PERFORMANCE REQUIREMENTS FOR MONITORING PULSED, MIXED RADIATION FIELDS AROUND HIGH-ENERGY ACCELERATORS

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Abstract
In preparation of the installation of a radiation monitoring system for the future LHC and its injectors comprehensive studies were performed to evaluate the suitability of different existing monitors for radiation protection measurements in pulsed and complex, mixed radiation fields. Different ionisation chambers were exposed to a mixed, high-energy reference field and it was shown that the results agreed well with Monte-Carlo calculations. In addition the chambers were exposed to short, high-intensity radiation pulses, where recombination effects and the capability of the electronics to process a high number of charges within very short time were studied in detail. These results are being used to optimize the design of the read-out electronics. Moreover, the results demonstrate that the investigated chambers are well suited to measure ambient dose equivalent and dose rates in these fields up to certain limits from where on recombination corrections should be taken into consideration.

INTRODUCTION

The monitoring of ionising radiation around high-energy accelerators like the Large Hadron Collider (LHC) and its injectors represents a major technical and metrological challenge due to the complex composition of the radiation field and the time structure of the pulsed particle beams. The radiation monitoring system RAMSES# [1] foreseen for LHC and its injectors has to meet these very specific physics requirements as well as the regulatory requirements of current radiation protection legislations. A state-of-the-art system has to be installed with the performance suitable for future certification by an authorised metrological institution.

Therefore it is essential to understand the response of the monitors to the various radiation fields and to demonstrate that the relevant quantities like ambient dose equivalent and ambient dose equivalent rate are reliably measured. At present, international standards exist only for monitors in conventional radiation fields, the outcome of the study will be provide an input into setting standards for ambient dose equivalent measurements in pulsed, mixed radiation fields around high-energy accelerators.

This paper gives an overview on the studies of the radiation monitors envisaged to be used by RAMSES for the radiation protection part; a description of the overall RAMSES can be found in reference [1].

RADIATION FIELDS AND MONITORS

The so-called prompt, mixed radiation fields around high-energy accelerators are composed of charged hadrons (protons, pions, kaons, etc.), neutrons, leptons (electrons, positrons, muons) and photons. The energies of these particles range from fractions of eV to several GeV. The particle and energy composition of the fields at a given point in or outside the accelerator tunnel depends strongly on its position with respect to the location of the beam loss and the shielding used. As a general rule radiation fields around high-energy accelerators are similar to cosmic radiation fields in the atmosphere. The time behaviour of the radiation fields follows the time structure of the pulsed particle beam. The pulse lengths depend on the accelerators and their various beam modes and range from some few nanoseconds to seconds with repetition times of some tens of nanoseconds up to several tens of seconds.

A thorough market survey revealed that no detector system from the shelf will be able to fulfil the special CERN needs. The radiation monitors that are in use at CERN's existing accelerators seem to be the most promising candidates for a reliable radiation monitoring of pulsed, mixed radiation fields. The detectors are ionisation chambers equipped with special, read-out electronics developed in-house. In a first step three types of monitors were studied in detail: a 3 litre, non-confined air ionisation plastic chamber (PMI, manufactured by PTW, Type 34031), operated under atmospheric pressure and 5.2 litre steel chambers filled with 20 bar of hydrogen or argon (Centronic IG5-H20 or IG50-A20).

PHYSICS PERFORMANCE OF IONISATION CHAMBERS IN PULSED, MIXED RADIATION FIELDS

The ionisation chambers were exposed to various stray radiation fields at CERN. The comparison between experiments and Monte Carlo simulations for the detector response was performed at the CERN-EU High Energy Reference Field Facility CERF [2], the influence of the ion recombination mechanism on the detector response was studied in the target area of the Antiproton Decelerator (AD) and close to the beam dump of the Proton Synchrotron Booster (PSB).

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#RAMSES: Radiation Monitoring System for Environment and Safety

Response to Mixed Radiation Fields

The CERN experimental facility CERF provides well-defined and well-known mixed radiation fields. A solid copper target (50 cm long, 7 cm in diameter) is irradiated by a mixed hadron beam of 120 GeV/c. Due to the slow extraction, the beam pulse had a length of 4.8 s, the repetition rate was 16.8 s and the beam intensity varied between 6×10^6 and 9×10^7 particles/pulse. The detectors were exposed to various radiation field compositions either close to the target inside the shielded area or behind shielding (80 cm of concrete). The experimental results were compared to Monte Carlo simulation, using the FLUKA code [3, 4].

In the following the study of the response of the PMIs to the mixed fields will be described as an example. Six PMI detectors were installed at CERF in close vicinity to the target. The detectors were arranged such, that the average energy of the radiation field composition increased continuously from position 1 to 6.

The simulations show that the energy deposition in the PMI chambers (see Fig. 1) originating from neutrons decreases continuously from 40 % (Pos. 1) down to 2 % (Pos. 6). The contribution of charged hadrons increases continuously from 14 % (Pos. 1) up to 35 % (Pos. 6). From Pos. 3 to 6 the electron/positron component contributed most to the energy deposition. Although neither the total number of particles nor the transported energy to the various detector positions was dominated by electrons and positrons, the detector response was strongly influenced by these particles because of the high linear energy loss of electrons/positrons at high energies (above 100 MeV) in air and which are dominating at these positions.

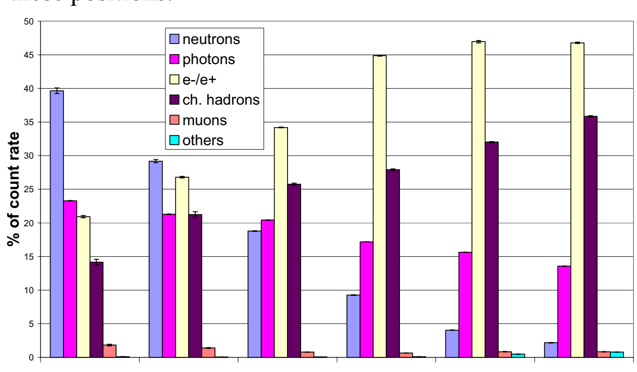

Figure 1: Relative contribution of the various particles to the energy deposition in the active volume of the PMI chambers.

An excellent agreement between the experimental and theoretical results was found. It is within the measurement uncertainties (10 to 15 %).

As most of energy deposition calculations for the LHC are performed for energy deposited in air it was of interest to study for the same radiation fields the difference between the energy deposited in the air filled plastic chamber and in pure air.

At the positions exposed to the low-energy part of the radiation field, the PMI detector experienced an up to 20 % lower energy deposition when compared to pure air. This is due to the absorption of low energy charged particles by the detector wall material. At the high-energy positions the PMI detectors experience a higher energy deposition of up to 20 % when compared with pure air. This is mainly caused by the production of charged particles due to nuclear interaction between the incoming hadrons and the detector wall material.

At present, the PMI detectors are only used for radiation protection purposes when the beam is switched off to measure dose caused by activated accelerator components. The results of this study clearly demonstrate that these simple chambers can be also used to measure reliably the energy deposition in prompt, mixed radiation fields, i.e. with beam on. More details can be found in [5]. Therefore, the CMS (Compact Muon Solenoid) experiment at CERN is intending to use these chambers.

Similar experiments were performed with the high pressure ionisation chambers IG5 at CERF. The radiation fields were monitored at four different positions behind 80 cm of concrete shielding lateral to the target position. The composition of these radiation fields resembles the ones that will be experienced in the LHC underground areas accessible during LHC operation with beam. Also in case of the IG5 chambers the comparison between Monte-Carlo simulations and experiments showed good agreement [6].

Recombination effects

The reliability of dose measurements by ionisation chambers decreases with increasing recombination rate of the produced ion/electron pairs. Significant recombination and thus an underestimation of the dose will happen preferentially in case of high-intense, pulsed radiation fields where within a very short period of time a high charge concentration will be produced inside the gas of the ionisation chamber. To study the recombination effects PMIs and IG5 chambers (H- and Ar-filled) were exposed to the pulsed field on top of the PSB beam dump (protons of 1.4 GeV, 4 bunches of 150 ns within a pulse of 2.9 σs) and in the target area of the AD (protons of 26 GeV/c on a target, 5 pulses within 500 ns). The detectors were exposed to various radiation dose rates up to about 160 σGy/pulse at the PSB and up to 50 mGy/pulse at the AD. The 90 % ion collection efficiency level for the PMI chamber corresponds to 48 σGy/pulse (in air) and for the Ar chamber to about 13 σGy/pulse (in Ar) (see Fig. 2). According to the results of the experiments at the AD the 90 % level of the H chamber was measured at 250 σGy/pulse. The results were compared with theoretical predictions using the recombination model proposed by J.W. Boag recommended in ICRU 34 [7]: the chambers filled with air (PMI) follow the recombination model, the volume recombination of H chambers in neutron dominated fields follows the model, too. In case of the Ar chamber there was no agreement: the recombination started abruptly and seemed to be independent from the chamber geometry or the gas pressure.

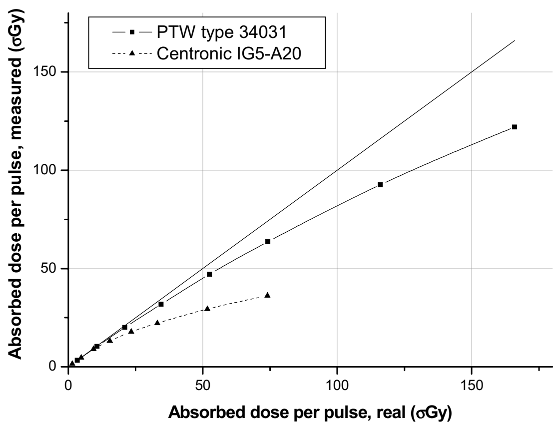

Figure 2: Measurement of the ion recombination effects at the PSB.

READ-OUT ELECTRONICS

The design of the read-out electronics of ionisation chambers in pulsed radiation fields is a demanding task, too. It must enable the accurate and stable measurement of both, very low currents (10^{-14} A) at natural background level and high currents at high radiation dose levels equivalent (10^{-5} A).

The measuring range of the existing CERN read-out electronics is limited to 5 to 6 decades depending on the measurement principle, electrometer or charge digitizer (Fig. 4) compared to the 9 decades required for the future RAMSES monitoring system.

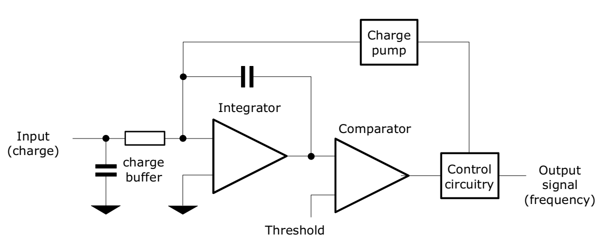

Figure 4: Charge digitizer.

Therefore, an optimisation of the read-out electronics has been performed in order to improve its capacity to process a high number of charges within a very short time interval. At the same time the adequate performances for very low current measurement have to be preserved. An adaptive charge digitizer had been developed according to the principle of Figure 5 with a single measuring range (no commutation) stretching from 10^{-14} A to 10^{-4} A. Preliminary tests have shown that this electronics is capable to measure charge pulses up to 300 nC/pulse (with 50 % of the charge collected in 2 ms) without requiring an additional input capacitor (charge buffer) which usually induces instabilities.

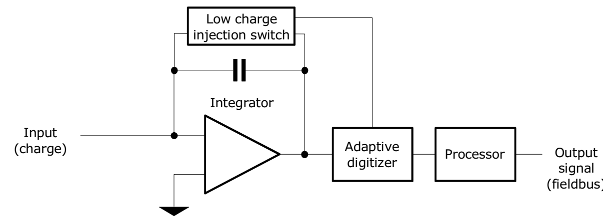

Figure 5: Adaptive charge digitizer.

CONCLUSION

Comprehensive studies were performed to quantify the response of ionisation chambers to pulsed, mixed radiation fields. The results demonstrate that the air filled PMI chamber and the high-pressure argon- and hydrogen-filled IG5 chambers are well suited to measure doses and dose rates in these fields up to certain limits above which recombination corrections should be taken into consideration. The agreement between experiments and Monte-Carlo simulations is excellent. Substantial progress was made in the design of the read-out electronics which is now able to cover a measuring range over ten decades without any commutation. In future the experiments and calculations will be continued (response to mono-energetic neutron beams) and extended to nitrogen-filled chambers as they may be used to replace the argon-filled IG5 chambers.

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