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Irradiation tests of the pixel front-end readout electronics for the ALICE experiment at LHC

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Abstract

The problem of radiation damage for the electronics of the pixel detectors in the Inner-Tracking-System of the ALICE experiment is discussed. Simulations allowed to estimate total doses and particle fluences during 10 years of operation period. Several irradiation tests have been carried out on the various prototypes of the readout chips. The results obtained so far points out that the recent prototypes will retain their functionality up to doses and neutron fluences well above those expected in ALICE. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

An important part of the design of the Inner-Tracking-System (ITS) [1] of the ALICE experiment [2] at the CERN LHC has been the implementation of radiation tolerant technologies for the electronic circuitry located close to the

interaction region. Such problem is of special concern for the electronics of the pixel detectors, which constitute the innermost two layers in the ALICE ITS. These layers are essential for the reconstruction of the primary vertex and for the measurement of the impact parameter of the secondary tracks originating from the decay of strange, charm and beauty particles. Such requirements can only be fulfilled by detectors which combine high precision and granularity, in order to operate near the collision vertex, where the track density may exceed 50 tracks/cm². The pixel

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detectors must survive an expected total dose in the order of 200 krad in 10 years [3,4]. This has demanded an effort in the electronic design which led to a sensible upgrading of the hardness with respect to the first readout chips of the Omega family [5], still in use in experiments at SPS. This effort from the Microelectronics Group at CERN has been accompanied by a series of irradiation tests carried out in several laboratories with different probes.

Section 2 discusses the radiation environment envisaged for the ITS during a realistic working scenario of the ALICE experiment. The development of the pixel readout electronics is shortly presented in Section 3, while some results concerning experimental tests of the radiation hardness for the readout electronics are reported in Section 4. Finally, some conclusions are drawn in Section 5.

2. The radiation environment for the pixel layers in the ALICE ITS

At the energy planned for the heavy-ion LHC program (6 TeV per nucleon), a large particle multiplicity is predicted by the current theoretical models, reaching values around 10^5 for a central Pb–Pb collision. Full simulations of the interaction of the primary and secondary particles generated by a heavy-ion collision with the overall structure of the ALICE detector have been carried out [4], allowing the evaluation of the total dose and particle fluence on the ITS detectors. Most of the simulations made use of the event generator program Heavy Ion Jet INteraction Generator (HIJING), version 1.35 [6]. This code was used to generate central, peripheral and intermediate impact parameter collisions, with a proper mixing of the events to simulate the real collisions. Primary and secondary particles were tracked using a GEANT package describing as closely as possible the geometry and materials planned for the ALICE detectors.

The total expected dose was evaluated by taking into account a reasonable scenario during 10 years data taking with protons, Ca and Pb beams, as envisaged in the ALICE Technical Proposal [2]

Table 1

ALICE scenario for an overall working period of 10 years

Parameter	pp	Ca–Ca low L	Ca–Ca high L	Pb–Pb
L ($\text{cm}^{-2} \text{s}^{-1}$)	10^{30}	3×10^{27}	10^{29}	10^{27}
Running time (s)	10^8	2.5×10^6	2.5×10^6	5×10^6
Rate (s^{-1})	10^5	8×10^3	3×10^5	8×10^3
No. of events	10^{13}	2×10^{10}	7.5×10^{11}	4×10^{10}

Table 2

Total expected dose (krad) and neutron fluence in 10 years for the individual ITS layers

Layer	pp	Ca–Ca	Pb–Pb	Total	neutron fluence ($10^{11}/\text{cm}^2$)
1	26	77	27	130	3.2
2	7	23	8	39	3.1
3	2.3	7.7	2.8	13	3.5
4	0.8	2.9	1.0	4.7	3.3
5	0.4	1.2	0.4	1.9	3.7
6	0.3	0.9	0.3	1.5	3.3

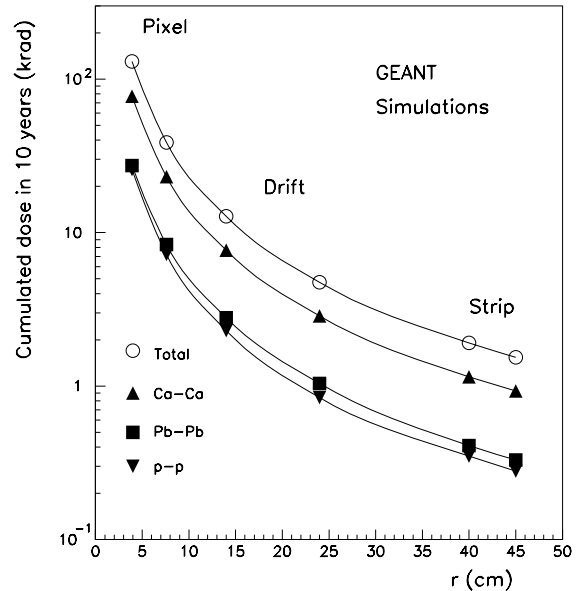


Fig. 1. Total expected dose in the ITS layers during a running period of 10 years, together with the contribution from pp, Ca–Ca and Pb–Pb collisions.

(see Table 1). A summary of the dose expected in the individual ITS layers in 10 years of operation is reported in Table 2 and Fig. 1.

Neutron fluences have been estimated by FLUKA simulations, which give values around 3×10^{11} n/cm² (energy-integrated) for the pixel layers (see Table 2). Recent simulations [7] also provide the contribution to the neutron fluence due to the front absorber and the energy distribution of the secondary neutrons, with a maximum yield in the range 100 keV–1 MeV.

3. Development of the pixel readout electronics

The first series of the pixel front-end readout chips (Omega2 and Omega3) are employed in the WA97 and NA57 experiments at CERN SPS [8]. While satisfying many of the requirements for the ALICE experiment, they were rather sensitive to radiation. The Omega3 front-end chip is a matrix of 16×127 active readout cells ($50 \times 500 \mu\text{m}^2$), manufactured in $1 \mu\text{m}$ SACMOS process, giving the same component density of a $0.6 \mu\text{m}$ standard CMOS process. Each front-end cell includes a preamplifier, a shaper filter, a discriminator, a delay line and the readout logic. A mask flip-flop allows the cell to be disabled when it is too noisy or defective (Fig. 2).

Further requirements in terms of the electronic circuitry needed for the ALICE experiment demanded a process with both a high component density and a good tolerance to radiation.

As a result of extensive R&D work [9] done by the Microelectronics Group at CERN, two proto-

types (ALICE1test and ALICE2test) have been developed. The first is a small test chip (65×2 cells, each measuring $50 \times 420 \mu\text{m}^2$), developed in $0.5 \mu\text{m}$ CMOS technology, with the use of NMOS devices in enclosed geometry and guardrings. The use of such techniques enhanced the radiation tolerance by a factor of 30–50 with respect to the Omega3 series (see following section). Such performance is adequate for the requirement of the ALICE experiment. However, the need for an even larger component density led to the choice of a deeper submicron technology ($0.25 \mu\text{m}$) for the design of the ALICE2test chip. Similar to the previous chip, ALICE2test is a matrix of 65×2 cells, containing this time about 50 000 transistors. The design of this second test chip also allowed incorporation of some additional features required for the final ALICE chip, such as an individual pixel threshold adjustment and a delay line based on the use of an 8 bit counter.

4. Experimental tests of the radiation damage for the pixel electronics

Systematic studies concerning the radiation tolerance of front-end chips of the Omega series were carried out by X-rays [1,10], and using a ⁶⁰Co gamma source [11], 15 MeV electrons [12] and a proton beam [11]. These studies all demonstrated that these chips cannot survive doses significantly higher than 30 krad. As a result, a common protocol for the irradiation of the submicron technology prototypes was established. With the advent of the new prototypes, designed in radiation-tolerant technology, additional irradiation tests were performed with various sources [1]. First of all, X-ray irradiations were carried out at CERN under the same conditions as for the individual transistors [10]. The result showed on a full circuit scale the effectiveness of enclosed NMOS devices and guardrings to prevent radiation-induced leakage. The ALICE1test chip was seen to degrade significantly only after 600 krad. Irradiations by γ -rays from ⁶⁰Co at the Istituto Superiore di Sanità (Rome) were then carried out at a dose rate of 610 rad/min, with a uniformity within 5% on the chip. The evolution of the supply

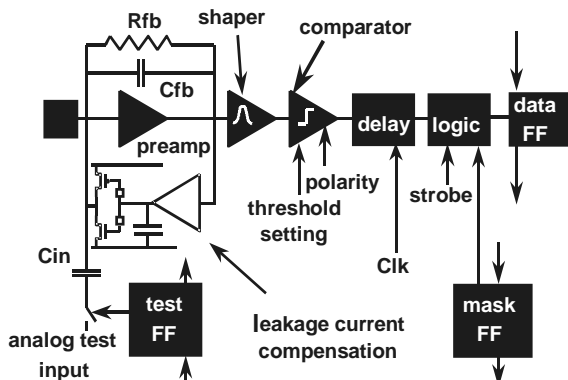


Fig. 2. Block diagram of a cell in the ALICE2test pixel readout chip.

currents (analog and digital), as well as the threshold and its dispersion were studied as a function of the absorbed dose. The results pointed out a functionality of the chip up to doses around 1 Mrad, where a degradation of the performance, including the number of responding cells, was seen. Partial recovery after a few days from irradiation was observed in the discriminator threshold, due to annealing effects. The tolerance to charged hadronic particles was also investigated, by the use of 6.5 MeV protons at the CN accelerator of the Legnaro National Laboratory, with a dose rate of 12 krad/min. Even in this case, serious degradation takes place only after 1 Mrad, with partial recover during the annealing phase. In another test [1] carried out at CERN with low energy electrons derived from the NA50 experiment, the chip was seen to survive up to a dose of 1.7 Mrad.

Even though it is extremely difficult to compare results concerning the damage caused by different radiation sources, a qualitative agreement between all these results was observed, which allows establishment of a radiation tolerance for such a prototype, built in 0.5 μm CMOS technology, up to doses in the order of 1 Mrad (0.6–1.7 Mrad), which is a factor about 30–50 higher with respect to the Omega3 chip.

Similarly to the previous prototype, the first measurements concerning the radiation tolerance of the ALICE2test chip were done by X-rays with a peak energy of 10 keV [1,10]. The chip was seen to be fully operational up to 30 Mrad, with a slight change of the pixel threshold and noise after 10 Mrad. Even in such a case, partial recovery due to annealing was observed. Further tests were carried out with ^{60}Co γ -rays up to 26 Mrad, observing a slight increase of the analog current (Fig. 3, top), and with 6.5 MeV protons with doses of 9, 19 and 48 Mrad (Fig. 3, bottom), where the same trend was observed. The chip ceased to work at 48 Mrad. High energy protons were also used at the CERN SPS machine, with a fluence of about 9×10^{14} protons/cm² over a 12 h period. A recent test [13] was also done with 14 MeV neutrons at the Frascati neutron generator using the $T(d, n)\alpha$ reaction. A fluence up to 1.3×10^{12} n/cm² was used, which corresponds roughly to $2.3 \times$

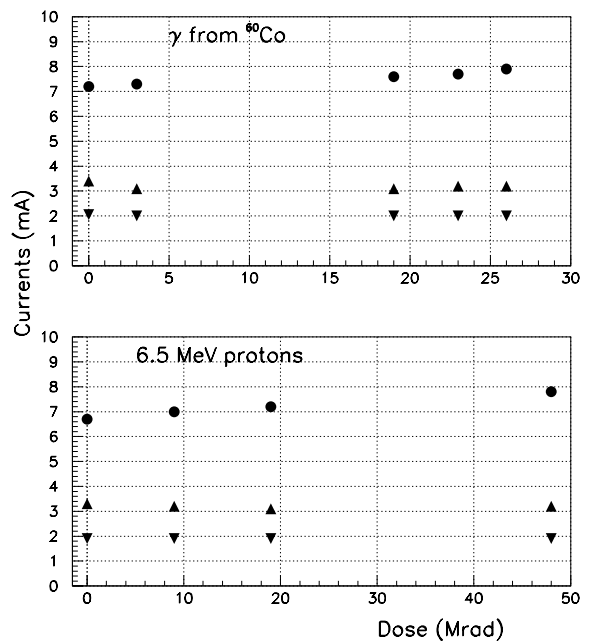


Fig. 3. Behavior of the analog (dots) and of the minimum and maximum digital (triangles) supply currents for the ALICE2test chip during irradiation with γ -rays from ^{60}Co and 6.5 MeV protons.

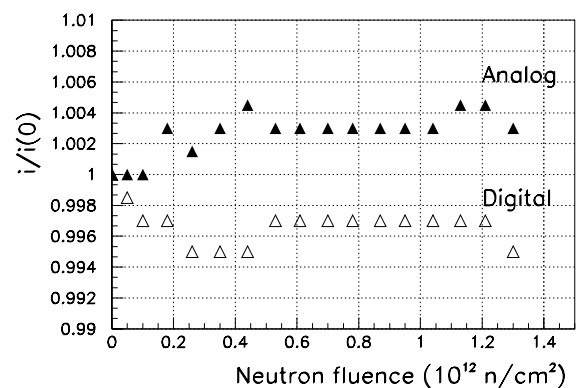


Fig. 4. Variation of the digital (open symbols) and analog (filled symbols) currents in the ALICE2test chip as a function of the neutron fluence. 14 MeV neutrons have been employed. Fluctuations are of the same order as the instrumental sensitivity.

10^{12} 1 MeV-equivalent neutrons/cm². The chip was powered as usual during all the irradiations, monitoring both the analog and digital currents (Fig. 4) which were seen to remain constant within 0.5%. A detailed electrical characterization of the

Table 3
Summary of irradiation tests carried out on the prototypes of the ALICE front-end pixel readout chips

Source of radiation	Prototype	Max dose/ particle fluence	Ref.
10 KeV X-rays	ALICE1test	800 krad	[10]
^{60}Co γ -rays	ALICE1test	1.5 Mrad	[1]
1 MeV electrons	ALICE1test	2.6 Mrad	[1]
6.5 MeV protons	ALICE1test	1.05 Mrad	[1]
10 KeV X-rays	ALICE2test	30 Mrad	[10]
^{60}Co γ -rays	ALICE2test	26 Mrad	[1]
High energy protons	ALICE2test	9×10^{14} p/cm ²	[1]
6.5 MeV protons	ALICE2test	48 Mrad	[1]
14 MeV neutrons	ALICE2test	1.3×10^{12} n/cm ²	[13]

chip prior and after the irradiation was also undertaken, checking the shape of the signals from the preamplifier and from the shaper, the linearity in the gain and the efficiency response. No degradation effect was seen, up to this neutron fluence, which is approximately one order of magnitude higher than expected in the 10 year ALICE scenario. For the sake of completeness, a summary of the irradiation tests, which have been carried out so far on the two prototypes, is reported in Table 3.

5. Summary and conclusion

Extensive work has been carried out to implement radiation tolerant techniques in the pixel front-end electronics for the ALICE experiment in order to reach the required hardness for the full operational period of the experiment. Several prototypes of the readout chips have been tested in various laboratories and employing very different probes, which include X-rays, ^{60}Co γ -rays, low and high energy protons, electrons and neutrons. Even though it is not easy to standardize a comparison between different sources of radiation, a common behavior has been obtained by different irradiations. For the first prototype, built in 0.5 μm technology, a tolerance around 1 Mrad has been achieved, whereas the second may be

considered as fully operational up to doses of the order of 10 Mrad. This result is well in excess for the requirements of the ALICE experiment, discussed in Section 2, and allows the conclusion that the R&D work, as far as the radiation tolerance is concerned, is now complete. We would like to stress that the conditions used in such irradiations are worse than the expected scenario during the ALICE run, because only a few months of exposure per year are planned, allowing annealing effects during the rest of each operational year.

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