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Beam Test Measurements on Planar Pixel Sensors for the CMS Phase 2 Upgrade

Finn Feindt on behalf of the CMS Tracker group

Abstract

The requirements for the CMS Inner Tracker for the high luminosity upgrade of the Large Hadron Collider (LHC) are driven by the high expected instantaneous luminosity of up to $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The detector will have to withstand a 1 MeV neutron equivalent fluence of up to $2 \times 10^{16} \text{ cm}^{-2}$ at 2.8 cm distance from the beam. To improve the spatial resolution and limit cluster merging in this environment the current pixel size of $100 \times 150 \mu\text{m}^2$ will be reduced by a factor of 6. Planar pixel sensors are the baseline technology for the outer 3 of the 4 pixel layers, where the irradiation level will reach a 1 MeV neutron equivalent fluence of $5 \times 10^{15} \text{ cm}^{-2}$. For the innermost layer 3D sensors are also considered. Several variants of new n^+p -planar pixel sensors with pixel sizes of $50 \times 50 \mu\text{m}^2$ and $100 \times 25 \mu\text{m}^2$ and an active thickness of $150 \mu\text{m}$ have been designed, produced and bump bonded to readout chips. Apart from the pixel size, the design variants differ with respect to the implantation and metalization layout as well as the pixel isolation and biasing scheme. To select the most promising design for the future CMS Inner Tracker, these sensors were irradiated with protons and neutrons up to 1 MeV neutron equivalent fluences of $14 \times 10^{15} \text{ cm}^{-2}$ and characterized at the DESY II test beam facility. The key requirement, a hit efficiency above 99 % at bias voltages below 800 V, is met for sensors proton irradiated to 1 MeV neutron equivalent fluences above $5 \times 10^{15} \text{ cm}^{-2}$, thus demonstrating the suitability of planar sensors for the pixel layers 2 to 4. In addition, the hit efficiency, signal to noise ratio and spatial resolution are determined as a function of the bias voltage, neutron equivalent fluence and angle, for proton and neutron irradiation and for different design variants, providing input for the final choice of the sensor design.

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Abstract—The requirements for the CMS Inner Tracker for the high luminosity upgrade of the Large Hadron Collider (LHC) are driven by the high expected instantaneous luminosity of up to $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The detector will have to withstand a 1 MeV neutron equivalent fluence of up to $2 \times 10^{16} \text{ cm}^{-2}$ at 2.8 cm distance from the beam. To improve the spatial resolution and limit cluster merging in this environment the current pixel size of $100 \times 150 \mu\text{m}^2$ will be reduced by a factor of 6. Planar pixel sensors are the baseline technology for the outer 3 of the 4 pixel layers, where the irradiation level will reach a 1 MeV neutron equivalent fluence of $5 \times 10^{15} \text{ cm}^{-2}$. For the innermost layer 3D sensors are also considered. Several variants of new n^+p -planar pixel sensors with pixel sizes of $50 \times 50 \mu\text{m}^2$ and $100 \times 25 \mu\text{m}^2$ and an active thickness of $150 \mu\text{m}$ have been designed, produced and bump bonded to readout chips. Apart from the pixel size, the design variants differ with respect to the implantation and metalization layout as well as the pixel isolation and biasing scheme. To select the most promising design for the future CMS Inner Tracker, these sensors were irradiated with protons and neutrons up to 1 MeV neutron equivalent fluences of $14 \times 10^{15} \text{ cm}^{-2}$ and characterized at the DESY II test beam facility. The key requirement, a hit efficiency above 99 % at bias voltages below 800 V, is met for sensors proton irradiated to 1 MeV neutron equivalent fluences above $5 \times 10^{15} \text{ cm}^{-2}$, thus demonstrating the suitability of planar sensors for the pixel layers 2 to 4. In addition, the hit efficiency, signal to noise ratio and spatial resolution are determined as a function of the bias voltage, neutron equivalent fluence and angle, for proton and neutron irradiation and for different design variants, providing input for the final choice of the sensor design.

I. INTRODUCTION

THE Large Hadron Collider (LHC) will be upgraded to the High Luminosity Large Hadron Collider (HL-LHC) [1] during the next major shutdown of the machine. In return the LHC experiments will conduct upgrades, known as Phase-2 Upgrade for the CMS detector [2]. The ultimate scenario for the instantaneous luminosity of the HL-LHC is $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. With increasing luminosity the number

of pp-collisions per bunch crossing (pileup) increases to an average of up to 200. After 10 years of operation, the integrated luminosity collected by the CMS experiment is expected to be 3000 fb^{-1} .

For the CMS Inner Tracker, a pixel detector, the current pixel size of $100 \times 150 \mu\text{m}^2$ will be reduced by a factor of 6 to either $50 \times 50 \mu\text{m}^2$ or $100 \times 25 \mu\text{m}^2$. This way, the spatial resolution will be improved and cluster merging can be limited despite the high track multiplicity coming with the high pileup.

The final integrated luminosity corresponds to a 1 MeV neutron equivalent fluence ϕ_{eq} of $2 \times 10^{16} \text{ cm}^{-2}$ and an ionizing dose of 12 MGy in the innermost layer of the pixel detector at 2.8 cm distance from the beam. To maximise charge collection at this high fluence, the thickness of the new sensors will be reduced from $285 \mu\text{m}$ to $150 \mu\text{m}$ to decrease the drift distance and increase the electric field at a given bias voltage. Planar sensors are the baseline technology for all but the innermost layers and rings. In the innermost layers and rings planar sensors compete with 3D sensors [3], of which the latter are not covered in this report.

Planar pixel sensors with different designs have been produced and tested for their suitability for the CMS Phase 2 Inner Tracker. The first aim of this study is to identify those sensor designs which provide a hit efficiency $> 99\%$ up to $\phi_{eq} = 5 \times 10^{15} \text{ cm}^{-2}$ expected in layer 2 of the upgraded pixel detector. To further characterize the sensors, properties like hit efficiency, signal-to-noise ratio and spatial resolution measured as a function of bias voltage, fluence and beam incidence angle are compared for different design variants.

II. PIXEL SENSOR DESIGN

The investigated sensors [4] are planar n^+p sensors with a p^+ backside implant. In order to identify sensor designs fulfilling the efficiency requirements, a number of sensors in different design variants were produced by Hamamatsu Photonics and tested.

All sensors have an active thickness of $150 \mu\text{m}$. The two tested pixel sizes are $50 \times 50 \mu\text{m}^2$ and $100 \times 25 \mu\text{m}^2$. For inter-pixel isolation either p-stop or p-spray technology is used and in general comparable results for both technologies are found. Due to the vendor's recommendation for p-stop pixel isolation, the results presented here focus on that technology.

In Fig. 1 drawings of some design variants with pixel sizes of $100 \times 25 \mu\text{m}^2$ and p-stop isolation are shown. A cross section of the implantation region for one of the p-stop designs is included in Fig. 1a, a top view in Fig. 1b. A design with enlarged implants, where the size of the implant window is

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enlarged from $9 \times 84.5 \mu\text{m}^2$ to $12.5 \times 87.5 \mu\text{m}^2$, is depicted in Fig. 1c (compare Fig. 1b).

A design including a bias dot is shown in Fig. 1d. The bias dot allows measurements of the current-voltage characteristics with grounded pixels before bump bonding to select sensors with breakdown above a specified threshold.

Fig. 1. Sensor design variants with pixel sizes $100 \times 25 \mu\text{m}^2$ and p-stop isolation. In (a) a cross section of the implantation region is shown for the baseline design, while the top view is shown in (b) for a group of 2×2 pixels. The red arrow indicates the position and orientation of the cross section. The bump bond pads (purple circles) are arranged in a staggered pattern matching the ROC4SENS readout chip discussed in III-A. In (c) a design variant with enlarged implants is presented. The gap between n^+ implant and p-stop is reduced from 6 to $5 \mu\text{m}$. In (d) a design variant with a bias dot common to 4 pixels is displayed.

III. SENSOR CHARACTERIZATION

To characterize the sensors and compare the design variants, the produced sensors are bump bonded to a ROC4SENS or RD53A readout chip. They are irradiated with neutrons or protons and finally tested in an electron beam at DESY to compare their performance. In the following section, the readout chips, the irradiation and the setup of the beam test are discussed.

A. Readout Chips

Two readout chips, ROC4SENS and RD53A, are used for the sensor characterization. If not stated otherwise, the former is used. In the following an assembly of sensor and readout chip will be called module.

The PSI ROC4SENS readout chip [5] is dedicated to sensor studies. On arrival of an externally generated trigger signal, the analogue signal is stored in each pixel cell to be read out and digitized by a dedicated FPGA board. This allows for data taking without zero suppression at rates of around 150 Hz. To save disk space only regions of interest, 7×7 pixels in size centered around a pixel above threshold, are digitized with 12 bit resolution and stored. The readout chip has a staggered bump bond pattern with a pitch of $50 \times 50 \mu\text{m}^2$, matching the pattern shown in Fig. 1, to allow for use with both pixel sizes.

The RD53A readout chip is a prototype for operation at the HL-LHC by the CMS and ATLAS collaborations [6]. It demonstrates the applicability of the 65 nm CMOS technology in high energy physics. The chip has 3 analogue front-end flavors, but only the linear front end is used in this study. It is self triggered and stores the time-over-threshold of signals with 4 bit accuracy. For non-irradiated chips a threshold below 1000 electrons is achieved. The bump-bond pads on the chip are not staggered, such that the bump bond pads on the sensor need to be placed on the pixel boundaries for $100 \times 25 \mu\text{m}^2$ pixel size, shown on the bottom of Fig. V-D.

B. Irradiation

After bump bonding to a readout chip the sensor modules were irradiated with protons or neutrons.

The neutron irradiation was performed in the TRIGA Mark II reactor in Ljubljana (TRIGA). The 1 MeV neutron equivalent fluences ϕ_{eq} are 0.5, 3.6, 7.2 and $14.4 \times 10^{15} \text{ cm}^{-2}$, determined using a hardness factor of 0.9 [7].

The proton irradiation was performed at the PS-IRRAD Proton Facility at CERN (PS) with a beam momentum of 24 GeV/c. Contrary to the neutron irradiation, the proton irradiation is nonuniform with an approximately Gaussian beam profile with FWHM between 12.5 and 15 mm. The mean fluences ϕ_{eq} are about 3 and $5.3 \times 10^{15} \text{ cm}^{-2}$, the precise numbers are given in the respective figures. For the sensors bump bonded to the ROC4SENS readout chip, the fluences, efficiencies, and signal to noise are quoted for a circular region with 2 mm radius around the point of highest irradiation. The uncertainties on the fluence are estimated to be 17 % in this case. For the sensors bump bonded to the RD53A readout chip, the fluences are averaged over the area of the linear front end being about 65 mm^2 . The hardness factor used for this calculation is 0.62 [8].

Except for the irradiation, transport and handling, the sensors are stored cold to avoid annealing.

C. Beam Test Setup

The beam tests were performed at the DESY II test beam facility using the EUDET DATURA beam telescope [9]. A schematic sketch of the setup is shown in Fig. 2. DESY II

provides an electron beam with energies between 1 and 6 GeV. If not stated otherwise, a beam energy of 5.2 GeV is used.

The beam telescope consists of 6 MIMOSA-26 planes and is separated into three plane triplets upstream and downstream with respect to the position of the investigated module. Due to the long integration time of 155 μs for MIMOSA-26 planes, tracks in-time with the readout cycle of the investigated module are selected with a CMS Phase 1 pixel module, serving as time reference plane.

Trigger scintillators upstream of the beam telescope provide a trigger signal for the telescope, time reference plane and the investigated module.

The investigated module can be moved remotely in the x and y-directions (orthogonal to the beam axis) and rotated around one axis of choice using a set of two translation stages and one rotation stage. If not stated otherwise, the beam incidence angle is normal to the sensor plane. To limit the leakage current for irradiated sensors, the modules are cooled to -24°C for the setup with the ROC4SENS and -26°C for the setup with the RD53A readout chip.

For the resolution measurements discussed in section V-E, the beam telescope is not used. Instead, 3 modules with the ROC4SENS readout chip are mounted along the beam axis, separated by 20mm, with an adjustable tilt angle (see Fig. 3). In this way, the necessary precision is achieved.

Fig. 2. Sketch of the setup used for the beam test measurements.

Fig. 3. Sketch of the setup for resolution measurements. The circles represent the position of a cluster in each of the three sensor planes in gray. The geometric interpretation of the residual Δx_3 is indicated.

IV. ANALYSIS PROCEDURE

To assess the sensor properties such as hit efficiency, signal-to-noise ratio and spatial resolution, the respective quantities need to be reconstructed from the raw data taken at the beam test.

The analysis of the beam test data starts with an iterative track reconstruction and alignment procedure to determine the relative shifts and rotations of the 8 sensor planes. The next step is a final track reconstruction within the 6 MIMOSA-26 planes, followed by a matching between the tracks and signals in the

time reference plane. These in-time tracks are expected to be in synchronization with the readout cycle of the investigated module, thus its hit efficiency and signal can be defined for them. The definition of the hit efficiency and signal as well as noise and resolution are given as follows.

A. Hit Efficiency

The hit efficiency ϵ and its error σ_ϵ are calculated according to

$$\epsilon = \frac{N_{ht}}{N_t} \text{ and } \sigma_\epsilon = \sqrt{\epsilon(1-\epsilon)/N_t}. \quad (1)$$

N_t denotes the number of in-time tracks reconstructed in the beam telescope passing the fiducial volume of the investigated module. N_{ht} denotes the number of those tracks with a hit in the investigated module within a radius of 0.2 mm. A hit is defined as a pixel over threshold, which is defined as 4 times the noise of the respective pixel. This threshold definition ensures an approximately constant noise rate for all samples and conditions.

B. Signal

The signal is reconstructed for the same track selection as the hit efficiency. For each of the N_{ht} tracks the largest cluster charge within a radius of 0.2 mm around the track is stored. A cluster is defined as a group of adjacent pixels above threshold, its charge is the sum of the pixel charges. The signal is determined as the most probable value (MPV) of a Moyal distribution, with two free parameters, MPV and width, fitted to the distribution of the track selected cluster charges.

C. Noise

The noise level of each pixel is given by the RMS of its response in the absence of particles. It defines each pixels individual threshold as discussed above. To calculate the signal-to-noise ratio under given conditions, the noise is averaged over all pixels inside the area (e.g. 2 mm radius for proton irradiated ROC4SENS modules) considered for the determination of efficiency and signal.

D. Resolution

As discussed above the resolution is measured in a setup of 3 modules with the ROC4SENS readout chip sketched in Fig. 3.

After performing an iterative alignment procedure, the x-position x_i of each cluster in the 3 planes is reconstructed. The residual Δx_3 is defined as

$$\Delta x_3 = x_B - \frac{x_A + x_C}{2}, \quad (2)$$

also indicated in Fig. 3. From the distribution of Δx_3 for selected events, $\sigma_{\Delta x_3}$ is calculated as the RMS of the central 95 % of the entries. Assuming that the resolution is the same for all three sensor planes, the single plane resolution σ_x is given by

$$\sigma_x = \sqrt{\frac{2}{3}} \sigma_{\Delta x_3}. \quad (3)$$

For the characterization of irradiated sensors, the central plane is exchanged with an irradiated one. Given σ_x for the non-irradiated sensors, the resolution for the irradiated sensors is calculated by

$$\sigma_{x,irr} = \sqrt{\sigma_{\Delta x_3,irr}^2 - \frac{1}{2}\sigma_x^2}. \quad (4)$$

V. RESULTS

In the following section the results on hit efficiency, signal-to-noise ratio and spatial resolution are presented for the proton and neutron irradiated sensors.

A. Neutron Irradiated Sensors

In this section the measurements performed on the neutron irradiated sensors are discussed. All sensors are read out with the ROC4SENS readout chip, have a pixel size of $100 \times 25 \mu\text{m}^2$ and the pixel isolation technology is p-stop. The investigated fluences ϕ_{eq} are 0.5 , 3.6 , 7.2 and $14.4 \times 10^{15} \text{ cm}^{-2}$. The sensor design is the design shown in Fig. 1b for the three sensors irradiated to the lower fluences, for the sensor irradiated to the highest fluence it is the design with enlarged implants shown in Fig. 1c.

Fig. 4. Efficiencies as a function of the bias voltage and fluence ϕ_{eq} for neutron irradiated sensors.

In Fig. V-A the hit efficiency measured for the four sensors is shown as a function of the applied bias voltage. The required bias voltages for an efficiency of 99 % are about 25, 85, 250 and 500 V from the lowest to the highest fluence respectively. The highest fluence $\phi_{eq} = 14.4 \times 10^{15} \text{ cm}^{-2}$ is above the fluence $\phi_{eq} = 11.5 \times 10^{15} \text{ cm}^{-2}$ collected in the innermost layer in the case of a replacement after half of the operation time. As discussed in V-B, the radiation damage induced by protons at the same neutron equivalent fluence is higher and so far only proton irradiated sensors irradiated up to $\phi_{eq} =$

$5.4 \times 10^{15} \text{ cm}^{-2}$ were characterized. Thus further studies need to be conducted in order to test if planar sensors satisfy the requirements for the innermost layer.

Fig. 5. Signal-to-threshold ratio as a function of the bias voltage and fluence ϕ_{eq} for neutron irradiated sensors.

In general, the reason for the reduction of the hit efficiency with increasing fluence is two fold: Due to trapping of charge carriers the signal decreases with increasing fluence, while the noise increases with fluence.

In Fig. V-A the signal-to-threshold measured for the four sensors is shown as a function of the applied bias voltage. The threshold is chosen as four times the noise — therefore the noise rate stays constant — to ensure a fair comparison between the measurements taken under different conditions. It should be said that noise as a function of bias voltage is constant to within 5 %, while it doubles from the lowest to the highest fluence. However the variation shown in the figure is by far dominated by the reduction of signal, caused by the reduction of collected charge.

Fig. V-A shows the inefficiency ($1 - \text{efficiency}$) as a function of the signal-to-threshold ratio. Independent of the fluence, the three sensors with the standard design reach an efficiency of 99 % at a signal-to-threshold ratio of about 3. For the design with the enlarged implants a signal-to-threshold ratio of about 2.5 is sufficient due to the reduced inefficiency close to the pixel edges discussed in V-C.

B. Neutron and Proton Irradiated Sensors

Next we attempt to quantify the different impact of neutron and proton irradiation [10] on the performance of the sensors.

The efficiency as a function of the bias voltage for two sensors irradiated with protons to $\phi_{eq} = 5.2$ and $5.4 \times 10^{15} \text{ cm}^{-2}$ is shown in Fig. V-B. One of the two sensors is bump bonded to the ROC4SENS readout chip, the other to the RD53A

Fig. 6. Efficiency as a function of signal-to-threshold ratio and fluence ϕ_{eq} for neutron irradiated sensors.

Fig. 7. Efficiency as a function of bias voltage for proton and neutron irradiated sensors. All ROC4SENS modules are measured at $-24\text{ }^{\circ}\text{C}$.

readout chip. For comparison, the two intermediate neutron fluences from Fig. V-A are included. It is concluded that the proton irradiated modules require about 400 V higher operating voltage for an efficiency of 99 %, for which there are two reasons.

One is the higher (factor of 30) ionizing dose deposited by the proton beam. Since the ROC4SENS readout chip is more sensitive to ionizing radiation, the steep rise to about

95 % occurs at higher bias voltages¹. The second reason is the difference in bulk damage, which is shown in [11] for neutron and pion irradiation.

These measurements show that the tested sensors reach an efficiency of 99 % for bias voltages significantly below 800 V for the fluences expected in the second layer of the upgraded pixel detector.

C. Sensor Design Comparisons

To choose the best sensor layout for the upgraded detector, different designs are compared after irradiation.

Fig. 8. Efficiency as a function of bias voltage for proton irradiated sensors with and without enlarged implants.

Larger implants are expected to yield higher efficiency, but potentially lead to increased risk of breakdown before irradiation. Current-voltage measurements were performed on about 70 sensors with enlarged implants, and no evidence of breakdown was observed. In addition, the direct comparison in Fig. V-C indeed shows a higher efficiency for the design with enlarged implants at the same bias voltage. As shown in Fig. V-C this is due to reduced efficiency losses at the pixel boundaries. Given the excellent performance of the designs with enlarged pixel implants, this design will be further tested in the next prototyping steps.

The comparison of sensors with pixel sizes of $50 \times 50 \mu\text{m}^2$ and $100 \times 25 \mu\text{m}^2$ shown in Fig. V-C demonstrates only minor differences. The decision between those two options will be driven by physics requirements, cross-talk [12] and performance at oblique track angles.

¹The module with the ROC4SENS readout chip reaches higher efficiencies at 800 V, because approximately 0.5 % of masked pixels for the module with the RD53A readout chip are included in the analysis.

Fig. 9. Efficiency as a function of position inside one pixel along the 100 μm direction. The results for sensors with and without enlarged implants are shown at 300 and 800 V. On the bottom one pixel cell of the standard p-stop design is shown. At 300 V the efficiency around the pixel boundaries at 0 and 100 μm is about 3 % higher for the design with enlarged implants, while the efficiencies are all within 1 % in the central region.

D. Charge Losses at the Bias Dot

For sensors with a bias dot, charge losses are expected when tracks hit the bias dot with an angle close to the sensor normal. To assess those losses in detail, the efficiency as a function of the in-pixel position is shown in Fig. V-D for angles between 0 and 33°. The investigated sensor is read out by an RD53A readout chip and was irradiated with protons to a fluence ϕ_{eq} of $5.6 \times 10^{15} \text{ cm}^{-2}$.

It is observed that angles larger than 22° are needed to overcome the efficiency loss at the bias dot which is as high as 30 % for 0°. Since angles close to 0° are expected to be frequent in the forward pixel detector, the design without a bias dot is clearly favoured. However, designs with a bias dot will be included in future prototype studies, since they offer the possibility of being tested before bump bonding.

E. Spatial Resolution

In Fig. 12 the single hit resolution along the 25 μm pitch direction is shown as a function of the angle between the beam and normal incidence, measured with non-irradiated sensors and with one sensor proton irradiated to $\phi_{eq} = 2.1 \times 10^{15} \text{ cm}^{-2}$. In addition, the cluster size, the number of pixels in a cluster, is shown.

The best resolution for the irradiated and non-irradiated sample is obtained close to $9.5^\circ = \text{atan}(\frac{25}{150})$, where the average cluster size is about 2. In general, the degradation of the resolution due to the irradiation is between 1 μm and 2.5 μm .

The measurements were performed at a beam energy of 5.6 GeV. At this energy, multiple scattering has a significant

Fig. 10. Efficiency as a function of bias voltage for sensors with pixel sizes of 50 $\times$ 50 μm^2 and 100 $\times$ 25 μm^2 .

Fig. 11. Efficiency as a function of position inside two pixels along the 100 μm direction for various track angles. The track angle is defined with respect to the sensor normal, the inclination is in the 100 μm direction. The measured sensors are read out by an RD53A readout chip, a top view of the design is included in the figure. The sensor was irradiated with protons to a fluence ϕ_{eq} of $5.6 \times 10^{15} \text{ cm}^{-2}$.

contribution to the measured resolution. To correct for this effect, a scan of the beam energy was performed. An intrinsic hit resolution of $2.03 \pm 0.01 \mu\text{m}$ was found for the non-irradiated sensor at the optimal angle when extrapolating to infinite energy.

Fig. 12. Spatial resolution (full symbols, left axis scale) and average cluster size (empty symbols, right axis scale) versus beam incident angle with respect to normal incidence. The error bars indicate the uncertainty on the angle. Note that different design variants were used for both measurements.

VI. CONCLUSION AND OUTLOOK

This study demonstrates that planar sensors reach efficiencies of 99 % for beam incidence normal to the sensor plane and at voltages between 400 and 500 V after neutron and proton irradiation to fluences ϕ_{eq} of up to 14.4 and $5.4 \times 10^{15} \text{ cm}^{-2}$ respectively. Both values are above the fluence expected in the second layer of the upgraded CMS Inner Tracker which is about $5 \times 10^{15} \text{ cm}^{-2}$. Studies for incident angles up to 40° are presented in [12] and demonstrate performance within specification up to this angle, while larger angles are to be studied in the future. Samples, proton irradiated to $\phi_{eq} = 11.5 \times 10^{15} \text{ cm}^{-2}$, expected in the innermost layer in the case of a replacement after half of the Inner Tracker lifetime, are foreseen to be tested to check for the applicability of planar sensors even in the innermost layer.

The final choice of the sensor design is still open, but the preference for p-stop sensors with an enlarged implant is indicated by this study. Designs without a bias dot are favoured due to measured efficiency losses at the bias dot. The decision between pixel sizes of $50 \times 50 \mu\text{m}^2$ and $100 \times 25 \mu\text{m}^2$ will be driven by physics requirements, cross-talk [12] and performance at oblique track angles.

The intrinsic single plane resolution along the $25 \mu\text{m}$ pitch direction was shown to be $2.03 \pm 0.01 \mu\text{m}$ for the non-irradiated sample at the optimal angle, while the degradation of the resolution after proton irradiation to $\phi_{eq} = 2 \times 10^{15} \text{ cm}^{-2}$ is between $1 \mu\text{m}$ and $2.5 \mu\text{m}$ between 0 and 30° .

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