CHARACTERISATION OF IONISATION CHAMBERS FOR A MIXED RADIATION FIELD AND INVESTIGATION OF THEIR SUITABILITY AS RADIATION MONITORS FOR THE LHC

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Monitoring of the radiation environment is one of the key tasks in operating a high-energy accelerator such as the Large Hadron Collider (LHC). The radiation fields consist of neutrons, charged hadrons as well as photons and electrons with energy spectra extending from those of thermal neutrons up to several hundreds of GeV. The requirements for measuring the dose equivalent in such a field are different from standard uses and it is thus necessary to investigate the response of monitoring devices thoroughly before the implementation of a monitoring system can be conducted. For the LHC, it is currently foreseen to install argon- and hydrogen-filled high-pressure ionisation chambers as radiation monitors of mixed fields. So far their response to these fields was poorly understood and, therefore, further investigation was necessary to prove that they can serve their function well enough. In this study, ionisation chambers of type IG5 (Centronic Ltd) were characterised by simulating their response functions by means of detailed FLUKA calculations as well as by calibration measurements for photons and neutrons at fixed energies. The latter results were used to obtain a better understanding and validation of the FLUKA simulations. Tests were also conducted at the CERF facility at CERN in order to compare the results with simulations of the response in a mixed radiation field. It is demonstrated that these detectors can be characterised sufficiently enough to serve their function as radiation monitors for the LHC.

INTRODUCTION

Radiation fields typically encountered at high-energy hadron accelerator are composed of many different particle types with energies ranging from fractions of eV up to a few GeV. Naturally, it is of vital importance to thoroughly study the response functions of monitoring devices to these so-called mixed radiation fields in order to assess their suitability for a radiological surveillance system. For the Large Hadron Collider (LHC) at CERN, a modern state-of-the-art radiation monitoring system for the environment and safety (RAMSES) will be implemented using different kinds of detectors. At present, it is foreseen to install high-pressure ionisation chambers in areas where the ambient dose-equivalent is present because of highly energetic, mixed radiation fields. To verify the choice of these monitors, an exemplary study was performed to characterise the response of high-pressure, argon- and hydrogen-filled ionisation chambers (IG5), manufactured by Centronic Ltd (Centronic Limited, Centronic House, Croydon CR9 0BG, UK), to mixed radiation fields. These monitors are now used at CERN's accelerators.

Since the current calibration procedure (using ^{137}Cs, ^{60}Co, ^{238}Pu–Be sources) does not accurately account for the sensitivity of the chambers in an environment with a different energy spectrum and particle population, independent, complex measurements are normally performed to characterise each field the chambers are used in and to deduce a specific so-called field quality factor. Taking this additional factor into account the ambient dose-equivalent can be determined for any kind of radiation environment. Since the radiation field to be expected around the LHC is unavailable at present, Monte Carlo simulations provide the only means for the evaluation of the suitability of high-pressure ionisation chambers as radiation monitors for the LHC and for calculating an appropriate field calibration factor. The particle transport code FLUKA(1,2) was used to calculate particle-specific response functions extending over a wide range of energy(3,4). For the validation of the results, comparisons to calibration measurements using monoenergetic neutrons and photons of various selected energies were performed(4,5). Subsequently, experiments in a known mixed radiation environment were conducted at the CERN–EU high-energy reference field (CERF) facility(6,7), providing a radiation field similar to the one occurring behind LHC shielding walls. Corresponding Monte Carlo calculations were carried out to demonstrate whether the behaviour of the monitors in mixed radiation fields can be simulated with sufficient precision allowing the calculation of appropriate field calibration coefficients.

MEASUREMENTS AT THE CERF FACILITY

The CERN–EU high-energy reference field facility

At the CERF facility a beam with a momentum of 120 GeV c^{-1} and a composition of 61% pions,

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35% protons and 4% kaons originating from a primary Super Proton Synchrotron (SPS) target, is directed to a secondary copper target. This cylindrical target with a diameter of 7 cm and a length of 50 cm, can be installed inside a cave under concrete or iron shield. The cycle period of the SPS beam is 16.8 s, of which 12 s are used to accelerate the beam to its nominal energy. In the remaining 4.8 s, the beam is extracted on the aforementioned primary target. For a detailed description of the facility (see Ref. (6)).

Experimental set-up

For the experiment, sets of three argon-filled IG5-A20 and three hydrogen-filled IG5-H20 ionisation chambers were used, in order to investigate the dependence of the results on the production series of the devices and the electronics. As shown in Figure 1, the monitor consists of a cylindrical steel shell with a spherical head. It contains two similarly shaped electrodes, delimiting an active volume of 5.2 litre filled with argon, or hydrogen, gas pressurised at 20 bar. The bottom of the chamber is sealed by a base plate, with a cylindrical steel case attached to it, containing the required electronics. Of the exposure locations available at CERF two positions on the top and two positions at the side of the 80-cm-thick concrete shield (Table 1) were used.

The side position CS2 and the top position CT6/T10 were chosen because in FLUKA simulations and former measurements(8,9) these positions show the maximum dose rate among all available locations outside the cave. Every monitor placed in one of these two positions has the same distance from the centre of the chamber to the beam axis. Hence, the readings were expected to be comparable. Another top location (CT4) was selected to allow cross-checking with previous studies(6,8). Additionally, a second side position (CS-50U) was used, as a softer neutron spectrum is expected in regions upstream of the target.

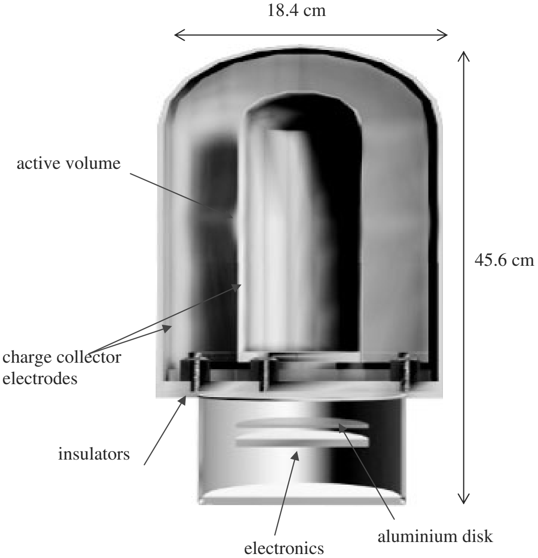

Figure 1. Geometry of the IG5 ionisation chamber as implemented in the FLUKA simulations.

The monitoring of the beam intensities at CERF is typically performed using an air-filled precision ionisation chamber (PIC) at atmospheric pressure, which is located upstream of the CERF target. The beam intensity is given in PIC counts per beam extraction, which is proportional to the number of particles impinging on the target during a period of 4.8 s. The calibration factor has been determined to be equal to $2.3 \times 10^4 \pm 10\%$ particles per count(6). Beam intensities were selected by adjusting two collimators located upstream of the CERF experimental area in the H6 beam-line.

In order to study the influence of different ionisation chamber production series, all measurements were performed subjecting each chamber to a permutation of exposure locations during the experiments conducted in July and August 2003. For each monitor, the charge produced in the active volume per beam extraction was recorded as a function of beam intensity and measurement position. Extrapolation of the recorded signal for an intensity of zero PIC counts yielded the contribution due to neutron background from the neighbouring beam-line and muon background originating from pion decay upstream in the H6-line(6,8).

Measurement results

All monitors showed significantly higher readings at the side location CS2 than on top of the shield (see Figure 2 for an argon-filled chamber). This can be explained by neutron backscattering due to an additional concrete wall placed behind the side

Table 1. Exposure locations used for the IG5 chambers at CERF

Abbreviation	Description
CS2	Concrete side position 2
CS-50U	Concrete side position, 50 cm upstream of the target front face
CT4	Concrete top position 4
CT6/T10	Boundary of concrete top position 6 and 10

The abbreviations, as given in the first column, will be used throughout this paper

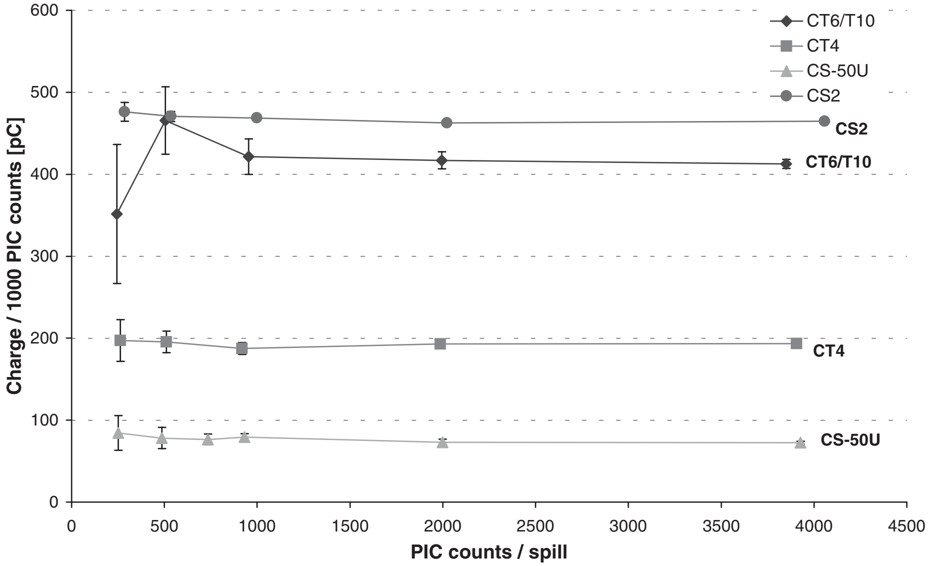

Figure 2. Charge per 1000 PIC counts created in the argon-filled chamber Ar-1 at various measurement locations as a function of PIC counts per spill.

measurement locations in order to shield the experiment control room.

Furthermore, the argon-filled ionisation chambers showed a significantly higher response than the hydrogen-filled ones regardless of the measurement position. Taking the response curves obtained by Monte Carlo simulations into account (see below) this effect can be understood by the high sensitivity of argon-filled chambers with respect to charged particles and high-energy neutrons. Further details on the results of the measurements can be found in Ref. (7).

MONTE CARLO SIMULATIONS

Calculation of the response functions

All calculations were carried out using the 2002 version of the Monte Carlo code FLUKA$^{(1,2)}$. The cascade simulations were based on a detailed treatment of the hadronic and electromagnetic shower induced in the chamber by an extended, parallel beam of monoenergetic particles of a certain type. The beam particles that were studied comprised photons in the energy range from 48 keV up to 1 GeV, electrons, protons, charged pions and neutrons with energies ranging from thermal energies up to 5 GeV. Lateral irradiation, perpendicular to the symmetry axis of the chamber, was performed using a disc-source covering the whole chamber. Secondary hadrons, except neutrons, were transported down to 100 keV, whereas neutrons were treated down to thermal energies. The electromagnetic cascade was simulated in detail down to kinetic energy thresholds of 200 and 10 keV for electrons/positrons and photons, respectively.

The calculated energy deposition in the active volume was converted into charge by applying the average energy required to produce an e^{-}–ion pair (*W*-factor)$^{(10)}$ given in Table 2.

For neutrons, the value strongly depends on the interaction processes and thus on the gas medium involved. As no unique neutron *W*-factor is available for argon gas the value for proton recoil was adopted for both gases, following the approach chosen for preliminary studies$^{(3)}$. It should be kept in mind that this simplification might contribute to deviations in the calculated response from measured values. Taking the area of the beam spot into account, the sensitivity of the chamber is obtained in terms of charge per unit fluence or charge per unit dose-equivalent after the application of appropriate fluence-to-dose-equivalent conversion factors$^{(11,12)}$. The calculated results for photons and neutrons were benchmarked with measurements using monoenergetic beams and as shown in Figure 3 for photon irradiation, good agreement was found in most cases. The energies used for the photon benchmarks ranged from 48 keV up to 1.33 MeV. In the case of neutron irradiation, the respective energies extended from 565 keV up to 14.8 MeV and good agreement was found for the hydrogen-filled chambers. However, for the argon-filled monitors some discrepancies were found that require further investigation$^{(4)}$.

Simulation of the experimental set-up

The FLUKA Monte Carlo transport code was used to score particle fluence spectra at the corresponding measurement locations, using a simplified cylindrical geometry[(13)] as well as a detailed model of the CERF experimental area[(14)]. In the first case, the complexity was drastically reduced by simulating the copper target surrounded by a cylindrical concrete shield, but retaining the actual dimensions, such as the thickness of the shield (80 cm), as well as the distance between the beam axis and the shield. Furthermore, a source routine was implemented to sample the spatial distribution of a beam with a momentum of 120 GeV c^{-1}, as a two-dimensional gaussian with a standard deviation of 1.3 cm in horizontal and 1.0 cm in vertical direction. For both set-ups, the beam composition was sampled corresponding to a mixed beam of 61% pions, 35% protons and 4% kaons. It should be noted that the ionisation chamber was not included in the detailed geometry but instead only the particle fluence spectra were scored in air volumes of a size of 50 cm × 20 cm × 20 cm at the exposure locations. In the case of the simplified geometry, the respective spectra were obtained in a 20-cm-thick cylindrical binning outside the concrete shell, which corresponds approximately to the diameter of the ionisation chambers.

Table 2. Average energy required to produce an ion pair.

Source particle	Argon (eV)	Hydrogen (eV)
Photon	26.40	36.50
Neutron	26.66	36.43

(W-factor) taken from Ref. (10). Values are given for two source particle types in argon and hydrogen gas. For charged particles such as pions and electrons the same values as for photons were adopted

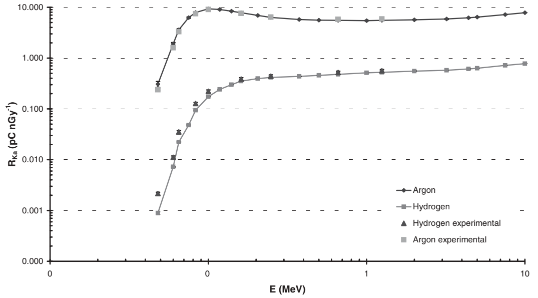

Figure 3. Calculated response R_{Ka} to photons expressed in terms of created charge per unit kerma for argon- and hydrogen-filled IG5 chambers. Experimental data measured with different calibration sources are also shown.

Convoluting the particle fluence spectra with the corresponding calculated response functions of the respective particles, expressed in terms of charge per unit fluence, yields the amount of created charge within the active chamber volume for each exposure location. Consequently, the total amount of produced charge per beam extraction can be obtained by summing over all considered particle types and normalising to the number of particles per extraction ($2.3 \times 10^4 \pm 10\%$). The result can be directly compared to the experimental values. The convolution was performed using the response functions of neutrons, protons, pions and photons as the contribution of electrons outside the shield to the response is of minor importance and can be neglected.

RESULTS

Calculating the ratio of the theoretical and the experimental values for various positions yielded the results given in Table 3.

As can be seen for the simplified geometry good agreement within the uncertainties was found for the CT6/T10 position. However, large deviations were obtained for the CS2 side location. This is owing to the fact that the additional shielding wall between the side measurement locations and the CERF control room was not taken into account in the cylindrical set-up. Thus, the contribution of scattered particles to the monitor readings, that is owing to these concrete blocks, was neglected. This additional concrete wall was considered in the simulations of the detailed geometry, thus leading to a better agreement with the experimental results.

For the position CT4, the cylindrical approximation results in an overestimation with respect to the measured value. This is owing to the fact that in the simplified model the distance travelled by the particles in the concrete shield is represented correctly

Table 3. Ratio of the simulation results and the experimental values for the created charge within the active volume of the IG5 chambers at different exposure locations.

Position	Ratio—Ar simplified geometry	Ratio—Ar detailed geometry	Ratio—H simplified geometry	Ratio—H detailed geometry
CS2	0.83 ± 18%	1.02 ± 19%	0.79 ± 12%	1.11 ± 14%
CT6/T10	1.02 ± 18%	1.00 ± 20%	1.09 ± 13%	1.10 ± 13%
CS-50U	0.95 ± 23%	1.21 ± 33%	0.86 ± 14%	1.38 ± 21%
CT4	1.42 ± 13%	1.05 ± 17%	1.47 ± 13%	1.14 ± 15%

The results are given for both chamber types using either the simple or the detailed geometry model in the simulation only for the CS2 and the CT6 position, whereas in reality the particles traverse a large amount of shielding before reaching the CT4 measurement location. Generally, good agreement is found with the detailed geometry for all positions outside of the shield, except for the overestimated upstream position CS-50U. The latter can be explained by the fact that during the measurements the ionisation chamber was oriented with the head facing upstream. Hence, in the upstream position CS-50U, the monitor was exposed to particles entering from the rear, i.e. penetrating the base plate. The sensitivity for exposure from the rear is lower than that for lateral irradiation(4). Since the calculated spectra were convoluted with the response functions for lateral irradiation, the obtained simulation results were overestimated with respect to the measured values.

CONCLUSIONS

This study demonstrates that the Monte Carlo code FLUKA can be used successfully to simulate the response of hydrogen-filled high-pressure ionisation chambers to mixed radiation fields. In the case of argon-filled chambers the results for mixed radiation fields dominated by high-energy neutrons look promising. However, further investigation is required as the experimental benchmarking of their calculated response to low-energy neutrons showed discrepancies that are not yet fully understood(4). In most cases the difference between measured and calculated value is <20% for both monitor types. Consequently, FLUKA simulations can be used to determine the field quality factors of the mixed fields at high-energy accelerators to obtain correct results for the ambient dose-equivalent. The study confirmed that high-pressure ionisation chambers, in particular, the hydrogen-filled monitors, might fulfil the task of measuring ambient dose-equivalent in the mixed radiation fields of the LHC. In future, the study will be extended to other gas types like nitrogen or methane.

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REFERENCES

1. Fassò, A., Ferrari, A. and Sala, P. R. *Electron–photon transport in FLUKA: status*. In: Proceedings of the Monte Carlo 2000 Conference, Lisbon, 23–26 October, 2000. Kling, A., Barao, F., Nakagawa, M., Tavora, L. and Vaz, P., Eds. (Berlin: Springer-Verlag) pp. 159–164 (2001).
2. Fassò, A., Ferrari, A., Ranft, J. and Sala, P. R. *FLUKA: status and prospective for hadronic applications*. In: Proceedings of the Monte Carlo 2000 Conference, Lisbon, 23–26 October 2000. Kling, A., Barao, F., Nakagawa, M., Tavora, L. and Vaz, P., Eds. (Berlin: Springer-Verlag), pp. 955–960 (2001).
3. Otto, T. *Preliminary simulation results for the sensitivity of Centronic high-pressure ionisation chambers*. CERN Technical Note TIS-RP-2002-011-RP-TN (Geneva: CERN) (2002).
4. Theis, C., Rettig, M., Roesler, S. and Vincke, H. *Simulation of the response functions of Centronic high-pressure ionization chambers using FLUKA*. CERN Technical Note SC-2004-23-RP-TN (Geneva: CERN) (2004).
5. Hess, A. *Détermination de la réponse de chambres d'ionisation prévues pour la surveillance du LHC*. Thesis, CERN/Haute Ecole Specialisee du Suisse Occidentale (2002).
6. Mitaroff, A. and Silari, M., *The CERN–EU high-energy Reference Field (CERF) facility for dosimetry at commercial flight altitudes and in space*. Radiat. Prot. Dosim. **102**, 7–22 (2002).
7. Theis, C., Aguilar, N., Pangallo, M., Perrin, D., Renou, M., Roesler, S. and Vincke, H. *Centronic high-pressure ionization chambers measurements in the mixed radiation field of the CERF facility*. CERN Technical Note TIS-2003-024-RP-TN (Geneva: CERN) (2003).
8. Mayer, S. *Dose equivalent measurements in mixed and time varying radiation fields around high-energy accelerators*. CERN doctoral thesis, CERN-THESIS-2003-012 (2003).
9. Dimovasili, E. and Silari, M. *Beam and reference field monitoring during the 2002 CERF run*, CERN Technical Note TIS-RP-2002-033-RP-TN (Geneva: CERN) (2002).
10. International Commission on Radiation Units and Measurements. *Average energy required to produce an ion pair*. ICRU Report 31 (Washington, DC:ICRU) (1979).
11. International Commission for Radiological Protection. *Conversion coefficients for use in radiological protection*. ICRP Publication 74 (Oxford: Pergamon Press) (1997).
12. Pelliccioni, M. *Overview of fluence-to-effective dose and fluence-to-ambient dose equivalent conversion coefficients for high energy radiation calculated using the FLUKA code*. Radiat. Prot. Dosim. **88**, 279–297 (2000).
13. Theis, C., Roesler, S. and Vincke, H. *Comparison of the simulation of Centronic high-pressure ionization chambers to measurements in the mixed radiation field of the CERF facility*. CERN Technical Note SC-2004-24-RP-TN (Geneva: CERN) (2004).
14. Vincke, H. *Benchmarking of the simulation of the ATLAS hall background*. Ph.D. thesis. CERN/Technische Universitaet Graz, Austria (2000).