Performance of CMS silicon microstrip detectors with the APV6 readout chip

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Abstract

We present results obtained with full-size wedge silicon microstrip detectors bonded to APV6 (Raymond et al., Proceedings of the 3rd Workshop on Electronics for LHC Experiments, CERN/LHCC/97-60) readout chips. We used two identical modules, each consisting of two crystals bonded together. One module was irradated with \(1.7 \times 10^{14}\) neutrons/cm\(^2\). The detectors have been characterized both in the laboratory and by exposing them to a beam of minimum ionizing particles. The results obtained are a good starting point for the evaluation of the performance of the “ensemble” detector plus readout chip in a version very similar to the final production one. We detected the signal from minimum ionizing particles with a signal-to-noise ratio ranging from 9.3 for the irradiated detector up to 20.5 for the non-irradiated detector, provided the parameters of the readout chips are carefully tuned. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

The CMS silicon tracker [2] will consist of roughly 6500 modules of silicon detectors, assembled in a central barrel and two endcap wheel structures. The measurements discussed in this paper are taken with two prototype modules which are very similar in size and characteristics to the final ones. It is extremely important to test as early as possible the response of a full-size detector bonded to the APV6, the available prototype of the final readout chip, in order to understand the behaviour of the electronics in realistic experimental conditions, so as to identify, before mass production starts, possible sources of problems. Some of the results we show here are still preliminary; it should be remarked that the work presented in this paper is based on a total of five APV6 chips, four bonded to full-size detectors and one on a test board. We plan further cross checks on a statistically significant sample of chips. These results are anyway an important input for the final production of the readout chips.

2. The wedge detector

The detectors used in our tests are sketched in Fig. 1. They are made of two different crystals (F1 and F2), wedge-shaped, glued to a carbon fiber support structure. The sensors are made from \(\langle 111 \rangle\) orientation n-bulk type silicon, 300 \(\mu\)m thick, with a resistivity of about 4 KΩ cm. The implant p\(^+\) strips are AC coupled to the readout chip through integrated capacitors made with a thin insulating layer between implants and aluminum electrodes. The coupling capacitance between...
The p\(^+\) strip and the readout electrode is approximately 15 pF/cm, a value which allows to collect about 90% of the primary charge released in the silicon. The bias voltage is distributed via polysilicon resistors connecting the p\(^+\) bias ring to each implant strip. The main parameters of the two crystals are reported in Table 1. All electrical parameters have been measured with a probe station using an HP 4248A LCR meter, an HP4145B Semiconductor Parameter Analyzer and a Keithley 237 High Voltage Source Unit [3]. Non-irradiated detectors have a full-depletion voltage < $80 \text{ V}$, and a total input strip capacitance (the two crystals bonded together), as seen from the input of the APV6, of $C_{\text{input}} = 13.5 \text{ pF}$. The total input strip capacitance is calculated from the measurements of the silicon bulk capacitance, of the interstrip capacitance between two adjacent metal strips (grounding the first neighbour strips) and of the coupling capacitance between the p\(^+\) implant and the metal of the same strip. One detector, without readout electronics, has been irradiated with $1.7 \times 10^{14}$ 1 MeV equivalent neutrons/cm\(^2\) using the 18 MeV cyclotron of ATOMKY, Debrecen, Hungary. This neutron fluence roughly corresponds to the effect of the first 10 years of LHC operation. The first preliminary results obtained with this detector will be reported at the end of this paper.

### Table 1

Main detector parameters. $N$ is the number of strips, $L$ is the average strip length, $W$ is the strip width, $P$ is the implant pitch, $R_B$ is the bias resistor value, $D_{\phi \text{m}}$ is the surface of the active area of the detector.

<table>
<thead>
<tr>
<th></th>
<th>$N$</th>
<th>$L$ (cm)</th>
<th>$W/P_1$ (µm)</th>
<th>$P_1$ (µm)</th>
<th>$R_B$ (MΩ)</th>
<th>$D_{\phi \text{m}}$ (cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>1024</td>
<td>6.21</td>
<td>0.28</td>
<td>50–60.5</td>
<td>5.7</td>
<td>35.08</td>
</tr>
<tr>
<td>F2</td>
<td>1024</td>
<td>5.37</td>
<td>0.23</td>
<td>61–70</td>
<td>12</td>
<td>36.02</td>
</tr>
</tbody>
</table>

3. The readout chip

The readout chip used is the APV6, described in detail in Ref. [1]. It is a 128 input channels charge-sensitive amplifier, made by Harris. It has a peaking time of 50 ns and the pulse response approximates an ideal CR-RC filter shape. The input signal is sampled every 25 ns. Upon arrival of a trigger signal, the data are read out in one of the two possible modes: peak or deconvolution [4]. In peak mode only the sample at the peak of the signal is sent to the 20 MHz output multiplexer, while in deconvolution three samples before the peak are fed to a weighted sum analog circuit, whose output is then sent to the multiplexer. Deconvolution decreases the shaping time to 25 ns. There is a set of internal registers which can be modified by the user [5]: the latency, corresponding to the number of clock cycles between write and trigger pointer in the internal pipeline (160 cells deep); the calibration pulse amplitude; the calibration skew; the analogue biases of the chip (four currents and four voltages); the mode: peak or deconvolution, and calibration or normal data taking. All these parameters can be controlled through an I2C serial interface. The equivalent noise charge dependence on the input capacitance is given by [1]

\[
ENC = (510 + 36C_{\text{input}}(\text{pF}))e^- \quad \text{in peak mode (1)}
\]

\[
ENC = (1000 + 46C_{\text{input}}(\text{pF}))e^- \quad \text{in deconvolution mode. (2)}
\]

4. The experimental set-up

We installed a laboratory set-up to test these detectors. The block scheme of the electronic chain is shown in Fig. 2. The main building block is the sequencer, which we implemented on a FPGA, with a RS232 interface to select a few parameters (like delays between physical trigger and APV trigger, calibration control, etc.) according to the working mode of the front-end electronics. The sequencer also produces the conversion signal for the 20 MHz ADC, synchronous to the multiplexed analog output of the APV6. The physics trigger (i.e. beta source) is accepted in a $\pm 3 \text{ ns}$ time window w.r.t. the rising edge of the clock.

The complete detector module, with a custom amplification and buffering board added (Florence Buffer in Fig. 2), is installed on top of a bending magnet. Inside the magnet there is a $^{90}\text{Sr}$ beta...
source. Only the electrons with momentum close to the end point (~2 MeV) are bent towards the detector thus simulating minimum ionizing particles (mips). A plastic scintillator with a low-noise fast photomultiplier located just above the silicon is used to trigger only on the particles that have crossed the silicon. The whole system is placed inside a climatic chamber, which allows to cool the detectors down to $-20^\circ$C. This is especially important for the irradiated module.

The converted signals are readout through FIFO memories on a VME system controlled by a cpu running UNIX, and stored on disk for subsequent analysis [6].

5. The data analysis

We search for a charge signal in the detector in the following way: first we calculate the pedestal for each preamplifier channel, then we evaluate the common noise in a group of 32 channels and use this value for common mode subtraction; finally for each channel we compute the noise $\sigma$ defined as the standard deviation of the common mode subtracted pedestals. In a second phase we look for a “seed” strip that has a signal $S_{\text{strip}} \geq 4\sigma_{\text{strip}}$. Having found one, in order to form a cluster we sum the charge of the contiguous neighbour strips if $S_{\text{neighbour}} \geq 2\sigma_{\text{neighbour}}$. The total charge of the cluster must satisfy $S_{\text{cluster}} \geq 5\sigma_{\text{cluster}}$. For signals due to minimum ionizing particles we fit the distribution of the cluster charge from all events with a three-parameter Landau curve, and take the value of the peak given from the fit as our most probable signal value; for calibration signals we use a Gaussian fit.

5.1. The non-irradiated detector

We first took data with the non-irradiated detector. Analysis of the data taken with the beta source, showed that biasing the silicon at $V < V_{\text{depl}}$ was not enough to collect all the charge released in the bulk of the silicon, since the collected charge kept increasing with higher bias voltages. A better collection efficiency was achieved at $V_{\text{bias}} \approx 3 \times V_{\text{depl}}$, as can be seen in Fig. 3. The signal-to-noise ratio ($S/N$) increased from 13.5 to 14.7 in peak mode, and from 8.2 to 9.7 in deconvolution mode. These values are not consistent with the signal-to-noise ratio expected from the measured input capacitance and the expected ENC from formulae (1) and (2). We then modified the value of the APV6 parameter VSHA, the shaper feedback bias voltage affecting the shaper time constants. We performed a scan in VSHA (see Fig. 4): the measurements show a clear increase in $S/N$ for lower shaper voltages. We then studied the effect of the variation in VSHA over the time evolution of the output signal in peak mode. This measurement was carried out varying the arrival time of the trigger with respect to the clock, with small delay steps of 6 ns, thus sampling the preamplifier output signal at various points. From these measurements we can reconstruct the shape of the signal. The results are shown in Fig. 5. It can be seen in Fig. 5 that the pulse shapes obtained with calibration data are consistent with the minimum ionizing particles data, and that the rising edge of the output signal is only moderately affected by the change in VSHA. To check if the change in VSHA had a sizable effect on the output signal in deconvolution mode, we performed a similar delay scan using only calibration data. Fig. 6 shows the resulting output shapes between the two extreme conditions VSHA = 2.0 and $-0.2$ V.

Taking into account these results we collected beta source data after optimizing the APV6
parameters and DAQ timing to achieve the best-possible performance in terms of $S/N$; the cluster charge and the cluster noise distributions are shown in Fig. 7. The Landau fit for the charge and a Gaussian fit for the noise are superimposed on the corresponding histograms; the Gaussian fit (due to some slightly noisier strips in the region illuminated by the beta source) is limited to the regions of the detector with a noise below 9 ADC counts. The tail with larger noise contains a sizeable fraction of events, but the use of the peak value of the fit is justified by the verification that the charge response is uniform over all the detector and independent of the noise. In peak mode we measure $S/N = 20.5$ and in deconvolution mode $S/N = 12.3$.

We investigated the effect of high VSHA values on the cluster finding in nearby latency cells, which could give rise to fake out-of-time events. We made a delay scan looking at the reconstructed charge

Fig. 3. Beta source charge distribution in peak (left) and deconvolution mode (right), for $V_{bias} \approx 1.2V_{depl}$ (top) and $V_{bias} \approx 3V_{depl}$ (bottom).

Fig. 4. $S/N$ in peak mode versus shaper voltage.
Fig. 5. Time evolution of the output signal for different VSHA values in peak mode. Open markers: calibration; full markers: beta source; full line CR-RC filter.

and at the relative cluster finding efficiency for minimum ionizing particles. From Fig. 8 it can be deduced that at ± 25 ns from the right latency the number of reconstructed clusters drops to 10%, while the average charge is approximately 40%. For low S/N the average charge is overestimated due to the cut of the cluster finding at S/N greater than 5. This effect is larger for a non-optimal latency.

Fig. 6. The shape of the output signal as a function of time at VSHA = 2.0 and -0.2 V for calibration in deconvolution mode.

Fig. 7. The cluster charge from beta source (left) and cluster noise (right), VSHA = -0.2 V, V_{bias} ≈ 3V_{dep} = 250 V. Top: peak mode, bottom: deconvolution mode.

Fig. 8. The cluster charge (top) and relative cluster finding efficiency (bottom) for mips, as a function of time. VSHA = -0.2 V, deconvolution mode.
The same detector module has been put in a 8 GeV/c pion beam at CERN in May 1999, with a new ADC (the FED [7]). We obtained with pions a S/N = 19.7 in peak mode, in agreement with our beta source result.

5.2. The irradiated detector

The irradiated detector was identical to the one discussed before. After irradiation the bulk silicon was completely type inverted from n to p [2]. The new full-depletion voltage has been inferred to be \( V_{\text{depl}} = 200 \, \text{V} \) from a C–V measurement, as can be seen in Fig. 9 in which both irradiated and non-irradiated crystals measurements are shown. After irradiation the input strip capacitance increased, its value depending on the applied bias voltage. For our expected S/N calculations we use the measured values of \( C_{\text{input}} = 20.6 \, \text{pF} \) at 300 V and \( C_{\text{input}} = 16.5 \, \text{pF} \) at 500 V. Initially, the detector was bonded to a PREMUX128 readout chip [8], which has the same input stage as APV6, but no tuning of internal parameters, no deconvolution filter, no pipeline and a slow (1 MHz) output multiplexer. The S/N obtained in test beam with this configuration before and after irradiation is shown in Fig. 10 as a function of the bias voltage. On the same module we then removed the hybrid with PREMUX128 and we bonded a different hybrid with APV6. Tests in our laboratory after a careful tuning of the APV parameters gave a preliminary S/N = 13.3 in peak mode and S/N = 9.3 in deconvolution mode. The operating conditions were: \( T \approx -20^\circ \text{C}, V_{\text{bias}} \approx 2.5 \, V_{\text{depl}}, \) total detector current \( I = 500 \, \mu\text{A}, \) VSHA = 0.3 V. Fig. 11 shows the charge and noise spectra from the irradiated detector in deconvolution mode.

5.3. Noise evaluation

To evaluate the performance of our detectors, we estimated the expected signal and the expected noise. The largest noise contribution comes from the readout chip, and is given by formulae (1) and (2). In addition to this we must also take into account the contributions from the shot noise of the reverse bias current and the thermal noise of the bias resistor and of the aluminium strip. Given the values for the shaping time of the amplifier, it turns out that the thermal noise contribution of the bias resistor is negligible. The shot noise is given by

\[
\text{ENC}_{\text{par}}^{\text{I}} \approx 108 \sqrt{I_b (\mu A) \tau (\text{ns}) e^-}
\]

and the thermal noise of the aluminium strip is given by

\[
\text{ENC}_{\text{therm}}^R \approx 13 C_{\text{input}} (\text{pF}) \sqrt{\frac{R_c (\Omega)}{\tau (\text{ns})}} e^-.
\]
Fig. 11. Distribution of cluster charge from beta source (top) and cluster noise (bottom) for the same detector of Fig. 10 after irradiation and with APV6 readout chip working in deconvolution mode. See text for operating conditions.

$I_b$ is the reverse bias current of one strip, $\tau$ is the shaping time of the readout chip and $R_s$ is the resistance of the metal strip. The shot noise starts contributing significantly only when $I_b$ is above a few hundreds nanoamperes. A summary of the results obtained with minimum ionizing particles compared to the expectations is given in Table 2; we took into account the appropriate values of the input strip capacitance and of the reverse bias currents. Our results are systematically lower than expectations, especially for the irradiated detector.

We have tried a different algorithm to reconstruct the charge released by a minimum ionizing particle to recover this apparent loss, that could be due to the cuts applied during clustering. In the new algorithm, after finding a cluster following the procedure described in Section 5, we form a new charge signal taking the highest strip charge in the cluster and adding to it the charge of the first neighbour strips regardless of their sign. In this way we get the expected $S/N$ for both detectors with the PREMUX128, and better than 95% of the expected $S/N$ with the APV6.

6. Conclusions

In this paper we report results on the first data taken with a full-size microstrip silicon detector, whose concept and design are very similar to the ones that will be used in the CMS tracker, bonded to the APV6 readout circuit. Up to now the published papers reported only data with calibration set-ups or with smaller size silicon microstrip detectors. Although certainly not conclusive, our data show a good agreement with what is expected in terms of signal-to-noise ratio. In particular, the first data taken with a heavily neutron-irradiated detector give very encouraging preliminary result, that are already at the level of the requested threshold for the first 10 years of operation of LHC. A special care and further investigation are needed in the choice of the APV6 internal parameters (currents and voltages), since variations of some of these largely influence the overall performance of the system.

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