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Measurement of track structure parameters of low and medium energy helium and carbon ions in nanometric volumes

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Abstract

Ionization cluster size distributions produced in the sensitive volume of an ion-counting wall-less nanodosimeter by monoenergetic carbon ions with energies between 45 MeV and 150 MeV were measured at the TANDEM-ALPI ion accelerator facility complex of the LNL-INFN in Legnaro. Those produced by monoenergetic helium ions with energies between 2 MeV and 20 MeV were measured at the accelerator facilities of PTB and with a ²⁴¹Am alpha particle source. C₃H₈ was used as the target gas. The ionization cluster size distributions were measured in narrow beam geometry with the primary beam passing the target volume at specified distances from its centre, and in broad beam geometry with a fan-like primary beam. By applying a suitable drift time window, the effective size of the target volume was adjusted to match the size of a DNA segment. The measured data were compared with the results of simulations obtained with the PTB Monte Carlo code PTra. Before the comparison, the simulated cluster size distributions were corrected with respect to the background of additional ionizations produced in the transport system of the ionized target gas molecules. Measured and simulated characteristics of the particle track structure are in good agreement for both types of primary particles and for both types of the irradiation geometry. As the range in tissue of the ions investigated is within the typical extension of a spread-out Bragg peak, these data are useful for benchmarking not only ‘general purpose’ track structure simulation codes, but also treatment planning codes used in hadron therapy. Additionally, these data sets may serve as a data base for codes modelling the induction of radiation damages at the DNA-level as they almost completely characterize the ionization component of the nanometric track structure.

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Keywords: nanodosimetry, track structure, light ions

(Some figures may appear in colour only in the online journal)

1. Introduction

Nanodosimetry focuses on investigating the physical characteristics of the microscopic structure of ionizing particle tracks, i.e. the sequence of the interaction types and interaction sites of a primary particle and all its secondaries, which reflects the stochastic nature of the radiation interaction. Taking the particle track structure into account is particularly important for the biological effects of ion beams, where the major fraction of radiation damage is mainly concentrated along and in close vicinity to the primary particle trajectory.

In view of the emerging radiation therapy with carbon ions, manifesting itself in the emergence of carbon ion therapy facilities (Combs et al 2010, Benedikt and Wrulich 2011, Rossi 2011) and in the increasing number of treated patients (Jermann 2015), the ionization structure of carbon ion tracks is of particular interest. This especially applies to the distal edge of the spread-out Bragg peak, which is expected to be of high importance for side effects of the treatment due to the pronounced increase of the RBE (Grün et al 2012, 2013). Carbon ion therapy is, in fact, the therapy of choice for tumours close to critical tissues, because of the well-defined carbon ion range. However, critical tissues are at risk of being severely damaged due to the distal edge of the spread-out Bragg peak, which occupies the last $1−2$ mm of the irradiated volume. The TANDEM-ALPI accelerator complex of the LNL-INFN can supply carbon ion beams of less than 270 MeV, having a range in tissue of $\sim 1.7$ mm. The energies of carbon ion beams used in this investigation are in the range between 40 MeV and 150 MeV, corresponding to a range in tissue from $\sim 80$ µm to $\sim 650$ µm (Ziegler et al 2006). Therefore, carbon ion beams of these energies are ideally suited to investigate the microscopic physical features of carbon ion beams at the distal edge of the spread-out Bragg peak.

Comparing the track structure of carbon ions with that of other light ions allows information on fundamental characteristics of the track structure of light ions to be obtained. Therefore, and also in view of the recent discussion (Krämer et al 2016) of using helium ions in radiation therapy (Saunders et al 1985), measurements with helium ions of 2 MeV and 20 MeV were also carried out at the accelerator facilities of PTB and with a $^{241}$Am alpha particle source. The range in tissue covered with helium ions of these energies lies between $\sim 10$ µm and $\sim 350$ µm (Ziegler et al 2006).

1.1. Nanodosimetric characteristics of particle track structure

In experimental nanodosimetry, the basic measuring quantity is the relative frequency distribution of the ionization cluster size, which is characteristic for the ionization component of the track structure. The ionization cluster size is defined as the number $\nu$ of ionizations generated in a target volume by a primary particle and its secondary electrons. As shown in figure 1, often a cylindrical target volume is regarded for reasons of simplicity.

A primary particle of radiation quality $Q$ (where $Q$ is determined by the particle type and its energy) can either traverse the target volume or pass it at a distance $d$ (impact parameter) with respect to the longitudinal axis of the cylinder. The superposition of the ionization component of the particle track structure and of the geometric characteristics of the target volume results in the ionization cluster size produced in the target. The ionization cluster size distribution
is the statistical distribution of the probabilities \( P_\nu(Q,d) \) that exactly \( \nu \) ions are created in the target volume. The probability distributions are normalized according to equation (1)

\[
\sum_{\nu=0}^{\infty} P_\nu(Q,d) = 1.
\]  

(1)

The statistical moments of the probability distributions are also suited to characterize the particle track structure. They are calculated according to equation (2).

\[
M_\xi(Q,d) = \sum_{\nu=0}^{\infty} \nu^\xi P_\nu(Q,d)
\]  

(2)

with \( \xi \) being the order of the moment of the distribution. Often, the first moment of the distribution, the mean ionization cluster size \( M_1(Q,d) \), is of particular interest.

\[
M_1(Q,d) = \sum_{\nu=0}^{\infty} \nu \cdot P_\nu(Q,d)
\]  

(3)

The ionization cluster size distribution \( P_\nu(Q,d) \) depends, on the one hand, on the radiation quality \( Q \) and, on the other hand, on the geometry of the target volume and its material composition and density.

A subset of the ionization cluster size distribution, which is of special interest, is the conditional cluster size distribution. It consists of those probabilities \( P^C_\nu(Q,d) \) with ionization cluster sizes of \( \nu \geq 1 \), i.e. it contains only those events, in which the primary particle has generated at least one ionization in the target volume

\[
P^C_\nu(Q,d) = \frac{P_\nu(Q,d)}{\sum_{\nu=1}^{\infty} P_\nu(Q,d)} \quad \text{for} \quad \nu \geq 1 \quad \text{with} \quad \sum_{\nu=1}^{\infty} P^C_\nu(Q,d) = 1.
\]  

(4)
Consequently, the statistical moments of the conditional cluster size distribution are calculated according to equation (5)

$$M^C_{\xi}(Q, d) = \sum_{\nu=1}^{\infty} \nu^\xi \cdot P^C_{\nu}(Q, d).$$

2. Methods

2.1. Setup of the experiment

The original setup of the experiment is described in detail in Garty et al (2002). Later improvements regarding the data acquisition system and the data evaluation procedure as well as an improved characterization of the device are described in detail in Hilgers et al (2015). The schematic setup of the nanodosimeter is shown in figure 2.

Filled with the target gas, the interaction region is located between the electrodes of a plane parallel plate capacitor. An ion entering the interaction region and traversing it parallel to the two electrodes is registered in a semiconductor detector, which triggers the data acquisition. The ionized gas molecules generated by this primary particle and its secondaries drift towards the lower electrode due to an electric field applied across the electrodes of the capacitor. Ions produced within the target volume, directly above a small aperture in the lower electrode, are extracted from the interaction region through this aperture and are detected in an ion-counting secondary electron multiplier. Repeating this measurement for a large number of single primary particles of radiation quality $Q$ at an impact parameter $d$ yields the relative frequency distribution $P^m_{\nu}(Q, d)$ of the ionization cluster size $\nu$ of detected ions. The measured data comprises a convolution of the frequency distribution of the number of created ions and the response function of the
experimental device, which describes the influence of all instrumental effects on the efficiency of the detection of the ions created. Hence, the number of ions actually detected in the experiment differs from the number of ions created. Consequently, the measured frequency distributions $P_m(Q, d)$ differs from the distribution $P_c(Q, d)$ defined in equation (1), which is based on the number of created ions. Basically, a deconvolution procedure needs to be applied to the measured data to remove the effects of the response function in order to obtain $P_c(Q, d)$. The development of such a procedure is in progress. For reasons of simplicity, the superscript ‘$m$’ in the notation of the measured ionization cluster size distribution will be omitted in the following text.

For operation of the nanodosimeter at an ion accelerator, the intensity of the ion beam is reduced to allow for single event counting by Rutherford scattering from a gold foil. The thickness of the gold foil depends on the energy of the primary carbon ions and ranged between 0.5 $\mu$m and 5.0 $\mu$m during the measurements at the LNL-INFN. In the measurements with helium ions at the PTB accelerators, a gold foil with a thickness of 0.1 $\mu$m was used. In front of the gold foil, an aperture of 3 mm in diameter limits the diameter of the primary beam, and thus, the diameter of the virtual ion source, i.e. the primary beam spot on the gold foil.

A Mylar foil of 2.5 $\mu$m in thickness serves as an entrance window and is mounted on an aperture of 6 mm diameter, separating the high vacuum of the scattering chamber from the nanodosimeter. The energy losses of the primary ions in the gold foil and in the Mylar foil and, after passing the Mylar foil, in the target gas along the primary ion’s track in the nanodosimeter were calculated with SRIM (Ziegler et al. 2006).

The data set with helium ions of 4 MeV was measured using alpha particles emitted from a $^{241}\text{Am}$ source. Due to the coverage of the source’s active area with 10 $\mu$m of Mylar, the energy spectrum of the emitted alpha particles, as measured with an alpha spectrometer, is shifted towards a mean energy of 4 MeV. In order to preserve the irradiation geometry, the source was positioned at the same distance to the target volume as the gold foil in the scattering chamber. The 2.5 $\mu$m Mylar foil was omitted.

In the setup described in Garty et al. (2002) and Hilgers et al. (2015), the nanodosimeter was only capable of measuring ionization cluster size distributions for primary particles traversing the target volume centrally (impact parameter $d = 0$). In order to allow measurements of ionization cluster size distributions for primary particles passing the target volume ($d \neq 0$), the trigger detector was replaced by a position-sensitive detector (PSD). The active area of the position-sensitive detector used for measurements with carbon ions is 20 mm in length and 3 mm in width, and 10 mm in length and 2 mm in width for the measurements with helium ions. The PSDs are not pixel based, but covered with a resistive layer and work according to the charge division principle. The impact position of the primary particle with respect to the centre of the detector is calculated according to equation (6):

$$X = L \cdot (Q_1 - Q_2) / (2 \cdot (Q_1 + Q_2)).$$

Here $X$ is the distance from the detector centre, $L$ is the length of the detector, $Q_1$ and $Q_2$ are the charges collected at the two detector output terminals. The sum of both charges represents the energy of the primary particle.

Since the active area of the PSDs is a ‘continuous’ detection area, during data processing, virtual pixels of arbitrary size can be configured. Neglecting the position information results in the ionization cluster size distribution of a broad beam radiation field, provided that the width of the nanodosimeter’s target volume is substantially smaller than the width of the radiation field, as it is in the present setup.

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2 (SiTek 1L20 (www.sitek.se/)).

3 (SiTek 1L10 (www.sitek.se/)).
Figure 3 shows the electrical configuration of the PSDs. The PSD itself is represented by the equivalent circuit diagram within the shaded box with $R_{\text{PSD}}$ symbolizing the resistive layer of the PSD. The arrow leading from the anode of the diode $D$ indicates a variable tap of $R_{\text{PSD}}$ and represents the position of the charged particle impinging on the detector surface. According to the position of the primary particle, the charge collected in the diode $D$ is divided by the two different branches of $R_{\text{PSD}}$ into two output charges $Q_1$ and $Q_2$ according to the ratio of the branches of $R_{\text{PSD}}$. The bias voltage $U_B$ is applied at the cathode of the diode. At the two output terminals, the two charges $Q_1$ and $Q_2$ are tapped. The network consisting of $R_i$ and $C_i$ is the typical way to configure the connection of an integrating charge-sensitive preamplifier. The sum of the output signals of the two charge-sensitive preamplifiers is used to trigger the data acquisition system.

In order to determine the charges $Q_1$ and $Q_2$ delivered at the two output terminals of the PSD, the output waveforms of the preamplifiers are digitized and processed with the trapezoidal shaping algorithm described in Jordanov et al (1994). This method has been favoured over the classical system using CR-RC shapers with subsequent ADCs. This is based on investigations of imaging the spatial distribution of the extraction efficiency using a 2D-PSD, where the linearity and position resolution measured with a classical system have been shown inferior compared to the values measured with a digital system. These investigations will be the subject of another paper.

However, in contrast to an ordinary non-position-sensitive semiconductor detector, the output waveforms of the charge-sensitive preamplifiers connected to the PSD are affected by a side effect, which must be taken into account when processing the waveform data digitally. The two capacitors $C_1$ and $C_2$ are charged with $Q_1$ and $Q_2$. After being charged with $Q_1$ and $Q_2$, $C_1$ and $C_2$ start to exchange their charges across $R_{\text{PSD}}$ in order to equalize the charge on each capacitor, which leads to a deformation of the exponentially decaying output voltage of charge-sensitive preamplifiers with a resistive feedback. However, the algorithm for processing the waveforms of resistive feedback charge-sensitive preamplifiers described in Jordanov et al (1994) requires an undisturbed waveform. Therefore, the decay time constant of the feedback of the preamplifiers must be substantially smaller than the time constant for the charge equalization of the capacitors $C_1$ and $C_2$ across $R_{\text{PSD}}$ for the charge exchange process not to
disturb the waveform of the exponentially decaying output voltage of charge-sensitive preamplifiers. In this setup, A250 amplifiers\(^4\) were chosen, since these amplifiers allow full access to the resistive feedback circuit and allow choosing the input FET to match the detector capacitance. The decay time constant of the A250 preamplifiers was chosen to be between 6 \(\mu\)s and 10 \(\mu\)s. For \(C_1\) and \(C_2\), a capacitance of 150 nF was chosen, which together with \(R_{\text{PSD}} = 50 \Omega\) lead to a time constant for the corresponding network of 7.5 ms. This time constant is sufficiently longer than the decay time constant of the A250 preamplifier’s feedback. For \(R_1\) and \(R_2\), resistors of 10 M\(\Omega\) were chosen.

### 2.2. Effective size of the target volume

In order to obtain a target volume of the size of a DNA segment, a time window of \(\pm 2.5 \mu\)s centred in the maximum of the drift time distribution of the ionized target gas molecules was applied. Figuratively, the maximum of the drift time distribution is associated with the height of the primary ion beam above the lower electrode.

To image the target volume in width and height, the aforementioned 1D-PSD was replaced by a 2D-PSD with an active area of 20 mm in width and in height\(^5\). The 2D-PSD triggers the data acquisition and records the coordinates of the point of impact of the primary particle on the detector’s surface. With this information, ionization cluster size distributions can be measured with respect to the reconstructed primary particle trajectory.

The result of such a measurement is the spatial distribution of the mean ionization cluster size \(M_1(d, h)\) depending on the impact parameter \(d\) and the height \(h\) of the primary particle trajectory. Since the extraction efficiency has cylindrical symmetry with respect to the central axis of the target volume, \(M_1(d, h)\) represents the Abel-transformed spatial distribution of this extraction efficiency onto the surface of the PSD. Two such measurements with \(^{241}\)Am alpha particles in 1.2 mbar C\(_3\)H\(_8\) for the complete drift time distribution and a drift time window of \(\pm 2.5 \mu\)s are shown in figures 4 and 5, respectively. The figures also show, for the same target gas and pressure, the Abel transform \(\zeta(d, h)\) of the simulated spatial distribution of the extraction efficiency \(\eta(d, h)\) for the corresponding drift time windows. To approximate the experimental conditions as close as possible, the simulation includes the convolution of the extraction efficiency \(\eta(d, h)\) with respect to (i) the geometrical setup, i.e. position and size of ion source and virtual detecting pixel, (ii) the position resolution of the 2D-PSD and (iii) the radial distribution of ionizations due to secondary electrons in the penumbra of the \(^{241}\)Am alpha particle tracks. The measured mean ionization cluster size \(M_1(d, h)\) and the simulated Abel transform \(\zeta(d, h)\) of the extraction efficiency \(\eta(d, h)\) are plotted as a function of \(d\) and \(h\), which in this case is the height at which the particle track is parallel to the plane of the lower electrode of the interaction region. Also shown is the difference between measurement and simulation to allow for an easier comparison. For both drift time windows, the data are normalized with respect to the maximum value of the mean ionization cluster size \(M_1^{\text{max}}(d, h)\) and the integrated extraction efficiency obtained \(\zeta_\text{int}^{\text{max}}(d, h)\) for the complete (full window, ‘fw’) drift time distribution.

For the complete drift time distribution (figure 4), a good agreement between measurement and simulation can be seen for both the shape and normalized values of \(M_1(d, h)\) and \(\zeta(d, h)\). Only minor deviations between measurement and simulation of \(-0.06\) and 0.02 were observed. For the drift time window of \(\pm 2.5 \mu\)s (figure 5), both shape and size of the measured and simulated distributions are in good agreement. The major difference between measurement and simulation can be seen in the normalized values of \(M_1(d, h)\) and \(\zeta(d, h)\). In the maxima of

\(^4\) (http://amptek.com/).

\(^5\) (SiTek 2L20 (www.sitek.se/)).
the distributions around $d = h = 0$ mm, a deviation of 0.05 occurs in which the measurement is larger than the simulation. However, this ‘under-response’ of the simulation with respect to the measurement is compensated to some extent around $h = 3$ mm and $h = −3$ mm, where the measurement is 0.03 smaller than the simulation. Overall, the simulations for both drift time windows agree well with the measured data. The experimental determination of the spatial distribution of the extraction efficiency will be the subject of another paper.

Compared to a previous investigation of the spatial distribution of the extraction efficiency with an almost identical device (Schulte et al. 2006), the shape and lateral extension of the two distributions are similar over the range covered by both devices. The deviation between measurement and simulation found in the present investigation is, however, smaller (see figure 8 in Schulte et al. (2006), which shows the result for operational conditions closest to those in this work). Owing to the different experimental conditions in Schulte et al. (2006) and this work, only a qualitative comparison is possible. In Schulte et al. (2006), the extraction efficiency was determined absolutely and 250 MeV protons were used as primaries, which are sparsely ionizing thus having a negligible contribution of secondary ionizations due to secondary electrons. In the present work, however, an absolute determination of the extraction efficiency was not possible and $^{241}$Am alpha-particles were used as primaries. Owing to the high energy of primaries in Schulte et al. (2006), the primary particle track could be determined with high resolution using two 2D silicon strip detectors. This was not possible in our case due to the low energy of the alpha particles and the size of the corresponding source. Additionally, in Schulte et al. (2006) only a full drift time distribution was used. Taking into account all the differences between the two investigations, the corresponding results are consistent.
The effective size of the target volume for the drift time window of ±2.5 μs was determined using two different methods. On the one hand, the extraction efficiency $\eta(d, h)$ was integrated along a primary particle track passing the target volume centrally at the nominal beam height, i.e. $h = 0$ mm and $d = 0$ mm, to determine the effective diameter, and along the line at $d = 0$ mm between $h = \pm 7$ mm, to determine the effective height. The result of this determination was an effective height $H$ of 1.83 mm or 0.4 $\mu$g cm$^{-2}$ and an effective diameter $D$ of 0.72 mm or 0.155 $\mu$g cm$^{-2}$ for 1.2 mbar C$_3$H$_8$. On the other hand, simulations were carried out using the PTra Monte Carlo code (Grosswendt 2002, Bug et al 2013) to simulate ionization cluster size distributions created in a cylindrical target volume of a specified diameter and height. The probability of counting an ionization was unity inside the target cylinder and zero outside. These simulations were carried out for the radiation qualities investigated and, after correcting the simulations with respect to the background of secondary ionizations (Hilgers et al 2015), they were compared to the measured ionization cluster size distributions for the impact parameter $d = 0$. This comparison is shown in figure 6 for the mean ionization cluster sizes $M_1(D, H)$ with different combinations of $D$ and $H$ determined from the simulated cluster size distributions and from the measured distributions. For helium ions and for carbon ions of energies above 80 MeV, a reasonable agreement between the simulated data set, which was obtained for an effective height $H = 1.83$ mm and an effective diameter $D = 0.72$ mm, and the measured data is achieved. For lower carbon ion energies, larger deviations are observed, which may be attributed to counting losses of the ionized target gas molecules due to the large number of target gas ions arriving within the drift time window of ±2.5 μs.
Applying the scaling procedure described in Grosswendt (2006), which has been verified experimentally in Hilgers (2010), using the ratio \( \frac{\rho_{\text{ion}}}{\rho_{\text{ion}}} \) for \( \text{C}_{3}\text{H}_{8} \) to \( \frac{\rho_{\text{ion}}}{\rho_{\text{ion}}} \) for \( \text{H}_{2}\text{O} \) with \( \lambda_{\text{ion}} \) being the ionization mean free path calculated from the ionization cross sections for \( \text{C}_{3}\text{H}_{8} \) and \( \text{H}_{2}\text{O} \) as used in PTra (Grosswendt 2002, Bug et al. 2013), leads to an approximate effective size of the target volume with \( D \approx 0.23 \mu\text{g cm}^{-2} \) and \( H \approx 0.61 \mu\text{g cm}^{-2} \), corresponding to 2.3 nm and 6.1 nm, respectively, expressed in terms of liquid water, which is in the order of the diameter and the height of two convolutions of the DNA strand.

2.3. Uncertainties

The uncertainties encountered in the experiment are described in detail in Hilgers et al. (2015). Due to the upgrade of the nanodosimeter with the position-sensitive detector, two additional contributions have to be taken into account, which affect the uncertainty of the impact parameter \( d \). These two parameters are the position resolution of the PSD and the linearity of the determination of the position of the particle impinging on the PSD’s surface. In order to determine these two parameters, a grid was placed in front of the detector in 1 mm distance to the detector’s surface, having a slit width and a strip width of 1 mm each. Then the detector was irradiated in the same setup as was used during the measurements of the ionization cluster size distributions. These measurements were carried out for carbon ions with energies of 43 MeV, 75 MeV, 88 MeV and 150 MeV and for helium ions with energies of 2 MeV and 4 MeV. Figure 7 shows the intensity distribution of the carbon ions of 88 MeV impinging on the detector surface in dependence of the length coordinate (\( x \)-coordinate) of the detector. The width of the virtual pixels is 20 \( \mu \)m. The slits and the strips of the grid in front of the detector are clearly visible. The change in the intensity from the left edge of the detector to the right edge is due to the angular dependence of the Rutherford scattering of the primary beam at the gold foil in the scattering chamber (see figure 7).

The position resolution is defined as the spacing between the two points of measurement of 10% intensity and of 90% intensity in an intensity profile across a sharp edge. Numerically, the position resolution can be determined by the convolution of a rectangular distribution.
representing the grid and a Gaussian distribution representing the slope of the intensity profile across the sharp edge with the FWHM of the Gaussian distribution being identical to the numerical value of the position resolution. Figure 8 shows the measured intensity profiles of two slits of the grid together with the corresponding fitted profiles obtained as described above, one in the centre of the detector around $-0.4$ mm and another one close to the edge around 7.6 mm. Except for the intensity, the two profiles differ by their position resolution (i.e. the FWHM of the Gaussian), which is about 50 $\mu$m in the centre and about 85 $\mu$m in a position close to the detector edge. This behaviour of the position resolution slightly decreasing with increasing distance is found in all measured intensity profiles.

In order to obtain the overall position resolution for the intensity profile over the whole length of the detector surface, the number of pixels in which the number of counts were between 10% and 90% of the mean value of the number of counts obtained in the pixels in the corresponding plateau was determined and averaged over the whole intensity profile. However, only data between the leftmost and the rightmost intensity minimum were taken into account in order to omit those data points which might be disturbed due to edge effects of the detector.

The relative root mean square (rms) detector non-linearity for the position is determined as in Banu et al (2008)

\[
\delta = \sqrt{\frac{\langle (X_m - X_t)^2 \rangle}{L}}
\]  

(7)

with $X_m$ and $X_t$ corresponding to the measured and the true coordinates of the edges of the slits of the grid, respectively, and $L$ denoting the length of the active area of the PSD. Since the position of the grid with respect to the detector surface was not precisely reproducible, the exact position of the grid relative to the detector was reconstructed from the measured intensity.
profile. Due to the irradiation geometry, a magnification factor of about 1.02 had to be taken into account in the measured intensity profile. Figure 9 shows the measured and reconstructed positions of the edges of the slits of the grid. In the data derived from the measured intensity profile, the intensity is set to ‘1’, if the number of the counts in the pixel is larger than the mean value averaged over all pixels in the region behind the respective slit. Otherwise it is set to ‘0’, with the region behind the slit extending between the centres of the two neighbouring strips. From the resulting (digital) intensity profile, the positions of the edges of the slits of the grid are determined. To obtain the reconstruction data set, an intensity profile of a grid having a slit width and a strip width of 1 mm each and being magnified by a factor of 1.02 was shifted in such a way that the positions of the edges of the slits of the grid coincide best with the measured intensity profile. The detector non-linearity was then calculated from these two data sets according to equation (7).

For all data sets measured with the larger of the two detectors, i.e. with carbon ions, the position resolution was determined to be 81 µm. Together with the detector non-linearity of 96 µm, the total uncertainty in the determination of the position where the primary particle hits the detector amounts to ±126 µm. For measurements with the smaller detector, i.e. with helium ions, position resolutions of 158 µm and 90 µm were found for helium ions with energies of 2 MeV and 4 MeV, respectively. Taking into account the detector non-linearity of 47 µm leads to a total uncertainty in the determination of the position where the primary particle hits the detector of ±165 µm and ±102 µm, respectively. As the position resolution degrades with a decreasing signal-to-noise ratio, i.e. with decreasing energy deposited by the primary particle in the detector’s active layer, it can be assumed that the position resolution for 20 MeV helium ions is at least as good as for 4 MeV helium ions. For carbon ions, no significant variation of the position resolution was observed in the energy range under investigation. This leads to the assumption that the position resolution is saturated for these energies deposited in the detector’s active layer but is limited by other electronic or detector characteristics.
The source of the primary particles, i.e. the spot on the gold foil hit by the primary beam, is approximately a circular source of 3 mm in diameter with a radial intensity depending on the primary beam profile. As the primary ion beam profile depends on various parameters, a worst-case scenario of a uniformly distributed intensity on the gold foil is assumed. Monte Carlo simulation was used to investigate the effect of a circular ion source and a 1 mm-wide virtual detecting pixel on the beam profile in the central plane of the target volume. In the simulation, both, the starting point on the ion source (i.e. the gold foil) and the end point on the virtual detecting pixel, were sampled from a uniform distribution. The coordinates where the resulting trajectory passed through the central plane of the target volume were recorded. This, together with the position resolution of the PSD, leads to ‘effective’ intensity profiles in the plane of the target volume for the two PSDs as shown in figure 10. The position resolution of these ‘effective’ intensity profiles is defined by a full width at half maximum of 560 µm. The scattering in the Mylar foil is neglected since the 5 cm distance between the gold and Mylar foils is much smaller than the 60 cm distance between the gold foil and target volume and between the gold foil and PSD (78 cm).

3. Results and discussion

3.1. Measurements of ionization cluster size distributions

Figure 11 shows ionization cluster size distributions measured in 1.2 mbar C3H8 with carbon ions of 88 MeV energy for different impact parameters $d\rho$, given in mass per area with $\rho$ being the density, and the distribution for the whole range of $d\rho$ covered by the PSD. Depending on $d\rho$, the cluster size distributions are of different shapes. At $d\rho = 0$ µg cm$^{-2}$ the primary ion hits the target volume centrally, i.e. the fraction of the particle trajectory which is inside the target volume is maximal. As the cluster size $\nu$ is proportional to the ratio $(D\rho)/(\lambda\rho)$, with $D$ being the diameter of the sensitive volume and $\lambda$ being the mean free path length for ionization, the corresponding cluster size distribution for $d\rho = 0$ µg cm$^{-2}$ shows the highest

Figure 9. Measured and reconstructed positions of the edges of the slits of the grid.
occurrence of large ionization clusters and the highest value of the ionization cluster size $\nu$ for the peak maximum. With increasing $d\rho$, the fraction of the particle trajectory which is inside the target volume decreases. Consequently, the occurrence of large ionization clusters decreases and the peak in the frequency distribution shifts towards smaller values of $\nu$ ($d\rho = 0.17\, \mu\text{g cm}^{-2}$ and $d\rho = 0.34\, \mu\text{g cm}^{-2}$). When $d\rho$ has increased to values where no more primary ions pass through the target volume, ionizations are exclusively produced by secondary electrons ($d\rho \geq 0.51\, \mu\text{g cm}^{-2}$) created outside the target volume. Due to the decreasing solid angle covered by the target volume as seen from the secondary electrons at their point of emission, the probability of occurrence for large cluster sizes $\nu$ decreases further while the probability of occurrence for small cluster sizes increases with increasing $d\rho$.

The cluster size distribution for impact parameters ranging from $-1.71\, \mu\text{g cm}^{-2}$ to $1.71\, \mu\text{g cm}^{-2}$ (labelled $d\rho = \pm1.71\, \mu\text{g cm}^{-2}$ in figure 11) was obtained without discrimination of $d\rho$ and represents the cluster size distribution for broad beam irradiation geometry. It can be described as the superposition of the cluster size distributions for the respective impact parameters. The frequency of the ionization clusters is maximal at $\nu = 0$ and decreases monotonically with increasing cluster size $\nu$ for the distribution with $d\rho = \pm1.71\, \mu\text{g cm}^{-2}$. However, it differs from the cluster size distributions for large impact parameters by a plateau-like region in the range of ionization cluster sizes between $\nu = 4$ and $\nu = 10$, which is due to those primary ions having trajectories penetrating the target volume. The contribution of these ions is nevertheless only small, since the majority of the primary ions pass by outside

![Figure 10](image_url). ‘Effective’ intensity profiles in the plane of the target volume for the two PSDs of detector size: $3\, \text{mm} \times 20\, \text{mm}$ (left) and $2\, \text{mm} \times 10\, \text{mm}$ (right). The profiles were obtained by simulations assuming an ion source of $3\, \text{mm}$ in diameter and a virtual detecting pixel of $1\, \text{mm}$ width. The starting point on the ion source, i.e. the gold foil, and the end point on the virtual detecting pixel were sampled from a uniform distribution. The coordinates where the resulting trajectory passed through the central plane of the target volume were recorded.
the target volume. On the other hand, this small fraction of ions with trajectories penetrating the target volume contributes significantly to the biological effect due to the large amount of interaction processes produced inside the target volume.

Figure 12 shows the mean ionization cluster size $M_1(Q, d\rho)$ measured in 1.2 mbar C$_3$H$_8$ for carbon ions of different energy as a function of the impact parameter $d\rho$. The shape of the measured $M_1(Q, d\rho)$ in dependence on $d\rho$ reflects the findings of the previous discussion: at $d\rho = 0 \, \mu g/cm^2$, where the primary ion hits the target volume centrally and the fraction of its trajectory being inside the target volume is maximal, hence, also $M_1(Q, d\rho)$ is maximal. With increasing $d\rho$ the fraction of the trajectory inside the target volume decreases, and $M_1(Q, d\rho)$ does as well. When $d\rho$ is in the range of the borders of the target volume, the decrease of $M_1(Q, d\rho)$ is most pronounced. A further increase of $d\rho$ leads to no more primary ions passing through the target volume, and the ionizations are produced by secondary electrons only. Due to the decreasing solid angle covered by the target volume as seen from the secondary electrons at their point of emission, $M_1(Q, d\rho)$ decreases further with increasing $d\rho$. However, due to the cross section for ionization, which decreases with increasing primary particle energy in the energy range under investigation, the measured $M_1(Q, d\rho)$ profiles are shifted with increasing primary particle energy towards lower values of $M_1(Q, d\rho)$.

Figure 13 shows the ratio of the mean ionization cluster sizes $M_1(Q, d\rho)$ divided by the corresponding mean number of primary ionizations ($D_{\text{eff}} \lambda_{\text{ion}}$) produced by the primary ion along the effective diameter $D_{\text{eff}}$ of the target volume. $\lambda_{\text{ion}}$ represents the mean free path length for primary ionization processes of the primary particle and is inversely proportional to the ionization cross section of the respective primary particle in the target gas. By dividing by ($D_{\text{eff}} \lambda_{\text{ion}}$), the differences between the $M_1(Q, d\rho)$ profiles corresponding to the different ion energies are reduced so that the measured $M_1(Q, d\rho)$ profiles almost coincide, especially for
Figure 12. Mean ionization cluster size $M_1(Q, d\rho)$ measured in 1.2 mbar C$_3$H$_8$ for carbon ions of different energy as a function of the impact parameter $d\rho$.

Figure 13. Ratio of the mean ionization cluster sizes $M_1(Q, d\rho)$ divided by the corresponding mean number of primary ionizations ($D_{eff}/\lambda_{ion}$) produced by the primary ion.
large impact parameters $d\rho$. Furthermore, it is found that for a central passage of the primary ion through the target volume, i.e. at $d\rho = 0$ $\mu$g cm$^{-2}$, the mean cluster size is close to $M_1(Q, d\rho) = 1$ for all $M_1(Q, d\rho)$ profiles. This behaviour confirms that the mean ionization cluster size produced by primary ions in nanometric volumes is mainly determined by the proportionality to the ionization mean free path length, whereas the contribution from secondary electrons, especially for large impact parameters $d\rho$, is almost invariant with the particle energy (Conte et al 2012), at least in the range of energies investigated.

Figure 14 shows the ionization cluster size distributions for broad beam geometry with impact parameters ranging between $d\rho = \pm 0.34$ $\mu$g cm$^{-2}$ and $d\rho = \pm 1.71$ $\mu$g cm$^{-2}$ measured with 88 MeV carbon ions. The range of the impact parameter of $d\rho = \pm 0.34$ $\mu$g cm$^{-2}$ marks the minimum extension of the primary beam needed to cover the diameter of the target volume. At this minimum extension, the shape of the cluster size distribution for a broad beam geometry has evolved. Increasing the extension of the primary beam does not significantly alter the shape of the distribution, but rather shifts the cluster size distribution towards lower frequencies (except for cluster size $\nu = 0$). This is due to a larger contribution of primary particles passing by the target volume, which increases with increasing extension of the primary beam.

The ionization cluster size distributions for the broad beam geometry with the impact parameter ranging between $d\rho = \pm 1.37$ $\mu$g cm$^{-2}$ measured for helium ions and between $d\rho = \pm 1.71$ $\mu$g cm$^{-2}$ for carbon ions of three different energies each are shown in figure 15. Independent of the energy and of the type of the primary ion, the frequency distributions are of similar shape. They mainly differ in the length of the plateau-like region, which is most pronounced for the ion of the respective type having the lowest energy (43 MeV for carbon ions and 2 MeV for helium ions) and only moderately visible for carbon ions of 150 MeV.
and even invisible for helium ions of 20 MeV. As discussed previously, the plateau is due to those primary ions having trajectories penetrating the target volume. As the cross section for ionization increases with decreasing primary ion energy, and consequently the mean free path length for ionization decreases, the number of ionizations produced by primary ions passing through the target volume increases, thus leading to an elongation of the plateau region towards larger ionization cluster sizes with decreasing energy. On the other hand, the mean free path length for ionization of 20 MeV helium ions is large, leading to a small number of ionizations inside the target volume and, therefore, the plateau in the cluster size distribution for 20 MeV helium ions vanishes completely. Since those ions with trajectories penetrating the target volume contribute significantly to the biological effect due to the large amount of interaction processes produced inside the target volume, the biological effect is expected to increase with decreasing energy due to the increase of interaction processes, which is reflected by the increasing length of the plateau region.

Figure 16 shows conditional ionization cluster size distributions measured in 1.2 mbar C\textsubscript{3}H\textsubscript{8} with carbon ions of 88 MeV energy for different impact parameters \(d_\rho\). At first glance, the conditional cluster size distributions shown on the left of figure 16 do not seem to differ much from the ionization cluster size distributions shown in figure 11 except for the frequency of occurrence of specific clusters. However, on closer inspection it is found that the frequency distributions for \(d_\rho > 0.51 \mu\text{g cm}^{-2}\) coincide within the experimental uncertainties (figure 16 right). This behaviour should be reflected in the statistical moments of the conditional cluster size distributions. The conditional mean ionization cluster size \(M^{C}_{1}(Q,d_\rho)\) is shown in the upper plot of figure 17. Compared to the monotonic decrease with increasing \(d_\rho\) of the mean ionization cluster size \(M_{1}(Q,d_\rho)\) found in figure 12, the conditional mean ionization cluster size \(M^{C}_{1}(Q,d_\rho)\) shows asymptotic behaviour: for \(d_\rho > 0.75 \mu\text{g cm}^{-2}\), \(M^{C}_{1}(Q,d_\rho)\) shows almost the same constant value independent of \(d_\rho\). Furthermore, this constant value is not only found for carbon ions of 88 MeV energy, but for carbon ions of all energies investigated, and moreover, also for helium ions of all energies investigated. In order to extend the comparison of the statistical moments, \(M^{C}_{2}(Q,d_\rho)\) (middle plot of figure 17) and \(M^{C}_{3}(Q,d_\rho)\) (lower plot of figure 17) were calculated from the conditional cluster size distributions. Both \(M^{C}_{2}(Q,d_\rho)\) and \(M^{C}_{3}(Q,d_\rho)\)
and $M_{\xi}^C(Q, d\rho)$ show the same behaviour as $M_{\xi}^1(Q, d\rho)$: for $d\rho > 0.75 \ \mu g \ cm^{-2}$, $M_{\xi}^C(Q, d\rho)$ and $M_{\xi}^1(Q, d\rho)$ show almost the same constant value independent of $d\rho$ for all radiation qualities investigated. However, the scatter of $M_{\xi}^C(Q, d\rho)$ increases with increasing $\xi$, since the influence of large clusters, which have a low frequency of occurrence and therefore a larger statistical uncertainty, is more pronounced (see equation (5)).

Figure 18 shows the conditional cluster size distributions measured for 88 MeV carbon ions with a broad beam geometry and an impact parameter ranging between $d\rho = \pm 0.34 \ \mu g \ cm^{-2}$ and $d\rho = \pm 1.71 \ \mu g \ cm^{-2}$ (see figure 14 for comparison). As expected from the previous discussion, the conditional cluster size distributions for broad beam geometry are also invariant with $d\rho$, since they can be described as the superposition of the cluster size distributions for the respective impact parameters.

As mentioned previously, at large distances from the primary ion trajectory, when the primary ion passes by outside the target volume, the ionization of the target gas inside the target volume is exclusively due to secondary electrons. By not taking into account the ionization clusters of size $\nu = 0$, the influence of the decreasing flux, due to the decreasing solid angle covered by the target volume as seen from the secondary electrons at their point of emission, is reduced and only the influence of the secondary electron spectrum is preserved. The invariance of $M_{\xi}^C(Q, d\rho)$ with the distance $d\rho$ and with the radiation quality $Q$ shows that, at large distances, the secondary electron spectrum changes only slightly with the distance between the target volume and the primary ion trajectory and with the radiation quality $Q$ (Conte et al 2012), at least for those radiation qualities and the range of $d\rho$ investigated.

Figure 19 shows the comparison of our results with measurements carried out in previously published investigations with 96 MeV carbon ions in 3 mbar C$_3$H$_8$ (Conte et al 2012) and with 4.8 MeV helium ions in 1.33 mbar C$_3$H$_8$ (Bashkirov et al 2009). For 96 MeV carbon ions (figure 19, left panel), the conditional cluster size distributions are compared for a few impact parameters $d\rho$. Qualitatively, the conditional cluster size distributions are of similar shape. However, for cluster sizes $6 \leq \nu \leq 14$ differences of up to a factor of 3 can be observed. This may be attributed to the very different setups and operational conditions.
Figure 17. Statistical moments $M_C(Q, d\rho)$ of the conditional cluster size distributions measured in 1.2 mbar C$_3$H$_8$ with helium ions and carbon ions for different impact parameters $d\rho$. 

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of the two instruments. For each instrument, the ionization cluster size distributions of the respective two impact parameters coincide. More generally, the conditional ionization cluster size distributions in the penumbra region are invariant with $d\rho$ (Conte et al 2012). In the right panel of figure 19, ionization cluster size distributions for $^{241}$Am alpha particles are compared for a number of impact parameters $d\rho$. The measurements in Bashkirov et al (2009) were carried out with a device almost identical to that used in this work. Although the experimental
conditions differ for the two sets of measurements with respect to the energy of the alpha particles and with respect to the target gas pressure, the measurements show a good agreement for central impact \( d_\rho = 0 \) \( \mu \)g cm\(^{-2}\) and for \( d_\rho \geq 0.5 \) \( \mu \)g cm\(^{-2}\). For an impact parameter \( d_\rho = 1.7 \) \( \mu \)g cm\(^{-2}\), the measurements differ by as much as a factor of 2. Overall, a satisfactory agreement between the measurements of this investigation with those previously published (Bashkirov et al. 2009, Conte et al. 2012) is observed.

3.2. Comparison with Monte Carlo simulations

The measured ionization cluster size distributions were compared with Monte Carlo simulations using the Monte Carlo code PTRA (Grosswendt 2002, Bug et al. 2013). The ‘effective’ intensity profiles shown in figure 10 are taken into account in the Monte-Carlo simulations. The simulated cluster size distributions were corrected with respect to the background of additional ionizations using the procedure described in Hilgers et al. (2015). In brief, the measured ionization cluster size distributions contain a background which arises from secondary ions produced due to the scattering of extracted target gas ions onto the cone-shaped electrode within the ion transport optics downstream of the extraction aperture. To compare the measured and simulated data, the background was included in the simulated ionization cluster size distributions. The background in the experimental data was determined using a model, which is based on two quantities: the probability \( \varepsilon \) of an ionized target gas molecule to hit the cone-shaped electrode after passing the extraction aperture and the expectation value \( \lambda \) of a Poisson distribution, representing secondary ions created by a single ionized target gas molecule hitting the cone-shaped electrode. The degree of agreement between the measured and simulated data was described by the quantity \( R \), defined in Hilgers et al. (2015). Due to the different length of the drift time window used in this investigation as compared to the length of the drift time window used in Hilgers et al. (2015), the values of \( \varepsilon = 0.014 \) and \( \lambda = 9 \) (see figure 20) obtained for the common minimum of the minimum deviation between the measured and the simulated data for the combination of all data sets differ from the values for \( \varepsilon = 0.0065 \) and \( \lambda = 15 \) obtained in Hilgers et al. (2015).

Figure 21 shows the comparison of the mean ionization cluster sizes \( M_1(Q, d_\rho) \) obtained from measured and simulated background-corrected ionization cluster size distributions for helium ions (left) and carbon ions (right), respectively, in 1.2 mbar C\(_3\)H\(_8\). For better clarity, the mean cluster sizes for 75 MeV and 88 MeV carbon ions are omitted.

For carbon ions, the data show a generally good agreement between measurements and simulations. For impact parameters \( d_\rho = 0 \) \( \mu \)g cm\(^{-2}\), i.e., for a central passage of the primary ion through the target volume, and for \( d_\rho \geq 0.7 \) \( \mu \)g cm\(^{-2}\), only minor deviations between the measured and the simulated mean cluster sizes are found, with the simulated \( M_1(Q, d_\rho) \) being slightly larger than those measured, except for carbon ions of 43 MeV and \( d_\rho = 0 \) \( \mu \)g cm\(^{-2}\). Here, the measured \( M_1(Q, d_\rho) \) is apparently smaller than the simulated one, which might be attributed to counting losses in the secondary electron multiplier due to the large number of ionized target gas molecules. In the range of \( d_\rho \) between 0.15 \( \mu \)g cm\(^{-2}\) \( \leq d_\rho \leq 0.55 \) \( \mu \)g cm\(^{-2}\), where the fraction of the trajectory inside the target volume decreases down to a grazing passage at the edge of the target volume, the measured \( M_1(Q, d_\rho) \) are apparently larger than those simulated (again except for the 43 MeV carbon ions, which suffer from counting losses). These differences at the border of the target volume might be caused by imperfections in the shape of the simulated spatial distribution of the extraction efficiency, which enters into the Monte Carlo simulation of the ionization clusters.
For helium ions of 2 MeV in the range of \( d\rho \) between \( 0.25 \, \mu g \, cm^{-2} \leq d\rho \leq 0.75 \, \mu g \, cm^{-2} \), the measured \( M_1(Q, d\rho) \) differ significantly from those simulated. The reason for this difference is not clear. However, for helium ions of 4 MeV and 20 MeV, the degree of the agreement between the measurement and the simulation is similar to that found for carbon ions.

Figure 20. Contour plot for the degree of agreement \( R \) (Reproduced from Hilgers et al 2015, with kind permission of The European Physical Journal (EPJ)) between measured and simulated ionization cluster size distributions as a function of expectation value \( \lambda \) and probability \( \epsilon \) of the distribution of the background of additional ionizations for the average of all data sets obtained with helium ions and carbon ions in 1.2 mbar \( C_3H_8 \).

Figure 21. Comparison of the mean ionization cluster sizes \( M_1(Q, d\rho) \) obtained from measured and simulated background corrected ionization cluster size distributions for helium ions (left) and carbon ions (right).
The comparison of measured and simulated background-corrected ionization cluster size distributions is shown in figure 22 for selected values of the impact parameters $d\rho$ for 94 MeV carbon ions in 1.2 mbar C$_3$H$_8$, and in figure 23 for 4 MeV helium ions.

For $d\rho = 0 \mu g/cm^2$, significant differences between the measurement and the simulation for carbon ions are found for large cluster sizes $\nu \gtrsim 30$, whereas for cluster sizes around the
maximum of the distribution, i.e. $\nu \lesssim 20$, the agreement is excellent. For the cluster size distributions of the other values of $d\rho$, only minor deviations are found in the comparison between the measurements and the background-corrected simulations.

For helium ions, the comparison between the measurement and the simulation shows significant deviations for $d\rho = 0.34 \, \mu g/cm^2$ for large cluster sizes $\nu \gtrsim 18$ and for cluster sizes $\nu \gtrsim 18$.
in the range $5 \lesssim \nu \lesssim 10$. For the cluster size distributions of the other values of $d\rho$, the degree of the agreement between the measurement and the simulation is similar to that found for carbon ions.

Figure 24 shows the comparison of measured and simulated background-corrected ionization cluster size distributions for broad beam geometry with the impact parameter ranging between $d\rho = \pm 1.37 \, \mu g \, cm^{-2}$ measured for helium ions (left) and between $d\rho = \pm 1.71 \, \mu g \, cm^{-2}$ for carbon ions (right) in 1.2 mbar C$_3$H$_8$.

For 150 MeV carbon ions, the frequency in the occurrence of clusters along the falling slope towards increasing cluster size is systematically smaller in the simulation as compared to the measured data. For 75 MeV carbon ions, an overall good agreement is found. Only in the knee at cluster size $\nu \cong 10$ are minor deviations found between the measurement and the simulation.

For 2 MeV helium ions, the frequency in the occurrence of cluster sizes in the range $15 \lesssim \nu \lesssim 20$ is lower in the simulation than in the measurement and larger for cluster sizes $\nu > 35$. For 20 MeV, the behaviour of the frequency in the occurrence of clusters is the opposite: here the occurrence of cluster sizes in the range $10 \lesssim \nu \lesssim 15$ is larger in the simulation than in the measurement and lower for cluster sizes $\nu > 20$.

In total, a good agreement is found in the comparison between measured and simulated background-corrected ionization cluster size distributions for both types of irradiation conditions, i.e. for the narrow beam geometry with specified impact parameters $d\rho$ as well as for the broad beam geometry with the impact parameter ranging between $d\rho = \pm 1.37 \, \mu g \, cm^{-2}$ for helium ions and between $d\rho = \pm 1.71 \, \mu g \, cm^{-2}$ for carbon ions.

4. Conclusions

Ionization cluster size distributions for helium and carbon ions were measured in a target volume having a cylindrical effective volume with a diameter of $D \approx 0.23 \, \mu g \, cm^{-2}$ and a height of $H \approx 0.61 \, \mu g \, cm^{-2}$, expressed in terms of liquid water. The effective size of the target volume corresponds to the size of a DNA segment. The ranges of the primary ions in tissue
were from ~10 µm to ~650 µm and are located at the distal edge of the spread-out Bragg peak. The data in this investigation provide fundamental information on the track structure of low-energy light ions in simulated nanometre-sized target volumes equivalent to the dimensions of a DNA-segment. Furthermore, they almost completely characterize the ionization component of the corresponding track structure.

Depending on the impact parameter $d\rho$, the cluster size distributions are of different shapes, which are determined by the combined effect of the length of the fraction of the particle trajectory inside the target volume on the one hand, and by the solid angle covered by the target volume as seen from the secondary electrons at their point of emission, on the other hand. For small values of $d\rho$, where the fraction of the particle trajectory inside the target volume is large, the distributions show a peak at cluster sizes $\nu > 0$, whereas for larger values of $d\rho$, where the fraction of the particle trajectory inside the target volume is small, the frequency of the ionization clusters is maximal at $\nu = 0$ and decreases monotonically with increasing cluster size $\nu$. When $d\rho$ has increased to such an amount that no more primary ions pass through the target volume, ionizations are exclusively produced by secondary electrons created by ions passing by outside the target volume. Due to the decreasing solid angle covered by the target volume as seen from the secondary electrons at their point of emission, the cluster size $\nu$ decreases further with increasing $d\rho$.

The cluster size distribution for broad beam irradiation geometry can be described as the superposition of the cluster size distributions for the respective impact parameters. The frequency of the ionization clusters is maximal at $\nu = 0$ and decreases monotonically with increasing cluster size $\nu$. However, it shows a plateau-like region, which is due to primary ions penetrating the target volume. The length of the plateau depends on the cross section for ionization of the primary particles, and the height depends on the width of the broad beam. However, the contribution of these ions is only small, since the majority of the primary ions pass by outside the target volume. On the other hand, this small fraction of ions with trajectories penetrating the target volume contributes significantly to the biological effect due to the large amount of interactions inside the target volume.

The statistical moments of the conditional cluster size distributions $M_C^1 (Q, d\rho)$, $M_C^2 (Q, d\rho)$ and $M_C^3 (Q, d\rho)$ show asymptotic behaviour: for $d\rho > 0.75 \, \mu \text{g cm}^{-2}$, $M_C^2 (Q, d\rho)$ show almost the same constant value independent of $d\rho$. Furthermore, this same constant value is found for carbon ions of all energies investigated, and moreover, also for helium ions of all energies investigated. In large distances from the primary ion trajectory, when the primary ion passes by outside the target volume, the ionization of the target gas inside the target volume is exclusively due to secondary electrons. By not taking into account the ionization clusters of size $\nu = 0$, the influence of the decreasing flux, due to the decreasing solid angle covered by the target volume as seen from the secondary electrons at their point of emission, is reduced and only the influence of the secondary electron spectrum is preserved. The invariance of $M_C^2 (Q, d\rho)$ from the distance $d\rho$ and from the radiation quality $Q$ shows that, at large distances, the secondary electron spectrum changes only slightly with the distance between the target volume and the primary ion trajectory along with the radiation quality $Q$ (Conte et al 2012), at least for those radiation qualities and the range of $d\rho$ investigated.

The measured ionization cluster size distributions were compared with Monte Carlo simulations using the Monte Carlo code PTra (Grosswendt 2002, Bug et al 2013). The simulated cluster size distributions were corrected with respect to the background of additional ionizations using the procedure described in Hilgers et al (2015). In total, a good agreement is found in the comparison between measured and simulated background-corrected ionization cluster size distributions for both types of irradiation conditions, i.e. for the narrow beam geometry with specified impact parameters $d\rho$ as well as for the broad beam geometry with
the impact parameter ranging between \( d_\rho = \pm 1.37 \, \mu g \, cm^{-2} \) for helium ions and between \( d_\rho = \pm 1.71 \, \mu g \, cm^{-2} \) for carbon ions.

The measurements presented in this investigation provide benchmark data for codes simulating the track structure of light ions. These simulations can then be used to estimate the biological effectiveness of such ions traversing biological matter. Comparisons of measured and simulated ionization cluster size distributions for all beam geometries investigated, i.e. for narrow beams passing through or passing by the target volume as well as for broad beams of different width, help to improve the models used in track structure simulations. These improvements are not restricted to models describing the effects due to the ions involved, but also to the secondary electrons as they are predominantly responsible for ionizations measured from narrow beams passing by the target volume as well as from broad beams.

Apart from serving as benchmark data for ‘general purpose’ track structure simulation codes, these data may also be relevant for radiotherapy with carbon ions as well as helium ions in future radiotherapy applications. Due to the comparatively low energies of the primary ions used in this work, the range of these ions in tissue is within the typical extension of the spread-out Bragg peak. Hence, these ions interact completely inside the biological target volume and are fully involved in the creation of the biological effect. These data are therefore useful not only as benchmark data for ‘classical’ treatment planning codes, but in particular for innovative nanodosimetry-based treatment planning codes.

The data in this work comprise an almost complete characterization of the ionization component of the nanometric track structure in a simulated nanometre-sized target volume of dimensions equivalent to a DNA-segment. Comparison of suitable endpoints (e.g. creation of strand breaks of different complexity) from radiobiological cell experiments (carried out in a radiation field of corresponding radiation quality) with quantities derived from (conditional) cluster size distributions for narrow or broad beam geometry may lead to a better understanding in the generation of radiation damages. Such an approach was already initiated in Conte et al (2017). Furthermore, these data sets may serve as a data base for codes modelling the induction of radiation damages based on the (spatial) distribution of ionizations.

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