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Applications of recombination chambers in the dosimetry of high energy radiation fields

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Abstract. High energy radiation fields exist in space, in the atmosphere at the height of commercial flights and in the vicinity of some accelerators. The characteristic features of these fields are their complex composition and broad energy spectrum. Estimation of the absorbed dose in such fields cannot be performed by consideration of the doses from all the radiation field components. The physically possible way to solve the problem is to determine the operational quantity-ambient dose equivalent H^* (10). The radiation detector used for the determination of H^* (10) should be large enough in order to simulate the ICRU sphere. Its effective wall thickness should not be very different than 10 mm of tissue. The REM-2 type recombination chamber is an example of such a detector.

The review paper presents specific challenges of high energy radiation field dosimetry and discusses a number of examples of measurements at high energy accelerators, including some international intercomparisons. We show that the REM-2 chamber is especially suitable for radiation monitoring in the vicinity of high energy accelerators.

Key words: initial recombination • ionization chambers • high energy radiation

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Introduction

According to the recommendations of the International Commission on Radiological Protection, ICRP [11], the quantity which should be used for limiting occupational exposure in mixed radiation fields is the effective dose, E, defined as:

$$E = \sum_T w_T \sum_R w_R D_{TR} \tag{1}$$

where D_{TR} is the absorbed dose due to radiation R, averaged over the tissue or organ T, w_R is the radiation weighting factor and w_T is the weighting factor for tissue T.

This paper is devoted to the dosimetry of high energy radiation fields. Here, high energy means energy above 10 MeV. All radiation fields formed by particles of such energies should be considered as mixed radiation fields, because even "pure" fields of high energy photon radiation are always contaminated by other particles, e.g. neutrons generated in (γ, n) nuclear reactions.

The upper limit of the "high energy" radiation is not defined and not important here. Particles of energies up to 10^{20} eV were observed in space radiation, but the energies of concern for practical radiation protection do not exceed the GeV range. The radiation hazard caused by particles of energies above a few hundred MeV is usually negligible, compared to that caused by particles of lower energies, even in the extreme cases of space flights or radiation in the vicinity of TeV accelerators.

Charged particle beams extracted from accelerators can be monoenergetic, but outside the beam, especially behind the accelerator shields, they always generate mixed radiation fields, composed of different particles featuring broad, usually unknown, energy spectra.

The number of different kinds of radiation near high energy accelerators can be very large, if particles of different rest mass or electrical charge are considered separately. It is obvious that not all of them contribute significantly to the radiation hazard, but many of them do, so the determination of the effective dose, E, according to the definition given by ICRP becomes unrealistic for two reasons. First – it is not possible to determine the doses in human organs D_{TR} separately for each kind of radiation. Second – the values of the weighting factors w_R have been specified by ICRP only for a few kinds of radiation. For other radiations, the ICRP suggests that the w_R values should be calculated basing on absorbed dose and radiation quality factor values in all organs of interest. Up to now, such calculations were performed only for neutrons and for pions in a limited energy range. No information is available for other radiations.

A more realistic approach involves the determination of an operational quantity-ambient dose equivalent, $H^*(10)$, which is the product of the absorbed dose $D^*(10)$ and of the quality factor Q^* which is defined as a function of the linear energy transfer, LET. Both quantities are determined at a depth of 10 mm in a special phantom – the ICRU sphere, defined by the International Commission on Radiation Units and Measurements, ICRU, [13]. $H^*(10)$ can be determined, without analysis of the radiation composition and spectra, by measuring $D^*(10)$ and Q^*, using the detector which simulates the ICRU sphere. The REM-2 type recombination chamber is an example of such a detector [28].

Another specific feature of the high energy radiation fields is that usually they are pulsed, with relatively long time intervals between pulses, often above 10 s [20]. This may cause additional problems during measurement.

The next specific feature is that usually it is not possible to achieve charged particle equilibrium, CPE, in the active volume of any detector. However, this is not important where $D^*(10)$ or $H^*(10)$ are to be determined, because lack of equilibrium concerns both the detector and the ICRU sphere. Also for the phantom measurements, the lack of CPE does not play any important role.

Local recombination of ions

Local ion recombination is the recombination which occurs within a column or group of ions formed by one charged particle. This type of recombination occurs a short time after the primary ionization events, before the ion column spreads out due to diffusion and ion drift in the electrical field in the detector. Later, volume recombination may occur.

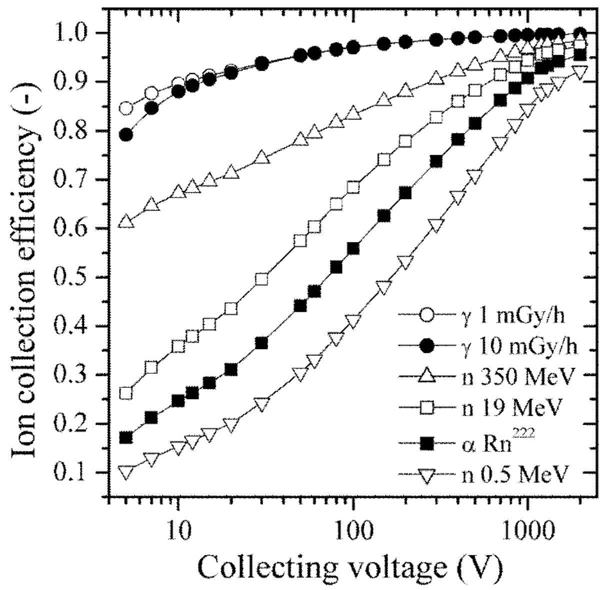

Fig. 1. Ion collection efficiency in REM-2 type recombination chamber.

Local recombination of ions does not depend on the dose rate, but it does depend on local ionization density in the track of the charged particle, thus it depends on LET (see Fig. 1), it can, therefore, be used for determination of the radiation quality factor. This kind of recombination dominates over volume recombination at gas densities of several kg/m^3, in ionization chambers with a relatively small gap between the electrodes (in the order of 1 mm) at electrical field strength above 1 kV/m, and provided that the absorbed dose rate in the gas is not too high.

It was shown earlier [3–5] that the ion collection efficiency, f, of the ionization chamber in which the local recombination occurs, can be described by a simplified formula:

$$f = \frac{1}{1+\mu\dfrac{1-f_{Cs}}{f_{Cs}}} \tag{2}$$

where μ is the relative local ion density of the considered charged particles, defined in such a way that $\mu = 1$ for gamma radiation in a reference radiation field of ^{137}Cs under conditions of initial recombination, f_{Cs}. Ion collection efficiency of the ionization chamber means here the ratio of the ionization current in the chamber at a given polarizing voltage to the saturation current. Values of f and f_{Cs} in Eq. (2) have to be determined at the same polarizing voltage. Equation (2) is a combination and generalization of theoretical relationships describing local recombination of ions in clusters [15, 16] and columns [14]. All the theories idealize, in different ways, the density distribution in tracks of charged particles. We term the parameter μ as relative local ion density but its physical meaning has not been specified precisely. It should be considered as a measurable quantity defined by Eq. (3), derived from Eq. (2):

$$\mu = \frac{1-f}{f}\cdot\frac{f_{Cs}}{1-f_{Cs}} \tag{3}$$

The quantity defined in this manner has a constant value for a given radiation (ionizing particles of given energy), if measured with an ionization chamber filled with pressurized gas at a definite range of density [4]. Therefore, it can be considered as a physical, measurable parameter which characterizes the radiation quality from the point of view of the ability of ions to recombine locally in charged particle tracks generated by this particular radiation.

In different theories of ionization energy deposition, the value of μ can be used as approximations of the following quantities:

– Ratio of the linear ionization density ν, of the considered ionizing particles to the mean linear ionization density of the standard gamma radiation ν_{Cs}:

$$\mu = \frac{\nu}{\nu_{Cs}} \tag{4}$$

Eq. (4) can be used at $\nu \geq \nu_{Cs} \approx 100$ ion pairs/μm H_2O.

– Ratio of the mean lineal energies $\bar{y}_d$:

$$\mu = \frac{\bar{y}_d}{(\bar{y}_d)_{Cs}} \tag{5}$$

The mean chord of the site, d, is in this case of about 25 nm, which corresponds to a sphere diameter of about 0.15 μm. Therefore, the dose mean lineal energy for ^{137}Cs gamma radiation is about 5 keV/μm [23].

– Ratio of the effective restricted LET of the considered particles and the reference radiation:

$$\mu = \frac{\bar{L}_\Delta}{(\bar{L}_\Delta)_{Cs}} \tag{6}$$

with the cut-off $\Delta \approx 500$ eV [19] or $\Delta \approx 70$ nm [24] if the cut-off is expressed in units of length. Effective restricted LET means here the mean value of restricted LET weighted by the transferred energy, taking into account the primary particle and delta electrons with energy $E_\delta > \Delta$, which are considered as the separate particles associated with the primary ones.

– Ratio of unrestricted LET of the considered particles and of the reference radiation:

$$\mu = L/L_0 \quad \text{for } L \geq L_0 \equiv L_{Cs} = 3.5 \text{ keV/μm} \tag{7}$$

$$\mu = 0.85 + 0.15(L/L_0) \quad \text{for } L < L_0 \tag{8}$$

– Ratio of the numbers of ion pairs generated in a micro-site with the mass of about 1 fg crossed by a particle track in the radiation fields of the considered and reference radiations:

$$\mu = v/v_{Cs} \tag{9}$$

– Ratio of the proximity function $T(x)$ [12] for the considered and reference radiations.

$$\mu = \frac{T(x)}{T(x)_{Cs}} \tag{10}$$

at $x = 70$ nm.

The equations given above may result in somewhat different values of μ for the same, well defied radiation. For example, if Eqs. (4) and (7) are used for particles with very high LET, then the resulting μ values will differ by about 10%, because of the difference in energy per ion pair for low- and high-LET particles [26]. Such inaccuracy is usually acceptable in radiation protection. Therefore, for the particles of a given energy, the relative local ionization density μ can be estimated without measurements, using any of Eqs. (4)–(10), at least for the needs of radiation protection. In radiation fields of unknown composition, μ can be determined experimentally from Eq. (3), using a recombination chamber. However, in this case determination of μ is not usually necessary, because the recombination chamber enables determination of other, more suitable parameters characterizing the radiation quality.

Recombination chambers and methods

Recombination chambers are detectors (mainly ionization chambers) in which the phenomenon of local recombination of ions occurs and is used for dosimetric measurements [28]. In dosimetric recombination methods, the recombination chambers are used for the determination of basic parameters of radiation fields, such as radiation quality factor, absorbed dose and dose equivalent in a specified point in a phantom placed in the radiation field. Also operational quantities like $H^*(10)$, $Q^*(10)$ and a number of other parameters can be determined by recombination methods [4, 6, 27]. There are over 20 recombination methods developed up to now. Almost all of them are based on the determination of ion collection efficiency. Especially important are methods which enable the radiation quality factor to be determined from measurements of the recombination index of radiation quality (RIQ, Q_R). The RIQ is defined as the ratio of the efficiency of local recombination in the considered and reference radiation fields [27]:

$$Q_R = \frac{1-f}{R} \tag{11}$$

where $R = 1 - f_{Cs}$ is the recombination efficiency in the reference radiation field.

The dependence of RIQ, with $R \approx 0.04$, on LET well approximates the function of LET defining the "old" quality factor $Q^{(21)}(L)$ [10] (Figs. 2–4), so the values of RIQ have been used as a measure of $Q^{(21)}$ for over 30 years, until the 1990-ties. When the new dependence $Q(L)$ was introduced by ICRP in 1991 [11], also new recombination methods, such as the recombination microdosimetric method (RMM) [3, 4] or extrapolation recombination method (ERM) [25] became more important, but the methods based on the RIQ concept are still successfully used, after appropriate modification.

Recombination chambers can be of very different design, depending on the expected area of application. Few tens of different chambers were designed up to now for three main groups of measurements:

1. In-phantom recombination chambers. Examples are shown in Fig. 5.
2. Cylindrical recombination chambers for the determination of dosimetric parameters in radiation beams (Fig. 6).

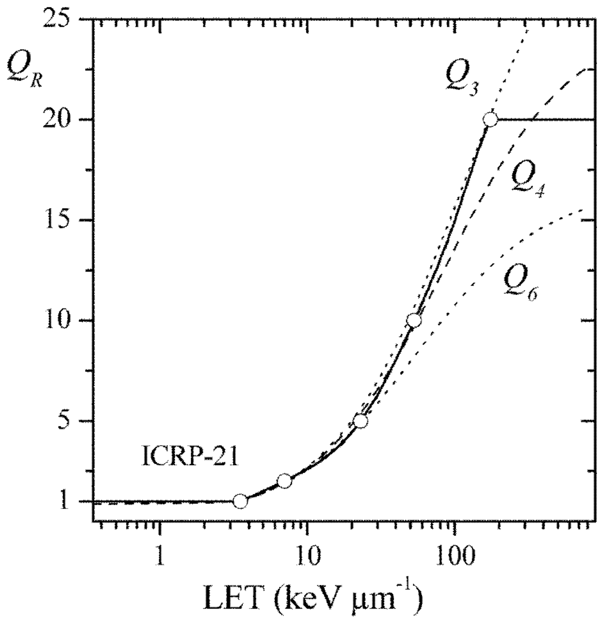

Fig. 2. Dependence of the recombination index of radiation quality Q_R on LET, in comparison with the $Q^{(21)}(L)$ function recommended in the ICRP-21 Report.

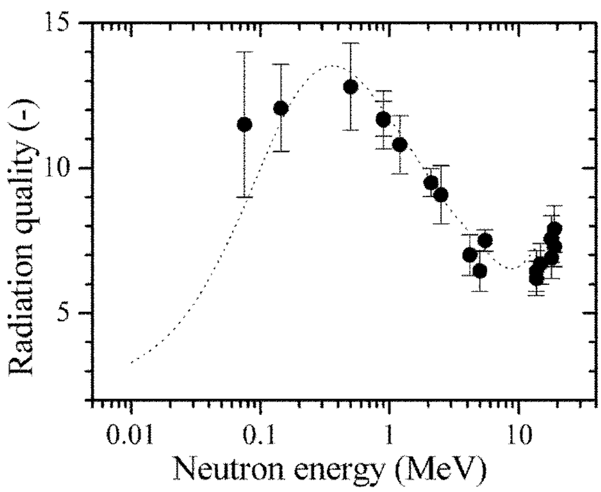

Fig. 3. Comparison of recommended values of Q (ICRP-21) and experimental values of Q_4 for monoenergetic neutrons.

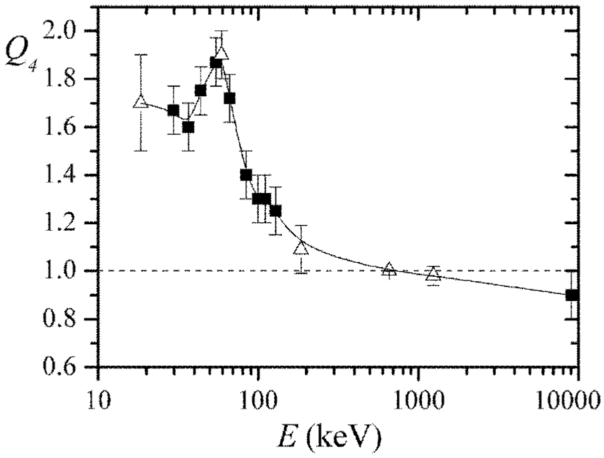

Fig. 4. Q_4 of photon radiation plotted as a function of gamma radiation energy for isotopic sources (△) and of mean energy of X-ray radiation (■).

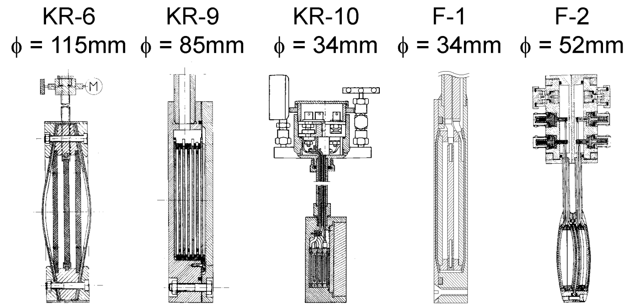

Fig. 5. In-phantom recombination chambers (type and diameter of active volume ϕ indicated).

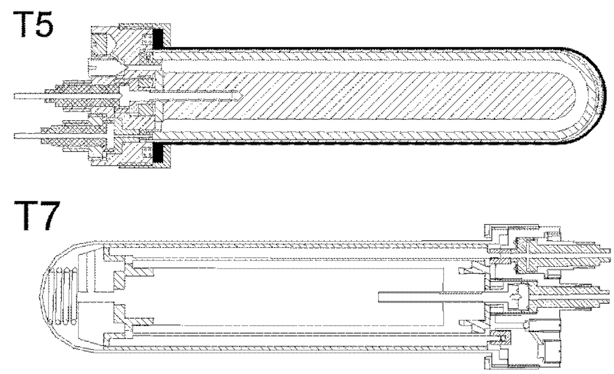

Fig. 6. Cylindrical recombination chambers.

3. Recombination chambers simulating the ICRU sphere, used mainly for the determination of ambient dose equivalent $H^*(10)$. An example is the REM-2 type chamber (Fig. 7) which was manufactured by POLON Bydgoszcz. The chamber approximates well the absorption and scattering features of the ICRU sphere, because of its large total mass of 6.5 kg, of which about 1 kg is the mass of 25 tissue equivalent electrodes defining the active volume of the chamber. The effective thickness of the chamber varies from 0.5 g/cm^2 to a few g/cm^2 depending on the direction of the incident radiation, so it is not much different than the depth of 1 g/cm^2 specified in the definition of $H^*(10)$. The atomic compositions of the walls, electrodes and fill gas do not differ considerably from the material of the ICRU sphere either.

An example of the method for determining $H^*(10)$ using the chamber simulating the ICRU sphere is described below.

The chamber is placed in the investigated radiation field. Two voltages U_S and U_R are applied consecutively to the chamber electrodes and the ionization currents $i_S \equiv i(U_S)$ and $i_R \equiv i(U_R)$ are measured. Prior to these measurements, the chamber should be calibrated in a reference gamma radiation field. The voltage U_S should ensure ion collection efficiency $f_{S_{Cs}} \equiv f_{Cs}(U_S) > 0.99$. The voltage U_R is chosen in such a way that:

$$0.03 < R' = 1 - \left(\frac{i_R}{i_S}\right)_{Cs} < 0.05 \tag{12}$$

During the calibration, also the calibration factor N is determined:

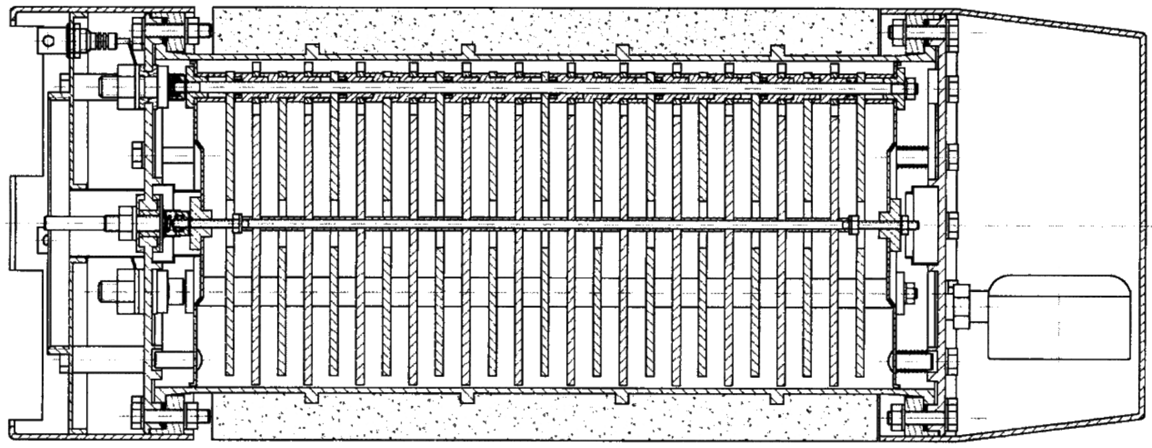

Fig. 7. Cross section of REM-2 recombination chamber.

$$N = \frac{D^*(10)_{\mathrm{Cs}}}{i_{S_{\mathrm{Cs}}}} \tag{13}$$

The dose equivalent rate in the investigated field is determined as:

$$H^*(10) = N \cdot i_S \cdot Q_i \cdot g \tag{14}$$

where $Q_i = (1 - i_R/i_S)/R'$ is the radiation quality index determined by a particular chamber; g is a correction factor dependent on the composition and energy of the radiation and also on the design of the recombination chamber. It may be assumed that the factor g can be expressed as a function of the parameter Q_i, only:

$$g(Q_i) = 1 - \beta(Q_i - 1) \tag{15}$$

The value of β is determined from the measurements of Q_i in the reference radiation field of a ^{239}Pu-Be neutron source at a point where the value of $H^*(10)$ is known.

Occasionally, correction of the directly measured values of the ionization currents i_R and i_S are needed, in order to take into account the influence of the leakage current, polarization effects, volume recombination and other side effects. Usually, a radiation monitor is needed for precise determination of i_R/i_S in the radiation fields at high energy accelerators.

Examples of measurements for radiation protection

This section shortly describes the measurements of ambient dose equivalent and quality factors in high energy radiation fields, performed using recombination chambers.

Synchrophasotron 10 GeV

Figure 8 displays the values of the quality factor measured in the building of a 10 GeV proton synchrotron at the Joint Institute for Nuclear Research in Dubna, JINR. Measurements were performed using a double ionization chamber, which made it possible to measure the ionization currents i_R and i_S simultaneously [17]. The obtained quality factor values were in the range between

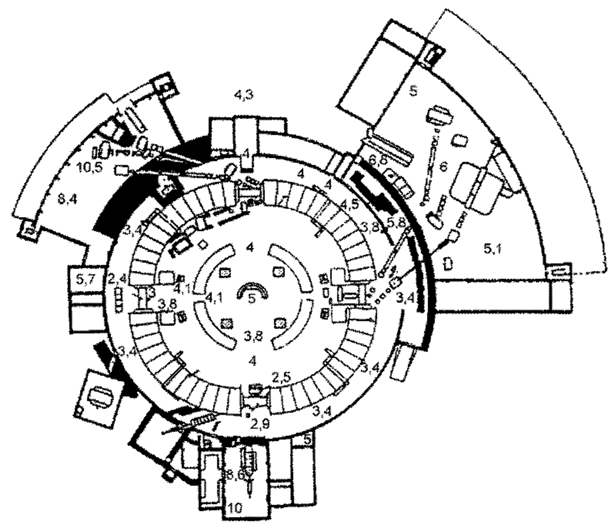

Fig. 8. Values of radiation quality factor, $Q^{(21)}$, in the 10 GeV synchrophasotron building.

3 and 10, depending on the site in the building, so a constant value of the quality factor could be associated with each working place. This facilitated the routine radiation protection as only the absorbed dose had to be monitored in the subsequent measurements.

Synchrocyclotron 660 MeV

Measurements with the recombination chamber were performed behind the steel shields of thicknesses between 0.5 and 2 m, to which a 660 MeV proton beam was directed. The results [31] show that the quality factor practically did not depend on the shield thickness, provided it is larger than the proton range. Later, the same conclusions were derived by computation.

High altitude civil flights

A set of three large recombination chambers was used as a three channel LET spectrometer for the determination of the quality factor and the dose equivalent at high altitudes. Measurements were performed for the CONCORDE project at the stage of aircraft design. Another chamber, named SUCHONA, was designed in the Soviet Union and used for similar purposes. Unfortunately, the results have not been published.

Accelerators at European Organization for Nuclear Research, CERN

Recombination methods have also been used for measuring the dose equivalent over different areas at CERN since 1965. A number of recombination chambers was used – among them the C2 and C3 chambers which were designed at CERN [28], KR-3 and G5 chambers [28] developed at the Institute of Atomic Energy, Otwock-Świerk and REM-2 type chambers which were purchased in Poland by CERN.

From the practical point of view, very important were the measurements at the antiproton accumulator (AA), performed in the conditions of simulated break down. Following these measurements, some areas earlier inaccessible for radiation safety reasons, could be made available.

Another important location was the so-called PS bridge, where the beam energy reaches a few GeV and radiation pulses are extremely short (24 ns up to 2 μs). In such strongly pulsed beam, the recombination chamber appeared to be very advantageous, compared with other available instrumentation [20].

15 MV medical accelerator

Medical linear accelerators accelerate only electrons which are directed to a target in order to generate the photon beam for patient irradiation. In principle, the therapeutic beams should contain only photons but, in practice they are slightly contaminated with neutrons, generated by photon-neutron nuclear reactions. This concerns practically all the accelerators operating with maximum photon energies of 10 MeV or higher. Outside the beam, the neutron contribution to $H^*(10)$ increases with the distance from the beam axis.

Measurements of $H^*(10)$ were performed in the treatment room of the Varian Clinac 2300C/D at the Oncology Center in Warsaw, with the accelerator producing photons with energy up to 15 MeV. The photon beam was collimated over an area of 10 × 10 cm² at a distance of one meter from the target. The measured neutron contribution at distances larger than 1.5 m from the isocenter, constituted over 50% of $H^*(10)$ [7]. The radiation quality factor at distances over 3 m from the beam axis was equal to 6.5 Sv/Gy.

Procedure room for 200 MeV proton therapy

Measurements of the ambient dose and ambient dose equivalent were performed near the phantom (Fig. 9) irradiated by 200 MeV protons in cabin No. 1 of the JINR phasotron [29]. Results of measurements are displayed in Fig. 9. All the values of the ambient dose equivalent rate were normalized to the absorbed dose rate of 1 Gy/min in the Bragg peak. The ambient dose equivalent near the phantom (or the patient) is in the order of a few hundred μSv during one therapeutic irradiation.

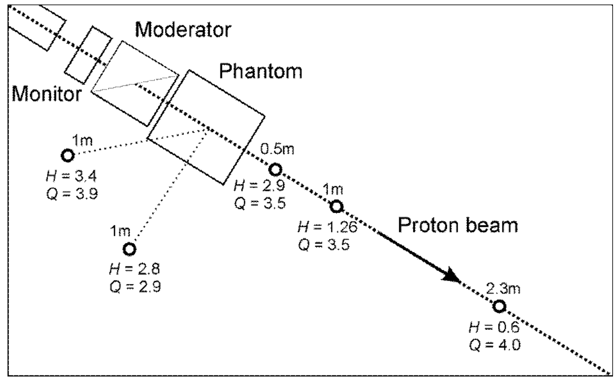

Fig. 9. 200 MeV proton therapeutic procedure room and values of H^* (10) and Q^*.

It can be expected that more extensive measurements, performed at different settings of the beam parameters, should clearly indicate areas in the cabin where $H^*(10)$ value will be well below 1 mSv. Therefore, it would be possible to allow assistance to the patient during irradiation in some special (extreme) cases where such assistance is justified for medical or psychological reasons.

Measurements in high-energy particles beams of specified energy

The main goal of the measurements performed in the beams of high energy particles was to verify experimentally calculations of the quality factor and dose equivalent in phantoms. This was especially important at the time of the early development of computational methods, when cross sections for high energy particle interactions with matter were known with rather poor accuracy.

209 MeV protons

Figure 10 shows the layout of the measurements performed [32] with the recombination chamber in a phantom irradiated by protons with the energy of 209 ± 9 MeV from the JINR synchrocyclotron in Dubna. The phantom, with dimensions 1 × 1 × 0.3 m³, was filled with tissue equivalent liquid and simulated an infinite wall of 0.3 m in thickness, such as assumed in Monte Carlo calculations [21]. The measured value of the quality factor at a depth of 5 cm (Q = 1.4) and of the absorbed dose to proton fluence ratio (D/Φ =

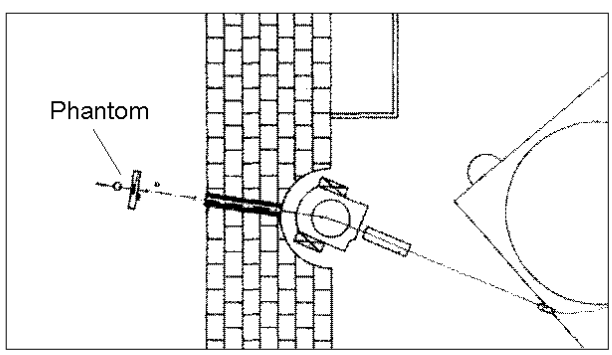

Fig. 10. Measurements layout of 209 MeV proton beam.

81 ± 8 fGy·m^2) were in good agreement with the calculated values (Q = 1.36, D/Φ = 86 fGy·m^2). Large disagreement was, however, observed at a distance of 28 cm, i.e. exceeding the proton range. The measured value of the quality factor was over 5 times higher than the calculated one. The reason was that neutrons generated in the phantom had not been taken into account during the calculations. This practically did not influence the results at distances shorter than the proton range but for larger distances, the results were incorrect.

Pions π^-

The in-phantom parallel-plate recombination chamber, with electrodes spaced no further than 2 mm, is a very convenient detector for precise determination of the absorbed dose and quality factor depth distributions in phantoms irradiated for pion radiobiology studies. The measured [22] $Q^{(21)}$ value was equal to 2.1 in the plateau of the depth distribution, 5.6 in the Bragg peak and 6.0 behind the peak (2.5 cm). The dose rate in the Bragg peak was about three times higher than that in the plateau region, mainly due to the energy of pion stars formed at the end of the particle range.

Neutrons with energies of hundreds MeV

Depth and radial distributions of the absorbed dose and of the recombination index of radiation quality were determined several times in phantoms irradiated with high energy neutrons from the JINR synchrocyclotron and phasotron, e.g. using the in-phantom recombination chamber of the F1 type [5]. The RIQ values at depths 10–20 cm, where a broad maximum of the absorbed dose is formed, was equal to 3.3 ± 0.3 for the beam with the average energy $E_n \approx 350$ MeV (Be target) and about 3.8 for the beam with $E_n \approx 240$ MeV (Pb target). The results are in agreement with MC calculations performed for the same beams and measurement conditions.

Intercomparisons

Computational methods used for the determination of the detector response in terms of $H^*(10)$ at high energy yield results with considerable systematic uncertainty because the physical data needed for the calculations are still uncertain. Experimental assessments are also practically impossible because there are no reference radiation fields covering the necessary range of energies and kinds of radiations. Therefore, intercomparisons play an important role, where measurements of $H^*(10)$ are performed with different instruments at the same reference points. Recombination chambers were used in intercomparisons organized in more than 20 different radiation fields, among them at the JINR (Dubna), IHEP – Institute of High Energy Physics (Serpukchov), PTB – Physikalische-Technische Bundesanstalt (Braunschweig), CERN (Geneva), GSI – Geselschaft für Schwerionenforschung (Darmstadt) and INP – Institute of Nuclear Physics (Kraków). The intercomparisons gathered different numbers of participants – from only a few [1, 2, 8] to about 30 [9, 18].

In all the intercomparisons, the H^* (10) determined by recombination chamber (most often REM-2) was only slightly different from the average value resulting from all the measurements, performed with different detectors and methods.

Conclusions

The results presented above and analysis of the physical principles of the recombination chamber operation, confirm that recombination chambers, especially of the REM-2 type, can be applied as the reference detectors for the dose equivalent measurements in high energy radiation fields.

As mentioned above, there are several recombination methods and the choice between them depends mainly on the experimental conditions. Comparison of the results obtained with 11 different recombination methods [30] showed that the resulting $H^*(10)$ values differ within an acceptable margin of uncertainty, at least from the radiation protection point of view. Therefore, even the simplest recombination methods can be applied for the determination of $H^*(10)$ in high energy radiation fields.

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