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CMS Conference Report

1 March 1999

High Voltage Operation of Heavily Irradiated Silicon Microstrip Detectors

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Abstract

We discuss the results obtained from the $R\&D$ studies, done within the CMS experiment at LHC, related to the behaviour of silicon microstrip prototype detectors when they are operated at high bias voltages, before and after having heavy irradiation, simulating up to 10 years of LHC running conditions. We have found detectors from several manufacturers that are able to work at $V_{bias} > 500\ V$ before and after the irradiation procedure, maintanining an acceptable performance with $S/N > 14$, efficiency close to 100% and few ghost hits.

Presented at *6th Intern. Conf. on Advanced Technology and Particle Physics* , Como, 5-9 october, 1998

Submitted to *Nucl. Phys. B Proc. Suppl.*

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1 INTRODUCTION

The CMS detector (Compact Muon Solenoid) will be one of the experiments installed on the LHC proton-proton collider [1]. The Central Tracker of CMS [2],[3] is divided in three parts: silicon pixels, silicon microstrips, microstrip gas chambers.

The Silicon Strip Tracker (SST) (fig. 1) consists of approximately $70\ m^2$ of instrumented detectors arranged in five cylindrical layers (the barrel), three minidisks (the mini-endcaps) and ten disks for each side (the end-caps). Each mini-disk and disk is further divided into a variable number of rings (from 2 to 4) according to the z distance from the interaction point. The total lenght of the subdetector is $\sim$ 5.6 m and covers the pseudo-rapidity region $|\eta| = 2.5$. The layers 1,2,5 of the barrel and rings 1 and 4 of the disks provide double-sided information, while the rest gives a single-sided measurement.

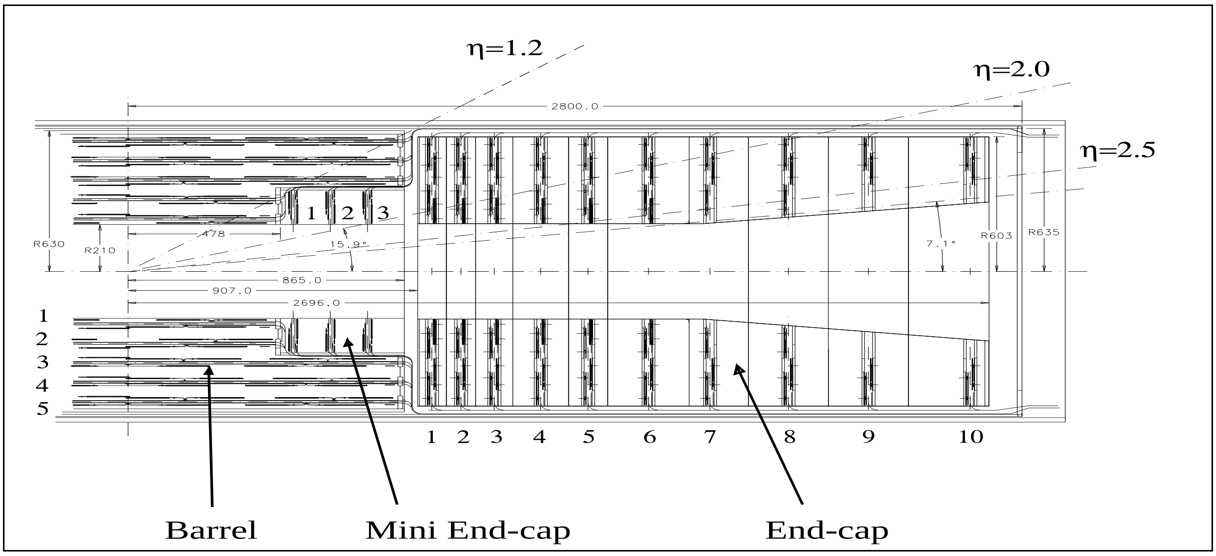

Figure 1: Longitudinal view of half of the Silicon Strip Tracker subdetector of the CMS.

The LHC physics program features proton-proton interactions at $\sqrt{s} \sim 14TeV$ with an initial luminosity of $10^{33}cm^{-2}sec^{-1}$ that should rise after two years up to $10^{34}cm^{-2}sec^{-1}$. This implies an enormous number of charged and neutral particles that will flow through the CMS detector. In particular, the SST first barrel layer will tolerate a flow equivalent to $1.6 \times 10^{13} neutrons\ cm^{-2}\ year^{-1}$, corresponding to an integrated luminosity of $5 \times 10^4 pb^{-1}$, at LHC full luminosity.

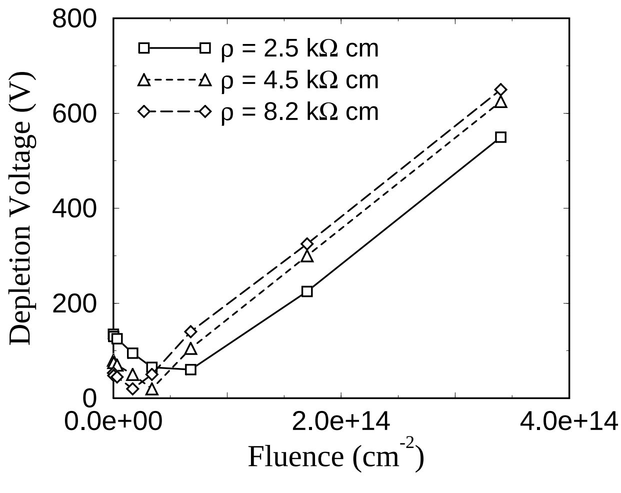

Figure 2: Evolution of the depletion voltage with the fluence for different resistivity values.

This flow will damage the silicon detectors modifying their behaviour and their performances, due to a surface damage (trapping of the holes in the oxide layer with a variation of the interstrip capacitance and a reduction of

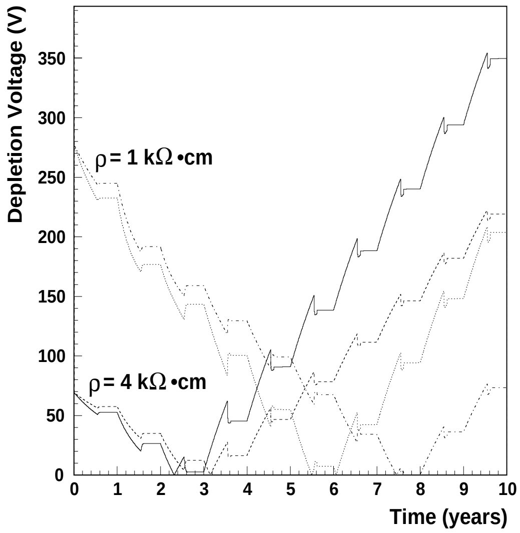

Figure 3: Time evolution of $V_{depletion}$ for two different resistivity, during the first 10 years of LHC. The upper curves for both scenarios incorporate a 1.5 safety factor.

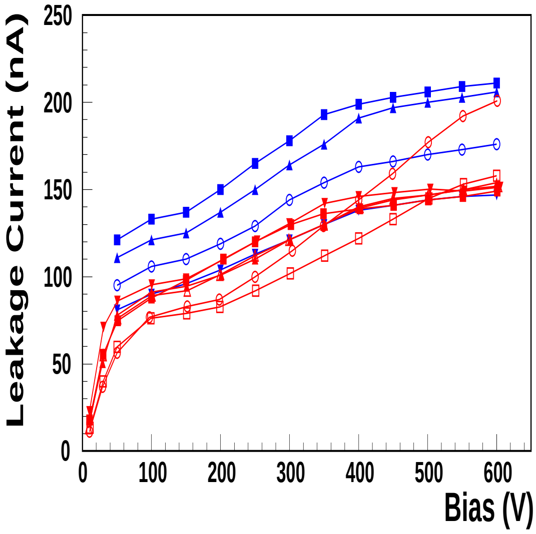

Figure 4: I-V plot for a batch of unirradiated devices produced by Hamamatsu; it should to be noted that no sign of breakdown appears up to $V_{bias} = 600\ V$.

the interstrip isolation) and the bulk damage caused by the lattice defects introduced by the passage of the incident particles, that are reflected into the increased leakage current, the decreased charge collection efficiency and the change in the effective doping concentration of the substrate material. In the next paragraphs we will first show how the radiation damage influences the choice of the working point of the detectors, and then we will examine some performances of the prototypes that satisfy our request of high bias voltage operation.

2 HIGH BIAS VOLTAGE OPERATION

Some preliminary requirements have been used to define which type of sensors should be investigated for our purposes. They should: survive 10 years of LHC running at high luminosity, be easy to build and assembly, cost as low as possible, be capable of operating at low temperatures ($-10\ ^oC$ is the reference value) and at high V_{bias}, be radiation resistant, have low mass.

The low temperature has been choosen to reduce the leakage current of the silicon devices and hence the power dissipation. All these costraints have led us to choose [2] single-sided devices 300 μm thick, with high resistivity ($2\ k\Omega\ cm$), built with the p^+ strips on over $n - bulk$ technology, AC coupled, and biased through polysilicon resistors [4].

Due to the evolution of the effective doping concentration of the substrate material with the radiation damage, the depletion voltage changes accordingly, decreasing from the starting value until the inversion-type point is reached, and then growing again linearly with the fluence. One important parameter that influence the depletion voltage value is the resistivity of the substrate; a simulation of the evolution of $V_{depletion}$ with the fluence for different starting values of the resistivity is shown in fig. 2 [5]. For a 2.5 $k\Omega\ cm$ resistivity the $V_{depletion}$ curve starts at a higher value ($\sim$ 150 V), reaches the inversion point at a higher fluence, and then rise with the same slope of the higher resistivity curve, reaching $V_{depletion}$ $\sim$ 220 V after $2{\times}10^{14}$ neutrons/cm^2, 80 V less that the other curves.

To extrapolate a time evolution of the depletion voltage, a realistic scenario for the LHC and CMS operations has been defined [2], featuring a cycle of one year of data taking divided into a running period at $-10\ ^oC$ (most of the time), a 21 days stand-by at $+15\ ^oC$ and 7 days at $+20\ ^oC$ foreseen for repairs and maintenance. In fig. 1 two sets of evolutions have been studied for different initial resistivity (1 and 4 $k\Omega\ cm$). Each set has a “standard” evolution and another one that includes a 1.5 safety factor. The inversion-type point is reached from 2 to 8 years after the start of data taking, and for all scenarios we have a $V_{depletion} < 350\ V$.

Taking into account the need to run at $V_{bias} \sim 1.5\ V_{depletion}$ to reduce the effects of the increased interstrip

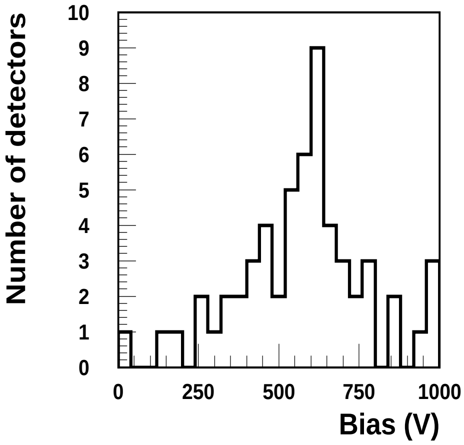

Figure 5: $V_{breakown}$ distribution for a batch of unirradiated devices produced by CSEM; the average $V_{breakown}$ is $\sim$ 580 V, while $\sim$ 70% has a $V_{breakown} > 500\,V$.

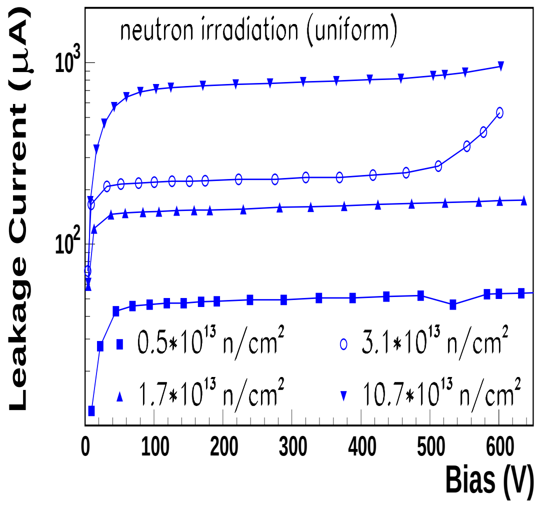

Figure 6: I-V plot for a Hamamatsu device (50 μm pitch) irradiated uniformly with neutron up to $1.1 \times 10^{14}\ neutrons\ cm^{-2}$.

capacitance due to the charge trapping in the oxide region and of the reduced charge collection efficiency, we have concluded that to run with a reasonable safety margin we need to be able to work at V_{bias} 500 V.

3 RESULTS ON PROTOTYPES

3.1 Breakdown Voltage

We have tested devices produced by several manufacturers, in order to check their high bias voltage capability, and we have obtained I-V plots with no sign of breakdown up until $600\ V$ (fig. 1, Hamamatsu). Also looking at the distribution (fig. 2) of the breakdown voltage for a batch of devices manufactured by CSEM, the average $V_{breakown}$ value was $580\ V$ and more than 70% of the devices had a $V_{breakown} > 500\ V$.

Then we irradiated the devices at several fluences, both omogeneously and inomogeneously (the forward detectors will be irradiated in a non-uniform way), with protons and neutrons to test the effects of the damage produced by charged and neutral particles. All these tests (see for example fig. 2) led us to conclude that we could indeed find devices that could stand V_{bias} $500\ V$ without showing any sign of breakdown even after an irradiation equivalent to 10 years of LHC data taking.

To increase the $V_{breakown}$ of the devices we investigated the effect of inserting around the detector multiguard ring structures meant to decrease the voltage drop from the guard ring to the edge of the device, and the results seem to show a further increase of the $V_{breakown}$ both before than after the irradiation [6] [7].

3.2 Signal/Noise ratio

The Signal/Noise ratio results are summarized in fig. 7, where is shown the behaviour of detectors, both unirradiated and irradiated at several fluences, as a function of V_{bias}, expressed in term of overdepletion units. The dark band represents the extrapolation of the most irradiated data of the plot to the LHC data taking conditions, inserting the design noise values for each of the elements of the DAQ chain that are currently missing from the experimental setup used to measure the data (final front-end chip, deconvolution algorithm, optical link).

It is important to note that, even after 10 years of LHC running conditions, we are able to reach 1.5 times the $V_{depletion}$ and that this should ensure a Signal/Noise of $\sim$ 10, good enough to have an high hit finding efficiency.

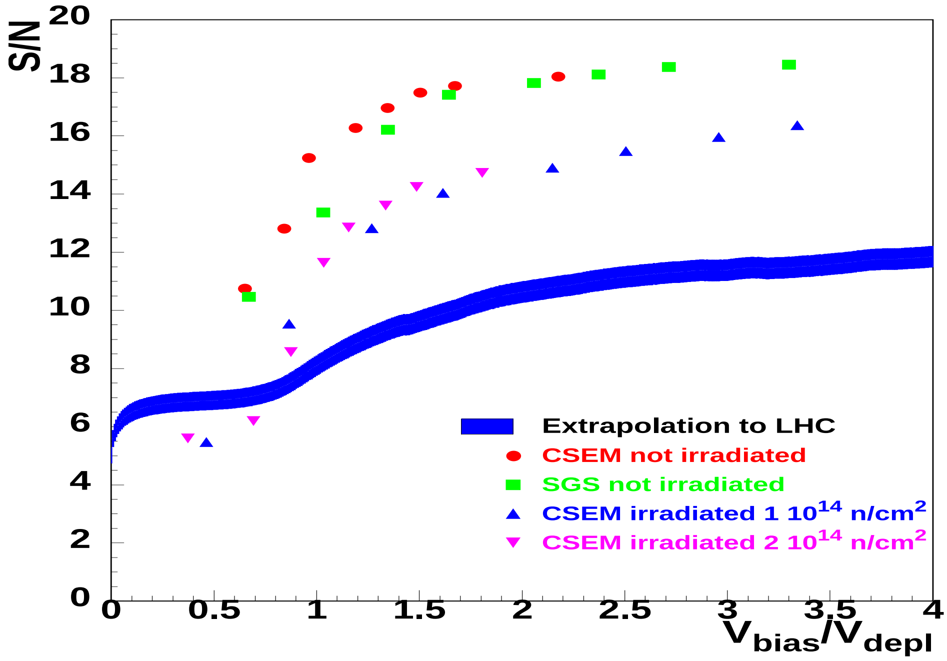

Figure 7: Signal/Noise measured for both unirradiated and irradiated devices. The dark band is the extrapolation to the LHC conditions taking into account the final front-end electronics and the entire DAQ chain.

3.3 Efficiency

Using a standard set of cuts to define the hits, we have measured the hit finding efficiency as a function of the applied V_{bias} (fig. 2). The full efficiency is basically reached just after the $V_{depletion}$ working point.

If we look instead to typical plot of efficiency vs Signal/Noise ratio obtained using a single irradiated detector with different temperature and V_{bias} (fig. 2), we can see that all the points are well aligned along the same curve, and that even at a value of S/N $\sim$ 7.5 the hit finding efficiency is of the order of 95%.

These results are obtained keeping at the same time the level of ghost hits below 1%.

4 CONCLUSIONS

In the framework of the $R\&D$ effort for the CMS Silicon Strip Tracker we have tested several detectors, from different vendors, that are able to reach a working point of $V_{bias} > 500\ V$ at a temperature of -10 ^oC. This is needed to withstand the radiation damage due to at least ten years of normal LHC running conditions.

For such detectors we have found a Signal/Noise ratio $\sim$ 14, that will reduce to $\sim$ 10 if we include all the missing noise contributions foreseen in the final DAQ chain.

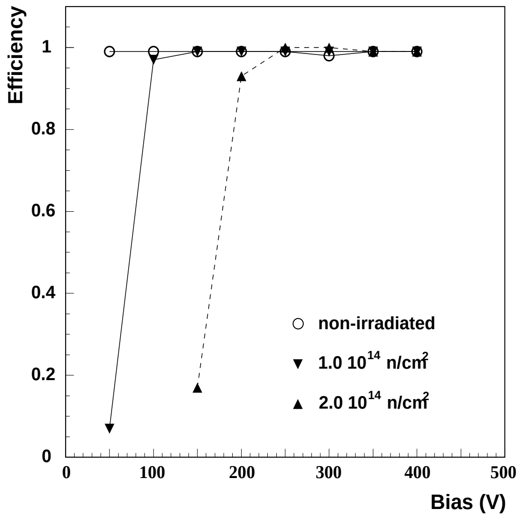

Figure 8: Efficiency vs V_{bias} measured for both unirradiated and irradiated devices (CSEM 75 μm pitch.

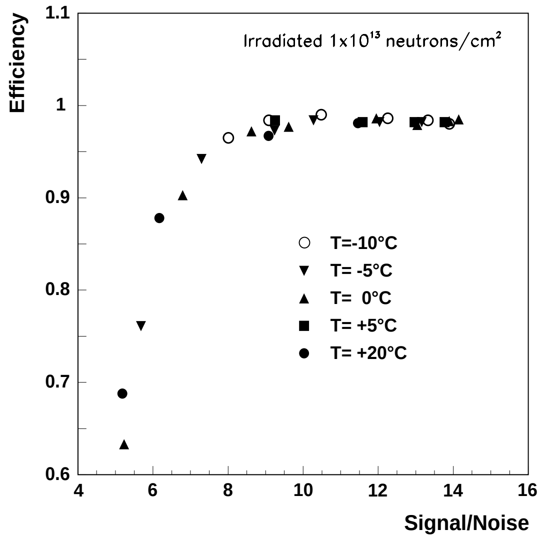

Figure 9: Efficiency vs Signal/Noise for an irradiated device (CSEM, 50 μm pitch) at several temperatures.

This result should be enough to permit an hit finding efficiency close to 100% while keeping the ghost rate at a manageable level (i.e. $< 1\%$).

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