH and GEANT4: For the Monte Carlo codes PENH and GEANT4, reported type-A uncertainties are between ~0.1% for low energies and ~0.3% for high energies in the considered publications. For f_Q factors determined with FLUKA, the reported type-A uncertainty is in the order of 0.3% for low energies and ~0.6% for high energies. Note that the statistical uncertainties of f_Q factors are comparable between the studies using GEANT4. Hence, a weighting by the statistical uncertainty would significantly reduce the impact of the Monte Carlo code FLUKA in the calculation of average f_Q factors. Nevertheless, we investigated the influence of the weighting by statistical uncertainties on the calculation of average f_Q factors. The results are shown in Appendix A.

Average f_Q factors were only calculated for ionization chamber models and energies for which at least one value was available for each of the three Monte Carlo codes. These are the plane-parallel chambers IBA NACP-02, IBA PPC-05, IBA PPC-40, PTW Roos, PTW Markus and PTW Advanced Markus at energies of 60, 70, 80, 100, 150, 200 and 250 MeV, and the cylindrical ionization chambers NE 2571, IBA FC-65G and PTW 30013 at energies of 150, 160, 200 and 250 MeV. In total, 195 values of f_Q factors were incorporated in the calculation of average f_Q factors.

Table 3
Average Monte Carlo calculated f_Q factors for monoenergetic proton beams as a function of initial proton energy. Additionally, the consensus f_{Q_0} factors in ^{60}Co radiation published by Andreo et al. [31] that were used to calculate k_Q factors are given. The depths z_{ref} at which the chambers were positioned and the corresponding residual ranges R_{res} are provided as well. The values within parenthesis correspond to one standard deviation $\sigma_{f_Q}(E)$ in the last digit(s).

Q	60 MeV	70 MeV	80 MeV	100 MeV	150 MeV	160 MeV	200 MeV	250 MeV	^{60}Co [31]
z_{ref} (g cm^{-2})	1	1	2	2	2	2	2	2	5
R_{res} (g cm^{-2})	2.16	3.17	3.30	5.89	14.11	16.03	24.49	36.70	
PTW Roos	1.1200(25)	1.1211(29)	1.1208(24)	1.1219(27)	1.121(6)		1.1262(20)	1.121(9)	1.142(5)
PTW Markus	1.1355(16)	1.1346(7)	1.1325(13)	1.1333(16)	1.130(6)		1.1316(6)	1.130(10)	1.143(5)
PTW Adv. Markus	1.139(3)	1.1387(29)	1.128(7)	1.126(6)	1.129(5)		1.1306(8)	1.132(8)	1.143(5)
IBA NACP-02	1.1174(4)	1.1200(14)	1.1197(9)	1.1194(8)	1.119(5)		1.120(7)	1.117(11)	1.154(5)
IBA PPC-05	1.110(7)	1.110(6)	1.1135(29)	1.1183(15)	1.119(3)		1.121(7)	1.116(11)	1.141(5)
IBA PPC-40	1.1191(25)	1.1209(21)	1.1194(21)	1.1204(29)	1.121(5)		1.122(7)	1.117(11)	1.142(5)
NE 2571					1.120(8)	1.122(6)	1.119(8)	1.115(11)	1.108(4)
PTW 30013					1.124(3)	1.125(3)	1.122(6)	1.118(6)	1.109(4)
IBA FC65-G					1.122(6)	1.122(5)	1.119(7)	1.117(6)	1.108(4)

To estimate the uncertainty of average f_Q factors, we evaluated two different assumptions. First, we assumed that the distribution of f_Q factors followed a Gaussian distribution. As such, we computed a weighted standard deviation $\sigma_{f_Q}(E)$ of the sample of Monte Carlo calculated f_Q factors as follows:

$$\sigma_{f_Q}(E) = \sqrt{\frac{\left(f_Q^{\mathrm{PENH}}(E)-\bar{f}_Q(E)\right)^2+\left(f_Q^{\mathrm{FLUKA}}(E)-\bar{f}_Q(E)\right)^2+\left(\frac{1}{N}\sum_{i=1}^{N}\left(f_Q^{\mathrm{GEANT4}}\right)_i(E)-\bar{f}_Q(E)\right)^2}{2}} \quad (3)$$

The denominator is the amount of different Monte Carlo codes reduced by 1. The weight of each data point was defined as in Eq. (2) so as to assign an equal weight to each Monte Carlo code.

Second, we assumed a rectangular distribution of the f_Q factors, with a width (Δ) equal to:

$$\Delta = \left(f_Q + u_A\right)_{\max} - \left(f_Q - u_A\right)_{\min} \quad (4)$$

where u_A is the reported statistical (type A) uncertainty (k = 1) of the maximum and minimum data points. For each chamber model and energy, we computed the standard deviation of the rectangular distribution as $\sigma = \Delta/2\sqrt{(3)}$.

Both approaches led to very similar standard deviations. Thus, in what follows, we will only present the results that assume a Gaussian distribution of the Monte Carlo calculated f_Q factors.

2.4. Calculation of k_Q factors

Monte Carlo calculated k_Q factors were derived as [32]:

$$k_Q = \frac{f_Q}{f_{Q_0}}\frac{W_{\mathrm{air},Q}}{W_{\mathrm{air},Q_0}} \quad (5)$$

$\bar{f}_Q(E)$ calculated following equation (2) was taken for f_Q. For f_{Q_0} we used the consensus factors as published by Andreo et al. [31]. The values for W_{air} were taken from the ICRU 90 report [28] to be (33.97 ± 0.12) eV for electrons and (34.44 ± 0.14) eV for protons. We used consensus f_{Q_0} factors to calculate k_Q factors and did not calculate average k_Q factors from the values published in the studies investigated since not all studies used the same Monte Carlo code for the calculation of f_Q factors in proton beams and f_{Q_0} factors in ^{60}Co radiation: Kretschmer et al. [9] used the Monte Carlo code EGSnrc [33] to calculate f_{Q_0} factors and Baumann et al. [10] did not calculate f_{Q_0} with FLUKA but used the consensus factors from Andreo et al. [31]. Hence, when calculating average k_Q factors from values published in the literature, FLUKA would not be considered for the photon-based part in k_Q. Furthermore, the use of consensus f_{Q_0} factors is more accurate since they are based on both experimentally determined as well as Monte Carlo calculated values and cover a large amount of data.

The overall uncertainty (k = 1) of Monte Carlo calculated k_Q factors was estimated as the propagation of the individual uncertainties of f_Q, f_{Q_0} and W_{air}. The relative uncertainty of f_{Q_0} is 0.4% for all air-filled ionization chambers investigated in this study [31]. The uncertainty of W_{air} is 0.35% for electrons and 0.41% for protons. As uncertainty of f_Q we used the standard deviation $\sigma_{f_Q}(E)$ as described in the preceding section.

3. Results

3.1. Average Monte Carlo calculated f_Q factors

Table 3 shows average Monte Carlo calculated f_Q factors as a function of initial proton energy. The depths z_{ref} at which the chambers were positioned and the corresponding Monte Carlo calculated residual ranges R_{res} are provided as well. The values within parenthesis correspond to one standard deviation $\sigma_{f_Q}(E)$ in the last digit(s).

Figs. 1 and 2 show average f_Q factors along with all f_Q factors published in the literature that were used for the calculation of average f_Q factors. We present these factors as a function of initial proton energy since this is how they were mainly reported in the literature. For individual data points, uncertainty bars correspond to one type-A standard uncertainty; whereas for average f_Q factors, they correspond to one standard deviation $\sigma_{f_Q}(E)$. Average f_Q factors are constant within 0.6% over the complete energy spectrum (except for the PTW Advanced Markus and IBA PPC-05 chamber with variations up to 1.2%).

Concerning the comparison of f_Q factors between the individual Monte Carlo codes for plane-parallel chambers, it can be seen that, except for the chambers IBA PPC-05 and PTW Advanced Markus, f_Q factors agree well for low proton energies with deviations of ~1% at maximum. For higher energies, the f_Q factors begin to diverge up to 2%. In most cases, the Monte Carlo codes FLUKA and GEANT4 lead to comparable results while the f_Q factors calculated with PENH are larger. Apparently, FLUKA leads to the smallest f_Q factors in most cases. For cylindrical ionization chambers, the deviations of f_Q factors increase with energy as well. Again, f_Q factors calculated with PENH are larger whereas those calculated with FLUKA are smaller.

In Fig. 3, the standard deviation $\sigma_{f_Q}(E)$ of Monte Carlo calculated f_Q factors are shown for each ionization chamber model as a function of proton energy. $\sigma_{f_Q}(E)$ is 0.3% on average and ~0.6% at maximum for low energies, representing the generally good agreement between the individual Monte Carlo codes for this energy regime. For high energies, where larger differences between the Monte Carlo codes can be observed, $\sigma_{f_Q}(E)$ is correspondingly larger with 0.8% on average and ~1% at maximum. A linear fit based on all values of $\sigma_{f_Q}(E)$ demonstrates this general dependency on proton energy. Although this trend is not necessarily true for each ionization chamber geometry individually – e.g. for the PTW Advanced Markus and IBA PPC-05 $\sigma_{f_Q}(E)$ is smallest for medium energies and larger for low as well as high energies – it visualizes that, on average, $\sigma_{f_Q}(E)$ increases with proton energy.

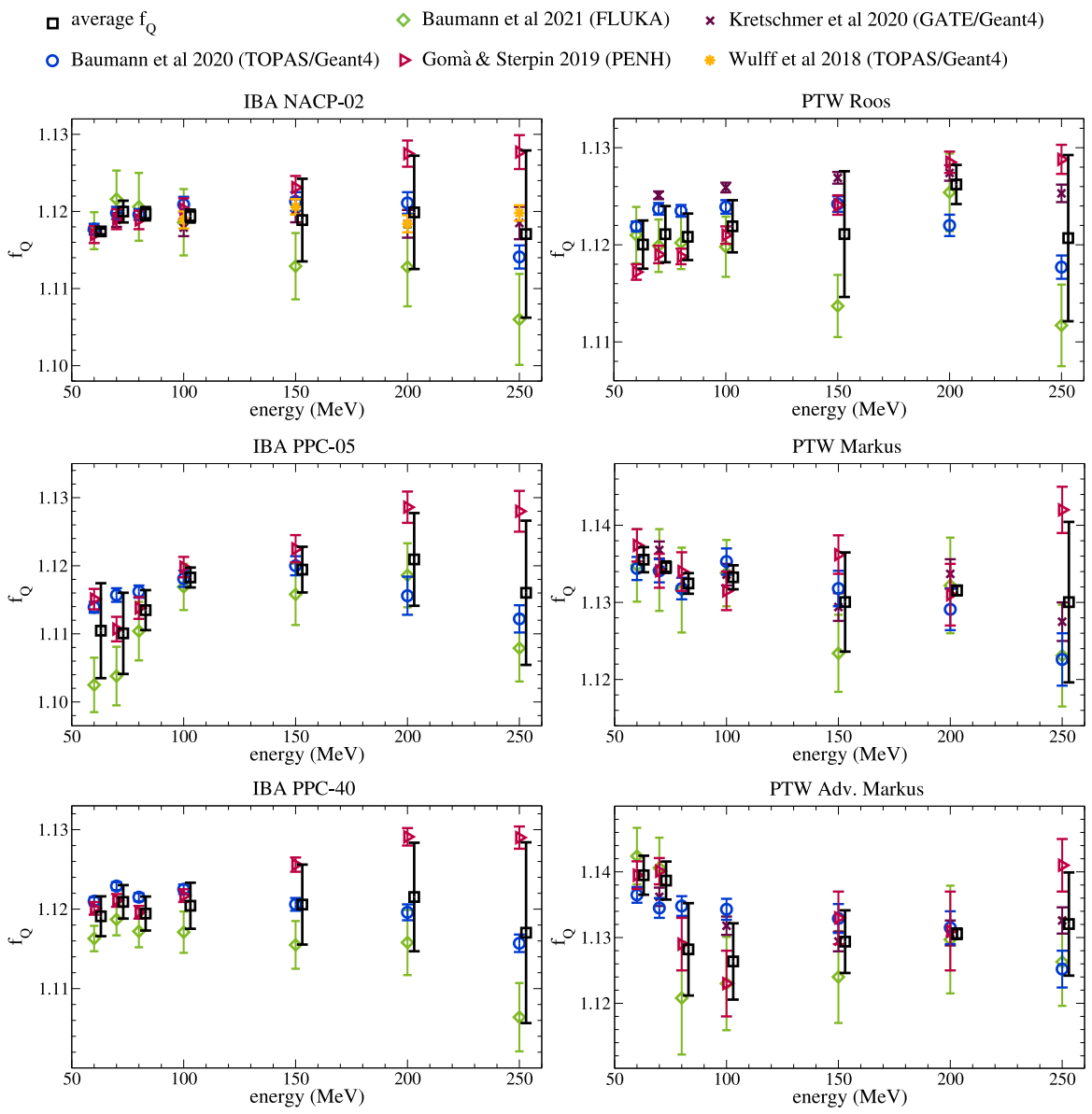

Fig. 1. Monte Carlo calculated f_Q factors for monoenergetic proton beams as a function of initial proton energy for different plane-parallel ionization chambers calculated with different Monte Carlo codes and average f_Q factors. Average f_Q factors are shifted to the right for better visibility. For individual data points, uncertainty bars correspond to one type-A standard uncertainty; whereas for average f_Q factors, they correspond to one standard deviation $\sigma_{f_Q}(E)$.

3.2. k_Q Factors derived from average Monte Carlo calculated f_Q factors

Table 4 summarizes beam quality correction factors k_Q derived from average Monte Carlo calculated f_Q factors as well as consensus f_{Q_0} factors as a function of initial proton energy. The depths z_{ref} at which the chambers were positioned and the corresponding residual ranges R_{res} are provided as well. The values within parenthesis correspond to the overall uncertainty (k = 1) in the last digit(s). Overall uncertainties are in the order of 0.7% for low energies and up to 1.2% for high energies. For low energies, the contributions to the overall uncertainty are similar for average f_Q, consensus f_{Q_0} and W_{air} values with ~0.4% each. For high energies, the dominant contribution to the overall uncertainty is the standard deviation $\sigma_{f_Q}(E)$ with 0.8% on average and ~1% at maximum.

In Fig. 4, k_Q factors calculated from average Monte Carlo calculated f_Q factors are shown along with the k_Q factors as determined following the IAEA TRS-398 CoP published in 2000 and the values previously published by Palmans et al. [4]. In contrast to the presentation of f_Q factors in Figs. 1 and 2, k_Q factors are presented as a function of residual range since this is the beam quality specifier used in the IAEA TRS-398 CoP. The uncertainty (k = 1) for the k_Q factors from the IAEA TRS-398 CoP is 1.7% for cylindrical ionization chambers and 2.1% for plane-parallel ones [1]. The uncertainty for the values from Palmans et al. [4] amounts to 1.4% independent on the ionization chamber type. k_Q factors calculated from average Monte Carlo calculated f_Q factors agree with the values from the IAEA TRS-398 CoP within one standard uncertainty. The maximum difference is 2.4%. The overall uncertainty of k_Q factors calculated from average Monte Carlo calculated f_Q factors is significantly smaller than the uncertainty for the values from the IAEA TRS-398 CoP. The agreement with the values published by Palmans et al. [4] is significantly better with deviations below 1% whereas the uncertainties of k_Q factors calculated from average Monte Carlo calculated f_Q factors are smaller for low energies. For high energies, uncertainties of Monte Carlo based k_Q factors are smaller for the PTW 30013 as well as PTW Roos chambers and comparable for the residual ionization chamber models.

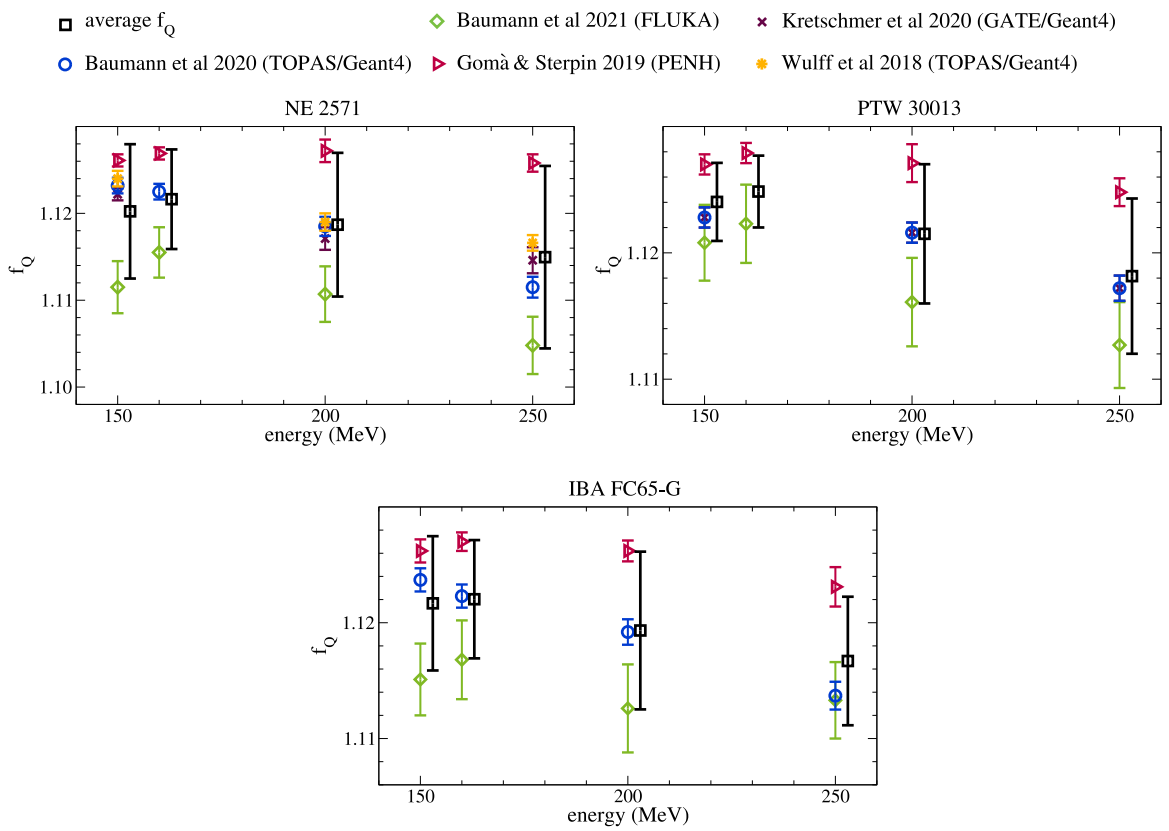

Fig. 2. Monte Carlo calculated f_Q factors for monoenergetic proton beams as a function of initial proton energy for different cylindrical ionization chambers calculated with different Monte Carlo codes and average f_Q factors. Average f_Q factors are shifted to the right for better visibility. For individual data points, uncertainty bars correspond to one type-A standard uncertainty; whereas for average f_Q factors, they correspond to one standard deviation $\sigma_{f_Q}(E)$.

Table 4
k_Q factors calculated from average Monte Carlo calculated f_Q factors for monoenergetic proton beams as a function of initial proton energy. The depths z_{ref} at which the chambers were positioned and the corresponding residual ranges R_{res} are provided as well. The values within parenthesis correspond to the overall uncertainty (k = 1) in the last digit(s). The k_Q factors were calculated from f_Q and f_{Q_0} factors summarized in Table 3.

Q	60 MeV	70 MeV	80 MeV	100 MeV	150 MeV	160 MeV	200 MeV	250 MeV
z_{ref} (g cm^{-2})	1	1	2	2	2	2	2	2
R_{res} (g cm^{-2})	2.16	3.17	3.30	5.89	14.11	16.03	24.49	36.70
PTW Roos	0.995(7)	0.996(7)	0.995(7)	0.996(7)	0.996(9)		1.000(7)	0.995(10)
PTW Markus	1.007(7)	1.007(7)	1.005(7)	1.005(7)	1.003(9)		1.004(7)	1.003(11)
PTW Adv. Markus	1.010(7)	1.010(7)	1.000(9)	0.999(8)	1.001(8)		1.002(7)	1.004(10)
IBA NACP-02	0.982(7)	0.984(7)	0.984(7)	0.984(7)	0.983(8)		0.984(9)	0.982(12)
IBA PPC-05	0.987(9)	0.986(8)	0.989(7)	0.994(7)	0.995(7)		0.996(9)	0.992(11)
IBA PPC-40	0.993(7)	0.995(7)	0.993(7)	0.994(7)	0.994(8)		0.995(9)	0.991(12)
NE 2571					1.025(10)	1.026(9)	1.023(10)	1.020(12)
PTW 30013					1.028(7)	1.029(7)	1.026(8)	1.023(9)
IBA FC65-G					1.026(9)	1.027(8)	1.024(9)	1.022(8)

4. Discussion

4.1. Calculation of average Monte Carlo calculated f_Q factors

As discussed in chapter 2.3, the calculation of average Monte Carlo calculated f_Q factors was designed to use the same weight for each Monte Carlo code. A weighting by the statistical uncertainty of the data points was discarded since the statistical uncertainty of the f_Q factors calculated with the Monte Carlo code FLUKA is larger compared to PENH and GEANT4. If employing a weighting by statistical uncertainties the impact of FLUKA would be reduced. Correspondingly, our approach of assigning the same weight to each Monte Carlo code has some limitations in the calculation of average f_Q factors: When considering the average f_Q factor for the PTW Roos chamber at 150 MeV (Fig. 1), it can be seen that both PENH and GEANT4 lead to similar results whereas the f_Q factor calculated with FLUKA is significantly smaller pulling the average f_Q factor downward. Since the statistical uncertainty of the f_Q factor calculated with FLUKA is significantly larger compared to PENH and GEANT4 this artefact would be weakened if weighting by statistical uncertainty leading to a ~0.2% larger average f_Q factor as shown in Appendix A. Hence, our approach used to calculate average f_Q factors is prone to this specific scenario where one Monte Carlo code shows an outlier in combination with a larger statistical uncertainty while the residual Monte Carlo codes lead to comparable results with small statistical uncertainties.

However, when considering the average f_Q factors for the cylindrical ionization chambers at 200 MeV (Fig. 2), it can be seen that all Monte Carlo codes lead to different results. In these cases, FLUKA pulls the average f_Q factor downward whereas PENH pushes it upward. Since these are no outliers, neither of FLUKA nor of PENH, a weighting by the statistical uncertainty would diminish the impact of

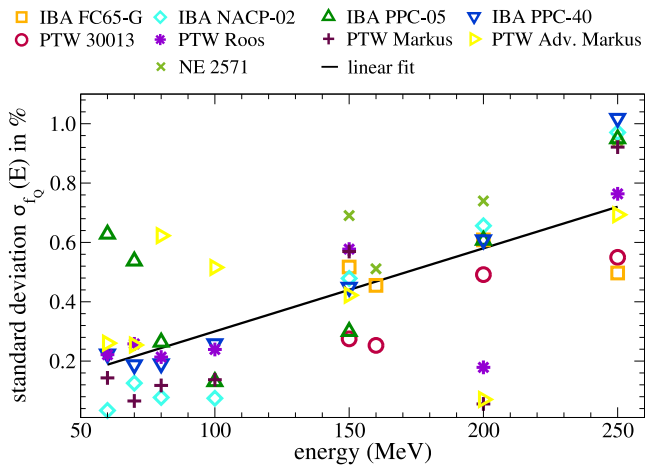

Fig. 3. The standard deviation $\sigma_{f_Q}(E)$ of Monte Carlo calculated f_Q factors for all ionization chamber models and proton energies investigated in this study. A linear fit demonstrates the general dependency on proton energy.

FLUKA without any justification in terms of PENH being the more accurate code just because the factor was calculated with a smaller statistical uncertainty. In conclusion, both approaches – weighting by statistical uncertainty or assigning an equal weight to each Monte Carlo code – are prone to specific scenarios of data sets. Furthermore, the maximum difference between average f_Q factors calculated with both approaches is 0.3% at maximum as shown in Appendix A. Hence, both approaches lead to comparable results and the difference between both approaches is smaller than the overall uncertainty of average Monte Carlo calculated f_Q factors.

4.2. Uncertainties of average Monte Carlo calculated f_Q factors

For the calculation of the standard deviation $\sigma_{f_Q}(E)$ of f_Q factors, we considered a large variety of Monte Carlo calculated f_Q factors derived with different Monte Carlo codes. Correspondingly, a wide range of code-specific as well as user-dependent uncertainties were accounted for. This includes – next to statistical type-A uncertainties – systematic type-B uncertainties such as different physics models employed by different Monte Carlo codes as well as the independent modelling of ionization chamber geometries, definitions of (composed) materials and the choice of transport parameters applied by the individual users. Due to this wide range of sources of uncertainties, the standard deviation $\sigma_{f_Q}(E)$ is considered an appropriate estimator for the overall uncertainty of average Monte Carlo calculated f_Q factors. Type-A uncertainties of f_Q factors were reported by the authors of the studies investigated and their contribution to the overall uncertainty is rather small: For the Monte Carlo codes PENH and GEANT4, type-A uncertainties are between ~0.1% for low energies and ~0.3% for high energies in the considered publications. For f_Q factors determined with FLUKA, the reported type-A uncertainty is in the order of 0.3% for low energies and ~0.6% for high energies. Hence, the dominant contribution to the overall uncertainty of average Monte Carlo calculated f_Q factors are type-B uncertainties.

4.3. Type-B uncertainties of Monte Carlo calculated f_Q factors

Sources of type-B uncertainties include the implementation of single and multiple Coulomb scattering [31] as well as cross-sections (e.g. for nuclear interactions), the selection of particle transport parameters, the quality of blueprints and material definitions, and the modelling of ionization chamber geometries in the Monte Carlo codes by the user. Whereas an estimation of type-A uncertainties for Monte Carlo calculated f_Q factors is, in general, straightforward, an estimation of type-B uncertainties is more challenging due to the large variety of possible sources.

One source is the modelling of nuclear interactions: Possible differences in the nuclear interaction modelling implemented in the different Monte Carlo codes lead to differences in f_Q factors between the different Monte Carlo codes especially for high energies [8] since the importance of these interactions increases with energy [7]. As a result, the overall uncertainty of average Monte Carlo calculated f_Q factors increases with energy. The role of nuclear interactions for the Monte Carlo calculation of f_Q factors in proton beams was investigated in several studies:

Baumann et al. [8] showed that f_Q factors for air-filled ionization chambers can differ by ~1.5% for 250 MeV proton beams when nuclear interactions are being deactivated.

Baumann et al. [34] investigated the contribution of primary protons and secondary particles (e.g. secondary protons, electrons, alpha particles and other fragments) to the dose deposited in the air-filled cavity of a PTW Roos chamber in a 250 MeV proton beam. It was shown that the dose deposition by secondary protons is in the order of 6% whereas an additional ~3% are deposited by electrons that are produced by secondary protons. Alpha particles contribute to the dose by ~1%. Furthermore, when deactivating nuclear interactions during the simulation, the dose deposited in the air cavity is reduced by ~10% underlining the influence of nuclear interactions at high energies.

The impact of nuclear interactions on the calculation of f_Q factors was also investigated by Gomà et al. [5] and Gomà and Sterpin [7]: Gomà et al. [5] calculated f_Q factors for air-filled ionization chambers while nuclear interactions were only considered in water in front of the ionization chamber but not inside the ionization chamber geometry. The Monte Carlo code GEANT4 was employed for the consideration of nuclear interactions in water. PENH was used for the simulation of radiation transport within the chamber geometry. Gomà and Sterpin [7] redid these simulations with an updated version of PENH considering proton nuclear interactions for all ICRU 63 isotopes inside the water phantom and the ionization chamber geometries. Differences in f_Q factors between those two studies were up to almost 1.1% indicating that nuclear interactions should be taken into account for the Monte Carlo calculation of f_Q factors.

A conclusion for the role of nuclear interactions in water can be drawn from the studies by Baumann et al. [35] and Baumann et al. [8]: Baumann et al. [35] calculated f_Q factors for simple air-filled cavities as representatives of ionization chambers placed in water for 150 MeV protons with the Monte Carlo codes PENH, GEANT4 and FLUKA. Baumann et al. [8] re-calculated these factors for 250 MeV protons using PENH and GEANT4. Interestingly, the difference of f_Q factors for 250 MeV protons between PENH and GEANT4 was with 0.6% comparable to the difference between the codes for 150 MeV. This suggests that the larger differences in f_Q factors between the codes for complete ionization chamber geometries are mainly due to nuclear interactions in materials different than water.

At last, Lourenço et al. [25] used FLUKA to calculate perturbation correction factors for the PTW Roos chamber in proton beams at energies of 60, 150 and 250 MeV. The authors showed that the total perturbation correction factor can differ up to ~0.8% when disregarding nuclear interactions whereas differences were larger for higher energies underlining the increased role of nuclear interactions at high energies. The results and conclusion from the individual studies are summarized in Table B.1.

Another source of type-B uncertainties is the modelling of the chamber geometry itself as well as the definition of material compositions and mass densities that can be different between individual users although employing blueprints from the manufacturers as shown in Tables 1 and 2.

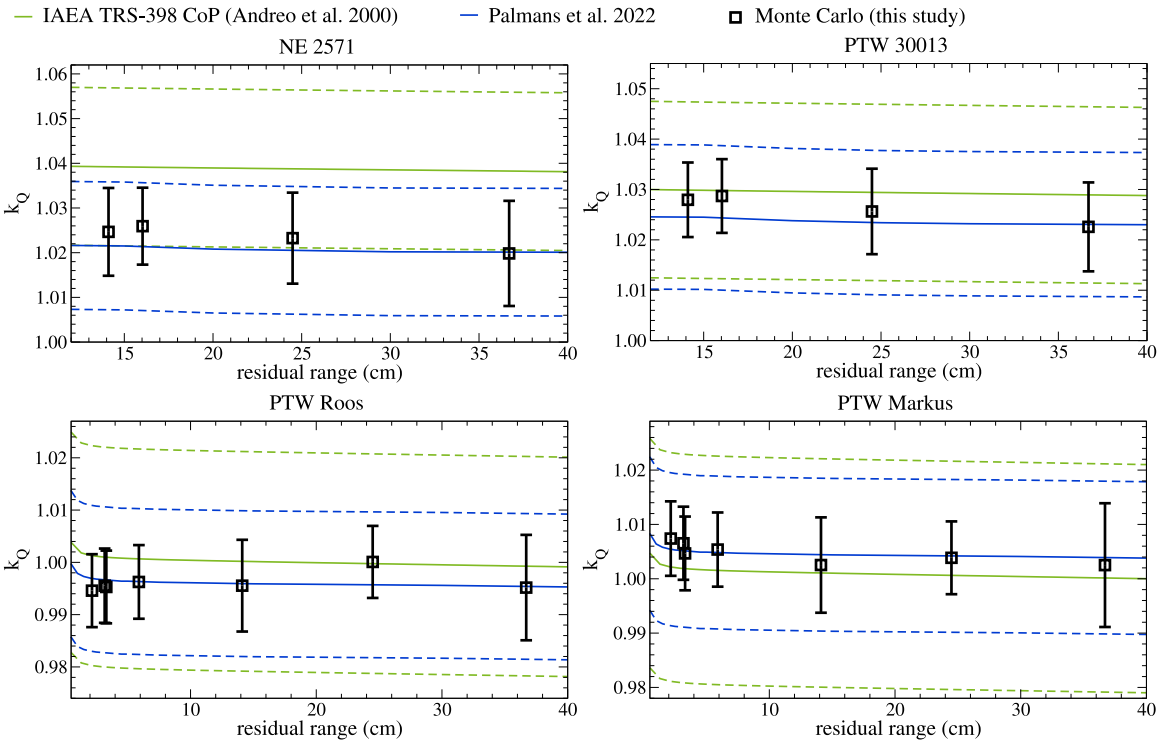

Fig. 4. k_Q factors determined following the IAEA TRS-398 CoP published in 2000 in solid green lines and corresponding uncertainties (k = 1) in dashed green lines. In solid blue lines k_Q factors as determined by Palmans et al. [4] that will be included in the upcoming version of IAEA TRS-398 CoP with corresponding uncertainties (k = 1) in dashed blue lines. In symbols, k_Q factors derived from average Monte Carlo calculated f_Q factors as well as consensus f_{Q_0} factors. The error bars depict the overall uncertainty (k = 1).

The contribution of the independent modelling of ionization chamber geometries to the overall uncertainty of average Monte Carlo calculated f_Q factors can be estimated by comparing the studies from Baumann et al. [8] and Kretschmer et al. [9] who both employed GEANT4. In these studies, the same geometry for the IBA NACP-02 ionization chamber was used with only slight differences in the applied physical densities of the materials PE and graphite (compare Tables 1 and 2). The differences in f_Q factors between both studies for this ionization chamber are 0.4% at maximum which most likely originates from the fact that Kretschmer et al. [9] used a newer version of GEANT4 and a larger value (0.2 compared to 0.05) for the parameter *dRoverR*. *dRoverR* defines the length of a condensed history step in relation to the residual range of a particle. Note that this parameter is related to electro-magnetic interactions only and has no influence on nuclear interactions. All remaining ionization chambers were modelled independently by Kretschmer et al. [9] and Baumann et al. [8] with small deviations as shown in Tables 1 and 2. For these chambers, the differences in f_Q factors between the two studies are 0.7% at maximum, while 0.4% might be due to the different versions of GEANT4 employed and different values for *dRoverR*. Hence, the effect of independent modelling of ionization chamber geometries seems to be rather small – especially compared to the influence of the transport parameter *dRoverR* and changes between different versions of GEANT4.

Monte Carlo codes are under constant development and corresponding updates of these codes can include changes in the physics models employed. This might lead to a change in calculated values of f_Q and k_Q factors which is another source for type-B uncertainties. As an example, a newer version of the Monte Carlo code PENH has been published introducing a refinement of both electromagnetic collision models as well as a different implementation of nuclear reactions [36]. However, to which extent these changes impact the calculation of f_Q and k_Q factors cannot be estimated from available data but needs to be investigated thoroughly.

4.4. Uncertainty of k_Q factors

The overall uncertainty of k_Q factors calculated from average Monte Carlo calculated f_Q factors is significantly smaller than the uncertainties estimated in the IAEA TRS-398 CoP. The dominant contributors to the uncertainty of k_Q factors from the IAEA TRS-398 CoP are the water-to-air stopping power ratio with ~1% and the considerably large uncertainties for the perturbation correction factors: in proton beams, these are estimated to be 0.8% for cylindrical and 0.7% for plane-parallel ionization chambers. The background is that, in the IAEA TRS-398 CoP, it is assumed that perturbation correction factors in proton beams are equal to unity, an assumption that is accounted for by correspondingly larger uncertainties. Additionally, the uncertainty of perturbation correction factors increases when further accounting for the perturbation effects in ^{60}Co radiation leading to overall uncertainties of ~1.1% for cylindrical and ~1.7% for plane-parallel ionization chambers. Especially the fluence perturbation correction for the chamber wall of plane-parallel ionization chambers in ^{60}Co radiation is connected to a large uncertainty of 1.5%. When directly determining k_Q factors by means of Monte Carlo simulations, fluence perturbations are automatically considered and no explicit values for the water-to-air stopping power ratio must be calculated. As a result, the overall uncertainty of Monte Carlo calculated k_Q factors is smaller, despite the uncertainties due to the possible different modelling of nuclear interactions in the individual Monte Carlo codes. The uncertainty of k_Q factors published by Palmans et al. [4] is with 1.4% for all ionization chamber models and proton energies significantly smaller compared to the uncertainty estimation of the IAEA TRS-398 CoP from 2000. The background is that Palmans et al. [4] derived k_Q factors from experimentally determined ones and Monte Carlo calculated f_Q and k_Q factors. The authors did not average those factors as done in this study, but used the data to quantify fluence perturbation effects for the individual ionization chamber models allowing for a smaller overall uncertainty estimation. However, this overall uncertainty is –

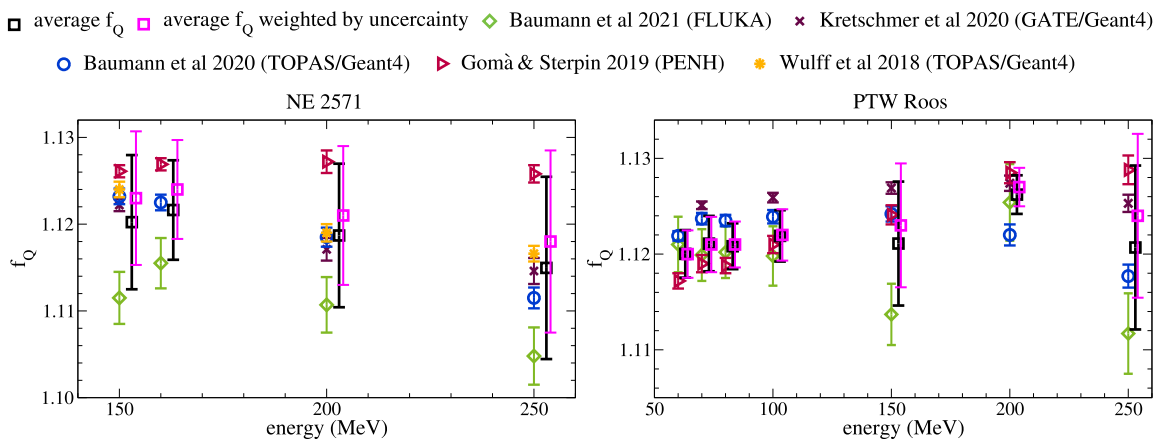

Fig. A.1. Monte Carlo calculated f_Q factors for monoenergetic proton beams as a function of initial proton energy for one exemplary cylindrical and plane-parallel ionization chamber calculated with different Monte Carlo codes and average f_Q factors calculated using two different methods. Average f_Q factors are shifted to the right for better visibility. For individual data points, uncertainty bars correspond to one type-A standard uncertainty; whereas for average f_Q factors, they correspond to one standard deviation $\sigma_{f_Q}(E)$.

in contrast to this study – neither depending on proton energy nor the ionization chamber model but represents a single generic standard uncertainty for the entire recommended k_Q data set also including ionization chamber models for which experimental and Monte Carlo data are scarce. The uncertainty of k_Q factors calculated in this study from average Monte Carlo calculated f_Q factors is smaller, especially for low proton energies. It is worth noting that k_Q factors derived in this study by averaging Monte Carlo calculated f_Q factors lead to comparable results as the approach used by Palmans et al. [4]. Note that it is not the goal of this study to provide a recommendation for values of k_Q factors in clinical proton beams.

The role of perturbation correction factors might be one factor in the explanation why Monte Carlo calculated k_Q factors are smaller than the values from the IAEA TRS-398 CoP. As shown by Baumann et al. [34], most of the air-filled ionization chambers investigated in this study show an over-response. Hence, the perturbation correction factors are smaller than unity as it is assumed in the IAEA TRS-398 CoP leading to comparably smaller k_Q factors.

In general, k_Q factors derived from average Monte Carlo calculated f_Q factors as presented in this study seem to be more precise and accurate compared to the values from the IAEA TRS-398 CoP, since these factors were derived by considering the individual characteristics of each ionization chamber geometry, especially concerning fluence perturbation effects in proton beams. In the IAEA TRS-398 CoP, individual ionization chamber characteristics are only accounted for in photon radiation. As a result, the estimated uncertainty for proton radiation is rather large. Concerning Monte Carlo derived k_Q factors, the overall uncertainty probably could be reduced even further by a thorough investigation of nuclear interaction modelling which seems to be the dominant contributor to the overall uncertainty at high proton energies.

5. Conclusion

Average Monte Carlo calculated f_Q factors were derived from values published in the literature for six plane-parallel and three cylindrical ionization chambers in monoenergetic proton beams. Additionally, overall uncertainties of these average f_Q factors were estimated. It was shown that the overall uncertainty increases with proton energy. The dominant contributor to the overall uncertainty are type-B uncertainties where the implementation of nuclear interactions in the Monte Carlo codes seems to be the key point. Overall uncertainties of Monte Carlo derived k_Q factors are smaller than the estimated uncertainties from the IAEA TRS-398 CoP since individual ionization chamber characteristics such as fluence perturbations are accounted for in Monte Carlo simulations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Alternative method to calculate average f_Q factors

In addition to the determination of average Monte Carlo calculated f_Q factors by weighting each Monte Carlo code equally (average f_Q), we investigated a different approach by weighting each data point by its statistical uncertainty (average f_Q weighted by uncertainty):

$$\bar{f}_Q(E) = \frac{\frac{1}{u^{\mathrm{PENH}}(E)} f_Q^{\mathrm{PENH}}(E) + \frac{1}{u^{\mathrm{FLUKA}}(E)} f_Q^{\mathrm{FLUKA}}(E) + \frac{1}{N}\sum_{i=1}^{N} \frac{1}{u_i^{\mathrm{GEANT4}}(E)} \left(f_Q^{\mathrm{GEANT4}}\right)_i(E)}{\frac{1}{u^{\mathrm{PENH}}(E)} + \frac{1}{u^{\mathrm{FLUKA}}(E)} + \frac{1}{N}\sum_{i=1}^{N} \frac{1}{u_i^{\mathrm{GEANT4}}(E)}} \tag{A.1}$$

where $f_Q^{\mathrm{PENH}}(E)$, $f_Q^{\mathrm{FLUKA}}(E)$ and $f_Q^{\mathrm{GEANT4}}(E)$ are the f_Q factors calculated with the different Monte Carlo codes and u are the corresponding reported statistical (type A) uncertainties (k = 1).

The resulting average f_Q factors are compared in Fig. A.1 for two exemplary ionization chambers. Concerning the cylindrical ionization chamber, the average Monte Carlo calculated f_Q factors using the weight by statistical uncertainty are larger by ~0.2–0.3% since the f_Q factors calculated with FLUKA have the largest statistical uncertainty and are smaller compared to the values calculated with PENH and GEANT4. Concerning the plane-parallel ionization chamber, average Monte Carlo calculated f_Q factors weighted by statistical uncertainty are comparable to the average factors using the same weight for each Monte Carlo code for low energies since for this energy regime, f_Q factors agree well between the individual Monte Carlo codes. The largest differences can be seen for energies of 150 MeV and 250 MeV with 0.2% and 0.3%, respectively. Again, this is due to the fact that the f_Q factors calculated with FLUKA are smaller compared to the values calculated with PENH and GEANT4 and have larger statistical uncertainties.

Appendix B. Summary of the role of nuclear interactions

See Table B.1.

Table B.1
The role of nuclear interactions in the Monte Carlo calculation of f_Q factors for air-filled ionization chambers in protons beams as concluded from various studies.

Study	Investigated aspect	Results and conclusion on the role of nuclear interactions
Gomà et al. [5] and Gomà and Sterpin [7]	Calculation of f_Q factors with consideration of nuclear interactions only in water (without ionization chamber geometry) and in the complete setup	f_Q factors differ by up to 1.1% indicating that nuclear interactions should be included in the Monte Carlo calculation of f_Q factors
Lourenço et al. [25]	Calculation of perturbation correction factors at energies of 60, 150 and 250 MeV	Perturbation correction factors differ by up to 0.8% when disregarding nuclear interactions
	Calculation with and without consideration of nuclear interactions	Larger differences for higher energies show that the role of nuclear interactions increases with energy
Baumann et al. [35] and Baumann et al. [8]	Calculation of f_Q factors for simple air-filled cavities placed in water with PENH and GEANT4 for 150 MeV and 250 MeV protons	f_Q factors differ by ~0.6% independent on proton energy suggesting that larger differences in f_Q factors for complete ionization chamber geometries are mainly due to differences in the nuclear interaction modelling in materials other than water
Baumann et al. [8]	Calculation of f_Q factors in 250 MeV proton beams with and without consideration of nuclear interactions	f_Q factors differ by 1.5% confirming that nuclear interactions should be included in the Monte Carlo calculation of f_Q factors
Baumann et al. [34]	Contribution of various particle species to the dose in the air cavity of PTW Roos chamber	~6% of dose deposited by secondary protons, ~3% by electrons produced by secondary protons, and ~1% by alpha particles
	Change in dose deposited when deactivating nuclear interactions	10% less dose deposited when deactivating nuclear interactions

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