



# FINAL PUBLISHABLE REPORT

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 Project  $k_Q$  factors in modern external beam radiotherapy applications to update IAEA TRS-398

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## 1 Overview

The purpose of the present project was to contribute, by measuring and calculating  $k_{Q,Q_0}$  factors, towards the update of the ‘Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry based on Standards of Absorbed Dose to Water’, by the International Atomic Energy Agency (IAEA). The fundamental contribution made by the project towards this update was on a self-assessment of all generated dataset, via internal comparisons, before their submission to the IAEA.

Data generated such as  $p_Q$  and  $k_{Q,Q_0}$  factors for a range of ionization chamber types, and multiple radiation beam modalities (e.g. latest beam technologies), were submitted to contribute towards this update on medium energy x-rays, conventional (filtered) and flattening filter free (FFF) MV photons, and scanned proton beam modalities.

## 2 Need

Prior to the start of this project, 3.4 million Europeans were diagnosed with cancer every year and about half of the resulting treatments involve radiation therapy with ionising radiation. Accurate beam delivery and dosimetry are critical for successful and safe treatments. Hospital physicists are therefore required to perform measurements in accordance with validated measurement codes of practice or protocols, ensuring that doses delivered to patients at European hospitals are traceable to the quantity ‘absorbed dose to water’ measured in the SI unit gray (Gy). It is important that such a protocol is to be able to correct the dosimeter response for differences between the beam quality, which relates to the energy distribution of the radiation field, at the calibration laboratory ( $Q_0$ ) and the beam qualities at the hospitals ( $Q$ ). These corrections are called ‘beam quality correction factors’ and are known as  $k_{Q,Q_0}$ .

The IAEA issued such a Code of Practice (the ‘TRS-398’) in 2000, which is the *de facto* norm for external beam radiotherapy dosimetry and is used on a worldwide basis. The data in TRS-398 include values of  $k_{Q,Q_0}$  factors that were calculated for clinical radiotherapy beams over the entire range of beam modalities that were available in the mid-1990s. Since the IAEA TRS-398 Code of Practice was first published, there have been significant advances in at least four areas: (i) treatment technology, including new beam modalities such as scanned proton beams, and flattening filter free photon beams, (ii) detector technology, *i.e.* new ionisation chamber types, (iii) improved metrology including the availability of new primary standards, and (iv) improved Monte Carlo simulation techniques. Prior to the start of the project, a major revision of 6 chapters of the IAEA TRS-398 was initiated in 2016 with a planned completion in 2019. New measured and calculated  $k_{Q,Q_0}$  factors based on modern treatment modalities, equipment, and computational codes were therefore required for this update. Therefore, the present project followed the IAEA call for organisations, and established consortia, to determine and provide up-to-date data for the TRS-398 update. The main goal of the present project included  $k_{Q,Q_0}$  factors traceable to absorbed dose to water primary standards needed to be measured and calculated for a selection of beam modalities and ionising radiation dosimeters (ionisation chambers).

## 3 Objectives

The overall objective of this project was to provide validated measured and calculated values of  $k_{Q,Q_0}$  factors for a series of ionisation chambers and a range of radiation beam modalities, which will contribute to the on-going revision of the Code of Practice IAEA TRS-398.

The specific objectives of the project were:

1. **kV x-ray beams between 100 kV and 250 kV:** (i) to measure  $k_{Q,Q_0}$  factors for 3 types of ionisation chambers and at least 8 beam qualities, ensuring direct traceability of the  $k_{Q,Q_0}$  factors to primary standards of absorbed dose to water; (ii) to calculate  $k_{Q,Q_0}$  factors for these beams using several validated Monte Carlo codes; (iii) to compare the new absorbed dose-to-water based formalism using  $k_{Q,Q_0}$  with a traditional air-kerma based formalism; iv) to compare the measured and calculated  $k_{Q,Q_0}$  factors for kV x-ray beams, and to provide IAEA with a validated consistent new dataset of  $k_{Q,Q_0}$  factors with target standard uncertainties better than 1.0 %.
2. **High-energy- (MV) photon beams between 4 MV and 20 MV, including flattening filter free beams (FFF):** (i) to measure  $k_{Q,Q_0}$  factors for at least 6 types of ionisation chambers and a range of beam qualities, ensuring direct traceability of the  $k_{Q,Q_0}$  factors to primary standards of absorbed dose

to water; (ii) to calculate  $k_{Q,Q_0}$  factors for these beams using several validated Monte Carlo codes; (iii) to compare the measured and calculated  $k_{Q,Q_0}$  factors for high-energy (MV) photon beams, and to provide IAEA with a validated consistent new dataset of  $k_{Q,Q_0}$  factors with target standard uncertainties better than 0.7 %.

3. **Scanned proton beams between 60 MeV and 250 MeV:** (i) to measure  $k_{Q,Q_0}$  factors for at least 4 types of ionisation chambers and a range of beam qualities, ensuring direct traceability of the  $k_{Q,Q_0}$  factors to primary standards of absorbed dose to water; (ii) to calculate  $k_{Q,Q_0}$  factors for these beams using several validated Monte Carlo codes; (iii) to compare the measured and calculated  $k_{Q,Q_0}$  factors for scanned proton beams, and to provide IAEA with a validated consistent new dataset of  $k_{Q,Q_0}$  factors with target standard uncertainties better than 2.0 %.
4. To work closely with the IAEA task group 'Update of TRS-398', to ensure that the outputs of the project are aligned with their needs toward the revision of the Code of Practice, therefore providing experimental and calculated data that can be incorporated in the upcoming revision of the Code of Practice. To facilitate the take up of the project's outputs by the end-users e.g. clinics, hospitals and manufacturers of ionisation chambers.

## 4 Results

### 4.1 Objective 1: kV x-ray beams between 100 kV and 250 kV

Dosimetry in radiotherapy treatments using kV x-ray beams (generated using vacuum tubes with operating voltages between 100 kV and 250 kV) was based at the beginning of the project, on primary standards of the dosimetric quantity *air kerma* ( $K_a$ ). To perform dosimetry in terms of the quantity *absorbed dose to water* ( $D_w$ ), the quantity of interest in radiotherapy dosimetry, a conversion procedure was therefore required. This conversion procedure, however, introduces additional uncertainties and may even lead to potential errors. In principle, a more desirable route to traceability would be to directly use absorbed dose to water primary standards as a starting point. However ideal, this approach suffers from the problem that only few such standards are available worldwide, and that only limited number of beam qualities have been realised by the primary standards laboratories, which often do not include the quality of interest of the final user. The limited availability of beam qualities was important also from the perspective that previous studies have found that the chamber-to-chamber variability (e.g. differences in physical dimensions of specific ionization chambers of the same model type, and reproducibility of the material composition across different lots of production) do not allow a reliable use of generic, *i.e.* chamber model-specific  $k_{Q,Q_0}$  correction factors representing model-specific changes in dose-to-water calibration coefficients from one beam quality ( $Q$ ) to a reference beam quality ( $Q_0$ )<sup>1</sup>.

To support the IAEA with data for specific ionization chambers and to help decide which traceability route to follow in the revised TRS-398 code of practice, the present project put together three national metrology institutes, VSL, LNHB, and ENEA, that had recently established their own primary standards of absorbed dose to water in kV x-ray dosimetry. Using such standards, as well as their more established standards of *air kerma*, the present project characterized cylindrical ionization chambers used clinically in Europe in kV x-ray beams using both air-kerma and absorbed-dose-to-water primary standards. These two approaches allowed the determination of correction factors,  $k_{Q,Q_0}$  in the context of the  $D_w$  traceability route, to account for the differences between the final user quality  $Q$  and the qualities realised at the primary standards dosimetry laboratory,  $Q_0$ , and  $p_Q$  factors, again chamber model-specific, required in the air-kerma traceability route. Both  $k_{Q,Q_0}$  and  $p_Q$  factors were determined, independently, using experiments at VSL, LNHB, and ENEA, and by Monte Carlo modelling by THM, IST-ID, and ENEA.

#### Traceability routes

The project studied two traceability routes for determination of absorbed dose to water,  $D_w$  in kV x-ray beams: the direct  $D_w$ -route and the indirect  $K_a$ -route.

<sup>1</sup> The subscript '0' in  $Q_0$  can be omitted in the context of  $k_{Q,Q_0}$  factors in MV photon energies, where the reference quality is that of  $^{60}\text{Co}$  sources. In the domain of kV x-rays, however, the quality  $Q_0$  is not set to that of  $^{60}\text{Co}$  because the latter is energetically too distant from the energies that are of interest in kV x-ray dosimetry.

*Direct  $D_w$ -route:* The absorbed dose to water,  $D_{w,Q}$ , in the user beam quality  $Q$  is determined by applying an absorbed dose to water calibration coefficient,  $N_{D_{w,Q}}$ , which was obtained by direct calibration of the recommended ion chambers in terms of absorbed dose to water,  $D_{w,Q}$ , against a primary standard:

$$D_{w,Q} = M_Q N_{D_{w,Q}} \quad (1)$$

Where in (1),  $M_Q$  is the reading of the ionization chamber in the beam quality  $Q$ , corrected for all influence quantities and referred to standard atmospheric conditions. When the primary standards dosimetry laboratory cannot realize the quantity  $D_{w,Q}$  in the user's beam quality  $Q$ , another step is necessary to derive the calibration coefficient  $N_{D_{w,Q}}$  (eq. 1) from the calibration coefficient of the same chamber, provided for the PSDL's beam quality  $Q_0$ ,  $N_{D_{w,Q_0}}$ . That is detailed in eq. (2):

$$D_{w,Q} = M_Q N_{D_{w,Q_0}} k_{Q,Q_0} \quad (2)$$

where  $k_{Q,Q_0}$  is the beam quality correction factor such that  $N_{D_{w,Q}} = N_{D_{w,Q_0}} k_{Q,Q_0}$ .

*Indirect  $K_a$ -route:* The absorbed dose to water,  $D_{w,Q}$ , in the user beam quality  $Q$  is determined by applying the ion chamber air-kerma calibration coefficient,  $N_{K,Q}$ , which was obtained by the calibration of the recommended ion chambers in terms of air-kerma,  $K_a$ , directly in the user beam quality  $Q$ . The ion chamber is placed in water and conversion from air-kerma in water to absorbed dose to water  $D_{w,Q}$  is done by multiplication by the ratio of mass-energy absorption coefficients of water and air averaged over the spectral energy fluence in the water phantom at the reference depth,  $(\bar{\mu}_{en}/\rho)_{w/air,Q}$ , and a beam quality, chamber model-dependent perturbation factor,  $p_Q$  that accounts for the replacement of water by the ionization chamber, for the effect on the chamber response of the difference in spectra at the chamber position for the calibration free in air and at the reference depth in the water phantom:

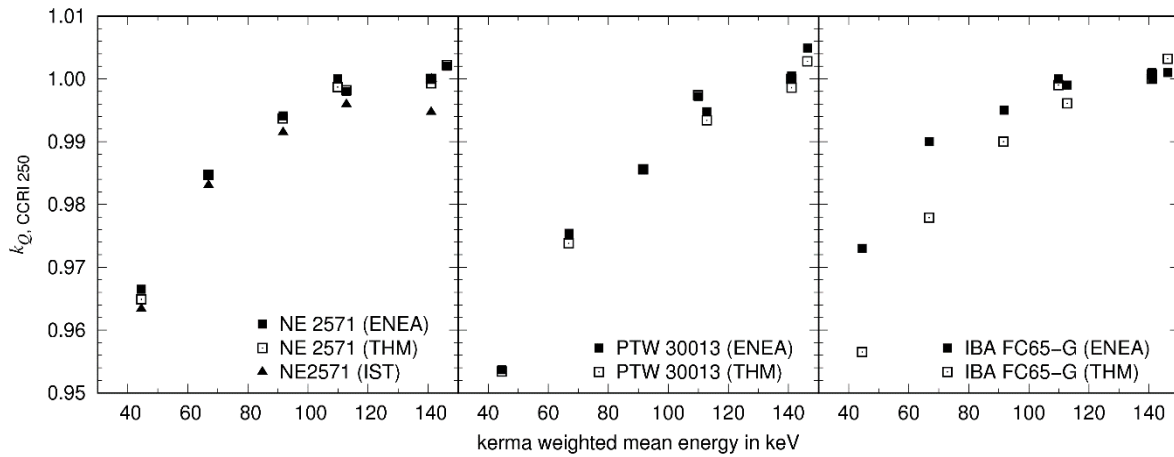
$$D_{w,Q} = M_Q N_{K,Q} (\bar{\mu}_{en}/\rho)_{w/air,Q} p_Q, \quad (3)$$

Both the  $D_w$  and  $K_a$  routes involve ion chamber measurements in a water phantom. However, in case of the  $D_w$ -route, equation (1) and (2), the ion chamber calibration coefficient is given in terms of absorbed dose to water.  $N_{D,w}$  is traceable to a primary absorbed dose to water primary standard. In case of the  $K_a$ -route, equation (3), the ion chamber calibration coefficient is given in terms of air-kerma, traceable to an air-kerma primary standard.

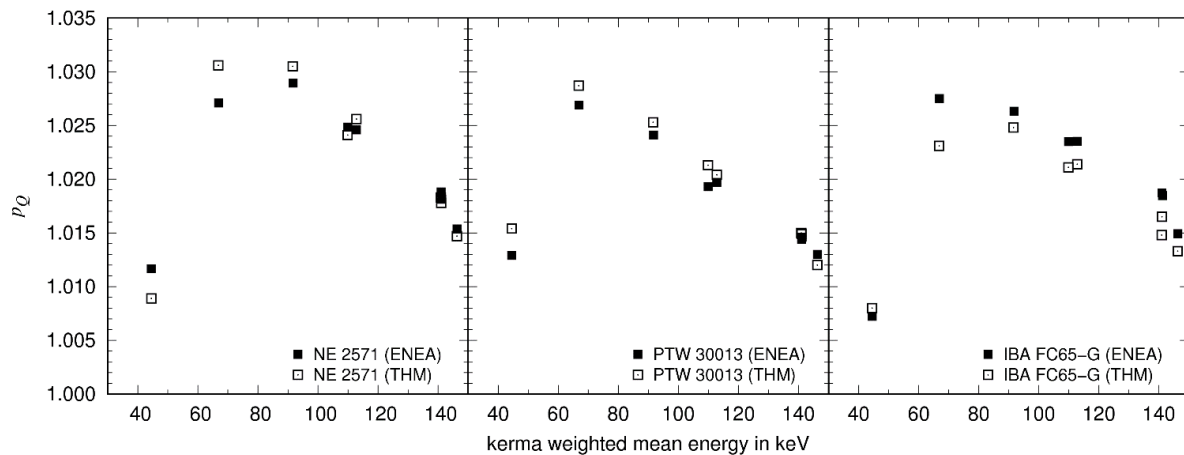
### Modelling $k_{Q,Q_0}$ and $p_Q$ datasets

Monte-Carlo modelling was carried out using mainly the EGSnrc code (THM, ENEA), and for one ionization chamber, also the PENELOPE code was used (IST-ID). All computations were carried out using ICRU-90 consistent data.

The  $k_{Q,Q_0}$  with CCRI 250 as reference beam quality and  $p_Q$  perturbation factors were computed by ENEA, THM and IST-ID for 6 different chamber models: NE2571, PTW 30013, PTW 31013, PTW 31010, and IBA FC65-G and FC65-GX. Representative results are shown in Fig. 1.1 and 1.2. Generally, there was good agreement between the three calculating laboratories, THM, ENEA, IST-ID, thanks to their preliminary efforts of comparing their independently generated computing geometries and having validated together the physics settings that pertain to the photon and electron transports. These proved key steps ensured results could be compared, and any differences could not be attributed to errors made by any given institute. The  $k_{Q,Q_0}$  and  $p_Q$  correction factors were in most cases less than 3 % within unity. The  $k_{Q,Q_0}$ -corrections tended to increase monotonically from about 0.97 at low mean photon energies to unity for higher energies. In contrast, the  $p_Q$  vs. mean energy tended to follow a parabolic relationship with a maximum value around 60 keV.



**Fig. 1.1:** Calculated beam quality correction factor  $k_Q$ , CCRI-250 as a function of kerma weighted mean energy. The calculations have been performed by ENEA, IST-ID and THM independently. The error bars are in the order of 0.2 %, given as Monte Carlo statistical uncertainty of 1  $\sigma$ , and are smaller than the symbol size. The difference between the values calculated by ENEA and THM is due to the fact that the two partners modelled two slightly different chamber types: the FC65-G (ENEA) and the FC65-GX (IST-ID), which differ both in the geometry itself and in the construction materials.



**Fig. 1.2:** Calculated perturbation factor  $p_Q$  as a function of kerma weighted mean energy for three different ion chambers. The calculations have been performed by ENEA and THM independently. The error bars are in the order of 0.2 %, given as Monte Carlo statistical uncertainty of 1  $\sigma$ . The error bars are smaller than the symbol size.

### Experimental datasets

Absorbed-dose-to-water and free-air-kerma primary standards were used by ENEA, CEA, and VSL. As shown in Fig. 1.3, ENEA used a graphite calorimeter in a water phantom for the absorbed dose to water measurements. CEA and VSL used water calorimetry. The VSL set-up is shown in Fig. 1.4.

$k_{Q,Q_0}$  and  $p_Q$  correction factors were measured for 3 ionization chamber models in 6 beam qualities in the range from 100 kV to 300 kV generating potential<sup>2</sup>. The chamber-to-chamber variability (expressed as a single standard deviation) typically was about 0.2 % for both for  $k_{Q,Q_0}$  and  $p_Q$  measurements. The combined standard uncertainty of the determinations typically was about 1 % ( $k=1$ ) at each individual laboratory but tended to increase at beam qualities centred on lower energies, where several effects stress the capacity of both water and graphite calorimeters to deliver accurate determinations of the quantity absorbed dose to water. To generate these datasets, accurate calculations had to be made starting from the determinations of the quantities air kerma, absorbed dose to water, and measurements done by the three laboratories on all chambers at all beam qualities, including measurements done after repeated positionings. Data were

<sup>2</sup> manuscript in preparation

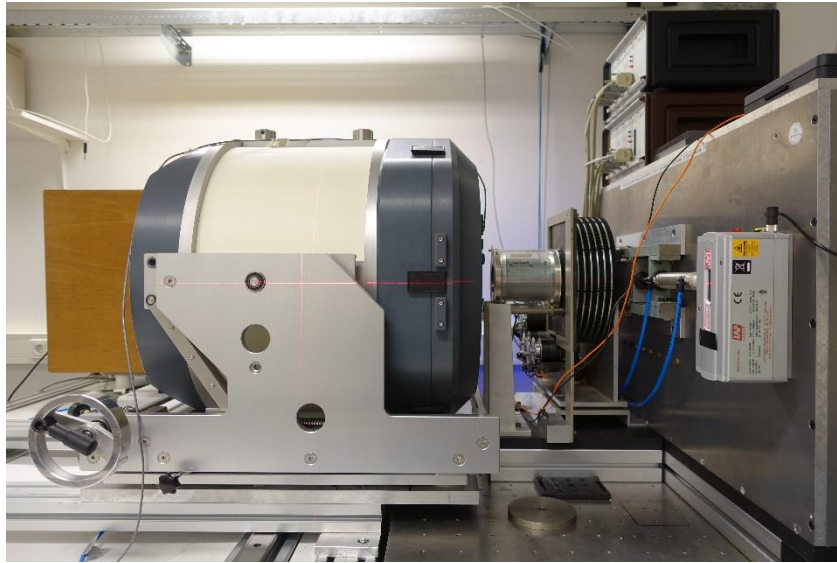
elaborated using spreadsheets and, independently, using Python scripts which were developed independently by two participants.

An important aspect that emerges upon comparing results compiled by the three participants is that their individual determinations of the quantity  $D_w$  at the beam qualities centred on the lower photon energies (qualities CCRI-100, CCRI-135) do not have the same level of agreement that they manifest at higher energies (see Fig. 1.5 for the case of the  $p_Q$  datasets). This is due to the complexity of the determination of  $D_w$  at low energies and in this domain of dosimetry, there has been a relatively short history of international comparisons, beginning in 2016 as part of EMRP HLT09 MetrExtRT Metrology for radiotherapy using complex radiation fields. Based on this baseline evidence, at such low photon energies, the advantages of obtaining a calibration coefficient directly traceable to a  $D_w$  primary standard, be this a graphite or a water calorimeter, were yet to be demonstrated.

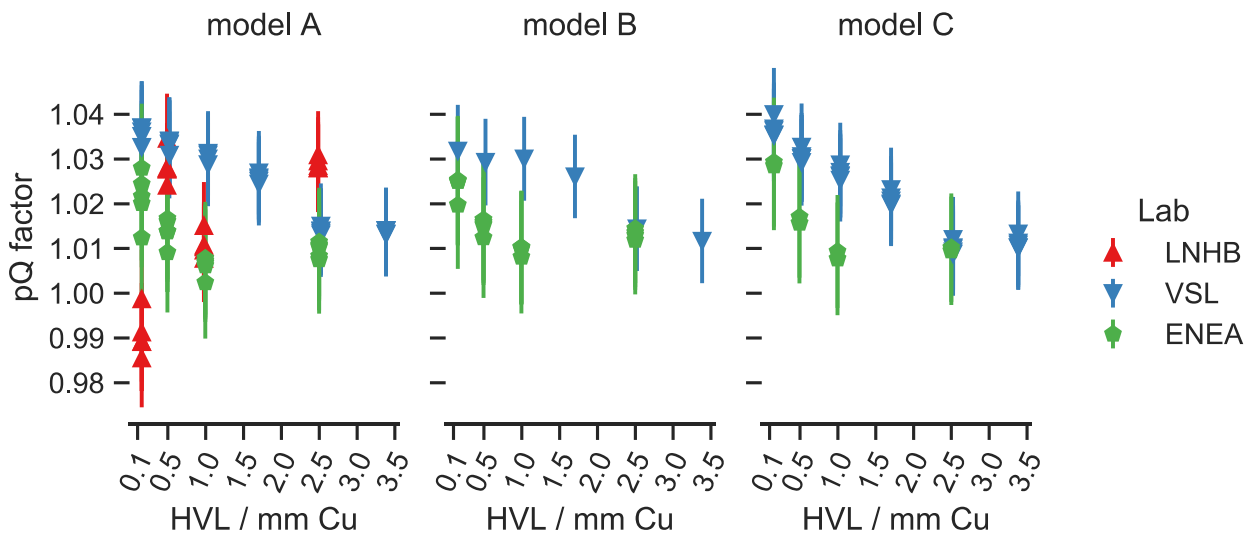
Importantly, it was evident from a comparison of the experimental and the Monte Carlo  $p_Q$  datasets (see Fig. 1.2 and 1.5) that the two datasets did not show the same trend with beam energy. While the Monte Carlo dataset manifested a parabolic shape (Fig. 1.2), the same cannot be said about the experimental dataset. This might be due to the relatively less accurate determination of the absorbed dose to water by the three primary standards involved in this work (the calorimeters at VSL, LNHB, ENEA), or also due to the limitation of the Monte Carlo geometric models of the chambers, which become ever more critical in the lower photon energy range.



**Fig. 1.3:** Representation of the technique and instruments used for the ENEA graphite calorimeter primary standard for kV x-rays. Measurements for the present project were done at 2 cm in water and SSD equal to 98 cm (The photograph shows the experimental setup at ENEA at an SSD of 70 cm).



**Fig. 1.4:** VSL water calorimeter primary standard for kV x-rays.



**Fig. 1.5:**  $p_Q$  factors determined by each participating institute for three chamber models. Data are plotted against the Half Value Layer in linear scale. Error bars indicate combined standard uncertainties ( $k=1$ ). LNHB contributed with chamber model A.

### Summary

Taken together, *Objective 1* was fulfilled in that the number of ionization chambers investigated was on target with the project aims. Data could only be provided for six radiation beams (of the eight initially planned) since the intensity of the calorimetric signal at two such qualities was insufficient. The combined standard uncertainties associated to the experimental determinations of both  $p_Q$  and  $k_{Q,Q_0}$  factors were typically around 1 % or slightly larger ( $k=1$ ), due to the limitations of the calorimetric standards at delivering accurate estimates of the quantity of interest at the lower beam energies, and not a limitation of the ionization chambers themselves. Both, the Monte Carlo and the experimental datasets of  $p_Q$  and  $k_{Q,Q_0}$  factors were submitted to the IAEA for inclusion in the update of the TRS-398 Code of Practice.

The main conclusion in this objective was that there is no substantial advantage in calibrating a chamber at quality  $Q_0$  in terms of the quantity  $D_w$  and then apply a generic, model-specific  $k_{Q,Q_0}$  factor to obtain its  $N_{D_w,Q}$ . This is in comparison with the air-kerma based approach where a calibration coefficient is obtained directly in the user beam  $Q$ , although in terms of the quantity air kerma.

## 4.2 Objective 2: High-energy (MV) photon beams between 4 MV and 20 MV, including flattening filter free beams (FFF)

External radiotherapy with MV photon beams is one of the most widely used modalities for cancer treatment in Europe. These treatments are delivered by linear electron accelerators (LINACs), typically with potentials from 4 MV to 20 MV. Hospitals are increasingly using 6 MV or 10 MV beams without flattening filter. These so-called flattening-filter free (FFF) beams have a less uniform dose distribution across the field size than conventional beams with flattening filter (cFF). The use of FFF beams is mainly driven by the increased dose rate that can be achieved in the absence of a flattening filter which decreases treatment time and offers certain potential clinical benefits.

If hospitals get their ionization chambers calibrated in a  $^{60}\text{Co}$  gamma beam they will need a  $k_Q$  factor to be able to perform traceable dosimetry in MV photon beams from linear accelerators. Under TRS-398 reference conditions (e.g. 10 cm x 10 cm field size, 1 m source to reference point distance) the hospitals will use the equation:

$$D_{w,Q} = M_Q N_{D_w,Q_0} k_Q \quad (4)$$

where:

$D_{w,Q}$  is the absorbed dose to water in the linac beam quality Q [Gy],

$N_{D_w,Q_0}$  is the  $^{60}\text{Co}$  absorbed dose to water calibration coefficient [Gy/C],

$k_Q$  is the beam quality correction factor,

$M_Q$  is the electrometer reading from the ionization chamber [C] in the linac beam quality Q corrected for influencing parameters such as recombination, polarity, and beam non-uniformity.

In this work, the beam uniformity corrections were carried out for all beams (both FFF and cFF linac beams, and  $^{60}\text{Co}$  gamma beams).

The existing IAEA TRS-398 code of practice made available in 2000, provides  $k_Q$  beam quality correction factors as function of the  $\text{TPR}_{20,10}$  beam quality index which essentially can be derived by hospitals from the ratio between the ionization chamber response at 20 cm or 10 cm of depth of water.

The following sections present the Monte Carlo modelling and experimental  $k_Q$  values for MV photon beams. Comparisons are made against two data sets:

- The existing TRS-398 results from 2000 with some updates from 2006. This comparison is of interest from the perspective that it helps identify the magnitude of the new improved  $k_Q$  values.
- The recent paper (March, 2020) entitled "*Determination of consensus  $k_Q$  values for megavoltage photon beams for the update of IAEA TRS-398*". The RTNORM results focus on ionization chambers in common use in Europe.

### Modelling datasets

The  $k_Q$  factor in beam quality Q was obtained from Monte Carlo simulations with the codes EGSnrc and PENELOPE as:

$$k_Q = \frac{(D_w / D_{\text{chamber}})_Q}{(D_w / D_{\text{chamber}})_{Q_0}} \quad (5)$$

where  $D_w$  is the dose to water in the reference point and  $D_{\text{chamber}}$  the dose to air averaged over the chamber cavity volume at the reference point corrected for volume averaging effects.  $Q_0$  refers to the  $^{60}\text{Co}$  gamma beam and Q is the linac beam quality. All modelling was based on data consistent with the key data in ICRU-90. Detailed Fano-test studies were carried out for selected problems.

The modelling for any given chamber was based on detailed blue-print information provided by the manufacturers. The particle sources used in the accelerator simulations were phase-space files, modelled linac heads or published linac spectra.

Beam quality indices  $TPR_{20,10}$  were estimated from Monte Carlo computed doses at 10 cm and 20 cm depth of water and a statistical model.

$k_Q$  values were computed for the following 10 cylindrical ionization chamber models: Exradin A12S, Exradin A1SL, IBA CC-13, IBA FC65-G, IBA FC65-P, NE 2571, PTW 30013, PTW 31010, PTW 31013, and PTW 31021.

The main simulation results are shown in Fig. 2.1, putting together the results provided by THM, STUK, ENEA, and IST-ID. The type A uncertainties were in most cases below 0.2 %. All partners provided data for the NE 2571 chamber for validation of the calculation methods. The results agreed within the (type A) uncertainties. Type B uncertainties related to, for example, fundamental interaction coefficients, approximations inherent in the Monte Carlo codes, or imperfections in how the accelerators were modelled were not explicitly quantified.

It can be seen in Fig. 2.1 that the new  $k_Q$  values tend to be about 0.5 % lower than the old TRS-398 values at  $TPR_{20,10}$  above 0.7 %.

Fig. 2.2 shows modelling results only for Elekta and Varian accelerators, which are the most frequently used accelerators in Europe. The data does not suggest any difference between these accelerators outside what is captured in the  $TPR_{20,10}$ . The data suggest that even after non-uniformity corrections, the FFF  $k_Q$  values for some chambers are less (about 0.3 % for the 10 MV Varian beams) than the  $k_Q$  values for corresponding cFF beams.

### Experimental datasets

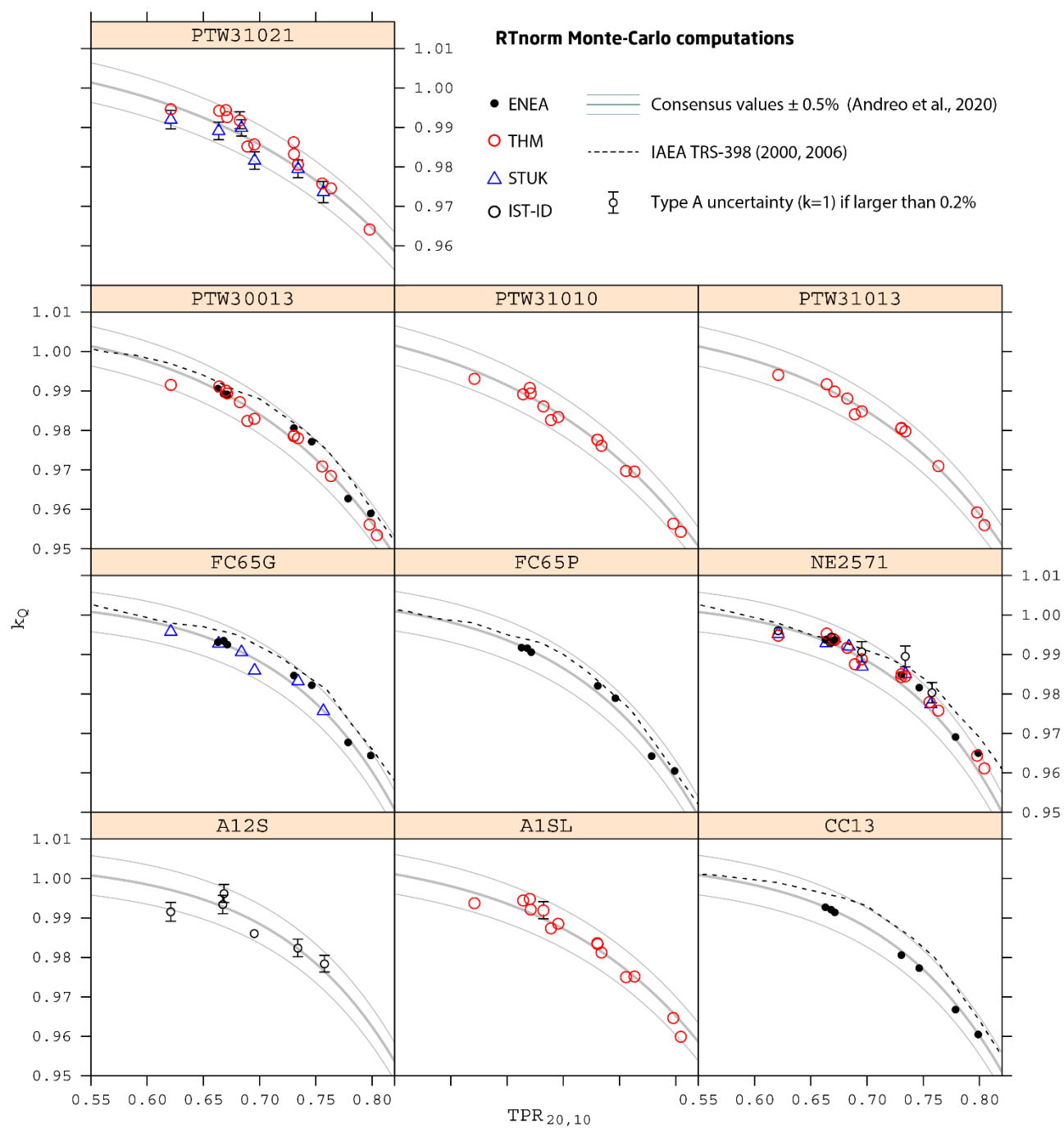
The absorbed-dose-to-water primary standards at VSL (water calorimetry) and LNHB/CEA (graphite calorimetry) were used as reference. Both standards are based on key data fully consistent with ICRU-90 values. The primary standards were used to calibrate linac monitor chambers to secure traceability for each individual beam used in the chamber characterization study. Fig. 2.3 and 2.4 show details of some of the experimental work.

$k_Q$  values were measured for the following 7 cylindrical ionization chamber models: Exradin A1SL, IBA FC65-G, NE 2571, NPL 2611, PTW 30012, PTW 30013, and PTW 31021.

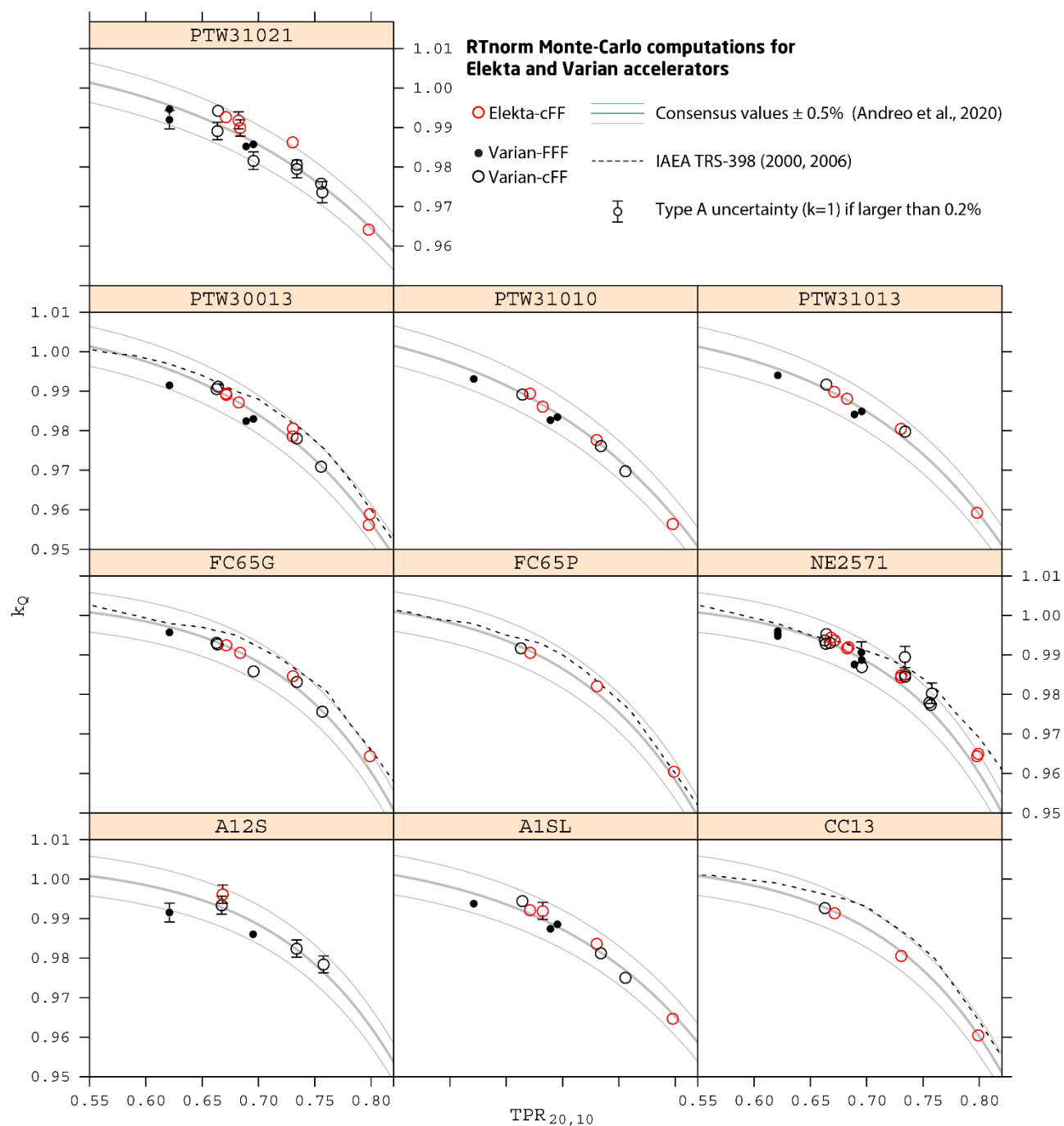
Five chambers of each type were studied. Typically, the  $k_Q$  values at any given chamber type and energy had a standard deviation of about 0.1 % or lower. This supports the rationale behind the use of generic  $k_Q$  values (i.e. that  $k_Q$  values may be used to represent the population of chambers of that type). Recombination and polarity measurements were carried out both for the chamber characterizations and for the experimental determination of the  $TPR_{20,10}$  values.

The main results for the experimental  $k_Q$  values are shown in Fig. 2.5. We note that the results for the different laboratories were consistent within the uncertainty. We also note, in agreement with the modelling results, that the new improved experimental  $k_Q$  values are about 0.5 % lower than the old TRS-398 values at  $TPR_{20,10}$  values above 0.7 %.

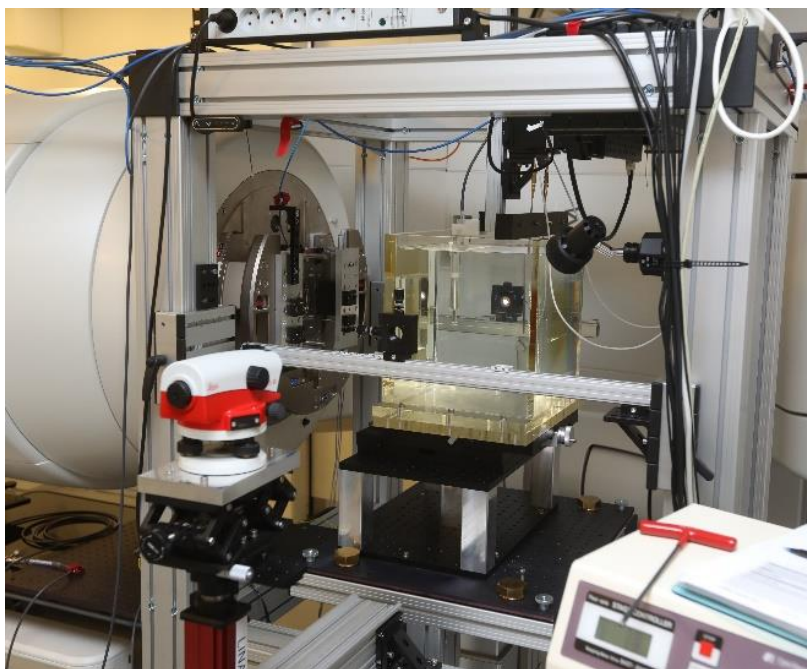
Fig. 2.6 shows experimental results only for Elekta and Varian accelerators. Considering the uncertainties associated with the measurements, these data do not demonstrate a significant difference between  $k_Q$  values for these two brands of accelerators. Likewise, the data does not demonstrate a significant difference between CFF and FFF beams after correction for non-uniformity. However, we do note that the  $k_Q$  values tend to be slightly smaller for Elekta than for Varian accelerators, and the FFF beams tend to be slightly smaller than the cFF beams after consideration of the general  $k_Q$ - $TPR_{20,10}$  relationship.



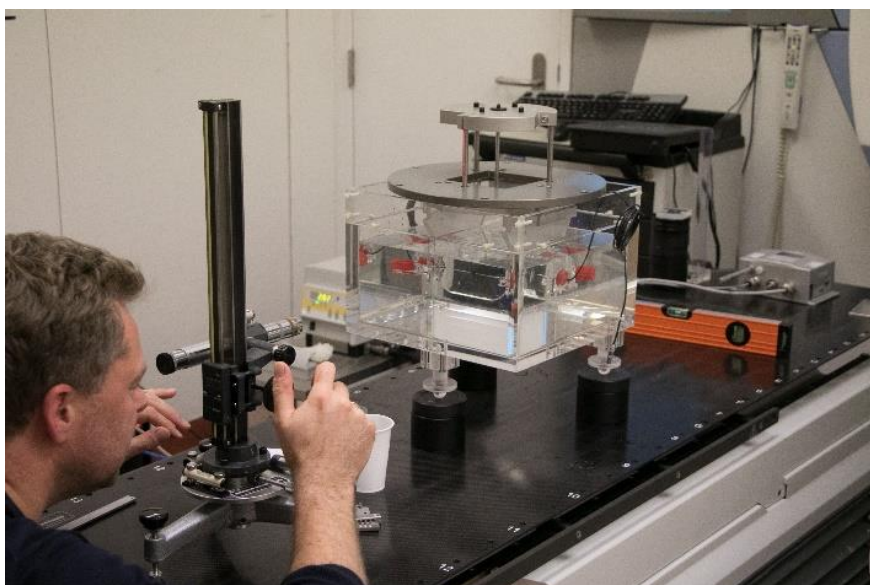
**Fig. 2.1:** Main RTNORM Monte Carlo modelling results for MV linac beams stratified by ionization chamber model and laboratory.



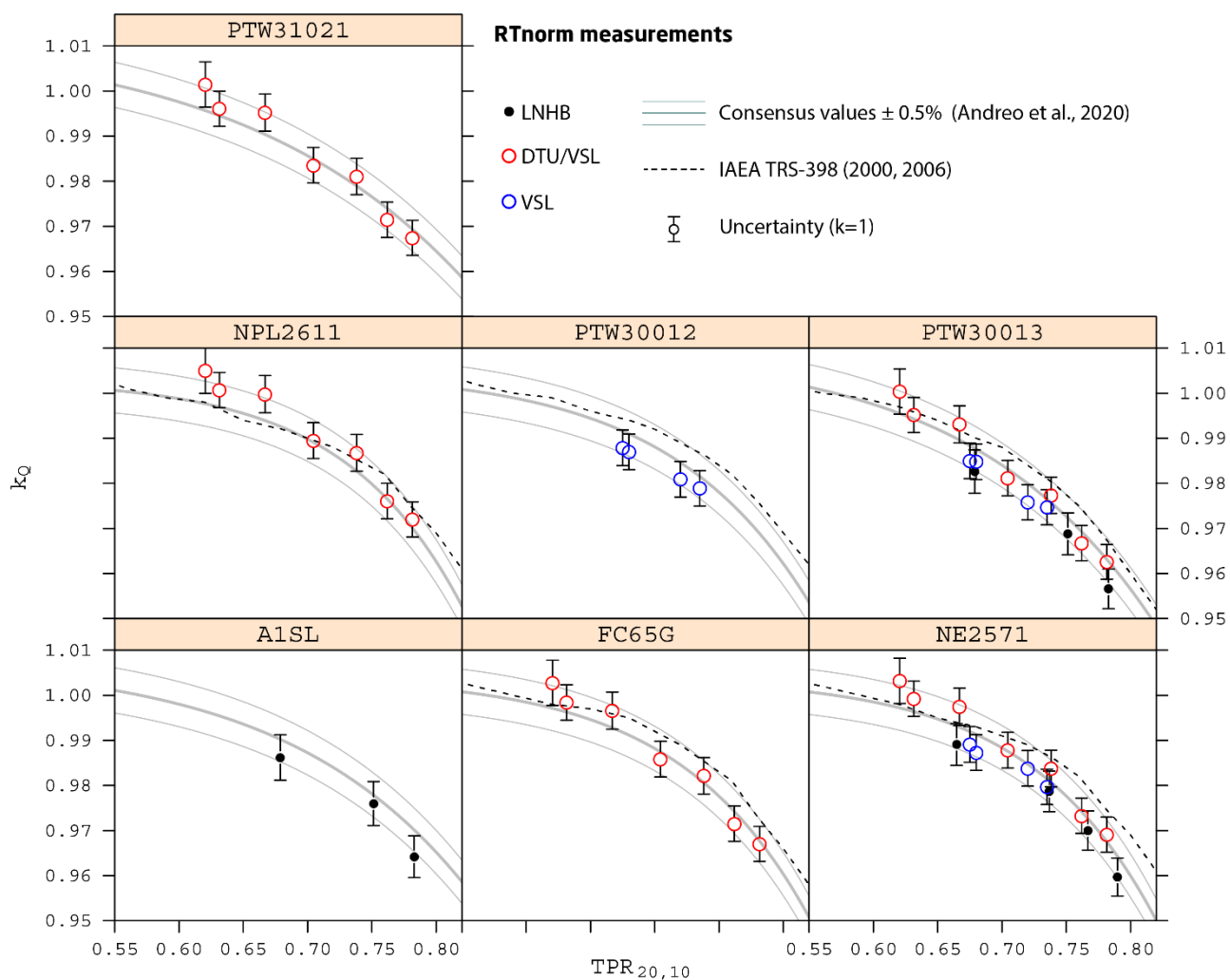
**Fig. 2.2:** Main RTNORM Monte Carlo modelling results for Elekta and Varian MV linac beams stratified by ionization chamber model and FFF vs. cFF beam. Note that no Elekta FFF beams were modelled.



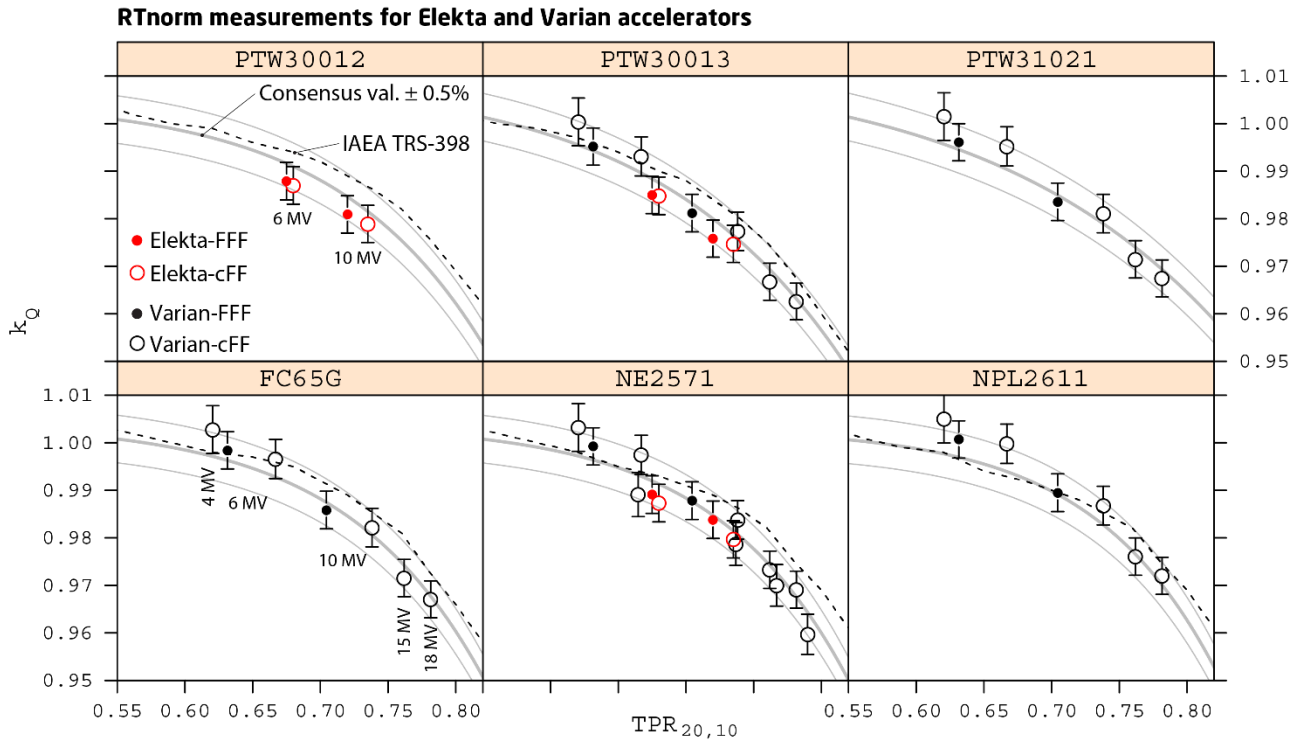
**Fig. 2.3:** Set-up used for ionization chamber irradiations in the Varian Truebeam accelerator at DTU. The reference position is defined by the optical axis indicated by the telescope. The water phantom is on a lift such that the ionization chamber can be positioned in air. An external monitor chamber can be seen at the head of the accelerator.



**Fig. 2.4:** Measuring the position of the thermistors in the VSL primary standard water calorimeter before use in the linac beam.



**Fig. 2.5:** Main RTNORM experimental results for MV linac beams stratified by ionization chamber model (see text for further details). The results are the means for  $N=5$  chambers of the given type, except for NPL 2611 where only  $N=2$  chambers were characterized.



**Fig. 2.6:** Main RTNORM experimental results for MV Elekta and Varian linac beams stratified by ionization chamber model and FFF vs. cFF beam (see text for further details). The results are the means for N=5 chambers of the given type, except for NPL 2611 where only N=2 chambers were characterized. The accelerator potentials for some of the beams are indicated in the lower left panel. The indicated uncertainties are one standard deviation ( $k=1$ ). The consensus value reference lines are from Andreo et al. (2020).

### Summary

In summary for MV photons,  $k_Q$  factors were experimentally determined for five out of six ionization chamber models, and for ten models using Monte Carlo calculations, which overall exceeds the objectives of this work package in terms of number of detectors investigated and for which datasets were compiled. Datasets were also compared across the two methods, and this strengthened confidence in the data generated before they were submitted for inclusion in the TRS-398 update, with uncertainties that were within the target 0.7 % ( $k=1$ ). Taken together, the objective was fulfilled.

### 4.3 Objective 3: Scanned proton beams between 60 MeV and 250 MeV

According to the Particle Therapy Co-Operative Group, there are now currently about 90 clinical proton facilities in operation worldwide, and about 50 % of these have been established during the period 2015-2020. More than 75 % of the new facilities offer spot scanning. For these beams, beam spots, for example, with a gaussian shape and a full-width half-maximum spot size of 10 mm, are delivered one by one with a beam-off time in between. The ability to control the pattern of beam spots and to change the proton energy for each individual beam spot enables highly conformal coverage of the target volume in the patient. An important benefit of proton spot-scanning treatments compared with external radiotherapy with megavoltage photons, is the ability to spare healthy tissue and organs at risk.

The aim of this work package was to provide validated Monte Carlo simulated and experimental  $k_Q$  values for a range of ionization chambers to be used for reference dosimetry in scanned proton beams. As for the megavoltage photon beams, the  $k_Q$  factor is equal to the ratio of the calibration coefficient in absorbed dose to water at a given beam quality (here, a scanned proton beam) to the calibration coefficient in absorbed dose to water in a  $^{60}\text{Co}$  gamma beam.

#### Modelling datasets

$k_Q$  values were computed for the following 16 different ionization chamber models: Exradin A10, Exradin A11, Exradin A11TW, Exradin A12, Exradin A19, Exradin A1SL, IBA FC65-G, IBA FC65-P, IBA NACP-02, IBA PPC-05, IBA PPC-40, NE 2571, PTW 23343 (Markus), PTW 30013, PTW 34001 (Roos), and PTW 34045 (Advanced Markus).

The computations were carried out using the Monte Carlo codes PENH (i.e. PENELOPE extended with proton transport) and/or TOPAS/Geant4. The combined standard uncertainty of the calculated  $k_Q$  values was in all cases smaller than 1 % ( $k=1$ ). For 9 studied chamber models both codes were used, and given the independence of the two codes, it is noteworthy that the calculated pairs of  $k_Q$  values in all cases agreed within uncertainty.

Key results from THM, FCRB, and KU Leuven are shown in Fig. 3.1 and 3.2 as the  $k_Q$  vs. initial proton energy for plane-parallel and cylindrical ionization chambers, respectively. The agreement between RTNORM results and the scarce data published in the literature was always within 2 %.

#### Measurements

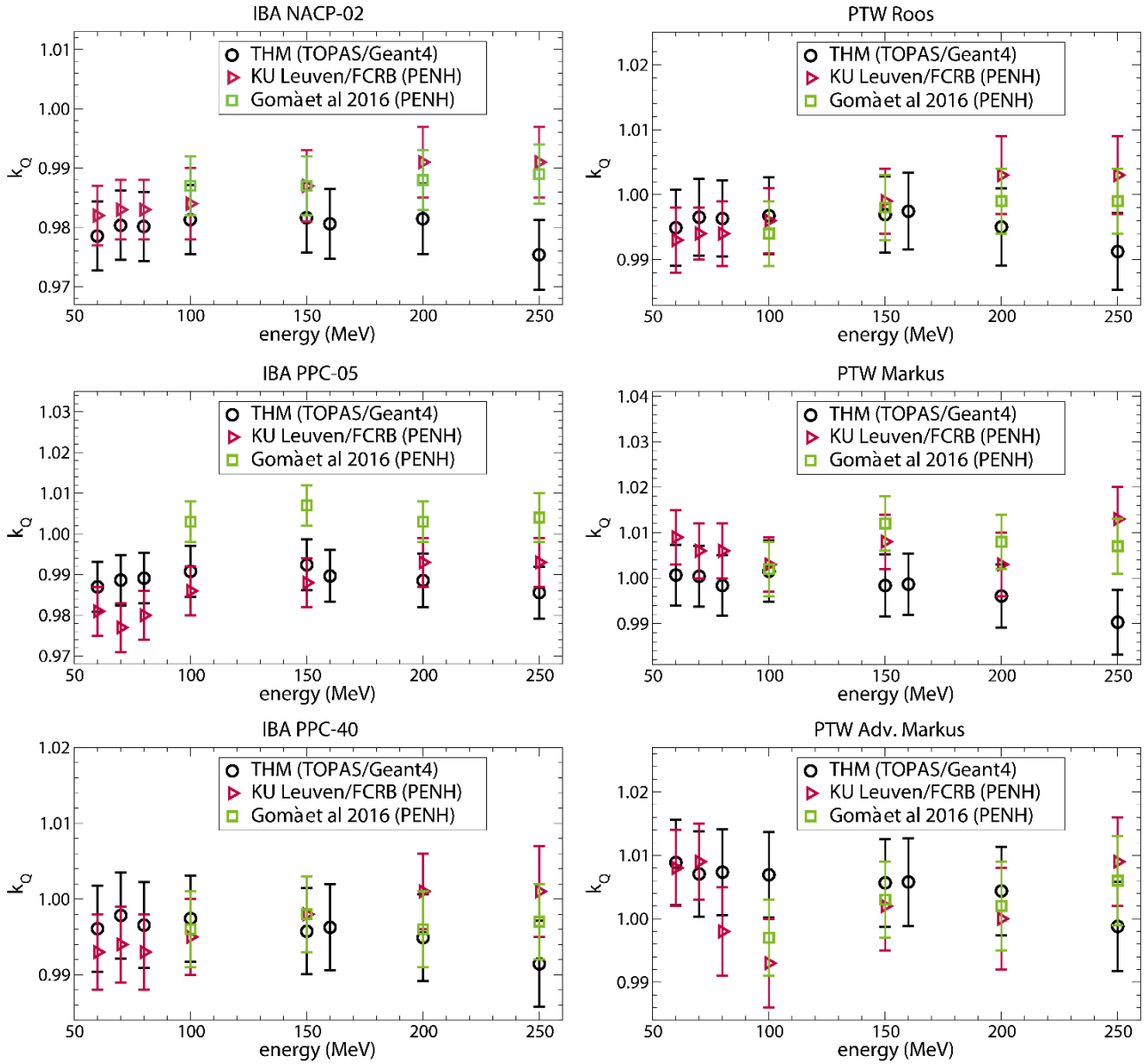
Data were acquired during all proton beam visits (Christies', Rutherford's IBA Centers in Newport/Northumberland and at PSI in Switzerland) and include measurements on seven types of ionization chambers (three experimental set-ups are shown in Fig. 3.3). Measurements in the reference quality ( $^{60}\text{Co}$  gamma beam) were made in the Theratron 780C facility at NPL.

Measurements were made at PSI using single energy-layer scanned fields of  $10 \times 10 \text{ cm}^2$ , 2.5 mm spot spacing and 21045 MU/spot as well as in a box field of  $10 \times 10 \times 10 \text{ cm}^3$  homogeneous dose volume centred at 15.0 cm deep in water. The measurements were performed for eight representative fields ranging between 70 MeV and 230 MeV.

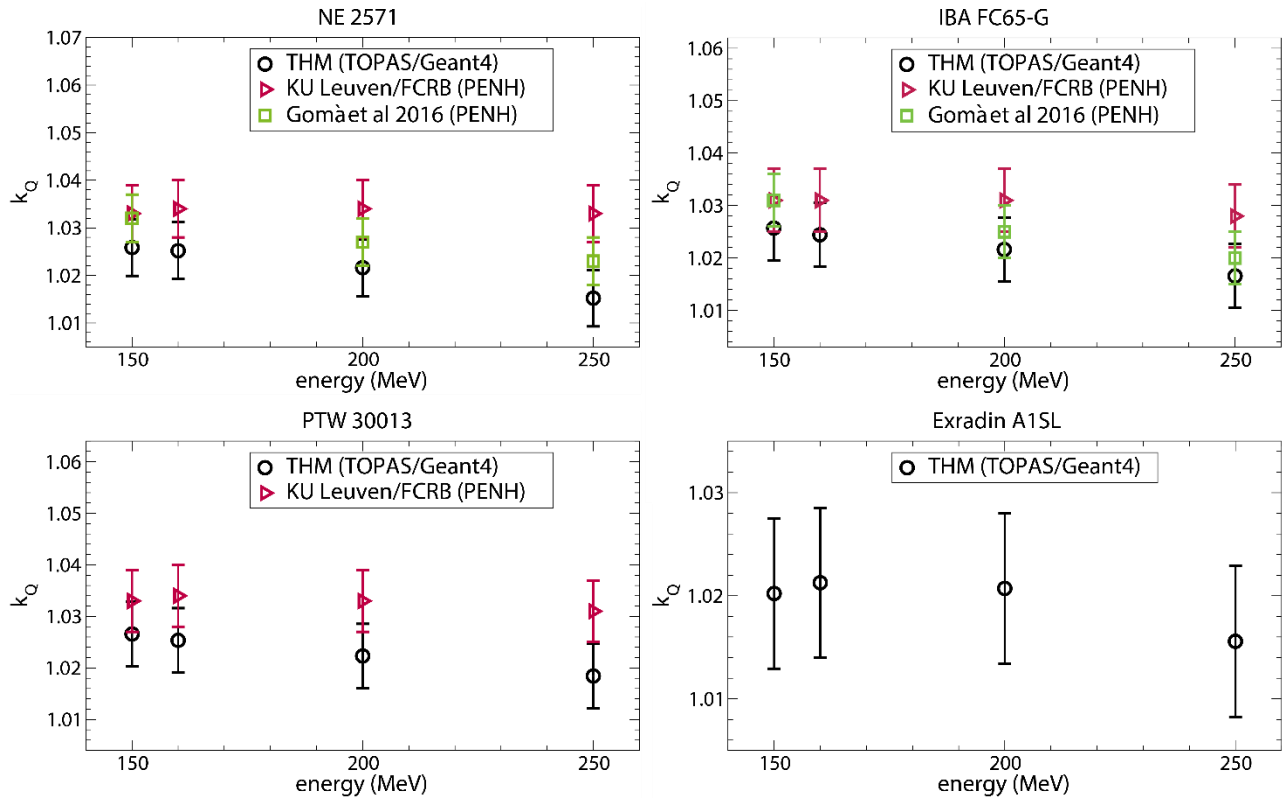
Steps were taken to improve the consistency and check all instrumentation used during the visits. Since the target uncertainty of 2 % was not met, additional beam sessions were planned outside of the project timeline.

#### Summary

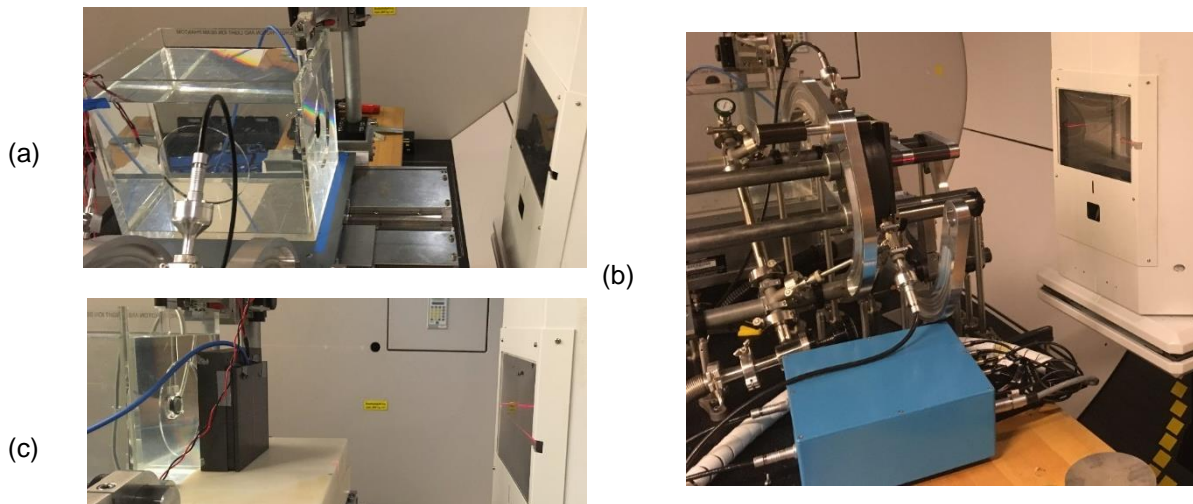
Although *experimental* datasets of  $k_Q$  factors did not achieve the target uncertainty of 2 % ( $k=1$ ), the dataset of *calculated*  $k_Q$  factors listed 15 types of chambers which largely exceeded the target of 4 chamber models. Monte Carlo generated datasets could not be benchmarked against experimental determinations based on the calorimetric measurements, nevertheless a validation was achieved through a cross-comparison of the results that were obtained using two independent Monte Carlo codes. Taken together, the objective was not fulfilled for the experimental data part, but was compensated by a large data set produced via the Monte Carlo calculations. No dataset from experimental measurements were submitted towards the IAEA TRS-398 update.



**Fig. 3.1:** Monte Carlo calculated  $k_Q$  values in scanned proton beams for 6 different plane-parallel ionization chambers as a function of the initial proton beam energy. For comparison, literature values from 2016 are also shown. The uncertainty bars correspond to one standard uncertainty ( $k=1$ ).



**Fig. 3.2:** Monte Carlo calculated  $k_Q$  values in scanned proton beams for 4 different cylindrical ionization chambers as a function of the initial proton beam energy. For comparison, literature values from 2016 are also shown. The uncertainty bars correspond to one standard uncertainty ( $k=1$ ).



**Fig. 3.3:** Three different experimental setups were considered. Setup a: ionization chamber in a water phantom. Setup b: NPL proton graphite calorimeter. Setup c: ionization chamber in a graphite phantom.

## 5 Impact

The project key route to a high impact was the publication of its unique measured and calculated data on  $k_Q$  factors towards the revision of IAEA TRS-398 Code of Practice. During the TRS-398 revision process, the IAEA received data from all over the world, to be selected and compiled after a thoughtful revision. Using a coordinated approach to validate data by means of internal comparisons, i.e. comparisons of results within this consortium, the present project ensured that the IAEA TRS-398 Update Core Group received high-quality data for the key European detectors and for new treatment modalities directly applicable to the medical physics communities at the cancer centres in Europe.

Project researchers offered fifteen presentations at European and Asian conferences (e.g. MCMA2017, ESTRO 37 and ESTRO 38). The project had major presence at various national meetings with end users such as hospital physicists in Italy, Germany, Spain, and Japan. The project successfully planned three training courses with ~400 attendees from European countries. One PhD thesis was part of the present project. The consortium published nine manuscripts and two more papers are pending. Finally, the project presented their progress regarding the datasets at EURAMET TC-IR, BIPM CCRI(I), ESTRO, NCS meetings, and IPEM committees.

### *Impact on clinical communities*

The IAEA TRS-398 is the world's leading protocol for radiotherapy dosimetry and has been endorsed by organisations such as the World Health Organization (WHO) and the European Society for Radiotherapy and Oncology (ESTRO). The IAEA TRS-398 is used worldwide, in Europe and beyond. The data obtained in this project are critical for dosimetry underpinning accurate cancer treatments in Europe. The  $k_{Q,Q_0}$  factors are essential for current and future dosimetry with ionisation chambers in modern clinical beams. With the eventual inclusion of its production in the TRS-398 update (projected late in 2020 or early in 2021), this project had a direct and substantial impact since European radiotherapy clinics use this code of practice on a daily basis for critical tasks, such as the calibration of linear accelerators used in external-beam radiotherapy. This project will ultimately benefit 1.7 million citizens undergoing radiotherapy cancer treatment annually as radiotherapy clinics will use and rely on the correction factors and measurement procedures described in the revision of the TRS-398 Code of Practice.

For reference dosimetry, hospitals generally do not use correction factors directly from the scientific literature, and hence in order to comply with TRS-398 the correction factors for their type of reference dosimetry ionisation chamber need to be included in that norm. In the case where new treatments are available for which the reference dosimetry is not covered in TRS-398 (such as flattening filter-free photon beams), hospitals may have to resort to alternative procedures, or they may decide not to offer the treatments to patients. The outputs of this project will therefore lead to further harmonisation of clinical reference dosimetry for both conventional radiotherapy modalities and recently developed beam modalities and enable hospitals and clinics to improve their existing radiotherapy and to adopt new treatment modalities.

### *Impact on industrial and other user communities*

This project ensured data for the leading producers of ionisation chambers (including European industry) and manufacturers of treatment equipment through the IAEA TRS-398. This will enhance their economic position, since the new ionisation chamber models potentially available in TRS-398 will be used as reference dosimetry at hospitals. European manufacturers of radiotherapy facilities have recently developed innovative new radiotherapy modalities such as scanned proton beams and flattening filter-free photon beams. They will benefit from the updated data sets determined in this project, as this new information will provide data which were lacking in previous version of the IAEA TRS-398 ensuring that these new modalities can be safely adopted in radiotherapy clinics.

### *Impact on the metrology and scientific communities*

One of the absorbed doses to water standards was used on two of the major commercially available clinical accelerators. This strengthens confidence in the use of the beam quality specifier for these radiation therapy modalities. Additionally, this project has shown what impact the adoption of the ICRU report n°90 recommendations has had on calculated correction factors for reference dosimetry [3, 5, 7].

### *Impact on relevant standards*

This project focused on the update of data that were central for the revision of the IAEA TRS-398, the world's leading dosimetry Code of Practice. In so doing, this project embraced the fundamental ideas underpinning the Code of Practice, which is to organise radiation dosimetry in a coherent manner and provide traceability to

primary standards of the physical quantity *absorbed dose to water*. The chapters that received contributions from the project were IAEA update TRS-398 TG 'kV X-rays', IAEA update TRS-398 TG 'high energy photons', and IAEA update TRS-398 'protons and heavy ion beams'. A contribution was also made to the CCRI(I) and the EURAMET Technical Committee on Ionizing Radiation meetings.

#### *Longer-term economic, social and environmental impacts*

In line with the original drivers for the first edition of the TRS-398 Code of Practice, the coherence that is ensured by the concerted traceability to primary standards of absorbed dose to water, in all radiation therapy modalities, will result in the simplification of clinical dosimetry procedures, will reduce the risk of errors in the clinical setting, and will overall strengthen the confidence in cancer radiotherapy. An improved radiotherapy will offer both social and economic benefits in the form of better treatments, better therapeutic outcomes, and higher patient survival rates.

## 6 List of publications

- [1] Baumann K S, Kaupa S, Bach C, Engenhardt-Cabillic R and Zink K 2020 Monte Carlo calculation of beam quality correction factors in proton beams using TOPAS/GEANT4 *Phys Med Biol* **65** 055015 <https://iopscience.iop.org/article/10.1088/1361-6560/ab6e53>
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- [3] Czarnecki D, Poppe B and Zink K 2018 Impact of new ICRU Report 90 recommendations on calculated correction factors for reference dosimetry *Phys Med Biol* **63** 155015. <https://iopscience.iop.org/article/10.1088/1361-6560/aad148>
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- [5] Pimpinella M, Silvi L and Pinto M 2019 Calculation of k<sub>Q</sub> factors for Farmer-type ionization chambers following the recent recommendations on new key dosimetry data *Physica Medica* **57** 221–30. [https://www.physicamedica.com/article/S1120-1797\(18\)31343-7/fulltext](https://www.physicamedica.com/article/S1120-1797(18)31343-7/fulltext)
- [6] de Prez L A, de Pooter J A, Jansen B, Perik T and Wittkämper F 2018 Comparison of k<sub>Q</sub> factors measured with a water calorimeter in flattening filter free (FFF) and conventional flattening filter (cFF) photon beams *Phys Med Biol* **63** 045023. <https://iopscience.iop.org/article/10.1088/1361-6560/aaaa93>
- [7] Tikkanen J, Zink K, Pimpinella M, Teles P, Borbinha J, Ojala J, Siiskonen T, Gomà C and Pinto M 2020 Calculated beam quality correction factors for ionization chambers in MV photon beams *Phys Med Biol* **65** 075003 <https://iopscience.iop.org/article/10.1088/1361-6560/ab7107>
- [8] Wittkämper, F., Perik, T., Jansen, B., de Pooter, J. and de Prez, L. 2019. Corrigendum: Comparison of k<sub>Q</sub> factors measured with a water calorimeter in flattening filter free (FFF) and conventional flattening filter (cFF) photon beams (de Prez et al 2018 *Phys. Med. Biol.* **63** 045023). *Phys Med Biol* **64**:3 039501. <https://iopscience.iop.org/article/10.1088/1361-6560/aaaa93/pdf>
- [9] Andreo P, Burns D T, Kapsch R P, McEwen M, Vatnitsky S, Andersen C E, Ballester F, Borbinha J, Delaunay F, Francescon P, Hanlon M D, Mirzakhani L, Muir B, Ojala J, Oliver C P, Pimpinella M, Pinto M, de Prez L A, Seuntjens J, Sommier L, Teles P, Tikkanen J, Vijande J and Zink K 2020 Determination of consensus k<sub>Q</sub> values for megavoltage photon beams for the update of IAEA TRS-398 <https://doi.org/10.5281/zenodo.3903294>

## 7 Contact details

None