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University of Montreal

January 1996

GPP-HEP/003

**Particle Contamination Measurements around Hadron Beams used
for Irradiation of Silicon Detectors for the LHC.**

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Abstract

While LHC silicon detector prototypes were irradiated with pions and protons for radiation damage studies at Villigen-**PSI** and CERN-**PS**, the nearby beam contaminations by neutrons, protons and photons was measured by means of various activation foils and dosimeters. The estimated fluxes due to neutron and proton contamination are a few percents of the pion and proton fluxes given to the silicon detectors. In all cases, the low energy neutron component is found to be dominant.

SCU9612

*Presented at: RADECS 95, 3ème Colloque Européen, Radiations et leurs effets
sur les composants et systèmes, Arcachon, 18-22 Septembre 1995.*

I. INTRODUCTION

Detectors and associated electronic components used in high-level radiation environment are subject to radiation damage. An example of such an environment is provided by the Large Hadron Collider (LHC), where head-on collisions of 7 TeV protons at a peak luminosity of $1.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ will produce high fluences of particles. Irradiation tests will be performed at dedicated facilities to evaluate the damage to be expected at LHC. The measurement of the particle fluences and absorbed doses available at these facilities is necessary to establish a correlation between the nature of damage inflicted to a given material and the type and level of irradiation it has been exposed to. Two charged beams were used to study the radiation damage effects in silicon detectors: a high intensity beam of pions (π E1) at the Paul Scherrer Institute (**PSI**-Villigen) with a particle momentum of 350 MeV/c and a beam of protons at the Proton Synchrotron (**PS**) at CERN with a particle momentum of 24 GeV/c. The unavoidable contamination of these sources by other types of particles, generated by the interaction of the pion and proton beams with the Si samples and surrounding materials, yields a situation of mixed fields that contributes additional damage to the silicon samples under study.

For the first time, a direct confirmation of this contribution is obtained with a simultaneous irradiation of Si detectors and characterization of the radiation field. The particle fluxes and absorbed doses near the beam were measured with alanine, LiF dosimeters and activation of metal foils (via nuclear activation reaction in In, Co and Ni). The pion and proton fluxes on the beam axis were measured by activation of Al and C foils.

II. FACILITIES

A. PSI

The π E1 beam line at **PSI** [1] supplies high intensity pion and muon beams. Pions are produced in the collision of the intense proton beam (maximum current of $800 \mu\text{A}$) with a graphite target. They come out with momenta ranging from 100 to 450 MeV/c and are guided via a beam line down to the irradiation casemate. After the graphite target, the presence of a large number of protons is eliminated by means of graphite plate absorbers. At the irradiation position, the pion beam is polluted by muons and electrons. Damage in silicon by leptons can be neglected, being one order of magnitude lower compared with damage inflicted by hadrons [2].

Figure 1: Set-up of the experiment at **PSI**

B. PS

The **PS** is at the heart of the complex of the CERN accelerators. It provides dedicated beams to test detectors in a variety of conditions, such as the T7, T9, T10 and T11 test beams avail-

able in the **PS** East Hall. The **PS** measurements reported in this article were performed using the T7 beam line. It offers a primary beam with a momentum of 24 GeV/c with from one to two spills of protons delivered to the irradiation zone per supercycle. A spill consists of a burst of protons for typically 400 ns. Two consecutive spills are separated by at least 2.4 s during a 14.4 s supercycle. The maximum proton intensity is 2×10^{11} protons per spill. No beam pollution was expected since the beam is coming directly from the synchrotron.

Figure 2: Set-up of the experiment at **PS**

III. FLUX AND DOSE

A. Set-Up of the Experiments

At **PSI**, the irradiation position was located 1 m downstream of the last quadrupole magnet. The pion momentum was 350 MeV/c. At **PS**, the irradiation position was about 3 m downstream of the vacuum pipe and the proton momentum was 24 GeV/c.

An ionization chamber, a X-Y chamber and a luminescent screen were used to monitor both the π^+ beam at the **PSI** and the p beam at **PS**. The Si samples were mounted inside square cardboard frames. These frames were stacked,

normal to the beam direction, in a box volume of $5 \times 5 \times 25$ cm³. At the same time, aluminium foils cut to the same shape as the Si samples were interleaved with the tested material. The box was mounted on a table, mobile along the three space axes (x, y, z) in order to optimize its position in the beam.

1) Neutron Flux Measurements:

Indium (In), Cobalt (Co) and Nickel (Ni) activation foils [3] were placed at different positions along both transverse axes for measuring the neutron contamination near the π^+ and p beams. The positions are shown in Fig. 1 and Fig. 2. Indium activation foils were chosen because of their very large cross sections for neutrons of thermal energies up to a few MeV that allows to quantify this particular component of the contamination responsible for a large part of damage to Si. To complete the understanding of the neutron spectrum of the contamination, Ni and Co foils were used with their dominant activation cross section at neutron energies of a few MeV and a few tens of MeV, respectively.

2) Proton Flux Measurements:

Ni and Co foils were used to quantify the proton contribution at **PSI** and at **PS**, since they present some reactions that are exclusively proton reactions. The positions of the foils are shown in Fig. 1 and Fig. 2.

3) Photon and Hadron Dose Measurements:

LiF:Mg,Ti (TLD-700) dosimeters were used to measure the photon absorbed doses near the π^+ beam, as shown in Fig. 1. TLD-700 was selected, with its main component of ^7Li of high photon sensitivity and negligible neutron sensitivity. Polymer alanine dosimeters (PAD) were placed at the rear of the box in order to measure the pion

and proton absorbed doses in alanine in the beam line. They are the sole dosimeters which provide linearity in a very large dose range (up to 30 kGy) [4].

IV. RESULTS

The activation of aluminium foils by $^{27}\text{Al}(\pi^+, \text{xN})^{24}\text{Na}$ and $^{27}\text{Al}(p, 3pn)^{24}\text{Na}$ reactions allowed the measurement of the pion and proton fluences. Graphite foils, activated by $^{12}\text{C}(\pi^+, \pi\text{N})^{11}\text{C}$ and $^{12}\text{C}(p, pn)^{11}\text{C}$ reactions, were used to provide a cross-check of the pion and proton fluences given by the Al foils. The cross sections for these nuclear reactions in Al and C were taken from [5, 6] for pions and from [7] for protons. The results obtained with Al and C foils were in agreement within 5 %.

The pion fluxes measured at **PSI** by means of Al foils along the irradiation box are shown in Fig. 3, the calculated pion dose-rate in silicon at the maximum pion flux was (691.1 ± 52.3) Gy/h.

The proton fluence-rate measured at **PS**, by Al foils was equivalent to $(2.7 \pm 0.15) \times 10^9 \text{ p cm}^{-2} \text{ s}^{-1}$ and the proton dose-rate in silicon was (3.0 ± 0.16) kGy/h. The calculated value uses the concept of minimum ionizing energy loss [8].

A. Neutron Flux Measurements

The irradiations of the activation foils at both facilities were performed simultaneously with a group of Si samples. The irradiation time at **PSI** was 28920 s while at **PS** it was 7440 s.

After irradiation, the activation foils were removed and the induced activities were measured with a high purity Ge(p)- γ spectrometer.

The gamma spectra were analyzed by using the INTERGAMMA code [9] permitting the identification of a variety of

Figure 3: Pion fluxes at **PSI**

created nuclei.

A total of four radionuclei coming from neutrons, were identified at **PSI**: two nuclei from In ($^{116}\text{In}^m$, $^{115}\text{In}^m$), one nucleus from Ni (^{57}Ni), and one nucleus from Co (^{57}Co). A total of seven radionuclei coming from neutrons, were identified at **PS**: two nuclei from In ($^{116}\text{In}^m$, $^{115}\text{In}^m$), three nuclei from Co (^{57}Co , ^{58}Co , ^{56}Mn), and two nuclei from Ni (^{57}Ni , ^{58}Co).

The neutron fluxes were estimated by considering the cross sections associated to the most probable neutron energy at which the nuclear reaction can be produced. The estimated neutron fluxes are shown in Fig. 4 for **PSI**, and in Fig. 5 for **PS**. The cross sections were taken from [10].

1) Results at **PSI**:

As shown in Fig. 4, the estimated neutron fluxes are decreasing with the distance from the pion beam axis and are generally decreasing with increasing threshold neutron energies. The low energy neutron component appears to be almost independent of the distance from the pion beam. The statistical fluctuations of these fluxes at the

same distance from the beam are varying between 6% to 27% at 5cm and between 16% to 19% at 19 cm.

Figure 4: Estimated neutron fluxes near pion beam at **PSI**

2) Results at **PS**:

Fig. 5 shows the estimated neutron fluxes of four of the seven nuclear reactions found at **PS**. The low energy neutron component is almost independent of the distance from the proton beam and, in general, the estimated neutron fluxes are decreasing from a distance of 5 to 10 cm from the proton beam.

The statistical fluctuations of these fluxes at the same distance from the beam are varying between 11% and 35% (depending on the energy) at 5cm, and between 5% and 12% at 10 cm.

The errors associated to the estimated neutron fluxes at **PSI** and **PS** were calculated by taking into account the errors associated to the activities and weights of the foils. The error on

the activity is the dominant error.

Figure 5: Estimated neutron fluxes near proton beam at **PS**

Fig. 6 and Fig. 7 show the estimated number of neutrons per incident pion at **PSI** and the estimated number of neutrons per incident proton at **PS** as a function of the neutron mean energy of the nuclear reaction. The number of neutrons created per incident hadron is observed to decrease exponentially with the neutron energy at 5 cm from the hadron beam. At 19 cm and 10 cm, the number of neutrons created per incident hadron is following the inverse of the neutron energy. The figure also shows that the main component of the neutron spectra is made of neutrons of low energy at both irradiation facilities.

B. Proton Flux Measurements

A total of three radionuclei, coming from protons, were identified at **PSI**: one nucleus from Co (^{52}Mn), and two

nuclei from Ni (^{55}Co , ^{52}Mn), while at **PS** four radionuclei were identified: two nuclei from Co (^{52}Mn , ^{48}V), and two nuclei from Ni (^{55}Co , ^{52}Mn).

The proton fluxes were estimated by considering the cross sections associated to the most probable proton energy at which the nuclear reaction can be produced. The cross sections were taken from [7].

Figure 6: Estimated n per π^+ at **PSI**

1) Results at **PSI**:

No radionucleus was found at 19 cm from the pion beam. The results are obtained only from the radionuclei produced in the sample positionned at 5 cm from the beam. This is possibly due because protons have a smaller mean free path in air. At this distance from the pion beam, the estimated proton fluxes are decreasing with the proton threshold energy.

The ratios of the observed proton fluxes to the maximum pion flux given to the Si samples, at 5 cm are: (0.00861 ± 0.00325) proton per incident pion (p/π_{inc}) above 7.8 MeV up to 164.0 MeV, and (0.00158 ± 0.00089) p/π_{inc} above 40.0 MeV up to 370.0 MeV.

Figure 7: Estimated n per p at **PS**

2) Results at **PS**:

The estimated proton fluxes at **PS** are decreasing with the proton threshold energy, but the more important proton component is above 70 MeV.

The ratios of the observed proton fluxes to the main proton flux given to the Si samples, at 5 cm are: (0.01080 ± 0.00023) proton per incident proton (p/p_{inc}) above 7.8 MeV up to 164.0 MeV, (0.00612 ± 0.00131) p/p_{inc} above 40.0 MeV up to 370.0 MeV, and (0.01370 ± 0.00212) p/p_{inc} above 70.0 MeV up to 370.0 MeV. As it was the case for the estimated neutron fluxes, the errors associated to the proton fluxes estimated at **PSI** and at **PS** were calculated by taking into account the errors associated to the activities and weights of the foils. The error on the activity is again the dominant error. The activation nuclear reactions used for these measurements are exclusively proton reactions.

C. Photon and Hadron Dose Measurements

LiF dosimeters, read by a standard TLD reader, were giving the photon contamination at **PSI**. The aver-

age photon absorbed doses in LiF are: (5.0 ± 0.8) Gy/h at 10 cm, and (0.74 ± 0.03) Gy/h at 28 cm from the pion beam. It is observed that the photon dose fell by a factor 6 from the first to the second position.

The photon dose in Si were not determined, but by assuming that Si would replace LiF in the same field, the doses would not change very much. If the photons have a mean energy of less than 150 keV, the photon dose measured in LiF will be increased by a factor of (1.6 ± 0.4) for Si. Above 150 keV and up to 8 MeV, the dose in Si will be slightly decreased by a factor of (0.96 ± 0.04) compared with LiF. At energies above 8 MeV, this dose will be moderately increased by a factor (1.2 ± 0.05) . These factors (1.6, 0.96, and 1.2) were calculated by taking into account the electromagnetic energy per unit of exposure (roentgen) absorbed by the Si material [11].

The alanine dosimeters were measured through Electron Spin Resonance technique, giving the pion and proton dose-rates in alanine. At **PSI**, the measured pion dose-rate is equivalent to (337.0 ± 7.2) Gy/h in alanine and the corresponding calculated value that uses the concept of minimum ionizing energy loss is equal to (262.0 ± 13.6) Gy/h. At **PS**, the measured proton dose-rate is (3.4 ± 0.08) kGy/h in alanine and the corresponding calculated value is equal to (3.2 ± 0.18) kGy/h.

The fact that the measured pion and proton dose-rates in alanine are larger than those calculated can be explained by the presence of other type of particles (neutrons, electrons and photons) that contribute to the dose-rate.

V. CONCLUSIONS

At **PSI**, the additional fluxes due to the contamination from neutrons and protons are a few percents of the main

pion flux. The neutron contamination does not depend strongly on the energy at 5 cm from the pion beam and follows an exponential shape. At 19 cm, it is strongly dependent on energy following the inverse of the neutron energy ($1/E$) and the low energy component dominates. Proton contamination was found only at 5 cm from the pion beam and the fluxes are decreasing as a function of the proton energy. The average photon doses measured are (5.0 ± 0.8) Gy/h and (0.74 ± 0.03) Gy/h at 10 cm and 28 cm from the pion beam, respectively.

At **PS**, the contamination of neutrons and proton are also a few percents of the main proton flux. In this case, the neutron contamination at 5 cm from the proton beam is decreasing exponentially with neutron energy and, at 10 cm, the neutron spectra behave as $1/E^{1.5}$ (where E is the neutron energy). The low energy component dominates. Proton contamination was found only at 5 cm from the proton beam and the dominant proton energy is above 70 MeV.

This first measurements of contamination around the irradiation beams gives a quantitative understanding with regards to the type and level of radiation damage of silicon detectors investigated simultaneously.

The radiation damage results for these Si samples can be found elsewhere [12].

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Acknowledgements

The authors are grateful to F. Lemeilleur and co-workers for giving us the opportunity to make these experiments. Our gratitude also goes to M. Tavlet and G. Roubaud from CERN-TIS Division, for providing the dosimeters and activation foils for these experiments.

The authors wish to thank R. Horisberger, K. Gabathuler, R. Frosch and A. Janett of the **PSI** for their help in providing the beam time, the beam diagnostic instrumentation, the gamma spectrometer and helping with the beam set-up.

The authors thank also the staff of the **PS** for their help and support in setting up the beam and providing smooth operation conditions.