EURAMET supplementary comparison of the personal dose equivalent at 0.07 mm and 3 mm depth, $H_p(0.07)$ and $H_p(3)$, for beta radiation

EURAMET Project No. 1398

BIPM KCDB: EURAMET.R(I)-S16

Instructions for Use for the transfer chamber and the electronic measuring device

Revision 2

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10-10-2018

Revision 2 (10-10-2018):
- page 3: clarification of the text
Revision 1 (14-02-2018):
- page 5: reference point’s depth to changed 12 mm
- page 5: details regarding accuracy of angular adjustment added
- pages 23 and 24: unit corrected from (fA to 1/fA)

Contents

1. Measuring system for the intercomparison

The calibration measurements for the intercomparison should be performed with the transfer chamber and the complete electronic measuring device sent together in a transport container. The transport container contains two boxes, see figure 1: a black case containing the transfer chamber and a blue box containing the complete electronic measuring system, see figure 1.

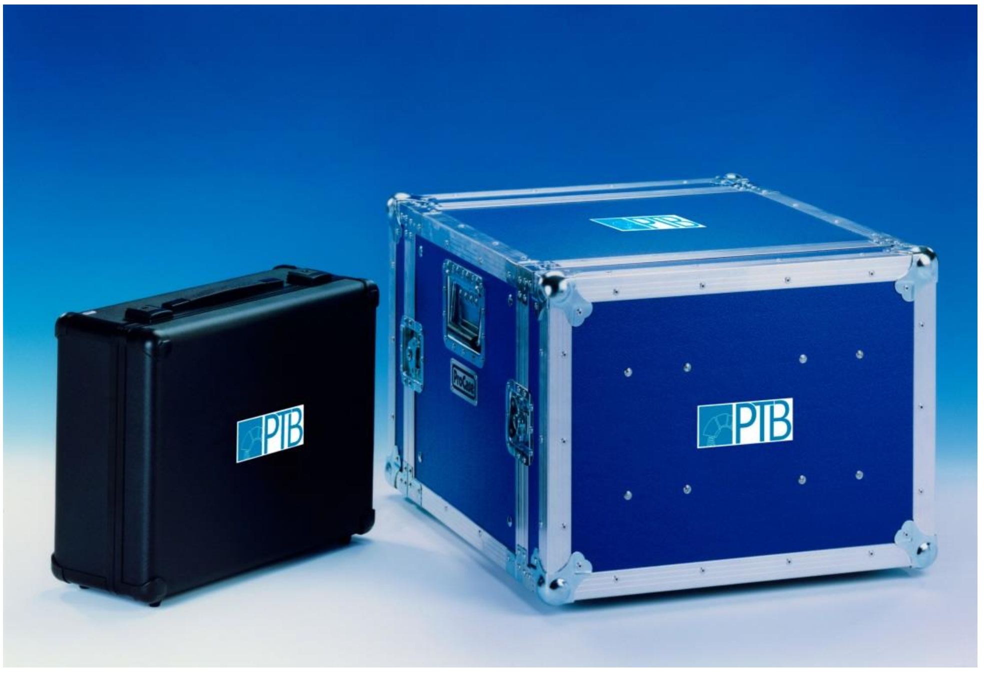

Figure 1: The two transport boxes: the black one containing the transfer chamber, the blue one the electronic measuring system

2. Transfer chamber

As transfer instrument, a flat ionization chamber is used, see figure 2. The chamber consists of a measuring part with a backscatter plate and with a stick which are fastened to each other. **It is not allowed to separate these parts!**

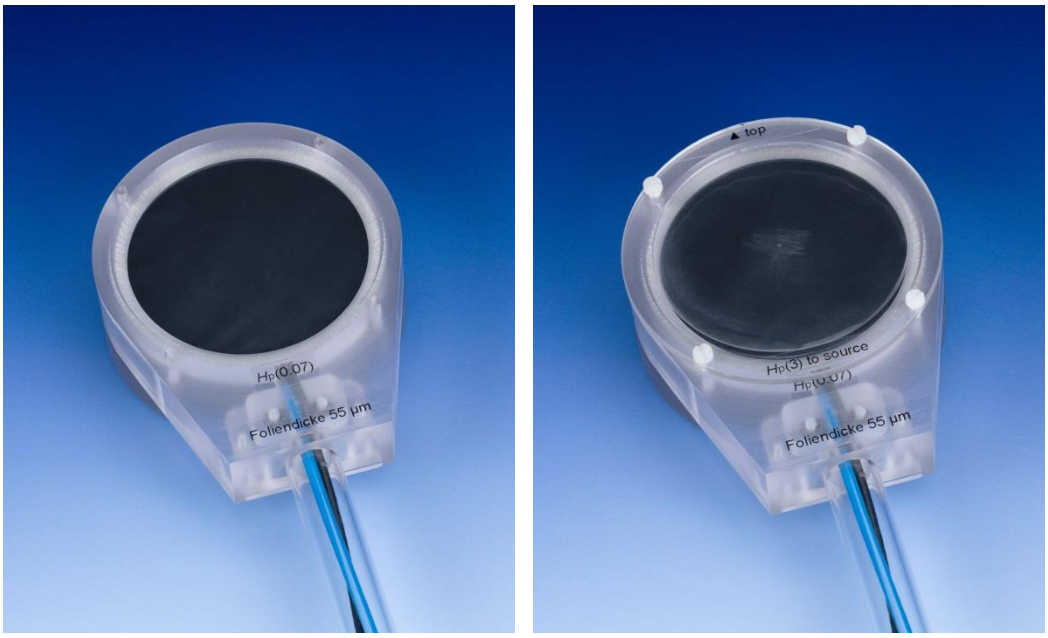

Figure 2: Transfer ionization chamber; view of the chamber‘s front face without (left) and with (right) protection cover (the cover is for $H_p(3)$ measurements)

The chamber has the geometry of a circular slab. The outside dimensions are 90 mm in diameter with a total thickness of 40 mm, see figure 3. The active volume is about 8 cm^3. In front of the active volume, an entrance window consisting of a graphite foil (approximately 80 % graphite in polycarbonate) with approximately 7 mg/cm^2 tissue equivalence, is fixed.

Attention: The entrance window of the chamber is on chamber voltage potential (300 V)

For calibration purposes, the front face of the chamber must be irradiated completely.

The electric field for separating the electrons and the ion charges is produced by two electrodes arranged in parallel. The HV electrode in front of the active volume is set to a potential of +300 V. The electrode on the back is set to zero potential.

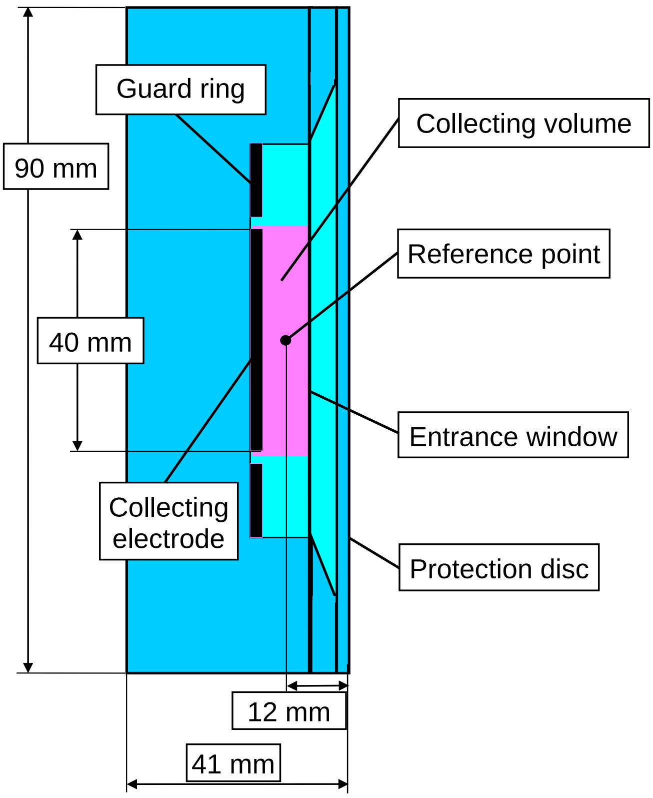

Figure 3: Sketch of the flat ionization chamber (not to scale)

The **reference point** of the chamber is in the center of the active volume. It is situated below the center of the chamber's front face, 12 mm below the front face of the protection disc (= cover for $H_p(3)$ measurements), see figure 3. The reference point of the chamber must be positioned in the point of test, for which the conventional quantity value is known.
The radiation beam axis must be the normal to the chamber's front face going through the reference point.

The chamber should be calibrated at different angles of incidence. For the rotation of the chamber the rotary axis must go through the reference point of the chamber.

The mounting rod is not the rotary axis.

The active volume of the chamber is rotationally symmetrical to the axis, normal to the front face of the chamber and contains the reference point. However, small deviations both from symmetry as, for example, small differences in the thickness of the entrance window and graphite layers of the chamber and from the **adjustment of the angle of incidence**, α, can lead to different measuring results depending on the beam incidence $+\alpha$ or $-\alpha$. To reduce this influence, the calibration measurements should be performed for the radiation qualities at the angle $+\alpha$ and $-\alpha$, i.e. beam incidence on both sides of the normal on the chamber's front surface. The mean value from the two measurements should be used for determining the calibration factors of the respective radiation quality. **The chamber is correctly adjusted to the beam axis if for the quantity $H_p(0.07)$ the calibration factors for Kr-85 determined at +45° and −45° agree within approximately ±2 % from the mean value, i.e. 4 % between the two values of +45° and −45° and for the quantity $H_p(3)$ the calibration factors for Sr-90/Y-90 determined at +45° and −45° agree within approximately ±2 % from the mean value, i.e. 4 % between the two values of +45° and −45°.**

Table of Contents

3. Subject of measurement

The subject of the comparison is the calibration of an ionization chamber in terms of the dose rates, $\dot{H}_p(0.07;\alpha)$ and/or $\dot{H}_p(3;\alpha)$. Each participant should calibrate the transfer chamber at several radiation qualities and different angles of incidence. The calibration factor for reference depth d = 0.07 mm and d = 3 mm is given by

$$N_{Hp(d;\alpha)} = \frac{\dot{H}_p(d;\alpha)}{I(d)_c}$$

with

- $I(d)_c$ the ionization current measured by the transfer chamber and corrected for the leakage current and the ambient air conditions to reference conditions, i.e. reference air density, in the collecting volume by the software, for
  - d = 0.07 mm, i.e. measured WITHOUT the cover for $H_p(3)$ and
  - d = 3 mm, i.e. measured WITH the cover for $H_p(3)$, and
- $\dot{H}_p(d;\alpha)$ the conventional quantity value of the dose rate $\dot{H}_p(0.07;\alpha)$ and $\dot{H}_p(3;\alpha)$ for d = 0.07 mm and d = 3 mm, respectively, at the ambient air conditions during the measurements with the transfer chamber. The values for $\dot{H}_p(0.07;\alpha)$ and $\dot{H}_p(3;\alpha)$ shall be valid for a slab phantom.

If possible, measurements should be performed with the following quantities, radiation qualities, and angles of incidence:

- **Pm-147** at 20 cm distance, with beam flattening filter, at **0°, ±45° and ±60° for H_p(0.07);**
- **Kr-85** at 30 cm distance, with beam flattening filter, at **0°, ±45° and ±60° for H_p(0.07);**
- **Sr-90/Y-90** at 30 cm distance, with beam flattening filter, at **0°, ±45° and ±60° for H_p(0.07) and H_p(3);**
- **Ru-106/Rh-106** at 20 cm distance, without beam flattening filter, at **0°, ±45° and ±60° for H_p(0.07) and H_p(3).**

Not all participants have to take part in all these combinations.

4. Electronic measuring device

4.1 Description

The calibration measurements should be carried out using the complete electronic measuring device supplied together with the transfer chamber, see figure 3. It consists of an electrometer, a high voltage power supply unit, a temperature, air pressure and relative humidity sensor and, for automatic data recording, a laptop with the measuring software.

The current measured by the chamber under ambient conditions is corrected by the measuring software to the current for reference air conditions, i.e. reference air density, in the collecting volume (air pressure: 101.3 kPa, temperature: 293.15 K, rel. humidity: 65 %).

The measurement result furnished by the software is the value of the mean current of the chamber with its standard uncertainty (k = 1). The leakage current is taken into account.

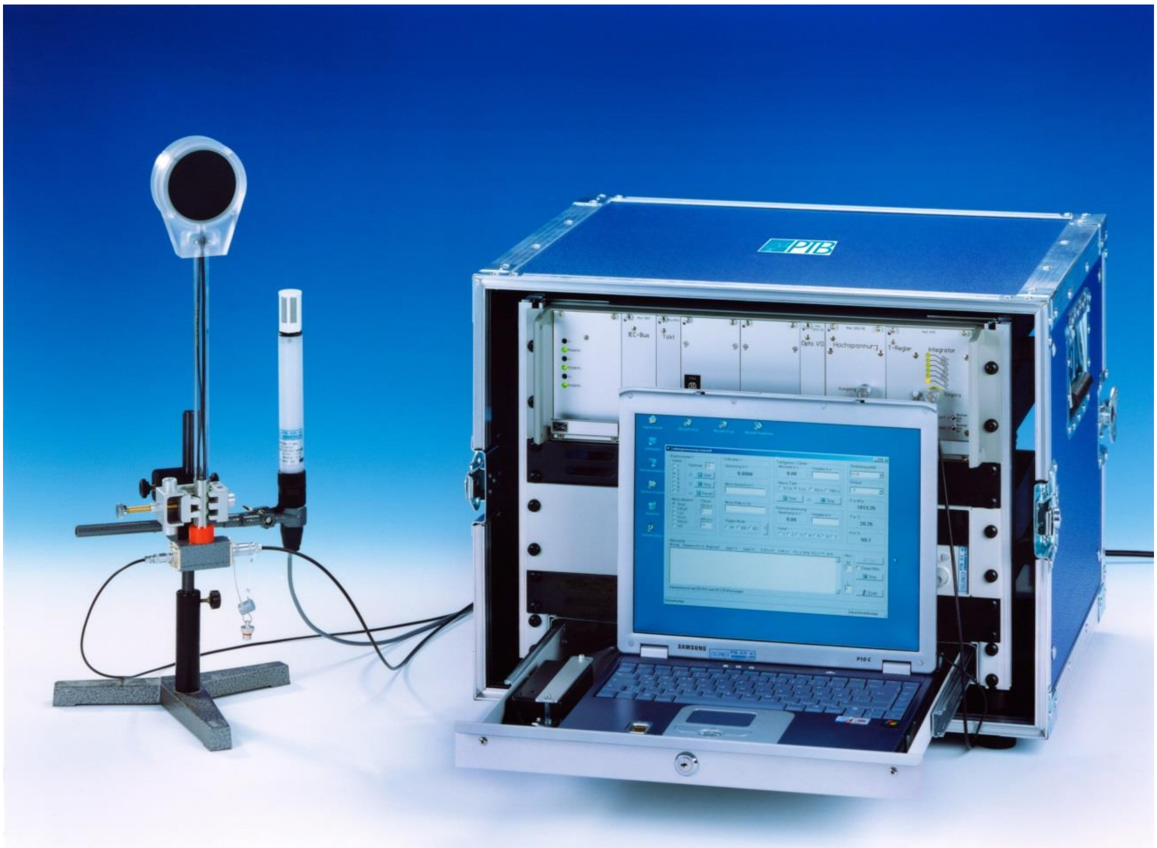

Figure 4: Transfer chamber and electronic measuring device

4.2 Preparations before starting the calibration measurements

4.2.1 Connection to mains and chamber

1.) The electronic device must be connected to a 230 V / 50 Hz mains. It is not possible to connect the device to a different mains voltage.
The electronic device is connected using the mains cable, see figure 4.

Figure 5: Back side of the electronic measuring device with distribution sockets and mains cable

2.) Before the mains voltage is switched on, the transfer chamber is to be connected to the electronic device. In the front cover of the blue box you find the cable for the chamber voltage and another one for measuring the chamber current, see figure 6. The cables are 10 m in length. The angle plugs must be put into the appropriate sockets on the front plate of the device, see figure 7. The plugs at the other end of the cables (straight plugs) are to be inserted into the appropriate sockets of the chamber.

Figure 6: Cables stored in the front cover of the blue box: one cable for the chamber voltage and one for measuring the chamber current

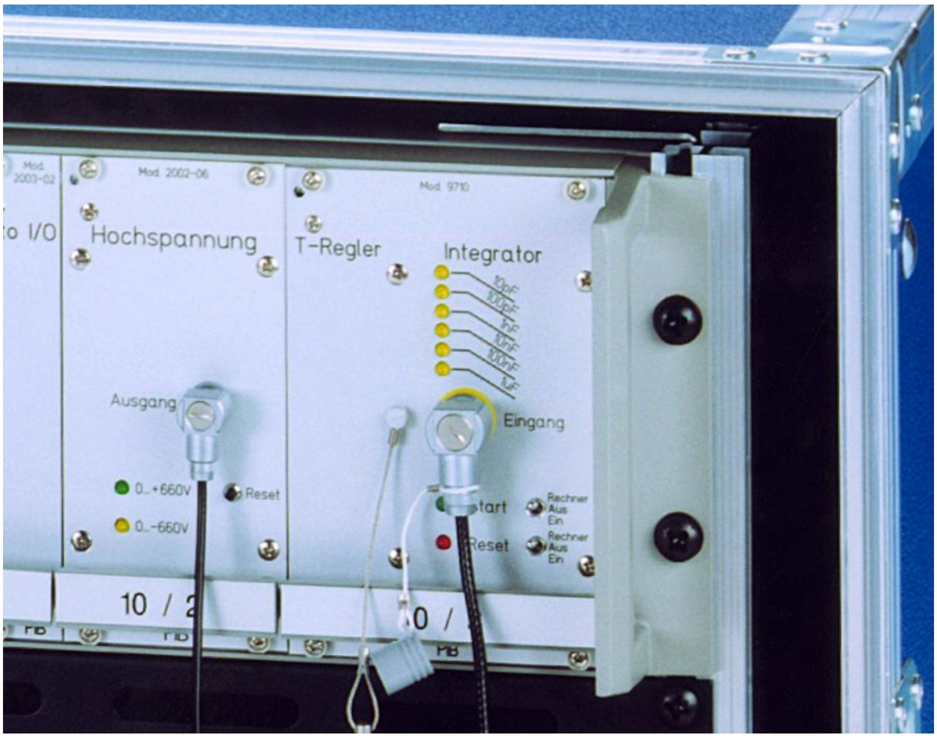

Figure 7: Front plate of the integrator and the high voltage power supply. The angle plugs must be put into the appropriate sockets at the front plate.

3.) A sensor for measuring the temperature and the relative air humidity, together with the cable for connection to the electronic device, can also be found on the front cover (see figure 8). This sensor must be positioned close to the chamber in the measuring room. **Attention!** This sensor must not be irradiated. The 15-pole Sub D plug of the cable of the temperature and humidity sensor is to be put in on the back of the electronic device, see figure 9.

Figure 8: Sensor for measuring the temperature and rel. humidity together with its cable inside the front cover of the blue box.

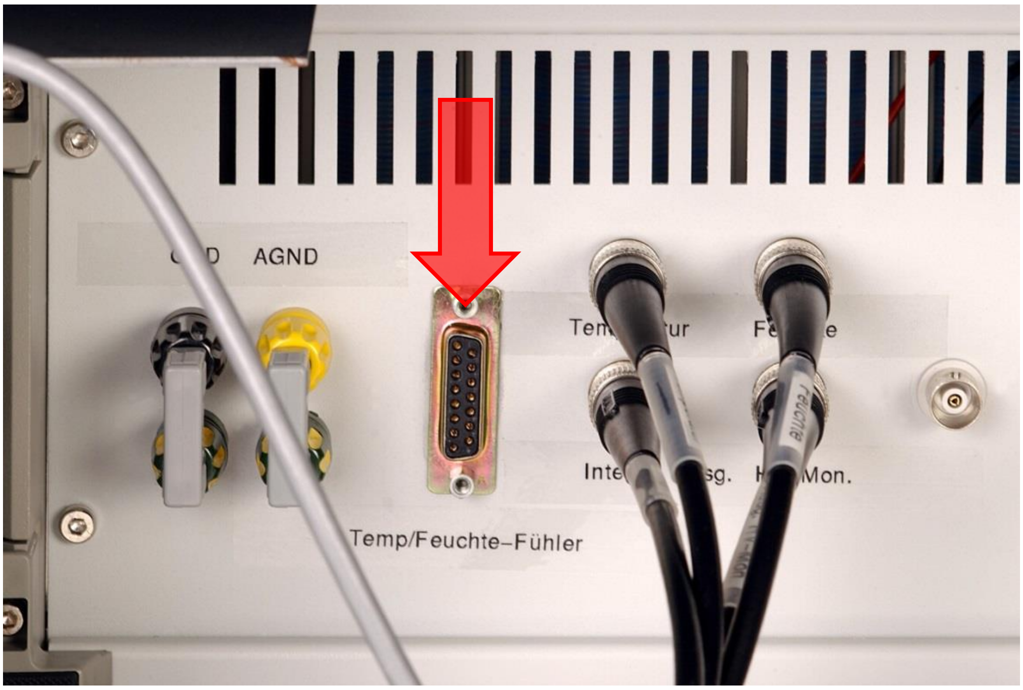

Figure 9: Socket at the backside of the electronic device for connecting the 15-pole Sub D plug of the cable of the temperature and humidity measuring sensor.

4.) The electronic device is switched on using the distribution sockets on the backside, see figure 10. All measuring instruments integrated in this device should be switched on after switching on the distribution sockets. If this is not possible, please check the power switch of the individual measuring instruments.

Figure 10: Switch of the distribution sockets on the back of the electronic device to switch on all electronic units.

5.) **Before starting the calibration measurements, the electronic device should be run up for at least 2 hours. Furthermore, the chamber is to be set for at least 1 h to the high voltage before the calibration measurements are started.** The chamber high voltage is to be switched on using the measuring program of the laptop (see chapter 4.2.2).

4.2.2 Starting the measuring program

- **Attention: The entrance window of the chamber is on chamber voltage potential (300 V)**
- **The two switches on the integrator must be in the „Rechner“ position.** The control of the electronic device and the calibration measurements are carried out using a laptop accommodated in the drawer of the blue box below the electronic measuring unit, see figure 4. After starting the laptop press the button ‘intercomparison‘. Then, you are asked for a password.

  The password is: euramet

  The measuring program “Current measurement“ is started with a double click on the icon  on the desktop.

- All parameters necessary for calibrating the transfer chamber are permanently set. It is not possible to change them. The user can, however, choose in the menu point ‘Configuration‘ between the **English- and the German program version.**

4.2.3 Check of electronic device and transfer chamber

4.2.3.1 Description of test procedure

Before the calibration measurements are started, the complete measuring system consisting of transfer chamber and electronic device must be verified using the test program.

The test procedure which is automatically controlled by the test program is the following: By variation of the chamber voltage, charge is transferred to the connected electrometer as a result of the chamber capacity. The value of the chamber capacity can be determined by variation of the chamber voltage, the electrometer capacity (calibrated against standards at the PTB) and variation of the output voltage of the integrator. Using the test program the chamber capacity is measured and compared with a reference value determined at the PTB before the measuring system (chamber and electronic device) was supplied to the other participants. If all measuring units work correctly and all instruments (also the chamber) are connected correctly, the chamber capacity measured with the test program must agree within 1 % with the reference value stored in a parameter file on the laptop

4.2.3.2 Starting the test program

The test program is started as follows: In the start window of the measuring program “Current measurement“ (see chapter 4.2.2) choose the menu point ‘Test‘ and then ‘Chamber capacity‘. The window ‘Chamber capacity measurement‘ is opened. All parameters necessary for the measurement of the chamber capacity are set and cannot be changed by the user.

The measurement of the capacity is started by a mouse-click on the ‘Start‘ button in the group box ‘Measurement’. The number of measurement is set to the value 5 in the field ‘Num. M‘ and cannot be changed. The values of the chamber capacity measured, the measuring time and the output voltages of the integrator are listed in the field ‘Measurement‘. At the end of the measurements, a mean value and its standard uncertainty is calculated. This mean value of the chamber capacity is compared with the reference value. On the screen the information whether or not the values agree is shown. Confirm the notification by pressing the button ‘OK‘. If they agree, you can perform the calibration measurements. For closing this window press the button ‘End‘. If they do not agree, please check the connections of the instruments and the cables and repeat the measurement. If they do not agree after some repetitions of the measurement, please contact the pilot laboratory (Rolf.Behrens@PTB.de).

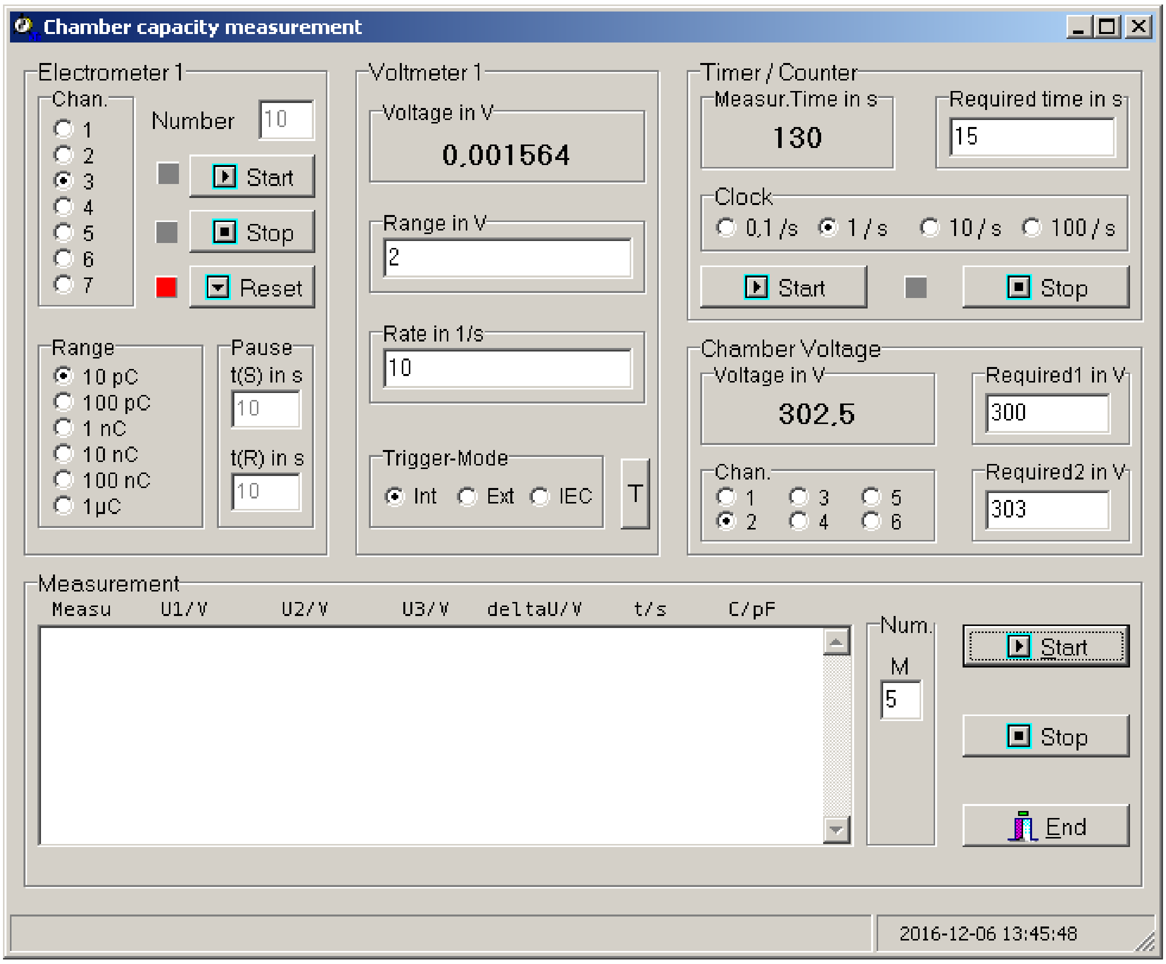

Figure 11: Window of the test program

4.3 Calibration measurement using the electronic device

4.3.1 Description of program flow

The program “Current measurement“ controls the electronic device and measures the current of the ionization chamber.

It is not possible for the program to control the beam shutter of the beta-ray facility. It must therefore be possible for the irradiation of the transfer chamber to be interrupted manually, e.g. using a manually controlled beam shutter. Every time the irradiation of the chamber must be interrupted or continued during the current measurement the screen displays the instruction to close or open the beam shutter and the irradiation, respectively. This instruction should be followed as rapidly as possible.

The value of the chamber current is determined from the charge collected by the ionization chamber. The charge is measured using an integrator with several feedback capacitors which can be switched. Further, a stop watch is integrated into the electronic measuring device. During the measurement, the output voltage of the integrator is measured once a second with the digital voltmeter. These values for the output voltage must linearly depend on the measuring time, i.e. the function is a straight line. The gradient of this straight line is proportional to the chamber current. The regression coefficient of the straight line is a measure of the quality of the charge measurement. The range of the regression coefficient covers the values between 0 and 1.

Measurements with a value of the regression coefficient higher than a value determined from the measured current and the capacitor used are rejected and marked in the record file by ‘X‘. They are repeated automatically. Using the field ‘Reg. evaluat.‘ positioned under the button ‘Stop‘ (see figure 12) the regression evaluation can be switched off. If no regression evaluation should be done, click in the field ‘Reg. evaluat.‘. Then no measurement is rejected. However, for information all measurements with a value of the regression coefficient higher than a value determined from the measured current and the capacitor used are now marked by ‘\‘ and not by ‘X‘. **However it is recommended to perform all measurements using the regression evaluation. The regression evaluation should be switched off only if otherwise no measurements are possible.**

In order to avoid switching effects, after starting the integrator and before starting the measurement, the measuring program provides a break of 10 s. After the measurement, the feedback capacitor is grounded also for 10 s. These time values cannot be changed.

The integrator used has an input current (leakage current) of some femtoampère (10^{-15} A). This leakage current should be determined for each calibration measurement. The measuring program automatically subtracts the leakage current when measured. To determine the influence of the output voltage of the integrator on the leakage current, the leakage current measurements are carried out using different output voltages. This is performed in the following manner: Before starting the leakage current measurement, the ionization chamber is irradiated. The feedback capacitor becomes charged. After a defined time, the irradiation terminates and the leakage current is measured.
A measurement cycle consists of a number of single measurements of the chamber current (the number can be defined in the field ‘M‘ in the group box ‘Num.‘) and a number of single measurements of the leakage current (the number can be defined in the field ‘L‘ in the group box ‘Num.‘). After every measurement cycle, the mean value of the chamber current and the mean value of the leakage current with the associated standard uncertainties are calculated and displayed in the field ‘Measurement‘. The corrected chamber current determined in this

measurement cycle is calculated as the mean value of the chamber current minus the mean value of the leakage current.

The corrected chamber current is given in the field ‘Measurement‘ together with its standard uncertainty with one standard deviation, $k = 1$.

The current measured by the chamber under the ambient conditions is corrected by the measuring software to the current under reference air conditions (air pressure: 101.3 kPa, temperature: 293.15 K, rel. humidity: 65 %), i.e. reference air density.

4.3.2 Record file

After each single measurement, all relevant data are stored in the record file. Before a measurement cycle can be started, a record file must be opened. Without such a file, the user cannot start the measurement. The record file can be opened in the menu ‘File‘ (‘Datei‘) using the menu item ‘Record file‘ (‘Protokolldatei‘). Here, it is to be chosen in the field ‘Suchen in‘ the directory in which the record file should be stored. Further in the field ‘Dateiname‘ the file name is to be filled in. The fields ‘Suchen in‘ and ‘Dateityp‘ (file extension) can be filled in using the list fields. The record files have the extension .txt, but this can be changed. If a new file is used, it is created in the directory chosen after having pressed the button ‘OK‘ and then it is opened. If an existing file is chosen, this is opened by operating the button ‘OK‘. The file opened can be changed. All changes in the file can be stored using the menu item ‘Save‘ (‘Speichern‘) in the menu ‘File‘ (‘Datei‘). Using the other menu item ‘New‘ (‘Neu‘) a new file can be created, and with the menu item ‘Open‘ (‘Öffnen‘) an existing file can be opened. To go back to the start window of the measuring program, choose menu item ‘Close‘ („Zum Hauptmenü“).

4.3.3 Working of the program

It is not allowed during a measurement to run other programs on the laptop.

Choosing the menu item ‘Current measurement (manual)‘ („Messung, Kammerstrom manuell“), the window to control the electronic device and to perform the measurements is opened, see Figure 12.

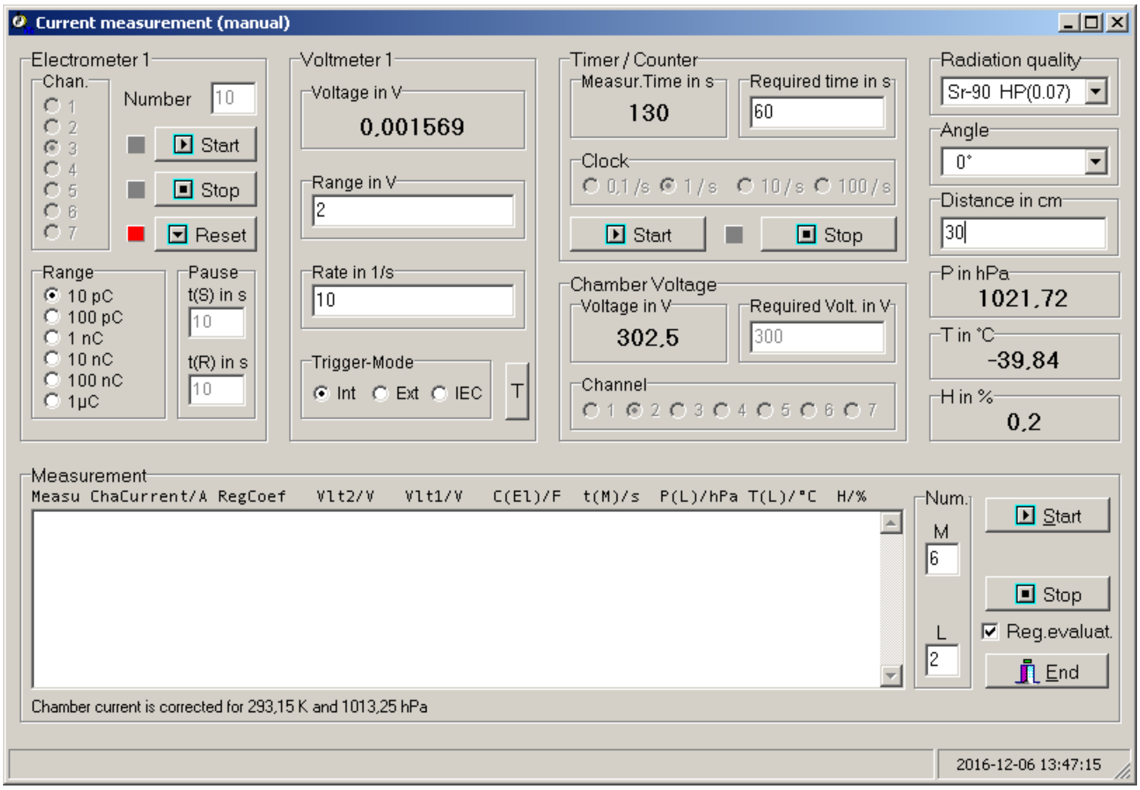

Figure 12: Window to control the electronic device and to perform the measurements

Most of the parameters necessary for the measurements are preset and cannot be changed. Only the radiation quality (in combination with the quantity) and the angle of incidence can be chosen by means of the list field. The distance in cm between the surface of the beta source and the point of test (reference point of chamber) is to be recorded in the field ‘Distance in cm‘ (‘Abstand in cm‘). The measuring time for one single measurement is set to 60 s, but this can be changed. Attention! If the measuring time is set too short, the uncertainty of the measuring results increases considerably. The number of current measurements (with irradiation of the chamber) (the number can be set in the field ‘M‘ in the group box ‘Num.‘) and the number of leakage current measurements (without irradiation of the chamber) (the number can be defined in the field ‘L‘ in the group box ‘Num.‘) can be chosen. It is defined in the program that at least one leakage current measurement must be chosen. If the chamber current is lower than 10^{-12} A, at least three single measurements of the leakage current should be carried out for a good statistic. The regression evaluation (see chapter 4.3.1) can be switched off in the field ‘Reg. evaluat.‘. However, it is recommended to perform the measurements using the regression evaluation. For measuring the chamber current at least five single measurements for each radiation quality and angle of incidence should be chosen.

After the calibration measurement, please compare the values of the ambient temperature, relative humidity and air pressure given in the field ‘Measurement‘ with the values measured with instruments from the laboratory participating. These values should agree.

After the start of the measurement, the optimal feedback capacitor is determined automatically and cannot be changed by the user.

After all parameters needed are entered in the respective fields, the measurement can be started by pressing the button ‘Start‘ in the group box ‘Measurement’. The order to open and to close, respectively, the beam shutter should be followed as rapidly as possible. The measurement can be interrupted by pressing the button ‘Stop‘. To close the window use the button ‘End‘.

All data of a calibration measurement are stored in the record file.

4.3.4 End of measurement

The record files can be copied using a USB memory stick. Please, do not erase the record file on the laptop.

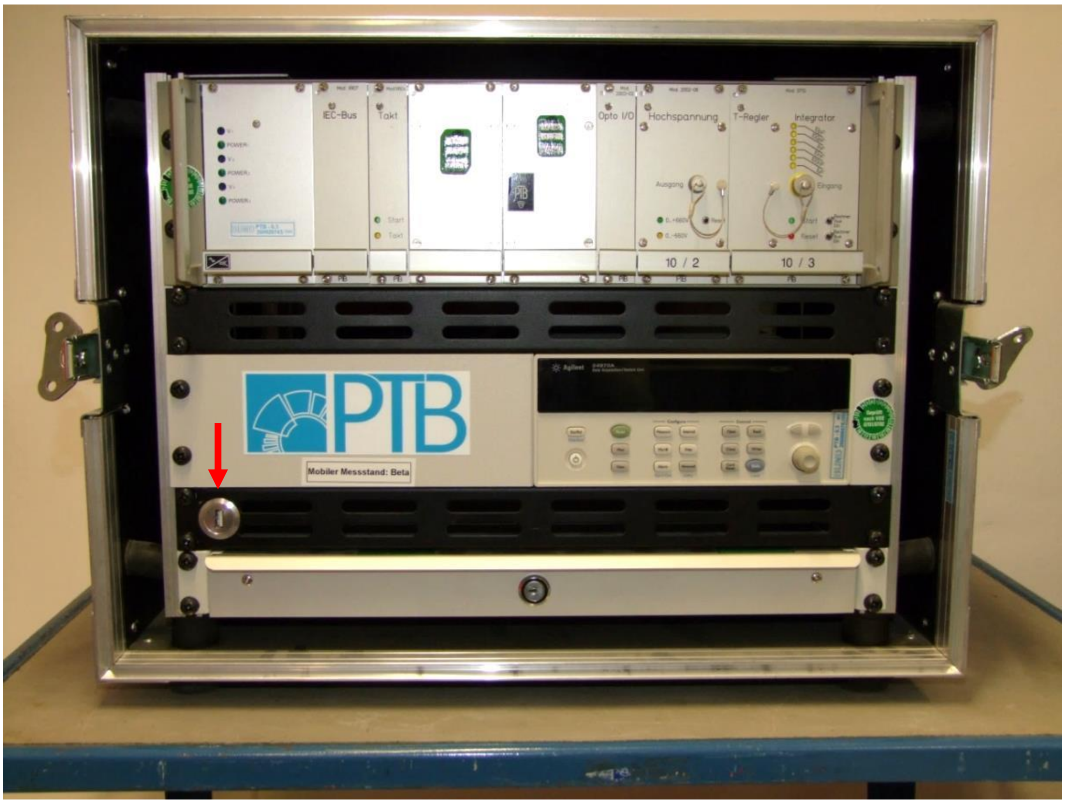

Figure 13: USB Port, connected to the Laptop

To switch off the electronic device, proceed as follows:

1. Switch off the distribution sockets (see figure 9)
2. Disassemble the experimental set-up. Put the caps on the plugs of the chamber current cable and put the cables into the cable boxes inside the blue transport box.
3. Put the caps into the sockets of the integrator input and the chamber current output.
4. Assemble the blue transport box with the covers for the front and back side. **Attention!** The two covers are not interchangeable. In the cover for the front side the boxes for the cables and the temperature and humidity sensor are installed.

5. Summary – how to proceed for the measurements

For performing the calibration measurements, the following is to be done and taken into account:

1. Experimental set-up:

- The chamber must be irradiated completely. The beam diameter at the point of test should be larger than 9 cm. A distance between the surface of the beta source and the reference point of the chamber of more than 10 cm is recommended. The beam axis must be the normal to the chamber front surface and go through the reference point. For the position of the reference point see Figure 3. The axis of rotation must go through the reference point.
- The reference point of the chamber is to be positioned in the point of test.
- The homogeneity of the dose rate across the active chamber volume should be about 5 % or better.
- If possible, the calibration should be performed at dose rates of at least about 3 mSv/h.
- The transfer chamber calibrations with respect to $\dot{H}_{\mathrm{p}}(0.07;\alpha)$ have to be performed without the protection cover while the ones with respect to $\dot{H}_{\mathrm{p}}(3;\alpha)$ have to be performed with the protection cover.

2. Electronic device:

- Switch on the electronic device, see chapter 4.2.1
- Start the measuring program "Current measurement", see chapter 4.2.2
- Check the chamber and the electronic device for proper function using the test program, see chapter 4.2.3
- Create a record file, see chapter 4.3.2

3. Performing the calibration measurements:

- Start the window "Current measurement (manual)" of the measuring program, see chapter 4.3.3
- Compare the values of ambient temperature, relative humidity and air pressure given by the measuring program with the values measured with instruments from the laboratory participating. These values should agree, see chapter 4.3.3.
- **Before the calibration measurements can be started the HV electrode of the transfer chamber is to be set to high voltage for at least 2 h (for example overnight). For this the window "Current measurement (manual)" must be opened on the laptop, see chapter 4.3.3.**
- Fill in the parameters needed and start the calibration measurement, see chapter 4.3.3
- For the angles of incidence 45° and 60°, the measurements should be performed at the angles $+\alpha$ and $-\alpha$, see chapter 1.

Check list for the preparation of the report on the measurements for the EURAMET comparison for $\dot{H}_p(0.07;\alpha)$ and $\dot{H}_p(3;\alpha)$

The measuring report must comprise the following details:

1. Complete address of the institute

2. Which quality management is established in the laboratory participating? (e.g. PTB has a quality management according to ISO 17025)

3. Date or period of the measurements

4. a) Description of the method to measure the conventional quantity value of the reference absorbed dose rate to tissue due to beta radiation $\dot{D}_{R\beta} = \dot{D}_t(0.07;0°)_\beta$. The value for $\dot{D}_{R\beta}$ should be valid for the slab phantom and for reference air conditions.
   b) Description of the measuring devices used for the determination of $\dot{D}_{R\beta}$ including information on the traceability to primary standards and their quality assurance.
   c) Information about the beta reference fields used (radionuclide, homogeneity at the calibration distances, beam flattening filter etc.).

5. a) Description of the calculation of the conventional quantity values of $\dot{H}_p(0.07;\alpha)$ and/or $\dot{H}_p(3;\alpha)$ at the radiation qualities used for this comparison, name all parameters and corrections used. The values for $\dot{H}_p(0.07;\alpha)$ and $\dot{H}_p(3;\alpha)$ shall be valid for a slab phantom and for the ambient air conditions during the measurement with the transfer chamber.
   b) Specification of the uncertainty, the confidence level (recommended: two standard deviations, $k = 2$) and the principal components of the uncertainty.

6. Description of the measurements with the transfer chamber, namely all parameters (beam diameter at the point of test, irradiation distance between the point of test and the surface of the source, etc.) and the experimental set-up, if possible with pictures.

7. Complete the form to document all parameters and results of the calibration measurements. The form is part of the report and is given in Annex A.

8. Results of the measurements and complete uncertainty budgets according to ISO/IEC Guide 98-3:2008 *Uncertainty of measurement -- Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*: Responses with expanded uncertainty ($k = 2$). An example for such uncertainty budgets can be found in Annex B.

9. The person in the laboratory who has been in charge of the comparison must be indicated in the report.

An example of the description of the measuring devices for and the method to measure $\dot{D}_{R\beta}$ is given in Annex C.

An example of the description of the beta reference fields is given in Annex D.

Annex A: Example tables for the results of the transfer chamber measurements

Symbols:

$\dot{H}_p(d;\alpha)$: Dose rate during the transfer chamber irradiation (mean value for positive and negative incidence)
I_c: Ionization current of the transfer chamber (mean value for positive and negative incidence)
N: Calibration factor of the transfer chamber (mean value for positive and negative incidence)
Δ_{mv}: Deviation of the calibration factors for positive (pos) and negative (neg) incidence from the mean value

Example table for the presentation of the results of the calibration measurements for H_p(0.07):

radiation quality and angle of incidence	irradiation distance cm	beam flattening filter (with or without)	dose rate $\dot{H}_p(0.07;\alpha)$ and stand. unc. (k=1) mSv/h	corrected current I_c and stand. unc. (k=1) *) fA	Calibration factor N and expanded uncertainty (k = 2) mSv/(h·fA)	Δ_{mv} = (N_{pos}− N_{neg}) / (N_{pos}+N_{neg}) and exp. unc. (k=2)	Remark
Pm-147; 0°	20	with	…	…	…	…	…
Pm-147; 45°	20	with	3.00 ± 0.09	100.0 ± 0.5	0.0300 ± 0.0018	-1.0 % ± 0.7 %	none
Pm-147; 60°	20	with	…	…	…	…	…
Kr-85; 0°	20	with	…	…	…	…	…
Kr-85; 45°	30	with	…	…	…	…	…
Kr-85; 60°	30	with	…	…	…	…	…
Sr-90/Y-90; 0°	20	with	…	…	…	…	…
Sr-90/Y-90; 45°	30	with	…	…	…	…	…
Sr-90/Y-90; 60°	30	with	…	…	…	…	…
Ru-106/Rh-106; 0°	20	without	…	…	…	…	…
Ru-106/Rh-106; 45°	20	without	…	…	…	…	…
Ru-106/Rh-106; 60°	20	without	…	…	…	…	…

*) given by the measuring software

Example table for the presentation of the results of the calibration measurements for H_p(3):

radiation quality and angle of incidence	irradiation distance cm	beam flattening filter (with or without)	dose rate $\dot{H}_p(3;\alpha)$ and stand. unc. (k=1) mSv/h	corrected current I_c and stand. unc. (k=1) *) fA	Calibration factor N and expanded uncertainty (k = 2) mSv/(h·fA)	Δ_{mv} = (N_{pos}− N_{neg}) / (N_{pos}+N_{neg}) and exp. unc. (k=2)	Remark
Sr-90/Y-90; 0°	30	with	…	…	…	…	…
Sr-90/Y-90; 45°	30	with	…	…	…	…	…
Sr-90/Y-90; 60°	30	with	…	…	…	…	…
Ru-106/Rh-106; 0°	20	without	…	…	…	…	…
Ru-106/Rh-106; 45°	20	without	…	…	…	…	…
Ru-106/Rh-106; 60°	20	without	…	…	…	…	…

*) given by the measuring software

Annex B.1

Example for the uncertainty budgets for the dose rate (example for Pm-147)

Corrected ionization current of the extrapolation chamber, I_{corr}:

Model function: $I_{corr} = I_{mean} \cdot k_{ad} \cdot k_{abs} \cdot k_{di} \cdot k_{pe} \cdot k_{sat} \cdot k_{ac} \cdot k_{el} \cdot k_{in} \cdot k_{de} \cdot k_{th} \cdot k_{St,a}$

List of Quantities:

Quantity	Unit	Definition
I_{corr}	fA	Corrected ionization current
I_{mean}	fA	Ionization current (mean value of positive and negative chamber polarity)
k_{ad}		Correction factor for the variations of air density in the collecting volume from reference conditions
k_{abs}		Correction factor for variations in the attenuation and scattering of beta particles between the source and the collecting volume due to variations from reference conditions
k_{di}		Correction factor for axial non-uniformity due to divergence of the beta particle field
k_{pe}		Correction factor for perturbation of the beta-particle flux density by the side walls of the extrapolation chamber
k_{sat}		Correction factor for ionization collection losses due to ionic recombination
k_{ac}		Correction factor for attenuation of beta particles in the collecting volume
k_{el}		Correction factor for electrostatic attraction of the entrance window due to the collecting voltage
k_{in}		Correction factor for interface effects between the air of the collecting volume and the adjacent entrance window and collecting electrode
k_{de}		Correction factor for radioactive decay of the beta particle source
k_{th}		Correction factor for the decrease of the distance due to the thickness of the absorbers in front of the ionization chamber
$k_{St,a}$		Correction factor for the change of the stopping power ratio depending on the depth in the thickness of the absorbers in front of the ionization chamber

Uncertainty Budget:

Quantity	Value	Standard Uncertainty	Distribution *)	Sensitivity Coefficient	Uncertainty Contribution
I_{mean}	56.150 fA	0.37 % (rel)	normal	1.0	0.21 fA
k_{ad}	0.9919	0.60 % (rel)	normal	59 fA	0.35 fA
k_{abs}	1.0767	1.05 % (rel)	normal	54 fA	0.61 fA
k_{di}	1.0050	0.10 % (rel)	normal	58 fA	0.058 fA
k_{pe}	1.0020	0.10 % (rel)	normal	58 fA	0.058 fA
k_{sat}	1.0055	0.20 % (rel)	normal	58 fA	0.12 fA
k_{ac}	1.0000	0.10 % (rel)	normal	58 fA	0.058 fA
k_{el}	1.0000	0.10 % (rel)	normal	58 fA	0.058 fA
k_{in}	1.0000	0.01 % (rel)	normal	58 fA	$5.8 \cdot 10^{-3}$ fA
k_{de}	0.9561	0.02 % (rel)	normal	61 fA	0.012 fA
k_{th}	0.9995	0.10 % (rel)	normal	58 fA	0.058 fA
$k_{St,a}$	1.0011	0.01 % (rel)	normal	58 fA	$5.8 \cdot 10^{-3}$ fA
I_{corr}	58.088 fA	0.755 fA			

**) used for the determination of the standard uncertainty*

Reference absorbed dose rate to tissue due to betas at 0.07 mm tissue equivalent depth, $\dot{D}_{Rß}$:

Model function:

$\dot{D}_{Rß} = s_{t,a} \cdot W_e \cdot k_{br} \cdot k_{ba} \cdot k_{hu} \cdot k_{ra} \cdot (dI_{corr}/dl\,)/(a \cdot \rho_{a0}) \cdot k_{FitExp} \cdot k_{FitDD}$

List of Quantities:

Quantity	Unit	Definition
$\dot{D}_{Rß}$	mGy/h	Reference absorbed dose rate to tissue due to betas at depth d = 0.07 mm
$s_{t,a}$		Quotient of mass-electronic stopping powers of ICRU tissue and air
W_e	J/C	Average energy to produce an ion pair in air under reference conditions
k_{br}		Correction factor for the effect of bremsstrahlung from the beta-particle source
k_{ba}		Correction factor for the difference in backscatter between tissue and the material of the collecting electrode and guard ring
k_{hu}		Correction factor for the effect of humidity of the air in the collecting volume on W_e
k_{ra}		Correction factor for radial non-uniformity of the absorbed dose rate in the beam
dI_{corr}/dl	fA/mm	Limiting value of the slope of the corrected current versus chamber depth l function
l	mm	Chamber depth
a	mm²	Effective area of the collecting electrode
ρ_{a0}	kg/m³	Density of air at reference conditions
k_{FitExp}		Correction factor for the fit of the extrapolation (Exp) curve (unity - only used to account for the uncertainty of the fit)
k_{FitDD}		Correction factor for the fit of the depth dose (DD) curve (unity - only used to account for the uncertainty of the fit)

Uncertainty Budget:

Quantity	Value	Standard Uncertainty	Distribution *)	Sensitivity Coefficient	Uncertainty Contribution
$s_{t,a}$	1.1240	1.50 % (rel)	normal	8.1 mGy/h	0.14 mGy/h
W_e	33.83 J/C	0.20 % (rel)	normal	0.27 (mGy·C)/(h·J)	0.018 mGy/h
k_{br}	0.9939	0.20 % (rel)	normal	9.2 mGy/h	0.018 mGy/h
k_{ba}	1.0000	0.40 % (rel)	normal	9.1 mGy/h	0.036 mGy/h
k_{hu}	1.0000	0.10 % (rel)	normal	9.1 mGy/h	$9.1\cdot10^{-3}$ mGy/h
k_{ra}	1.0000	0.70 % (rel)	normal	9.1 mGy/h	0.064 mGy/h
dI_{corr}/dl	58.088 fA/mm	1.30 % (rel)	normal	0.16 (mGy·mm) / (h·fA)	0.12 mGy/h
a	724.81 mm²	0.07 % (rel)	normal	-0.013 (mGy) / (h·mm²)	$-6.3\cdot10^{-3}$ mGy/h
ρ_{a0}	1.1974 kg/m³	0.04 % (rel)	normal	-7.6 (mGy·mm) / (h·fA)	$-3.8\cdot10^{-3}$ mGy/h
k_{FitExp}	1.0000	0.19 % (rel)	normal	9.1 mGy/h	0.017 mGy/h
k_{FitDD}	1.0000	0.39 % (rel)	normal	9.1 mGy/h	0.036 mGy/h
$\dot{D}_{Rß}$	9.106 mGy/h	0.201 mGy/h			

**) used for the determination of the standard uncertainty*

Total personal dose equivalent rate at depth d = 0.07 mm or 3 mm in the slab phantom (due to betas and photons) during the measurement with the transfer chamber at positive (pos) angle of incidence, $\dot{H}_p(d;\alpha)_{pos}$:

Model functions:

$\dot{H}_{beta} = (T \cdot R - \tau_{br}) \cdot (\dot{D}_{Rß} / (1 - \tau_{br})) \cdot c_{absDist} \cdot c_{absMeas} \cdot c_{absFit} \cdot k_{de} \cdot k_{Dist}$
$\dot{H}_{phot} = \tau_{br} \cdot \dot{D}_{Rß} / (1 - \tau_{br}) \cdot k_{de} \cdot k_{Dist}$
$\dot{H}_p(d;\alpha)_{pos} = \dot{H}_{beta} + \dot{H}_{phot}$

List of Quantities:

Quantity	Unit	Definition
$\dot{D}_{Rß}$	mGy/h	Reference absorbed dose rate to tissue due to betas at depth d = 0.07 mm
T	Sv/Gy	Depth factor for depth d = 0.07 mm or 3 mm in the phantom (unity for d = 0.07 mm and, thus, no uncertainty; the value is different from unity at d = 3 mm and has an uncertainty)
R		Angular factor for angle of incidence α (at depth d) in the phantom
τ_{br}		Photon dose divided by total dose at d = 0.07 mm tissue depth [1)]
$c_{absDist}$		Correction due to absorption and scattering in air; uncertainty contribution due to uncertainty in the distance is taken into account here
$c_{absMeas}$		Correction due to absorption and scattering in air; uncertainty contribution due to uncertainty in the distance is taken into account here
c_{absFit}		Correction due to absorption and scattering in air (always unity but an uncertainty contribution due to the fit of the depth dose curve is taken into account here)
k_{de}		Correction for radioactive decay
k_{Dist}		Correction due to uncertainty in the distance (always unity but uncertainty contribution due to quadratic distance law is taken into account here)
$\dot{H}_{beta}$	mSv/h	Dose rate due to betas at depth d = 0.07 mm or 3 mm
$\dot{H}_{phot}$	mSv/h	Dose rate due to photons at depth d = 0.07 mm or 3 mm
$\dot{H}_p(d;\alpha)_{pos}$	mSv/h	Total personal dose equivalent rate at depth d = 0.07 mm or 3 mm in the slab phantom (due to betas and photons) at positive (pos) angle of incidence α

1) In principle, it is $k_{br} = 1 - \tau_{br}$. However, small deviations occur as τ_{br} is valid for d = 0.07 mm tissue equivalent depth and is an average over several measurements of many sources while k_{br} is valid for the actual source and the actual measurement depth which is slightly different from 0.07 mm tissue depth.

Uncertainty Budget:

Quantity	Value	Standard Uncertainty	Distribution *)	Sensitivity Coefficient	Uncertainty Contribution
T	1.0 Sv/Gy	0.0 % (rel)	normal	3.2 (mSv·Gy)/(h·Sv)	$0.32 \cdot 10^{-9}$ mSv/h
R	0.720	1.76 % (rel)	normal	4.5	0.057 mSv/h
τ_{br}	$5.50 \cdot 10^{-3}$	42 % (rel)	normal	3.0 mSv/h	$7.0 \cdot 10^{-3}$ mSv/h
$\dot{D}_{Rß}$	9.106 mGy/h	2.21 % (rel)	normal	0.35 mSv/mGy	0.071 mSv/h
$c_{absDist}$	1.0498	1.27 % (rel)	normal	3.0 mSv/h	0.041 mSv/h
$c_{absMeas}$	1.0000	0.50 % (rel)	normal	3.2 mSv/h	0.016 mSv/h
c_{absFit}	1.0000	0.40 % (rel)	normal	3.2 mSv/h	0.013 mSv/h
k_{de}	0.46585	0.02 % (rel)	normal	6.9 mSv/h	$0.64 \cdot 10^{-3}$ mSv/h
k_{Dist}	1.0000	0.46 % (rel)	normal	3.2 mSv/h	0.015 mSv/h
$\dot{H}_p(d;\alpha)_{pos}$	3.223 mSv/h	0.103 mSv/h			

**) used for the determination of the standard uncertainty*

Annex B.2

Example for the uncertainty budgets for the calibration factor of the transfer chamber (example for Pm-147)

Calibration factor of the transfer chamber (mean value of positive and negative angle of incidence), *N*, and *deviation of the calibration factors for positive and negative incidence from its mean value,* Δ_{mv}:

Model functions:

$N_{pos} = \dot{H}_p(d;\alpha)_{pos} / I_{ch,pos}$

$N_{neg} = \dot{H}_p(d;\alpha)_{neg} / I_{ch,neg}$

$N = (N_{pos} + N_{neg}) / 2$

$\Delta_{mv} = (N_{pos} - N_{neg}) / (N_{pos} + N_{neg})$

List of Quantities:

Quantity	Unit	Definition
N_{pos}	mSv/(h·fA)	Calibration factor of the transfer chamber at positive (pos) angle of incidence
$\dot{H}_p(d;\alpha)_{pos}$	mSv/h	Total personal dose equivalent rate at depth d = 0.07 mm or 3 mm in the slab phantom (due to betas and photons) at positive (pos) angle of incidence
$I_{ch,pos}$	fA	Ionization current of the transfer chamber at positive (pos) angle of incidence
N_{neg}	mSv/(h·fA)	Calibration factor of the transfer chamber at negative (neg) angle of incidence
$\dot{H}_p(d;\alpha)_{neg}$	mSv/h	Total personal dose equivalent rate at depth d = 0.07 mm or 3 mm in the slab phantom (due to betas and photons) at negative (neg) angle of incidence
$I_{ch,neg}$	fA	Ionization current of the transfer chamber at negative (neg) angle of incidence
N	mSv/(h·fA)	Calibration factor of the transfer chamber (mean value of positive and negative angle of incidence)
Δ_{mv}	%	Deviation of the calibration factors for positive and negative incidence from their mean value (mv)

Correlations:

The dose rate at positive and negative angle of incidence are directly correlated as they are determined using the same method. The ionization currents for positive and negative angle of incidence, $I_{ch,pos}$ and $I_{ch,pos}$, *are assumed to be uncorrelated as the chamber is irradiated in a different orientation. The corresponding correlation matrix is*

	$\dot{H}_p(d;\alpha)_{pos}$	$I_{ch,pos}$	$\dot{H}_p(d;\alpha)_{neg}$	$I_{ch,neg}$
$\dot{H}_p(d;\alpha)_{pos}$	1.0	0	1.0	0
$I_{ch,pos}$	0	1.0	0	0
$\dot{H}_p(d;\alpha)_{neg}$	1.0	0	1.0	0
$I_{ch,neg}$	0	0	0	1.0

Uncertainty Budgets:

N_{pos}: *Calibration factor of the transfer chamber at positive (pos) angle of incidence*

Quantity	Value	Standard Uncertainty	Distribution *)	Sensitivity Coefficient	Uncertainty Contribution
$\dot{H}_p(d;\alpha)_{pos}$	3.000 mSv/h	3.00 % (rel)	normal	$9.9\cdot10^{-3}$ 1/fA	$0.89\cdot10^{-3}$ mSv/(h·fA)
$I_{ch,pos}$	101.0 fA	0.50 % (rel)	normal	$-0.29\cdot10^{-3}$ mSv/(h·fA²)	$-0.15\cdot10^{-3}$ mSv/(h·fA)
N_{pos}	0.02970 mSv/(h·fA)	0.00090 mSv/(h·fA)			

**) used for the determination of the standard uncertainty*

N_{neg}: *Calibration factor of the transfer chamber at negative (neg) angle of incidence*

Quantity	Value	Standard Uncertainty	Distribution *)	Sensitivity Coefficient	Uncertainty Contribution
$\dot{H}_p(d;\alpha)_{neg}$	3.000 mSv/h	3.00 % (rel)	normal	0.010 1/fA	$0.91 \cdot 10^{-3}$ mSv/(h·fA)
$I_{ch,neg}$	99.0 fA	0.50 % (rel)	normal	$-0.31 \cdot 10^{-3}$ mSv/(h·fA²)	$-0.15 \cdot 10^{-3}$ mSv/(h·fA)
N_{neg}	0.03030 mSv/(h·fA)	0.00092 mSv/(h·fA)			

**) used for the determination of the standard uncertainty*

N: *Calibration factor of the transfer chamber (mean value for positive and negative incidence)*

Quantity	Value	Standard Uncertainty	Distribution *)	Sensitivity Coefficient	Uncertainty Contribution
$\dot{H}_p(d;\alpha)_{pos}$	3.000 mSv/h	3.00 % (rel)	normal	$5.0 \cdot 10^{-3}$ 1/fA	$0.45 \cdot 10^{-3}$ mSv/(h·fA)
$I_{ch,pos}$	101.0 fA	0.50 % (rel)	normal	$-0.15 \cdot 10^{-3}$ mSv/(h·fA²)	$-0.074 \cdot 10^{-3}$ mSv/(h·fA)
$\dot{H}_p(d;\alpha)_{neg}$	3.000 mSv/h	3.00 % (rel)	normal	$5.1 \cdot 10^{-3}$ 1/fA	$0.45 \cdot 10^{-3}$ mSv/(h·fA)
$I_{ch,neg}$	99.0 fA	0.50 % (rel)	normal	$-0.15 \cdot 10^{-3}$ mSv/(h·fA²)	$-0.076 \cdot 10^{-3}$ mSv/(h·fA)
N	0.03000 mSv/(h·fA)	0.00091 mSv/(h·fA)			

**) used for the determination of the standard uncertainty*

Δ_{mv}: *Deviation of the calibration factors for positive and negative incidence from its mean value*

Quantity	Value	Standard Uncertainty	Distribution *)	Sensitivity Coefficient	Uncertainty Contribution
$\dot{H}_p(d;\alpha)_{pos}$	3.000 mSv/h	3.00 % (rel)	normal	17 (%·h)/mSv	1.5 %
$I_{ch,pos}$	101.0 fA	0.50 % (rel)	normal	-0.50 (%·h)/mSv	-0.25 %
$\dot{H}_p(d;\alpha)_{neg}$	3.000 mSv/h	3.00 % (rel)	normal	-17 (%·h)/mSv	-1.5 %
$I_{ch,neg}$	99.0 fA	0.50 % (rel)	normal	0.51 (%·h)/mSv	0.25 %
Δ_{mv}	-1.00 %	0.35 %			

**) used for the determination of the standard uncertainty*

For the final results the standard deviation has to be multiplied by an appropriate coverage factor to obtain a coverage interval of about 95 %. Once a normal distribution can be assumed for the probability density function of the resulting quantity, N, a coverage factor of k = 2 is appropriate.

Annex B.3

Literature for the model functions and uncertainty budgets

1) Literature for the reference absorbed dose rate to tissue due to betas, $\dot{D}_{Rß}$:
   - ISO 6980-2, International Organization for Standardization *Reference beta-particle radiation – Part 2: Calibration fundamentals related to basic quantities characterizing the radiation field* (2004).
   - J. Brunzendorf *Determination of depth-dose curves in beta dosimetry*, Rad. Prot. Dosim. **151** (2012) 203-210.
   - J. Brunzendorf *Depth-dose curves of the beta reference fields ^{147}Pm, ^{85}Kr and ^{90}Sr/^{90}Y produced by the beta secondary standard BSS2*, Rad. Prot. Dosim. **151** (2012) 211-217.

2) Literature for the total personal dose equivalent rate (due to betas and photons), $\dot{H}_p$:
   - R. Behrens and G. Buchholz *Extensions to the PTB Beta Secondary Standard BSS 2.* J. Instrum. **6** P11007 (2011) and Erratum: J. Instrum. **7** E04001 (2012) and Addendum: J. Instrum. **7** A05001 (2012). A consolidated version is available.

Annex C Example for the description of the measuring devices for and the method to determine $\dot{D}_{\text{Rß}}$

Annex C.1 Determination of the conventional quantity value of $\dot{D}_{\text{Rß}} = \dot{D}_{\text{t}}(0.07;0°)_{\text{ß}}$

The primary standard measuring device for realizing the unit of absorbed dose rate to tissue due to beta radiation at 0.07 mm depth at PTB uses an extrapolation ionization chamber. Detailed descriptions of this device can be found in publications [1],[2]. The most important parameters are summarized in Table C.1.

Table C.1: Main characteristics of the beta primary standard measuring device of PTB used for the comparison measurements

Parameter	PTB
Type of chamber	Extrapolation chamber
Entrance window: Material Mass per area in mg/cm² Equivalent tissue depth d_{win} in mm	 graphited Hostaphan (polyethyleneterephtalate, PET) 0.6224 0.005737
Additional absorber: Material Mass per area in mg/cm² Equivalent tissue depth d_{abs} in mm	 Hostaphan (PET) 6.963 0.06504
Collector: Material Thickness in mm Diameter in mm Area in mm² of collecting electrode used Guard ring width in mm Width / depth of insulation gap in mm	 Polymethyl methacrylate (PMMA) 31 30.38 724.8 15 0.2 / 0.2
Range of chamber depth l for extrapolation in mm	0.25 to 2.5
Chamber voltage applied in V	± 2.5 to ± 25 proportional to the chamber depth
Charge measurement system (electrometer) [3]	Keithley 642
Bias current in fA	< 1
Standard feedback capacitor, C in pF	20

For measurements of the absorbed dose rate to tissue, $\dot{D}_{\text{Rß}}$, in the beta radiation reference fields, the primary standard measuring device of PTB was used. Without describing these procedures in detail, the equation (1) for the dose rate calculation should be mentioned here [4],[5],[6]:

$$\dot{D}_{\text{Rß}} = \left(\frac{\mathrm{d}}{\mathrm{d}l}(k\, I_{\text{mean}})\right)_{l=0} \cdot k' \cdot \left(\frac{\overline{W_{\mathrm{o}}}}{e}\right) \cdot \frac{s_{\mathrm{t,a}}}{a \cdot \rho_{\mathrm{a0}}} \tag{1}$$

with

I_{mean} Ionization current (mean value of positive and negative chamber polarity)

k Product of the correction factors which are dependent on the chamber depth including the following correction factors

- k_{ad} Correction factor for the variations of air density in the collecting volume from reference conditions
- k_{abs} Correction factor for variations in the attenuation and scattering of beta particles between the source and the collecting volume due to variations from reference conditions

k_{di}	Correction factor for axial non-uniformity due to divergence of the beta particle field
k_{pe}	Correction factor for perturbation of the beta-particle flux density by the side walls of the extrapolation chamber
k_{sat}	Correction factor for ionization collection losses due to ionic recombination
k_{ac}	Correction factor for attenuation of beta particles in the collecting volume
k_{el}	Correction factor for electrostatic attraction of the entrance window due to the collecting voltage
k_{in}	Correction factor for interface effects between the air of the collecting volume and the adjacent entrance window and collecting electrode
k_{de}	Correction factor for radioactive decay of the beta particle source
k_{th}	Correction factor for the decrease of the distance due to the thickness of the absorbers in front of the ionization chamber
$k_{St,a}$	Correction factor for the change of the stopping power ratio depending on the depth in the thickness of the absorbers in front of the ionization chamber
k'	Product of the correction factors which are independent on the chamber depth including the following correction factors
k_{br}	Correction factor for the effect of bremsstrahlung from the beta-particle source
k_{ba}	Correction factor for the difference in backscatter between tissue and the material of the collecting electrode and guard ring
k_{hu}	Correction factor for the effect of humidity of the air in the collecting volume on W_e
k_{ra}	Correction factor for radial non-uniformity of the absorbed dose rate in the beam
$s_{t,a}$	Quotient of mass-electronic stopping powers of ICRU tissue and air
W_e	Average energy to produce an ion pair in air under reference conditions
I_{corr}	Corrected ionization current
dI_{corr}/dl	Limiting value of the slope of the corrected current versus chamber depth l function
l	Chamber depth
a	Effective area of the collecting electrode
ρ_{a0}	Density of air at reference conditions
$\dot{D}_{R\beta}$	Reference absorbed dose rate to tissue due to betas at depth d = 0.07 mm

Table C.2 shows the constants used in equation (1) at PTB

Table C.2: Constants for dose rate calculation in equation (1) used at PTB

Constant	**Values used at PTB**
$\overline{W}_0/e$	33.83 eV for air with a relative humidity of 0.65
$s_{t,a}$ for ^{147}Pm $s_{t,a}$ for ^{85}Kr $s_{t,a}$ for $^{90}Sr/^{90}Y$ $s_{t,a}$ for $^{106}Ru/^{106}Rh$	1.124 1.121 1.110 1.099
ρ_{a0}	1.1974 kg/m³ for air with a relative humidity of 0.65, a temperature of 293.15 K and a pressure of 101.3 kPa
$T_{1/2}$ for ^{147}Pm $T_{1/2}$ for ^{85}Kr $T_{1/2}$ for $^{90}Sr/^{90}Y$ $T_{1/2}$ for $^{106}Ru/^{106}Rh$	958.2 d 3915 d 10523 d 373.59 d
E_{mean} for ^{147}Pm E_{mean} for ^{85}Kr E_{mean} for $^{90}Sr/^{90}Y$ E_{mean} for $^{106}Ru/^{106}Rh$	0.07 MeV 0.25 MeV 0.8 MeV 1.2 MeV

Annex C.2 Determination of the conventional quantity values of $\dot{H}_p(0.07;\alpha)$ and $\dot{H}_p(3;\alpha)$

From $\dot{D}_{R\beta}$ the conventional quantity values of $\dot{H}_p(0.07;\alpha)$ and $\dot{H}_p(3;\alpha)$ for the slab phantom were determined via [7]

$$\dot{H}_p(d;\alpha) = h_{p,D}(d;source;\alpha) \cdot \dot{D}_{R\beta} \,/\, (1 - \tau_{br}) \qquad (2)$$

with

$\dot{H}_p(d;\alpha)$ Total personal dose equivalent rate at depth d = 0.07 mm or 3 mm in the slab phantom (due to betas and photons) at an angle of incidence α

$h_{p,D}(d;source;\alpha)$ Conversion coefficient from $\dot{D}_{R\beta}$ to $\dot{H}_p(d;\alpha)$ for angle α and *source* type (the subscript "$_{p,D}$" denotes "conversion from absorbed dose D to personal dose")

source Specifies the radionuclide, the beam flattening filter, and the distance of the radiation source from the point of irradiation

α Angle of incidence

τ_{br} Photon dose divided by total dose at d = 0.07 mm tissue depth

The conversion coefficients, $h_{p,D}(d;source;\alpha)$, were taken from ISO 6980-3 for d = 0.07 mm [8] and from the literature for d = 3 mm [7]. Values for the photon contribution, τ_{br}, were also taken from the literature [7]. The data are given in Table C.3.

Table C.3: Conversion coefficients for $h_{p,D}$(0.07 mm;*source*;α), top, for $h_{p,D}$(3 mm;*source*;α), middle, and for τ_{br}, bottom, for the slab phantom for radiation fields of the BSS 2 beta sources

Source: Nuclide	Source: Beam flattening filter	Source: Distance (cm)	Conversion coefficient $h_{p,D}(0.07;\alpha)_{slab}$ and its relative standard uncertainty for a value of α of: 0°	$u_{rel}(0°)$ [1)]	45°	$u_{rel}(45°)$	60°	$u_{rel}(60°)$
^{147}Pm	yes	20	1.00	0.0 %	0.72	1.76 %	0.53	3.00 %
^{85}Kr	yes	30	1.00	0.0 %	0.88	1.17 %	0.72	2.00 %
^{90}Sr/^{90}Y	yes	30	1.00	0.0 %	1.12	1.17 %	1.14	2.00 %
^{106}Ru/^{106}Rh	no	20	1.00	0.0 %	1.151	1.17 %	1.256	2.00 %

[1)] The uncertainty of $h_{p,D}(0.07;0°)_{slab}$ is zero as $H_p(0.07;0°)$ is directly given by the reference dose rate, $\dot{D}_R$.

Source: Nuclide	Source: Beam flattening filter	Source: Distance (cm)	Conversion coefficient $h_{p,D}(3;\alpha)_{slab}$ and its relative standard uncertainty for a value of α of: 0°	$u_{rel}(0°)$	45°	$u_{rel}(45°)$	60°	$u_{rel}(60°)$
^{90}Sr/^{90}Y	yes	30	0.4311	0.51 %	0.2035	1.83%	0.0983	3.04%
^{106}Ru/^{106}Rh	no	20	0.7710	0.51 %	0.4850	1.83%	0.2691	3.04%

	^{147}Pm 20 cm, with filter	^{85}Kr 30 cm, with filter	^{90}Sr/^{90}Y 30 cm, with filter	^{106}Ru/^{106}Rh 20 cm, without filter
τ_{br}	0.0055	0.00025	0.00062	0.0023
$u(\tau_{br})$	0.0023	0.00009	0.00023	0.0012

Note: In principle, it is $k_{br} = 1 - \tau_{br}$. However, small deviations occur as τ_{br} is valid for d = 0.07 mm tissue equivalent depth and is an average over several measurements of many sources [6] while k_{br} is valid for the actual source and the actual measurement depth which is slightly different from 0.07 mm tissue depth.

Annex D Example for the description of the beta reference fields

The Beta Secondary Standard BSS 2 of the department 'Radiation protection dosimetry' of the Physikalisch-Technische Bundesanstalt consists of an irradiation facility and a set with three beta sources of the radionuclides ^{147}Pm, ^{85}Kr, ^{90}Sr/^{90}Y and ^{106}Ru/^{106}Rh produced by the company Eckert & Ziegler [9]. The calibration of these beta sources took place by measurements with the primary standard measuring device of the PTB.

The BSS 2 facility is controlled completely automatically via computer and provided software.

As to see in figure 1, the homogeneity of the radiation field at the calibration distances is better than ± 10 % across the outer diameter of the transfer chamber and better than ± 5 % across the diameter of the active chamber volume [10].

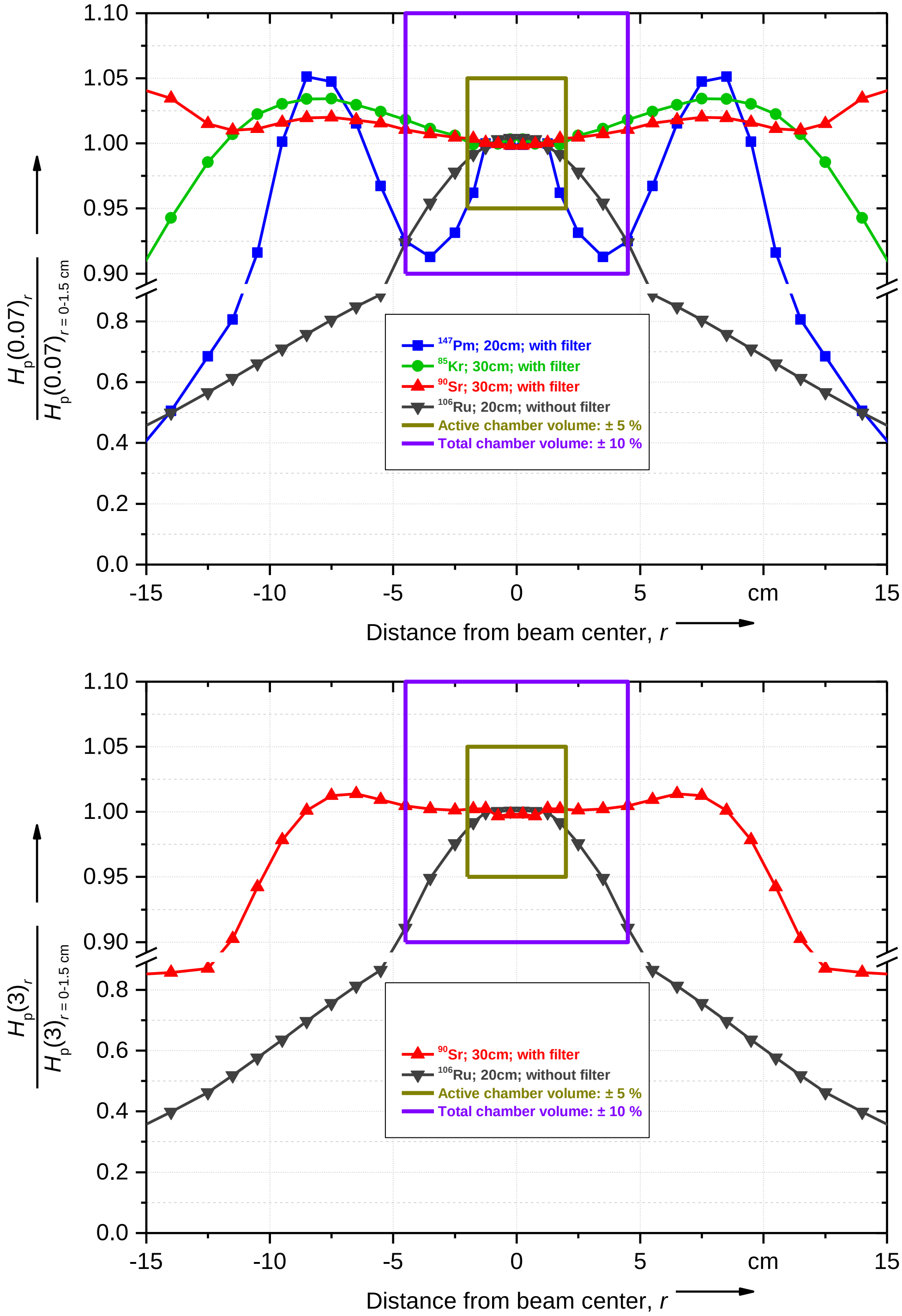

Figure 1: Homogeneity of the radiation fields in cross-section for the sources of the BSS 2 at the calibration distances at 0.07 mm (top) and 3 mm (bottom) depth dose.

Annex E Literature for the Annexes

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[4] ISO 6980-2, International Organization for Standardization, *Reference beta-particle radiation – Part 2: Calibration fundamentals related to basic quantities characterizing the radiation field* (2004)

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