The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

26 February 2020 (v5, 03 August 2020)

Development of Planar Pixel Sensors for the CMS Inner Tracker at the High-Luminosity LHC

Georg Steinbrück for the CMS Tracker Group

Abstract

The LHC is planning an upgrade program which will bring the luminosity up to about $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in 2027, with the goal of delivering an integrated luminosity of 3000 or even 4000 fb^{-1} by the end of 2037. This High Luminosity phase, HL-LHC, will present new challenges of higher data rates and unprecedented radiation levels for the pixel detector. A fluence of $2.3 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$, or equivalently 12 MGy, is expected for the inner layer of the CMS Inner Tracker (IT) for 3000 fb^{-1} of integrated luminosity. To maintain or even improve the performance of the present system, new technologies have to be exploited for the so-called Phase-2 upgrade. Among them is the future version of front-end chips in 65 nm CMOS technology by the CERN RD53 Collaboration, which supports small pixel sizes of 50×50 or $100 \times 25 \mu\text{m}^2$ and low pixel charge thresholds ($\approx 1000 \text{ e}^-$). Thin planar n-in-p type silicon sensors with a thickness of the active layer of $150 \mu\text{m}$, segmented into pixel sizes of $100 \times 25 \mu\text{m}^2$ or $50 \times 50 \mu\text{m}^2$, will be used throughout most of the IT. They have been shown to allow for a good detector resolution that is much more stable with respect to radiation damage compared to the Phase-1 detector. CMS has launched several R&D submissions for the development of suitable planar silicon sensors at Hamamatsu Photonics K.K. and FBK Trento. We present results for measurements on such prototype sensors bump bonded to the RD53A prototype chip developed by the RD53 Collaboration at CERN. Different pixel cell designs are compared and evaluated in beam tests at CERN, DESY and FNAL for spatial resolution and hit efficiency at various track angles before and after irradiation. As an example, hit efficiencies of 99% at vertical incidence were reached after irradiation to $5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, which corresponds to the layer 2 lifetime fluence of the CMS IT.

Presented at *HSTD12 12th International Hiroshima Symposium on the Development and Application of Semiconductor Tracking Detectors*

Development of planar pixel sensors for the CMS Inner Tracker at the High-Luminosity LHC

G. Steinbrück for the CMS Tracker Group*

*Institute for Experimental Physics, University of Hamburg,
Luruper Chaussee 149, 22761 Hamburg, Germany.*

Abstract

The LHC is planning an upgrade program which will bring the luminosity up to about $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in 2027, with the goal of delivering an integrated luminosity of 3000 or even 4000 fb^{-1} by the end of 2037. This High Luminosity phase, HL-LHC, will present new challenges of higher data rates and unprecedented radiation levels for the pixel detector. A fluence of $2.3 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$, or equivalently 12 MGy, is expected for the inner layer of the CMS Inner Tracker (IT) for 3000 fb^{-1} of integrated luminosity. To maintain or even improve the performance of the present system, new technologies have to be exploited for the so-called Phase-2 upgrade. Among them is the future version of front-end chips in 65 nm CMOS technology by the CERN RD53 Collaboration, which supports small pixel sizes of 50×50 or $100 \times 25 \mu\text{m}^2$ and low pixel charge thresholds ($\approx 1000 \text{ e}^-$). Thin planar n-in-p type silicon sensors with a thickness of the active layer of $150 \mu\text{m}$, segmented into pixel sizes of $100 \times 25 \mu\text{m}^2$ or $50 \times 50 \mu\text{m}^2$, will be used throughout most of the IT. They have been shown to allow for a good detector resolution that is much more stable with respect to radiation damage compared to the Phase-1 detector. CMS has launched several R&D submissions for the development of suitable planar silicon sensors at Hamamatsu Photonics K.K. and FBK Trento. We present results for measurements on such prototype sensors bump bonded to the RD53A prototype chip developed by the RD53 Collaboration at CERN. Different pixel cell designs are compared and evaluated in beam tests at CERN, DESY and FNAL for spatial resolution and hit efficiency at various track angles before and after irradiation. As an example, hit efficiencies of 99% at vertical incidence were reached after irradiation to $5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, which corresponds to the layer 2 lifetime fluence of the CMS IT.

Keywords: Tracker, Pixel sensors, Beam test, Radiation damage.

1. Introduction

In the High Luminosity running phase of the LHC (HL-LHC), starting in 2027, the instantaneous luminosity will be increased by a factor of 5-7 compared to the nominal LHC, and a total integrated luminosity of 3000 or even 4000 fb^{-1} will be delivered. The HL-LHC is expected to run at 13 or 14 TeV with a bunch-crossing separation of 25 ns and up to 200 events (pileup) per crossing at the peak luminosity. To maintain or even improve the physics capability of the CMS experiment in this challenging environment, CMS will undergo a major upgrade in the long shutdown before the HL-LHC, LS3. The entire tracking system will be replaced, as seen in Fig. 1 [1]. It consists of an Outer Tracker (OT) and an Inner Tracker (IT) with a pseudorapidity coverage up to about $|\eta| = 4$.

At the foreseen inner pixel radius of 3 cm, a fluence of particles corresponding to a non-ionizing energy loss (NIEL) of $\Phi = 2.3 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ and a total ionizing dose (TID) of 12 MGy will be reached after ten years of operation corresponding to an integrated luminosity of 3000 fb^{-1} . For vertex detection, CMS will reduce the pixel size by a factor of six with respect to the current detector. Currently, both square pixels,

Figure 1: Layout of the CMS Tracker for Phase-2, consisting of the OT and IT. The IT comprises a short barrel section (TBPX), eight endcap discs (TFPX), and four forward discs (TEPX) on each side. In the IT, pixel detector modules with four readout chips (2x2), yellow, and two readout chips (1x2), green, are used [1].

*Corresponding author. Email: georg.steinbrueck@desy.de

$50 \times 50 \mu\text{m}^2$, and rectangular pixels, $100 \times 25 \mu\text{m}^2$, are considered. Since both options are compatible with the $50 \times 50 \mu\text{m}^2$ bump bond pattern of the readout chip currently under development by the CERN RD53 Collaboration [2], the final decision will be taken when the two options have been studied in more detail.

Fine pitch planar silicon pixel sensors with an active thickness of $150 \mu\text{m}$ are the baseline choice for the entire pixel detector except for the innermost TBPX layer and the inner ring of TFPX, where 3D sensors are considered as an option. In this paper, planar pixel sensors for the IT are discussed. Several R&D submissions of prototype planar pixel sensors for the CMS Phase-2 upgrade were launched at Hamamatsu Photonics K.K. (HPK) [3] and at FBK, Trento [4]. These wafers contain small sensors for a variety of readout chips including the ROC4Sens R&D readout chip [5], and the RD53A chip developed by the CERN RD53 Collaboration. Both chips have $50 \times 50 \mu\text{m}^2$ bump bond patterns.

The RD53A chip is a half-size prototype of the final ATLAS and CMS chip, with 76800 pixels, produced in 65 nm CMOS technology at TSMC [6]. It is radiation hard and features serial powering capabilities. It contains three sections with different analog front-ends, called synchronous, linear and differential front-end. The results presented in this paper are for the linear front-end, as this is the choice for the final CMS readout chip.

The ROC4Sens chip, developed at the Paul Scherrer Institute in Switzerland based on the PSI46 chip [7] (IBM 250 nm), allows for detailed charge collection studies due to its non-sparsified readout.

All results shown in this paper are for sensors bump bonded at Fraunhofer IZM [8].

2. Planar Pixel Sensor Development

Planar pixel sensors for the CMS IT have been developed with HPK and at FBK, Trento. Details about the Hamamatsu wafer design can be found in Ref. [9]. In this paper, characterisation and evaluation results for HPK and FBK prototype sensors are shown and compared. The goal of the R&D program is the development of planar sensors which fulfill the requirements listed in Table 1.

CMS is evaluating sensors with and without a punch through bias dot (PT) [10]. A bias dot is a small implant isolated from the pixel implant by a small gap. It is connected to a metal pad, routed to a grid, and provides a high resistive punch through connection to all pixels. It allows to bias the sensors before bump bonding to readout chips. Bad sensors are identified by their current-voltage characteristics. After bump bonding to readout chips, the DC coupled pixels are grounded via the bump bond connection to the preamplifier. The bias dot area always introduces some hit inefficiency, especially for perpendicular tracks. As an alternative, the FBK wafers included a temporary metal layer for measuring current-voltage curves for sensors on the wafer for sensors without a bias dot. This temporary metal was removed before bump bonding using chemical etching.

Table 1: Selected requirements for planar pixel sensors. The full depletion voltage and the hit efficiency are denoted by V_{depl} and hit ϵ , respectively.

Parameter	Value	Measured at
polarity	n^+p	
active thickness	$150 \mu\text{m}$	
pixel size	$50 \times 50 \mu\text{m}^2$ $100 \times 25 \mu\text{m}^2$	
breakdown voltage	300 V	before irradiation
breakdown voltage	800 V	after $5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$
leakage current at $V_{depl}+50 \text{ V}$	$0.75 \mu\text{A}/\text{cm}^2$	before irradiation
leakage current at 600 V	$45 \mu\text{A}/\text{cm}^2$	after $5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$
hit ϵ before irradiation	99%	$V_{depl}+50 \text{ V}$
hit $\epsilon > 5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$	99%	800V, -20°C
hit $\epsilon > 1 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$	98%	800V, -20°C

2.1. Radiation Hardness Studies

A major focus of this work is to evaluate the performance of thin planar pixel sensors up to the end of the HL-LHC lifetime by irradiating them with reactor neutrons or protons to the expected fluences and testing them in the lab and in beam tests. Different assemblies of an HPK sensor bump bonded to an RD53A readout chip were irradiated with protons and evaluated at beamline 21 at the DESY-II beam test facility [11] using the EUDET telescope DATURA [12]. DESY-II is an electron/positron synchrotron delivering beams with energies between 1 GeV and 6 GeV. An overview of the tested samples and their measurement conditions is given in Table 2. The hit efficiency versus bias voltage for inclined tracks is shown in Fig. 2 after proton irradiation at the ZAG Zyklotron AG Karlsruhe and at the CERN PS to fluences corresponding approximately to the lifetime fluence of layer 2 of the barrel pixel detector, $5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$. The efficiency is shown for assemblies with $100 \times 25 \mu\text{m}^2$ and $50 \times 50 \mu\text{m}^2$ pixel size and for sensors with and without punch through bias dots. The sensor without punch through bias dot reaches 99% efficiency at approximately 300 V, while the sensors with bias dots need higher voltages. In Fig. 3, the hit efficiency is shown for an irradiated HPK module with $100 \times 25 \mu\text{m}^2$ pixel size and punch through bias dot. The efficiency is plotted as a function of the position in the long-pixel direction within a 2×2 pixel cell in for a variety of track inclination angles. The corresponding sensor cell layout is also shown. The hit efficiency dips in the vicinity of the bias dot, an effect that only disappears at angles around 25° .

Similarly, the hit efficiency for vertical beam incidence versus bias voltage is shown for irradiated FBK sensor modules with and without punch through bias dot in Fig. 4, top. The overall hit efficiency is larger for the module without punch through bias dot, and this module reaches 99% efficiency even at vertical beam incidence. The bottom plot shows the hit effi-

Table 2: Overview of tested devices with reference to the figures in which they appear, and their measurement conditions. If not denoted otherwise, the sensors were bump bonded to RD53A readout chips, whereas the sensors bump bonded to ROC4Sens chips are denoted by "R4S". Devices with punch through biasing (PT) and without (no PT) were tested. The fluence Φ is in units of $10^{15} \text{ n}_{eq}/\text{cm}^2$. Irradiations were done either with protons at the CERN PS (23 GeV), or at Karlsruhe (Ka, 23 MeV), or with reactor neutrons at Ljubljana (n). The thresholds (thr) are given in units of electrons for the RD53A assemblies after threshold tuning and charge calibration. For the ROC4Sens samples, the charge calibration is less straightforward and no numbers are given. A detailed discussion on sensor studies with irradiated ROC4Sens assemblies can be found in Ref. [13].

Fig.	Type	Φ	thr [e]	T [°C]
2/6	HPK 100x25 no PT	5.2 PS	1300	-26
2/10	HPK 50x50 PT	5.3 Ka	1200	-25
2	HPK 50x50 PT	6.6 PS	1400	-26
2	HPK 100x25 PT	5.6 PS	1600	-26
3	(same module)	5.6 PS	1500	-26
4	FBK 50x50 no PT	5.0 PS	1400	-27
4/5	FBK 50x50 PT	5.0 PS	1200	-27
6	HPK 100x25 R4S no PT	0.5 n		-24
6	HPK 100x25 R4S no PT	3.6 n		-24
6	HPK 100x25 R4S no PT	7.2 n		-24
6	HPK 100x25 R4S no PT	14.4 n		-24
6/7	HPK 100x25 R4S no PT	5.4 PS		-24
7	HPK 100x25 R4S no PT	5.4 PS		-24
7	HPK 100x25 R4S no PT	5.4 PS		-24
8	HPK 100x25 PT	0	700	RT
8	(same module)	0	1200	RT
10	HPK 100x25 no PT	0	1000	RT
10	HPK 50x50 no PT	0	700	RT

ciency versus track inclination angle for the sensor with punch through bias dot. The hit efficiency within a 2×2 pixel cell for the module with punch through bias dot operated at 390 V is shown for three different inclination angles in Fig. 5. The efficiency is reduced in the region around the bias dot. This inefficiency largely disappears at 20° .

In this study, the highest fluences were reached for neutron-irradiations at the TRIGA reactor in Ljubljana. The hit efficiency versus bias voltage for neutron irradiated HPK sensors bump bonded to the ROC4Sens chip is shown in Fig. 6 (top plot) for several fluences. For the highest fluence, $1.4 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$, a hit efficiency of 99% is reached at 500 V. Figure 6 (bottom plot) shows the hit efficiency versus bias voltage for sensors bump bonded to the ROC4Sens chip irradiated with neutrons and protons for comparison. It can be seen that the efficiency after proton irradiation is much lower up to bias voltages of 500 V for the proton irradiated ROC4Sens assembly, likely due to a combination of more severe bulk damage after proton irradiation for a given 1 MeV neutron equivalent fluence, a sign that NIEL-scaling is violated, and stronger damage to the readout chip due to ionizing radiation. The same figure also shows the efficiency for a sensor assembly with the RD53A readout chip irradiated with protons. An efficiency of 99% is reached around 400 V. The difference between the two proton irradiated assemblies is likely due to the more radiation

Figure 2: Hit efficiency for inclined tracks versus bias voltage for proton-irradiated HPK pixel sensor modules with $100 \times 25 \mu\text{m}^2$ and $50 \times 50 \mu\text{m}^2$ pixel size. The inclination angles with respect to perpendicular beam incidence were 34° for the $100 \times 25 \mu\text{m}^2$ modules, and 18° (green) and 30° (black) for the $50 \times 50 \mu\text{m}^2$ modules.

Figure 3: Hit efficiency for an HPK-module with $100 \times 25 \mu\text{m}^2$ pixel size and punch through bias dot irradiated with protons to $5.6 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$. The module was operated at 775 V with a pixel threshold of 1.5 ke. The efficiency is projected onto a double cell along the $100 \mu\text{m}$ pixel axis. The layout showing a 2×2 pixel cell for the same module is shown as an insert.

hard design of the RD53A chip manufactured in 65 nm CMOS technology.

2.2. Implant Size Optimization

A pixel sensor with $100 \times 25 \mu\text{m}^2$ cell size with an enlarged implant with respect to the standard cell was produced by HPK for the ROC4Sens readout chip. The hit efficiency versus bias voltage is shown in Fig. 7 after proton irradiation to $5.4 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$ for a standard-size implant sensor with p-stop pixel isolation, and for two identical sensors with enlarged pixel implants. The sensors with enlarged implants reach a hit efficiency of 99% at an operation voltage at least 100 V less than that required for the sensor with a standard implant. The bottom plot shows a cross section of the device.

2.3. Cross Talk

A cross talk of around 10% has been observed in the $100 \times 25 \mu\text{m}^2$ pixel sensors bump bonded to RD53A chips owing to

Figure 4: Hit efficiency at vertical beam incidence versus bias voltage for proton-irradiated FBK pixel sensor modules with $50 \times 50 \mu\text{m}^2$ pixel size and with punch through bias dot (PT) and without (no PT). The module with bias dot was operated at a pixel threshold of 1.2 ke, the module without bias dot at a threshold of 1.4 ke (top). Hit efficiency versus incidence angle for proton-irradiated FBK pixel sensor modules with $50 \times 50 \mu\text{m}^2$ pixel size with punch through bias dot operated at 390 V (bottom).

an unavoidable pairwise overlap between the metal and the implant. This overlap is due to a combination of the mapping of $100 \times 25 \mu\text{m}^2$ pixels to the $50 \times 50 \mu\text{m}^2$ bump bond pattern of the RD53A readout chip, and the required bump bond pad and implant sizes. As a result, when running with a low pixel threshold of 700 electrons, in 72% of the cases the first pixel in a cluster has an even row number, while at 1200 electrons, this is the case in only 53% of the cases (Fig. 8). TCAD simulations indicate that the capacitive coupling to the neighbor pixel can be reduced by $\approx 30\%$ with a semi-circular cutout in the implant (Fig. 9). This design has been implemented for recent submissions to FBK and HPK and will be evaluated in the near future.

2.4. Spatial resolution

The spatial resolution of the pixel sensor modules is determined using tracks reconstructed in the beam test telescope, corrected for multiple scattering effects. The resolution as a function of turn angle is shown in Fig. 10 (top) for a non-

Figure 5: Hit efficiency within a 2×2 pixel cell at vertical beam incidence for proton-irradiated FBK pixel sensor modules with $50 \times 50 \mu\text{m}^2$ pixel size and with punch through bias dot. The module was operated at 390 V. The inclination angle of the modules are 0° (top), 12° (center), and 20° (bottom).

irradiated $100 \times 25 \mu\text{m}^2$ pixel sensor without punch through bias dot operated at 120 V. The sensors used for this study were bump bonded to RD53A readout chips. A minimum of $2.3 \mu\text{m}$ is reached for an optimal angle of 8.5° . The bottom plot shows the spatial resolution for a non-irradiated $50 \times 50 \mu\text{m}^2$ pixel sensor without punch through bias dot operated at 120 V, and for a $50 \times 50 \mu\text{m}^2$ pixel sensor with punch through bias dot after proton-irradiation to $5.3 \times 10^{15} n_{\text{eq}}/\text{cm}^2$, operated at 800 V. While the resolution is similar at vertical incidence and approximately the digital resolution ($\text{pitch}/\sqrt{12}$), the angle for optimal resolution is shifted to a larger value after irradiation, owing to the fact that the charge is collected only for part of the sensor depth, and the resolution deteriorates at large angles for the irradiated device.

3. Summary and conclusions

For the HL-LHC phase CMS will completely replace its central tracking detector. The new Inner Tracker consists of barrel, forward and forward extension regions and will have an angular coverage up to $|\eta| = 4.0$. The requirements on the pixel detector are very demanding in terms of radiation hardness and track separation in a high density environment.

In this paper, studies focussing on the performance of small prototype planar sensors produced at FBK, Trento and Hamamatsu Photonics (HPK) before and after irradiation are dis-

Figure 6: Hit efficiency at vertical beam incidence versus bias voltage for neutron-irradiated HPK pixel sensor modules with $100 \times 25 \mu\text{m}^2$ pixel size bump bonded to the ROC4Sens readout chip (top). Hit efficiency at vertical beam incidence versus bias voltage for neutron- and proton-irradiated HPK pixel sensor modules with $100 \times 25 \mu\text{m}^2$ pixel size bump bonded to the ROC4Sens readout chip and for a proton-irradiated RD53A sensor module for comparison (bottom). The sensors have no punch through bias dot.

cussed. Most modules consist of sensors bump bonded at Fraunhofer IZM to the RD53A prototype chip developed at CERN, while some studies were performed with the ROC4Sens R&D chip developed at PSI.

Planar sensors have been shown to fulfill the requirements for the second layer of TBPX or the inner ring of TFPX, where the lifetime fluence is about $5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$. Hit efficiencies of 99% were measured in beam tests both for FBK and HPK sensor modules. Considerably lower voltages are required after irradiation to reach an efficiency of 99% (or any given lower efficiency) when sensors without a bias dot are used. The inefficiencies in the bias dot region are especially pronounced at vertical beam incidence, which is important for tracking in the forward detector regions. Therefore, sensors without punch through bias dot are now the baseline for CMS.

For a sensor with a pixel size of $100 \times 25 \mu\text{m}^2$ with a turn angle of 8.5° a resolution of $2 \mu\text{m}$ has been achieved.

4. Acknowledgements

This work was supported by the German Federal Ministry of Education and Research (BMBF), and the Italian National In-

Figure 7: Hit efficiency versus bias voltage for pixel sensor modules with $100 \times 25 \mu\text{m}^2$ pixel size after proton irradiation to $5.4 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$ for a standard-implant sensor with p-stop pixel isolation, and for two identical sensors with enlarged pixel implants (top). Cross section of the pixel cell showing the increase in implant size (bottom).

stitute for Nuclear Physics (INFN); the project received funding also by EU H2020 AIDA-2020, GA no. 654168. Individuals have received support from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2121 “Quantum Universe” – 390833306.

5. References

References

- [1] CMS Collaboration, The Phase-2 Upgrade of the CMS Tracker, CERN-LHCC-2017-009 (2017) <https://cds.cern.ch/record/2272264>.
- [2] RD53 Collaboration, RD53A Integrated Circuit Specifications, Technical Report CERN-RD53-PUB-15-001, CERN, Geneva, 2015.
- [3] Hamamatsu Photonics K.K., <http://www.hamamatsu.com>.
- [4] Fondazione Bruno Kessler, <http://www.fbk.eu>.
- [5] T. Rohe et al., ROC4SENS – a generic readout chip for sensor studies, 31st RD50 workshop, CERN, Geneva, Nov. 20-22, 2017, <https://indico.cern.ch/event/663851/contributions/2788211/>.
- [6] Taiwan Semiconductor Manufacturing Company Limited (TSMC), <https://www.tsmc.com>.
- [7] H. C. Kästli et al., Design and performance of the CMS pixel detector readout chip, Nucl. Instr. and Meth. A 565 (2006) 188-194.
- [8] Fraunhofer IZM, <https://www.izm.fraunhofer.de>.
- [9] J. Schwandt for the CMS Collaboration, CMS Pixel detector development for the HL-LHC, Nucl. Instr. and Meth. A 924 (2019) 59-63.
- [10] Y. Allkofer et al., Design and performance of the silicon sensors for the CMS barrel pixel detector, Nucl. Instr. and Meth. A 584, Issue 1 (2008) 25-41.
- [11] R. Diener et al., The DESY II test beam facility, Nucl. Instr. and Meth. A 922, (2018) 265-286.
- [12] H. Jansen et al., Performance of the EUDET-type beam telescopes, EPJ Techn. Instrum. 3 (2016) 7.
- [13] F. Feindt for the CMS Tracker Group, Beam Test Measurements on Planar Pixel Sensors for the CMS Phase 2 Upgrade, 2019 IEEE Nuclear Science Symposium (NSS) and Medical Imaging Conference (MIC), Manchester, UK, CMS-CR-2019-298, <http://cds.cern.ch/record/2713732>.

Figure 8: Row number for first pixel in a cluster for a non-irradiated HPK-module with $100 \times 25 \mu\text{m}^2$ pixel size for a pixel charge threshold of 700 electrons (left) and 1200 electrons (right).

Figure 9: New design for the $100 \times 25 \mu\text{m}^2$ pixel cell with semi-circular cutout in the implant to reduce cross talk. The implant is shown in green, the metal in purple.

Figure 10: Spatial resolution versus turn angle for $100 \times 25 \mu\text{m}^2$ pixel size (top). Spatial resolution versus turn angle for $50 \times 50 \mu\text{m}^2$ pixel size before (red) and after proton-irradiation (blue) to $5.3 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ (bottom).