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ON THE USE OF A RECOMBINATION CHAMBER FOR RADIATION MEASUREMENTS IN CERN-EU HIGH ENERGY REFERENCE RADIATION FIELDS

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Abstract — Ambient dose equivalent was determined in high energy reference radiation fields at CERN (CERF facility) using a recombination chamber and recombination methods developed in IAE. The chamber was also used for measuring the low LET background radiation which locally accompanies the fields at CERF. The measurements included determination of the absorbed dose and recombination index of radiation quality at different beam intensities. It was shown that the background might considerably influence the measurements of the absorbed dose, however, its influence on the ambient dose equivalent remains important only at low beam intensities.

INTRODUCTION

A CERN-EC reference radiation facility for the calibration and intercomparison of dosimetric devices in high energy stray radiation fields has been available at CERN since 1993(1). The facility (called now CERF) provides the reference neutron fields that are similar to the cosmic ray field encountered at 10–20 km altitude. The facility is set up at one of the secondary beams (H6) from the 450 GeV Super Proton Synchrotron (SPS) in the North Experimental Area of CERN. The stray radiation fields are created by positive or negative hadron beams with momentum of either 120 or 205 GeV/c. The hadron beams are incident on a copper target and produce secondary particles which then pass through a shielding made up of either 80 cm of concrete or 40 cm of iron. Rather uniform reference radiation fields (mostly neutrons) exist in four experimental areas of 2×2 m^2 behind the shielding. A detailed description of the CERF facility can be found elsewhere(1–6) and in several other papers listed therein. At present, the facility provides well-defined exposure locations. The neutron spectral fluences were calculated for all the reference positions by the Monte Carlo method using the latest version of the FLUKA code(2,3). Other dosimetric parameters were determined in several international measurements campaigns, using a number of different techniques.

This paper briefly presents an experimental procedure used for determination of ambient dose equivalent, H*(10) with the recombination chamber of the REM-2 type(7,8) as well as the most important results obtained. Special attention is devoted to the problem of 'background' radiation, because of its practical importance.

In several cases, the comparison of the results obtained at CERF with different detectors was considerably disturbed by the influence of some low LET radiation(4–6) which locally accompanied the radiation originating from the CERF target. This background radiation is composed mainly of high energy muons and electrons and is not controlled from the CERF area. If not taken into account, it appears as an apparent non-linearity of a detector response when measurements are performed at different intensities of the incident hadron beam. This concerns ionisation chambers, TEPC counters and other devices which have considerable sensitivity to low LET radiation.

The REM-2 chamber was therefore used for measurements of the background radiation in order to complete the information available for the CERF facility users. The absorbed dose and the recombination index of radiation quality(9,10) were measured at different intensities of the hadron beam. The data obtained showed for which conditions and for what kind of measurements the background radiation should be taken into account.

MEASUREMENTS

As mentioned above, there are four areas at the CERF facility where the detectors can be placed. Two of the areas are on the roof of the beam line shielding — either on the concrete or iron cover. Each of the roof areas is divided into 16 squares (numbered from 1 to 16) of 50×50 cm^2. Each element of these 'grids' represents a reference exposure location. Two other areas (each consisting of 8 squares) are behind the lateral shielding of the irradiation cave at the same angles with respect to the target as for the two roof positions. Shielding of these side positions is either 80 cm or 160 cm of concrete. For convenience, the measuring locations are denoted(11) with letters C (concrete), I (iron), T (top) and S(side). For example, the code CT6 (concrete top 6) means the location number 6 on the concrete roof shield.

The time characteristic of the field has a pulsed structure with a pulse length of 2.6 s and a repetition time of 14.4 s. It was observed that background radiation passes over the roof together with the beam pulse.

The REM-2 recombination chamber, manufactured in Poland by POLON-Bydgoszcz is a cylindrical, parallel-plate ionisation chamber with 25 tissue-equivalent electrodes. It has a volume of 2000 cm^3, mass of 6 kg and an effective wall thickness of about 2 $g.cm^{-2}$. The chamber is filled with a mixture of methane and nitrogen (5%) at a pressure of about 1 MPa. Before the measurements, the chamber was calibrated(4) in the CERN calibration facility in the reference radiation field of a ^{137}Cs source.

All the measurements described here concern the hadron beam with the momentum of 120 GeV/c. The intensity of the beam was monitored by an air-filled precision ionisation chamber (PIC) at atmospheric pressure, placed in the beam just upstream of the target and connected to a current-digitising circuit. One PIC count corresponds (within ±10%) to 2.2×10^4 particles(2).

EXPERIMENTAL RESULTS

Measurements of ambient dose equivalent

The output signal of the recombination chamber is the ionisation current as a function of collecting voltage (the saturation curve). The chambers are operated in such a way that the ion collection efficiency is governed by the initial recombination of ions which depends on the local ion density and can be related to the absorbed dose distribution versus LET. The measurement of the ionisation current was performed at 10–15 collecting voltages and further mathematical analysis of the saturation curve(12–14) enabled separation of low LET and high LET dose fractions and determination of H*(10) according to the Q(L) relationship given in the ICRP 60(15) recommendations.

Table 1. Ambient dose equivalent rates (according to ICRP 60) on top of the concrete roof shield at a hadron beam intensity of about 4800 PIC counts per pulse. The values are in nSv per PIC count. The cells of the table are numbered according to the scheme of the measuring locations at CERF.

CT1	CT5 0.3 ± 0.05	CT9	CT13
CT2	CT6 0.325 ± 0.05	CT10 0.34 ± 0.05	CT14
CT3	CT7	CT11 0.34 ± 0.05	CT15
CT4 0.20 ± 0.04	CT8 0.27 ± 0.05	CT12 0.29 ± 0.05	CT16 0.24 ± 0.04

The results of measurements performed on the concrete roof shield at the hadron beam intensity of about 4800 PIC counts per pulse are presented in Table 1 according to the numbering scheme of the reference positions at CERF. For the side location CS2 the measured H*(10) (0.5 ± 0.06 nSv per PIC count) was significantly higher than for any CT location, whereas the absorbed doses are comparable (0.103 and 0.113 nGy per PIC count, for CT6 and CS2 locations respectively). The difference in H*(10) between side concrete and top concrete locations is, therefore, mainly due to the difference in radiation quality factor and can be well explained by the presence of the background radiation at CT locations (see next section).

At the IT6 position on the iron roof shield, the H*(10) was equal to 1.55 ± 0.2 nSv per PIC count, again at an incident beam intensity of about 4800 PIC counts per pulse. The absorbed dose was equal to 0.18 nGy per PIC count. The higher H*(10) value compared to the CT6 position can be mainly attributed to a much larger contribution from neutrons with energies between 0.1 and 1 MeV(1,2).

H*(10) at the IS2 location behind the thick (160 cm) concrete wall was equal to 0.04±0.008 nSv per PIC count.

All the above results are in good agreement with the values measured by the HANDI TEPC(11) which is considered as a reference instrument for the facility.

Background radiation

Figure 1 presents the results of the measurements performed at the CT6 location at different intensities of the incident hadron beam. It can be seen that the value of the absorbed dose per PIC count exhibits a non-linear dependence on the beam intensity for the location on the roof shield, while the same quantity is constant for the side location. The effect is clearly related to the presence of the background radiation. When the same data (from Figure 1) are presented relative to the total absorbed dose per pulse (rather than per PIC count number) the dependence on PIC count becomes linear

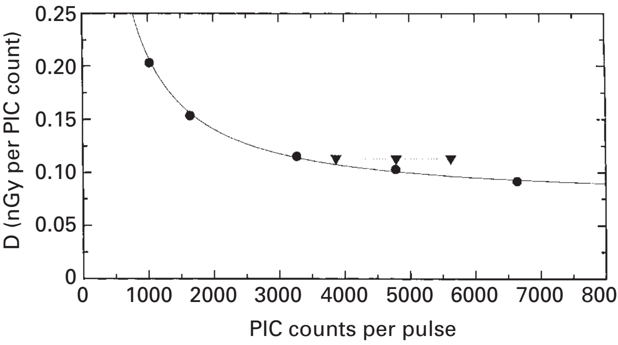

Figure 1. Total absorbed dose per PIC count for top concrete CT6 (circles) and side concrete CS2 (triangles) locations, measured at different intensities of the hadron beam on the target.

(see Figure 2) and the background radiation can be determined as a component independent of the beam intensity.

The absorbed dose (per beam pulse) due to the background radiation, D_B, determined from Figure 2 was equal to 137 ± 7 nGy per pulse at the time of measurements (September 1997). This value compares well with the value of $D_B = 140 \pm 20$ nGy per pulse estimated from previous measurements performed in September 1993(4).

The influence of the background radiation was not pronounced at the side location CS2.

The measurements on the concrete roof shield were repeated in April 1998 and resulted in the value of $D_B = 125 \pm 10$ nGy per pulse for the CT6 location. The background radiation dose rate measured on the iron shield on the same day but not simultaneously was $D_B = 165 \pm 10$ nGy per pulse for the IT6 location.

The background radiation also influences the composition of the radiation field. For the purposes of the background characterisation this influence could be observed by measuring the H*(10) at one beam intensity and the recombination index of radiation quality, Q_4, at several intensities. Such a procedure is much faster than direct determination of H*(10) for all beam intensities since the ionisation current has to be measured for each intensity only at two collecting voltages.

The Q_4, which is an LET-dependent quantity(10,13) is measured according its definition(9) as:

$$Q_4 = \frac{(1 - f(U_R))}{(1 - f(U_R))_{cal}} \qquad (1)$$

where $f(U_R)$ is the ion collection efficiency in the chamber operated at a specially chosen recombination voltage U_R(10) below saturation.

With reasonable approximation, the dependence of Q_4 on LET can be expressed(13) as:

$$Q_4 = \frac{1}{D} \int q_4(L)\, d(L)\, dL \qquad (2)$$

with

$$q_4(L) = \frac{L/L_0}{1 + 0.04(L/L_0 - 1)} \text{ for } L \geq 3.5 \text{ keV.}\mu\text{m}^{-1} \qquad (3)$$

and

$$q_4(L) = 0.85 + 0.15\, L/L_0 \text{ for } L < 3.5 \text{ keV.}\mu\text{m}^{-1} \qquad (4)$$

where L is the linear energy transfer (LET); $L_0 = 3.5$ keV.μm^{-1}; D is the absorbed dose and $q_4(L)$ and $d(L)$ are the differential distribution of the Q_4 and dose versus LET.

The influence of the background on the composition of the CERF radiation fields is illustrated in Figure 3 where the measured values of Q_4 are presented for different beam intensities and for two measuring locations (CT6 and CS2). It can be seen that the Q_4 value is constant for the side location, while at the top location it increases non-linearly with the increasing beam intensity.

The Q_4 is an additive quantity(9) and can be expressed as:

$$Q_4 = Q_{4T} - (Q_{4T} - Q_{4B})\,\frac{D_B}{D} \qquad (5)$$

where D_B, Q_{4B} and D_T, Q_{4T} are the absorbed dose and Q_4 values for the background and target radiation, respectively.

The Equation 5 enables the experimental determination of the Q_{4T} and Q_{4B} values from the measurements of Q_4 by plotting them as a linear function of D_B/D with $D_B = 137$ nGy per pulse earlier derived from the fit shown in Figure 2. The procedure resulted in the values of $Q_{4T} = 3.35$ and $Q_{4B} = 1.22$. The value of Q_{4T} obtained was equal to the value of Q_4 measured at the side location CS2, therefore it seems to be truly associated with the radiation coming from the target.

The value of ambient dose equivalent of background radiation calculated as $H^*(10)_B = D_B Q_{4B}$ was equal to

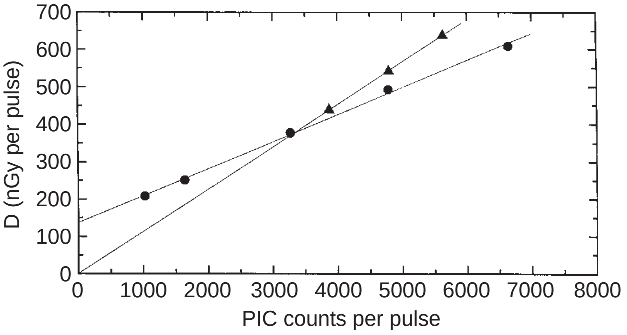

Figure 2. Total absorbed dose per radiation pulse measured at different intensities of the beam on the target. The results are given for the CT6 location on concrete roof (solid circles) and for the CS2 side location (triangles).

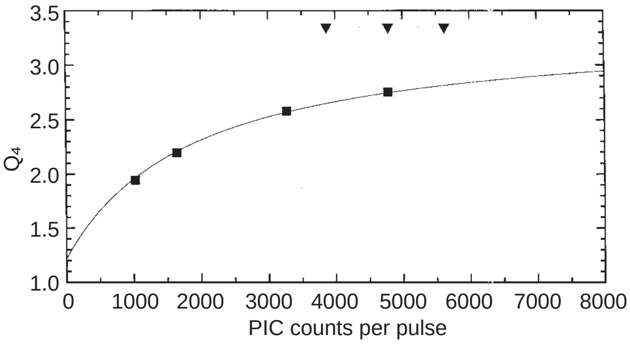

Figure 3. Recombination index of radiation quality Q_4 measured at different intensities of the hadron beam on the target. Circles, CT6 location on the concrete roof. Triangles, side location CS2.

160 ± 30 nSv per pulse and 200 ± 30 nSv per pulse for the CT6 and IT6 locations, respectively.

The experimental data given above were used for calculation of the H*(10) per PIC count for different beam intensities as$^{(16)}$:

$$H^*(10) = D\,Q^* = D\,(xQ_{4B} + (1 - x)cQ_{4T}) \qquad (6)$$

where x is the dose fraction due to the background radiation determined from the additivity of Q_4 as:

$$x = \frac{Q_{4T} - Q_4}{Q_{4T} - Q_{4B}} \qquad (7)$$

and

$$c = \frac{Q_{eff}}{Q_{4T}} = \frac{H^*(10) - H^*(10)_B}{D\,(Q_4 - XQ_{4B})}$$

is the ratio of the effective quality factor for the target radiation to the Q_{4T} value derived from the measurements of H*(10) values given in Table 1. The results are shown in Figure 4.

Comparison of Figures 1 and 3 shows that the increase of the absorbed dose per PIC count at low beam intensities is accompanied by some decrease of the Q_4. This mitigates the dependence of H*(10) on the hadron beam intensity so far that the H*(10)/PIC value becomes practically constant at a beam intensity above 3000 PIC counts per pulse (see Figure 4).

A similar extrapolation method was earlier applied to the data from a tissue-equivalent proportional counter$^{(5)}$. The content of each of its 16 channels logarithmically spaced in lineal energy y was plotted against the beam intensity of the 205 GeV/c hadron beam hitting the copper target. Extrapolation to zero intensity yielded the background spectrum with an upper limit in lineal energy of 10 keV.μm^{-1}. Its absorbed dose rate was found to be 60 nSv per beam pulse on the concrete shielding and 80 nSv per beam pulse on the iron shielding. The higher muon background could be expected in present measurements, as at 205 GeV/c the beam consists of approximately 2/3 protons and only 1/3 pions compared with about 2/3 pions and 1/3 protons for the 120 GeV/c beam.

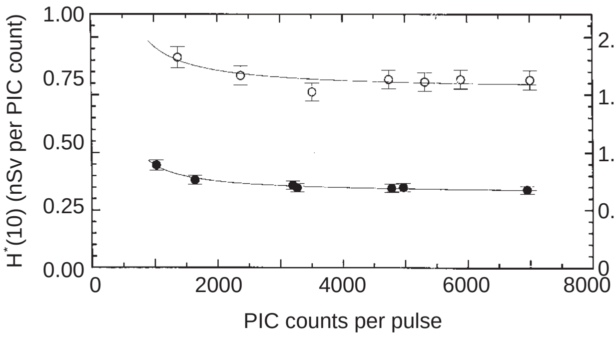

Figure 4. H*(10) for CT6 (solid circles, left scale) and IT6 (open circles, right scale) locations in dependence on the hadron beam intensity on the target.

DISCUSSION AND CONCLUSIONS

Recombination chambers have been used in dosimetry of mixed radiation fields for rather a long time (since the middle sixties) but the method of the H*(10) determination is relatively new$^{(12,13)}$ and was intensively tested in recent years. The measurements at the CERF facility, together with the measurements in monoenergetic neutron beams of lower energies$^{(8)}$ confirmed the usefulness of the method for radiation protection purposes. The comparison of all the active detectors used in the experiments at CERF is still in preparation but it can be already seen that all the results obtained with the REM-2 chamber are in good agreement with the reference values.

The measurements of background radiation showed that its contribution to the absorbed dose was considerable for the concrete and iron roof shields. Therefore, the usual way to present the results of measurements at CERF as related to the number of the PIC monitor counts can be misleading if the incident beam intensity is not indicated.

The measurements at the CT6 location were repeated several times during the five year period. The background dose rate during all the measurement cycles with positive hadron beams (120 GeV/c) was equal to D_B = 130 ± 20 nGy per pulse. This means that, for example, even at the rather high intensity of 5000 PIC counts per pulse, the background component D_B constitutes over 25% of the total dose, almost 40% of the low LET dose and about 10% of the total ambient dose equivalent for the CT6 measuring location on the concrete roof shield.

The background dose rate on the iron roof shield (IT6 location) was measured only once and the value of D_B = 165 ± 10 nGy per pulse was recorded. No influence of the background radiation was observed for the CS2 side location.

The presence of the background radiation increases the total absorbed dose but decreases the radiation quality factor (or radiation weighting factor). Because of the inverse correlation between changes of these two quantities, the influence of the background on the ambient dose equivalent remains important only at low beam intensities. At the hadron beam intensities over about 3000 PIC counts per pulse, the total value of the H*(10) can be considered as being independent of the beam intensity for most of the practical applications.

The measurements presented here together with our earlier measurements of Q_4 and H*(10) performed during the five year period$^{(4,13)}$, indicated that the background component was stable in time within 20% even at the time when the distribution of the primary beam between secondary lines was undergoing some considerable changes. Nevertheless, the observed stability could be apparent and generally there is not enough information on the question of the possible variations of this component in time. In any case the use of the recombination chamber enables fast estimation of the actual background. Because of its excellent stability over time[8] and no service requirements the REM-2 chamber is also well suited to serve as an additional monitor of the total dose rate.

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