Progress Report

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

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Contents

1. Progress Report of the Department 'Dosimetry for Radiation Therapy and Diagnostic Radiology' 2
1.1. Dosimetry for External Radiation Therapy using high-energy photon and electron radiation 2
1.2. Alanine Dosimetry 8
1.3. Dosimetry for brachytherapy 11
1.4. Air kerma standards and dosimetry of x-rays 14
1.5. Publications and Conference Presentations (2011 – 2013) 16
2. Progress Report of the Department 'Radiation Protection Dosimetry' 24
2.1. Pulsed radiation in radiation protection dosimetry 24
2.2. Progress in the field of beta dosimetry at PTB 25
2.3. Progress in the field of dosimetry at low dose rate 25
2.4. Comparisons 25
2.5. Publications (2011 – 2013) 27
3. Progress Report of the Department 'Ion Accelerators and Reference Radiation Fields' 29
3.1. New measurements of *W*-values for protons, α-particles and C-ions in argon, nitrogen and air 29
3.2. Irradiation of cells with low-LET and high-LET particles using the PTB microbeam 29
4. Progress Report of the Department 'Fundamentals of Dosimetry' 29
4.1. Interaction cross-sections of DNA constituents 29
4.2. Nanodosimetry 33
4.3. Biological effectiveness of ionizing radiation; track structure simulation 36
4.4. Stopping power of water for carbon ions in the Bragg peak region 39
4.5. EMRP Joint Research Project SIB06 BioQuaRT 40
4.6. Publications (2011 – 2013) 41

1. Progress Report of the Department 'Dosimetry for Radiation Therapy and Diagnostic Radiology'

U. Ankerhold, M. Anton, L. Büermann, R.-P. Kapsch,
A. Krauss, T. Schneider and H.-J. Selbach

Physikalisch-Technische Bundesanstalt, Brauschweig, Germany

1.1. Dosimetry for External Radiation Therapy using high-energy photon and electron radiation

1.1.1. Optimization of the research accelerator

The research accelerator has been modified substantially in order to stabilize and optimize the beam properties, to improve the output rate and to allow a thorough characterization of the beam properties.

The magnet spectrometer used for measuring the spectral fluence of the electron beam has been optimized by assembling a new vacuum chamber and detection system. The distribution of the magnetic field strength inside the spectrometer has been measured and an analysis algorithm (and the corresponding software) to evaluate the spectral electron fluence has been developed (see Figure 1.1).

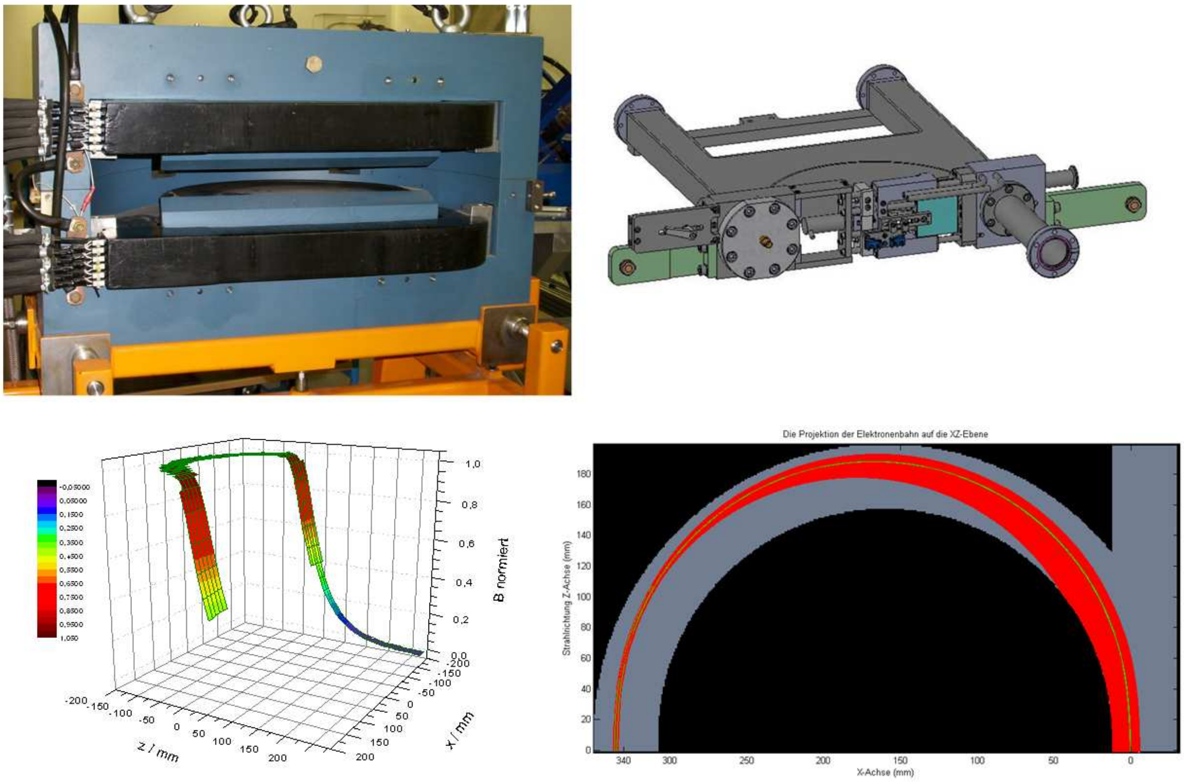


Figure 1.1: The spectrometer magnet (top left), the new vacuum chamber which has been assembled in the magnet (top right), the magnetic field strength inside the vacuum chamber (bottom left), and a calculation of electron trajectories in the spectrometer with valid paths marked in green (bottom right).

Additional instruments for the measurement of the beam position, the beam profile, and the beam current have been integrated at several positions in the beam line in order to determine the important beam properties. These instruments (together with the spectrometer) are now used routinely to measure the beam parameters needed for the experiments performed using the research accelerator (cf. 1.1.2).

Two Faraday cups have been manufactured at PTB in order to calibrate the beam current monitors included in the beam line. These devices are now characterized and put into operation (see

Figure 1.2); an analysis method has been developed for the measurement of the beam charge.

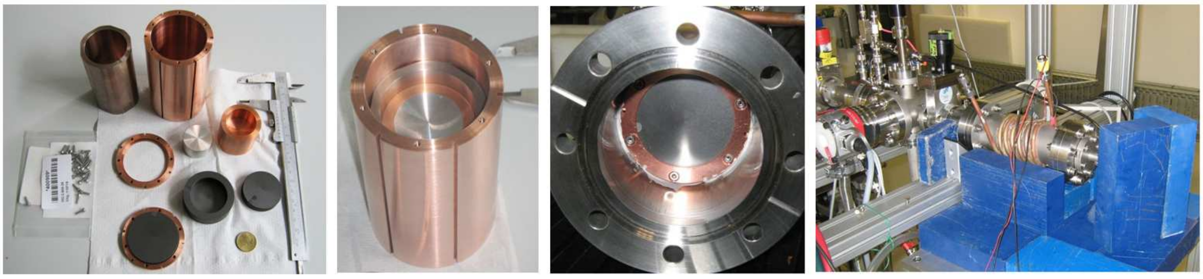


Figure 1.2: Stages in the assembling of the Faraday cup from the single components (left) to the use at the accelerator.

1.1.2. **Monte-Carlo benchmark experiment**

A benchmark experiment for the absolute verification of Monte-Carlo calculations is currently performed at the research accelerator. This experiment, which is being done in the framework of a PhD work, aims at the comparison of the absorbed dose *per incident electron* measured at the research accelerator under well defined conditions with the dose *per incident electron* calculated by Monte-Carlo methods for the same conditions. In contrast to the usual methods of the verification of Monte-Carlo calculations no normalization of dose values is involved (i.e. no relative dose values are compared) so that information about the correctness of absolute dose calculations using Monte-Carlo methods can be gained.

For this experiment dose measurements are done using two copies of the cavity ionization chambers employed as PTB's primary standards for air kerma (see Figure 1.3 left). These chambers have been constructed and manufactured by PTB, therefore the design, dimensions and materials of the chambers are known very precisely. Based on this knowledge a detailed geometrical model of the chambers was developed which is used in Monte-Carlo calculations (see Figure 1.3 right). Additionally, the properties of the beam (spectral fluence, shape, position, beam current) have to be known very precisely – these parameters are measured using the instrumentation mentioned in 1.1.1. Finally a very detailed model of the real experiment has been developed and is used to calculate (by means of Monte-Carlo methods) the dose in the measuring volume of the ionization chambers, which in turn will be compared with the measured dose.

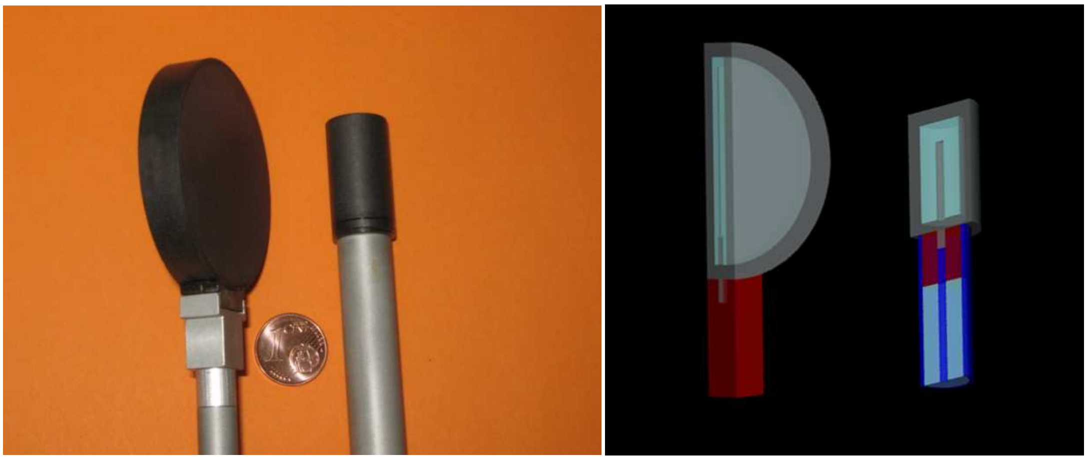
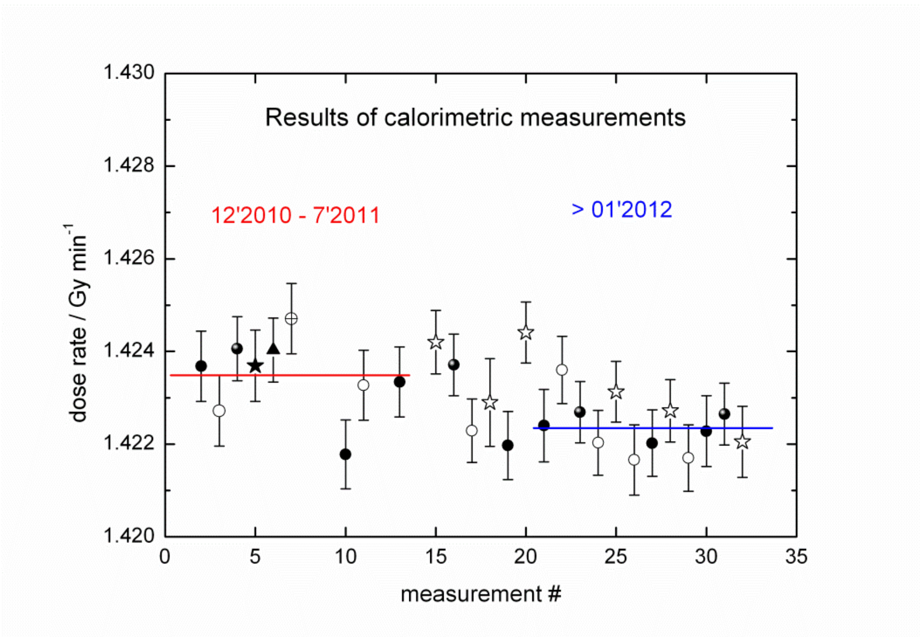


Figure 1.3: The cavity ionization chambers used for the benchmark measurement (left) and the models of the chambers used for the Monte-Carlo calculations (right).

1.1.3. Calorimetric determination of absorbed dose to water D_w

1.1.3.1 Calorimetric determination of absorbed dose in water D_W in ^{60}Co radiation

After the delivery of a new ^{60}Co source in October 2010, measurements with PTB's primary standard water calorimeter have been performed over a time period of about 6 month to re-establish the absorbed dose rate of the new source for reference conditions. The corresponding mean value was taken as the "new" reference value for D_W. By comparing the D_W-calibration factors of several ionization chambers determined at the "old" and the "new" ^{60}Co source, an agreement of better than 0.1% was found. The following picture offers the results of the calorimetric measurements; the different symbols correspond to different detectors used during the course of the experiments. The red line refers to the mean value of measurements taken between December 20120 and July 2011 and was used for re-establishing the absorbed dose rate of the ^{60}Co source for reference conditions.



However, the results of the latest calorimetric measurements might indicate a slight change of the dose rate of the new ^{60}Co source. The blue line shown in the figure corresponds to the mean value of the calorimetric measurements taken in 2012. The ratio of the two mean values is

1.0008 ± 0.0003. This finding is supported by ionization chamber measurements performed over the same time period, showing a similar change of the relative response for all chambers.

1.1.3.2 Calorimetric determination of k_Q factors in 10 cm x 10 cm and 3 cm x 3 cm photon beams

For photon energies between 4 MV and 25 MV which are available at PTB's medical electron accelerators, k_Q factors of different thimble type ionization chambers (NE2561, NE2571, FC65G) in 10 cm x 10 cm photon beams were determined experimentally by use of a water calorimeter. Typically, 2 – 4 complete calorimetric experiments (involving different calorimetric detectors) and with consecutive ionization chamber calibrations were performed for each radiation quality. This way, each experiment took about 1 week. The required corrections factors, like heat transport corrections or perturbation corrections have been obtained either experimentally or by calculation (for the case of heat transport corrections). The consideration of all correction factors and the detailed investigation of influence quantities, for example the stability of the required monitor chamber, finally leads to a relative standard uncertainty of 0.31% for the experimentally determined k_Q factors. The following table summarizes the results for reference conditions, i.e. the k_Q factors for the different ionization chambers vs. radiation quality index $TPR_{20,10}$.

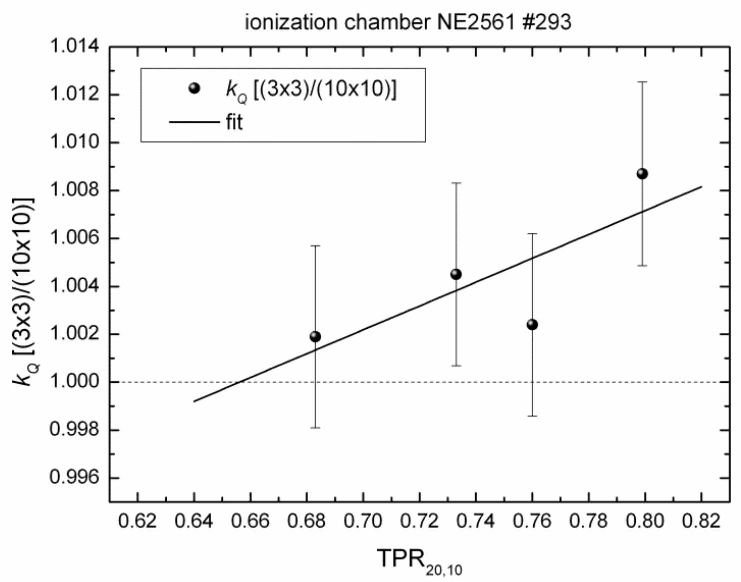
	k_Q factor					
$TPR_{20,10}$	NE2561 #293	NE2561 #297	NE2571 #1748	NE2571 #2906	FC65G #771	GC65G #1108
0.638 (4 MV)	0.9979	0.9972	0.9964	0.9967	0.9936	0.9932
0.683 (6 MV)	0.9932	0.9921	0.9912	0.9904	0.9886	0.9884
0.714 (8 MV)	0.9882	0.9876	0.9883	0.9869	0.9829	0.9841
0.733 (10 MV)	0.9866	0.9850	0.9830	0.9826	0.9794	0.9799
0.760 (15 MV)	0.9821	0.9818	0.9795	0.9788	0.9755	0.9762
0.799 (25 MV)	0.9691	0.9693	0.9659	0.9662	0.9634	0.9623

As a contribution to the former EURAMET JRP7-project (2008-2011), k_Q factors were determined in 3 cm x 3 cm radiation fields of 6 MV and 10 MV photons. The available results for the NE2561 ionization chamber at the end of the project indicated that there is no dependence of the k_Q factors with field size, i.e. the ratio $k_Q(3x3)/k_Q(10x10)$ was equal to one within the standard uncertainty of the experimental data. Within PTB's working program the investigation in small fields was continued and extended to higher photon energies. Detailed measurements were carried out for 15 MV and 25 MV photons. Furthermore, the existing data for 6 MV and 10 MV were re-analyzed, mainly because of an error in the consideration of the polarity effect of the ionization chambers.

For the experimental determination of k_Q factors in small radiation fields, two correction factors become very significant. First, the corrections for the heat transport occurring in the calorimeter due to the limited lateral size of the 3 cm x 3 cm beams are substantially larger compared to those for 10 cm x 10 cm beams. The second one is the correction k_v which considers the "volume effect" of ionization chambers. This correction is given by the inverse ratio of the chamber reading in the 3 cm x 3 cm field and the reading in a large homogenous field. This correction enters the determination of the k_Q factors because the water calorimeter determines D_W "point-like" at the central axis of the 3 cm x 3 cm field. The correction k_v is determined by integrating the measured lateral dose distribution across the volume of the NE2561 chamber. The following table specifies the resulting correction factors k_v including their standard uncertainties which have been determined by shifting the position of the ionization chamber by 1 mm in each direction perpendicular to the beam axis.

correction factor k_v			
6 MV	10 MV	15 MV	25 MV
1.0017 ± 0.0002	1.0031 ± 0.0004	1.0087 ± 0.0003	1.0057 ± 0.0009

The evaluation of new data for 15 MV and 25 MV together with the revised data for 6 MV and 10 MV now leads to a different conclusion. The ratio k_Q(3x3)/k_Q(10x10) for the NE2561 chamber is no longer constant but increases nearly linear from 1.000 to 1.008 with increasing quality index $TPR_{20,10}$. The relative standard uncertainty of the ratio k_Q(3x3)/k_Q(10x10) is less than 0.4% and considers that some of the uncertainty contributions for the determination of k_Q(3x3) and k_Q(10x10) are correlated. The following picture summarizes the experimental data.



Further experiments as well as theoretical investigations by help of Monte-Carlo calculations are required to consolidate this finding. It should be mentioned for clarification, that the ratios k_Q(3x3)/k_Q(10x10) given in the figure would be larger if the correction factor k_v would not have been applied.

1.1.3.3 Calorimetric determination of D_W in high-energy electron beams

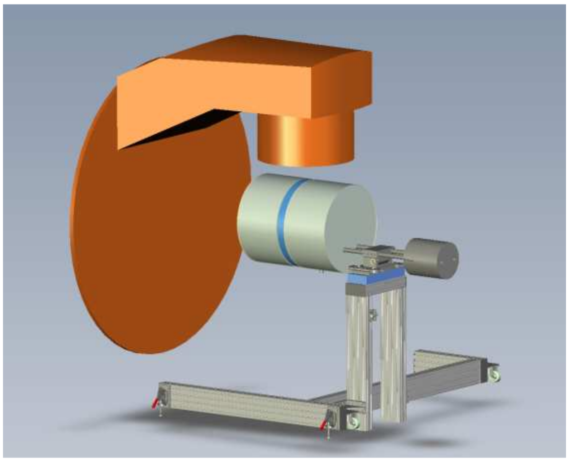
As a prerequisite for calorimetric measurements in high-energy electron beams the properties of several high-energy electron beams available at the clinical Elekta Precise linacs have been determined (measurement of depth dose distributions and beam profiles, evaluation of long- and short-term stability of the monitors used etc.) and the linac parameters have been optimized (if necessary).

Measurements with PTB's transportable water calorimeter have been started in high-energy electron beams. Similarly to the determination of k_Q factors in photon beams, corresponding k_E factors of ionization chambers (thimble type and plane-parallel type) will be derived. First experiments have been done for 15 MeV and 20 MeV electrons with a beam size of 10 cm x 10 cm.

1.1.3.4 New water calorimeter with cylindrical phantom

A new water calorimeter with a cylindrical water phantom made of Perspex has been assembled (see pictures below). The dimensions of the phantom are 260 mm in diameter and 360 mm in length with a wall thickness of 10 mm. The calorimeter is operated at 4°C and the temperature stabilization system is designed similarly to that of PTB's so-called transportable water calorimeter. The calorimeter is adjusted in front of a medical accelerator such that the cylinder is aligned horizontally and that the radiation head can be rotated around the phantom by about 270°. The radiation entrance window of the phantom has a width of 60 mm with a reduced wall thickness of about 4 mm. The pictures below show the CAD design of the new water calorimeter and a photo taken during the first commissioning.

A cigar-shaped cylindrical detector will be used inside the water phantom. The detector can be aligned either on the cylinder axis of the phantom or off-axis.



Due to its rotational geometry, this water calorimeter is applicable for the determination of D_W in various small and composite non-standard radiation fields, like fields realized by the superposition of IMRT radiation fields from different angles or in tomotherapy radiation fields. By help of the calorimeter it could be possible to calibrate ionization chambers directly for various clinical relevant irradiation conditions ("plan-class specific reference fields").

1.1.4. Calibration of secondary standards in small photon beams

During the EURAMET project JRP7 "External Beam Cancer Therapy" the ability to calibrate secondary standards in high-energy photon beams of small dimensions (IMRT conditions) was compared between PTB and LNE–LNHB. The results of this comparison have been published in Metrologia 49, S203.

The comparison was based on the calibration of two small-volume ionization chambers of types Exradin A1SL and PTW 31010 at PTB and LNE-LNHB, respectively, in photon beams of nominal accelerating voltages 6 MV and 10 MV with field sizes from 10 cm × 10 cm to 2 cm × 2 cm. The calibration factors determined by PTB and LNE-LNHB for these chambers are in agreement within 1.5 standard uncertainties.

1.1.5. **Comparisons**

BIPM.RI(I)-K6

The key comparison BIPM.RI(I)-K6 “Calorimetric Comparison of Absorbed Dose to Water at High Energies” between PTB and BIPM has been finished. The report has been published in Metrologia 48, Tech. Suppl. 06020.

This comparison was based on the determination of absorbed dose to water for three radiation qualities using the primary standards of absorbed dose to water of the PTB and the BIPM, respectively. The comparison result, reported as the ratios of the PTB and the BIPM evaluations, are shown in Figure 1.4.

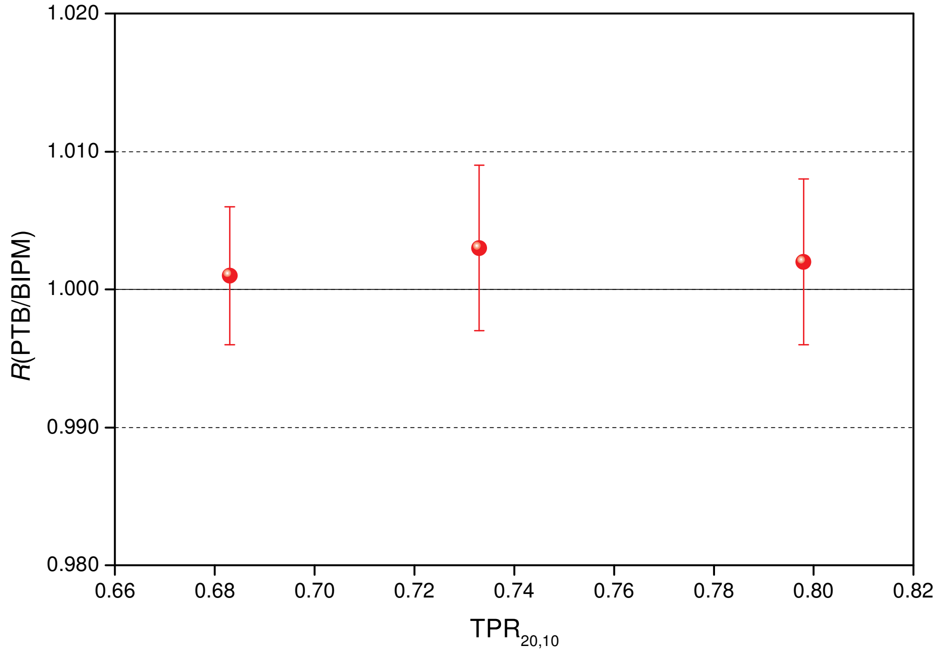


Figure 1.4: Results of the comparison at high energies of the calorimetric absorbed dose to water standards of the PTB and the BIPM, shown as a function of $TPR_{20,10}$. The uncertainty bars represent the combined standard uncertainty of each comparison result.

1.2. Alanine Dosimetry

1.2.1. Relative Response of the Alanine dosimetry system

The main subject of ongoing research is the investigation of the response of the alanine dosimetry system for different radiation modalities, i.e. the D_w-response relative to the response to Co-60 radiation.

The major part of the work was dedicated to the investigation of the response to MV x-rays for the reference field size of 10 cm x 10 cm, which was caused by a seeming discrepancy between data published in 2008 and data acquired at the new accelerator facilities. The published data had been acquired for 8 MV and 16 MV, the two new accelerators provided data for 4 MV, 6 MV, 8 MV, 10 MV, 15 MV and 25 MV x-rays.

In the course of the investigations, a number of possible causes for a discrepancy could be ruled out. The influence of the material used for the holder containing the alanine detector during irradiation turned out to be negligible, be it 2 mm thick polymethylmatacrylat or 0.2 mm of polyethylene. Different ways of dose determination at the accelerator as well as different measuring devices were tested, all yielded compatible results. Even a possible influence of parasitic neutrons at the higher energies was excluded with the help of measurements at neutron reference fields at PTB. The parameters of the electron spin resonance spectrometer (ESR) were put to a test. The batch homogeneity for different alanine pellets was investigated as well, with the result that the uncertainty budget published earlier was revised. Some components are now calculated in a different way; the resulting overall uncertainty is slightly higher than previously published.

As the source of the apparent discrepancy could still not be identified, a blind test conducted by the BIPM using Co-60 radiation was carried out, with the result that the dose determined by PTB agreed within 0.12% with the dose administered by the BIPM, with an uncertainty of 0.45%. A further comparison was carried out with the NRC using MVX radiation. However, the source of the discrepancy turned out to be an error in the data published earlier.

Due to the large set of data gathered over a period of more than four years overall, the relative response for MV x-rays can now be well quantified. A new finding is that, deviating from general belief, a small dependence of the response on the energy can be quantified. While a quality correction for alanine would be equal to k_Q=1.004 for 4 MV, the correction for 25 MV is k_Q=1.011, thereby approaching the value k_E=1.012 valid for electrons with nominal energies between 6 MeV and 20 MeV (Zeng et al 2005 and Vörös et al 2012). The dependence could be confirmed by NRC, if their published data are revised using recently published k_Q data for ionization chambers, their revised data agree very well with the new PTB data.

The energy dependence was reproduced by Monte Carlo calculations carried out by the working group of K. Zink from the Technische Hochschule Mittelhessen in Giessen (Germany). In order to achieve agreement, the density correction for crystalline alanine has to be used for the calculation, as had been proposed by the NRC for electrons (Zeng et al., Phys. Med. Biol., 2005). It can be shown that the dependence of the relative response can be described by a unique curve, valid for MV x-rays and MeV electrons, if the response is plotted as a function of the average CSDA range of the secondary electrons. Publications of the data were submitted in autumn 2012, at the time being we are awaiting a decision of the editor board.

In view of the necessity of providing accurate dose measurements also in small fields, investigations for MV x-rays with a field size of 3 cm x 3 cm were continued. The k_Q factors for the NE 2561 ionisation chamber used for the reference dose measurements were provided by the PTB's water calorimeter. Preliminary response data are now available for 4 MV, 6 MV, 10 MV and 25 MV. At present, there appears to be small field size dependence. Different from statements published earlier, it seems that the response to MV x rays with 3 cm x 3 cm field size is 0.45% higher than for the corresponding 10 cm x 10 cm field, but this is still ongoing research.

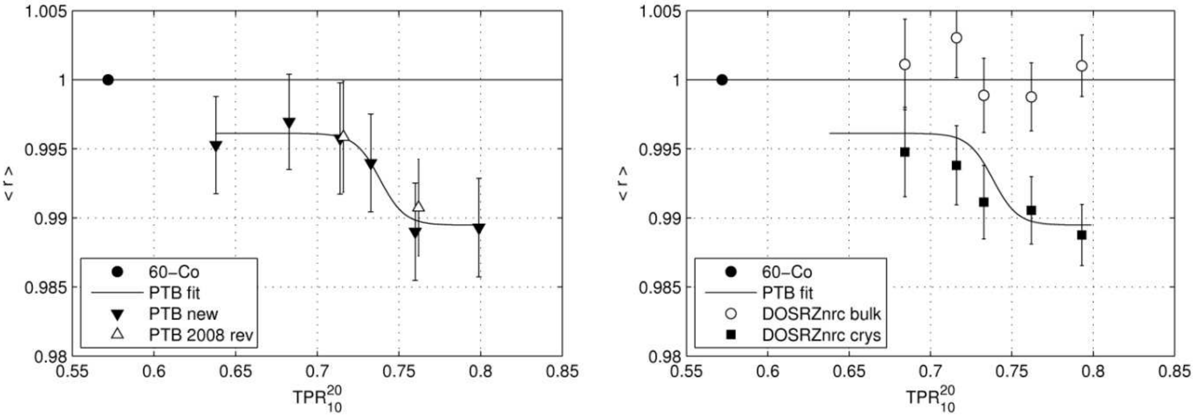


Figure 1.5: D_w-response of alanine relative to Co-60 radiation for 4 MV, 6 MV, 8 MV, 10 MV, 15 MV, 16 MV and 25 MV as a function of the tissue-phantom ratio. Left: Experimental data, the continuous curve is shown to guide the eye. Right: Monte Carlo data, the results represented by the open circles were obtained using the density correction for the bulk density of the alanine/paraffin pellets while the filled squares were obtained using the bulk density, but the density correction for crystalline alanine

The response of alanine was also determined for medium energy x-rays (T or TH-series) with accelerating voltages between 70 keV and 280 keV. As was expected, the relative response drops significantly with decreasing photon energy. While for Cs-137 with an average energy of 660 keV the relative response is still unity, it is 9% smaller for an accelerating voltage of 280 keV and 30% less for 70 keV. Measurements and uncertainty analysis are almost finished, the relative response data will be available with an uncertainty of slightly more than 1%. A publication is planned as soon as Monte Carlo data will be available.

Within the framework of the new EMRP project HLT09 MetrExtRt, measurements also started for the determination of the response to Ir-192 radiation used in brachytherapy. The response depends on the thickness of the layer of water between the source and the detector, the average energy of the Ir-192 radiation drops from 333 keV at 10 mm depth to 250 keV at 50 mm. The preliminary results show that the response decreases from 0.976 at 10 mm to 0.956 at 50 mm. An overall uncertainty of approximately 2% will be achieved, where the contribution from the alanine measurement varies between 0.75% and 0.37%, depending on the distance to the source. The preliminary results agree well with data published by Schaeken et al. in 2011. Accurate response data are needed for dose measurements in radiation fields of partly shielded Iridium sources, i.e. for the investigation of the influence of different applicators for brachytherapy planned for the next two years.

For both the small-field measurements and the Iridium investigations, volume corrections and corrections for the position-dependent sensitivity of the ESR resonator are required. Monte Carlo and experimental investigations on the subject are under way.

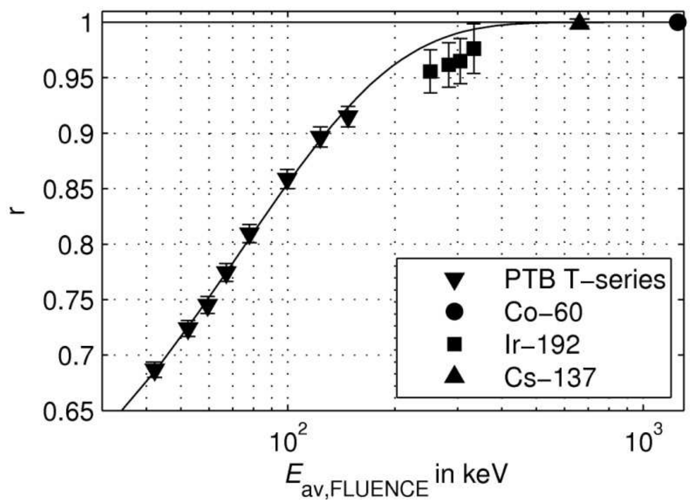


Figure 1.6: D_w-response of alanine relative to Co-60 radiation for the medium x-ray T-series, for Ir-192 and Cs-137 as a function of the average energy in keV (average with respect to fluence), experimental data. The continuous curve is shown to guide the eye.

1.2.2. **Cooperations**

For the Marienhospital Düsseldorf, measurements with alanine were carried out in different fields of an IORT electron accelerator and compared to measurements using an advanced Markus chamber. The data will shortly be published as a Master's thesis.

In cooperation with the University Hospital of Marburg, dose measurements *in vivo* during RT treatments of head and neck cancers are in preparation.

The cooperation with the Belgian Beldart QA project for radiotherapy at the NuTec Center (Xios Hoogeschool Limburg) was continued , calibration data were provided as well as consulting for quality assurance of the ESR measurements.

1.3. Dosimetry for brachytherapy

1.3.1. Low-Dose Rate (LDR) brachytherapy sources

The primary standard in terms of reference air kerma rate for ^{125}I-brachytherapy sources is now regularly used in calibration service. Within the EURAMET joint research project iMERAPlus JRP6 "Brachytherapy" it was used for the calibration of a ^{125}I-seed of type I.25-S16 from Eckert & Ziegler BEBIG GmbH for the experimental determination of the dose rate constant Λ for this seed type.

Within the same iMERAPlus project PTB has established a new extrapolation chamber with water equivalent walls, allowing the determination of the absorbed dose to water in 1 cm depth of a water equivalent material (RW1) for the realization of absorbed dose to water in the photon energy range of LDR brachytherapy sources (E< 50 keV). At present, calibration service in D_w is not requested, which might be explained by a lack of corresponding dosimetry protocols.

1.3.2. Brachytherapy with miniature x-ray devices

At present, two miniature x-ray tubes (MXT) are commercially available: the "Intrabeam®"-system from Carl Zeiss and the "Axxent®" tube from Xoft. More than 200 miniature x-ray tubes are sold worldwide. Both MXT emit a continuous x-radiation field with a maximum energy of 50 keV and a mean energy around 25 keV. At the lower part of the photon spectra characteristic fluorescence lines can be found between 8 keV and 15 keV. The emitting field of the Intrabeam has its maximum in forward direction, whereas the emitting field of the Axxent- tube has its maximum perpendicular to the axis of the needle, similar to Ir-192 HDR-sources. The delivered dose rate amounts to 2 - 3 Gy/min in 1 cm depth in water.

Individual Intrabeam devices have been already used over ten years. Thereby a high stability in the beam characteristics was observed. Nevertheless before each treatment a sophisticated QA-procedure must be carried out.

The individual Axxent tubes have an application time of about 2 - 4.5 hours. All Axxent-tubes undergo an intensive validation procedure at the manufacture in which the sources accepted for human use have to meet certain constraints concerning the characteristics of the radiation field. For the dissemination of the Reference Air Kerma Rate to the clinics quantity a well type chamber as a transfer instrument is delivered as a part of the equipment.

The calibration system for the Intrabeam device is based on a soft x-ray ionization chamber PTW TM 23342. The calibration is based on measurements in a water phantom in terms of absorbed dose to water. As no NMI offers calibration of this device in terms of absorbed dose to water D_W in a certain depth in a water phantom, this calibration factor is derived from Air Kerma calibrations and a conversion into D_W according to ICRU 17. The Treatment Planing System (TPS) delivered together this device relies on a depth dose curve determined with this chamber in a water phantom.

The basic dosimetry for these sources will be established within the EURAMET joint research project JRP HLT09 MetrExtRT "Metrology for radiotherapy using complex radiation fields" in WP4 "Brachytherapy" in which CMI and PTB is involved. The work is subdivided into four steps: the dosimetric characterization of both sources, MC-simulations: modelling and calculations, establishing of a primary standard in terms of absorbed dose to water on base of the standard for ^{125}I. Finally the gathered information will be utilized to give recommendations on a calibration chain.

For this project a laboratory version of the "Intrabeam®"-system was purchased in 2012. The Xoft-system was purchased in 2008.

1.3.3. Development of measuring techniques for the verification of treatment planning systems in HDR-Brachytherapy

In HDR-Brachytherapy with Ir-192 sources, applicator related shielding effects are the greatest limitations of the present dosimetry given in the AAPM TG-43 protocol. AAPM and ESTRO are aiming to bring up the treatment planning to the level already achieved in External Beam Radiation Treatment (EBRT), manifested in the work of the AAPM- TG 186 task group in close cooperation with the European society ESTRO.

In most publications the results of Treatment Planning Systems are compared only to MC-calculations. Therefore it is the aim of this task to develop measuring techniques to determine the 2D or 3D dose distribution in a water phantom in the presence of clinical applicators. From a dosimetric point of view this means a step apart from standard fields to complex fields close to clinical condition.

Within the new EMRP project JRP HLT09 MetrExtRT “Metrology for radiotherapy using complex radiation fields” the capability of three measuring systems – alanine, scintillators and storage foils – to determine the dose distribution in the presence of clinical applicators within 2% (k=1) will be investigated. In addition the agreement between the three measuring systems, MC calculations and the Treatment Planning Systems will be checked at a level of 3% (k=1). As all compared systems will be traceable to the PTB-standard, the uncertainty of the absolute value is not included in the overall uncertainties.

The measurement will be performed in a new water phantom and the positioning of the detectors will be performed by means of a robotic arm. Both components have been purchased meanwhile.

1.3.4. Calorimetric determination of absorbed dose to water for ^{192}Ir-HDR brachytherapy sources in near-field geometry (JRP6-project)

Within the iMeraPlus project JRP 6, the PTB has built up a primary standard for the calibration of ^{192}Ir and ^{60}Co HDR brachytherapy sources in terms of absorbed dose rate to water. The standard is based on a modified water calorimeter with the possibility to position an HDR brachytherapy source close in front of the calorimetric detector.

Up to now calorimetric measurements have been performed for two different ^{192}Ir brachytherapy sources, i.e. of type GammMed 12i and of type Nucletron micro selectron classic. For both types, the dose rate constants Λ, which is the ratio of absorbed dose rate to water at a distance of 10 mm from the source and the reference air kerma rate were already determined. At present the Nucleotron micro selectron V2-type is being investigated.

1.3.5. Chamber type specific radiation quality correction factor k_Q ($N_k(^{60}Co)$/ $N_k(^{192}Ir)$)

The aim of the investigations was to determine a chamber type specific radiation quality correction factor k_Q which allows the measurement of the reference air kerma rate of ^{60}Co brachytherapy sources with a well-type ionization chamber calibrated for ^{192}Ir-radiation. For this purpose six well-type ionization chambers of type HDR 1000 Plus from Standard Imaging Inc., Wisconsin, USA, were investigated at the Physikalisch-Technische Bundesanstalt.

First of all the reference air kerma rate of a ^{60}Co and a ^{192}Ir brachytherapy source was determined, then the well-type ionization chambers were calibrated with the sources and finally the chamber type specific radiation quality correction factor k_Q was determined. The measurements were carried out using the Eckert & Ziegler universal applicator “LAA1400-RU” and the Standard Imaging adapter “REF 70110". The mean value of the ratios of the calibration factors was taken as the radiation quality correction factor and was determined to k_Q = 1,052 with a relative expanded uncertainty of 0.3 %.

1.3.6. Comparisons

1.3.6.1 BIPM.RI(I)-K8: Comparison for the measurement of Reference Air Kerma Rate for HDR 192Ir brachytherapy sources

The measurements for the comparison were performed at PTB’s brachytherapy facilities. PTB provided a 192Ir HDR source of type “microselectron version 2”, which was calibrated prior to the measurements in collimated beam geometry in terms of reference air kerma rate. At the time of the measurements (28. -30. September 2011), the source had an activity of about 335 GBq. The measurements were performed with a well-type-ionization chamber of type Standard Imaging HDR

1000 plus and a thimble transfer chamber NE 2571 as described in the comparison protocol BIPM.RI(I)-K8. The report on the comparison is in progress.

1.3.6.2 Comparison of secondary standards for measurements of the absorbed dose to water for beta brachytherapy sources

Every year, about 1000 persons contract a malignant eye tumour in Germany. About 50% of these patients are treated by means of brachytherapy with so-called beta eye applicators. For an effective and gentle treatment, an exact knowledge of the dose distribution in the clinically relevant near field is necessary - on the one hand to apply the necessary dose required for the treatment in the tumor and, on the other hand, to minimize the dose in risk organs such as the optic nerve. For an optimal realization of the therapy, an adequate dosimetry in the near field of the utilized applicators in units of absorbed dose to water is therefore required. To enable the users to trace back their dose measurements to a national standard, PTB has developed a primary standard measuring device on the basis of an extrapolation chamber for the realization of the unit of absorbed dose to water of beta brachytherapy sources. Together with the University Hospitals of Tübingen and Essen, as well as the only manufacturer of eye applicators worldwide, the Berlin-based company BEBIG, the PTB carries out a comparison of the basic dosimetry of the eye applicators. As reference field, the near field of a Ru-106 source in the water phantom was chosen which is to be measured by the participants in units of the absorbed dose to water. For this purpose, a not yet curved standard applicator was provided by BEBIG. The special problem of dosimetry in the near field of beta brachytherapy sources is the very steep dose distribution with gradients of up to a factor of 3 within one millimetre. Due to this fact, a local resolution of the detector probes used in the sub-millimetre range is required. The plastic scintillator detectors used by all participants fulfill this requirement due to their relatively small detector volumes (cylinder with a diameter of 1 mm and a length of about 0.5 mm). The PTB in-house developed plastic scintillator detector, which was absolutely calibrated in the field of the PTB Beta Secondary Standard (BSS), measured seven clinical relevant points, in fact from 1 mm to 7 mm along the symmetry axis of the source. The PTB relative combined standard uncertainty of absorbed dose to water varied depending on the depth between 4.9 % and 5.6 %. At the clinical and manufacturers sites the absorbed dose to water was measured by means of scintillation detector systems, which are traceable to a NIST absolute calibrated beta source. The measured point covered the same clinical relevant depths as those in the PTB measured. After the completion of the comparison a very good agreement of better than 1.5 % of the relative values of the measured depth dose curve along the symmetry axis of source could be found. The evaluation of the absolute values is in progress.

1.4. Air kerma standards and dosimetry of x-rays

1.4.1. Primary air kerma standards

The PTB operates primary standard measuring devices (free-air and cavity ionisation chambers) for the realization of the unit of air kerma for x-rays (10 kV - 400 kV) and γ-rays (^{137}Cs, ^{60}Co). No substantial changes on the operating standards were made since the last progress report in 2011.

Since several years there was a significant increase in the demand for calibration of secondary standards used in mammographic x-radiations. Due to the fact that PTB has a high workload in air kerma calibrations of secondary standards it was decided in 2010 to construct a new free-air ionisation chamber with a design especially optimized for radiation qualities used in mammography. Meanwhile the new free-air ionisation chamber, designated as PK100N, was manufactured in the PTB workshop. The PK100N was taken into operation in January 2013 and is a supplement to the existing free-air chamber PK100 which is used since 1954 as primary air kerma standard for low-energy x-radiations produced with tube high voltages in the range 10 kV-100 kV. Like the PK100, the PK100N is of the parallel-plate design. In contrast to the PK100 the new chamber was constructed without guard strip wires crossing the entrance window of the chamber and hence no correction is needed for the attenuation of photons passing the entrance window. It was nevertheless possible to realize a minimum attenuation length (which is the distance between the defining plane of the diaphragm and the centre of the collecting region) of 84 mm which is about 13 mm less than those of the PK100. This could be achieved by a special design of the resistance divider close to the entrance window which keeps the correction factor for the electric field distortion close to unity. The other correction factors needed for the PK100N were calculated by Monte Carlo methods using the 'EGSnrc' based user code 'egs_fac' [1]. Currently, the new chamber is tested for its practical suitability as a new primary air kerma standard. If the tests will be passed successfully it is intended to use this chamber for the direct key comparisons BIPM.RI(I)-K2 and –K7.

[1] Ernesto Mainegra-Hing, Nick Reynaert and Iwan Kawrakow: *Novel approach for the Monte Carlo calculation of free-air chamber correction factors.* Med. Phys. **35** (2008) 3650 – 3660

1.4.2. Measurement of the mass energy-absorption coefficient of air for x-rays in the range from 3 to 60 keV

General scientific summary of a work published in Phys. Med. Biol. 57 (2012) 8231-8247

The photon mass-energy absorption coefficient of air is of fundamental interest in low- and medium-energy X-ray dosimetry. Usually, calculated values are used which are tabulated together with those of other materials of interest. The uncertainties of these values were estimated at 5 % up to 5 keV and 2 % above 5 keV photon energy. This work presents measured values in the range 3 keV – 60 keV with relative standard uncertainties below 1 %. Measurements of this kind were made possible by the availability of monochromatized synchrotron radiation at the Berlin electron storage ring BESSY II, the absolute determination of radiant power by means of a cryogenic electrical substitution radiometer and deposited energy in air by means of a free air chamber. The measured values were found to be systematically smaller by about 2 % than those calculated by state-of-the-art methods and can be used to improve the underlying physical models.

1.4.3. Calorimetric determination of the absorbed dose to water for medium-energy x-rays with generating voltages from 70 kV to 280 kV

General scientific summary of a work published in Phys. Med. Biol. 57 (2012) 6245-6268

In medium-energy X-ray radiotherapy, the absorbed dose to water, D_w. is the measurement quantity in common use. Current primary standards are based on indirect measuring methods which need calculated conversion factors to obtain D_w. Uncertainties can be significantly lowered if a direct method based on a water calorimeter is used. However, only one such device has been developed up to now in The Netherlands. This work describes the determination of D_w for medium-energy X-rays with a water calorimeter developed in Germany. The quantity D_w was determined with relative standard uncertainties well below 1%. Experimental results were confirmed by Monte Carlo calculations in which type B uncertainties were included in the uncertainty analysis. Suitable ionization chambers can now be calibrated with standard uncertainties as low as about 1%. Furthermore, the so-called overall chamber correction factors can be determined for commonly used ionization chambers with much lower uncertainties than before.

1.4.4. **Comparisons**

BIPM.RI(I)-K7

In 2010, PTB participated for the first time in the key comparison BIPM.RI(I)-K7 of the air-kerma standards of the PTB, Germany and the BIPM in mammography x-rays. Results are published in Metrologia: 48 (2011), Tech. Suppl., 06011

COOMET.RI(I)-S1

PTB acted as pilot laboratory in the COOMET 445 comparison of national standards of air kerma for Cs-137 at protection level, registered in the KCDB as COOMET.RI(I)-S1. Participants are VNIIM (Russia), BelGIM (Belarus), CPHR (Cuba); GEOSTM (Georgia), INSM (Moldova), NSC-'IM' (Ukraine, SMU (Slovakia), BIM (Bulgaria) and IAEA (International). Measurements started in June 2011 and were finished in January 2013. Draft A of the comparison report is in preparation.

AFRIMETS.RI(I)- S1

PTB will participate and act as a link laboratory in the AFRIMETS comparison of national air kerma standards for Co-60, Cs-137 gamma radiation and the ISO 4037 x-radiations narrow series qualities N-40, N-100, N-150 and N250. The pilot laboratory is NMISA, South Africa. The comparison started in March 2011 and was scheduled to finish in November 2012. Due to some delays in the course of the comparison with other participants PTB has not yet received the transfer chambers for measurements.

EURAMET Project 1177

PTB participated in the EURAMET comparison of the calibration of KAP meters in terms of air kerma area product which is piloted by the Greek Ionizing Radiation Calibration Laboratory of the Greek Atomic energy Commission (IRCL/GAEC-EIM). PTB finished its measurements in September 2011. Draft A of the comparison report is in preparation.

EURAMET.RI-S10

A comparison of the air kerma standards for X-ray radiation qualities used in general diagnostic radiology and mammography was performed between the PTB and the IAEA. Two spherical and two parallel plate reference class ionization chambers of the IAEA and 12 beam qualities standardized in the IEC standard 61267:2005 and additional 7 standard beam qualities established at both laboratories were selected for the comparison. The calibration coefficients were determined for the transfer chambers at the PTB in September 2012 and before and after this at the IAEA Dosimetry Laboratory. The results show the calibration coefficients of both laboratories to be in good agreement within the standard uncertainty of the comparison of about 0.4 %. Draft B of the report is submitted to CCRI(I) for review and intended to be published soon in the technical supplement of Metrologia.

1.5. Publications and Conference Presentations (2011 – 2013)

1. *Ankerhold, Ulrike; Anton, Mathias; Büermann, Ludwig; Derikum, Klaus; Kapsch, Ralf-Peter; Krauss, Achim; Selbach, Hans-Joachim:*
Progress report Department "Dosimetry for Radiation Therapy and Diagnostic Radiology".
Dosimetry report from the PTB,(2011), 3-20,
www.bipm.org/cc/CCRI(I)/Allowed/20/CCRI(I)-11-13.pdf,BIPM.

2. *Sievers, Peter; Schneider, Thorsten; Michel, Thilo; Anton, Gisela:*
X-ray spectroscopy with photon counting imaging detectors such as Timepix.
2011 IEEE Nuclear Science Symposium and Medical Imaging Conference, (2011), 1826-1828,
dx.doi.org/10.1109/NSSMIC.2011.6154692
Piscataway, NJ: IEEE. ISBN 978-1-4673-0118-3; ISBN 978-1-4673-0119-9

3. *Krauss, Achim; Kapsch, Ralf-Peter; Rouijaa, Mustapha:*
Calorimetric determination of k_Q factors for an NE2561 ionization chamber in 3 cm x 3 cm beams of 6 MV and 10 MV photons.
Standards, applications and quality assurance in medical radiation dosimetry (IDOS): proceedings of an International Symposium on Standards, Applications and Quality Assurance in Medical Radiation Dosimetry (IDOS). Vol. 1; (STI/PUB: 1514), (2011), 209-218, Vienna: IAEA. ISBN 978-92-0-116210-6

4. *Büermann, Ludwig; Böttcher, Reinulf:*
Performance test of multi-parameter measuring devices used for quality assurance in diagnostic radiology.
Standards, applications and quality assurance in medical radiation dosimetry (IDOS): proceedings of an International Symposium on Standards, Applications and Quality Assurance in Medical Radiation Dosimetry (IDOS). Vol. 2; (STI/PUB: 1514), (2011), 33-41, Vienna: IAEA. ISBN 978-92-0-116210-6

5. *Kapsch, Ralf-Peter; Gomola, Igor:*
Beam quality correction factors for plane parallel chambers in photon beams.
Standards, applications and quality assurance in medical radiation dosimetry (IDOS) : proceedings of an International Symposium on Standards, Applications and Quality Assurance in Medical Radiation Dosimetry (IDOS). Vol. 1; (STI/PUB: 1514), (2011), 297-308, Vienna: IAEA. ISBN 978-92-0-116210-6

6. *Renner, Franziska; Kapsch, Ralf-Peter; Jannek, D.:*
A benchmark experiment for the verification of radiation transport calculations.
Abstracts: 12th International Symposium on Radiation Physics,(2012), 07- 12 Oct. 2012, Rio de Janeiro, Brasil

7. *Buhr, H.; Büermann, L.; Gerlach, M.; Krumrey, M.; Rabus, H.:*
EXPERIMENTAL MASS ENERGY-ABSORPTION COEFFICIENT OF AIR FOR X-RAYS FROM 8 keV TO 60 keV., Abstracts: 12th International Symposium on Radiation Physics, (2012), 07- 12 Oct. 2012, Rio de Janeiro, Brasil

8. *Renner, Franziska; Kapsch, Ralf-Peter; Büermann, Ludwig; Jannek, Dunja:*
Erarbeitung von Ionisationskammermodellen für EGSnrc im Zusammenhang mit einem Benchmark-Experiment.
43. Jahrestagung der Deutschen Gesellschaft für Medizinische Physik: Abstractband, (2012), 626-630, www.conventus.de/fileadmin/media/2012/dgmp/Abstractband/, Jena

9. *Schwab, Andreas; Renner, Franziska; Kapsch, Ralf-Peter; Jannek, Dunja:*
Eine Methode zur Bestimmung der kinetischen Energie von Elektronen an der hochenergetischen Beamline des PTB-Forschungsbeschleunigers.
43. Jahrestagung der Deutschen Gesellschaft für Medizinische Physik, Jena: Abstractband, (2012), 635-640, www.conventus.de/fileadmin/media/2012/dgmp/Abstractband/

10. *Hupe, Oliver; Ankerhold, Ulrike:*
Determination of the dose of persons assisting when X-radiation is used in medicine, dentistry and veterinary medicine.
European Conference on Individual Monitoring of Ionising Radiation (IM2010); in: Radiation Protection Dosimetry, 144 (2011), 1/4, 478-481, dx.doi.org/10.1093/rpd/ncq351 - Oxford Univ. Press. ISSN 0144-8420

11. *Kaulich, Theodor W.; Quast, Ulrich; Bamberg, Michael; Selbach, Hans-Joachim:*
Direct reference air-kerma rate calibration of ^{192}Ir for a thimble-type ionization chamber in a cylindrical solid phantom.
Metrologia, 49(2012), 5, S241-S245, dx.doi.org/10.1088/0026-1394/49/5/S241, stacks.iop.org/Met/49/S241, IOP. ISSN 0026-1394

12. *Gabris, Frantisek; Zeman, Jozef; Valenta, Jiri; Selbach, Hans-Joachim:*
Exploitation of secondary standard for calibration in units of $D_{w,1\ cm}$ and assessment of several HDR brachytherapy planning systems.
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Experimental determination of the dose rate constant for selected I-125 and Ir-192 brachytherapy sources.
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14. *Schneider, Thorsten:*
The PTB Primary Standard for the absorbed-dose to water for I-125 interstitial brachytherapy sources.
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15. *Pimpinella, Maria; Anton, Mathias; Rouijaa, Mustapha; Stravato, Antonella:*
Comparison of D_w measurements by alanine and synthetic diamond dosimeters in photon beams with 1cm × 1 cm field size.
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X-Ray spectrum reconstruction with photon counting imaging detectors such as Medipix/Timepix.
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42. *Sipilä, P.; Pooter, J. de; Kapsch, Ralf-Peter; Pimpinella, M.; Kosunen, A.; Ankerhold, Ulrike:*
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46. *Büermann, Ludwig:*
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6-8 June 2012, Legnaro, Italy

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Bayesian deconvolution as a method for the spectroscopy of X-rays with highly pixelated photon counting detectors.
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2. Progress Report of the Department 'Radiation Protection Dosimetry'

P. Ambrosi, R. Behrens, O. Hupe, S. Neumaier, H. Dombrowski

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

2.1. Pulsed radiation in radiation protection dosimetry

PTB has established a special pulsed X-ray facility which can produced pulsed reference radiation fields with well-known parameters like pulse duration, high voltage, dose rate in the pulse, which are all traceable to primary standards and can be adjusted independently, see J. Klammer et al. “Novel reference radiation field for pulsed photon radiation installed at PTB”, Radiation Protection Dosimetry Vol. 151, No. 3, pp. 478-482 (2012), see list of publications.

In parallel, the PTB has initiated and accompanied as project leader the now finished international efforts to develop a Technical IEC specification IEC TS 62743:2012-09 “Radiation protection instrumentation – Electronic counting dosemeters for pulsed fields of ionizing radiation” for testing counting dosemeters with respect to the performance in pulsed fields.

PTB performed first measurements to prove the feasibility of the test procedures given in IEC 62743:2012-09. A description of the requirements and results for the Thermo Fisher EPD Mk2 can be found in H. Zutz et al., Radiation Protection Dosimetry Vol. 151, No. 3, pp. 403-410 (2012). Measurements with DIS-1 dosemeters and an XR200 X-Ray flash unit demonstrates the basic applicability of such dosemeters for measuring the ns duration pulses generated by the XR200, see H. Zutz et al., Radiation Protection Dosimetry, doi:10.1093/rpd/ncs265 (2012).

PTB has made also a new work item proposal for an ISO Technical Specification ISO/TS 18090-1 “Radiological protection — Characteristics of reference pulsed radiation – Part 1: Photon radiation” and is accompanying as project leader.

A new pixelated detector (Medipix/Timepix) combined with a novel deconvolution method was used to investigate the spatial- and time-dependent behaviour of pulsed x-ray fields. With its high time-resolution, it was possible to investigate the time-behaviour of the x-ray spectra, while switching on commercially available generator-pulsed x-ray equipment. This behaviour was compared to those obtained at the PTB reference field for pulsed radiation using a grid-controlled X-ray tube instead. It came up that the high-voltage of a grid-controlled tube is at high level within a few µs, while at the x-ray equipment with a generator-control several hundreds of µs are needed.

The high spatial resolution of the detector was used to investigate the angular dependence of the Heel-effect at an X-ray tube. Further details can be found in the corresponding publications, P. Sievers et al. “Bayesian deconvolution as a method for the spectroscopy of X-rays with highly pixelated photon counting detectors” J. Instrum. Vol. 7, P03003 (2012) and P. Sievers et al. “Time-resolved spectrometry for the characterization of a reference field for pulsed radiation” J. Instrum. Vol. 7, T10002 (2012), see list of publications.

Measurements at Elekta Precise medical electron accelerators:

On the way of evaluating the basic suitability of radiation fields emitted by medical linear accelerators for the use in the course of type testing, PTB performed first explanatory measurements. The basic idea was to create a well-defined scattering field for irradiations of dosemeters by using dedicated scattering objects. The scattered field is of interest because the doserate in the direct beam is much too high for current personal and ambient dose(rate)meters while it should be lower by orders of magnitude in the scattered beam. During the measurements at the Elekta Precise accelerators of PTB it turns out that major sources of scattered radiation are located inside the accelerator head. Therefore additional measurements were performed in the surrounding of the accelerator head and in the maze to evaluate the spatial doserate distribution. Doserates in the range of a few µSv/h (maze) up to some Sv/h (primary beam) were measured.

2.2. Progress in the field of beta dosimetry at PTB

$H_p(3)$ was implemented in the primary beta dosimetry at PTB. The application for a corresponding CMC entry was submitted to the BIPM in January 2012. Subsequently, $H_p(3)$ was implemented in the beta secondary standard (BSS 2). A corresponding software update for the BSS 2 was distributed (free of charge) to the users in December 2012. By this, all users of a BSS 2 can perform irradiations in terms of $H_p(3)$ using their old $^{90}Sr/^{90}Y$ source. For the future, a comparison is envisaged.

2.3. Progress in the field of dosimetry at low dose rate

2.3.1. Installation of the new underground laboratory UDO II

In 2012 PTB installed a new underground laboratory for dosimetry (UDO II) at the 430 m level inside the commercial salt mine Braunschweig-Lüneburg (run by esco). A unique calibration facility is situated inside the underground laboratory. Currently, it is the only facility worldwide which allows the traceable calibration of detectors at low dose rates, i.e. in the ambient dose equivalent rate range from 10 nSv/h to 1 µSv/h and especially in the region around 100 nSv/h, which is typical for ionising radiation in the natural environment. By using the calibration facility, the investigation of important detector properties is possible, in particular the inherent background, the energy dependence and the dose rate dependence of the response of detectors for ionising radiation. These detector properties have to be known if precise measurements in the natural environment have to be performed. All calibration measurements are traceable to the primary standards of PTB.

Due to the shielding against secondary cosmic radiation (430 m below ground, the muon flux inside UDO II is reduced by almost four orders of magnitude) and the low specific activity of the rock salt by which the laboratory is surrounded, the ambient dose equivalent rate within UDO II is only (1.6 ± 0.2) nSv/h. Such a low and well-defined background is needed when the inherent background of a radiation detector is to be measured precisely. In addition, the photon fields produced by the irradiation facility are very well defined because the background relative to the spectra produced by radioactive sources is almost negligible.

The new calibration facility inside UDO II replaces the old, similar calibration facility within UDO, which was located inside the Asse salt mine near Remlingen (35 km away from PTB). The salt mine Braunschweig-Lüneburg is accessible in Grasleben, 50 km away from PTB.

2.4. Comparisons

2.4.1. EURAMET Comparisons

<u>EURAMET.RI(I)-S5</u>

The EURAMET project 738 “EURAMET supplementary comparison of the personal dose equivalent quantity for photon radiation” is finished. The final report is available in Metrologia Vol. 49 Tech. Suppl. 0601 (2012), see list of publications. Measurements were made by participants in 17 countries: Austria, France, Czech Republic, Finland, Germany, Greece, Hungary, Norway, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, the Netherlands, the United Kingdom and by one international organization. PTB was the pilot laboratory.

EURAMET project 1132

The upcoming comparison EURAMET project 1132 is focused on the special needs for calibration of area dosemeters in terms of ambient dose equivalent: large radiation fields and low dose rates at the radiation qualities S-Cs and N-60. The proposed transfer instrument is a spherical ionisation chambers having 10 litre volume. The comparison is scheduled to start in 2013 and to be finished in 2014. The comparison has 17 participants with PTB as pilot laboratory.

2.4.2. Bilateral beta comparison of PTB and VNIIM

In 2010, a bilateral comparison for the unit of the absorbed dose rate in 0.07 mm tissue depth for beta radiation was finished. In this comparison, radiation fields of the radionuclides $^{90}Sr/^{90}Y$, ^{85}Kr, and ^{147}Pm were compared by means of an exchange of radioactive sources. The measured values agree within the uncertainties, i.e. ±2 % for $^{90}Sr/^{90}Y$ and ^{85}Kr and ±4 % for ^{147}Pm ($k = 2$). A paper was published in Metrologia, Vol. 48, 317-323 (2011), see list of publications.

2.4.3. Sixth EURADOS intercomparison to harmonize European early warning network systems

PTB performs regular tests of area dose rate detectors which are or could be installed in European early warning network systems. The sixth EURADOS intercomparison of such systems was organised by EURADOS working group 3 (Environmental Radiation Monitoring) and held in September 2012. Three reference measuring sites were used to characterize 12 detector systems, operated by 5 different organisations from the following European countries: Belgium, Germany, Lithuania, Netherlands and Spain.

During the intercomparison, measurements were performed on different reference measuring sites, i.e. in the (new!) underground laboratory UDO II, where calibrations at low dose rates and different energies were performed and the inherent background of the detectors was determined, on the floating platform where the response to secondary cosmic radiation was measured, and on a free-field measuring site where an uncollimated irradiation facility was operated in the natural environment to study the influence of artificially increased dose rates on detector systems, so that the effects of a passing radioactive plume on the detectors could be tested.

The main aim of the intercomparison was to ensure that during a nuclear accident different European countries report consistent results to the EURDEP data base, which is run by the European Commission, so that comparable conclusions can be drawn by responsible governmental offices in the affected EU countries. Furthermore, the results of the permanently operated networks (covering the whole European Union) can be used for further scientific investigations regarding, e.g., soil moisture or radon exhalation rates, because these results can be indirectly assessed by evaluating network dose rate data.

As a result of six EURADOS intercomparisons of this type, important basic data of 35 different detector types including commercial dosemeters and spectrometry systems were gathered, including data which are needed for quantitative area dose rate measurements in the natural environment, but which are not supplied by the manufacturers of the systems, like inherent background, response to cosmic radiation, variance of the measured data at low dose rates and influence of dose rate or energy on the response.

2.4.4. PTB intercomparison of passive area dosemeters

From October 2011 to April 2012 an intercomparison for passive area dosemeters was performed by PTB to study the long-term behaviour of passive $H^*(10)$ dosemeters. Such dosemeters are in particular used to monitor photon and neutron radiation in the surrounding of nuclear installations so that the influence of the installations on the effective dose rate of the population can be evaluated. 12 participants (measuring bodies) from Germany, Swiss, Austria and Croatia supplied about 200 single dosemeters. As a consequence, 16 different types of photon dosimetry systems and 4 types of neutron dosimetry systems could be tested. The reference values were supplied by PTB on the basis of permanent measurements using different active detector systems.

The dosemeters were exposed on two different reference measuring sites and a number of photon and neutron dosemeters was also exposed in PTB irradiation facilities. The terrestrial response was determined by exposing the dosemeters on the free-field reference site, while the response to secondary cosmic radiation was measured on the reference site for comic radiation, which is identical to the floating platform also used for EURADOS intercomparisons of active dosemeters.

The results of the passive photon dosimetry were promising, because permissible tolerances defined in appropriate standards were not exhausted. Almost all data recorded on the free-field deviated from the conventional quantity value by less than 20 %. But the results of the neutron dosemeters differed by a factor of 10 relative to each other because the systems are, in general, not sensitive enough to be used for measuring the low neutron dose values occurring in the natural environment.

2.5. Publications (2011 – 2013)

1. M. Voytchev, P. Ambrosi, R. Behrens and P. Chiaro: IEC standards for individual monitoring of ionising radiation. Rad. Prot. Dosim., Vol. 144, 33-36 (2011)
2. R. Behrens: Monitoring the eye lens. Acta Ophthalmologica, 89: 0. doi: 10.1111/j.1755-3768.2011.2163.x: *http://onlinelibrary.wiley.com/doi/10.1111/j.1755-3768.2011.2163.x/abstract*
3. R. Behrens, G. Dietze: Dose conversion coefficients for photon exposure of the human eye lens. Phys. Med. Biol., Vol. 56, 415-437 (2011)
4. R. Behrens, J. Engelhardt, M. Figel, O. Hupe, M. Jordan, R. Seifert: Hp(0.07) photon dosemeters for eye lens dosimetry: Calibration on a rod vs. a slab phantom. Rad. Prot. Dosim., Vol. 148, 139-142 (2012)
5. M.S. Kulkarni, M. Luszik-Bhadra, R. Behrens, K.P. Muthe, N.S. Rawat, S.K. Gupta, D.N. Sharma: Studies on new neutron-sensitive dosimeters using optically stimulated luminescence technique. Nuclear Instruments and Methods in Physics Research B, Vol. 269, 1465-1470 (2011)
6. R. Behrens, S. Fedina, A. Oborin: Direct comparison of extrapolation chamber measurements of the absorbed dose rate for beta radiation between PTB (Germany) and VNIIM (Russia). Metrologia, Vol. 48, 317-323 (2011)
7. R. Behrens, G. Hilgers: Photon spectra from beta sources of the Beta Secondary Standard BSS 2. J. Instrum., Vol. 6, P09006 (2011)
8. R. Behrens, G. Buchholz: Extensions to the Beta Secondary Standard BSS 2. J. Instrum., Vol. 6, P11007 (2011) and Erratum: J. Instrum., Vol. 7, E04001 (2012) and Addendum: J. Instrum., Vol. 7, A05001 (2012)
9. R. Behrens: Spectrometer for pulsed and continuous electron and photon radiation. Indian Journal of Pure and Applied Physics, Vol. 50, 450-453 (2012)

10. R. Behrens: Air kerma to Hp(3) conversion coefficients for a new cylinder phantom for photon reference radiation qualities. Rad. Prot. Dosim., Vol. 151, 450-455 (2012)
11. R. Behrens: Monitoring the eye lens. Paper at IRPA13, Glasgow: TS7e.3: http://www.irpa13glasgow.com/information/downloads
12. R. Behrens: On the operational quantity Hp(3) for eye lens dosimetry. J. Rad. Prot., Vol. 32, 455-464 (2012)
13. R. Behrens: Dose conversion coefficients for electron exposure of the human eye lens: Calculations including a full human phantom. Rad. Prot. Dosim., doi:10.1093/rpd/ncs325
14. Ankerhold, U., Hupe, O.: EURAMET supplementary comparison of the personal dose equivalent quantity for photon radiation. Metrologia **49** Tech. Suppl. 0601 (2012)
15. Sievers, P., Weber, T., Michel, T., Klammer, J., Büermann, J. and Anton, G.: Bayesian deconvolution as a method for the spectroscopy of X-rays with highly pixelated photon counting detectors. J. Instrum. Vol. 7, P03003 (2012)
16. Sievers, P., Weber, T. Michel, T., Klammer, J., Büermann, L. and Anton, G.: Erratum: Bayesian deconvolution as a method for the spectroscopy of X-rays with highly pixilated photon counting detectors. J. Instrum. Vol. 7, E08001 (2012)
17. Sievers, P., Klammer, J., Hupe, O., Michel, T. and Anton, G.: Time-resolved spectrometry for the characterization of a reference field for pulsed radiation. J. Instrum. Vol. 7, T10002 (2012)
18. Sievers, P., Klammer, J., Michel, T., Hupe, O., Anton, G.: Improving the spectral resolution of a highly pixelated detector by applying a pixel-by-pixel energy calibration for investigating the spectral properties of the anode heel effect, Journal of Instrumentation,7 (07), 16. Doi:10.1088/1748-0221/7/07/P07011 (2012) J. Instrum. (2012)
19. Zutz, H, Hupe, O., Ambrosi, P., Klammer, J.: Determination of relevant parameters for the use of electronic dosemeters in pulsed fields of ionising radiation. Radiation Protection Dosimetry, Vol. 151, No. 3, pp. 403–410 (2012)
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22. Hupe, O., Zutz, H. and Klammer, J.: Radiation protection in pulsed fields. Paper at IRPA13, Glasgow: TS2f.3: http://www.irpa13glasgow.com/information/downloads
23. Dombrowski, H., Neumaier, S., Zuber, K.: Precision half-life measurement of the 4-fold for-bidden beta decay of ^{50}V, Phys. Rev. C 83, 054322 (2011).
24. Sauerwein, A. Becker, H. W., Dombrowski, H., Elvers, M., Endres, J., Giesen, U., Hasper, J., Hennig, A., Netterdon, L., Rauscher, T., Rogalla, D., Zell, K. O. and Zilges, A: Determination of ^{141}Pr(alpha,n)^{144}Pm cross sections at energies of relevance for the astrophysical p process using the gamma gamma coincidence method, Phys. Rev. C 84, 045808 (2011).
25. Gasparro, J., Hult, M., Marissens, G., Hoshi, M., Tanaka, K., Endo, S., Laubenstein, M., Dombrowski, H. and Arnold. A: Measurements of 60Co in massive steel samples exposed to the Hiroshima atomic bomb explosion, Health Physics, 102, 4 (2012) 400.
26. Dombrowski, H. and Neumaier, S.: Long-term PTB intercomparison of passive H*(10) dose-meters used in area monitoring, JINST 7 P04017 (2012).
27. Dombrowski, H.. Commentary on Stochioiu, A., Sahagia, M. and Tudor, I., Area dosimetry in the Praid-salt mine, Radiat. Prot. Dosim. 152, 4 (2012) 475.
28. Neumaier, S. Dombrowski, H. Motzkus, K.-H. and Häusler, U.: Type testing and type approval of basic-protection devices in Germany. European ALARA Newsletter, 28. Issue (2011) 9.

3. Progress Report of the Department 'Ion Accelerators and Reference Radiation Fields'

U. Giesen

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

3.1. New measurements of *W*-values for protons, α-particles and C-ions in argon, nitrogen and air

A new experimental set-up was developed at PTB and consistent measurements of *W*-values in argon, nitrogen and air for protons and α-particles with energies from 0.7 MeV/u to 3.5 MeV/u at PTB, and for carbon ions between 3.6 MeV/u and 7.0 MeV/u at GSI were carried out. Corrections for ion recombination, beam-induced background radiation and impurities of the gases were carefully measured. These measurements were the subject of a doctoral thesis and a publication of the results is in preparation.

3.2. Irradiation of cells with low-LET and high-LET particles using the PTB microbeam

The department participates in the EMRP-Project SIB06 BioQuaRT: *Biologically weighted quantities in radiotherapy*. In cooperation with project partners, different cell lines are irradiated at the microbeam with exact numbers of protons having LET-values of about 5 keV/µm and 18 keV/µm, and alpha-particles with LET-values of 36 keV/µm, 90 keV/µm and 160 keV/µm. Initial DNA double-strand breaks are studied with the γ-H2AX assay, while late damage and repair effects are studied using assays for micronuclei and dicentric chromosomes. These data will provide a set of biological data to be used as benchmarks for the prediction of multi-scale models of biological effects of radiation.

4. Progress Report of the Department 'Fundamentals of Dosimetry'

A. Arndt, W. Y. Baek, M. U. Bug, T. Buhr, G. Hilgers, H. Nettelbeck, H. Rabus, J. Rahm, M. Wang

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

4.1. Interaction cross-sections of DNA constituents

4.1.1. Electron scattering cross sections of the DNA constituent pyrimidine

Electron scattering cross sections of pyrimidine, the basic component of the nucleic bases cytosine and thymine, were measured for electron energies up to 1 keV. These cross sections comprehend total, differential elastic and double differential inelastic scattering cross sections. In addition to the experimental determination, total and elastic scattering cross sections were calculated using the spherical optical potential model [Jain et al., Phys. Rev. A45, 202 (1992)] and the modified independent atom model [Hayashi et al., J. Phys. Soc. Jpn. 41, 1724(1976)], respectively.

Fig. 4.1 shows the energy dependence of the experimental total electron scattering cross sections σ_t of pyrimidine. The experimental results are compared to the semiempirical data that are obtained from σ_t of N_2 [Nickel et al., J. Phys. B: At. Mol. Opt. Phys. 25, 2427 (1992)] and C_2H_2 [Sueoka et al, J. Phys. B: At. Mol. Opt. Phys. 22, 963 (1989)] using the additivity law and to the experimental data for benzene which has the same number of valence electrons as pyrimidine. It is evident from Fig. 4.1 that the semiempirical data determined using the additivity law agrees with the measured results within the experimental uncertainties over the whole energy range. The present experimental results are also well reproduced by the total scattering cross sections of benzene measured by Mozejko et al. while they are significantly greater than the benzene data of Sueoka in the low-energy region.

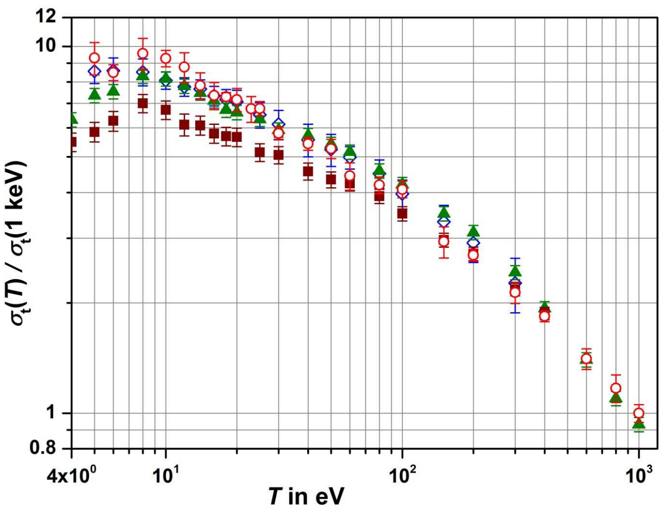

Fig. 4.1: Energy dependence of the total electron scattering cross sections of pyrimidine. The ratio of the TCS of pyrimidine to that at 1 keV is shown as function of the electron energy T: (○) present results, (◊) semiempirical values obtained by means of the additivity law, (▲) TCS of benzene by Mozejko et al. [Chem. Phys. Letters 257, 309 (1996)], (■) TCS of benzene by Sueoka [J. Phys. B: At. Mol. Opt. Phys. 21, L631 (1988)].

The energy dependence of the theoretical total scattering cross sections calculated by means of the spherical optical potential model agrees reasonably well with that of the measured data (Fig. 4.2). The theoretical total scattering cross sections were obtained by summing up the integral elastic und inelastic scattering cross sections including the contribution of rotational excitation of the molecule.

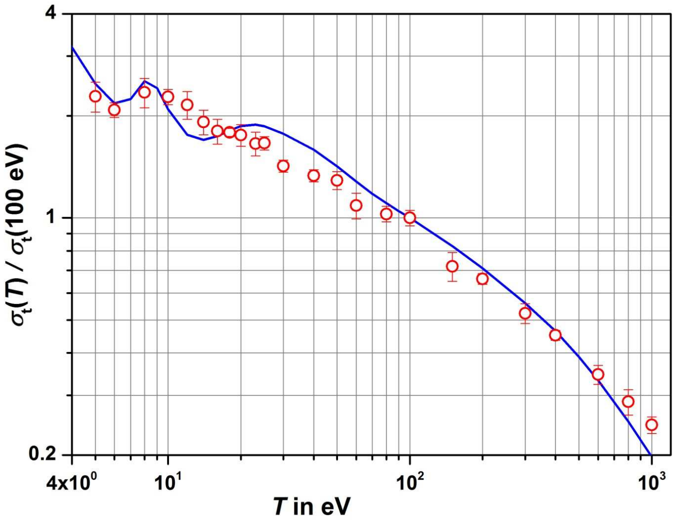

Fig. 4.2 Energy dependence of the pyrimidine total scattering cross section: calculation by means of the spherical optical potential model (─) vs. measurement (○).

Differential elastic scattering cross sections of pyrimidine are shown in Fig. 4.3 for three electron energies as function of the scattering angle. The results of the present measurement are compared to the experimental data from literature and to the theoretical values computed using the modified independent atom model. It is evident from Fig. 4.3 that the agreement between the measured and theoretical values becomes better with increasing energy. This can be expected due to the approximation used in the theoretical model. In addition, the shoulder structure in the experimental data is well reproduced by the theoretical values in the scattering angle range around 35°, which indicates that the structure is realistic. The present experimental results show large deviations from those of Maljković et al. for scattering angles above 60°. For electrons with a kinetic energy of 100 eV, the relative deviation in this scattering angle range amounts to approximately 80 %.

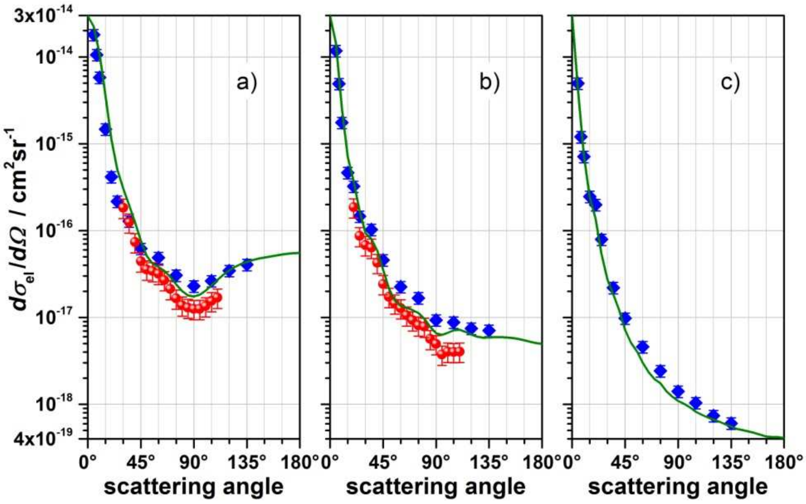

Fig. 4.3 Differential elastic scattering cross sections of pyrimidine for electrons with energies of 100 eV (a), 300 eV (b) and 1 keV (c): (♦) present experimental results, (●) experimental data of Maljković et al. [Phys. Rev. A 79, 052706 (2009)], (─) theoretical values calculated using the modified independent atom model.

Since secondary electrons released during the penetration of primary particles in matter further produce electrons by ionization processes, the energy and angular distribution of these electrons are of importance for the assessment of radiation damages by ionizing radiation. Therefore, the ionization cross sections of pyrimidine by electrons were measured doubly differentially as function of the energy of secondary electrons and scattering angle. The measured energy of secondary electrons ranged from 4 eV to (T-I)/2, where T is the primary electron energy and I is the ionization potential of pyrimidine. The measurement was carried out for emission angles from 5° to 135°. As an example, Fig. 4.4 shows the energy spectra of secondary electrons produced by the ionization of pyrimidine by 100 eV-electrons for four emission angles.

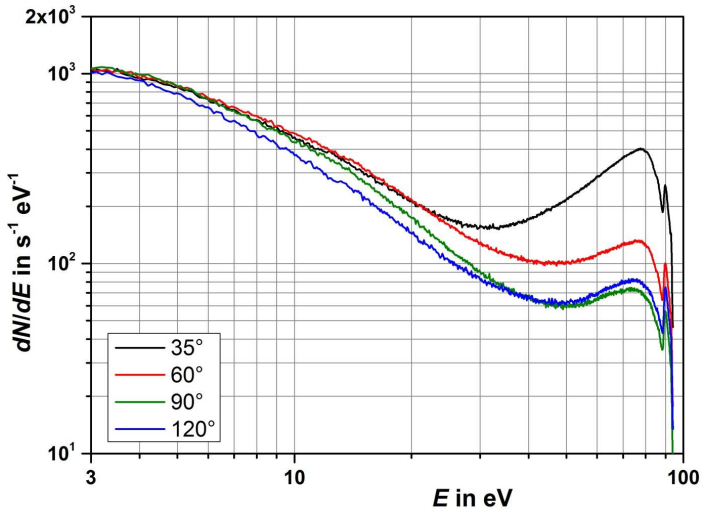

Fig. 4.4 Energy distribution of secondary electrons produced by 100 eV-electrons in pyrimidine for different emission angles.

4.1.2. Absolute cross sections for the fragmentation of biomolecules after ionization

The models proposed so far for relating nanodosimetric ionization cluster size distributions and the damage to the DNA contain adjustable parameters such as the conditional probability for an ionization of the DNA molecule to result in a strand break. The induction of a strand break as the consequence of an ionization cluster in a segment of DNA could be modeled without free parameters, if the cross sections for fragmentation of the molecular building blocks of the DNA backbone were known.

Therefore, an experimental apparatus has been developed to measure the cross sections of radiation-induced fragmentation processes of DNA components. In the crossed-beam experiment, using a pulsed electron gun or an ion accelerator as the radiation source, the target material to be investigated is transported to the interaction volume in a supersonic jet with argon as a carrier gas. The molecular fragments are recorded in a time-of-flight mass spectrometer. A specialized heated-nozzle mounting has been designed and built that allows the mixing of argon with the target material in variable concentration. In particular, target gas jets of molecules originating from liquid or solid samples can be prepared.

4.1.3. Low-energy ion accelerator for measuring the cross sections for the interaction of light ions with biomolecules

A low-energy ion accelerator is being developed at the PTB to investigate the cross sections for ionization and fragmentation of biomolecules by light ions with energies below and in the vicinity of the stopping power maximum. This will be performed in a crossed beam experiment by means of low-energy angle-resolved electron spectrometry and time-of-flight spectrometry of the fragment ions. Protons, helium and carbon ions with kinetic energy of up to 150 keV/*q* will be used as primary particles (where *q* is the charge of the ion).

Fig. 4.5 shows the general layout of the ion accelerator. An extractor type ion source with a Wien mass filter produces the q/m filtered ions, where m is the mass of the ion. An electric pulsing stage and an electrostatic deflector are placed between the ion source and the electrostatic accelerator tube. The pulsing stage impresses a time structure on the ion beam required for time-of-flight measurements. The deflector aids the ion beam's alignment with respect to the accelerator tube's axis. An electrostatic quadrupole triplet is used for focusing the ion beam in horizontal and vertical direction to the target region. Another electrostatic deflector between the accelerator tube and quadrupole triplet assists the ion beam to enter the quadrupole along its axis. This is to avoid the steering of the ion beam with the quadrupole lens. A third electrostatic deflector is located behind the quadrupole to correct any beam deflection. The ion beam size in the target region is defined by an aperture. An hemispherical-mirror spectrometer will be used to measure the energy and angular distributions of the emitted electrons or ions.

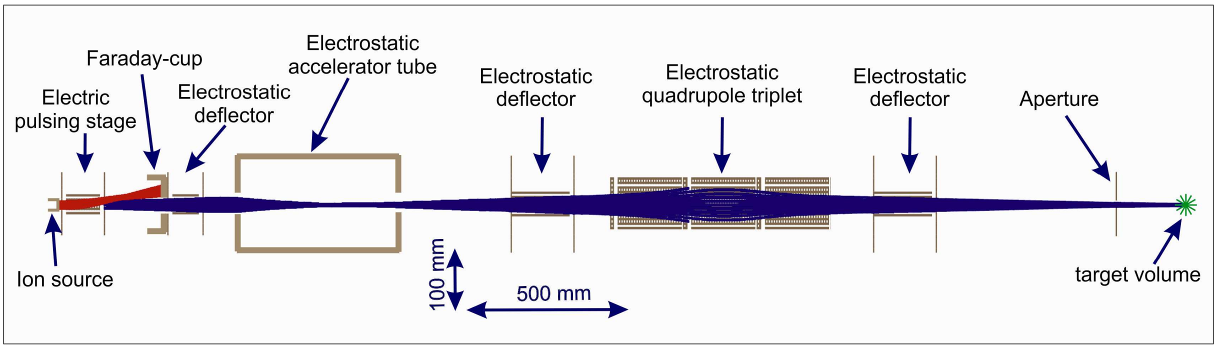

Fig. 4.5: Schematics of the ion accelerator.

4.2. Nanodosimetry

4.2.1. Verification of the scaling relation for ionisation cluster size distributions

In nanodosimetry, the key characteristics of particle track structure are the frequency distributions of ionization cluster size which can be measured using a nanodosimeter, basically a gas filled counter of the produced ions operating at low pressure. These distributions are assumed to be representative of those produced in nanometric targets of condensed matter, based on a density scaling procedure proposed by Großwendt to obtain equivalent ionisation cluster size distributions in different materials and target sizes.

Ionisation cluster size distributions were measured with the nanodosimeter for mono-energetic proton and alpha particle beams with energies ranging from 0.1 MeV to 20 MeV using C_3H_8 and N_2 as working gases and for mono-energetic proton beams with energies ranging from 0.1 MeV to 10 MeV using C_3H_8 and THF as working gases. Due to the limitations of the vacuum system and the vacuum measuring system, the maximum pressure which can be applied in the ionisation volume is 1.2 mbar. According to the NIST databases for stopping power and mean ionisation energy, equivalent cluster size distributions for protons and alpha particles should be obtained for pressures of 0.31 mbar C_3H_8 and 1.2 mbar N_2 and for 1.2 mbar C_3H_8 and 1.0 mbar THF for protons. However, measurements reveal the best agreement with pressures of 0.425 mbar C_3H_8 and 1.2 mbar N_2 for protons and 0.425 mbar C_3H_8 and 1.2 mbar N_2 for alpha particles and with pressures of 1.2 mbar C_3H_8 and 0.77 mbar THF for protons.

The reason for this difference is found in the pressure dependence of the spatial distribution of the extraction efficiency. Simulations of the extraction efficiency distribution show the extraction efficiency to change in such a way that it increases with increasing pressure of the working gas. Therefore the pressure for C_3H_8 has to be increased in order to obtain cluster size distributions equivalent to those measured for 1.2 mbar N_2. The extraction efficiency η integrated along the primary particle track is 0.23 for 1.2 mbar N_2 and 0.16 for 0.46 mbar C_3H_8. For identical η, identical $M_1(T)$ would be achieved for 1.2 mbar N_2 and 0.31 mbar C_3H_8, but for the given values of η, identical $M_1(T)$ are achieved for 1.2 mbar N_2 and $(0.23 / 0.16) \cdot 0.31$ mbar $= 0.44$ mbar C_3H_8. Simulations of the spatial distribution of the extraction efficiency of THF are in progress.

4.2.2. Basic check of the PTB Ion Counter nanodosimeter

To verify the correct basic operation of the nanodosimeter, a check procedure which is independent of any type of simulation and which can be traced back to fundamental considerations is required. The electronic stopping power of a substance depends on the type, the charge state and the energy of the ionising particle being stopped. According to Bethe's theory, the stopping power is identical for different ions of the same charge and identical velocity. The first moment of the frequency distribution of the number of ionizations, that is the mean ionization cluster size $M_1(Q)$, is proportional to the stopping power. The extraction efficiency η is only depending on the transport properties of the target gas ions in the neutral target gas, but does not depend on the type of generation of the target gas ions. Therefore, $M_1(Q)$ should also be identical for primary particles which are isotopes (i.e. identical atomic number Z, but different mass number A), if the charge states and particle velocities are the same.

The comparison of the mean ionisation cluster sizes $M_1(v)$ in dependence on the primary particle velocity v for protons and deuterons for 1.2 mbar N_2 and 1.2 mbar C_3H_8 shows a good agreement within the experimental uncertainties for both target gases, thus showing the correct basic operation of the nanodosimeter.

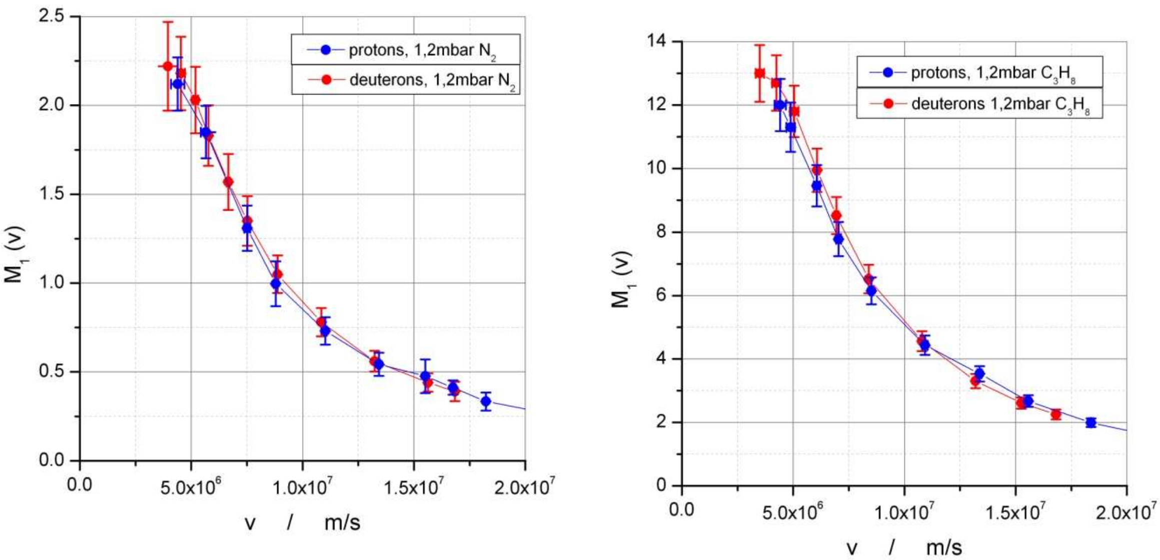

Fig.4.6: Mean ionisation cluster sizes $M_1(v)$ in dependence on the primary particle velocity v for protons and deuterons for 1.2 mbar N_2 and 1.2 mbar C_3H_8.

4.2.3. PTB Ion Counter modified to enable direct comparisons of nanodosimeters

In framework of the EMRP joint research project BioQuaRT, the PTB nanodosimeter had to be modified to enable direct comparisons with the nanodosimeters of the NCBJ (Poland) and INFN (Italy) in measurements of ionisation cluster size distributions of carbon ions. For this purpose, the primary particle detection scheme was augmented (see following sections) and the whole mechanical setup had to be changed to allow operation of the PTB nanodosimeter at the HIL accelerator facilities of Warsaw University and at the INFN-LNL in Legnaro. Test setups were successfully carried out at LNL and HIL, and first measurement shifts at the two accelerator facilities are scheduled for the first quarter of 2013.

4.2.4. Position sensitive primary particle detection

With the original setup of the nanodosimeter, only measurements of ionisation clusters generated by primary particles hitting the centre of the sensitive volume were possible. In order to allow also measurements of ionisation clusters due to primaries passing the sensitive volume in a certain distance, the nanodosimeter was equipped with a detector allowing the detection of the primary particle's position when hitting the detector. The distance of the position, where the primary particle hits the detector, to the detector's centre reveals the distance in which the primary particle passes the sensitive volume. Measurements of ionisation clusters due to primaries passing the sensitive volume in a certain distance allow obtaining information on ionisation clusters generated by secondary particles, which mostly are electrons, in the penumbra of the primary particle track.

First measurements of cluster size distributions with the position sensitive detector have been carried out with alpha particles of 8 MeV and 20 MeV and with alpha particles from an ^{241}Am-source in 1.2 mbar C_3H_8. The measured mean ionisation cluster size $M_1(T)$ shows a steep decrease with increasing distance D_{SV} from the centre of the sensitive volume. The ionisation cluster size distributions measured with the position sensitive detector in the centre of the sensitive volume are in good agreement with the measurements carried out in the previous measuring geometry.

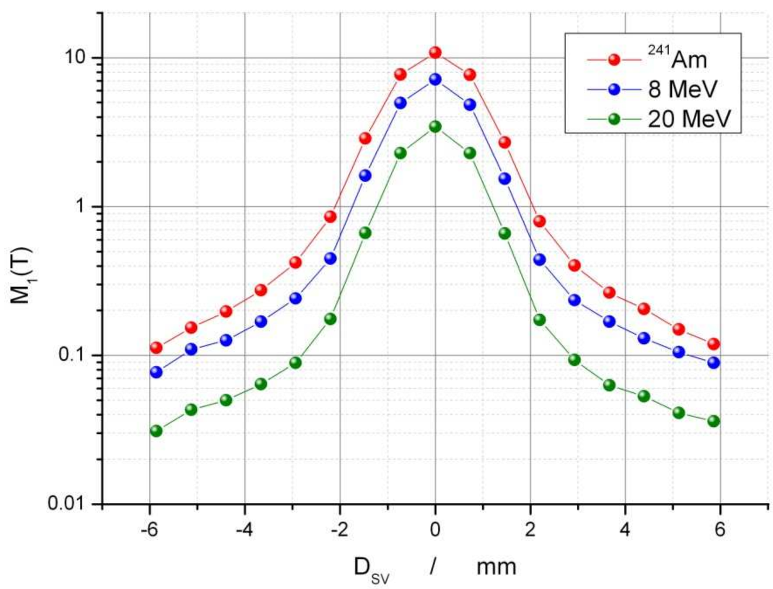

Fig. 4.7: Mean ionisation cluster size $M_1(T)$ for different distances D_{SV} from the centre of the sensitive volume for alpha particles in 1.2 mbar C_3H_8

4.2.5. Combining micro- and nanodosimetric measurements

In order to allow simultaneous measurements of microdosimetric and nanodosimetric quantities, the nanodosimeter was equipped with a silicon microdosimeter, a Si-micro-telescope, which replaces the previous trigger detector. The Si-micro-telescope provides besides the total energy of the primary particle also the energy loss in a thin silicon layer.

The Si-micro-telescope consists of a stack of two individual detectors embedded into the same substrate: a thin layer of silicon absorbing only a small fraction of the primary particle's energy and thus acting as an energy loss spectrometer, and a thick layer of silicon located beyond the thin layer absorbing the remaining energy of the primary particle. Using the summed signal of the two detecting layers as trigger signal for the existing data acquisition system allows the measurement of ionization cluster size distributions, which is a nanodosimetric quantity. In addition, the sum signal of the two detectors yields the energy of the primary particle. The signal of the thin detector stage provides information on microdosimetric quantities, thus the integration of the Si-micro-telescope into the nanodosimeter allows combined micro- and nanodosimetric measurements.

The pictures below show the first preliminary measurements with the Si-micro-telescope integrated into the nanodosimeter. The measurements were carried out at the accelerator facilities of the PTB with protons and alpha particles in the range between 0.26 MeV and 2.5 MeV, using 1.2 mbar C_3H_8 as target gas. The data show the energy deposition (pulse height) in the thin detector layer, denoted as ΔE-stage, and the thick detector layer, denoted as E-stage, together with the first moment of the ionisation cluster size distribution, that is the mean ionization cluster size M_1.

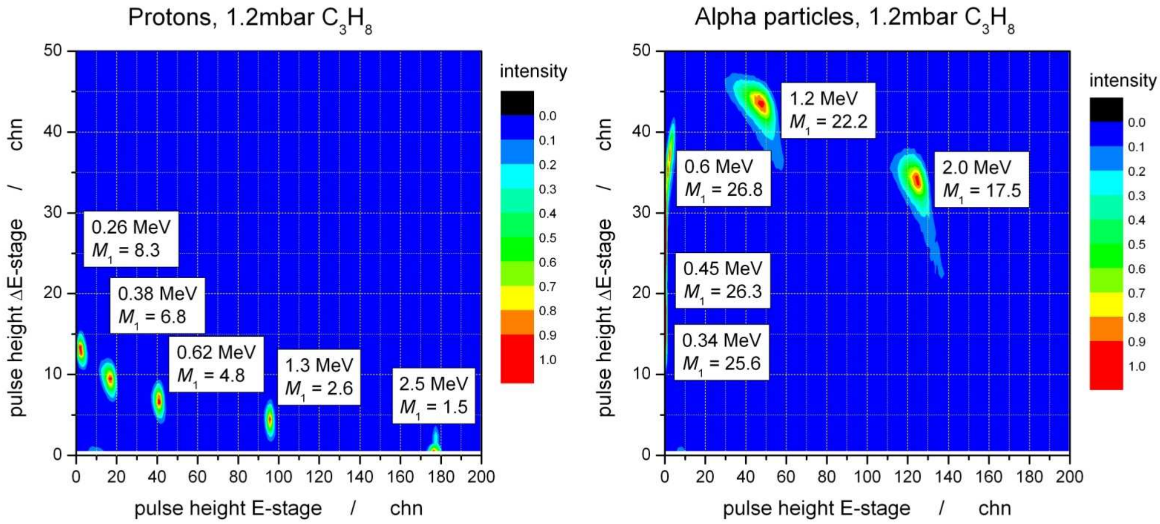

Fig.4.8: Measurement results (lineal energy vs. particle energy) from the combined micro-/nanodosimetric measurements for protons and alpha particles in 1.2mbar C_3H_8.

4.3. Biological effectiveness of ionizing radiation; track structure simulation

4.3.1. Comparison of the Monte Carlo codes Geant4-DNA and PTra for nanodosimetry

Biological effectiveness of ionizing radiation in form of initial damage to the DNA of human cells can be estimated from parameters characterizing the track structure of a particle, such as the number of ionizations (ionization cluster size) directly produced by a single particle within short segments of DNA. The ionization cluster size distribution and other nanodosimetric quantities, however, cannot be directly measured in biological targets. But they are conventionally assessed by Monte Carlo simulations of particle tracks in water.

The aim of this work was to quantify the difference of nanodosimetric quantities when calculated by two different Monte Carlo codes, namely the widely-used open-source code Geant4-DNA and the track structure code PTra, which was developed at the PTB [8]. The transport of incident electrons of energy between 50 eV and 10 keV, of protons of energy between 0.3 MeV and 10 MeV and of alpha particles of energy between 1 MeV and 10 MeV was simulated to compare nanodosimetric quantities obtained within nanometric-sized volumes, equivalent to a DNA segment of ten base pairs length and a nucleosome.

Good agreement of nanodosimetric quantities determined from both Monte Carlo codes was observed in the high energy range of all particle types. For electrons and light ions of lower energies, where the energy transfer per path length is larger, the results of Geant4-DNA simulations systematically show a higher number of ionizations produced in the target volume. Significant differences occurred for estimates of the biological effectiveness. Here, the largest relative difference was about 50 %, but generally the results agreed within 10 % and 20 %.

4.3.2. Benchmarking track structure Monte Carlo simulations

A tool for benchmarking the secondary electron transport in a track structure simulation has been suggested by Toburen et al., who have measured angle-dependent secondary electron spectra induced by 6 MeV protons in a thin layer of amorphous solid water (ASW) [9]. The transport of secondary electrons is particularly important as those particles are produced by any kind of ionizing radiation and subsequently deposit the major fraction of the primary particle energy in the medium. The secondary electron spectrum produced by protons of 6 MeV in the ASW target is theoretically well-defined, so that it can be assumed that the initial electron distribution used in the simulations is similar to the distribution in the experiment. Therefore, this study allows the evaluation of the electron transport in a simulation.

Simulations were performed for the set-up of the experiment, using the PTB Track structure code (PTra) and Geant4-DNA Version 9.4 p.02. To enable electron transport below the ionization threshold, additional excitation and dissociative attachment anion states were included in PTra and activated in Geant4. Additionally, a surface potential was introduced in both simulations, such that the escape probability of an electron depends on its energy and impact angle at the ASW/vacuum interface.

For a vanishing surface potential, the simulated spectra were in good agreement with the measured spectra for electron energies above 50 eV. Below this energy, the simulations overestimated the yield of electrons by a factor up to 4 (PTra) or 7 (Geant4). The agreement of the simulation results with experimental data was significantly improved by using a work function of about 3 eV, while a positive potential barrier seems inappropriate (Fig. 4.9).

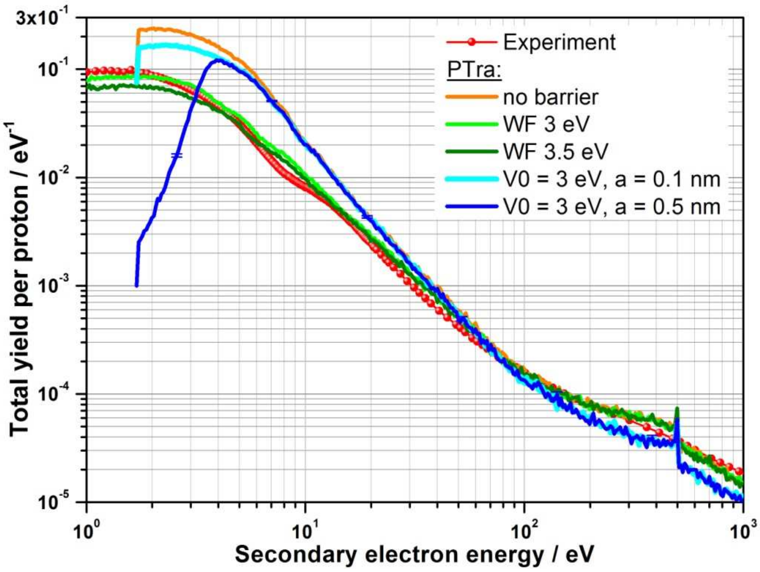

Fig. 4.9: Total yield of secondary electrons as function of energy obtained by integrating measured and simulated angle-resolved spectra over the emission angle. Shown are the simulations spectra obtained by PTra using different assumptions for the surface barrier.

4.3.3. Track structure simulations of electrons in DNA constituents tetrahydrofuran and pyrimidine

Radiation damage to the DNA can be estimated by nanodosimetric quantities characterizing the track structure. Such a quantity is, for example, the ionization cluster size, which is the number of ionizations produced per incident particle within a volume equivalent to a short DNA segment.

Nanometric quantities for such small volumes can be obtained by simulations of the particle track structure. Such kind of simulation requires physical interaction cross section data for all types of interaction of those particles with DNA molecules (i.e. deoxyribose, phosphatic acid and the four nucleobases consisting of pyrimidine or purine). As for now there exists, however, no complete data set for interaction cross sections of DNA constituents, generally the cross sections of water are used as a model for biological media.

Measured electron cross section data for tetrahydrofurane (comprising the ring of the deoxyribose molecule) and pyrimidine were analysed and a full set of interaction cross section data for a track structure simulation was derived.

Due to similarities in their molecular structure, track structure simulations of electrons in pyrimidine show a similar ionization cluster size as simulations in tetrahydrofuran for a target volume equal to a DNA segment of ten base pairs (Fig. 4.11). The ionization cluster size produced by low secondary electron energies in water, however, is significantly smaller than in both DNA constituents.

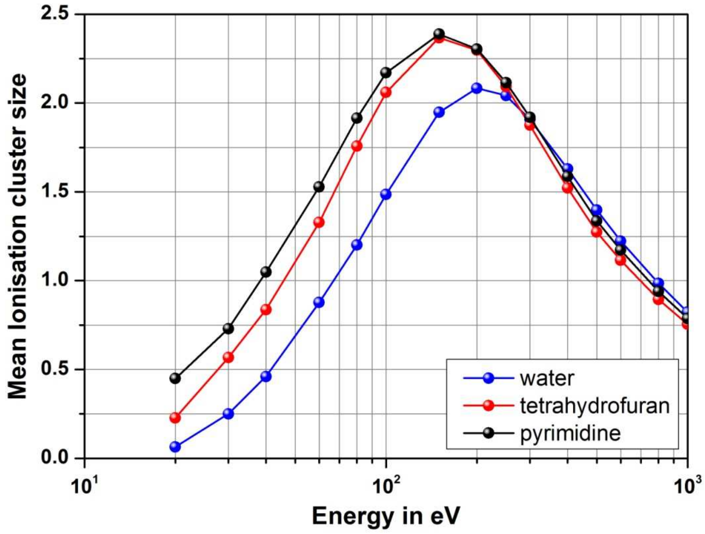

Fig. 4.11: Mean ionization cluster size as function of electron energy obtained by track structure simulations in a medium consisting of water, tetrahydrofuran and pyrimidine.

4.4. Stopping power of water for carbon ions in the Bragg peak region

For carbon ions in the energy region of the Bragg peak in liquid water, the stopping power is generally obtained by theoretical calculations or estimated from measurements which were performed in water vapour or D_2O-ice and therefore disregard phase effects. The aim of this work is to determine the stopping power of carbon ions in liquid water experimentally for the Brag peak energy region. The principle of this experiment is measurement of the inverted Doppler shift attenuation (IDSA) of gamma photons emitted in the decay of the first excited state (about 4.43 MeV) of carbon nuclei, using the known life time of this state. The emitted photon has a Doppler shift depending on the instantaneous velocity vector of the carbon ion and the emission direction of the photon. For carbon nuclei slowing down in water, the Doppler-shifted spectrum recorded with an HPGe detector will be a convolution of the initial energy distribution of the carbon ions, the distribution of decay times and of the relation between carbon velocity and decay time (related to the energy dependent stopping power).

The excited carbon nuclei will be produced by the inelastic scattering of alpha particles in carbon through the $^{12}C(\alpha,\alpha)^{12}C^*$ reaction. For this purpose a target is being developed which consists of a thin entrance foil coated with a thin layer of carbon (~25nm). The entrance foil separates the accelerator vacuum from a small water volume and has to be thick enough to withstand the pressure difference. Its impact on the energy and angular straggling of traversing alpha particles was investigated in a Monte Carlo simulation and proved negligible. The required initial energy distribution of the carbon ions will be obtained from the Doppler-shifted γ-spectrum originating from the decay of the excited carbon nuclides while traversing a vacuum volume. To facilitate the de-convolution of the measured spectra, a Monte Carlo based simulation software is in development which will be capable of calculating the expected gamma spectra for different primary energy distributions of the carbon ions.

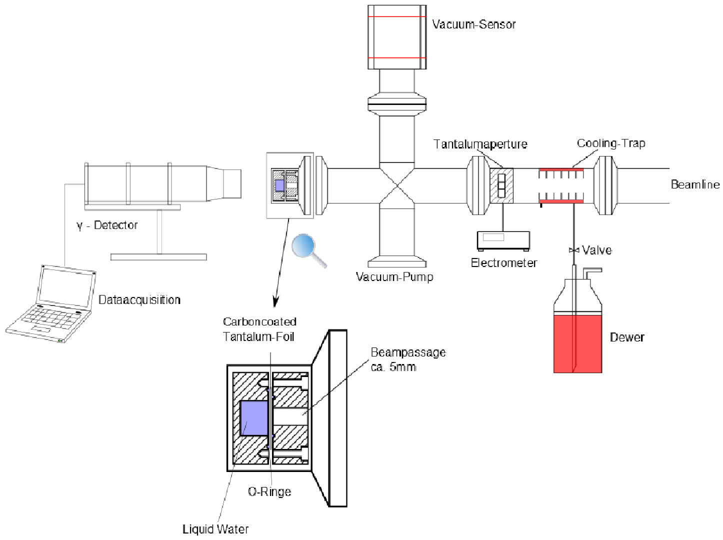

Fig. 4.12: Schematic layout of the experiment for measurement of the stopping power of water for carbon ions.

4.5. EMRP Joint Research Project SIB06 BioQuaRT

The aim of BioQuaRT is to develop measurement and simulation techniques for determining the physical properties of ionising particle track structure on different length scales, and to investigate at the cellular level how these track structure characteristics correlate with the biological effects of radiation. The relevant length scales range from about 2 nm (diameter of the DNA double helix) to about 10 µm (diameter of the cell nucleus).

BioQuaRT addresses the following objectives:

- Development of micro-calorimeters for the direct measurement of energy transfer (lineal energy) for different particles and energies. These will be used to assess whether corrections are needed when obtaining lineal energy spectra obtained from conventional microdosimeters that measure ionisation.

- Further development of measurement techniques for particle track structure at different length scales down to the nanometer range. This will allow us to perform a multi-scale characterisation of the radiation qualities used in therapy and the measurement of relevant radiobiological effects within this JRP SIB06 BioQuaRT

- Investigation of the indirect effects of radiation, which is in addition to the direct ionisation damage caused by the production of reactive molecules close to the DNA. The JRP consortium will build a prototype system to determine the spatial distribution of biologically relevant reactive species and the relative yield of their production in different ion beams

- The expertise of the JRP partners and their different simulation tools for micro- and nanometric track structure properties will be combined to develop a multi-scale model relating the characteristics of track structure to the biological consequences of radiation interaction.

- Biological reference data and benchmarks for the multi-scale model will be created by performing radiobiological assays in cultured tissue cells to quantify the induction of initial

DNA damage as well as late effects such as the misrepair of double strand breaks. Well-characterised single ion microbeams of protons, alpha and ^{12}C-ions will be used to cover a range of relevant radiation qualities.

4.6. Publications (2011 – 2013)

1. H. Nettelbeck, H. Rabus, *Nanodosimetry: the missing link between radiobiology and radiation physics?,* Radiation Measurements 46 (2011), 893-897.
2. H. Rabus, H. Nettelbeck, *Nanodosimetry: bridging the gap to radiation biophysics,* Radiation Measurements 46 (2011), 1522-1528.
3. M. Bug; G. Hilgers; H. Nettelbeck; H. Rabus, *Ionisierende Strahlungswechselwirkung mit der DNS: Nanodosimetrie*, PTB-Mitteilungen: 121 (2011), 127-135.
4. H. Rabus, *Novel dosimetry concepts based on nanodosimetry*, Brazilian Journal of Medical Physics, S5 (2011) 45.
5. P. Lazarakis, U. Giesen, S. Schmeißer, F. Langner, B. Oborn, S. Guatelli, M. Gomolka, U. Kulka, H. Nettelbeck, H. Rabus and A. Rosenfeld, *The effect of a static magnetic field on single cells under ion irradiation – integrating a magnet with a single-ion microbeam*, Proc. 10th International Workshop: Microbeam Probes of Cellular Radiation Response, (2012) 31-32.
6. M. Bug, W. Y. Baek, H. Rabus, *Simulation of ionization clusters formed in nanometric volumes of the desoxyribose-substitute tetrahydrofuran,* International Journal of Radiation Biology 88 (2012), 137-142.
7. P. Lazarakis, M. Bug, E. Gargioni, S. Guatelli, S. Incerti, H. Rabus, A. B. Rosenfeld, *Effect of a static magnetic field on nanodosimetric quantities in a DNA volume,* International Journal of Radiation Biology 88 (2012), 183-188.
8. P. Lazarakis, M. U. Bug, E. Gargioni, S. Guatelli, H. Rabus and A. B. Rosenfeld, *Comparison of nanodosimetric* parameters *of track structure calculated by the Monte Carlo codes Geant4-DNA and PTra*, Physics in Medicine and Biology 57 (2012) 1231–1250.
9. Marion Bug, Hans Rabus, Anatoly Rosenfeld, *Electron emission from amorphous solid water after proton impact: benchmarking PTra and Geant4 track structure Monte Carlo simulations,* Radiation Physics and Chemistry 81 (2012) 1804-1812.
10. W. Y. Baek, M. Bug, H. Rabus, E. Gargioni, and B. Grosswendt, *Differential elastic and total electron scattering cross sections of tetrahydrofuran*, Physical Review A 86 (2012) 032702, 1-15.
11. H. Buhr, L. Büermann, M. Gerlach, M. Krumrey and H. Rabus, *Measurement of the mass energy-absorption coefficient of air for x-rays in the range from 3 to 60 keV*, Physics in Medicine and Biology 57 (2012) 8231–8247.
12. *M. Bug, E. Surdutovich, H. Rabus, A.B. Rosenfeld and A.V. Solov'yov, Nanoscale characterization of ion tracks: MC simulations versus analytical approach,* Eur. Phys. J. D 66 (2012) 291, 1-6. DOI: http://dx.doi.org/10.1140/epjd/e2012-30183-4.