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Characterization of ultra radiation hard pixel detectors for the high luminosity phase of the CMS experiment at the LHC(*)

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Summary. — The High Luminosity upgrade of the CERN Large Hadron Collider (HL-LHC) calls for new radiation tolerant silicon pixel sensors. In the case of the CMS experiment, the innermost tracker layers will have to withstand an integrated fluence up to 2.3×10^{16} n_{eq}/cm^2 (1 MeV equivalent neutrons) while preserving high tracking efficiency. In order to maintain or even improve the performance of the CMS inner tracker in this harsh environment an extensive R&D program has been put in place by the CMS collaboration targeting thin planar and 3D pixel sensors. The basic cell size of the module has an area of 25×100 μm^2 and an active thickness of 150 μm. The modules are read out by the CMS Read Out Chips (CROC) built in 65 nm technology and developed by CMS and ATLAS Collaborations within the RD53 Collaboration. This contribution describes test beam results of the new 3D and planar sensor prototypes read out by a single chip, both before and after irradiation and of the first planar quad sensor, *i.e.*, read out by four chips, before irradiation. The modules performance were evaluated in terms of hit detection efficiency and resolution. The analysis of collected data shows excellent performance even for the irradiated modules.

1. – Overview

To improve the potential for discoveries at the Large Hadron Collider (LHC) a significant luminosity increase of the accelerator is targeted. CERN plans to upgrade the LHC to the high luminosity configuration (HL-LHC) during the Long Shutdown 3, scheduled for the years 2026 - 28, with the goal of achieving a peak luminosity of 5.0×10^{34} cm^{-2}s^{-1} nominal, or even $7.5 \cdot 10^{34}$ cm^{-2}s^{-1} in the ultimate performance scenario. The increased luminosity will be accompanied by a significant increase in the number of collisions per bunch crossing (up to 200), five times higher than the current conditions. The Tracker detector will be significantly upgraded to maintain or even improve the performance of CMS in this harsh environment. In particular, the inner layers of the Tracker, based on silicon pixel modules, will be entirely replaced.

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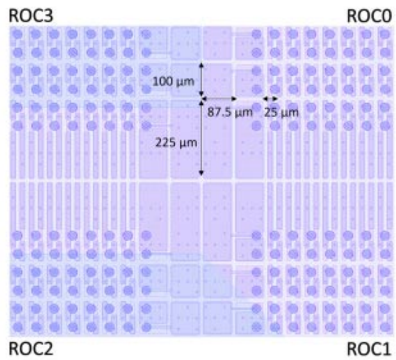

Fig. 1. – Cell geometry of the planar pixel module read out by four CROCs.

During the HL-LHC the new Inner Tracker (IT) will have to withstand up to 1.2 Grad of Total Ionising Dose (TID), a hadron fluence of $2.3 \times 10^{16} \mathrm{n_{eq}/cm^2}$ and cope with hit rates of up to 3.2 $\mathrm{GHz/cm^2}$ for the innermost layer (30 mm from the beam line). Moreover, a trigger latency of 12.8 μs and a trigger rate of 750 kHz are expected [1]. The stringent requirements for a low material budget, capability to sustain high hit rates, and high efficiency and resolution for tracking are met by using detector elements that are highly granular and radiation-hard. The sensors pixel pitch will be 25×100 μm^2 while the total active thickness will be 150 μm. Unlike the present n-in-n type sensors an n-in-p sensor technology is chosen. Two pixel technologies are being considered: planar pixel sensors, where the electrodes are parallel to the sensor surface, and 3D pixel sensors, where electrodes penetrate the bulk material, forming narrow vertical columns. Planar sensors represent the baseline choice for the whole IT except for the innermost layer of the barrel for which instead 3D pixel sensors have been chosen. 3D silicon sensors offer in fact an intrinsic higher radiation tolerance and lower power dissipation because of the shorter distance between the electrodes. However, since the production process is more expensive they are not suitable for large volumes and their use is limited to the regions of highest particle fluences. In order to simplify the detector construction and integration and to minimize the number of required spares, only two types of sensors modules are foreseen, read out either by 1x2 or by 2x2 CMS Read Out Chips (CROC) built in 65 nm technology and developed by CMS and ATLAS Collaborations within the RD53 Collaboration [2].

2. – Planar Pixel Modules

The planar pixel sensors studied in this paper were fabricated by Hamamatsu. The modules, read out by a single CROC, were irradiated up to a fluence of $1 \times 10^{16} \mathrm{n_{eq}/cm^2}$ at the CERN IRRAD Facility with a 24 GeV/c proton beam and tested at the DESY Test Beam Facility with a 5.2 GeV/c electron beam while the non irradiated planar quad module was tested at the Fermilab Test Beam Facility with a 120 GeV/c proton beam. The characterization campaign for the planar HPK sensors read out by one CROC resulted in excellent production yield and very good electrical behavior before and after irradiation (breakdown always above 800 V). The efficiency of the non irradiated module is greater than 99% at around 5 V while, for the irradiated modules, the efficiency is

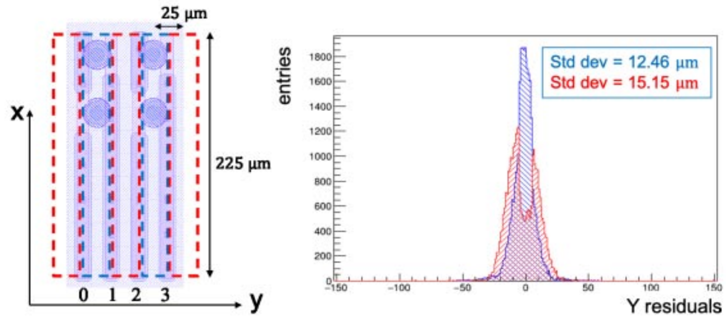

Fig. 2. – Grid of four 25×100 μm^2 pixel cells (left) and residual distributions evaluated for the corresponding sensor regions (right).

greater than 99% at around 400 V. The measured resolution is always lower than the digital resolution along both the 25 μm (y axis) and 100 μm pitch (x axis) as expected.

In addition to the sensors read out by a single chip, a fresh planar quad module was tested for the first time. The module was tuned to an average pixel thresholds of 1100 electrons with a dispersion of about 100 electrons. This module includes standard cells measuring 25×100 μm^2 as well as larger cells that are positioned to bridge the gap between the four CROCs. In fig. 1, a schematic representation of the sensor highlights the different types of cells. The module features two non-standard rows with 25×225 μm^2 pixel cells, four non-standard columns with 87.5×100 μm^2 pixel cells and eight non-standard 87.5×225 μm^2 pixel cells, placed in the center of the module, at the intersection of the 4 CROCs. Figure 2 shows the residual distributions evaluated for the corresponding sensor regions in a grid of four non-standard 25×225 μm^2 pixel cells at $V_{bias} = 100$ V for orthogonal incident tracks on the module. When a track pass through the area where pixels are coupled by bump bonds, regular charge sharing is expected and the residual distribution evaluated between pixel 0 and 1 (or 2 and 3) shows a single peak. Instead, when a track pass through the area where pixels are not coupled by bump bonds (between pixel 1 and 2) the residuals are larger than expected because the neighbors cells (pixel 0 or 3) also register a hit. This results in a double peaked distribution, that slightly spoils the spatial resolution. This deterioration of the resolution can be attributed to the so-called *cross talk* effect due to a parasitic capacitive coupling between two neighbours pixels which causes the charge accumulated in a pixel to spread to other adjacent pixels. For this reason an offline correction of the position estimate is foreseen. However, the *cross talk* effect is dominant only for perpendicular tracks and even for small rotation angles its contribution is expected to be negligible. Studies of the hit detection efficiency were carried out for all cells of the modules. The efficiency is consistently above 99% for both standard and non-standard cells at 120 V. Furthermore, studies of the efficiency, for the entire illuminated region of the module, as function of the bias voltage, show that the efficiency is above 99% even for 20 V bias. The results obtained are therefore very encouraging towards the construction of the High Luminosity phase of the CMS tracker.

3. – 3D Pixel Modules

3D pixel sensors studied in this paper were fabricated by the FBK foundry in Trento, in collaboration with INFN (Istituto Nazionale di Fisica Nucleare, Italy), and by the

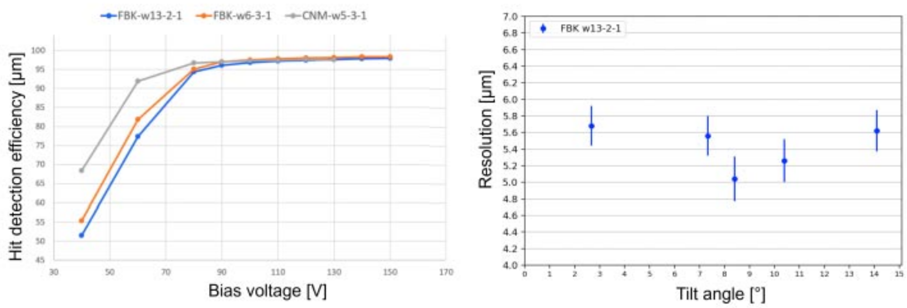

Fig. 3. – Left: Hit detection efficiency as a function of the bias voltage for the three 3D modules. Right: 3D FBK module position resolution as a function of the measured tilt angle for $V_{bias} = 120V$.

CNM foundry (Barcelona, Spain). Three 3D pixel modules read out by a single CROC were irradiated up to a fluence of 1×10^{16} $\mathrm{n_{eq}/cm^2}$ with a 24 GeV/c proton beam at the CERN IRRAD Facility and were tested with a 120 GeV/c pion beam at the CERN SPS Test Beam Facility. The modules were tuned to an average pixel thresholds of 1000 electrons, with a dispersion of about 100 electrons. The hit detection efficiency of the three DUTs as a function of bias voltage is shown in fig. 3 (left) for orthogonal beam incidence. The efficiency plateau starts around 90 V and is around 60 V wide. At lower bias voltages, the CNM module appears to be more efficient, most likely due to improved threshold tuning. At a bias voltage of 130 V, all three modules attain a maximum hit efficiency of $\sim 98\%$ [4] (right). It should be noted that because the sensor columns contain passive material, the hit detection efficiency is decreased at the column boundaries when the beam is orthogonal to the module. As a result, achieving 100% efficiency with orthogonal beam incidence is not possible. In fig. 3 the results of the study of the resolution as a function of incidence angle are shown for one of the DUTs produced by FBK. The resolution is expected to be close to the binary resolution at perpendicular incidence (7.22 μm for a pitch of 25 μm), and to improve with charge sharing as the cluster size increases, reaching an optimal value at the arctangent of the pitch-to-thickness ratio, corresponding to $\approx 9.5°$ for a sensor active thickness of 150 μm. In fact, if particles pass through the pixel detector at this angle they release charge in at least two pixels, which leads to a better hit resolution. The results are in agreement with expectations. As can be seen, the minimal spatial resolution is reached at $\approx 9°$ tilt angle and it is equal to 5 μm for all tested modules, significantly below the digital resolution of $25/\sqrt{12}$ μm.

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