Direct determination of $k_Q$ for Farmer-type ionization chambers in a clinical scanned carbon ion beam using water calorimetry

J-M Osinga-Blättermann$^{1,2,4}$, S Brons$^3$, S Greilich$^2$, O Jäkel$^{2,3}$ and A Krauss$^1$

$^1$ Department of Dosimetry for Radiation Therapy and Diagnostic Radiology, Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, D-38116 Braunschweig, Germany
$^2$ Division of Medical Physics in Radiation Oncology, German Cancer Research Center (DKFZ), INF 280, D-69120 Heidelberg, Germany
$^3$ Heidelberg Ion-Beam Therapy Center (HIT), INF 450, D-69120 Heidelberg, Germany

E-mail: julia-maria.osinga@ptb.de

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Abstract

Until now, the dosimetry of carbon ions with ionization chambers has not reached the same level of accuracy as that of high-energy photons. This is mainly caused by the approximately threefold larger uncertainty of the $k_Q$ factor of ionization chambers, which, due to the lack of experimental data, is still derived by calculations. Measurements of absorbed dose to water, $D_w$, by means of water calorimetry have now been performed in the entrance channel of a scanned 6 cm $\times$ 6 cm radiation field of 429 MeV/u carbon ions, allowing the direct calibration of ionization chambers and thus the experimental determination of $k_Q$. Within this work, values for $k_Q$ have been determined for the Farmer-type ionization chambers FC65-G and TM30013. A detailed investigation of the radiation field enabled the accurate determination of correction factors needed for both calorimetric and ionometric measurements. Finally, a relative standard measurement uncertainty of 0.8% ($k = 1$) could be achieved for the experimental $k_Q$ values.

For both chambers, the experimental $k_Q$ factors were found to be about 1% larger than those tabulated in the German DIN 6801-1 protocol, whereas...
compared to the theoretical values stated in the TRS-398 protocol, the experimental $k_Q$ value agrees within 0.4% for the TM30013 chamber but is about 1% lower in the case of the FC65-G chamber.

Keywords: $k_Q$ factor, absolute dosimetry, water calorimetry, absorbed dose to water, carbon ions, raster-scan method

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

1. Introduction

Radiation therapy with carbon ions began more than 20 years ago in the first clinical facility at the Heavy Ion Medical Accelerator (HIMAC) in Chiba, Japan. Although more than 19 000 (1994–2015) patients have been treated (PTCOG 2017), the dosimetry of ion beams to date has not reached the same level of accuracy as that of conventional high-energy photon or electron beams. While the standard measurement uncertainty assigned to the clinical reference dosimetry of high-energy photons by means of calibrated ionization chambers (ICs) is stated with about 1% in several national and international dosimetry protocols (Andreo et al 2006, Aalbers et al 2012, McEwen et al 2014), the corresponding uncertainty related to the dosimetry of ions is still higher by about a factor of two in the case of proton beams or a factor of three in the case of carbon beams (Andreo et al 2006).

This larger uncertainty is mainly caused by the uncertainty of the calculated $k_Q$ factor. This factor accounts for the different response of the IC exposed to the actual user beam quality $Q$ compared to the reference beam quality $Q_0$ used for calibration in terms of absorbed dose to water.

In general, the following expression as for example given in the International Code of Practice for the Dosimetry of External Radiotherapy Beams TRS-398 (Andreo et al 2006) can be used to calculate the $k_Q$ factor:

$$k_Q = \frac{(s_{w,air})_Q \cdot (W_{air})_Q \cdot P_Q}{(s_{w,air})_{Q_0} \cdot (W_{air})_{Q_0} \cdot P_{Q_0}}.$$  (1)

Here, $s_{w,air}$ is the water-to-air stopping power ratio, $W_{air}$ is the mean energy expended in air per ion pair formed and $p$ is the perturbation factor taking into account the departures from the ideal Bragg–Gray conditions. For ion beams, the overall uncertainty of calculated $k_Q$ factors is mainly determined by the uncertainties for the values of $(s_{w,air})_Q$ and $(W_{air})_Q$ ranging both between 1% and 2% (Andreo et al 2006, DIN 2016, ICRU 2016). Based on appropriate absorbed dose standards, a direct measurement of $k_Q$ by calibrating the IC at the actual beam quality $Q$ avoids the consideration of the different components in equation (1) and their uncertainties.

With respect to high-energy photon or electron radiation, numerous detailed investigations have yielded consistent data on experimental as well as calculated $k_Q$ factors with recently published standard uncertainties going down to about 0.4% (e.g. Cojocaru et al 2011, Muir et al 2011, Krauss and Kapsch 2014, Muir and Rogers 2014, Renaud et al 2015). For ion beams in general, however, there is still a lack of experimental data with low standard uncertainties. This is due to the fact that primary standards for the direct calibration of ICs in ion beams, and thus for the experimental determination of $k_Q$, do not exist yet. Clearly, there is the need to broaden the data basis on $k_Q$ factors in ion beams and to consider these data in upcoming clinical dosimetry protocols.
Few experimental efforts to determine absorbed dose to water, \( D_{w,Q} \), or \( k_Q \) factors for ICs have been made so far in passively scattered and actively scanned proton beams using water calorimetry (e.g. Siebers et al 1995, Palmans et al 1996, Vatnitsky et al 1996, Brede et al 2006, Medin et al 2006, Medin 2010, Sarfehnia et al 2010, Renaud et al 2016). For example, experimental \( k_Q \) factors for a NE 2571 IC with standard uncertainties between 0.7% and 1.3% have been determined in a scattered and in a scanned proton beam (Medin et al 2006, Medin 2010). Furthermore, Monte-Carlo calculated \( k_Q \) factors for several ICs in monoenergetic proton beams were published very recently by Gomà et al (2016) showing agreement with the mentioned experimental values within about 1%. With respect to carbon ion beams, however, even less work has been performed so far. The most recent work was carried out by Sakama et al (2009) and Rossomme et al (2014), who both used graphite calorimetry for the absolute determination of absorbed dose to water, \( D_{w,Q} \), and who concentrated on the experimental determination of the \( (W_{air})_Q \) value rather than the determination of \( k_Q \) factors.

In the present work, water calorimetry is implemented in the entrance channel of a 429 MeV/u scanned carbon ion beam at the Heidelberg Ion-Beam Therapy Center (HIT). The aim of this work is to experimentally determine the \( k_Q \) factor for two Farmer-type ICs and to significantly decrease the uncertainty of IC-based dosimetry of clinical ion beams. Therefore, the detailed characterization of the irradiation parameters and the resulting radiation field are of major importance as they strongly influence several calorimetric and ionometric correction factors and thus directly affect the overall achievable measurement uncertainty.

## 2. Material and methods

### 2.1. Beam delivery at HIT

All calorimetric and IC measurements were performed at HIT, which relies on the intensity-controlled raster scanning method (Haberer et al 1993). Due to the synchrotron-based beam delivery, the irradiation has a pulsed structure with beam-on and beam-off times, where new particles are accelerated to the requested energy, of both about 5 s.

The beam delivery is controlled by a beam application monitoring system (BAMS) by Siemens, which is based on the original design from the Helmholtzzentrum für...
Schwerionenforschung GSI, Darmstadt, Germany (Haberer et al 1993, Kraft and Weber 2011). It features a redundant system of three identical large area ICs regulating the number of particles delivered per irradiation spot, which are framed by two multi-wire proportional chambers (MWPCs) controlling the beam position. The time-resolved measurements of the MWPCs as well as the ICs containing all the irradiation-relevant information such as e.g. beam position, beam width, irradiation duration, and number of delivered particles per spot are recorded for each irradiation within the irradiation records.

2.2. Irradiation parameters

For the $k_Q$ measurements, an irradiation plan has been used which nominally should ensure that the irradiation field dependent correction factors for the water calorimeter (e.g. heat conduction corrections) are as small as possible. In summary, a field size of about 5.8 cm × 5.8 cm (realized by 26 × 26 spots with 2.3 mm spacing on a rectangular grid) was chosen and optimized for homogeneity as well as reproducibility by performing a re-painting (figure 1). A pencil beam of about 5.5 mm full width at half maximum (FWHM) was selected, as the corresponding intensity distribution shows the best symmetry (figure 2) which is also beneficial in terms of heat conduction calculations (section 2.4.1). To enable a preferably short irradiation time, the highest clinically used particle flux of $8 \times 10^7$ ions per second was chosen, resulting in an irradiation time per spot of about 32 ms and of about 95 s for the complete scan. In total, an absorbed dose to water of about 1.5 Gy was applied. In order to have a large distance between the calorimetric measurement position (at a nominal water depth of 50 mm) and the Bragg peak, an energy of 429 MeV/u was

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Left: result of a processed KODAK EDR2 (Extended Dose Range) film (Carestream Health Inc., Rochester, NY, USA) irradiated with a single carbon ion pencil beam behind the water-equivalent slab phantom. It was found that the relative dose profiles of the pencil beam (right image) can be well approximated by a superposition of two—in x- and y-direction—symmetric 2D Gaussian distributions with a mean ratio of 1.844 for the amplitudes and mean FWHMs of 4.31 mm (standard deviation: 0.06 mm) and 7.34 mm (standard deviation: 0.25 mm).
selected corresponding to a residual range \( R_{\text{res}} \) of 24.1 cm in water (\( R_{\text{res}} = R_p - d \), with \( d \) being the measurement depth and \( R_p \) the practical range defined as the depth at which the absorbed dose beyond the Bragg peak decreases to 50\% of its maximum value (Lühr et al. 2011). The residual range is a measure of the radiation quality \( Q \) according to DIN 6801-1 (DIN 2016), while TRS 398 assumes \( Q \) to be energy-independent. As shown in figure 3, the corresponding depth dose distribution (\( ddd \)) is very flat around the calorimetric measurement position exhibiting a small relative dose gradient of \(-0.023\% \text{ mm}^{-1}\). As the precise knowledge of the irradiation parameters and the resulting dose distribution is essential for the evaluation of correction factors required for the \( D_w \) and subsequent \( k_Q \) determination, corresponding measurements were directly performed at the measurement position of the water calorimeter and frequently repeated over the course of all \( k_Q \) measurements. Hence, an experimental set-up was designed to mimic the real measurement conditions of the water calorimeter (including the phantom and the calorimetric detector) by means of a water-equivalent slab phantom (figure 4). The 2D IC array STARCHECK by PTW (Freiburg, Germany) consisting of 527 air-filled ICs (dimensions: 8 mm \( \times \) 3 mm \( \times \) 2.2 mm, max. spatial resolution: 3 mm) was used for the measurement of relative lateral dose profiles. To increase the spatial resolution, the STARCHECK array has been repositioned multiple times. Prior to its use at HIT, extensive measurements in the well-characterized \(^{60}\text{Co} \) irradiation field at PTB allowed a reduction of the relative absorbed dose to water calibration uncertainty for all of the array’s chambers from 1\% (as stated by the manufacturer) to 0.3\%. Therefore, it is assumed that the relative response of the different detectors of the STARCHECK array is known within 0.3\% also in the carbon beam. The long-term reproducibility of the beam delivery system has been monitored through frequent measurements with a thimble IC. The data showed that the beam delivery system at HIT in combination with the irradiation plan used enables very reproducible measurement conditions with a relative standard deviation of 0.3\% found for the delivered dose at the central axis of the field over the course of all \( k_Q \) measurements (7 months).
2.3. Set-up and operation of the water calorimeter

The PTB transportable water calorimeter is operated at a water temperature of 4 °C. Its design, temperature stabilization system and the detector measuring the radiation-induced temperature rise have been previously described in detail (e.g. Krauss et al 2012, Krauss 2006). Briefly, the radiation-induced temperature rise is measured by two calibrated thermistors each fused in the conically shaped tip of a glass pipette. The glass pipettes themselves are centrally arranged inside a water-filled (high-purity water saturated with hydrogen gas) thin-walled plane-parallel glass cylinder perpendicular to the cylinder axis, with the two thermistors facing each other having a distance of about 7 mm. The glass cylinder is positioned inside the water phantom with the cylinder axis oriented parallel to the beam direction. The measurement depth of the thermistors with respect to the beam entrance window of the water phantom is nominally set to 50 mm as schematically shown in figure 5. The spacing was frequently checked directly before and after each calorimetric beam time (BT). Small distance changes occurring due to a time-dependent bowing of the entrance window of the water phantom were found to be negligible.

Within this investigation, two calorimetric detectors (using the same type of glass cylinder and the same type of preparation) with slightly different spacings between the thermistors were used. Both detectors were employed in the primary standard water calorimeter at PTB in 60Co radiation in order to prove the response of the detectors just before and after their usage at HIT.

The resistance of each thermistor (about 10 kΩ at 4 °C) is independently determined within a separate 1.5 V DC-powered voltage divider circuit with the thermistor being one part of the voltage divider and a calibrated high-precision resistor with a well-known resistance value (nominally 20 kΩ) the second. This allows measuring the resistance of the thermistor with a resolution of better than 1 mΩ (Krauss and Kapsch 2014).
In total, three separate BTs were performed within a time period of 7 months, each comprising between 60 and 80 calorimetric measurements. Figure 6 shows a typical thermistor signal for a series of ten irradiations. For each irradiation, the separate measurement signals of both thermistors were analyzed by performing linear fits over the pre- and post-irradiation drift curves, extrapolating the fits to the mid-run position and taking the corresponding difference as the radiation-induced resistance change of the thermistor. Time intervals of 110 s for the pre- and post-irradiation drift curves, with the fit interval for the post-irradiation drift curve starting 10 s after the end of an irradiation, were applied (Krauss and Kapsch 2014). It was found that the standard uncertainty of the mean value for the relative resistance change during irradiation amounts to 0.15% for each calorimetric experiment.

2.4. Experimental determination of $k_Q$ factors

The basic definition of the $k_Q$ factor is given as the ratio of the chamber’s absorbed dose to water calibration coefficients $N_{D,w,Q}$ at the radiation quality $Q$ and $N_{D,w,Co}$ at the reference beam quality (here: $^{60}$Co):

$$k_Q = \frac{N_{D,w,Q}}{N_{D,w,Co}}$$

(2)
The calibration coefficients $N_{D,w,Co}$ of the ICs used are traceable to PTB’s primary standard water calorimeter operated in a 60Co beam under reference conditions (Krauss 2006). The calibration coefficients $N_{D,w,Q}$ with respect to the raster scanned carbon ion beam at HIT are determined by means of the transportable water calorimeter in a two-step procedure. First, the calorimeter is used to measure $D_w,Q$ in a certain measurement depth $z$ on the central axis of the irradiation field. Second, after heating the water to about 18 °C and replacing the calorimetric detector by an IC positioned with its reference point, $P_{ref}$ at $z$, the reading $M_Q$ of the IC is directly measured in the water phantom of the calorimeter. Then, $N_{D,w,Q}$ is determined by the following equation:

$$N_{D,w,Q} = D_w/Q(M_Q k_v).$$

(3)

Here, $M_Q$ is corrected for the influence quantities temperature and pressure, electrometer calibration, polarity effect and ion recombination. As the measurement of $D_w,Q$ by means of water calorimetry is rather point-like, the volume correction factor $k_v$ is required to account for the volume-averaging effect of the IC to ensure comparable measurement conditions. $k_v$ depends on the lateral dose distribution and the volume of the IC.

It is important to note that the values of the experimentally determined $k_Q$ factors are not directly comparable with the theoretical $k_Q$ factors stated in TRS-398 (Andreo et al 2006) or DIN 6801-1 (DIN 2016), as the procedures described in the protocols regarding chamber positioning and consideration of the displacement effect differ from the above-mentioned experimental procedure. Following the protocols, $P_{ref}$ of the IC has to be positioned 0.75 · $r_{cyl}$ ($r_{cyl}$: inner radius of the chamber in mm) deeper than $z$, while the common calibration procedure for the determination of $N_{D,w,Co}$ implies positioning $P_{ref}$ at $z$. Additionally, there is a difference between both protocols in the consideration of the displacement correction (as part of the perturbation factor $p_Q$ in equation (1)) for 60Co as reference beam quality. While in TRS-398 the displacement correction for 60Co is considered within the overall perturbation factor, DIN
6801-1 separately addresses this effect by introducing a further chamber-dependent correction factor $k_r$. Thus, the experimental $k_Q$ values, referred to as $k_Q^{cal}$ in the following equations, have to be transformed into $k_Q^{DIN}$ and $k_Q^{TRS}$, respectively, in order to be comparable and applicable for reference dosimetry of ion beams according to DIN 6801-1 and TRS-398:

$$k_Q^{DIN} = \frac{k_Q^{cal}}{k_r} \cdot (1 + 0.75 \cdot r_{cyl} \cdot \delta_{12C})^{-1}$$ \hspace{1cm} (4)

$$k_Q^{TRS} = \frac{k_Q^{cal}}{k_r} \cdot (1 + 0.75 \cdot r_{cyl} \cdot \delta_{12C})^{-1}$$ \hspace{1cm} (5)

Here, $\delta_{12C}$ is the relative depth dose gradient at $z$ in the carbon ion field (figure 3) and $k_r$ is given by $k_r = (1 - 0.003 \cdot r_{cyl})^{-1}$ and therefore amounts to $k_r = 1.0092$ for both thimble ICs used (DIN 2016).

### 2.4.1. Calorimetric determination of $D_{w,Q}$ in the carbon ion beam.

The principles of the calorimetric determination of $D_{w,Q}$ have been described in full detail in e.g. Ross and Klassen (1996), Krauss (2006) and Seuntjens and Duane (2009). Briefly, the measured radiation-induced relative resistance change at the position of the thermistor of the calorimetric detector leads to a corresponding temperature rise $\Delta T$ which can be extracted by applying the thermistor’s temperature calibration coefficient. $D_{w,Q}$ at the central axis of the radiation field is then given by the following equation with $c_p$ being the specific heat capacity of water at a temperature of 4 °C and the $k$’s being correction factors for several influence quantities:

$$D_{w,Q} = T \cdot c_p \cdot k_h \cdot k_{c} \cdot k_p \cdot k_{I} \cdot k_{R} \cdot (6)$$

As the calorimetric detector comprises two thermistors, $D_{w,Q}$ has been obtained separately for each, taking into account position depend correction factors for each thermistor. The mean of both $D_{w,Q}$ values has been taken as the final result of a calorimetric BT.

In the following, detailed information is given on the principal methods for the experimental and/or theoretical determination of the correction factors used in equation (6). Corresponding results for the main correction factors $k_h$, $k_c$ and $k_p$ are presented in section 3.3.

The factor $k_h$ considers the correction for the so-called heat defect which is a possible deviation between the absorbed radiation energy and the energy which appears as heat. The heat defect is caused by chemical reactions triggered by the radiolysis of water together with potential additives or impurities in the water. For some aqueous systems, the heat defect can be calculated on the basis of a radiolysis model (e.g. Klassen and Ross 2002) allowing to compare the corresponding results on a relative basis with the results from water calorimeter experiments. For hydrogen-saturated water these calculations predict a stationary state for the products of the radiolysis after a small pre-irradiation dose, i.e. the heat defect is zero by definition. It was shown experimentally that this assumption of a zero heat defect is reasonable within a relative standard measurement uncertainty of 0.14% (Krauss 2006). Sassowsky and Pedroni (2005) performed model calculations of the radiolysis of water for radiation with higher linear energy transfer (LET). For the H$_2$ system, they showed for proton radiation up to an LET of 25 keV $\mu$m$^{-1}$ that the same stationary state with a zero heat defect occurs confirming the results obtained by Palmans et al (1996). As the radiolysis model for the H$_2$ system predicts this stationary state for all irradiation conditions independent of the LET or type of the radiation, this result can also be taken to be valid for heavier ions within the investigated LET region. The carbon beam at HIT has a maximum LET of about 11.3 keV $\mu$m$^{-1}$ at the calorimetric measurement position (section 3.2) and consequently, for the determination of $D_{w,Q}$ by means of water calorimetry in the scanned carbon ion beam, the correction $k_h$ is taken to be 1.000 within a relative standard uncertainty of 0.14%. Before and after a detector was used in the carbon ion beam
at HIT its response was proven in $^{60}$Co $\gamma$-radiation at PTB to be stable and to coincide with the expected response of a zero heat defect within 0.1%. This possible variation of the detector response has been considered also for the measurements in the carbon beam.

The factor $k_c$ corrects for the influence of heat transport effects on the determination of $D_w$ and is typically investigated by heat transport calculations on the basis of the finite element method. In order to account for the heat conduction effects occurring during and after a calorimetric measurement, the real calorimetric measurement conditions need to be reproduced as precisely as possible within finite element calculations (here: COMSOL Multiphysics version 4.3a). For static irradiation fields this method is well established (e.g. Krauss 2006, Seuntjens and Duane 2009). However, for the raster scan pattern used in this investigation (figure 1) it was found to be not feasible to model the heat conduction effects of the entire irradiation field by computing the time-dependent temperature evolution of each of the 1352 raster spots with 32 ms irradiation time. Therefore, a computational model had to be developed which is based on the assumption that the total time-dependent temperature drift at a given measurement point can be calculated by the undisturbed superposition of the corresponding temperature drifts caused by each raster spot. Thus, the temperature evolution over a total time of 200 s of only a single pencil beam applied for 32 ms to the center of the water calorimeter was calculated within a rotational symmetric 2D model. The corresponding time and space dependent temperatures $T(t, r)$ at the position $z$ corresponding to the water depth of the calorimetric detector were recorded with 1 ms resolution in time and with 0.1 mm resolution in space for $r = 0$ to $r = 60$ mm. In principle, the temperatures $T(t,r)$ are the same for each spot of the raster scan but a translation in space $r$ and in time $t$ according to the real spatial irradiation pattern and the real time structure used in the calorimetric measurement has to be considered. Then, the total temperature rise with respect to the measurement position of the thermistor probe can be simulated by superimposing the temperature drifts of each spot.

For the finite element calculations of the single pencil beam, the water phantom including the flat glass walls of the detector cylinder was approximated in a rotational symmetric 2D geometry model with the lateral dose distribution of the spot considered by a symmetric 2D Gaussian distribution (figure 2). The dose distribution in $z$-direction was taken from the measured dose $d$ (figure 3).

Prior to its application, this kind of convolution model was validated in detail for different raster scan patterns comprising only a few pencil beams with different widths. By comparing the corresponding results with the results of full 3D heat conduction calculations, agreement within 0.2% was found. A very similar approach for the calculation of heat conduction effects in scanned ion beams as used here has been independently developed at the Dutch metrology institute VSL (Zavgorodnyaya 2015). It has been shown that this convolution model is suitable for both homogeneous and inhomogeneous irradiation fields realizing a fast and flexible method easily applicable to different scanning patterns.

The factor $k_l$ in equation (6) corrects the non-uniformity of the lateral dose distribution, which causes a difference between the value of $D_{w,Q}$ measured off-axis with each thermistor of the calorimetric detector and the value of $D_{w,Q}$ at the central axis of the radiation field. The position-dependent $k_l$ values can be evaluated either from the measured lateral dose profiles by interpolating the corresponding data to the individual thermistor position or from the calculated dose profiles using the modified raster spot positions and the measured pencil beam width (section 3.1).

The perturbation correction $k_p$ accounts for the change of the radiation field due to the presence of the calorimetric detector and has been determined experimentally by using a ‘dummy detector’ in combination with the thimble IC TM30013 (PTW). By turns, measurements have been performed with the IC placed inside the water phantom of the calorimeter with and without the surrounding ‘dummy’ glass cylinder. In total, 16 (11) measurements were performed
without (with) the ‘dummy detector’. Moreover, the radiation field perturbation factor has been verified via a Monte Carlo simulation (section 2.5) by comparing the dose deposition with and without the presence of the glass cylinder at the measurement position of the thermistor probes.

The correction $k_T$ accounts for the effect of the difference in the water temperature between the calorimetric measurements ($4 \degree C$) and the IC calibrations (about $18 \degree C$). This correction must be applied to the calorimetrically determined value of $D_{w,Q}$ in order to obtain its value at $18 \degree C$. Depending on the difference in density between water of $4 \degree C$ and $18 \degree C$ and considering the very small depth dose gradient of $-0.023\% \text{ mm}^{-1}$ at the measurement position of the water calorimeter, it was found that the $k_T$ values were generally very small. A value of $k_T = 0.9990$ with a relative standard uncertainty of $0.01\%$ was considered for the calorimetric $D_{w,Q}$ determination.

A further correction $k_e$ was considered for the change in the thermistor’s electrical power during an irradiation, as a change in the thermistor’s electrical power also changes the difference between the thermistor temperature and the temperature of the surrounding water. Based on the set-up of the resistance measuring circuit as well as the thermal coupling between thermistor and water, $k_e$ was calculated to $1.0004$.

### 2.4.2. IC measurements.

Within this investigation, $N_{D,w,Q}$ and thus the $k_Q$ factors for carbon ions have been determined for the two Farmer-type ICs FC65-G by IBA (Schwarzenbruck, Germany), and TM30013 by PTW (Freiburg, Germany) having a sensitive volume of $0.65 \text{ cm}^3$ (height: $23 \text{ mm}$, diameter: $6.2 \text{ mm}$) and $0.60 \text{ cm}^3$ (height: $23 \text{ mm}$, diameter: $6.1 \text{ mm}$), respectively. Prior to their use at HIT, $N_{D,w,Co}$ for both chambers has been determined in the $^{60}\text{Co}$ reference field at PTB with a relative standard uncertainty of $0.25\%$.

The measurements with the thimble ICs at HIT were performed directly after the calorimetric measurements. After the water temperature in the phantom of the calorimeter had been increased to about $18 \degree C$, the reference point of the IC was positioned at the same depth of water in the phantom of the calorimeter as the calorimetric detector during the calorimetric measurements. By using an ionometric measuring system developed by PTB, the IC charge, the water temperature inside the calorimeter phantom, and the ambient air pressure were recorded during the irradiation with a sample rate of $1 \text{ Hz}$, allowing continuous correction of the IC reading $M_Q$ for the influence of air temperature and pressure. Analogue to the analysis of the calorimetric measurement data, the integral radiation-induced charge has been determined by extrapolating the linear fits of the pre- and post-irradiation drift curves to the mid-run position. The chambers were operated at voltages of $+300 \text{ V (FC65-G)}$ and $+400 \text{ V (TM30013)}$, respectively. In total, 100 (90) measurements were performed with the FC65-G (TM30013) chamber over the course of all three BTs. The relative standard deviation of the measurements was found to be $0.3\%$, which is consistent with the observed long-term reproducibility of the irradiation conditions discussed in section 2.2. The required corrections for the saturation effect and for the polarity effect, $k_s$ and $k_p$, were determined experimentally following the procedures described in DIN 6801-1.

The exact computation of the volume correction $k_v$ (equation (3)) would require both the knowledge of the dose response function of the IC, which is a measure of the chamber’s ability for spatial resolution (Looe et al 2013, 2015), and the dose distribution itself. Extensive work has been recently carried out to measure dose response functions for commonly used ICs with respect to photon beams (e.g. Butler et al 2015, Ketelhut and Kapsch 2015 and references therein). However, this concept has not yet been transferred from the dosimetry of photon beams to the dosimetry of ion beams. On the other hand, it can be expected that in smoothly-varying dose distributions without steep dose gradients the method of simple spatial
averaging over the cross-sectional area of the IC already provides a sound approximation for $k_v$. Therefore, the lateral dose distribution has been numerically integrated over the cross-sectional area of the IC perpendicular to the beam axis without considering their real cylindrical form. The volume correction factor is then given by the ratio of the relative dose value at the position of the reference point of the chamber (located at the central axis) and the result of the integration. Thus, the method is based on the mean relative lateral dose distribution measured with the STARCHECK array with the corresponding vertical and horizontal profiles shown in figure 7. A second approach is based on the calculated 2D dose distribution using the modified raster spot positions derived from the original irradiation records (see section 3.1).

2.5. Monte Carlo simulations

Monte Carlo (MC) simulations have been performed using the FLUKA code version 2011.2c.0 (Ferrari et al 2005, Böhlen et al 2014) to provide more information about the ‘quality’ of the radiation by simulating the LET distribution of the particle spectrum at the actual measurement position as well as the contribution of the different particles to the total deposited dose. Furthermore, FLUKA has been used to calculate the perturbation correction $k_P$ of the calorimetric detector. The real measurement condition of the water calorimeter, i.e. all materials including Styrofoam insulation and its inhomogeneous composition, water phantom, and glass cylinder of the calorimetric detector, has been implemented in FLUKA and verified by comparing the simulated $ddd$ with the corresponding measured $ddd$. The deviation between
experimental and simulated data has shown to be in the order of 0.2pp (percentage points) in the entrance channel, maximal 2.0pp in the raising shoulder of the Bragg peak and about 0.4pp in the tail region. Since the calorimetric measurements are performed in the entrance channel of the ion beam with a very small gradient of the $dE/dx$, the impact of the differences seen in the raising area of the Bragg peak can be assumed to be minor. The distance between the water calorimeter surface and the synchrotron comprising the vacuum window and the BAMS of the beam nozzle has been taken into account by using the appropriate phase-space file provided by HIT (Tessonnier et al. 2016). The recommended default settings for hadron therapy, HADROTHE, were used. Moreover, full transport of light and heavy ions was activated, evaporation of heavy fragments considered, $\delta$-ray production by muons and charged hadrons deactivated, charged hadron transport step size decreased to a corresponding 0.5% loss of kinetic energy, and the transport cutoff in terms of kinetic energy reduced to 10keV for all charged hadrons. The absorbed dose deposited at the measurement position of the thermistor probes was estimated using USRBN in a water region of 1 mm thickness (approximately the sensitive area of the thermistor probes) and a cross-section of $30 \text{cm} \times 30 \text{cm}$. In addition to the scored dose deposited by all particles, $D_{all}$, the dose deposited by particles with atomic number $Z = 1$ to $Z = 6$ regardless of their mass number $M$, was determined via FLUKA’s auxscore card. The particle spectrum was estimated using FLUKA’s USRYIELD detector by scoring the particle yield $d^2N/(dLET \times dE)$ with respect to LET and energy $E$ in a cross-section of $30 \text{cm} \times 30 \text{cm}$ water at the measuring depth of the thermistor probes, with auxscore filtering the particle yield by atomic number $Z$.

3. Results and discussion

3.1. Lateral dose distribution

Figure 7 shows the relative lateral dose profiles as measured by means of the STARCHECK array within the inner $40 \text{mm} \times 40 \text{mm}$ area of the irradiated carbon ion field. Between the different BTs, the reproducibility, calculated as the mean value over the standard deviation for each data set per IC, amounts to 0.28%, demonstrating stable lateral dose distributions. Thus, for the determination of the field-dependent correction factors $k_l$ and $k_v$, mean relative lateral dose distributions were used.

The data in figure 7 shows pronounced dose inhomogeneities having a maximal difference of about 3% between the central beam and the marginal regions of the radiation field. These large deviations were not expected from the initial irradiation plan. Furthermore, by taking the data of the irradiation records regarding the spatial irradiation pattern, the number of particles delivered to each raster, and the measured width of the ion pencil beam, the 2D dose distribution can be calculated by superimposing the intensity distributions of each spot. As also shown in figure 7, the derived theoretical dose profiles in both horizontal and vertical direction indicate an almost homogenous irradiation field for all three BTs and thus show no agreement with the experimental data. A possible explanation for the disagreement could be deviations of the raster spot positions as regulated by the MWPC located in the beam nozzle. If single wires of the MWPC are not located at their nominal position but within the production tolerance of about $\pm 0.10 \text{mm}$, ion beams delivered to this specific position will have a systematic shift due to the misplaced MWPC wires, whereas the irradiation records of the MWPC would record the coordinates of the nominal raster spot position. It could be shown by repetitive simulations that by varying the position of single raster spots as recorded by the MWPC within $\pm 0.06 \text{mm}$, assuming a systematic shift of the corresponding MWPC wires, the measured relative lateral dose distributions in both horizontal and vertical direction can be well approximated by the
calculated profiles (figure 8). Although this hypothesis could not be verified experimentally yet, these slightly modified raster spot positions have been used for the calculation of the heat conduction correction $k_c$.

3.2. Particle spectrum

In order to specify the radiation quality of the carbon ion beam beyond the determination of $R_{res}$ (section 2.3), figure 9 summarizes the results of the MC simulation regarding the LET distribution of the particle spectrum as well as the contribution of primary particles and fragments to the total deposited dose. Although this additional information is not necessary for the comparison of the experimentally determined $k_Q$ factors with the theoretical $k_Q$ factors stated in current dosimetry protocols, it has been added in foresight as it might be of importance for continuing work. As expected, carbon ions ($Z = 6$) show the most narrow peak at the highest median LET of $11.3 \text{ keV } \mu\text{m}^{-1}$ corresponding to a kinetic energy of about $368 \text{ MeV/u}$. This value is in agreement with the expected energy loss of the primary carbon ions ($E = 429 \text{ MeV/u}$) passing the corresponding water-equivalent thickness from the synchrotron to the measurement position of the water calorimeter. The lightest particles with $Z = 1$ show the broadest peak at the lowest median LET of $0.4 \text{ keV } \mu\text{m}^{-1}$, while all other particles with $Z = 2-5$ are located in between. Protons, deuterons and tritons ($Z = 1$) dominate the particle spectrum with a fraction of 48%, whereas carbon ions only contribute with 39% to the total number of particles scored at the measurement position of the water calorimeter. However, due to the difference in LET, the total dose is mainly deposited by carbon ions (85%), while the dose contribution of particles with $Z = 1$ is only 8%. Helium ions ($Z = 2$) make 10% of the total number of particles, while their contribution to the deposited dose is only 3%. Lithium ($Z = 3$), beryllium ($Z = 4$), and boron ($Z = 5$) are rare in the spectrum (less than 2% each) and deposit about 4% of the total dose all together. Particles with higher $Z$ have not been explicitly considered in the simulation, since the sum over the doses from $Z = 1$ to 6 agrees within 99.8% with the total deposited dose scored independent of particle type. Thus, target fragments like oxygen and other heavier fragments only contribute with 0.2% to the total deposited dose and are therefore neglected in the particle spectrum shown.

Figure 8. Comparison of the measured mean lateral dose distributions in horizontal and in vertical direction with the corresponding calculated profiles on the basis of the modified raster spot positions.
3.3. Correction factors for calorimetric $D_{w,Q}$ determination

The $k_l$ factors are directly given by the reciprocal of the interpolated relative dose at the individual thermistor position, as the dose profiles in figures 7 and 8 have been normalized to the value at the central axis of the irradiation field. Differences well below 0.2% occur if either the mean relative lateral dose distribution measured with the STARCHECK array or the calculated relative dose distribution using the modified raster spot positions of the MWPC is used for the $k_l$ determination. The mean of both approaches was taken as the true thermistor-specific $k_l$ values. Depending on the specific thermistor position, values for $k_l$ lie between 1.0071 and 1.014 with a mean relative uncertainty of 0.36% dominated by the uncertainty of the measured mean lateral dose distribution. In addition, positioning uncertainties of the calorimeter, which are conservatively assumed to $\pm 1\, \text{mm}$, cause a possible variation of the $k_l$ values within a relative standard measurement uncertainty of 0.14%, which is separately addressed in the overall uncertainty budget for the $k_Q$ determination (table 2).

The perturbation correction $k_P$ was determined as the mean ratio of IC measurements without and with the glass cylinder of the calorimetric detector present to $k_P = 1.0021$ with a relative standard error of the mean of only 0.07%. This uncertainty contribution already includes the effects from small positioning variations of the IC during the course of measurements. Nevertheless, a possible systematic difference between the real calorimetric and the ‘dummy detector’ geometry (e.g. absence of thermistor probes) must be considered and is accounted for by an assumed uncertainty contribution of 0.2%. Thus, $k_P$ was taken to 1.0021 with an overall relative standard uncertainty of 0.21%. As a result from the MC calculations, the value for $k_P$ was found to be 1.0014 and thus confirms the experimental result.

| $Z$ | $N_i/\sum N_i$ | $D_l/D_{all}$ |
|-----|----------------|--------------|
| 1   | 48.1%          | 8.4% ± 0.8%  |
| 2   | 10.0%          | 2.8% ± 0.8%  |
| 3   | 1.1%           | 0.6% ± 1.0%  |
| 4   | 0.6%           | 0.7% ± 1.4%  |
| 5   | 1.6%           | 2.4% ± 0.3%  |
| 6   | 38.6%          | 84.9% ± 0.1% |

rest 0.2%

Figure 9. The figure summarizes the results of the MC simulation at the measurement position of the water calorimeter showing (I) the yield of the different particles (number of particles, $N$, per primary simulated particle, $N_0$) with respect to LET in water (median LET highlighted), (II) the percentage of the different particles with respect to the total number of particles scored, as well as their (III) percental contribution to the total deposited dose. The errors given for the dose estimation are directly taken from the MC simulation and thus only consider statistical uncertainties.

\[ \text{LET}(Z=1): 0.4 \text{ keV}/\mu\text{m} \]
\[ \text{LET}(Z=2): 1.2 \text{ keV}/\mu\text{m} \]
\[ \text{LET}(Z=3): 2.8 \text{ keV}/\mu\text{m} \]
\[ \text{LET}(Z=4): 5.0 \text{ keV}/\mu\text{m} \]
\[ \text{LET}(Z=5): 7.8 \text{ keV}/\mu\text{m} \]
\[ \text{LET}(Z=6): 11.3 \text{ keV}/\mu\text{m} \]
By means of the convolution method (section 2.4.1), the heat conduction correction $k_c$ was determined to 1.0177 within a relative standard uncertainty of 0.50% using the slightly modified raster spot positions according to the knowledge gained from the measured lateral dose distribution (section 3.1), the measured size of the pencil beam (figure 2), and a mean time structure with a total irradiation time of 95 s. The value for $k_c$ is given here as a position-independent heat conduction correction, as the variations of $k_c$ for the different thermistor positions were found to be less than 0.2%, which is therefore incorporated in the given standard uncertainty. Additionally, the uncertainty for $k_c$ comprises the following components: (I) Variations of the time structure occurring from irradiation to irradiation due to different numbers of ‘spills’ delivered from the synchrotron as well as variations of the lateral dose distribution between different BTs are accounted for by performing calculus of variations using the measured fluctuation range. This component contributes to the total uncertainty with about 0.3%. (II) Uncertainties of the applied convolution model especially with respect to the complex raster pattern and the influence of the detector cylinder wall on raster spots positioned close by are also estimated to be approx. 0.3%. (III) Usually, the exact time evolution of the series of consecutive irradiations is considered in the heat transport calculations (Krauss 2006). This method, however, would lead to almost impractical data handling for the convolution method used here. Therefore, to further validate the convolution method, full heat conduction calculations were performed for a static irradiation field. It was assumed that the lateral dose distribution discussed in section 3.1 was permanently applied during an irradiation time of 95 s. Further, in order to estimate the influence of the consecutive irradiations, the heat conduction calculations have been performed for a series of 10 irradiations interrupted by breaks of 3 min. Maximal differences between the irradiation specific $k_c$‘s were found to be 0.2% with a mean $k_c$ value of 1.0118. Thus, this variation is considered as an additional contribution to the overall uncertainty of the irradiation independent heat conduction correction. (IV) The uncertainty of the geometrical water calorimeter model as well as the thermal parameters used within the finite element calculations is assumed to contribute approx. 0.1% to $k_c$.

### 3.4. Correction factors for IC measurements

According to the procedure described in DIN 6801-1, $k_c$ has been determined to 1.0022 (1.0023) for the FC65-G (TM30013) chamber operated at +300 V (+400 V). Via calculus of variations, where the number of data points in the Jaffé diagram has been slightly varied and its impact on the resulting $k_c$ value studied, the total measurement uncertainty for $k_c$ was estimated at 0.22% for both chambers including a small uncertainty contribution from the fit parameters used with respect to the analysis of the Jaffé diagram.

Table 1. Summary of main correction factors required for the determination of $k_Q$, separated into corrections required for the calorimetric and ionometric measurements, respectively.

| Calorimetric corrections | Ionometric corrections |
|--------------------------|-----------------------|
| $k_l$                    | $k_s$ | 1.0102$^a$ | 1.0013$^a$ |
| $k_c$                    | $k_p$ | 1.0177$^a$ | 1.0003$^a$ |
| $k_P$                    | $k_v$ | 1.0021    | 1.0129    |

$^a$ Mean values for the corresponding correction.
The polarity corrections $k_p$ have been determined to 1.0012 (0.9993) for the FC65-G (TM30013) chamber. The relative standard uncertainty was found to be 0.07% in both cases dominated by the standard error of the mean of the repeated measurements.

However, for the determination of $k_Q$ the ratio of $k_s$ as well as $k_p$ between carbon ions and $^{60}$Co as reference beam quality is required with $k_s,Co = 1.001$ (for both chambers) and $k_p,Co = 1.001$ ($k_p,Co = 0.999$) for the FC65-G (TM30013) chamber as taken from the calibration certificates.

The volume correction factor $k_v$ of the ICs (section 2.4.2) was found to be 1.0129 on average. The relative standard uncertainties are taken to be 0.26% comprising an assumed uncertainty contribution of 0.20% for the simplified method for the determination of $k_v$ itself and 0.17% from the mean lateral dose distribution measured with the STARCHECK array (figure 7). Analogue to the lateral positioning uncertainty of the thermistor probes, an additional uncertainty contribution of 0.10% to $k_v$ results from possible positioning uncertainties ($\pm 1$ mm) of the IC.

In summary, the main correction factors required for the calorimetric $D_{w,Q}$ determination and the ionometric measurements are given in table 1.
3.5. $k_Q$ factors for FC65-G and TM30013 chamber and uncertainty budget

The combined standard measurement uncertainties of the $N_{D,w,Q}$ and the $k_Q$ factors were evaluated in accordance with the recommendations of the GUM, Guide to the Expression of Uncertainty in Measurement (JCGM 2008). They are composed of the uncertainty contributions from the calorimetrically determined $D_{w,Q}$ (as the mean of the absorbed dose values from both thermistors), the ionometric measurement of $M_Q$, as well as the uncertainty of the calibration factor $N_{D,w,Co}$. Because both $N_{D,w,Q}$ and $N_{D,w,Co}$ are determined by use of water calorimetry, the uncertainties for the specific heat capacity of water, for the heat defect, and for the uncertainty contribution caused by the Pt-25 standard thermometer used for the calibration of the thermistor probes are common in both cases and thus will be omitted in the calculation of the overall standard measurement uncertainty of $k_Q$ (Krauss and Kapsch 2007a, Krauss and Kapsch 2007b). Table 2 summarizes the complete uncertainty budget for the experimentally determined $N_{D,w,Q}$ and for the $k_Q$ factors. As the uncertainties for the ionometric measurements performed with both ICs are very similar, the uncertainty budget is valid for the $k_Q$ factors determined with both ICs. In addition to the uncertainties of the calorimetric and ionometric correction factors discussed in section 3.4 and 3.5, additional contributions need to be considered for the measured relative resistance change $\Delta R/R$ (0.15%) with the calorimeter, the charge measurement (0.09%) with the ICs as well as a 0.30% contribution for possible variations in the dose deposition occurring between the calorimetric and ionometric measurements (section 2.2). The first two mentioned contributions comprise statistical measurement uncertainties, uncertainties of the calorimetric and ionometric measurement systems and uncertainties introduced by the data analysis methods.

Figure 10. $k_Q$ factors for carbon ion beams, as determined with the water calorimeter for the different measurements performed between August 2014 and February 2015. The error bars indicate the standard uncertainty of 0.8% with the dashed line showing the mean value. See equations (4) and (5) for conversion into $k_Q^{TRS}$ and $k_Q^{DIN}$, respectively.
Thus, an overall standard measurement uncertainty of 0.82% for the $k_Q$ factors determined for each IC per calorimetric/ionometric BT has been achieved. The corresponding $k_Q$ factors are shown in figure 10 agreeing well within the given uncertainties. The final $k_Q$ factor per IC is taken to be the mean value of the three experimentally determined factors. Please note that the mean $k_Q$ values given in the figure need to be transformed into $k_Q^{\text{DIN}}$ (equation (4)) and $k_Q^{\text{TRS}}$ (equation (5)), respectively, in order to be used for the reference dosimetry of ion beams according to DIN 6801-1 (DIN 2016) and TRS-398 (Andreo et al 2006). The corresponding $k_Q^{\text{DIN}}$ and $k_Q^{\text{TRS}}$ values are summarized in table 3 and are compared to the data from literature.

### 4. Discussion and conclusions

It has been shown for the first time that the experimental determination of the $k_Q$ factor for carbon ion beams by means of water calorimetry is achievable with a relative standard measurement uncertainty of 0.8%. This corresponds to about a threefold reduction of the uncertainty compared to calculated values and therefore enables the significant reduction of the overall uncertainty related to ionization-based dosimetry of clinical carbon ion beams. The comparison between theoretical and experimental $k_Q$ factors given in table 3 shows that, with respect to DIN 6801-1, the experimentally determined $k_Q^{\text{DIN}}$ values for both chambers having a similar design are about 1% larger than the theoretical ones. However, the same tendency is not observable with respect to TRS-398. While for the TM30013 chamber the experimentally determined $k_Q^{\text{TRS}}$ value is about 0.4% larger than the corresponding literature value, it is about 1% lower than the theoretical value in the case of the FC65-G chamber. In order to further investigate the inconsistency between measured and calculated $k_Q$ factors allowing to draw a conclusive statement with respect to literature values, more experimental data is needed.

Nevertheless, the increased accuracy of the experimentally determined $k_Q$ factor might open up the possibility to gain further insight and to validate individual components of the calculated $k_Q$ factor for ion beams such as the $(W_{\text{air}}/e)_Q$ value or the stopping-power-ratio $(s_{\text{w,air}})_Q$, which—up to now—dominate the overall uncertainty of the calculated $k_Q$ factor. For example, using the individual values (including their standard uncertainties) for the different parameters of equation (1) given in TRS-398 and DIN 6801-1, respectively, an ‘experimental’ value for $W_{\text{air}}/e$ can be deduced from the experimentally determined $k_Q^{\text{TRS}}$ and $k_Q^{\text{DIN}}$ values. With respect to the TM30013 chamber (table 3), the ‘experimental’ value for $W_{\text{air}}/e$ amounts to $W_{\text{air}}/e = (34.62 \pm 0.87) \text{ J/C}$ and to $W_{\text{air}}/e = (34.97 \pm 0.64) \text{ J/C}$ according to the TRS-398 and the DIN 6801-1 protocol, respectively. Within their standard uncertainties, both values are

|                | TM30013 | FC65-G |
|----------------|---------|--------|
| Literature     | 1.014 ± 2.2% | 1.032 ± 2.8% |
| Calorimetry    | 1.026 ± 0.8% | 1.036 ± 0.8% |
| Δ%/ Literature | −1.2%   | −0.4%  |
| Calorimetry    | 1.012 ± 2.2% | 1.042 ± 2.8% |
| Δ%/ Calorimetry| −0.9%   | +1.1%  |

Table 3. Comparison of the experimental $k_Q^{\text{TRS}}$ and $k_Q^{\text{DIN}}$ factors (see equations (4) and (5)) determined by means of water calorimetry in the clinical carbon ion beam at HIT with the calculated $k_Q$ values for ion beams as stated in TRS-398 and DIN 6801-1. The uncertainties given are the standard uncertainties for the experimental and calculated $k_Q$ values, respectively.
in agreement with the theoretical values $W_{\text{air/e}} = (34.50 \pm 0.52)$ J/C given in TRS-398 and $W_{\text{air/e}} = (34.71 \pm 0.52)$ J/C given in the new recommendations of the ICRU (ICRU 2016). The 1% discrepancy between both ‘experimental’ $W_{\text{air/e}}$ values are mainly caused by the different stopping-power data ($s_{\text{w,air}}$) considered by the TRS-398 and the DIN protocol. In comparison, Sakama et al (2009) found a mean value of $(35.72 \pm 0.54)$ J/C for carbon ion beams having an initial energy between 135 MeV/u and 430 MeV/u by means of graphite calorimetry, which is about 3.5% larger than the literature value. Preliminary results obtained by Rossomme et al (2014) in an 80 MeV/u carbon ion beam also by means of graphite calorimetry indicate a $W_{\text{air/e}}$ value of $(35.50 \pm 0.90)$ J/C and are thus in good agreement with the mean value found by Sakama et al (2009).

Besides precise calorimetric and ionometric measurements, the low uncertainty of the experimental $k_Q$ factors could only be reached by a detailed characterization and monitoring of the irradiation field. Most importantly, it was found that accurate knowledge of the lateral dose distribution is essential in order to determine the corresponding calorimetric (i.e. $k_c$ and $k_l$) and ionometric correction factors (i.e. $k_v$) with sufficient accuracy, as the simple assumption of a homogeneous dose distribution as predicted by the irradiation plan would lead to severe mistakes. For example, in the case of the volume correction factor $k_v$ it turns out that this correction should not be neglected since especially scanned ion beams tend to exhibit intrinsic inhomogeneities with partly significant dose gradients.

The total standard measurement uncertainty of the experimentally determined $k_Q$ factor for carbon ion beams could potentially be further decreased by using a more advanced 2D dosimetry device in order to determine the lateral dose distribution with higher accuracy and spatial resolution compared to the STARCHECK array. In addition, the investigation of spatial dose response functions of ICs with respect to carbon ion beams to enable a sound determination of $k_v$ would be desirable in order to converge to the same level of dosimetric accuracy as that of conventional high-energy photon beams.

As a projection of this investigation, it would be highly desirable to extend the experimental determination of the $k_Q$ factor by means of water calorimetry to different energies and different particle species (e.g. p, He, O). Even more conclusive results with respect to the comparison with calculated $k_Q$ values stated in literature as well as the possibility to investigate a potential energy/LET dependency of the $k_Q$ factor are expected from these additional measurements. Furthermore, as graphite calorimetry is also commonly used as a primary standard for absorbed dose to water in many standard laboratories worldwide (Seuntjens and Duane 2009), a direct comparison of water and graphite calorimetry in a clinical (scanned) carbon ion beam would be of great importance in order to further validate the experimental results found in this investigation.

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