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Observation of radiation induced latchup in the readout electronics of NA50 multiplicity detector

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Abstract

During the data taking of the NA50 experiment, the CMOS digital pipeline chips (CDP) used for the readout of the multiplicity detector were exposed to high levels of radiation resulting in an ionizing radiation dose of more than 200 krad and displacement damage equivalent to 1 MeV neutron fluence of more than 5×10^{11} eq. neutrons cm^{-2}. Some of these chips showed anomalies of behaviour which we attribute to radiation induced latchup phenomena. Here we present the analysis of the data taken during the 1996, 1998 and 1999 ion runs together with the results of measurements performed in the laboratory. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction and description of front end electronics

The multiplicity detector (MD) in NA50 experiment [1] is a silicon microstrip detector composed of two identical planes (MD1 and MD2) which is used to measure the number and the angular distribution of the charged particles produced in Pb–Pb collisions. Since only the hit/no hit information from the strips is used, a binary readout scheme has been implemented. It consists of a full-custom front end electronics and a VME data acquisition system.

The front end electronics are based on a pair of 64 channel chips: the analog chip FABRIC [2] (a bipolar device that amplifies, shapes and discriminates the analog signal from the strip) and the digital pipeline chip (CDP). These chips have a channel pitch of 50 μm, low power consumption and are radiation hardened. They are placed a few cm from the beam axis, as can be seen in Fig. 1, in

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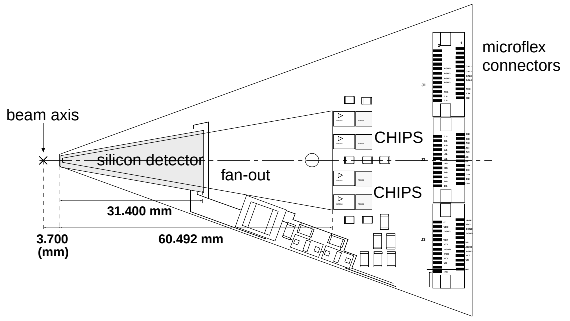

Fig. 1. Scheme of the board.

which the layout of a single detector board is shown, and so they are exposed to high radiation levels.

The CDP [3] is a clock driven digital data buffer pipeline that stores the data during the trigger latency period ($\sim 1\ \mu s$) and then sends it to the data acquisition system. It is an 81 column, 64 row RAM memory realized in 0.8 μm CMOS technology. Each row reads and stores the data from one FABRIC channel, 0 if no particle hit the strip and 1 if the strip was hit. Each CDP can store the data of 64 strip elements, so 216 CDPs are necessary to serve the 13 824 channels of the MD. Each CDP is identified with a number (from 1 to 216). The distribution of the main power supply of the CDPs (V_{DD}) has been designed in such a way that there are three lines ($V_{DD_{123}}$, $V_{DD_{456}}$ and $V_{DD_{789}}$) for MD1 and three for MD2, therefore each V_{DD} line supplies the power to 36 CDPs. Of the 216 CDPs used in 1996, five were HPMOSIS prototypes used in the first tests, which were not made using radiation hardened technology. The other 211 CDPs were produced by Honeywell with a radiation hard technology that can resist up to radiation dose levels greater than 1 Mrad. Both chips were fabricated according to almost identical designs.

2. Estimation of dose and fluence

NA50 is a fixed target experiment using the 158 A GeV/c SPS lead beam. During the 1996 data taking period, the beam intensity was $\sim 5 \times 10^7$ ions/burst and the Pb target was 12 cm thick (32% of an interaction length). The number of particles produced in a single Pb–Pb collision is very high (~ 1000 for central collisions) and $\sim 80\%$ of them are pions. The radiation levels have been estimated from Monte Carlo simulations [4] and the fluence of charged particles has been converted to the equivalent 1 MeV neutron fluence [5]. Since the two MD planes are placed very close to the target (~ 10 cm), the radiation level reached, respectively, 10^{14} eq. neutrons cm^{-2} of fluence and 10 Mrads of dose for the innermost strips of the detectors during the whole 1996 data taking period. The CDPs are located at $r \approx 6.8$ cm from the beam axis (see Fig. 1), so we can estimate the fluence received by them in 1996 as $\approx 5 \times 10^{11}$ eq. neutrons cm^{-2} and the dose as ≈ 200 krad (see Fig. 4 of Ref. [4]).

In 1998, the target thickness was reduced to 3 mm of Pb ($\approx 8\%$ of interaction length) so that the total dose received by the CDPs in 1998 was 25–30% of 1996 absorbed dose. In 1999, the lead beam energy was 40 A GeV/c instead of 158 A GeV/c of the previous years, the data taking period was very short (only ~ 100 h, instead of the ~ 900 of the previous years) and the beam intensity significantly lower (4×10^6 ions/burst). So the total dose received by the CDPs in 1999 was at least two orders of magnitude lower than in 1996.

3. Radiation effects during 1996 data taking

A measure of the performance of a CDP is given by the fraction of events in which it is in timeout, i.e., does not respond correctly. In fact, the data transmitted by each CDP are checked on-line by an algorithm that generates an output bit: if this bit is on, the data are correct and so the event is marked as good. If, on the contrary, this bit is off, it means that there has been a data transmission error: for that event the CDP is considered in timeout and all of its data are rejected. During normal operation, the fraction of events in timeout for most of the CDPs is few percent.

3.1. Observation of latchup phenomena in CDPs

During data taking periods with the lead beam, the timeout fraction of CDPs and the values of the

V_{DD} currents were kept under constant observation. During the first 5 days of 1996 data taking, no anomalous behaviour of the electronics was observed. After that we started to observe, with rather constant frequency, an anomalous behaviour for some of the CDPs. The timeout fraction of a CDP suddenly dropped to 100% (which meant that the CDP stopped responding) and then, after turning off and on the V_{DD} power supply, returned to its normal value. We also observed that the value of I_{DD} was much higher than normal during the 100% timeout fraction period and that this current went back to its nominal value after turning off and on the power supply. Usually such events were registered in the experiment's logbook.

When this anomalous behaviour started to appear regularly and we noticed that it happened usually to the same CDPs, we started to suspect that the chips were latching up [6]. In fact if one of the components of a CDP was in latchup, the chip would not operate normally and so its timeout fraction would be 100%. The transition from normal functioning to 100% of timeout would occur suddenly, immediately after the ionizing event that induced latchup. Besides, since latchup is a stable condition, the CDP would remain in 100% timeout until the power supply is turned off in order to deactivate the bipolar tyristor that causes the latchup. Since the increase of the current was not limited by the power supply and since the latching up was not destructive for the chips, there must have been a mechanism inside the CDP which limited the maximum CDP current during the latchup.

3.2. Analysis

We analysed the data of the tapes recorded during the 1996 ion run. In the following, we will consider a "good" latchup candidate an event that satisfies the following conditions:

(1) A CDP goes suddenly from normal functioning to 100% of timeout
(2) The timeout fraction remains at 100% until the power is switched off and then subsequently on

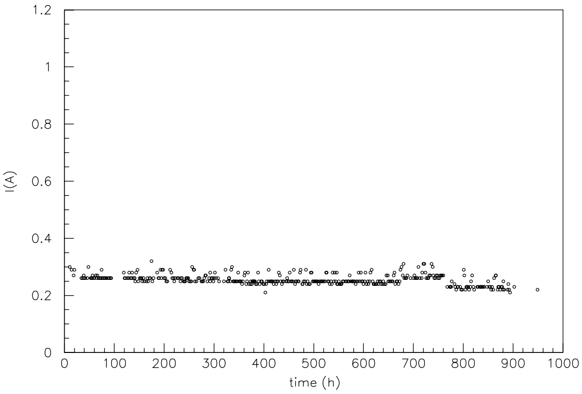

Fig. 2. $I_{DD_{123}}$(MD1) vs. time (CDPs 1–12, 37–48, 73–84).

(3) After switching on the power supply the CDP returns to normal operation
(4) While the CDP is in timeout, the value of I_{DD} is much higher than normal.

It was not always possible to verify if this fourth latchup condition was satisfied because the current values were recorded every 2 hours. The total number of candidate latchup events is 69. For 38 (55%) of these events we do have a recording of a high value of current, while for the other 31 candidate events we have no information about the currents because latchup condition lasted for a short period and was removed by cycling the power supply before the values of current were recorded.

In Fig. 2, we show a typical I_{DD} current vs. the time passed since the beginning of the run for a group of 36 CDPs which did not show anomalous behaviour: the I_{DD} is almost constant ($\approx$0.25 A, about 7 mA per CDP) during the whole data taking period.

In Fig. 3, the I_{DD} current vs. time for a group of 36 CDPs including four CDPs that latched up frequently (CDPs 49, 50, 51 and 52 on MD1) is shown. Let us stress that, since one line supplies at the same time 36 CDPs, the dramatic change in power consumption of one CDP, caused by latchup, causes only a $\sim$30–50% change in the total current. When one CDP is in latchup the current for the group of 36 CDPs increases by $\approx$50–150 mA, which represents a tenfold increase

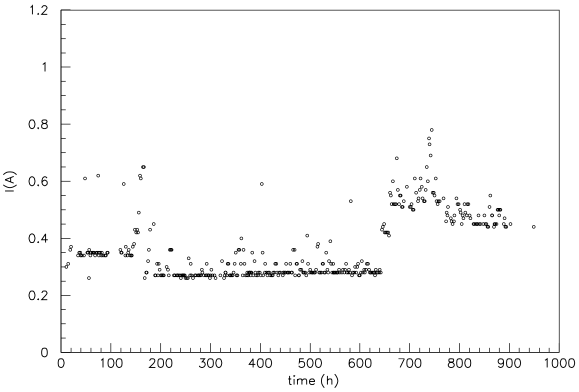

Fig. 3. Currents $I_{DD_{456}}$(MD1) vs. time (CDPs 13–24, 49–60, 85–96).

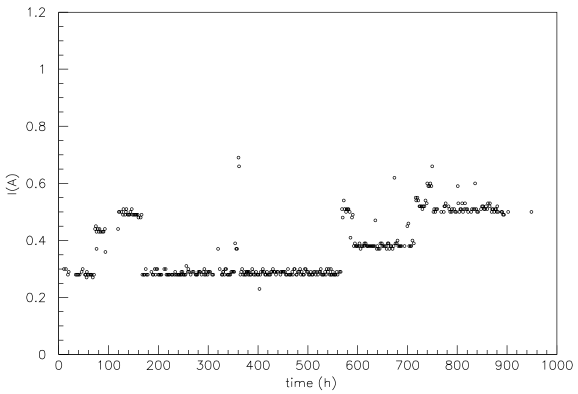

Fig. 4. Currents $I_{DD_{789}}$(MD2) vs. time (CDPs 133–144, 169–180, 205–216).

for that chip. Other CDPs that presented latchup were 214, 215 and 169 (on MD2). In Fig. 4, the I_{DD} current for the corresponding group of 36 CDPs is represented. Since these CDPs were all working correctly at the beginning of the data taking, and they started latching up only after some irradiation, we assume that the latchup probability was growing with the total received dose.

A summary of the analysis is reported in Table 1, where the number of candidate latchup events is written as $(x+y)$, where x is the number of events for which high currents were recorded and y is the number of events which lasted less than 2 h and therefore, we cannot assure high current evidence.

3.3. Results for HPMOSIS CDPs

As mentioned, five out of 216 CDPs mounted on the MDs during the 1996 data taking were HPMOSIS non-radiation hardened chips. On all of these five HPMOSIS chips, latchup events have been observed. We can estimate the average number and the standard deviation of latchup events induced on these chips as $\langle N_{\text{latchup}} \rangle = 10.4$ and $\sigma = 4.8$.

Let us recall that the lead ion beam never hit the electronics, so the flux on the readout chips was given by the secondary particles produced in the interaction of the beam in the target. We can make the assumption that latchup occurred when a nuclear interaction between an incident hadron and a silicon nucleon took place and caused high ionization inside the CDP. From the silicon interaction length and density ($\lambda_{\text{INT}} = 106\ \text{g cm}^{-2}$, $\rho = 2.33\ \text{g cm}^{-3}$) we can calculate the probability of a nuclear interaction in the silicon active layer of the CDP, whose thickness is ~ 5–$10\ \mu\text{m}$. The result is

$$P = \frac{\rho s}{\lambda_{\text{INT}}} \approx (1.1 - 2.2) \times 10^{-5}.$$

By multiplying this probability for the hadron fluence received by the CDPs ($\phi \sim 10^{12}\ \text{cm}^{-2}$) and for the CDP area ($\approx 3.0 \times 2.75\ \text{mm}^2$) we obtain the number of nuclear interactions in the CDP during the whole 1996 data taking period: $N_{\text{INT}} \approx (0.8 - 1.6) \times 10^6$.

We can estimate the fraction of CDP area which is sensitive to latchup multiplied by the fraction of nuclear interaction which can cause a latchup as the ratio of the number of latchup events observed and the number of nuclear interactions in the CDP:

$$\frac{\langle N_{\text{latchup}} \rangle}{N_{\text{INT}}} \approx (0.6 - 1.3) \times 10^{-5}.$$

3.4. Results for Honeywell chips

Let us consider now the 211 Honeywell radiation hard chips. During the whole 1996 data taking, we observed latchup candidate events only on two of them, while we have not seen any anomalous behaviour on the other 209 chips.

Table 1
CDPs that exhibited latchup behaviour

CDP number	CDP kind	Number of latchups observed
49	Honeywell	7+7
50	HPMOSIS	10+7
51	HPMOSIS	6+1
52	HPMOSIS	5+3
169	Honeywell	2+1
213	HPMOSIS	5+9
214	HPMOSIS	3+3

It is important to remark that the two Honeywell chips on which latchups occurred are very close to HPMOSIS chips. Since latchup causes high current consumption and a big increase of the temperature in the chip [7], these Honeywell CDPs were often working in high temperature conditions that cause an increase of the latchup probability [8].

CDP number 169 is located on the same bias line as 213 and 214 and at 5 mm distance from them. Furthermore, the number of candidate latchup events observed on this chip is small (3 instead of ~ 10) with respect to the other CDPs that showed anomalous behaviour (see Table 1). The working environment is even worse for CDP 49 because it is located on the same board of HPMOSIS CDPs 50, 51 and 52 and therefore it is powered by the same power lines, so that its operation may be influenced by the unstable conditions caused by the frequent latchups on the other three chips. It also should be mentioned, however, that these chips were also used in the data taking periods of 1994 and 1995, so the total dose received is somewhat ($\approx 35\%$) larger than for most of the other chips.

Having in mind the particularity of the environment for the two Honeywell chips which showed anomalous behaviour, we cannot attribute these latchups only to radiation effects.

3.5. Total dose effects

In Fig. 4, we can see that at $t \approx 550$ h I_{DD} jumped suddenly to a higher value, as if a CDP went into a high current state and remained permanently in this state. We found that CDP 214 at $t = 566.5$ h went abruptly into 100% timeout, as if a single event latchup had occurred, but afterwards the turning off and on of V_{DD} had no effect: the timeout fraction remained 100% and the current stayed high until the end of data taking. Later ($t = 730$ h) the same situation occurred for CDP 215 and this caused the second jump in Fig. 4 to a higher current value.

Table 2
CDPs that were permanently in a latchup-like state at the end of the run

CDP number	CDP kind	Time (h) when it went into 100% timeout
214	HPMOSIS	566.5
52	HPMOSIS	643
51	HPMOSIS	710
215	Honeywell	716

Similarly, we found that from a certain time CDPs 52 and 51 went into 100% timeout and remained permanently in this state. The results obtained are summarized in Table 2. CDPs 51, 52 and 214 are HPMOSIS CDPs which latched up many times during the data taking (see Table 1), while CDP 215 is a Honeywell chip with which we had never seen latchup. However, the apparent timeout state of CDP 215 is due to the fact that CDP 214 was responding twice, once as 214 and once as 215.

We can interpret this behaviour of CDPs 51, 52 and 214 as staying permanently in latchup-like state (100% timeout and high currents) after a decrease of the Linear Energy Transfer (LET) threshold for latchup [6] due to the total dose received by the chips. In particular, for a few chips the latchup threshold could have become so low [7] that almost every particle passing through them (or a transient during the switching on of the power supply) could induce latchup. For these chips the parasitic bipolar transistors were permanently on and so the CDPs remained permanently in latchup.

4. Results from 1998 and 1999 data taking

Most of the MD modules were substituted between the 1996 and 1998 data taking runs, so that no HPMOSIS (non-radiation hard) CDP remained on the detector. Approximately two-thirds of the CDPs mounted in 1998 and 1999 had not been used before, while one-third of the CDPs ($\approx$70) had already been used in 1996 data taking.

We did not observe any latchup event during the whole of the 1998 and 1999 data taking periods and the I_{DD} currents were always stable. The $\approx$70 Honeywell CDPs used in 1996, 1998 and 1999 resisted well the total dose received in these three data taking periods. According to this result, we believe that the few latchups observed in 1996 on Honeywell chips cannot be considered as radiation induced latchup.

5. Laboratory measurements on the CDPs that presented latchup

After the end of the 1996 data taking period, the multiplicity detector was disassembled and the boards were kept in a refrigerator at $-18°C$. The boards containing the six CDPs (49,50,51,52,213 and 214) that latched frequently during 1996 data taking were taken to Turin where we performed some measurements on them in order to see if these CDPs could still work in absence of radiation.

We supplied the four CDPs placed on the same board with different V_{DD} voltages and we measured the corresponding I_{DD} current. We also looked for each V_{DD} value at the signals from the chips in order to evaluate if they were responding and working properly. It is important to observe the CDP's behaviour at lower voltages because the total dose received may have caused a decrease of the voltage V_{trig} necessary to induce latchup [6]. The same measurements have been performed on the same boards in 1997 and 2000 in order to evaluate the possibility of annealing effects (the boards during these 3 years were kept in a fridge and not further irradiated).

The results obtained for the I_{DD} current are reported in Fig. 5 and show that the current in the boards with CDPs that presented latchup is very high ($\sim$0.25 A instead of the normal value of $\sim$0.01 A). The values of the current at normal power supply ($V_{DD} = 5.5$ V) are the same in 1997 and 2000 even if the shapes of the I–V characteristics are slightly different.

In 1997, none of these chips worked at the nominal power supply voltage ($V_{DD} = 5.5$ V),

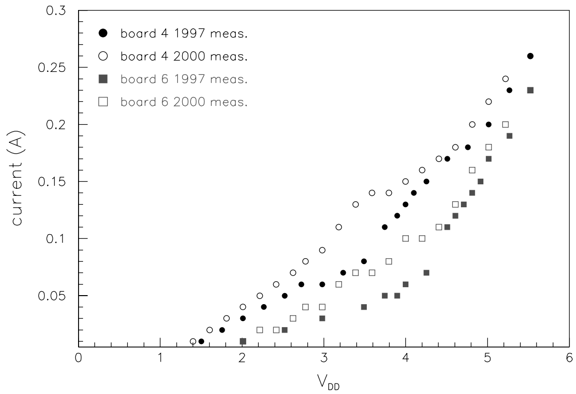

Fig. 5. I_{DD} vs. V_{DD} for the two boards (four CDPs each) whose CDPs showed problems due to radiation damage.

whereas with a lower power supply voltage ($V_{DD} \approx 3.90$–4.00 V) all of them would respond (of course they could not work properly due to the insufficient voltage supplied). It seems that radiation damage has weakened the chips by causing a decrease of the voltage V_{trig}.

In 2000, we observed that CDPs 49, 51 and 213 worked with $V_{DD} = 5.5$ V, while CDP 52 did not respond at all, even with a lower power supply voltage. The other two analysed CDPs (50 and 214) were working very badly (as in 1997), but CDP 50 worked correctly for lower clock frequencies (12.5 MHz instead of 50 MHz). After this measure we tried to get a better evaluation of the current drawn by single CDPs cutting the bonds of the chips which were not working (or working badly) and measuring the current drawn by the correctly-functioning CDPs. We found that the I_{DD} current was normal (0.01 A) for CDP 213 and was few times higher for 49 and 51.

We can summarize these results by saying that four out of six CDPs that presented latchup during 1996 data taking showed improvements after 3 years without irradiation. We can interpret these results as a consequence of a total dose effect that has been recovered by some annealing effect.

6. Conclusions

Radiation induced latchup was observed in 1996 data taking on HPMOSIS non-radiation hard

CDPs. On these chips we also observed total dose effects (a decrease of LET threshold and of V_{trig} voltage) that were partially recovered for some chips by 3 years of annealing.

We verified that no Honeywell (radiation hard) chip showed permanent problems due to radiation damage (as it should be since they can resist at doses ~ 1 Mrad). This is confirmed by the fact that all the ~ 70 Honeywell CDPs used in 1996, 1998 and 1999 worked properly during the 1998 and 1999 data taking periods.

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