

# UNIVERSIDAD DE CANTABRIA



ESCUELA DE DOCTORADO DE LA UNIVERSIDAD DE CANTABRIA

PROGRAMA DE DOCTORADO EN *Ciencia y tecnología*

---

## TESIS DOCTORAL

Sensores pixelados altamente resistentes a la radiación para la mejora a alta luminosidad del detector CMS del Gran Colisionador de Hadrones

## PhD THESIS

Highly radiation tolerant pixelated sensors for the high luminosity upgrade of the CMS detector of the Large Hadron Collider

---

Presentada por: **ANDREA GARCÍA ALONSO**

Dirigida por: **Dr. GERVASIO GÓMEZ GRAMUGLIO**

**Dr. JORDI DUARTE CAMPDERRÓS**

Tutor: **Dr. IVÁN VILA ÁLVAREZ**

Santander, Junio de 2021



July 2021



Me gustaría dedicar esta tesis de doctorado a todas las personas increíbles que habéis  
formado parte de mi vida durante estos años.

Me habéis hecho una versión mejor, más fuerte y más feliz de mí misma.

Gracias.

I would like to dedicate this PhD thesis to all the incredible people who have been part of my  
life during these PhD years.

You made me a better, stronger and happier version of myself.

Thank you.



## **Declaration**

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements.

Andrea García Alonso

July 2021



## Acknowledgements

Part of the activities carried out during this PhD was supported by the Spanish Ministry of Science under grants FPA2015-71292-C2-2-P and FPA2017-85155-C4-1-R; and the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168. (AIDA-2020).

---

Gracias a las tres personas que han dirigido esta tesis: Jordi Duarte, Gervasio Gómez e Iván Vila. Con Jordi he sufrido (incluso llorado), pero he aprendido más y me lo he pasado aún mejor. Referente de esfuerzo y conocimiento. Siempre disponible en mis momentos más bajos con el código, el análisis, la Física, la vida. Gracias por estar ahí cuando todo falla. Gracias Gerva por sacarme una sonrisa, por ver siempre el lado positivo a todo, por confiar en mí y en mi trabajo, valorándome y ayudándome, aunque estuvieras desbordado de trabajo. Te llevas el premio a la locura sana, las risas, haciendo de cada Test Beam (¡lo vamos a petar!) una fiesta con tu buen rollo y energía. Eres imprescindible. Iván, un modelo a seguir. Gracias por apostar por mí, por empujarme fuera de mi zona de confort, por hacerme presentar y presentar, obligándome a perder el miedo a defender mis resultados delante de tanta gente. Gracias por las lecciones de Física, por mandarme a la escuela del EIROforum o a vivir al extranjero. Cada estancia me ha hecho más fuerte y he aprendido infinito.

Gracias al resto de mis compañeros del SIFCA, menuda panda. . . Me lo he pasado genial con todos, sois el mejor equipo que podría haber imaginado. Gracias Marcos por todos los consejos, lecciones de Física y de salsa, por las risas e idas de pinza. Richard y Javi, Javi y Richard, compañeros de galletas pre-IFCAcharla, de cotilleos, risas, conversaciones de todo tipo y de momentazos test beam. Frases míticas como *el Fistro Krummenacher* y lo *monguerlerders* que somos en un TB porque todo es muy *grounded*.

Soy muy afortunada de formar parte del SIFCA. He aprendido y trabajado a tope, pero me siento muy feliz y muy a gusto. Trabajar con vosotros es un honor. En mi primer test beam pulsé un botón que NO se debía tocar salvo en extrema emergencia y lo pasé fatal. Ahora lo recuerdo con cariño y sé que os dejó una anécdota graciosa para que me recordéis (y no toquéis el botón).

Gracias a todo el equipazo del IFCA, personas maravillosas que me han dado su cariño y su ayuda desde el minuto uno. Me habéis abierto la puerta al fascinante mundo de la Física de Partículas y habéis apostado por mí no sólo a nivel investigador si no también como mujer, representante, divulgadora, amiga y ganadora de concursos.

Thanks to the Michael Moll's SSD group of building 28 at CERN. My first work team abroad, a little family where I had the chance to meet incredible people that today are very close friends. I had a great time during the months I worked there and since then I feel at home every time I go back. The original team is now spread over many countries, but we are still *partying like teenagers*, loving cakes, holding great memories and supporting each other like when we were together. Thanks Esteban, Isidre, Joaquín, Julio, Laura, Marius, Matteo, Michael, Moritz, Pedro, Rudy, Sofía, William, and Yana.

Vielen Dank, Hamburg University group! The second international group I was lucky to work with. I had a great time in Hamburg, joining the little family in building 63.b at DESY. Thanks for making me feel part of the group since the beginning. All of you taught me a lot, prepared me for test beams, helped me with the analysis, supported me during my many presentations or listened my desperation while I was publishing my first paper. Danke Georg, Erika, Daniel, Ali and Joern. Special thanks to my office mates Mohammed and Caroline for all we shared, and to Finn for the teas when I felt sick, the support after each presentation, and the fun partying in Hamburg. Gracias a mi pendeja Carmen, por entrar aquel día en mi oficina para revolucionar mi mundo. Mi estancia en Hamburgo fue increíble en gran parte por ti. Rathi, Macumba, Sternchanze, Elbphilharmonie, . . . todo es risas y amor contigo. Gracias por tus consejos, tu apoyo y por lo mega genial que lo pasamos descubriendo cada rincón de Hamburgo. Thanks to the rest of PhD candidates and students who drove me to the parties at DESY and introduced me to the fun I lived there.

Thanks to all my friends around the world. To those who were already in my life before I started the PhD and to those who appeared during this period. Excuse me if I choose to not write names, but I refer to my many friends from Spain, to the friends I met in Geneva, in Hamburg, in Leiden, all those who CERN put in my life, and those who arrived thanks to them. Thanks for travelling and living with me, showing me other cultures, food or languages, for the parties, conversations, love, laughs, craziness, . . . During the PhD I've changed, grown up, become stronger, better. If I've been able to polish myself along these years, it's thanks to all these incredible people who decided to become part of my life.

Ana catalana. Te debo tanto. Enorme apoyo, amiga de diez, cachondeo personificado, compañera de todo, confidente y guía. No me creo todo lo que hemos compartido. Gracias por las risas y los dramas. Gracias por existir, hermana. T'estimo.

Vlad, merci pour tout, baby. Thanks for your advices, trust and faith in me. For hugging, comforting and cheering me up when I'm overwhelmed with work. For being proud, admiring and loving me, while being the greatest person on Earth. Me has traído tanta luz, alegría, cariño, risas y amor. Merci d'être mon coach, mon partenaire de danse, mon meilleur ami, mon psychologue, mon professeur, fan numéro un et parfait camarade d'aventures. Ma moitié. Te quiero.

Gracias por todo a mis padres, Armando y Merche, y a mi hermano Fran. Por soportarme, entenderme, valorarme, quererme y por creer tantísimo en mí, mi capacidad y mi esfuerzo. Si soy como soy, es mayormente por vosotros. Este éxito es vuestro. Sois la mejor familia que pudiera haber deseado. Os quiero mucho.

Gracias a toda mi familia por vuestro cariño incondicional.

Gracias.

## Abstract

Due to its large instantaneous luminosity, the future upgrade of the largest particle accelerator of the world, the Large Hadron Collider (LHC), is going to set strong requirements on the radiation hardness of all the technology involved in its accelerating system, but also in its particle detection machines. One of the big detectors recording the energetic proton collisions is the Compact Muon Solenoid (CMS). The sensors comprising its inner tracker (IT) will have to face an unprecedented rate of collisions, ten times higher than the current detector. The silicon 3D pixel technology, with its superior radiation hardness and lower operation voltage and power dissipation, is being considered in CMS as a valid option for the innermost layers in order to cope with these extremely high radiation tolerance requirements.

After contextualizing the current CMS situation, as well as stating the future upgrade conditions, a study of the Physics behind the detection processes and the state-of-the-art is carried out. This will bring us to the presentation of the technology I have tested - the 3D sensors - together with the characterisation techniques and analysis processes employed.

A full study and characterisation of pixelated 3D silicon sensors fabricated by Centro Nacional de Microelectrónica (CNM, Spain) and Fondazione Bruno Kessler (FBK, Italy) is performed. The sensors were bump-bonded to ROC4SENS and RD53A readout chips. They were measured, both fresh and after proton irradiation, at several test beams in the LHC Super Proton Synchrotron (SPS), and in the German Electron Synchrotron (DESY).

Chapter 1 introduces the current LHC and its high luminosity upgrade future necessities. The requirements 3D sensors must fulfill to be successfully operated inside the upgraded CMS IT are explained. Chapter 2 gives a comprehensive overview of the physical processes and working principles behind silicon sensors, as well as how they are structured and fabricated. Chapter 3 introduces the devices under test, their irradiation process and testing setups, as well as the data reconstruction algorithm and parameters of interest. Chapter 4 constitutes the summary of the results obtained from the full characterisation. Results on hit efficiency, charge collection, cluster size and hit resolution, for fresh and irradiated samples, are presented. Response as a function of bias voltage, particle beam incidence angle and temperature is considered.

This thesis aims to demonstrate that the 3D technology is highly suitable for the CMS innermost tracking layers.



## Resumen

Debido a su alta luminosidad instantánea, la futura renovación del Gran Colisionador de Hadrones (LHC), impondrá estrictos requisitos en términos de tolerancia a la radiación a toda la tecnología implicada en su cadena de aceleración, así como en su maquinaria de detección de partículas. Uno de los grandes experimentos encargados de registrar las energéticas colisiones de protones es el Solenoide Compacto de Muones (CMS). Los sensores que conforman su detector de trazas interno (IT) deberán enfrentarse a una tasa de colisiones sin precedentes, diez veces mayor que la del detector actual. La tecnología de píxeles 3D de silicio, con su superior tolerancia a la radiación, y su reducido voltaje de operación y disipación de potencia, es considerada como opción válida para las capas más internas del IT, soportando sus altos niveles de radiación.

Tras contextualizar la situación actual de CMS y establecer las condiciones de su futura actualización, se presenta la Física que hay detrás de los procesos de detección y las tecnologías existentes. Esto llevará a la presentación de la tecnología que he testado - los sensores 3D - así como las técnicas de caracterización y procesos de análisis empleados.

Se realiza un estudio y caracterización de sensores de silicio 3D pixelados, fabricados por el Centro Nacional de Microelectrónica (CNM, España) y la Fondazione Bruno Kessler (FBK, Italia). Los sensores se operan conectados mediante micro-soldaduras a los chips de lectura ROC4SENS y RD53A. Antes y después de irradiarlos con protones, se someten a varias medidas "test beam" en el Súper Sincrotrón de Protones del LHC (SPS) y en el Sincrotrón Alemán de Electrones (DESY).

En el Capítulo 1 se presenta el LHC actual, así como sus futuras necesidades una vez actualizado a alta luminosidad (HL). Se explican los requisitos que los sensores 3D deben satisfacer para ser operados con éxito dentro del nuevo IT de CMS. El Capítulo 2 se adentra en los procesos físicos que explican el funcionamiento de los sensores de silicio, así como su estructura y fabricación. El Capítulo 3 introduce los dispositivos en estudio, su proceso de irradiación y los lugares de medida, así mismo, se explica el algoritmo de reconstrucción de datos y los parámetros de interés. El Capítulo 4 constituye el resumen de los resultados obtenidos tras la completa caracterización de los sensores. Se estudia la eficiencia de hit, colección de carga, tamaño de clúster y resolución de hit, tanto como para sensores nuevos como irradiados. Se tiene en consideración la respuesta en función del voltaje, ángulo de incidencia del haz de partículas y temperatura.

La presente tesis pretende demostrar que la tecnología 3D es altamente adecuada para las capas más internas de reconstrucción de trazas del detector CMS.



# Table of contents

|          |                                                                                  |           |
|----------|----------------------------------------------------------------------------------|-----------|
| <b>1</b> | <b>Experimental Particle Physics: Cutting-edge facilities. Goals and future.</b> | <b>1</b>  |
| 1.1      | The Large Hadron Collider . . . . .                                              | 3         |
| 1.2      | The Compact Muon Solenoid of the LHC . . . . .                                   | 8         |
| 1.3      | CMS Tracker . . . . .                                                            | 11        |
| 1.4      | High Luminosity LHC . . . . .                                                    | 14        |
| 1.4.1    | CMS IT Upgrade . . . . .                                                         | 16        |
| 1.4.2    | CMS High Granularity Calorimeter . . . . .                                       | 18        |
| 1.4.3    | CMS Endcap Timing Layer . . . . .                                                | 19        |
| <b>2</b> | <b>Silicon Detectors for Particle Physics</b>                                    | <b>21</b> |
| 2.1      | Interaction of particles with matter . . . . .                                   | 23        |
| 2.1.1    | Charged particles . . . . .                                                      | 23        |
| 2.1.2    | Low energetic photons . . . . .                                                  | 25        |
| 2.1.3    | High energetic photons . . . . .                                                 | 25        |
| 2.2      | Semiconductor physics fundamentals . . . . .                                     | 26        |
| 2.2.1    | Intrinsic Semiconductors . . . . .                                               | 28        |
| 2.2.2    | Extrinsic semiconductors . . . . .                                               | 30        |
| 2.2.3    | Generation and recombination of charge carriers . . . . .                        | 32        |
| 2.2.4    | Carrier transport . . . . .                                                      | 34        |
| 2.3      | The PN junction . . . . .                                                        | 36        |
| 2.3.1    | PN Junction in equilibrium creating the depletion region . . . . .               | 40        |

|          |                                                                                                 |           |
|----------|-------------------------------------------------------------------------------------------------|-----------|
| 2.3.2    | Diode current and capacitance . . . . .                                                         | 42        |
| 2.4      | Radiation effects: sensor damage . . . . .                                                      | 44        |
| 2.4.1    | Displacement damage . . . . .                                                                   | 44        |
| 2.4.2    | Ionisation damage . . . . .                                                                     | 48        |
| 2.5      | State-of-the-art of Silicon sensors for vertexing . . . . .                                     | 49        |
| 2.5.1    | Hybrid pixel detectors . . . . .                                                                | 49        |
| 2.5.2    | Monolithic pixel detectors . . . . .                                                            | 57        |
| 2.5.3    | Other hybrid architectures . . . . .                                                            | 58        |
| <b>3</b> | <b>Working methodology for sensor characterisation</b>                                          | <b>63</b> |
| 3.1      | Devices under test . . . . .                                                                    | 64        |
| 3.1.1    | Sensors . . . . .                                                                               | 64        |
| 3.1.2    | Readout ASIC . . . . .                                                                          | 69        |
| 3.1.3    | Charge injection calibration process . . . . .                                                  | 71        |
| 3.2      | DUT basic operating information: IV/CV setup . . . . .                                          | 74        |
| 3.3      | DUT fluence degradation: IRRAD facility . . . . .                                               | 75        |
| 3.4      | Full DUT study: Test beam campaign . . . . .                                                    | 78        |
| 3.4.1    | Test beam setup . . . . .                                                                       | 78        |
| 3.4.2    | Data analysis framework . . . . .                                                               | 83        |
| 3.4.3    | Parameters for the characterisation . . . . .                                                   | 86        |
| <b>4</b> | <b>Experimental results. Sensor characterisation and fulfillment of the CMS IT requirements</b> | <b>93</b> |
| 4.1      | Electrical and thermal characterisation.<br>Determination of operation parameters . . . . .     | 93        |
| 4.2      | Test beam characterisation: Hit efficiency . . . . .                                            | 95        |
| 4.2.1    | Global sensor response . . . . .                                                                | 95        |
| 4.2.2    | Full front-end pixel cell maps . . . . .                                                        | 98        |
| 4.2.3    | DUT response per fluence region . . . . .                                                       | 102       |

|                          |                                                                    |            |
|--------------------------|--------------------------------------------------------------------|------------|
| 4.2.4                    | Study over several points along a pixel quarter . . . . .          | 108        |
| 4.2.5                    | Summary of the hit efficiency dependency with fluence . . . . .    | 111        |
| 4.3                      | Test beam characterisation: Pixel resolution . . . . .             | 112        |
| 4.3.1                    | Cluster size distributions . . . . .                               | 112        |
| 4.3.2                    | Cluster size at normal incidence . . . . .                         | 115        |
| 4.3.3                    | Cluster size at angular incidence . . . . .                        | 117        |
| 4.3.4                    | Summary of the cluster size dependency with fluence . . . . .      | 118        |
| 4.3.5                    | Residual pixel cell maps of the whole DUT surface response . . . . | 119        |
| 4.3.6                    | Residual pixel cell maps of each fluence region . . . . .          | 121        |
| 4.3.7                    | Resolution dependency with the fluence . . . . .                   | 123        |
| 4.3.8                    | Extended study over further incidence angles . . . . .             | 124        |
| 4.4                      | Power dissipation . . . . .                                        | 127        |
| 4.5                      | Summary . . . . .                                                  | 128        |
| <b>Conclusions</b>       |                                                                    | <b>131</b> |
| <b>References</b>        |                                                                    | <b>135</b> |
| <b>Appendix Appendix</b> |                                                                    | <b>145</b> |
| .0.1                     | Response at shallow angle: Cluster breaking . . . . .              | 145        |
| .0.2                     | Presence of a bias dot structure . . . . .                         | 146        |



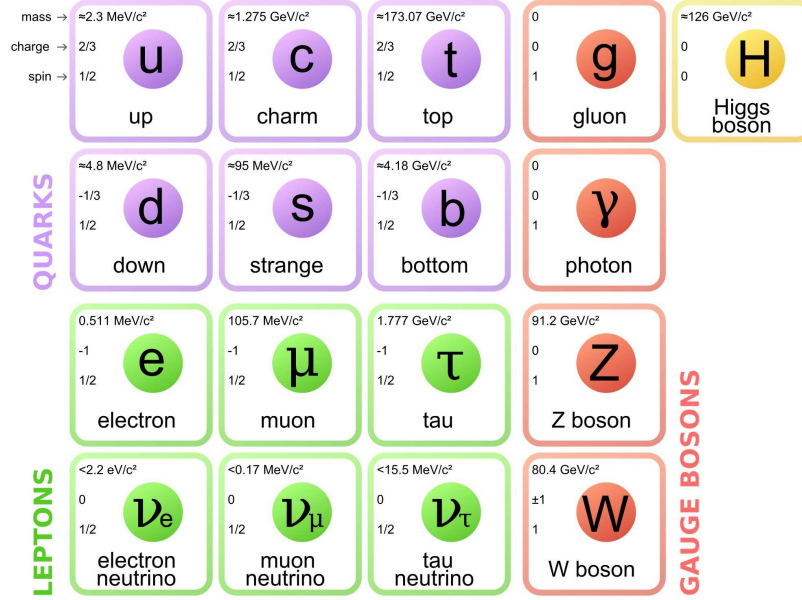
# Chapter 1

## Experimental Particle Physics: Cutting-edge facilities. Goals and future.

In order to fully understand the nature and composition of the universe surrounding us, the structure of matter has been deeply studied. This research has led towards a framework to explain the basic constituents of matter and the forces acting on them: the Standard Model (SM). This quantum field gauge theory sets the basics of Particle Physics. It establishes that all (visible) matter is made up of a reduced number of fermionic elementary particles, six quarks and six leptons, kept together through forces mediated by gauge vector boson particles.

The photon, the particle of light, has no mass and it is the mediator of the electromagnetic force. The gluon, which also has no mass and no electric charge, constitutes the mediator of the strong nuclear force. On the contrary, heavy elementary particles mediate the weak nuclear force: the Z and W bosons. All the already discovered particles considered by the Standard Model are shown in Figure 1.1. They are divided in three generations (the three columns in the illustration) of four matter particles; in each generation they are grouped in doublets. There are six quark flavors: up, down, charm, strange, top and bottom, and each one can have any of three different *color* quantum numbers (not in the illustration). In this way, inside a generation the sum of the charges is zero. The quarks compose all hadrons, like protons or neutrons. The six leptons are the electron, muon, tau, and their associated neutrinos. The last experimentally observed piece of this model is the Higgs boson, theoretically predicted but not detected until 2012. It is so far the only elementary scalar particle observed in nature, and it is associated to the so called spontaneous electroweak symmetry breaking. In the Standard Model, this is the mechanism through which elementary

particles can acquire mass without explicitly breaking the electroweak gauge symmetry of the Lagrangian.



**Fig. 1.1** Classification of the so far known elementary particles: quarks in purple and leptons in green. The four bosons mediating the forces in red. The Higgs boson setting the mass of the others in yellow. [1]

However, although supported by experience, the SM is not complete, and it is necessary to extend it. For instance, there is a force left out, gravity, whose mediator particle is not represented here: the postulated *graviton*. For the moment, no successful quantum field theory of gravity exists. Completing the SM is the role of big experiments, like the Large Hadron Collider LHC, (presented in Section 1.1), where the Higgs boson was first detected. At this kind of experiments, huge energy density conditions are achieved, making more likely the production and discovery of new heavy, elementary particles. Nowadays, this is important not only for the SM completion, but also for many other big topics claiming for answers: the origin of matter-antimatter asymmetry, the nature of dark matter and dark energy or the solution to the hierarchy problem.

All the quarks and leptons have their corresponding antiparticles, which conform antimatter. These are particles which have the same mass but opposite quantum numbers such as color, electric charge, lepton or baryon number. When matter and antimatter meet, they annihilate each other, converting into radiation. However, if during the first seconds after the Big Bang there was a perfect symmetry between the amount of matter and antimatter, the annihilations would have depleted both of them. Matter should not have survived. This fact leads to an initial asymmetry which is still not understood.



In 1933, the existence of a hugely abundant, unseen form of matter was first postulated. Around 1970, the rotational velocity of galaxies as a function of distance from the galactic centre was measured. It showed that most of the stars orbit at roughly the same speed. This leads to the fact that the density of matter was constant far beyond the visible galactic core, agreeing with the existence of dark matter. In 1998, evidences of the acceleration of the universe expansion were found. To explain it, the dark energy was postulated as a new kind of energy. Nowadays, we know that dark matter and dark energy make up around 96% of the energy content of the universe, although we cannot detect them.

In Particle Physics, the most important hierarchy problem is why the weak force is  $10^{24}$  times stronger than gravity. This leads to the question of why the Higgs boson, having a mass around the electroweak scale, is so much lighter than the Planck mass: there is no experimentally confirmed symmetry (such as Supersymmetry) or physical energy scale which would prevent radiative corrections to the Higgs mass from making the Higgs as heavy as the Planck mass.

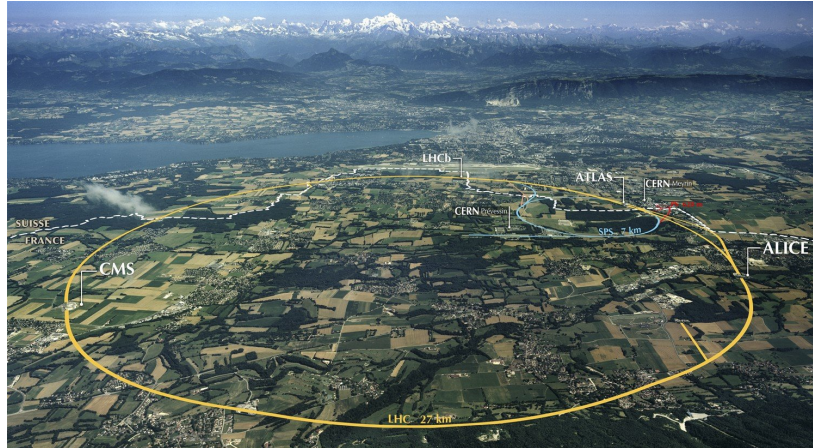
Finding the answers to these topics, simulating the conditions which took place right after the Big Bang, completing the Standard Model, contributing to the development and innovation in many fields of daily life, . . . all this is the potential of the Large Hadron Collider.

## 1.1 The Large Hadron Collider

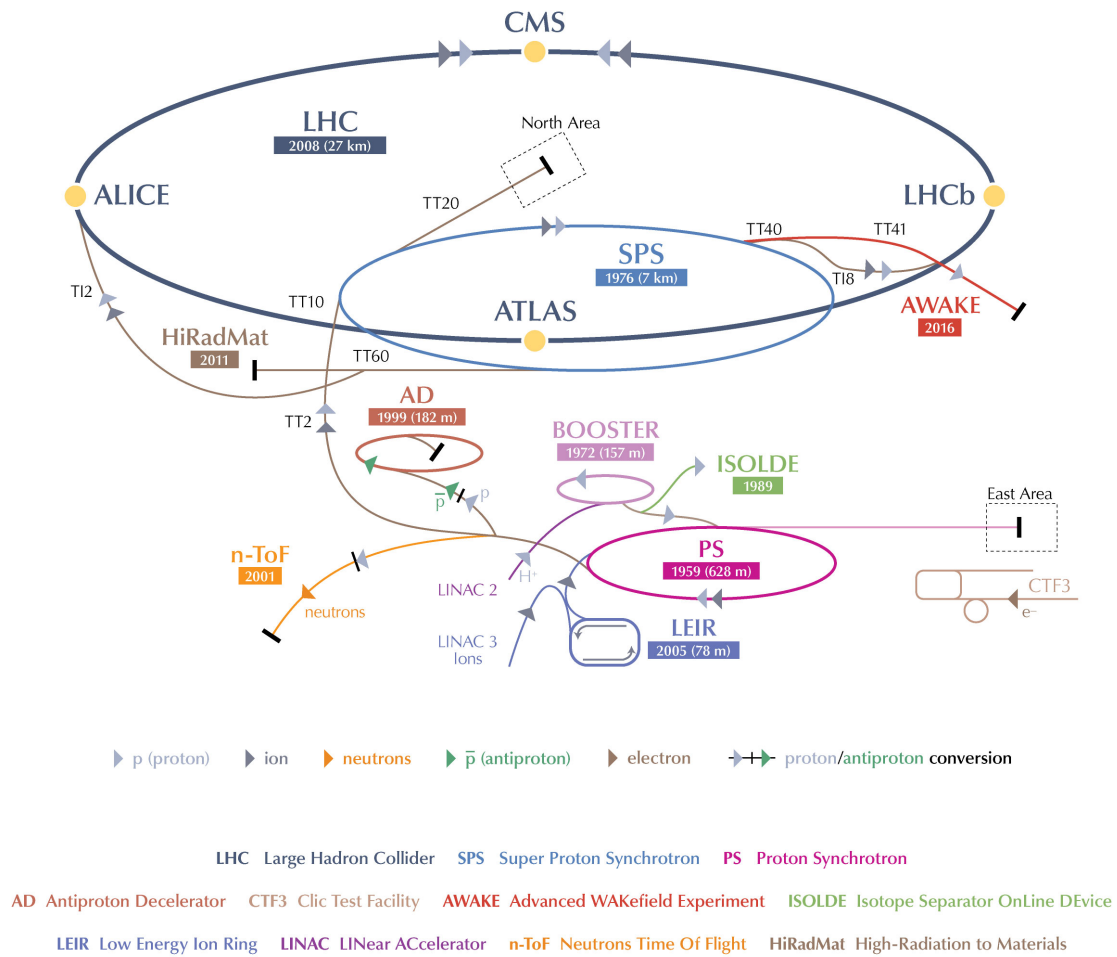
The Large Hadron Collider LHC [2] is the biggest particle accelerator in the world. This circular proton accelerator of 27 km circumference is located at the European Laboratory for Nuclear Research: CERN. Close to the city of Geneva (Switzerland), it is housed in a tunnel 100 meters underground, extended under both France and Switzerland, in a unique flat area surrounded by mountains, shown in Fig. 1.2.

This incredible machine constitutes the final and most modern piece of a large accelerating complex composed by several shorter accelerators, represented in Fig. 1.3. Thanks to the contribution of each of the pieces of this complex, protons are gradually boosted up to velocities close to the speed of light, and energies up to 7 TeV. At this maximum energy, the particles circle the 27 km of the LHC tunnel 11.245 times per second.

The acceleration process starts with the extraction of protons from hydrogen gas through ionization, by application of an electric field. By means of a system of electric fields changing during time, the protons are accelerated. Magnetic fields bend them to follow the desired trajectory. The protons enter in Linac 2, the first accelerator of the chain, and the only linear



**Fig. 1.2** Picture of the area where the CERN accelerating complex is located, 100 m underground [3].

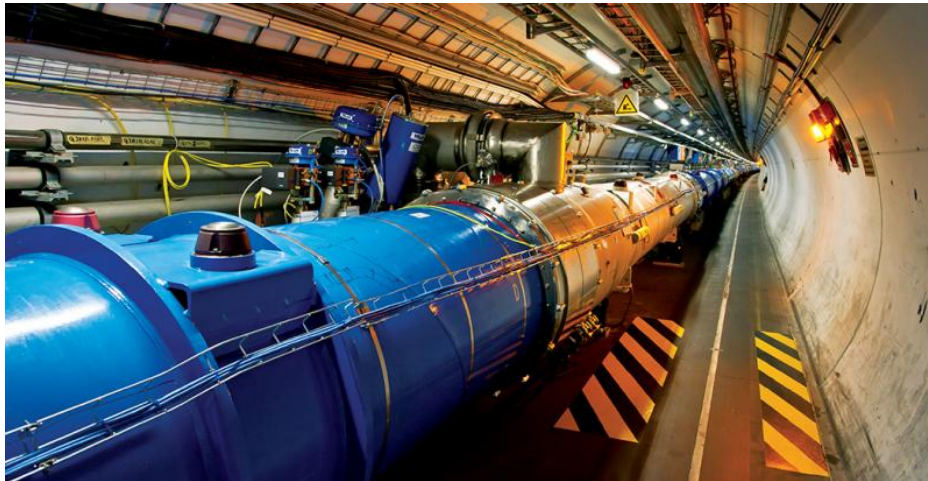


**Fig. 1.3** The CERN accelerating complex [4].

one for protons. Once there, the protons are firstly accelerated up to an energy of 50 MeV,

gaining a 5% increase in mass. After Linac 2, protons are injected into the first circular accelerator, the Booster, where they reach an energy of 1.4 GeV. At this point they are sent to a bigger accelerator: the Proton Synchrotron (PS). When the protons achieve an energy of 25 GeV, they are injected into the SPS (Super Proton Synchrotron) and boosted to an energy of 450 GeV. Finally they are injected into the LHC machine.

As Fig. 1.3 shows, there are other acceleration starting points, like Linac 3, as well as other ending points, like North Area, AWAKE or East Area. For example, since CERN facilities also accelerate lead ions apart from protons, Linac 3 is the first linear booster sending the ions to the Low Energy Ion Ring (LEIR). Here they are confined to short pulses and accelerated from 4.2 MeV to 72 MeV. Once they get this maximum energy, they enter into the PS, continuing the same path as protons until reaching the LHC. Regarding extraction points, there is one for the PS at the East Area and another one for the SPS at the North Area. They provide proton beams of different energies for irradiations, fixed target experiments, or test beams. In particular, the SPS exit makes possible to carry out test beams. The proton beam is deviated to an industrial unit where it is split into several beam lines, along which R&D experiments take place. As I will explain in detail in Section 3.4.1 of Chapter 3, here is where I have tested sensors (the basic particle detecting units), thanks to the radiation beam traversing them at the user areas.



**Fig. 1.4** Picture of the LHC tunnel, 100 meters underground [5].

All the CERN acceleration process is achieved thanks to the application of some forces. Without them, the particles would drift apart and their momentum would carry them in straight line. In order to drive the particles, more than 50 types of magnets guide them while radiofrequency electric fields increase their speed. Figure 1.4 shows a part of the LHC

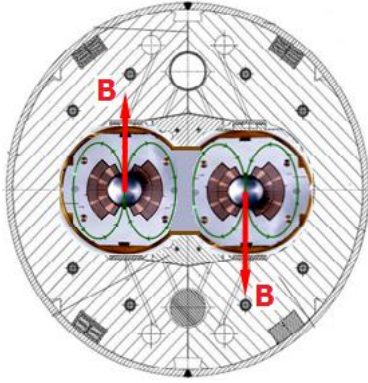
tunnel, composed by radiofrequency cavities, dipole magnets in blue covers, and quadrupole magnets in white ones. These three pieces are explained in the next three paragraphs.

Sixteen radiofrequency (RF) cavities are found on the LHC. Each one is a metallic chamber containing an electromagnetic field and housed in four cylindrical refrigerators called cryomodules, to work in a superconducting state [6]. The RF cavity is molded to a specific size and shape so that electromagnetic waves become resonant and build up inside the cavity. The field in an RF cavity is made to oscillate (switch direction) at a certain frequency, which is 400 MHz in the LHC. Charged particles passing through the cavity feel the force of the resulting electromagnetic field, and they are pushed forward. Conductors ahead of the particles pull them, while those behind push them. The ideally timed proton, with the right energy, will see zero accelerating voltage when the LHC is at full energy. Protons with slightly different energies arriving earlier or later will be accelerated or decelerated to stay close to the ideal particle energy. In this way, the particle beam is sorted into discrete packets: the *bunches* [7].

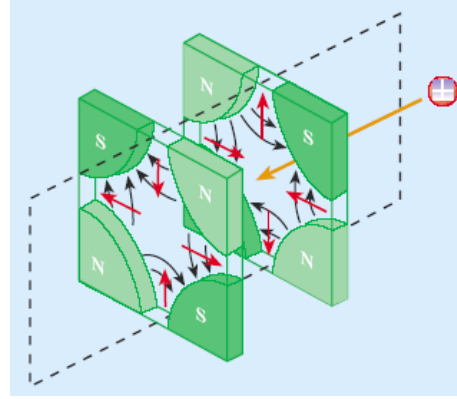
The LHC contains 1232 dipole magnets, or main bends, in charge of bending the protons trajectory. They fill 2/3 of the LHC circumference and generate 8.3 Tesla magnetic fields, ( $10^5$  times the Earth's magnetic field, whose value is between 25 and 65  $\mu\text{T}$ ). Each main bend weighs 35 tons, measures 14.3 m, and flows through its coils a current of around 11.7 kA. Using copper stabilized NbTi Rutherford cables or singlestrands, these superconducting magnets operate in superfluid helium at 1.9 K. The magnets have two apertures, one for each of the proton beams travelling in opposite directions, as shown in Fig. 1.5. The dipolar magnetic field is created by superconductive currents circulating on each side of the pipe where the protons travel. The wiring is arranged in individual double layers around each tube, circulating in opposite senses on each side. This design is called 2-in-1 and generates an opposite magnetic field on each pipe. The forces over both proton beams act towards the centre of the LHC, curving their trajectory and making possible to follow the circumference.

It is also necessary to focus the proton beams. Small quadrupole magnets maintain the particles in a tight beam. Since protons are charged particles, if they are let free, they will separate. The 3.3 m long quadrupole magnets focus the beam, reducing its diameter to the smallest possible area. With the 392 quadrupole magnets, protons are constrained to a certain width and height, so they remain inside the vacuum chamber while moving. As shown in Fig. 1.6, pairs of quadrupoles are required to focus the protons, keeping them tightly bunched in order to achieve the maximum number of collisions at the interaction points.

Injection in the LHC takes place at two different points and in opposite directions. The charged particles travel along two beam pipes, in bunches of around  $10^{11}$  particles, with a



**Fig. 1.5** LHC dipole magnet transversal cut representation. A dipole per beam pipe applies an equal but opposite magnetic field on the protons travelling in both senses [8].



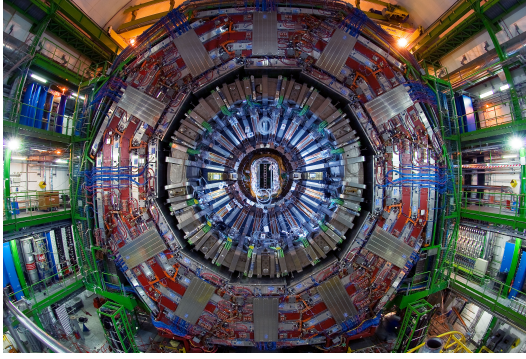
**Fig. 1.6** Two LHC quadrupoles: the first one reducing the width and the second one reducing the height of the proton beam [9].

bunch-to-bunch spacing of 25 ns and at a revolution frequency of 11 kHz. When the target particle energy is reached, the ring is switched from synchrotron mode to collision mode. The bunches are brought to collision at four experimental interaction points located along the LHC.

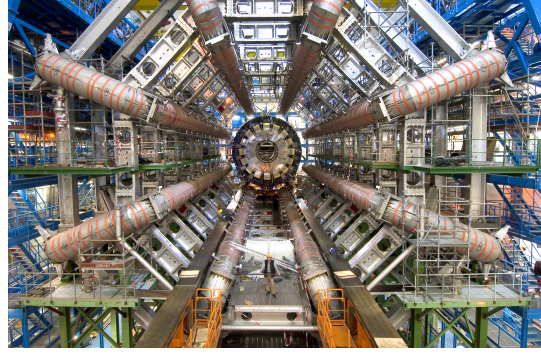
At each of these points of interaction, the collision points, enormous detection systems are built: ATLAS (A Toroidal LHC AparatuS), CMS (Compact Muon Solenoid), ALICE (A Large Ion Collider Experiment) and LHCb (LHC-beauty). ATLAS and CMS are the biggest general-purpose detectors, investigating the largest possible range of physics. ALICE was designed to study the physics of strongly interacting matter at extreme energy densities. LHCb specializes in investigating the slight differences between matter and antimatter, studying the *b quark* and hadrons containing it. All these big machines are illustrated in Fig. 1.7, with pictures from different angles.

Each of these complex machines is composed of several layers with different detecting purposes and technologies. From all the kinds of sensor technology for each of their regions, it is necessary to study in depth the behaviour and response in order to assure the chosen technology is the optimal one. All this, while satisfying operational requirements such as consumption, thermal dissipation, occupied volume, material budget, etc. The sensors studied in this thesis have been designed to be implemented in the innermost part of the CMS detector. Consequently, the next section goes in depth in the CMS experiment, which is also one of the largest international scientific collaborations in history, with thousands of scientists, engineers, technicians and students, connecting research institutes from countries all over the world.

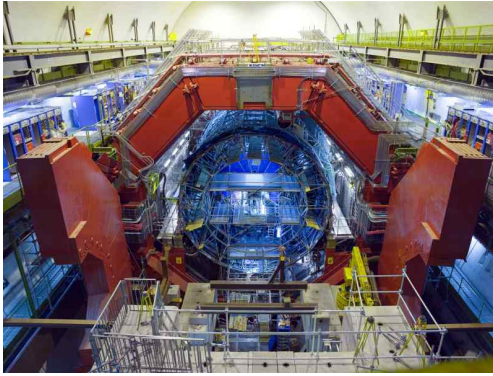




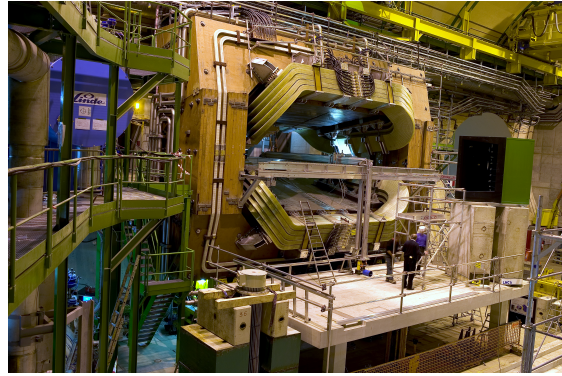
(a) CMS detector [10]



(b) ATLAS detector [11]



(c) ALICE detector [12]



(d) LHCb detector [13]

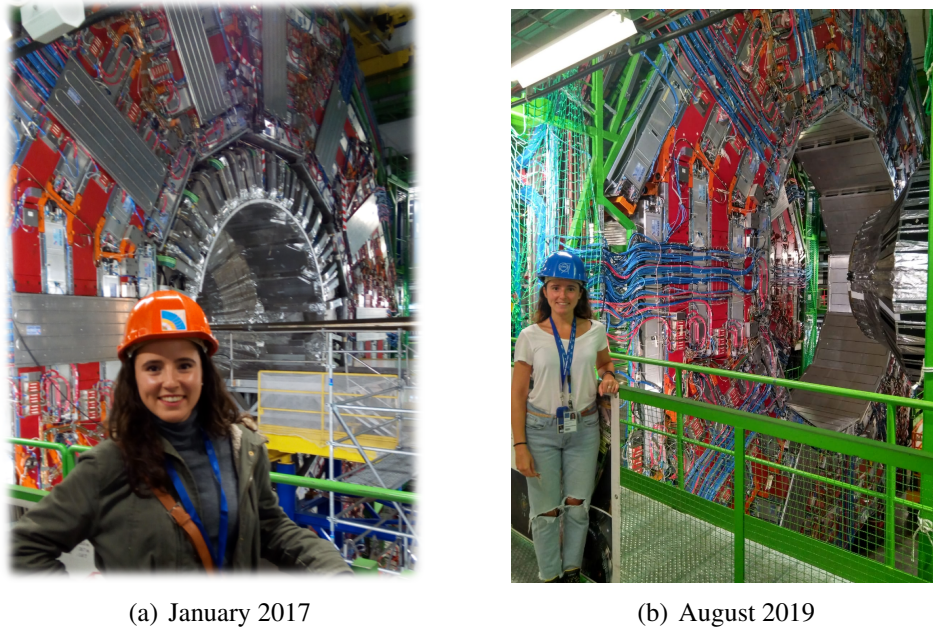
**Fig. 1.7** Pictures of the four largest detection experiments located along the LHC tunnel.

## 1.2 The Compact Muon Solenoid of the LHC

The 21 m long, 15 m wide and 15 m high particle detector at the LHC is the Compact Muon Solenoid (CMS). It is composed by several layers of different sensors, each of them in charge of the detection of certain kinds of particles produced in the highly energetic proton collisions.

A picture of my very first visit to this incredible experiment, in January 2017, is shown on the left of Fig. 1.8(a), during my also first time at CERN. On the right, my second visit to the experiment, in summer 2019, with already plenty of experience in test beam campaigns, its data analysis, shifts at CMS control room, oral talks in several conferences, living in the CERN area during 8 months, etc.

This general-purpose detector has a broad physics program ranging from studying the Standard Model to searching for extra dimensions and particles that could make up dark matter. It has the same goals as the ATLAS detector, but using different technical solutions

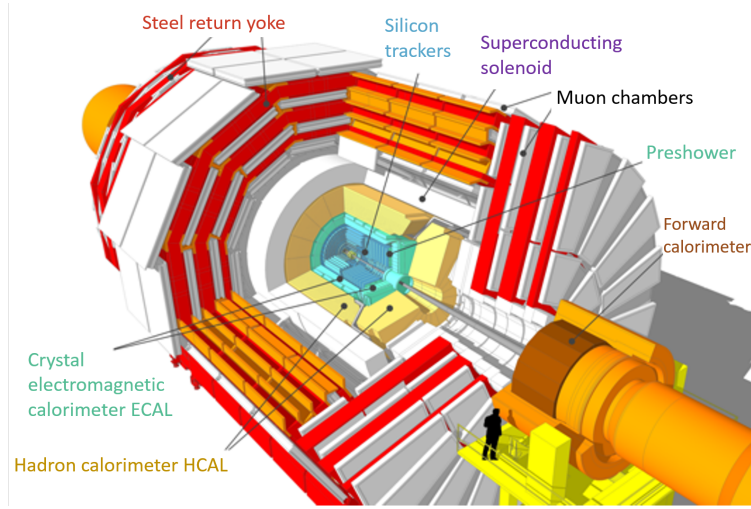


**Fig. 1.8** Pictures with the CMS experiment when opened during shutdown.

and magnet-system design [14]. The CMS technical requirements are: detect and measure muons, electrons, photons, and charged and neutral hadrons, while preventing particles from escaping undetected.

CMS is made up of a complex system in the shape of concentric layers, as represented in Fig. 1.9. The most relevant part is the huge solenoid magnet, a cylindrical coil of superconducting cable cooled to  $-268.5^{\circ}\text{C}$ , that generates a 4 Tesla magnetic field [15]. This magnetic field bends the trajectories of particles emerging from the LHC collisions. In this way, by reconstructing the particle track, the momentum is determined. A strong magnet intensely bends the tracks and, combined with high-precision position measurements in the tracker and muon detectors, accurate measurement of the momentum of even high-energy particles turns possible. The magnet has other missions like providing most of the experiment's structural support, while facing the forces of its own magnetic field.

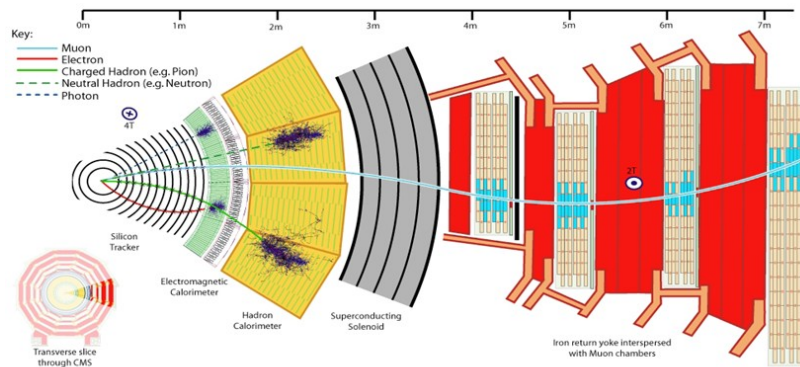
Particles emerging from collisions first meet the tracker, made entirely of silicon detectors, that charts their positions as they move through the detector. Outside the tracker, the electromagnetic and hadron calorimeters measure the energy of electrons, positrons, photons and hadrons. While the tracker should interfere with particles the least possible, the calorimeters are specifically designed to highly interact, to stop particles within their volume and measure their energy. The size of the magnet allows the tracker and calorimeters to be



**Fig. 1.9** Full CMS front cut and components identification. A person close to the LHC tunnel is shown for size comparison.

placed inside its coil, resulting in an overall compact detector, fact that gives CMS its first name: *Compact*.

The innermost calorimeter is the Electromagnetic Calorimeter (ECAL). It is made of lead-tungstate, a very dense material that produces light when particles interact with it. Crystals made of this material are read out with avalanche photo diodes (APDs). ECAL measures principally the energy of photons, electrons and positrons. The second calorimeter, the Hadron Calorimeter (HCAL), detects any hadron. It consists in the barrel region of brass absorber plates and plastic scintillator layers. They used to be read out by hybrid photodiodes (HPDs), but then replaced by silicon photomultipliers (SiPMs).



**Fig. 1.10** Transverse cut of a CMS section split in its concentric layers. Different particle trajectories starting at the collision point are shown [16].



The CMS outer part, the iron magnet *return yoke*, confines the magnetic field. It is interleaved with four layers of muon detectors: the muon chambers, reconstructing the muon tracks. Muons are charged particles, like electrons and positrons, but more than 200 times heavier. Their role is truly important since they are expected to appear in the decay of particles like the Higgs boson. The muon chambers are placed in the outermost part of CMS, as shown in Fig. 1.10, since muons are not stopped by the calorimeters, and they can go through many meters of iron. The capacity of measuring muons is indicated in the second part of the CMS name.

Although taking as much information as possible is the ideal situation, within the LHC, bunches of particles collide up to 40 million times per second. Therefore, a huge amount of information is read by the CMS sensors. A *trigger* system, saving only those events of potential physics interest is essential. The first level of the trigger, the Level-1 (L1) system, is implemented in hardware, based on custom electronics. It selects events containing detector signals consistent with an electron, photon, muon, tau lepton, jet, or missing transverse energy. This last one, the so-called missing  $E_T$  of each event, is crucial to indirectly infer the presence of neutrinos, since these particles escape from CMS undetected. A programmable menu of hundreds object-based algorithms is used to select the events for subsequent processing. The rate of  $10^9$  interactions per second is reduced to 100 kHz, the upper limit imposed by the CMS readout electronics. These stored events are forwarded to the High Level Triggers. This second level, implemented in software, relies upon commercial processors and further refines the purity of the output stream, selecting a rate of at least 1 kHz for offline event storage, the maximum rate that can be archived by the online computer farm.

This thesis focuses on the characterisation of one type of sensor technology that can be part of the CMS tracker. As a consequence, from all the parts of CMS that have been explained here, the next section goes in detail into the innermost layer: the silicon tracker.

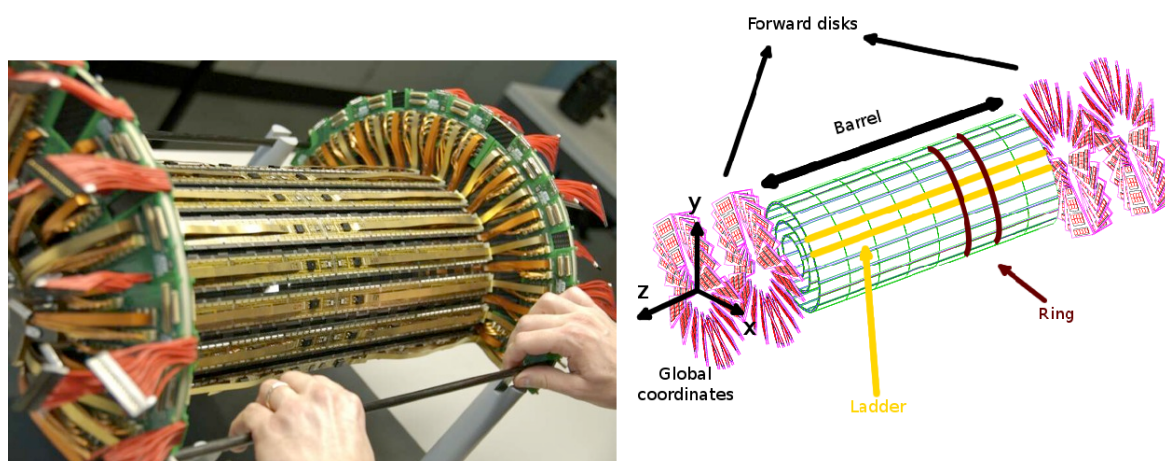
## 1.3 CMS Tracker

The most interior, and therefore closest to beam, CMS layers are those of the inner and outer trackers. Occupying this position implies that the levels of radiation here are the highest inside CMS. Additionally, the volume reserved for this part of the detector is minimum. This is the region of CMS that enables the detector to track charged particles and measure their momenta. Excellent spatial resolution and low occupancy are achieved thanks its finely segmented sensors, either in the shape of strips or pixels.



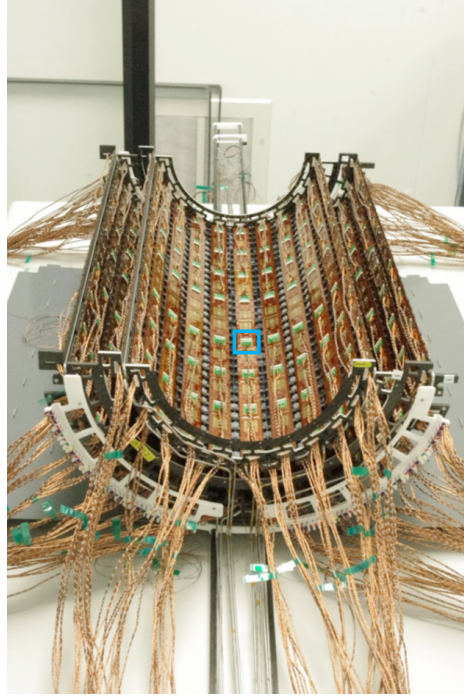
**Fig. 1.11** Installation of the Inner Tracker inside CMS [17].

The tracker detecting volume is made entirely of silicon. Its innermost part is the Inner Tracker IT, also called pixel detector. It is composed of 66 million pixels and its installation is shown in Fig. 1.11. The IT is located at the very core of the detector, conveniently close to the collision point, and deals with the highest particle intensity. Its location and resolution make the IT the most precise part of CMS to determine the collision origin, or primary vertex, reason why it is also called vertex detector. The second part of the tracker, or Outer Tracker OT, is made of 10 million silicon microstrips, surrounding the IT. Thanks to its position, somewhat further away from the collision point, the OT controls the tracking process, determining the momentum of charged particles thanks to a large lever arm and the strong magnetic field.

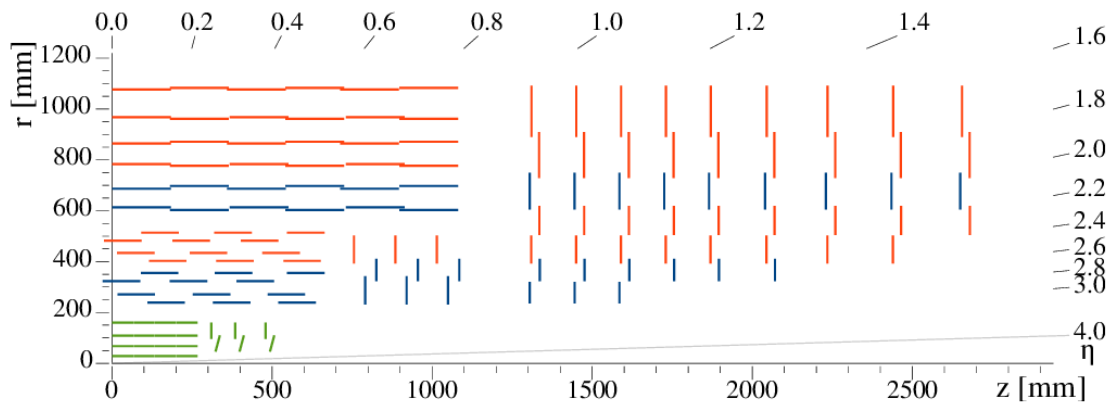


**Fig. 1.12** The Inner Tracker on the left and its parts on the right (barrel and disks) [18].

The IT is composed of three main parts, as shown by the picture and representation of Fig. 1.12. The cylindrical layers constitute the barrel, while the endcap disks at each end are the forward part of the detector. The mean radius of layers 1, 2 and 3 are 4.4 cm, 7.3 cm and 10.2 cm, respectively. The barrel is divided into ladders (along the  $r - \phi$  plane) and rings (along the  $z$  axis). The intersection of a ladder and a ring is a module, the basic building block of the detector, which is highlighted in Fig. 1.13.



**Fig. 1.13** One part of the CMS IT, where a module is highlighted in blue [18].



**Fig. 1.14** One quarter of the upgraded Phase-1 CMS Tracker layout, in  $r - z$  view [19].

In 2016-2017, the LHC was stopped and the tracker was upgraded to the so-called Phase-1. In Fig. 1.14 a quarter of the upgraded CMS Tracker layout is shown in the  $r - z$  plane. The radial region below 200 mm is equipped with pixelated detectors, the IT, represented by green color. The horizontal lines represent the barrel and the others on their right are the disks of one side. For Phase-1, the barrel was increased by one layer (four in total) and the innermost one was moved closer to the beam line (from a 4.4 cm radius to 2.9 cm). The upgrade also increased the number of disks per side from two to three. Beyond 200 mm radius, the present outer tracker features single-sided strip modules (in red) and double-sided modules (in blue) composed of two back-to-back silicon strip detectors. Double-sided modules provide coarse measurements of the  $z$  and  $r$  coordinates in the barrel and endcaps, respectively [19].

As particles travel through the tracker, the pixels and microstrips produce tiny electric signals that are amplified and detected. The tracker employs sensors covering an area the size of a tennis court, with 75 million separate electronic read-out channels. Only the pixel detector has around 6000 connections per square centimetre.

The tracker reconstructs the trajectories of charged particles by finding their positions at a number of key points. Since the particle trajectories have to be recorded accurately, the tracker has to be lightweight, reducing as much as possible the interaction with the particle, avoiding its trajectory modification. This is done by taking position measurements so accurate ( $10\ \mu\text{m}$ ) that tracks can be reliably reconstructed using just a few measurement points. Being the innermost layer of the detector also means that it receives the highest flux of particles: its materials have to be highly resistant to radiation [20].

## 1.4 High Luminosity LHC

An upgrade of the LHC is planned for the years 2026-2027, turning the Large Hadron Collider into the High Luminosity LHC or HL-LHC. Its instantaneous luminosity (rate of collisions) will increase up to a peak of  $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , around five times more than the current one. It will reach an integrated luminosity (total collisions created) of  $300\text{-}400 \text{ fb}^{-1}/\text{year}$ , with the goal of  $4000 \text{ fb}^{-1}$  after about 12 operation years, a factor of 10 increase with respect to the LHC [21]. This will enable the experiments to enlarge their data sample by one order of magnitude compared with the LHC baseline program. A high track density is expected, with a pile-up -or average number of hard proton-proton collisions during any single proton bunch crossing- exceeding 200, and with the 25 ns of time space between bunches crossing. The LHC past plan development and the future goals are shown in Fig. 1.15.



**Fig. 1.15** LHC and HL-LHC past and future plans (January 2021 update version) [22].

At the beginning of the decade of 2020, many critical components of the accelerator are reaching the end of their lifetime due to radiation damage, needing to be replaced. This, together with the fact that, after years of design study and R&D, the HL-LHC requires about ten years of developments, prototyping, testing and implementation, its operation is not expected to start before 2026–2027 [23].

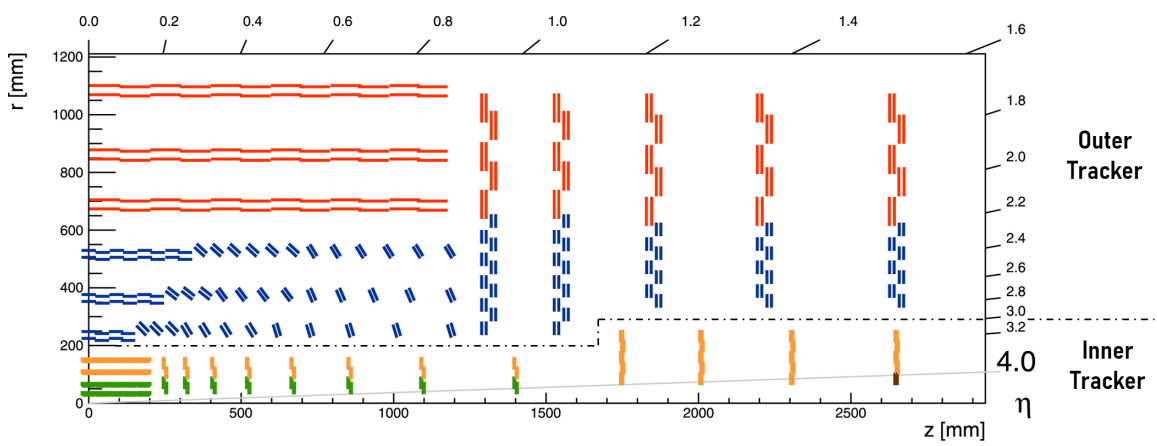
The HL-LHC will rely on a number of key innovative technologies, including cutting-edge 11-12 T superconducting magnets, compact superconducting crab cavities with ultra-precise phase control for beam rotation, new technology for beam collimation, high-power, loss-less superconducting links, etc. A detailed description of the project and its technological and operational challenges is provided in the HL-LHC Technical Design Report [24] and the HL-LHC book [25].

Therefore, the four LHC experiments, including CMS [19], will be upgraded. Their characteristics have to be renewed to cope with the HL-LHC requirements. The IT will be exposed to the most extreme conditions, requiring advanced technologies and novel solutions, notably for the readout and powering electronics, as well as all support structures. Other parts of the upgraded CMS, like the High Granularity Calorimeter (HGCAL) or the Endcap Timing Layer (ETL), are as well based on radiation tolerant silicon to cope with the new high fluences, as it is later expounded in this chapter.

### 1.4.1 CMS IT Upgrade

At the moment when the LHC reaches the High Luminosity phase, the so-called Phase-2 period, CMS will need a completely new tracker detector in order to fully exploit the highly-demanding operating conditions and the delivered luminosity. The new tracker ought to also have trigger capabilities. For this, R&D activities are ongoing to explore options and develop solutions that would allow including tracking information at Level-1.

In this way, the CMS silicon tracker will be completely replaced for the HL-LHC by a new system featuring increased radiation hardness and capability to handle higher data rate and longer trigger latency. The CMS Tracker Phase-2 layout in  $r - z$  view is shown in Fig. 1.16. Comparing it with the Phase-1 layout previously shown in Fig. 1.14, it can be seen how the IT (now in green and also yellow) will be extended. Pixel modules with  $1 \times 2$  readout chips are represented by the green lines, and those with  $2 \times 2$  readout chips by the yellow ones. The rest of lines compose the OT: in blue the pixel-strip (PS) modules and in red the strip-strip (2S) modules [26].

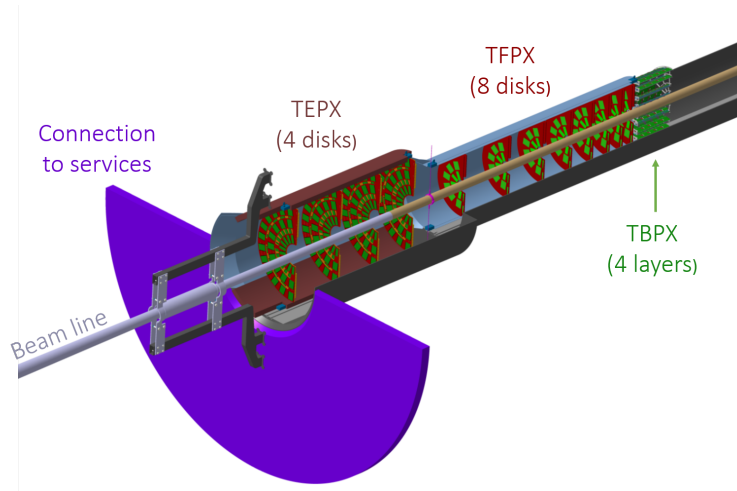


**Fig. 1.16** One quarter of the upgraded CMS Phase-2 Tracker layout, in  $r - z$  view. Adapted from [19].

The new barrel has four layers and it is called Tracker Barrel Pixel (TBPX), as shown in Fig. 1.17. The endcaps right next to the TBPX are the Tracker Forward Pixel (TFPX), which are made of eight disks of four rings. The outermost endcaps are the Tracker Extension Pixel (TEPX), made of four disks.

The IT is the part of the tracker we are going to focus on for the contents of this thesis. Note its particular and extreme requirements, consequence of its special position inside CMS. Requirements which, with the next LHC upgrades, are going to be even harsher. In short, the IT will deal with an occupancy of up to  $3 \text{ GHz/cm}^2$  in pixel layer 1 (located at just 3 cm from the beam line), radiation levels up to  $3.5 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$  (for an integrated luminosity of





**Fig. 1.17** One quarter of the upgraded Phase 2 CMS IT.

$4000 \text{ fb}^{-1}$ ), and a total ionizing dose of  $1.91 \text{ Grad}$ . Sensors with a small charge carrier drift distance and high electric field close to the collecting structures are required to minimize the impact of radiation-induced trapping, a kind of radiation damage produced inside the sensor bulk (see Chapter 2) [27].

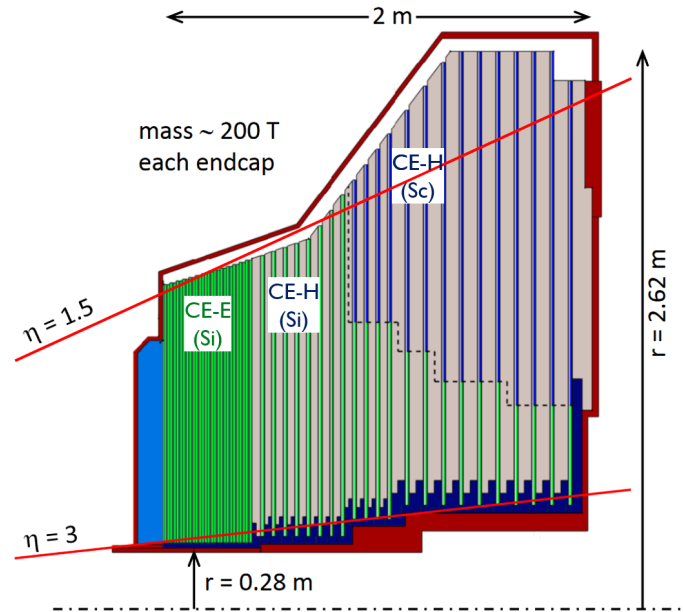
The new requirements set a new challenge on the radiation tolerance of the sensors composing this part of the detector. Silicon sensors with active thicknesses of  $150 \mu\text{m}$  are being considered. When segmented into  $25 \times 100$  or  $50 \times 50 \mu\text{m}^2$  pixels (narrower pitches than the present  $100 \times 150 \mu\text{m}^2$  pixel detector) they provide a better transverse and longitudinal impact parameter resolution. Sensors in the first layer of the TBPX and in the first ring of all the TFPX disks must be able to resist at least half of the  $3.5 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$  fluence, since this is the expected value for when a technical stop and replacement is scheduled. To establish the best technology, able to suit all these requirements, planar and 3D pixel sensors are under consideration. This thesis focuses on the 3D sensor technology, and we will later show why it is an appropriate candidate for the innermost layers.

However, although the present thesis studies this silicon-based technology for the new CMS Inner Tracker, silicon sensors are widely employed in many detection experiments. In particular, radiation tolerant silicon sensors are present not only in the CMS tracker but also in its calorimeter or its timing layer. Furthermore, outside of CMS, radiation tolerant silicon sensors are also found in ATLAS, LHCb or ALICE, inside vertex detectors, ion detectors, or expected in future detecting technologies. The following two subsections aim to extend the vision of radiation tolerant silicon sensors to fields outside of particle tracking.

### 1.4.2 CMS High Granularity Calorimeter

During the HL-LHC era, the CMS forward calorimetry will also suffer from the high radiation levels and intensified pile-up on its detectors. For this reason, the CMS collaboration is designing a High Granularity Calorimeter (HGCAL) to replace the existing endcap calorimeters (CE). The current implementation of the CMS Calorimeter Endcap has a  $\text{PbWO}_4$ -based electromagnetic and a plastic scintillator-based hadronic calorimeters. In May 2015, a new silicon-based calorimeter was chosen for the HL upgrade.

In the mechanical design (see Fig. 1.18), the HGCAL consists of a sampling calorimeter with silicon and scintillators as active material in the electromagnetic (CE-E) and innermost regions of the hadronic (CE-H) compartments, where the radiation is expected to be higher (up to  $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ ). Plastic scintillator tiles are used in the outermost regions of the hadronic section. Unprecedented transverse and longitudinal segmentation for CE-E and CE-H facilitates particle-flow calorimetry, where the showers fine structure can be determined and used to enhance pile-up rejection and particle identification, whilst achieving good energy resolution.



**Fig. 1.18** HGCAL design divided in the electromagnetic (CE-E) and hadronic (CE-H) sections. Adapted from the HGCAL overview by K. Gill in the 22/04/2020 HGCAL Annual Review [28].

The new CE-E contains 28 sampling layers with silicon sensors as active material and steel-clad lead as main absorber. Next to the electromagnetic part, the CE-H has 8 silicon sampling layers and 16 layers where both silicon sensors and silicon photomultipliers are

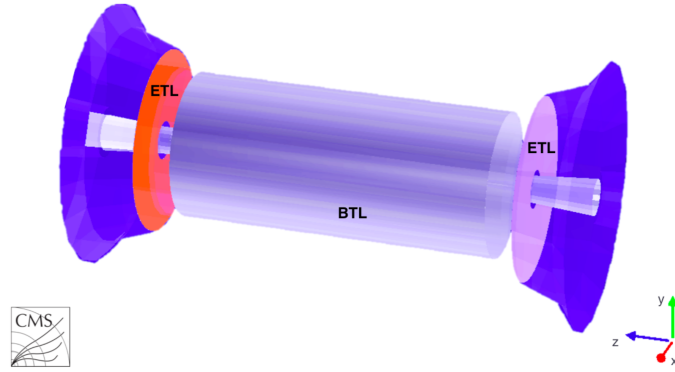


mounted on tiles of plastic scintillators. About  $640 \text{ m}^2$  of silicon, are needed in total [29]. The sensor technology employed in this part of the CMS detector are hexagonal silicon sensors, explained in Section 2.5.1 of next chapter.

### 1.4.3 CMS Endcap Timing Layer

Although precision timing can be provided by the front section of the upgraded CE and the ECAL barrel, these detectors will not provide efficient precision timing information for minimum ionizing particles (MIPs). Global event timing able to reconstruct the vertex time and exploit time information in charged particle reconstruction requires a MIP Timing Detector (MTD) [30] covering the barrel and endcap regions.

The MTD is instrumental in maintaining good resolution and reconstruction efficiency for the physics objects. Reconstructing the time of displaced vertices will provide enhanced capability in searching for long-lived particles (LLPs) by measuring their relativistic velocity parameter  $\beta_{LLP}$ , and in some cases, allowing LLP mass reconstruction. Precision timing will let the MTD also serve as an excellent TOF<sup>1</sup> detector for charged hadron identification, valuable in Heavy Ion Physics and in certain studies of low mass quantum chromodynamics and flavor physics.



**Fig. 1.19** GEANT4 simulation of the MTD timing layers, implemented in CMSSW<sup>2</sup>, comprising a barrel layer (BTL), and two silicon Endcap Timing Layers (ETLs). Image from [30].

<sup>1</sup>TOF (Time Of Flight) detector is a particle detector discriminating between two same momentum elementary particles with different masses, using their time of flight between two scintillators.

<sup>2</sup>CMSSW: overall CMS collection of software built around a Framework, an Event Data Model (EDM), and Services needed by the simulation, calibration and alignment, and reconstruction modules that process event data so that physicists can perform analysis.

The MTD, as shown in the GEANT4<sup>3</sup> simulation of Fig. 1.19, is divided in two sections: the Barrel Timing Layer (BTL) and the Endcap Timing Layer (ETL). The BTL will be integrated into the OT support tube, inside its inner radius, and at larger radius than any barrel tracking layer. The ETL, also represented in Fig. 1.18 with light blue, will be supported between the Tracker and the CE, in front of the endcap calorimeter.

The radiation levels expected at the ETL location are the main driver for the choice of silicon sensors there. While the main part of the sensors will be exposed to a fluence of less than  $8 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ , the innermost 10% of the detector will be exposed to more than  $1 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$  [32]. As explained in Section 2.5.3 of next chapter, the chosen silicon sensor for the ETL is the LGAD, providing a time resolution per MIP around 30 ps.

---

<sup>3</sup>GEANT: *Generation of Events ANd Tracks* simulation software series developed at CERN and designed to describe elementary particles passage through matter, with Monte Carlo methods [31].

# Chapter 2

## Silicon Detectors for Particle Physics

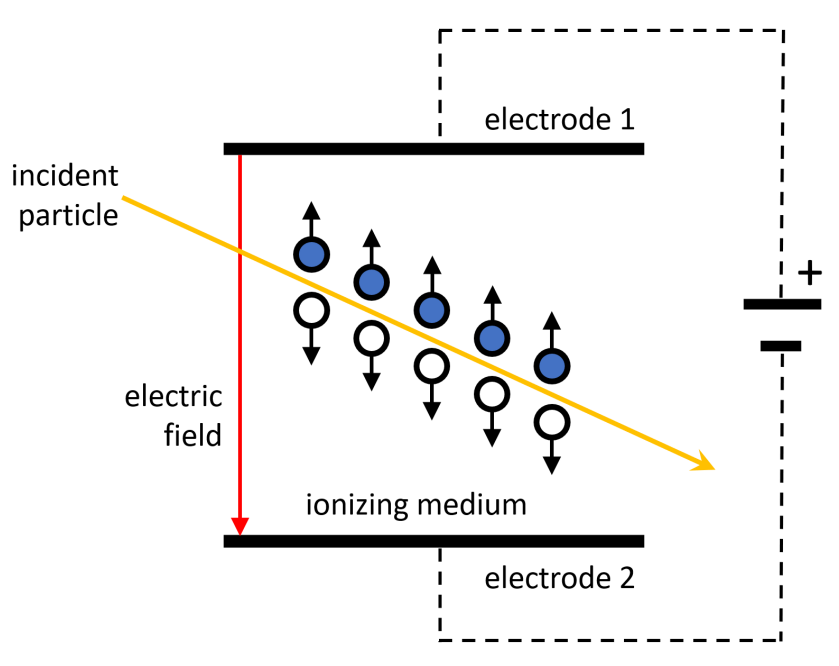
Unifying all existing forces of Nature, discovering new phenomena, or explaining the origin of the Universe are some of the Elementary Particle Physics goals. To achieve them, the early universe conditions are recreated in the accelerating and detecting facilities introduced in Chapter 1. High velocities, high energies, energetic collisions, ultra-fast readout, . . . All this requires unique hardware and software developments. This chapter focuses on the main detecting technologies available at the moment, explaining the Physics concepts and processes on which their functioning is based.

From each LHC collision, the resulting particles travel in all possible directions. Therefore, particle detectors like CMS must cover the entire interaction region, while resisting the released radiation, which deteriorates their detecting capabilities. From the existing detection techniques, the ones based on ionisation are the most common. And two kinds of detectors can be distinguished inside this group: gaseous ionisation detectors and silicon-based detectors. To cover large volumes or areas, gaseous ionisation detectors are normally chosen. However, when compactness, precision and speed are required for detection, the silicon-based position sensitive detectors are the most used. The gaseous ionisation devices detect the presence of particles with enough energy to ionize a gas atom or molecule. They detect the current flow due to the electrons and ions generated by ionizing particles. On the other hand, the silicon-based detectors, as introduced in the previous chapter, are the best candidate for special high radiation environments, reason why this chapter is dedicated to them.

In view of the HL-LHC upgrade (Section 1.4), radiation tolerant silicon sensors are being developed in the framework of ATLAS, CMS, RD50 and other sensor R&D collaborations and projects. Nonetheless, before going in detail with the sensors specifications and the

characterisation I have carried out, it is necessary to start with the basics. Along this chapter, I introduce the types of interaction with matter, semiconductor physics fundamentals related with energy bands, charge carriers, etc.

This chapter explains how silicon is engineered to become an ionizing radiation detector. The consequences of exposing a sensor to radiation, as well as the ways of dealing with them, are explained in this chapter. Finally, the 3D sensor is presented and compared with other kinds of silicon technologies.



**Fig. 2.1** Schematic of an ionizing radiation detector with its basic components: ionizing medium, electric field and electrodes. A particle passing through ionizes the atoms of the medium generating charge.

An ionizing radiation detector is constituted by an ionizing medium, an electric field and electrodes, as represented by Fig. 2.1. As this chapter explains, silicon provides the ionizing medium, where charged particles passing through generate ionisation charge; the PN junction structure creates the electric field  $\vec{E}$  that transports the ionisation charge; and the PN junction contacts are the electrodes, separated by a distance  $d$ , collecting the generated charge.

The signal measured by the detector is the electric current  $I$  induced by the ionisation charge  $q_0$ , during its drift towards the electrodes. The electric current induced by a single charge carrier is given by the Ramo's Theorem.

## 2.1 Interaction of particles with matter

Detection is based on the interaction between particles and the *sensing* medium. This is done through energy deposition, which can be done in two ways. If the particles lose all their energy while travelling through the detector, they are completely stopped before getting out of it, so all their energy can be detected. However, in case the particles pass almost undisturbed, like it happens inside the CMS tracker, just a fraction of their energy is deposited.

In a particle detector, the 90% of the generated particles are pions and very high momentum muons and electrons. Silicon detectors are used to detect the interaction with photons and electrically charged particles. These interactions are explained in the following three subsections, depending on the type of particle passing through: charged particles, low energetic photons and high energetic photons.

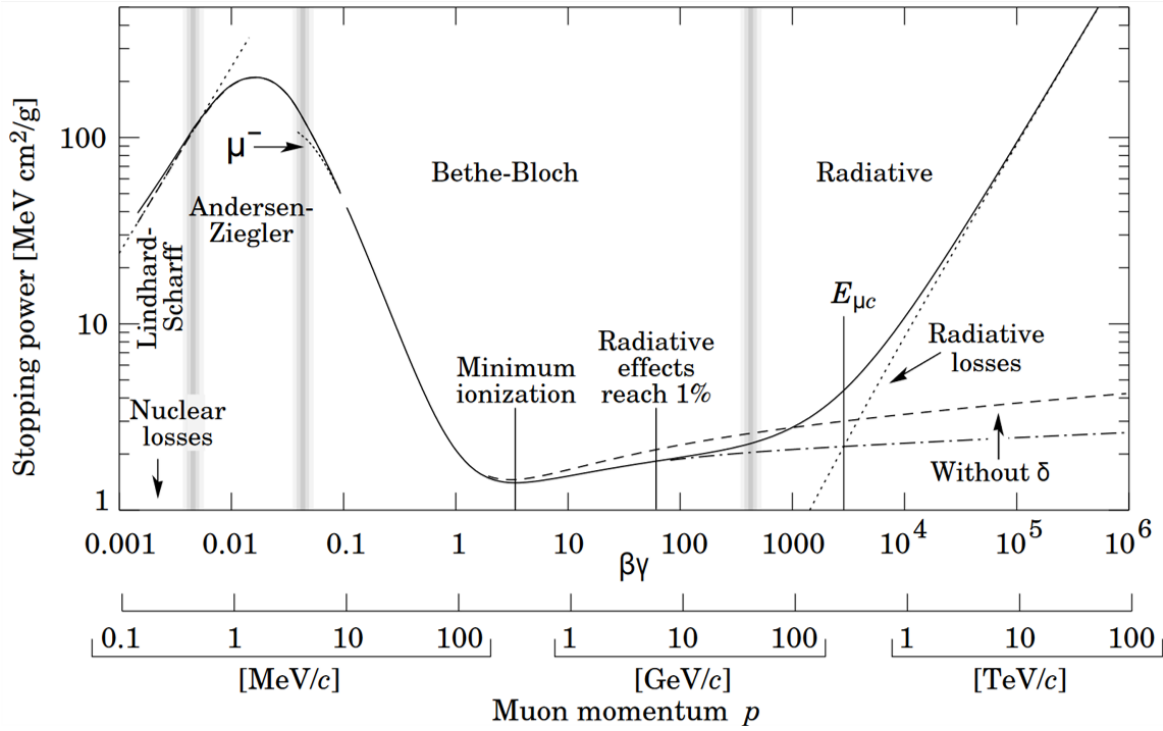
### 2.1.1 Charged particles

The total energy loss in the medium is calculated as the sum over each individual stochastic interactions. The Bethe-Bloch formula, given by Eq. (2.1), describes the average energy loss of charged particles when travelling through matter, per distance travelled, i.e. the *stopping power*.

$$\frac{-dE}{dx} = 4\pi m_e (r_e \cdot z \cdot c)^2 \rho \frac{N_A Z}{A} \frac{1}{\beta^2} \left( \frac{1}{2} \ln \frac{2m_e (\gamma \cdot \beta \cdot c)^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right) \quad (2.1)$$

This is the Bethe-Bloch formula for heavy charged particles. It expresses the energy loss by unit length  $\frac{-dE}{dx}$ , as a function of the classical electron radius  $r_e$ , the medium density  $\rho$ , the atomic  $Z$  and mass  $A$  numbers, the Lorentz factor  $\gamma$ , the density effect correction to ionisation energy loss  $\delta(\beta\gamma)$ , and the mean excitation potential  $I$ . This energy loss is given in units of MeV cm<sup>2</sup>/g. The term  $T_{max}$  is the maximum energy transfer in a single collision,  $\beta$  is the velocity ratio  $v/c$  of the incident particle, and  $\gamma$  is the inverse of  $\sqrt{1 - \beta^2}$ .

The Bethe-Bloch equation describes the mean energy loss per unit distance well in the range  $0.1 \lesssim \beta\gamma \lesssim 1000$ , as shown in Fig. 2.2. At higher energies, radiative processes need to be considered. At lower energies, shell corrections are required. An important limitation to the Bethe-Bloch equation is that it does not describe very well the energy loss of electrons or positrons. This is due to their low mass and, in the case of electrons, scattering on the same particle. Equation (2.1) yields the average stopping power, it does not describe the distribution for individual particles.

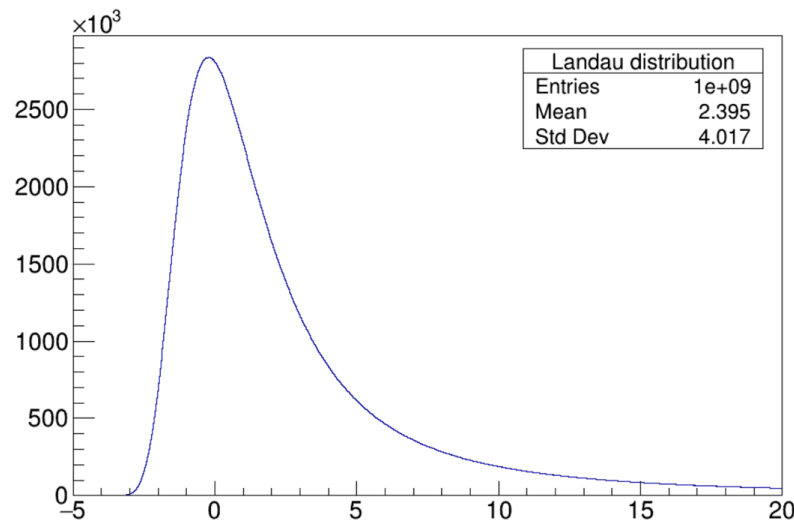


**Fig. 2.2** Mass stopping power  $-\frac{dE}{dx}$  for positive muons in copper as a function of  $\delta(\beta\gamma)=p/Mc$ , momentum and kinetic energy. The solid curve represents the total stopping power. [33].

In the regime of interest in High Energy Physics (HEP), the stopping power mainly depends on  $\beta$ . A particle in the broad minimum over the large range of  $\beta\gamma$  is a minimum-ionising particle (MIP). Protons, pions and other types of charged particles are often close to MIPs.

When charged particles traverse matter, the fluctuation of their energy loss by ionisation is described by the Gauss and/or Landau distributions. For thick detectors the measured energy loss distribution approaches a Gaussian. However for thin detectors, including silicon sensors, it is better described by the Landau distribution. This asymmetric probability density function, shown in Fig. 2.3, presents a long upper tail, due to the few individual collisions with a small probability of transferring large amounts of energy. Theoretically, the tail extends to infinite energies, although the energy deposited by an incoming particle cannot exceed its own energy [34].

In rare cases, secondary electrons can be released by the primary particle passing through the detector leading to larger ionisation. These high energetic electrons (keV) are named *delta electrons*. In practice, the Landau distribution is usually convoluted with the gaussian for the purpose of modeling the noise.



**Fig. 2.3** Typical Landau distribution.

### 2.1.2 Low energetic photons

Photons ionize silicon and in the case of low energetic photons, this is useful to perform sensor characterisation with laser. There are three effects which dominate the photon-matter-interaction at low energies: photoelectric effect, Compton and electron/positron pair creation.

At low energies the photoelectric effect dominates, although Compton scattering, Rayleigh scattering, and photonuclear absorption also contribute.

The photoelectric cross section is characterized by discontinuities (absorption edges) as thresholds for photoionisation of various atomic levels are reached. The photoelectric effect dominates up to the order of 10 keV. The incident photon is fully absorbed by an electron which is emitted. This is direct ionisation.

At higher energies, the Compton effect takes over, which is inelastic scattering. During this process again an electron is released, although the photon is not fully absorbed, but re-emitted with an increased wavelength (or decreased frequency).

At energies sufficient to produce electron-positron pairs, i.e. slightly above 1 MeV, pair production is possible and will become the dominant effect of photon-matter interaction.

### 2.1.3 High energetic photons

Silicon detectors are also used to detect electromagnetic and hadronic cascades. High-energy photons predominantly lose energy in matter by  $e^+e^-$  pair production. The characteristic

amount of matter traversed for pair production is called the radiation length  $X_0$ , usually measured in  $\text{g cm}^{-2}$ . It is the appropriate scale length for describing high-energy electromagnetic cascades. When a high-energy electron or photon is incident on a thick absorber, it initiates an electromagnetic cascade as pair production and bremsstrahlung generate more electrons and photons with lower energy. The longitudinal development is governed by the high-energy part of the cascade, and therefore scales as the radiation length in the material. Electron energies eventually fall below the critical energy, and then dissipate their energy by ionisation and excitation rather than by the generation of more shower particles.

Distance is measured in units of radiation length and energy in units of critical energy, given by Eq. (2.2).

$$t = \frac{x}{X_0}, y = \frac{E}{E_c} \quad (2.2)$$

## 2.2 Semiconductor physics fundamentals

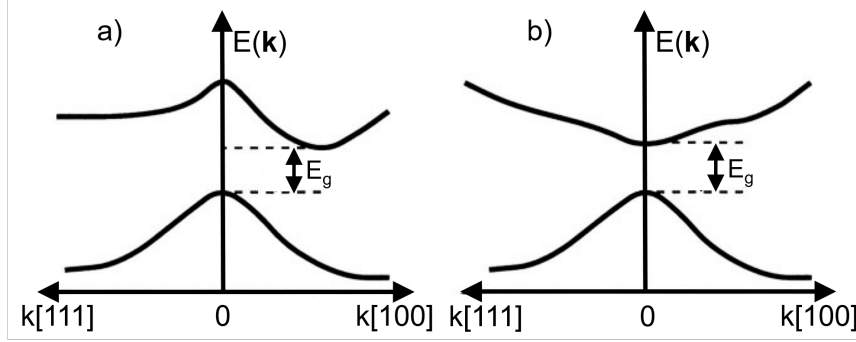
Silicon is the second most abundant element on the Earth's crust. It is easy and cheap to obtain. Silicon is a semiconductor, thus its atoms are arranged in a crystalline lattice that establishes a periodic potential.

The electrons in a single atom can access discrete energy levels. However, when the atoms are brought together in a periodic arrangement to form a crystal, these levels merge in energy bands. These bands are represented by the  $E$ - $k$  curves, defining the energy  $E$  of the electron wavefunction along the  $k$ -space or *momentum space* [35]. In the reciprocal lattice of the crystal, or Fourier space,  $k$  is the three-dimensional wave vector giving the propagation direction of the electron wavefunction. It defines the crystal momentum  $p$  of the electron in the lattice as  $p = \hbar k$ , where  $\hbar$  is the reduced Planck constant. The energy band structure gives the allowed energy and momentum states of an electron inside the crystal. This energy dispersion relation is based on the tight binding model, which considers the lattice potential over the electrons. The valence orbitals of the atoms form the valence band, while the empty atomic orbitals constitute the conduction band. Conduction is created by partially filled bands, which can happen both in the valence and conduction bands [36].

In the case of silicon, whose atoms form a diamond-cubic crystal structure, a simplification of its band structure is shown in Fig. 2.4a. The forbidden range of energies, is called band gap. It represents the difference in energy between the valence band edge (bottom curve in Fig. 2.4a) and the conduction band edge (top curve). The former is the valence band highest energy, while the latter is the conduction band lowest energy. The value of the silicon



energy gap at 300 K temperature is  $E_g = 1.125$  eV. This is the required energy to break the silicon covalent bond.

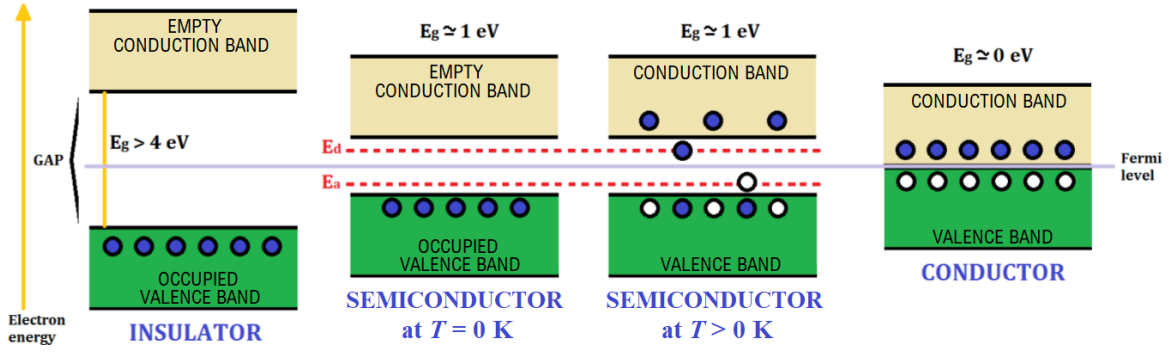


**Fig. 2.4** Examples of simplified energy band diagrams. a) Indirect band gap semiconductor, like silicon. b) Direct band gap semiconductor. Adapted from [36].

Since the conduction band edge minimum and the valence band edge maximum have different crystal momenta (or  $k$ -vectors in the reciprocal space), silicon presents an *indirect gap*. In this case an electron moving from the edge of the conduction band to the valence band does not emit a photon. The electron passes through an intermediate state, transferring momentum to the crystal lattice, and involving both a photon and a phonon. The *direct gap* case is shown in Fig. 2.4b, where the lowest conduction band energy and the highest valence band energy would have the same crystal momenta. Here, the electron transition from the conduction to the valence band is direct, a photon is released and no change in momentum is performed. In these diagrams, the crystallographic plane notation is used to identify positions over the momentum space.

In an insulator, the valence and conduction bands are largely separated by a forbidden energy gap ( $E_g > 4$  eV), as represented in Fig 2.5. However, in conductors these bands overlap ( $E_g = 0$  eV), allowing the free promotion of electrons to the conduction band even at  $T = 0$  K, leaving vacancies or *holes* in the valence band. Both the conduction band electrons and the holes contribute to the electrical conductivity.

With an intermediate band gap ( $E_g \cong 1$  eV), semiconductors represent the case in between insulators and conductors. The 1.125 eV band gap of silicon is large enough to prevent the free movement of electrons between the two bands at  $T = 0$  K. At zero Kelvin there is no thermal energy, electrons fill completely the valence band while the conduction band remains empty, no carriers exist. At temperatures above zero, however, the thermal energy is continuously exciting electrons from the valence band to the conduction band. At room temperature, the silicon conduction band is still maintained almost empty [37].



**Fig. 2.5** Energy band sketches for energy band gap  $E_g$  comparison. In insulators,  $E_g$  is high, but low or null in conductors. In semiconductors, with an intermediate  $E_g$ , the introduction of intermediate energy levels (donor  $E_d$  or acceptor  $E_a$ ) allow extra electron transitions. Blue circles are electrons, white ones are holes.

The model of a semiconductor is an ideal gas of free electrons with effective masses at constant temperature. These free electrons present two values of the state density effective mass, one for the conduction electron and another one for the hole. The curvature of the maximum/minimum edge of the valence/conduction band defines the value of the effective mass of the hole/electron. The charge carrier concentration in this ideal gas model is given by the chemical potential. In a semiconductor, the chemical potential equals the Fermi level, also represented in Fig 2.5, since it describes well the experimental data. Numerically, the Fermi level coincides with the energy level about which there is a 50% probability of finding a carrier.

### 2.2.1 Intrinsic Semiconductors

In an intrinsic or pure semiconductor, the generation of a free electron in the conduction band implies the generation of a hole in the valence band. Therefore, the concentrations of conduction electrons  $n$  and holes  $p$  are the same  $n = p = n_i$ . Creation of conduction electrons and holes happens through thermal promotion of electrons from the valence band.

The energy of the topmost filled level in the ground state of an  $N$  electron system at room temperature is the Fermi energy  $E_i$ . In three dimensions, it is given by Eq. (2.3). The occupied orbitals are represented as points inside a sphere in  $k$  space: the *Fermi surface*. In this way, the energy at the Fermi surface is the Fermi energy, where the wavevector magnitude is  $k_F$  [37].

$$E_i = \frac{\hbar^2}{2m} k_F^2 = \frac{\hbar^2}{2m} \left( \frac{3N\pi^2}{V} \right)^{2/3} \quad (2.3)$$

This expression relates the Fermi energy to the electron concentration  $N/V$ . The total number of orbitals with an energy equal or less than a given one is obtained from Eq. (2.3). And from this one, the number of orbitals per unit energy range, this is the density of states  $D(E)$ , is defined as shown by Eq. (2.4), which corresponds to the model of free particle inside a box.

$$D(E) = \frac{dN}{dE} = \frac{V}{2\pi^2} \left( \frac{2m}{\hbar^2} \right)^{3/2} E^{1/2} \quad (2.4)$$

The Fermi-Dirac distribution gives the probability that an orbital at energy  $E$  will be occupied in an ideal electron gas in thermal equilibrium. The Fermi level  $E_F$  is the chemical potential of the electrons of the gas. The energy  $E$  is given by the temperature and the Fermi level.

The concentration of intrinsic carriers can be expressed as a function of the temperature  $T$ , the band gap and the Fermi level. The concentration of conduction-band electrons  $n_i$ , is determined by adding up the conduction electron concentration over all the conduction band energy, from the bottom of the band  $E_C$  to the top  $E_\infty$ , as expressed in Eq. (2.5). Here, the concentration of conduction electrons at any energy  $N(E)$  is the product of the density of states  $D_e(E)$ , or number of conduction states, with the Fermi-Dirac distribution  $f(E)$ , or probability of a conduction electron orbital being occupied. At room temperature,  $E - E_F \gg k_B T$  is satisfied for the conduction band of a semiconductor, which reduces the Fermi-Dirac distribution function to  $f_e(E) \approx \exp\left(\frac{E_F - E}{k_B T}\right)$  [35] [38].

$$\begin{aligned} n &= \int_{E_C}^{E_\infty} N_e(E) dE = \int_{E_C}^{E_\infty} D_e(E) \cdot f_e(E) dE \approx \\ &\approx \int_{E_C}^{E_\infty} \frac{1}{2\pi^2} \left( \frac{2m_e}{\hbar^2} \right)^{3/2} \sqrt{E - E_C} \cdot \exp\left(\frac{E_F - E}{k_B T}\right) dE = \\ &= 2 \left( \frac{m_e k_B T}{2\pi\hbar^2} \right)^{3/2} \cdot \exp\left(\frac{E_F - E_C}{k_B T}\right) = N_d \cdot \exp\left(\frac{E_F - E_C}{k_B T}\right) \quad (2.5) \end{aligned}$$

Here,  $E_C$  is the energy of the conduction band edge,  $E_V$  in the case of the valence band. If the holes near the top of the valence band behave as particles with effective mass  $m_h$ , the density of hole states  $D_h(E)$  is given by the same expression as  $D_e(E)$  but substituting  $m_e$  by  $m_h$  and  $\sqrt{E - E_C}$  by  $\sqrt{E_V - E}$ . In an intrinsic semiconductor the Fermi level is in the middle of the forbidden gap  $E_F \approx \frac{1}{2}E_{gap}$ , since both carrier densities are equal. In this way  $E_F - E_C = E_V - E_F$  is satisfied and both expressions of  $n$  and  $p$  are identical [36].

The electron and hole effective masses appear as a consequence of solving the quantum problem of the periodic potential. A conduction electron is not deflected by ion cores arranged on a periodic lattice because matter waves can propagate freely in a periodic structure [39]. The concept of density of states effective mass will be explained later on (Section 2.2.4).

At 300 K, the carrier concentration in silicon is  $n_i = 1.45 \times 10^{10} \text{cm}^{-3}$ . The intrinsic conductivity and intrinsic carrier concentrations are largely controlled by  $\frac{E_g}{k_B T}$ , the ratio of the band gap to the temperature, where  $k_B$  is the Boltzmann constant. When this ratio is large, the concentration of intrinsic carriers will be low and the conductivity will be low.

## 2.2.2 Extrinsic semiconductors

By adding intermediate energy levels, electron transitions can be facilitated at  $T > 0$  K. These levels were already represented in Fig 2.5 with red discontinuous lines. Levels close to the valence band are acceptor levels  $E_a$ , introducing vacancies or holes in the valence band, by accepting electrons from it. Levels close to the conduction band are donor levels  $E_d$ , providing with electrons able to be easily promoted to the conduction band, to contribute to the conduction process. In this way, the creation of a conduction electron is not necessarily related to the appearance of a hole anymore. As well as the promotion of an electron does not necessarily mean that an electron is added to the conduction band.

The inclusion of these new electronic available states is done by introducing different atoms in the silicon lattice. The process of introducing impurity atoms in the silicon is called *doping the semiconductor*. Controlled amounts of special impurity atoms are added to the lattice: donors enhance the electron concentration, while acceptors increase the hole concentration. Since Si is a column IV element, doping with boron (column III) creates one vacancy per atom, this is a lack of electron, a hole. The new atom *accepts* an electron from a nearby Si-Si bond. A P-type or Positive silicon is formed. On the other hand, with phosphorus (column V), an extra electron per atom is introduced in the lattice. Effectively, the new atom *donates* a conduction band electron to the system. An N-type or Negative silicon is constituted.

These configurations modify the electron and hole concentrations, changing the energy required to allow the transitions between levels. Figure 2.8 shows the simplified energy level illustrations of the valence and conduction bands edges  $E_v$  and  $E_c$ , the Fermi energy for an intrinsic semiconductor  $E_i$ , and the Fermi level  $E_F$  for an N-type semiconductor in a) and a P-type in b). The Fermi energy in an intrinsic semiconductor  $E_i$  is the energy of the highest occupied level when the electron and hole concentrations in the material are the same.

Therefore, the relative position between  $E_i$  and  $E_F$  in an energy band diagram immediately defines the kind of semiconductor represented. The difference between them is defined by  $kT \ln \frac{N_a}{n_i}$ , being  $k$  the Boltzmann constant,  $T$  the temperature,  $N$  the impurity density in the doped semiconductor ( $N_a$  for P-type and  $N_d$  for N-type) and  $n_i$  the carrier density in the intrinsic semiconductor.

The expressions of the carrier densities in an extrinsic semiconductor are the same as in an intrinsic semiconductor, given by Eq. (2.5). However, since the Fermi level changes when introducing the impurities, the values of  $n$  and  $p$  change too. The Fermi-Dirac distribution is  $f_h(E) = 1 - f_e(E)$ , leading to the hole density expression given by Eq. (2.6).

$$\begin{aligned} p &= \int_{E_{-∞}}^{E_V} \frac{1}{2\pi^2} \left( \frac{2m_h}{\hbar^2} \right)^{3/2} \sqrt{E_V - E} \cdot \exp\left(\frac{E - E_F}{k_B T}\right) dE = \\ &= 2 \left( \frac{m_h k_B T}{2\pi\hbar^2} \right)^{3/2} \cdot \exp\left(\frac{E_V - E_F}{k_B T}\right) = N_a \cdot \exp\left(\frac{E_V - E_F}{k_B T}\right) \quad (2.6) \end{aligned}$$

By multiplying the expression for  $n$  and  $p$ , to obtain the equilibrium relation, with  $-E_C + E_V = -E_{gap}$  obtaining Eq. (2.7). This leads to the law of mass action of Eq. (2.7), a relation about the concentrations of free electrons and electron holes under thermal equilibrium. It states that, in equilibrium conditions, the product of the free electron concentration  $n$  and the free hole concentration  $p$  is equal to the constant square of the intrinsic carrier concentration  $n_i$ .

$$n \cdot p = 4 \left( \frac{k_B T}{2\pi\hbar^2} \right)^3 \cdot (m_e m_h)^{3/2} \cdot \exp\left(\frac{-E_{gap}}{k_B T}\right) = N_d \cdot N_a \cdot \exp(E_V - E_C)/kT = n_i^2 \quad (2.7)$$

This relationship is trivial for the intrinsic semiconductor, but it is extremely important in the extrinsic semiconductor. Knowing the concentration of one kind of carrier, the other one can be calculated. The mass action law provides a powerful analytical tool for the determination of the minority carrier concentration.

These types of doped semiconductors are used for creating semiconductor structures like the PN junction. In this structure, silicon gets depleted from free carriers, as will be explained in Section 2.3.

### 2.2.3 Generation and recombination of charge carriers

The carrier concentration and the neutrality of the silicon crystal are considered just in a static way. However, in the real device there is a dynamic equilibrium: electron–hole pairs are continuously created and eliminated. The average concentration is what remains constant. Carrier generation and recombination are the processes producing these changes and keeping the mass action law satisfied in equilibrium. They are crucial parameters since they govern device characteristics and performance [37].

In a semiconductor, carrier generation is the creation of electron-hole pairs, through impurities and direct promotion. Carrier recombination is the opposite process: an electron is absorbed by a hole, leading to carrier loss. In an ideal indirect semiconductor, phonons are required to conserve energy and momentum when free electrons recombine. In a real device, recombination is dominated by the forbidden gap additional levels. In this way, recombination is determined by lattice defects, impurity atoms, with an energy state *deep* in the band gap, far from the band edges: deep levels. In an extrinsic semiconductor, the promotion to and from intermediate levels is actually the one taking place. Direct and phonon contributions are negligible. The Shockley-Read-Hall SRH statistics explain these recombination processes taking deep levels into account: the trap-assisted recombination. This kinetic model can be used to calculate carrier capture and emission rates based on the defect energy level in the band gap and the carrier capture cross section [40].

The deep levels are often called generation-recombination centres, briefer recombination centres or intermediate-level states. The process leads to a reduction of minority carrier lifetime, influencing device characteristics. The emission/capture rates are primarily defined by the deep level cross-section  $\sigma_{n,p}$ , the energy difference to the valence/conduction band and the fraction of deep level states originally occupied by electrons  $n_{dl}$  or holes  $p_{dl}$ , naturally dependent on temperature. The subindex  $n$  is used for electrons and  $p$  for holes.

Each defect type has a generation rate  $G_t$  given by Eq. (2.9). This rate depends on the total donor and acceptor defect concentration  $N_t$ , the defect occupancy  $f_t$  and the electron and hole emission rates  $R_{en}$  and  $R_{ep}$ . The impact of each defect can be calculated with the capture cross sections for holes  $\sigma_p$  and electrons  $\sigma_n$ , the position in the band gap, the type of defect and the total defect concentration  $N_t$ . The defect occupancy with electrons  $f_t$  can be calculated by Eq. (2.8).

$$f_t = \frac{c_n \cdot n + R_{ep}}{c_n \cdot n + R_{en} + c_p \cdot p + R_{ep}} \approx \frac{R_{ep}}{R_{en} + R_{ep}} \quad (2.8)$$

$c_n$  and  $c_p$  are the capture coefficients of each carrier type,  $n$  and  $p$  are their densities and  $R_{en}$  and  $R_{ep}$  their emission rates. The electron capture coefficient depends on its thermal velocity  $v_{th,n}$  like  $c_n = \sigma_n v_{th,n}$ . Since the detector space charge region has very low charge carrier densities, they can be neglected leading to the second part of the equation.

The recombination rate  $R$ , is related to the carrier density  $n$  or  $p$  as shown in Eq. (2.10). Through recombination, the carrier density decreases, and as long as the carriers disappear in pairs, this rate remains the same for both types of carrier.

$$G_t = N_t \cdot f_t \cdot e_n = N_t \cdot (1 - f_t) \cdot e_p = N_t \cdot \frac{e_n \cdot e_p}{e_n + e_p} \quad (2.9)$$

$$R = -\frac{dn}{dt} = -\frac{dp}{dt} \quad (2.10)$$

Two emission processes are distinguished:  $R_{en}$  for electrons and  $R_{ep}$  for holes.  $R_{en}$  is the rate with which electrons from the deep level state go up to the conduction band. This is a scattering of electrons with phonons.  $R_{ep}$  is the transit rate of holes from deep level down to the valence band, or also of electrons up to the deep level.

There are two capture processes as well:  $R_{cn}$  for electrons and  $R_{cp}$  for holes.  $R_{cn}$  is the transit rate of electrons from conduction band down to deep level. This is a process of scattering between the electron and the trap.  $R_{cp}$  is the rate of holes from valence band up to deep level, or electrons in the deep level down to the valence band.

$$R_{cn} = v \cdot \sigma_n \cdot n \cdot N_t \cdot (1 - f(E_{dl}, T)) \quad (2.11)$$

$$R_{en} = E_n \cdot N_t \cdot f(E_{dl}, T) = v \cdot \sigma_n \cdot n_i \exp((E_t - E_i)/k_B T) \quad (2.12)$$

In the capture rate,  $v$  is the group velocity of the corresponding carriers,  $\sigma_e$  is the scattering cross section of the deep level for electrons.  $N_t \cdot (1 - f(E_{dl}, T))$  is the number of empty traps, where  $f(E_{dl}, T)$  is the Fermi distribution, expressing the probability of the traps being occupied.  $E_{dl}$  is the energy of the deep level,  $n_i$  is the intrinsic carrier density,  $E_i$  the intrinsic Fermi energy and  $k_B$  the Boltzmann constant. In steady state/thermal equilibrium, the emission and capture rates are the same  $R_{en} = R_{cn}$  and  $R_{ep} = R_{cp}$ .

From Eq. (2.9), the total generation current  $I$  in the sensor can be calculated (see Eq. (2.13)) by summing over all defects and taking into account the active volume of the device, defined by the depletion region width  $w$  and the area  $A$ . The elementary charge is represented by  $q_0$ . Because only defects located in the space charge region contribute to the generation current in the bulk,  $I$  depends on the voltage in the same way as the width  $w$  of

the depleted region, and saturates when the applied voltage is equal to the depletion voltage.

$$I = q_0 \cdot w \cdot A \cdot \sum_t^{defects} G_t \quad (2.13)$$

The generation current also depends on the mean free time between collisions, or lifetime  $\tau_L$ , whose expression is shown in Eq. (2.14). Although in this case, the proportionality goes inversely. The lifetime is completely defined by the impurities, like interstitial atoms, the dopant atoms, phonons, crystal dislocation or grain boundaries. Depending on the placement of the levels, lifetime values range from ns to ms. In Eq. (2.14),  $v_{th}$  is the thermal velocity,  $\sigma$  the charge carrier cross-section and  $N_t$  the impurity/trap concentration. All this is referred to indirect semiconductors since this is the case of silicon.

$$\tau_L = \frac{1}{\sigma \cdot v_{th} \cdot N_t} \quad (2.14)$$

Defects take the function of step stones to generate or recombine free charge carriers. The impurities act not only as traps but also as generation centres for electron-hole pairs. The direct band to band generation or recombination is technically negligible. Dislocations or precipitates in the active device regions or point defects in the silicon crystal and especially metal impurities introduce new *deep* levels inside the band gap.

The effect of fluence on the sensor leads to an increase of the number of traps. Fluence and the defect or trap concentration  $N_t$  are lineally related. Since the generation current directly depends on  $N_t$ , after irradiating a sensor the generation current proportionately increases, as an SRH consequence.

### 2.2.4 Carrier transport

For the purpose of simplification a one-dimensional silicon crystal is assumed. When an electric or magnetic field is applied to the semiconductor, an electron in the periodic potential is accelerated with respect to the lattice, behaving like a free electron in vacuum and exhibiting an effective mass  $m^*$ . Its wavefunction is periodic and extends over the size of the material. The presence of the periodic potential, due to the atoms in the crystal, changes the properties of the electron, and its mass differs from the free electron mass.

The density of states effective mass is directly proportional to the curvature of the band (second derivative of the energy with respect to the wave vector  $k$ ) and defined by Eq. (2.15). As a consequence,  $m^*$  is positive when the electron is close to the bottom of a band, and



negative when it is close to the top of a band. The physical meaning of an electron with negative effective mass is that, in response to an applied force, the electron will accelerate in a direction opposite to the one expected from classical considerations.

$$\frac{1}{m^*} = \frac{1}{\hbar^2} \frac{d^2 E}{dk^2} \quad (2.15)$$

The electric current  $J$  in each band is given by Eq. (2.16), where  $q$  is the electron charge,  $L$  is the length of the one-dimensional crystal,  $v$  is the electron velocity and the sum is done over all the states in the band. From this equation it is deduced that empty and filled bands carry no current. The former due to the lack of charge carriers creating the current. The latter because of the band symmetry and the filling of all the available states. In this case, for every electron travelling in the  $+x$  direction with a velocity given by  $v(E) = (1/\hbar)(\frac{dE}{dk})$ , there will be another electron travelling with the same velocity in the  $-x$  direction. In addition, the application of any force cannot modify the velocity distribution within the band, since there are no empty states.

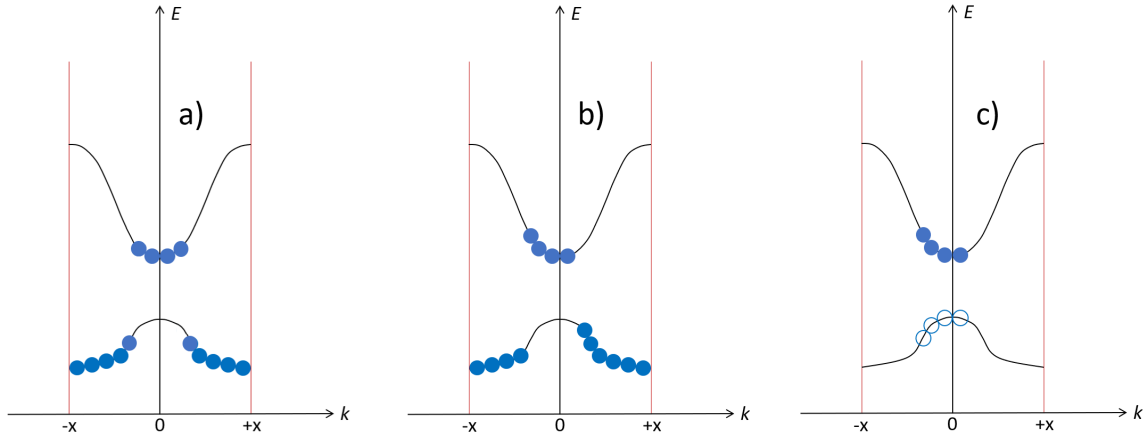
$$J = -\frac{q}{L} \sum_i v_i \quad (2.16)$$

By increasing the temperature of the solid, electrons in the highest occupied band (just below the Fermi level) are promoted to the next upper band. Since the number of electrons at each side of the  $k = 0$  position in the lattice would still be the same, in equilibrium conditions, no current is still expected in either of the two partially filled bands. The filled-state distribution in each of these bands is symmetric about the band center and no current flows. However, by applying an external electric field, electrons inside the valence band will move in the direction to the field, and those in the conduction band in the opposite one, due to the effective mass values. This will cause the skew of the filled-state distribution, as represented in Fig. 2.6 and both bands will contribute now with a current. This current in a partially occupied band, which we denote with  $PO$ , is given by Eq. (2.17), and deduced from Eq. (2.16).

$$J_{PO} = -\frac{q}{L} \sum_{i(\text{filled})} v_i = -\frac{q}{L} \sum_{i(\text{all})} v_i + \frac{q}{L} \sum_{i(\text{empty})} v_i \quad (2.17)$$

The electric current is given by those states in a band which are filled with electrons. As established previously, the summation of  $v_i$  over all states in a band is identically zero. Since the contribution of filled states, together with the empty ones give the total current in a band, the last term in Eq. (2.17) is the sum of zero plus the current from empty states in the band. In this way, the current due to the electrons is the same and opposite to the current due to the spaces left by the electrons, which we call holes. These vacancies behave as positive

charges placed in the empty electronic states. The action of electrons in almost filled bands can be expressed in terms of this positively charged entity occupying empty electronic states. In Fig. 2.6 the illustration of this concept can be found. These valence-band holes have a negative effective mass, which is opposite to the conduction-band electrons one, reason why they move towards  $-x$  even if the electric field is applied in the  $+x$  direction.



**Fig. 2.6** a) Filled state distribution in 1D crystal in equilibrium conditions: electrons are distributed symmetrically respect to  $k = 0$ . b) Skewed filled state distribution when applying an external field parallel to  $k$  axis. c) Same plot using the hole concept as an alternative to the electronic configuration in the lower energy band. Electrons are filled circles, holes empty ones. Figure inspired by [35].

Inside a semiconductor, charge carriers move through either diffusion or drift. While diffusion is driven by concentration gradients, drift is caused by external applied forces. Thermal energy makes carriers move in random directions. However, in the presence of a concentration gradient, carriers collide more frequently on the direction of the higher concentration. Diffusion makes the charges net motion be directed towards the lower concentration. Nonetheless, when an external voltage is applied, the created electric field drifts the charge carriers, on average, parallel to its lines. The drift velocity of carriers is proportional to the applied electric field, following Eq. (2.18), where  $\mu$  is the carrier mobility.

$$\vec{v} = \mu \vec{E} \quad (2.18)$$

## 2.3 The PN junction

A detector based on ionisation requires a medium where particles can generate charge carriers that can be collected. To assure the readout signal is due to solely external particles reaching

the detector, the free charges originally present in the medium must disappear. The PN junction is a structure capable of achieving this situation. Simply represented by Fig. 2.7, the PN junction constitutes the base of almost all current electronic devices, as it is found in diodes or rectifiers and transistors.

The PN junction is formed when a single semiconductor crystal is doped with acceptors on one side and donors on the other. In this way, a P-type and an N-type regions are created, separated by a metallurgical boundary. Originally, the boundary between the two regions is located at  $x = 0$  of Fig. 2.7. In real devices, this interface region has an area of less than  $10^{-4}\text{cm}^2$ .

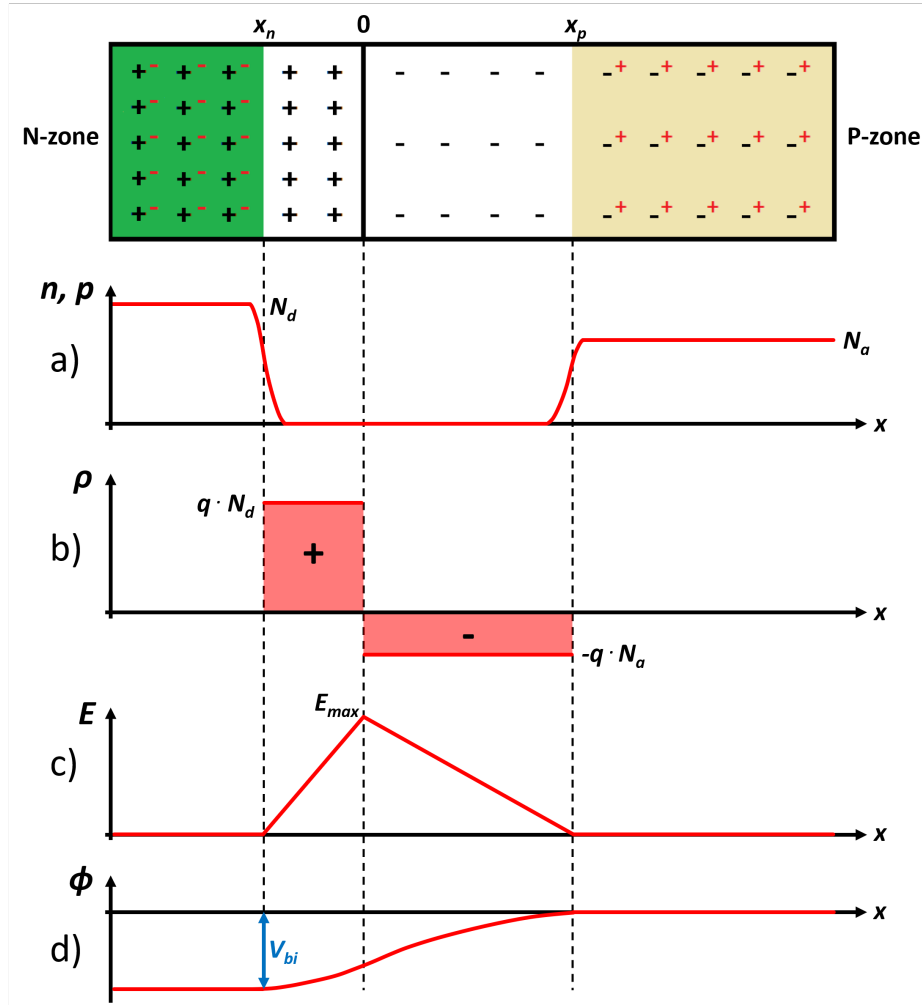
On the left of Fig. 2.7, in green color, the N-type semiconductor is represented, with its majority charge carriers, electrons, symbolised in red. On the right, the P-zone is represented in beige, where the majority carriers are holes. Black '+' symbols in the N-zone are used to represent the ionized donor impurity atoms, while the acceptor ones of the P-zone are '-' signs, all of them fixed in the lattice.

In the moment the PN junction is created, both  $x_n$  (edge of the N-zone containing free carriers) and  $x_p$  (same edge for the P-zone) lie on  $x = 0$ . Immediately, charge carriers start diffusing and recombining along the junction ( $x = 0$ ), due to the different charge densities on each side. Electrons cross the junction in order to occupy the holes at the P-zone, leaving a space depleted from free charge carriers at both sides, due to the electric field set by the impurity ions.

One of the zones is generally more doped than the other, extending the diffusion exchange to the largest volume possible. For the sake of simplicity, it is usually assumed that donor and acceptor densities in each part are uniform and that the junction is abrupt. Assuming the N-zone is highly doped ( $N_d \approx 10^{16} \text{ cm}^{-3}$ ) over a reduced volume, the P-zone doping concentration has to be lower ( $N_a \approx 10^{12} \text{ cm}^{-3}$ ) and extend over a larger space. This satisfies the neutrality condition and will require just few volts to deplete the entire bulk, as it will be explained further on.

At  $x = 0$ , the electric field generated by the ionized atoms remaining in the depleted volume of the lattice finds its maximum value. This field decreases with distance to the boundary and its intensity is given by solving Poisson's equation (Eq. 2.19). The electric field intensity and electrochemical potential dependence with position along the PN junction are shown in Fig. 2.7.

$$-\frac{d^2\Phi(x)}{dx^2} = \frac{\rho}{\epsilon_r\epsilon_0} = \frac{q_0 \cdot N_{eff}}{\epsilon_r\epsilon_0} \quad (2.19)$$



**Fig. 2.7** Representation of a PN junction. Free charge carriers are represented in red. The depletion region in white, is graphically divided in two by the boundary between the P and N-type regions. Under the representation, the space dependence of a) Electron and hole concentrations  $n(x)$  and  $p(x)$ , b) charge density  $\rho(x)$ , c) electric field  $E(x)$  and d) electric potential  $\Phi(x)$ .

In Eq. (2.19), the electrical permittivity of silicon ( $\epsilon = 1.04 \times 10^{-12}$  F/cm) is expressed as a function of its relative permittivity  $\epsilon_r = 11.9$  and the one of the vacuum  $\epsilon_0 = 8.854 \times 10^{-12}$  F/cm. The charge density  $\rho$  is the sum of the charges due to the holes, electrons, ionized acceptors and ionized donors. Since in the space charge region the former two are negligible, the only two contributions can be merged into the product of the elementary charge and  $N_{eff}$ . The last one refers to the effective doping concentration, given by the difference between the concentration of ionized donors and acceptors in the space charge region.

The diffusion current drives the recombination of the free carriers at the junction. The ionized donor or acceptor atoms remain fixed to the silicon lattice, creating a space charge

region (SCR) free of carriers (depleted region). The SCR creates a built-in electric field  $E_{bi}$  from the N-zone towards the P-zone, opposing the diffusion of carriers, that is, creating a drift current that compensates the diffusion current.

Integrating Eq. (2.19), the electrical field strength is obtained, which depends linearly with the position along the space charge region. We assume the full-depletion approximation: the depletion region around the metallurgical junction has well-defined edges, allowing the expression of the electric field given by Eq. (2.20). Therefore, the electrical field out of the depleted region is zero. The electrical field in the PN junction finds its maximum  $E_{max}$  at the boundary of the metallurgic junction ( $x = 0$ ), as shown in Fig. 2.7. As Eq. (2.21) shows, it can be expressed in terms of each type region or of both together depending directly on the depleted region width  $w$  in the PN junction, which is explained in the following subsection.

$$E(x) = -\frac{d\Phi(x)}{dx} = \begin{cases} +\frac{q_0 \cdot N_d}{\epsilon_r \epsilon_0} (x + x_n) & -x_n < x < 0 \\ -\frac{q_0 \cdot N_a}{\epsilon_r \epsilon_0} (x - x_p) & 0 < x < x_p \end{cases} \quad (2.20)$$

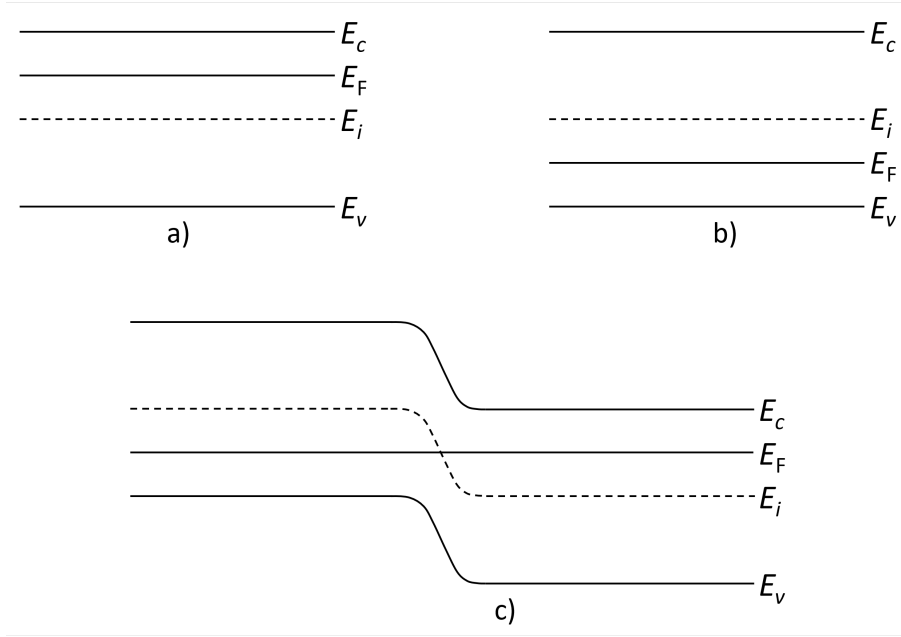
$$E_{max}(x) = \frac{q_0 \cdot N_d \cdot x_n}{\epsilon_r \epsilon_0} = \frac{q_0 \cdot N_a \cdot x_p}{\epsilon_r \epsilon_0} = \frac{q_0 \cdot N_{eff}}{\epsilon_r \epsilon_0} \cdot w(V) \quad (2.21)$$

Finally, a further integration of the electric field leads to the expressions of the electric potential, given by Eq. (2.22) [38].

$$\Phi(x) = \begin{cases} -\frac{1}{2}|E_{max}| \cdot x_n \cdot \left[ \left( \frac{x}{x_n} \right)^2 + 2 \frac{x}{x_n} \right] & -x_n < x < 0 \\ +\frac{1}{2}|E_{max}| \cdot x_p \cdot \left[ \left( \frac{x}{x_p} \right)^2 - 2 \frac{x}{x_p} \right] & 0 < x < x_p \end{cases} \quad (2.22)$$

As carriers continue recombining,  $V_{bi}$  increases, slowing down the diffusion. At some point, the intensities of the drift and diffusion currents get equal, the carriers can no longer overtake the potential barrier and the depleted region stops growing. The total difference of potential along the space charge region gives the built-in voltage  $V_{bi}$  (Fig. 2.7).

Figure 2.8(c) introduces the representation of the energy levels modification in the PN junction. The carrier population progressively changes from predominantly holes on the left (P-type silicon), to electrons on the right (N-type silicon). Since the Fermi level is a constant, despite the differences it does not change along the PN junction. The conduction band edge in the P-type region and the valence band edge in the N-type region are placed at the same level as in the intrinsic semiconductor, equally separated from the Fermi level  $E_F$ . However, the valence band edge in the P-type region and the conduction band edge in the



**Fig. 2.8** Simplified energy band diagrams representing the edge of the valence and conduction bands ( $E_v$  and  $E_c$ ), the intrinsic Fermi energy  $E_i$  and the Fermi level  $E_F$  in: a) an N-type semiconductor, b) a P-type semiconductor and c) a PN junction. Figures inspired by [35].

N-type region are bent towards  $E_i$ . This level  $E_i$ , is as well bent along the PN junction since it is always right in the middle between  $E_v$  and  $E_c$ .

### 2.3.1 PN Junction in equilibrium creating the depletion region

The built-in potential, represented in Fig. 2.7, reaches a value proportional to the bent  $\Delta\epsilon$  of the bands in the PN junction energy band diagram, since  $\Delta\epsilon = -qV_{bi}$  with  $q$  the electron charge. This is the same to the sum of the  $|E_i - E_F|$  value in each zone. Since these differences were already introduced in Section 2.2, the expression of  $V_{bi}$  in Eq. (2.23) is immediate.

$$V_{bi} = \frac{kT}{q} \ln \frac{N_a \cdot N_d}{n_i^2} \quad (2.23)$$

However, the built-in voltage can also be expressed in terms of the potential already introduced in the previous subsection. Taking into account that the resistivity  $\rho = \frac{1}{q_0 \cdot \mu \cdot N_d}$ .

$$V_{bi} = \Phi(x_n) - \Phi(x_p) = \frac{1}{2} |E_{max}| \cdot w = \frac{1}{2\mu \cdot \rho \cdot \epsilon} w^2 \quad (2.24)$$

$$w = \sqrt{\frac{2\epsilon}{q} \left( \frac{1}{N_a} + \frac{1}{N_d} \right) V_{bi}} \quad (2.25)$$

The width  $w$  of the depletion region is directly correlated with the barrier potential, as shown by Eq. (2.25). This width is also given as a function of the electron charge  $q$ , the doping densities  $N_a$  and  $N_d$ , and the dielectric constant  $\epsilon$ , whose value for silicon is  $\epsilon = 1.04 \times 10^{-12}$  F/cm. In this way, the higher is the  $V_{bi}$ , the wider the depletion region is. And as the depletion region gets wider, the current across the bulk, this is the leakage current (see Section 2.4.1), decreases. There is a smaller capacitance and a lower electronic noise.

Despite the equilibrium reached at the PN junction, it is interesting to keep enlarging the depleted region. A minimum ionizing particle (MIP) traversing a silicon detector creates along its path, on average, 76 electron-hole (e-h) pairs per micron by ionisation [41]. Outside the depleted region, since the charge carrier concentration is many orders of magnitude larger and the electric field is null, this signal gets lost. However, inside the depleted region, the only possible charge carriers are those resulting from the ionisation. The e-h pairs created here travel, inducing a detectable current on the collecting structures. These structures are the electrodes, metallic depositions through which an external voltage to the PN junction can be applied. At them is where also the generated signal induces the current which constitutes the final measurement.

Therefore, the depletion region constitutes the sensitive part of the detector. The largest it is, the largest detection coverage is achieved. When an external bias voltage is applied to the PN junction to reduce the built-voltage, called *direct bias*, current is conducted since charge carriers are allowed to flow. This configuration constitutes a silicon controlled rectifier (SCR). If a reverse external voltage is applied (positive voltage at the N-zone and negative at the P-zone), no current flows but the depletion zone grows. In this way, the free carriers in the N-zone, confined by the potential, accumulate in the region opposite to the PN junction. The same applies to the holes in the P-zone, which also get away from the PN junction, attracted by the negative potential.

All this leads to the growth of the depleted region from both sides. This process takes place until the depletion region covers the entire sensor volume. At that point the sensor is completely depleted and operates at the most efficient configuration. The applied voltage at which this is achieved is the *full depletion* voltage  $V_{dep}$ . This magnitude, given by Eq. (2.26), depends on the effective space charge density  $N_{eff}$  and the detector thickness  $d$ . In this equation,  $q$  is the electron charge,  $\epsilon$  the relative permittivity of silicon and  $\epsilon_0$  the vacuum

permittivity.

$$V_{dep} = \frac{q \cdot |N_{eff}| \cdot d^2}{2 \cdot \epsilon \cdot \epsilon_0} \quad (2.26)$$

The  $V_{dep}$  is essential when characterising a sensor since it gives its operating voltage threshold. At this bias voltage, an electric field over the full device thickness is established. Detector full charge collection is only achieved with voltages equal or over  $V_{dep}$ .

### 2.3.2 Diode current and capacitance

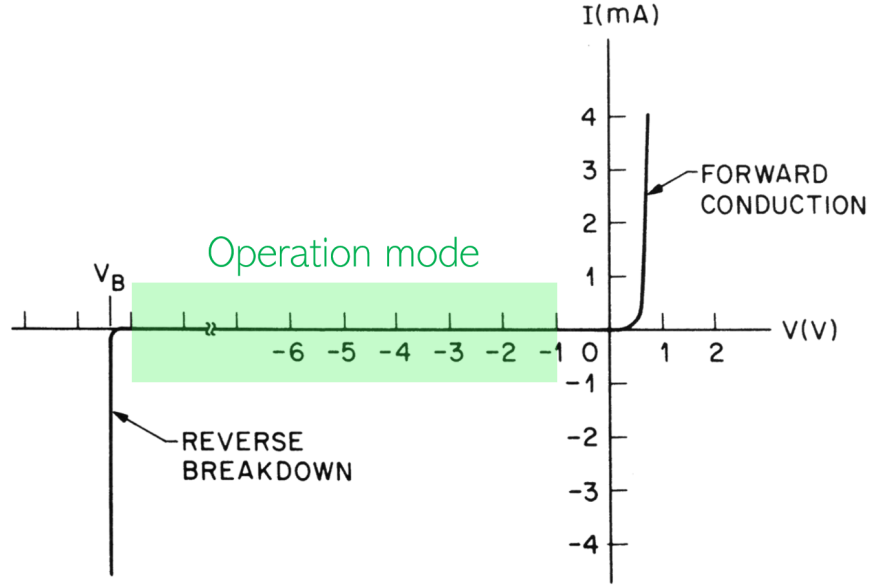
A silicon detector is a diode operated under reverse bias voltage, with the depleted zone acting as a solid state ionisation chamber. A MIP traversing 300  $\mu\text{m}$  of silicon deposits energy with a most probable value around 90 keV. Since, at room temperature, the required average energy to produce an electron-hole pair in silicon is 3.6 eV [38], this leads to a generation of more than 20000 electron-hole pairs.

At full depletion, all generated electrons and holes drift inside the electric field towards the electrodes with velocities  $v_{dr,n}$  and  $v_{dr,p}$  respectively. These velocities are given by  $v_{dr,n,p} = \mu_{n,p} \cdot E(x)$ , where the mobility depends on the effective mass and the mean free time between collisions as  $\mu_{n,p} = \frac{e \cdot \tau_{n,p}}{m_{n,p}}$ . For silicon, the carriers mobilities are  $\mu_n = 1450 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  and  $\mu_p = 450 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ , at room temperature. During this charge carrier movement, the signal measured by the detector is generated. The signal, this is the electric current  $I$  induced by every charge carrier, is described by the Ramo's Theorem in Eq. (2.27), expressing  $I$  as a function of the sensor thickness  $d$ . This is the full depletion region length  $w = d$  when  $V = V_{dep}$ .

$$I = q_0 \frac{v_{dr,n,p}}{d} \quad (2.27)$$

The electric current and bias voltage dependence in a silicon detector is shown in the diode I-V curve of Fig. 2.9. Applying a forward bias, electric conduction is possible from a voltage value which let the electrons overtake the intrinsic voltage step  $V_{bi}$ . This increase in the current is exponential. On the other hand, in reverse bias a saturation regime is achieved, along which the PN junction can be operated, since the sensor is fully depleted. If the bias is too intense, the carriers will accelerate so much that will be able to ionise more atoms from the lattice, ending up in a breakdown.





**Fig. 2.9** Typical current against voltage plot for a PN junction (diode), adapted from [37].

The capacitance is another basic magnitude to characterise a detector. In a PN junction, it is defined per unit area by Eq. (2.29).

$$C = \frac{dQ}{dV} = \frac{dQ}{dw} \frac{dw}{dV} \quad (2.28)$$

Where the incremental change in depletion charge  $dQ$  on each side of the junction is proportional to the applied voltage incremental change  $dV$ . Since the total charge in a depletion region with volume  $V = A \cdot w$  is  $Q = q_0 \cdot N_{eff} \cdot A \cdot w$ , the charge differential is  $dQ = q_0 \cdot N_{eff} \cdot A \cdot dw$  (assuming a diode with planar geometry), and the capacitance can be expressed as follows.

$$C = \epsilon \cdot \epsilon_0 \cdot \frac{A}{w} = A \sqrt{\frac{\epsilon \cdot \epsilon_0 \cdot q_0 \cdot |N_{eff}|}{2(V + V_{bi})}} \quad (2.29)$$

This relation is satisfied up to full depletion, showing that capacitance decreases while increasing the applied voltage. Once full depletion is achieved  $V = V_{dep}$  so  $w = d$ , the capacitance gets a constant value, the *geometrical capacitance*, given by Eq. (2.30).

$$C_{full} = \frac{\epsilon \cdot \epsilon_0 \cdot A}{d} \quad (2.30)$$

## 2.4 Radiation effects: sensor damage

Silicon detectors get damaged when exposed to radiation for a long time period: radiation induces defects. Particles traversing the silicon lattice can damage it, causing its properties to dramatically change.

These damages modify the electric field and energy band structure, and create traps where charge carriers get stuck. This leads to a reduction of the charge collection capability and sensor efficiency. Discerning the signal produced by the incident radiation from noise becomes more complicated. Additionally, the depletion voltage rises, and operating conditions get more demanding and power consuming. The dark current (generated charges without incident outside radiation) also increases, and lower temperatures are required to safely operate the sensor.

In short, radiation damage makes the detection process significantly harder. These detector modifications need to be understood in order to design more resistant sensors, and also to have an idea of how the operating conditions of the detector are expected to evolve with time. To do so, radiation damage is considered in two groups, according to the silicon affected zone and the kind of produced modifications: displacement and ionisation damages. Displacement is damage inside the bulk, while ionisation damage occurs at the surface. Both of them are explained next.

### 2.4.1 Displacement damage

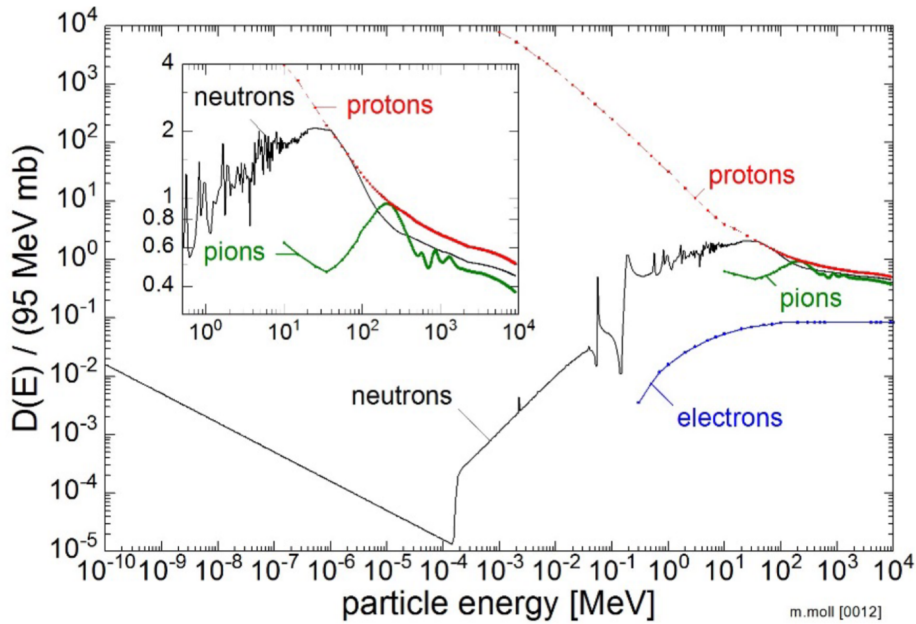
Displacement damage effects arise from the dislocation of silicon crystal lattice atoms from their normal lattice sites by energetic radiation. Displacement damage is also called bulk damage. It constitutes the limiting factor for the use of silicon detectors in the intense radiation fields close to the particle collision points of the LHC.

Hadrons or higher energetic leptons displace a primary knock on atom (PKA) out of its lattice site, leading to a silicon interstitial and left over vacancy. This point defect in silicon is called Frenkel defect, and the displaced atom and the left vacancy constitute a Frenkel pair [42]. This pair can migrate through the lattice and may finally form point defects with impurity atoms in the silicon.

The displacement damage effects are proportional to the so called displacement damage cross section  $D$ . It is equivalent to the Non Ionizing Energy Loss (NIEL) which gives the portion of energy lost by a traversing particle that does not go into ionisation and eventually leads to displacement damage [43]. Nevertheless, just a fraction of the NIEL -that depends on

the impinging particle energy- leads to displacements, because part of the energy is dissipated in phonons. NIEL is defined in units of  $\text{MeVcm}^2/\text{g}$  or as NIEL cross-section (displacement damage function  $D$ ) in  $\text{MeVmb}$  units [44].

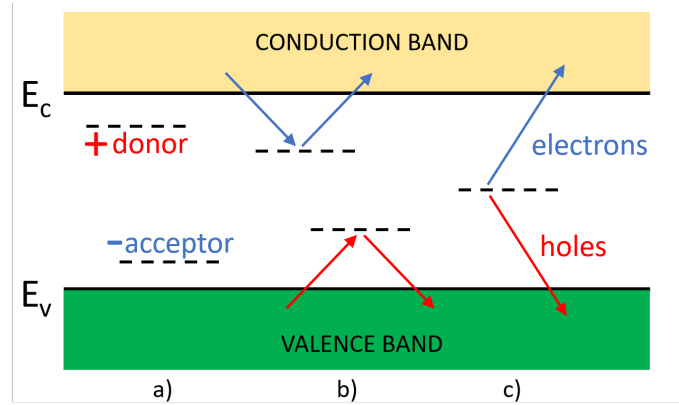
The proportionality between the NIEL-value and the resulting damage effects is referred to as the NIEL-scaling hypothesis [44]. This hypothesis assumes that radiation damage effects scale linearly with NIEL irrespective of the distribution of the primary displacements over energy and space. For silicon, with  $A = 28.086 \text{ g/mol}$  the relation between  $D$  and NIEL is:  $100 \text{ MeVmb} = 2.144 \text{ keVcm}^2/\text{g}$  [45]. The displacement damage cross section for 1 MeV neutrons equivalent has been fixed to the normalized value  $D_n(1 \text{ MeV}) = 95 \text{ MeVmb}$  [45]. On the basis of the NIEL scaling, the damage efficiency of any particle with a given kinetic energy  $E$  can then be described by the hardness factor  $k$ , defined as  $k(E) = D(E)/D_n(1 \text{ MeV})$  [45]. In Fig. 2.10, normalized values  $D(E)/95 \text{ MeVmb}$  for NIEL cross-sections are shown. The damage produced by different particles or particles with different energy should be scalable via their NIEL (i.e. number of displacements) and the data given in Fig. 2.10 should allow to normalize the damage from different particles or particles with different energy to each other.



**Fig. 2.10** NIEL cross-sections normalized to 95 MeVmb [43].

The bulk defects with energy levels in the silicon band gap can be electrically active, generating macroscopic effects. The impact on the device performance can be described in the framework of the SRH statistics. Bulk damage is proportional to the number of defects in the sensor bulk.

On the device performance level three main detrimental impacts of defects can be identified: effective space charge, trapping and leakage current. They are shown in Fig. 2.11 and described next.



**Fig. 2.11** Defect levels scheme showing the three main bulk damage contributions: a) effective space charge, b) trapping, c) leakage current.

### Effective space charge

Radiation can induce defects leading to a change in the effective space charge along the sensor bulk. This change is reflected in a change in the depletion voltage, due to both are directly correlated, as shown in Section 2.3.1. Changes to the effective space charge lead to a change of the electric field distribution within the device, shifting the depletion voltage to lower or higher values.

Assuming an N-type sensor, in its positive space charge, radiation will induce negative charges [43]. The initial space charge reduces with increasing fluence until the overall space charge becomes negative. This point is called *type inversion* or *space charge sign inversion*, due to from here the space charge gets more and more negative with an according rise in depletion voltage. Higher operation voltages have to be applied to establish an electric field throughout the full sensor volume in order to avoid under-depletion and loss of active volume and therefore signal. If sufficiently high voltage cannot be applied or breakdown of the sensor is at risk, sensors will have to be operated under-depleted with the corresponding loss in efficiency.

Inhomogeneous distribution of space charge might lead to double junction effects or the shift of the highest electric field towards regions that are unprofitable for segmented sensors. High local fields can lead furthermore to impact ionisation effects or breakdown. It has been

shown that the change of the space charge in silicon is strongly material dependent (e.g. oxygen content) and depending on the irradiation particle (e.g. neutron vs. proton damage). This implies that this damage effect does not directly scale with NIEL and can be altered or mitigated by defect engineering approaches (e.g. change of impurity content).

In order to deal with type inversion, during an inactivity period of the sensor, it is possible to change the polarity of bias voltage to come back to the previous type. Another option is to just increase the bias voltage until the sensor breakdown, which is the end of its operating life.

### Trapping

Charge carriers generated by ionizing particles or photons in the space charge region travel towards the electrodes and constitute the sensor signal. If these carriers are trapped by defects, they no longer contribute to the signal and the consequence is an overall loss of charge collection efficiency and signal height. Trapping increases with fluence and becomes the limiting factor for high fluence applications. Mitigation of this problem is possible through device modifications leading to shorter collection distances (i.e. device engineering). In segmented sensors the collection of electrons instead of holes at the sensing electrodes can be an advantage due to the higher drift mobility of electrons and the possibility to exploit charge multiplication by impact ionisation at lower fields and without device breakdown.

### Leakage current

Ideally, a reverse-biased diode is non-conducting. Nonetheless, when applying a bias voltage, a small current actually flows through the semiconductor junction. In an irradiated device, defect levels close to the middle of the band gap facilitate the promotion of electron-hole pairs. They are generation centers and the origin of the leakage current. This current also receives the name of *reverse current*, *generation current* or *dark current*. It has a noise component and sets a limit on the smallest signal pulse that can be observed at the detector output. An increase of leakage current leads to an increase of noise in the amplifiers and to an increase of power consumption.

It has been experimentally demonstrated the relation between leakage current and particle fluence. When irradiating silicon sensors with high energetic particles with enough energy to produce defect clusters, the leakage current increases with the particle fluence. This increase happens independently of the type, resistivity and impurity content of the silicon device,

because the leakage current follows the NIEL Hypothesis, meaning that defect engineering (i.e. impurity content of the silicon) has no impact. The proportionality factor is given by the associated current related damage factor  $\alpha$ , given by Eq. (2.31).

$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}} \quad (2.31)$$

The leakage current depends exponentially on the temperature, reason why cooling is a very effective means to mitigate its detrimental effects. The temperature dependence is dominated by the position of the energy levels contributing to the current, their cross sections, concentrations relative to each other and temperature dependence of the band gap itself [46]. The most efficient generation centers are the ones falling on the intrinsic energy level. In this case the leakage current temperature dependence will follow the one of the intrinsic carrier concentration  $n_i$  and result in an effective energy  $E_{eff}$  of about 1.21 eV at temperatures close to room temperature. In non-irradiated sensors the bulk generation current is typically quite small and can easily be obscured by a current over the physical edge, soft breakdown, etc. For irradiated Si sensors the standard parameterisation of the current-temperature dependence is given by Eq. (2.32) [40]. The current reference value in the HEP community for temperature correction (scaling) of the leakage current is:  $E_{eff} = 1.214 \pm 0.014$  eV [43].

$$I(T) \propto T^2 \exp\left(-\frac{E_{eff}}{2k_B T}\right) \quad (2.32)$$

The annealing temperature is the temperature at which the samples are heated to accelerate the defect reactions in the silicon bulk. Annealing the devices leads to a decrease of the leakage current with time: the annealing has a beneficial effect. This reduces the depletion voltage, until the beneficial annealing limit is reached. As introduced in Eq. (2.32), the strong dependence of the leakage current with temperature leads to the necessity of cooling down irradiated sensors while operation and storage, to avoid changes in the leakage current and preserve the sensor behaviour.

### 2.4.2 Ionisation damage

In contrast to bulk effects, surface and interface related changes, produced by the ionizing energy loss (radiation dose), play a minor role for lifetime limitations of silicon detectors. However, it affects the interstrip or inter-pixel capacitance (noise factor) or the breakdown behavior, among other things. The damage on the surface or ionisation damage is due

to Ionizing Energy Loss (IEL). This produces the accumulation of positive charges in the passivation layers at the surface, this is the oxide ( $\text{SiO}_2$ ) and the  $\text{Si}/\text{SiO}_2$  interface of silicon detectors. The electron-hole pair creation in the silicon lattice is a completely reversible process without any damaging effect. This is not true in insulators such as the oxide passivation layer at the surface. Depending on the electric field, part of the electron-hole pairs does not recombine, but gets separated. The damaging effect is caused by holes drifting towards the  $\text{SiO}_2$ -interface, where they get trapped. This leads to an increase in oxide charges and interface states, which are responsible for a shift in the flatband voltage and an increase in the surface generation current. For more information and studies related with this kind of sensor damage, see [47].

This type of damage also produces leakage current in the detector.

## 2.5 State-of-the-art of Silicon sensors for vertexing

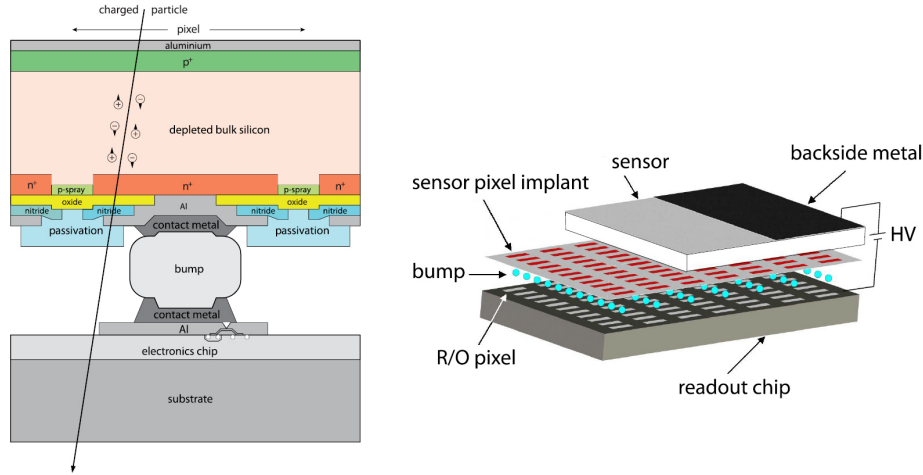
Silicon sensors are widely used in Particle Physics detectors. Some features of silicon detectors are: compactness, suitability for large scale production, and good spatial and timing resolution. In comparison with a conventional gaseous detector, silicon sensors have a much smaller ionisation energy (only 3.6 eV whereas in gases it is about 30 eV). Besides, the ionisation density for a MIP in Silicon is of 76 electron-hole pairs per micron, against the less than  $10^{-3}$  ions per micron in gases [41].

In HEP, two architectures of semiconductor detectors are used: hybrid and monolithic technologies. In the hybrid architecture, the sensor and the readout chip (ROC) are independently fabricated and subsequently connected. On the contrary, in monolithic designs, sensor and readout are integrated in the same silicon substrate. The present section summarizes the state-of-the-art of the semiconductor detectors used for vertexing in HEP. First, hybrid pixel detectors are explained, introducing the planar and 3D pixel technologies. The monolithic designs are presented next, focusing on CMOS sensors and Depleted Monolithic Active Pixel Sensors (DMAPS). Finally, other kinds of hybrid silicon detectors for timing purposes (LGAD, iLGAD, AC-LGAD, TI-LGAD and DJ-LGAD), are described.

### 2.5.1 Hybrid pixel detectors

The hybrid sensor architecture results from the combination of two elements: the sensor and the readout ASIC, as illustrated by Fig. 2.12. This allows for a separate optimisation of the

readout ASIC and the sensor. The interconnection between sensor and ASIC can be done through different bonding techniques, like the bump-bonding represented in Fig. 2.12.



**Fig. 2.12** Hybrid pixel detector. On the left, one sensor pixel is bump-bonded to one readout electronics cell. On the right, the representation of an interconnected hybrid pixel matrix [48].

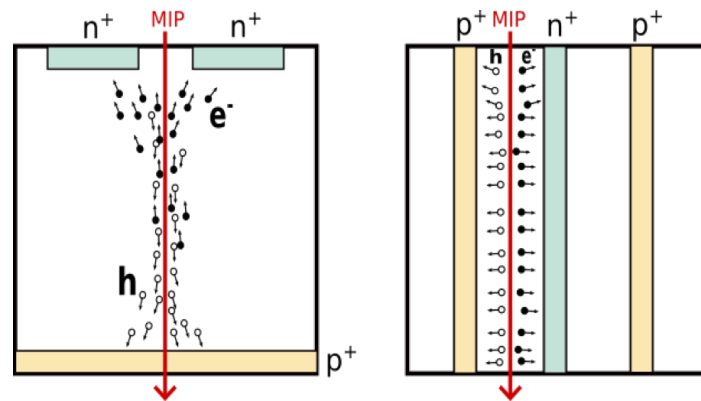
For pixelated devices, planar sensors manufactured using standard microelectronics planar process are the dominating technology. Much more recently, sensors with columnar junctions, named as 3D sensors, were introduced as the alternative to the planar technology for very high radiation environments. This technology is the object of this thesis. In the next section, a brief review of these two pixelated technologies will be carried out.

### The 3D pixel sensor

First proposed in 1997 [49], the 3D pixel sensor presents an arrangement of the electrodes as columns perpendicular to the sensor surface. This is the main difference with the planar technology, see Fig. 2.13 [50].

In Fig. 2.13 the illustration of a planar sensor on the left is compared with the 3D on the right. Electrodes in both cases are represented by green regions ( $n^+$  implants) and yellow ones ( $p^+$  implants). These regions, notated with the '+' symbol, are more highly doped than the bulk which is also doped but with a lower concentration of impurities. The boundary between the  $n^+$  implant with the p-type bulk creates the PN junction, while at the  $p^+$  implant defines the ohmic contact. Electric field lines go from the PN junctions towards the ohmic contacts. When a particle passes through the sensor, it generates charge carriers (electrons  $e^-$  and holes  $h$ ). These carriers move as represented, following the electric field, until being





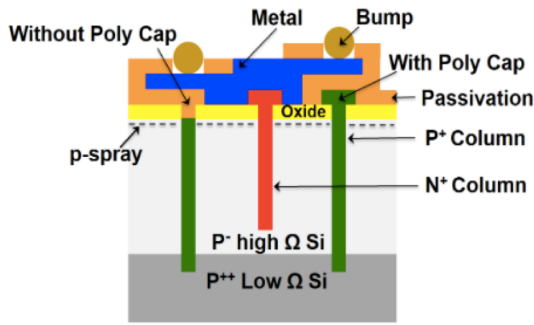
**Fig. 2.13** Illustration of the transverse cut of a planar (left) and 3D sensor (right). Electrodes are represented with green and yellow regions. A MIP goes through the bulk generating electron/hole ( $e^-/h$ ) pairs which drift towards the electrodes.

collected at the electrodes. While moving, they induce a current in the electrodes, creating the signal.

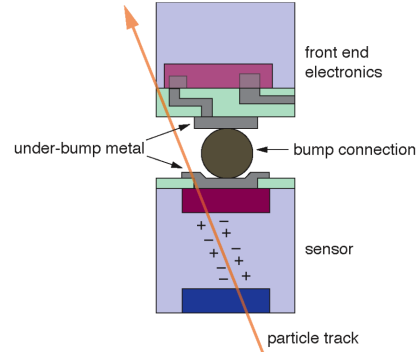
In more detail, a 3D sensors cross-section is shown in Fig. 2.14. The PN junction is located at the boundary between the N column (in red) and the  $P^-$  bulk. In green, the P columns represent the ohmic contacts. A strong electric field is formed between the N column and the P column, enabling the fast drift of excess carriers, being collected at the columns. The N column is connected with a metal to the bump-bond. The bump-bonding connects each of the pixels of the sensor and the channels of the readout chip. A detail of a bump bond connection is shown in Fig. 2.15.

One strong point of 3D sensors, a consequence of their electrodes' arrangement, is the decoupling between the sensor thickness and the inter-electrode distance. In planar pixel sensors, all the layers are parallel to the surface of the sensor, including the electrodes. Consequently, closer electrodes reduce the thickness and active volume; on the contrary, reducing the electrode spacing in 3D architectures does not reduce the active volume of the sensor. The 3D sensors require a notably lower depletion bias voltage, resulting in lower thermal dissipation and preventing thermal runaway and sparking problems which can arise when operated at high bias voltage. Furthermore, Fig. 2.13 shows the charge carriers shorter drift path, that reduces the collection time and the chance of trapping an excess carrier, which is a limiting factor for planar pixel sensors at large fluences (the trapping concept was introduced in Section 2.4). Another singular feature is the reduced charge sharing. Charge sharing is the share of the excess carriers between neighbouring pixels; thus, reducing the charge peak value per pixel. One more difference between 3D and planar technologies is that the 3D architecture is an intrinsic *slim edge* technology where the peripheral ohmic columns

stabilize the electric field at dicing edge; for planar sensors one or multiple *guard rings* are required. The wafer dicing produces mechanical damage in the silicon crystal, making the sensor edge conductive and equipotential with the back-side. In planar sensors, to prevent a short between the grounded front-side contacts and the sensor edge at bias voltage, a *guard ring* structure at the sensor edges is needed for preventing breakdowns by creating a smooth voltage transition between the high and low voltage regions.



**Fig. 2.14** Si on Si FBK 3D sensor transverse cut. The red column is the N-type electrode, and together with the bulk it constitutes the PN junction. Green columns are the ohmic contacts.



**Fig. 2.15** Detail of a bump bond connection. The detector is located at the bottom, while the readout chip is on top of it. From [51].

The 3D pixel sensors are under operation in 25% of the active area of the *ATLAS Insertable B-Layer (IBL)* since 2015. IBL is the first detector to use 3D pixel sensors in HEP experiments. IBL 3D sensors were fabricated at FBK<sup>1</sup> [52] (with pass-through columnar electrodes) and CNM<sup>2</sup> (stopping the electrode etching 20  $\mu\text{m}$  from the opposite side) with double-sided technology. With a  $250 \times 50 \mu\text{m}^2$  pixel size, 230  $\mu\text{m}$  thickness, 12  $\mu\text{m}$  electrode diameter and inter-electrode spacing between opposite type columns of around 67  $\mu\text{m}$  [53] [54]. Two N-type electrodes span the 250  $\mu\text{m}$  readout pitch [55].

The radiation tolerance of IBL sensors is designed up to  $5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ , at low temperatures around  $-20^\circ\text{C}$  [56]. The nominal operating bias voltages were 20 V non-irradiated and 160 V at  $5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ .

The successful operation of the IBL since 2015 demonstrates the viability of the 3D technology for vertexing detectors at the LHC experiments. The sensors were operated efficiently at high luminosity, and Effects of Single Event Upsets (SEUs) were measured at rates close to expectations based on previous tests beams with 24 GeV protons [57].

<sup>1</sup>FBK: Fondazione Bruno Kessler. Research institute in Italy

<sup>2</sup>IMB-CNM: Institute of Microelectronics of Barcelona - Centro Nacional de Microelectrónica. Research institute in Spain

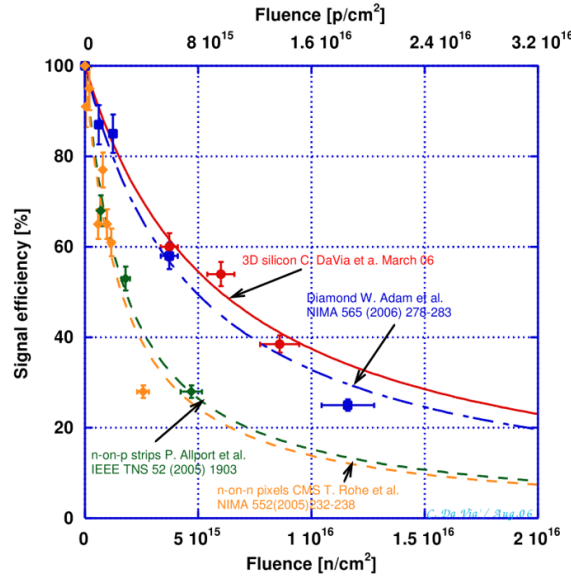
As part of the IBL modules prototyping, using the FE-I4A front-end ROC, the ATLAS 3D Collaboration measured FBK and CNM 3D sensors in test beams at the CERN SPS (120 GeV pions) and at DESY (4 GeV positrons). Efficiencies were measured above 99% fresh and 95% irradiated at  $5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ . When tilting  $15^\circ$ , the 99% efficiency was recovered [58]. They were operated at 20 V fresh and 140 V after irradiation. Measured charge collections were around  $20 \text{ ke}^-$ . The leakage current values are of the order of 100 nA when fresh and 10  $\mu\text{A}$  after 800 MeV proton irradiation. Depletion voltages of 20 V, breakdown voltages around 25-35 V kept after irradiation, efficiencies of 97.5% that increase when tilting the sensor with respect to the beam [59].

The *CMS-TOTEM Precision Proton Spectrometer* (CT-PPS) and the *ATLAS Forward Proton Project* (AFP project) are also two projects using 3D pixel sensors. Both aim to detect leading protons in their forward area. These protons emerge intact from the interaction and escape at small angles inside the LHC beam pipe, losing just a small fraction of their momentum [60].

The CT-PPS tracking system, installed in April 2017, consisted of two stations installed on each side of the CMS experiment; each station with six planes of 3D silicon pixel sensors bump-bonded to the PSI46dig ROC (the same used for the CMS Phase I pixel detector) [61] [62]. Tests were done with prototypes from CNM, FBK, and SINTEF sensor producers [62]. CNM sensors were implemented in the CT-PPS in a double-sided non-passing-through technology. The sensors were 230  $\mu\text{m}$  thick with columns 200  $\mu\text{m}$  deep. A 200  $\mu\text{m}$  slim edge implemented with ptype column fences surrounded the sensitive area. The pixel size was  $150 \times 100 \mu\text{m}^2$  with an inter-electrode distance of 62.5  $\mu\text{m}$  [61]. Resolutions of 25  $\mu\text{m}$  and 10  $\mu\text{m}$  for clusters of size 1 and 2, respectively. Mean efficiencies higher than 99.5% before irradiation were obtained, and higher than 95% after irradiation [60].

As a candidate for the innermost layers of the upgraded *CMS and ATLAS vertex detectors*, the 3D sensor designs are optimized with a reduced pixel cell size of  $25 \times 100 \mu\text{m}^2$  and  $50 \times 50 \mu\text{m}^2$ , thinner active layers around 150  $\mu\text{m}$  and necessary less separated (30  $\mu\text{m}$ ) and narrower columns with diameters around 5  $\mu\text{m}$  [64]. There are two main producers of pixelated 3D sensors: FBK and CNM. The present thesis presents a characterisation of those optimised designs.

Some of our tests on 3D sensors for the CMS IT have been already published in [50], [65] and [27] and will be treated in this thesis. Studies on radiation hardness of 3D sensors 230  $\mu\text{m}$  thick for the ATLAS ITk have demonstrated the high tolerance of this technology when readout with the FE-I4 chip.



**Fig. 2.16** Efficiency of 3D detectors as a function of the fluence of 1 MeV equivalent  $n/cm^2$ . It is compared with n-on-p strip, p-on-n pixel and diamond detectors. Image from [63].

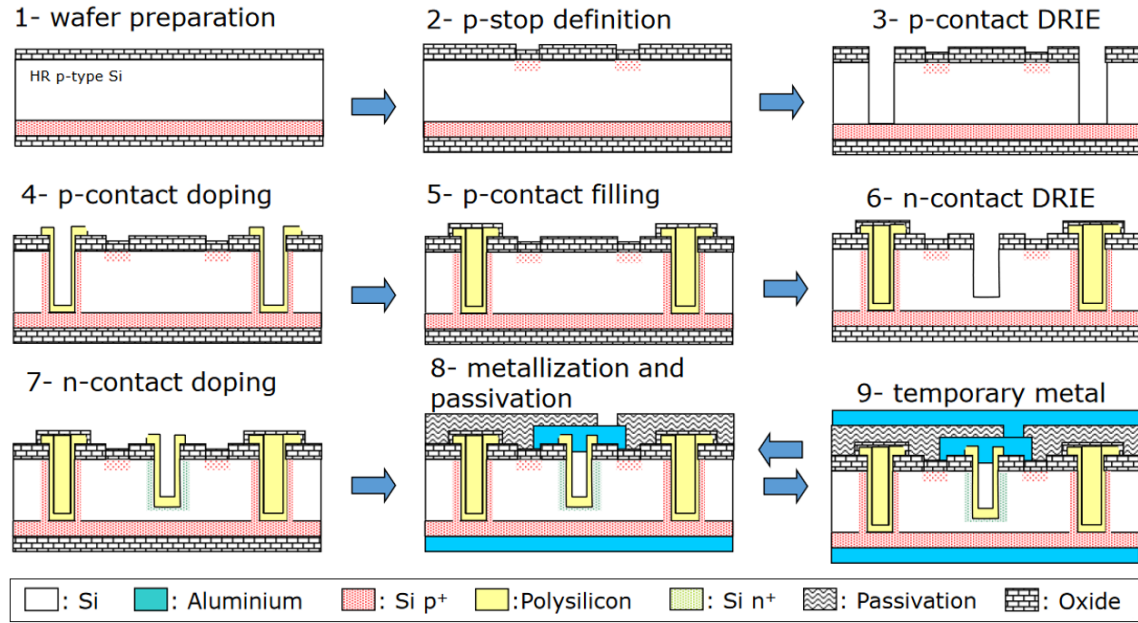
The 3D sensors are also being considered for timing purposes like in the *TIMESPOT project*. They have been optimised for time resolution. TIMESPOT aims to develop a full tracker demonstrator of reduced size (few thousand channels and 4-5 tracking planes) [66]; 55  $\mu m$  pitch 3D-trench sensors were expressly designed for timing applications, with a 150  $\mu m$  thickness, obtaining a 30 ps timing resolution.

Studies with 3D pad and strip detectors at extreme fluences ( $1 \times 10^{17}$  and  $3 \times 10^{17}$   $n_{eq}/cm^2$  respectively) have been recently performed [67] for the Future Circular Collider (FCC).

### Fabrication process of 3D sensors

The fabrication process of 3D sensors is Silicon-on-Silicon (SiSi), where two silicon wafers are welded one over the other. One works as a support wafer, thick and with a low resistivity, while the one on the top is thinner and presents a high resistivity. In short, the SiSi production chain (shown in Fig. 2.17) comprises a series of processes performed over this double silicon wafer, including seven photo-lithographic mask levels and a temporary metal.

The first step is the definition of the P-stops, structures which guarantee an homogeneous distribution of the electric field and a correct isolation of the different column types. Their implantation is done with the growth of the silicon dioxide layer with a wet oxidation on the silicon surface. Then, for the P-contacts, the column etching is performed using Deep Reactive Ion Etching (DRIE), which opens the space for the column inside the bulk of the



**Fig. 2.17** Summary of 3D fabrication process with Silicon-on-Silicon and single side technology. Description provided by Dr. Salvador Hidalgo (IMB-CNM).

wafer. This is followed by the column doping and filling and the N-contacts DRIE and doping. Finally, metallic layers deposition (using sputtering systems) and passivation (to protect the side-wall of the holes from the etching) are performed. A temporary metal is placed on top for protection [68]. All the structures are grown only on one of the surfaces of the sensor, what is called single side technology.

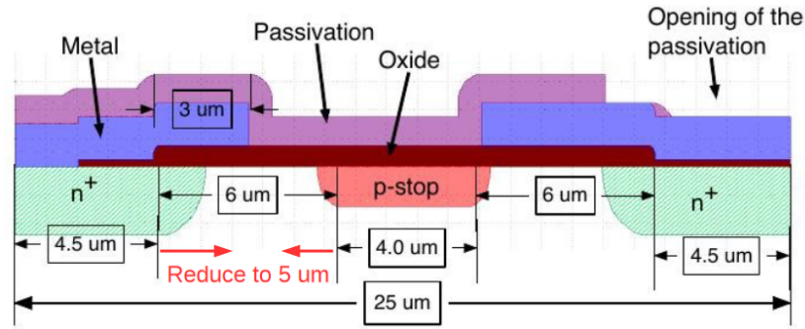
In the case of the classic double-sided 3D sensors, n-type (junction) columns at the center of the p-stop rings are etched from the top surface into a p-bulk, while p-type (ohmic) columns are etched from the bottom surface. The fabrication process is more complex (see [69]) since both surfaces of the wafer are treated in order to grow column structures, but the techniques are the same. In the case of the CNM double-sided 3D sensors, all the columns are etched from the same surface, but the electrodes are created from both sides, which is an approximation of the standard or classic double-sided process.

### Planar pixel sensor

Planar pixel sensors are the standard technology in HEP tracking and vertex detectors, and they are the baseline technology for the high-luminosity upgrade of the vertex detectors for fluences below the  $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ . This technology is relatively easy to fabricate since it is based in the standard planar semiconductor process.

The cross-section of two adjacent planar pixel cells is shown in Fig. 2.18, where two n-in-p pixel cells are isolated by a p-stop structure. The n-in-p technology will replace the previously used n-in-n technology for the high-luminosity upgrade of CMS and ATLAS vertex detectors. The n-in-p avoids the substrate inversion that takes place in n-in-n technology and that obliged to read through the ohmic contact [70].

Other R&D challenges are currently under study for planar sensors: improving the radiation tolerance by reducing the active thickness to  $150\text{ }\mu\text{m}$ ; minimize inactive borders using etched and doped edges, called *active edges*, that reduce them from  $400\text{ }\mu\text{m}$  to  $50\text{ }\mu\text{m}$  [71]; guaranteeing operation safety by solving the breakdown due to high bias voltages; sparking protection or the thermal runaway.

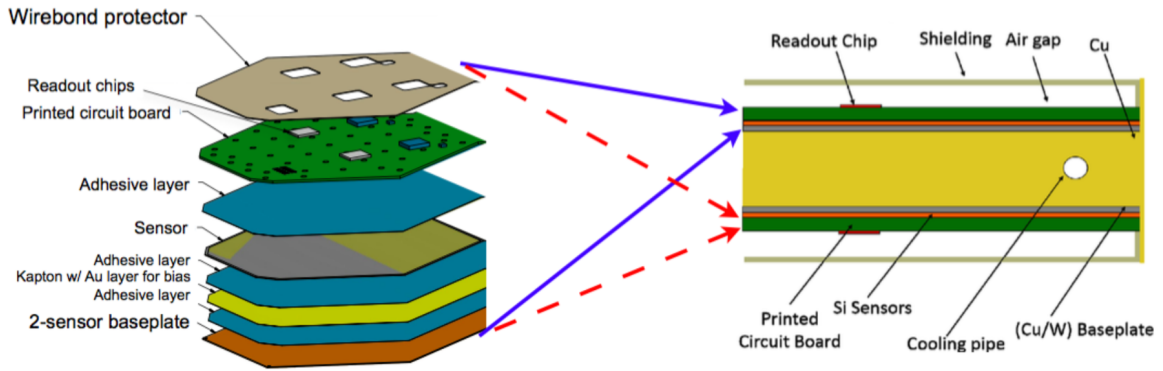


**Fig. 2.18** Transverse cut of an n-on-p HPK planar pixel sensor [72]. The PN junction is given by the boundary of the P bulk in white and the  $N^+$  implant in green. Metal conducts the collected charge towards the connection with the readout electronics. P-stops assure homogeneous electric field distribution and correct isolation among pixels. The passivation serves as external protection.

Planar pixel sensors performance has been broadly tested since 2009, for the ATLAS Insertable B-Layer and the High Luminosity LHC upgrades [73]. Test beam data from HPK and FBK planar sensors showed hit efficiencies of 99%. After irradiation, lower voltages are needed to reach the 99% efficiency or lower for sensors without bias dot structure. Since at normal incidence, severe efficiency drops are found at the bias dot regions, sensors without punch through bias dot are being considered for HL upgrades. Resolutions of  $2\text{ }\mu\text{m}$  for rectangular pixel sizes of  $25 \times 100\text{ }\mu\text{m}^2$ , at a particle beam incidence of  $8.5^\circ$ . Fresh  $50 \times 50\text{ }\mu\text{m}^2$  planar sensor samples with  $150\text{ }\mu\text{m}$  active thickness present an operating bias voltage of  $120\text{ V}$ . This value increases until  $800\text{ V}$  when irradiated at  $5.3 \times 10^{15}\text{ n}_{\text{eq}}/\text{cm}^2$  [74].

Planar sensors and 3D pixel sensors are the two technologies being under consideration for the innermost layers of the HL-LHC pixel systems. When comparing both of them, planar sensors present an easier fabrication process and a lack of regions with lower efficiency at normal incidence.

Planar sensors are already present in the trackers of CMS and ATLAS, but they are also the chosen technology for the future CMS HGCAL. Hexagonal silicon planar sensors with 235 cells of about  $1 \text{ cm}^2$  have been chosen for the HGCAL, where a whole wafer works as one sensor. The hexagonal sensor geometry was chosen since it is the tile-able polygon with the highest possible number of corners. Each cell in a hexagonal sensor is a diode, implemented by a thin implant of opposed bulk polarity, and a metal layer on top. For  $120 \mu\text{m}$  and  $200 \mu\text{m}$  thick sensors, these diodes will be p-type. For  $300 \mu\text{m}$  thick sensors, the type is not decided yet.



**Fig. 2.19** Exploded view of an hexagon module screwed on either side of a copper support plate and built as a glued stack of Cu/W baseplate (mechanical rigidity and thermal pathway to the copper plate), Si sensor and PCB board (on the left). Schematic cross section on the right [29].

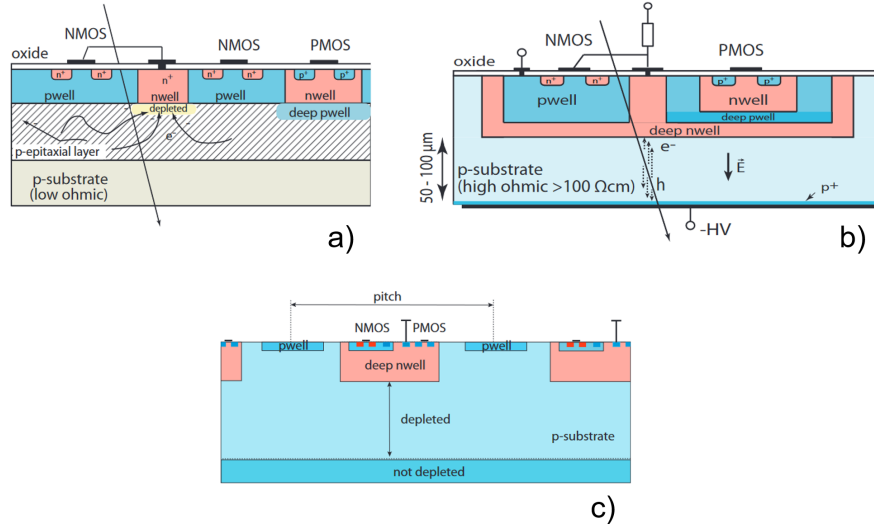
## 2.5.2 Monolithic pixel detectors

Despite their many advantages, hybrid pixel sensors cost is high. As an alternative, monolithic pixel detectors integrate sensor matrix and readout in just one piece of silicon. They are produced through industrial Complementary Metal-Oxide-Semiconductor (CMOS) processes, where the lack of hybridization between sensor and ROC reduces costs and assembly complexity. Monolithic CMOS sensors are an interesting technology to equip large tracker surfaces, they reduce the material volume since they allow for very thin detector layers down to  $50 \text{ mm}$ . Additionally, a smaller pixel pitch (less than  $50 \times 50 \mu\text{m}^2$ , the current baseline pitch for pixel FE chips for the ATLAS and CMS HL upgrades) is possible since the bonding technology does not constrain it.

In the 1990s, monolithic pixel detectors produced with CMOS technologies were proposed [75] and realized [76]. Years later, Monolithic Active Pixel Sensors (MAPS) were presented, where each pixel has a photodiode [77]. MAPS present an epitaxial layer normally grown on a lower quality substrate wafer and hosting the CMOS circuitry, as shown by



Fig. 2.20 [78]. MAPS devices combine excellent position resolution with sufficient radiation tolerance and low power dissipation. They are present in the STAR experiment at RHIC [79] [80].



**Fig. 2.20** Transverse cut representations of: a) MAPS, b) DMAPS and c) CMOS with HV add-on structures. Figures adapted from [48].

The charge collection of a CMOS sensor is based on diffusion, like in the TowerJazz 180 nm sensor for the ALICE tracker, or the MIMOSA-26 sensor of the EUDET telescopes. HV-CMOS sensors are typically reverse biased at voltages larger than 60 V. In a p-substrate, a deep n-well is not only the collection electrode but also shields the electronics from the applied high voltage (HV).

CMOS current developments look for fully depletable, radiation tolerant, and high rate capable monolithic pixel devices. In order to deal with the HL-LHC rates and fluences, improved designs like the depleted monolithic active pixel sensors (DMAPS) aim to obtain better signal and fast timing. Monopix DMAPs developments are currently taking place for fast front-end implementations and preserve charge collection after irradiation [81].

### 2.5.3 Other hybrid architectures

The high rate of concurrent collisions per beam crossing (pileup) at the HL-LHC poses a big new challenge for the CMS components. Due to the increase in particle flux, the CMS IT needs sensors with good time capabilities. This will make possible to distinguish particles passing through the detector very close in time.

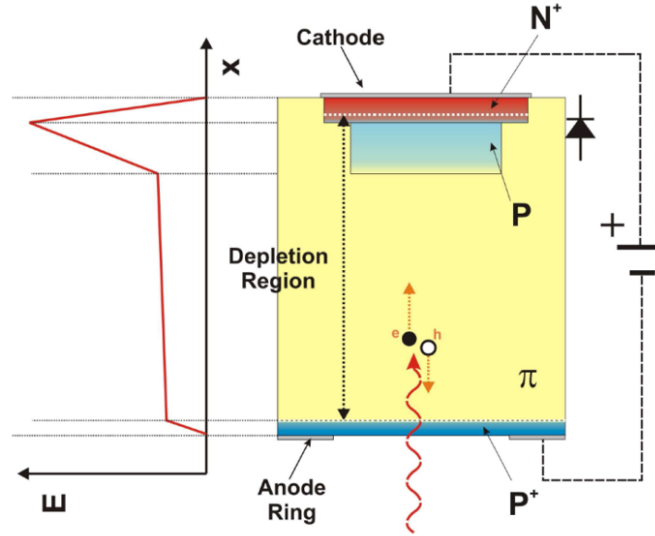


Inside the CMS Endcap Timing Layer (ETL) good time performance detectors able to resolve about 30 ps, are needed to create an hermetic precision MIP timing detector in the CMS endcap region. The chosen technology is the Low-Gain Avalanche Detectors (LGADs). This technology has the same basic principles as planar detectors, the layers of components are grown in parallel. But the difference is that LGADs are based on APD (Avalanche Photo-Diodes) architecture with impact charge multiplication. An APD schematic cross-section is shown in Fig. 2.21. The multiplication layer is represented in light blue, and it is placed inside the sensor bulk and next to the N-type region, where the PN junction is located, and consequently where the electric field is the most intense. This multiplication layer is doped with the same kind of impurities as the bulk, but in a higher concentration, rising the intensity of the electric field. In APDs operated at high reverse bias voltage, charge carriers are so accelerated due to the intense electric field when traversing the gain layer, that they ionize more atoms, generating more electron-hole pairs from the silicon depleted region. Original and secondary carriers are accelerated while inside the high electric field region, generating again new electron-hole pairs. This triggers an avalanche process which multiplies the collected charge carrier amount in both electrodes placed at the surfaces of the detector.

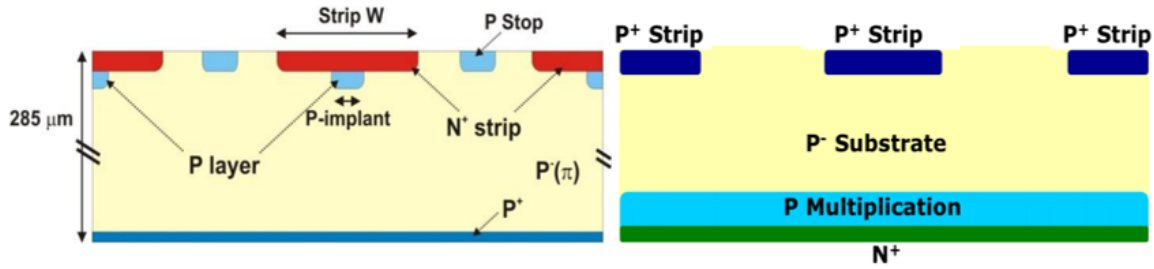
The difference between charge collection and electron-hole pair generation rates define the avalanche process duration. If the first one is higher, the ionisation process decreases with time until the avalanche process is completely stopped (linear mode operation). Nevertheless, if the pair generation is so high that carriers do not have enough time to be collected, the avalanche process is uncontrolled, increasing until breakdown (Geiger mode operation). LGADs are APDs operated in linear mode, where breakdown voltage is never reached. In this way, a great part of the generated charges can get out of the region with high electric field. These charges do not increase their velocity enough to create new pairs, so the avalanche process is under control.

LGADs constitute the first segmented sensors with gain. Their electrodes are arranged in strips or pixels, providing them with spatial resolution. The multiplication layer is segmented as well, together with each electrode. Thanks to the signal multiplication, LGADs achieve better signal-to-noise ratio, improving momentum and time resolution. In particular, the momentum resolution is improved due to the minimization of multiple scattering, thanks to their reduced thickness, and high signal-to-noise ratio. On the other hand, the time resolution is improved thanks to their fast signal rise time.

However, the segmentation of the multiplication layer in the LGAD degrades the timing resolution when a particle hits the inter-pixel region, since there is no signal amplification



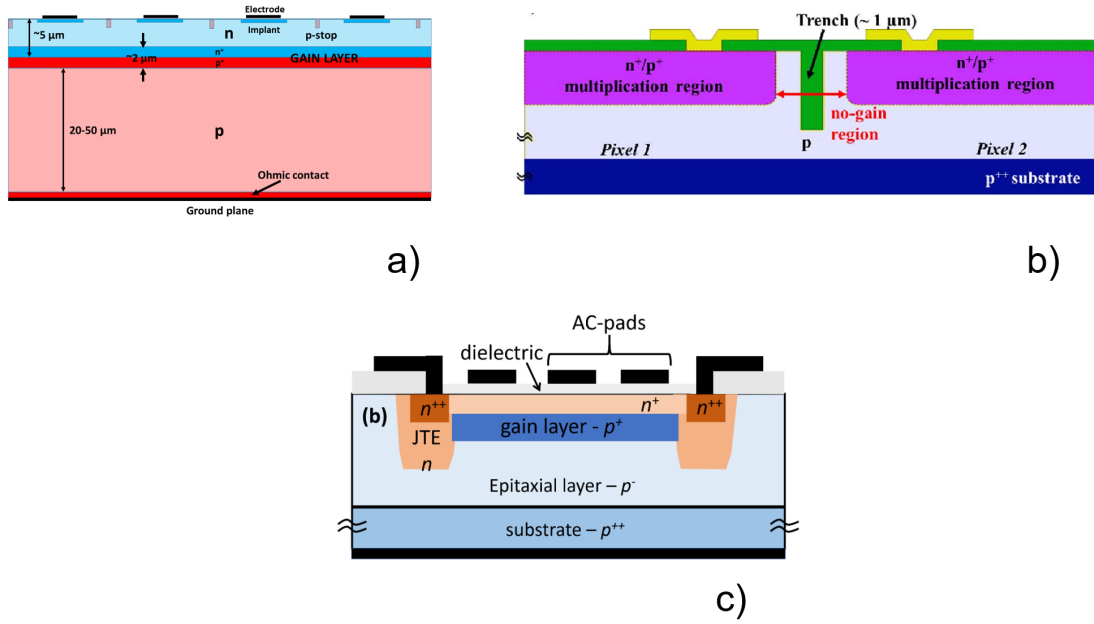
**Fig. 2.21** Avalanche Photo-diode schematic cross-section. The gain layer is represented in blue. On the left the electric field dependence with position [82].



**Fig. 2.22** Schematic cross-sections of an LGAD (left) and iLGAD (right) segmented into strips. The LGAD designs shows how the multiplication layer (P layers) are segmented on each of the electrodes, while in the iLGAD only one continuous multiplication layer is placed on the surface without segmented electrodes [83].

there [84]. The inverse LGAD or iLGAD, aims to solve this LGAD fill-factor problem. In this design, the gain layer is placed at the opposite detector surface. The iLGAD multiplication layer is not segmented, assuring that all the particles crossing the sensor will produce multiplication. A representation of both the LGAD and the iLGAD is shown in Fig. 2.22. The typical LGAD collected charge distribution shows the contribution of two main track families, due to two groups of particles: those passing through regions with multiplication layer and those without. However, in the iLGAD charge distribution, only one contribution is found since all the particles cross the multiplication layer [85].

LGADs will be present in both CMS and ATLAS HL upgrades, with a granularity limited to the millimeter scale. However, for future applications like 4D tracking at forthcoming



**Fig. 2.23** Schematic cross-sections of: a) DJ-LGAD b) TI-LGAD and c) AC-LGAD. Adapted at different scales from [86] [87] [88].

colliding beam facilities, the granularity needs to be improved. In LGADs, this granularity limitation comes from the spatial segmentation, which requires a proper termination at the edge of the readout electrodes: the Junction Termination Extension (JTE) structures. These protective structures avoid breakdown produced by the strong electric field at the LGAD gain layer, but since there is no charge collection or amplification, they create dead regions between pixels. New approaches aim to improve the granularity, like the AC Coupled LGAD (AC-LGAD), the Trench-Isolated LGAD (TI-LGAD) or the Deep Junction LGAD (DJ-LGAD).

The AC-LGAD [88], presents, as the iLGAD, an unsegmented multiplication layer, as shown in Fig. 2.23c). In the AC-LGAD, the JTE is eliminated by replacing the LGAD highly doped N implant by a much less doped, more resistive N layer. The electrodes are AC coupled to this layer through a thin insulator. The resistive N layer collects the multiplied electrons and when the signal discharges to ground, the signal on the AC pad is induced. Almost 100% fill factor is achieved, and the JTE is only present at the edge of the active area of the sensor. Nonetheless, the signal formation mechanism is not the best for high-count-rate environments, due to the AC coupled signal, the slow charge drain by resistive layer and the charge sharing in the N layer [87].

The TI-LGAD [87] is a promising solution for finely pixelated LGAD sensors, represented in Fig. 2.23b). The multiplying core structure is preserved but deep and narrow trenches, with a width around the micron, replace the standard pixel termination structures. The trenches are filled with silicon dioxide at the pixels borders. They are a physical barrier for electron drift/diffusion and provide electrical isolation among neighbouring pixels [86].

In the DJ-LGAD design [86], the multiplication layer is buried some microns under the sensor surface. The multiplication layer is a high-field diode junction, this is a highly doped PN junction. A low field region remains between it and the readout, able to maintain the carrier drift-velocity saturation. This structure avoids inter-channel breakdown, while allowing the pixelization of the readout plane and reducing the granularity to tens of microns. The design of the DJ-LGAD is shown in Fig. 2.23a).

Finally, and just to mention other silicon detecting technologies, there are light detectors which convert electromagnetic radiation into electronic signals. In particle physics, this kind of detectors can be found in the form of solid state silicon photomultipliers (SiPM). SiPM consist on arrays of APDs operated, unlike LGADs, at high reverse bias voltage, which is called Geiger mode. The APDs are polarized above the breakdown voltage of its PN junction, so the generated electric field is intense enough to make the main part of the charge carriers contribute to the avalanche process. In Geiger mode, the APDs work similarly to Geiger counters where the number of events is measured, but not their intensity, and a setup capable of containing the avalanche is required. Nonetheless, the signal of the SiPM is proportional, within a certain range, to the number of activated APDs, and therefore to the number of photons detected, giving a measurement of the light intensity. As a consequence, this kind of detection technology cannot be used for tracking, since they require a lot of space and their spatial resolution is less competitive. However, they are an excellent choice in hadron calorimeters, for scintillator light readout [89].

## Chapter 3

# Working methodology for sensor characterisation

The present chapter explains the procedures used in this thesis to characterize pixel sensors, and describes the parameters of interest. Some specifications of the detectors such as thickness, layout, geometry or kind of bulk are well known from their fabrication; others, such as the depletion voltage and leakage current, must be measured before starting other complex tests on the sensor. One of the basic procedures to measure these magnitudes is the current Intensity over Voltage (IV) and Capacitance over Voltage (CV) characterisations, carried out with a probe station, as Section 3.2 explains.

Fluence degradation processes can be carried out on fresh devices to simulate the performance after years of operation inside big collider experiments like CMS. This is done to ensure proper performance over decades of operation in these harsh radiation environments. In order to test their radiation tolerance, the sensors studied in this thesis were irradiated at the CERN IRRAD facility, explained in Section 3.3.

With the operating parameters set, we subject the sensors to special conditions, similar to the ones they are expected to face during operation inside CMS. This test places the sensor and its readout chip inside a particle beam, in an experimental setup called *test beam*. Depending on the beam characteristics, different energy, luminosity or particles hit the sensor, and consequently several test beam scenarios are found. Through this process, performance features are measured, like: charge collection and charge sharing, hit efficiency, noise, spatial resolution, timing or readout electronics thresholds. For the characterisation, test beams at CERN and DESY, as Section 3.4.1 explains, took place. This chapter finishes (Section 3.4.3) with the presentation of the parameters for which results are shown in Chapter 4.

## 3.1 Devices under test

The devices that were tested and whose results are studied in Chapter 4 are introduced in this section. From now on, our particular samples will be referred to as *Devices Under Test* or DUTs. These are the actual sensors together with their readout chips (ROC), since they are bump-bonded. The DUTs were mounted on two different types of custom printed circuit board (PCB) cards called single-chip cards (SCC) developed by RICE and Bonn universities.

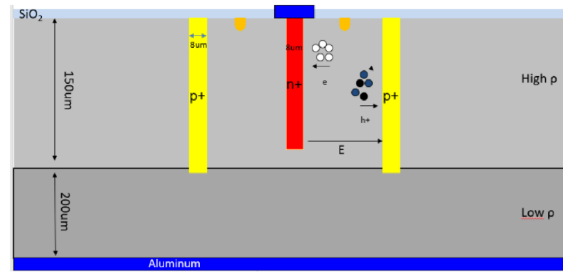
### 3.1.1 Sensors

The design advantage of 3D sensors is that the detector depletion takes place along the radial direction, instead of orthogonally to the sensor surface. Thanks to this characteristic and the short distance between the two types of columns, depleted volumes are found in the bulk of fresh sensors even with no applied bias voltage, and with just few volts the whole bulk is depleted. In addition, the short charge collection distance for ionizing particles, give 3D structures an intrinsic resistance to the effect of bulk silicon damage.

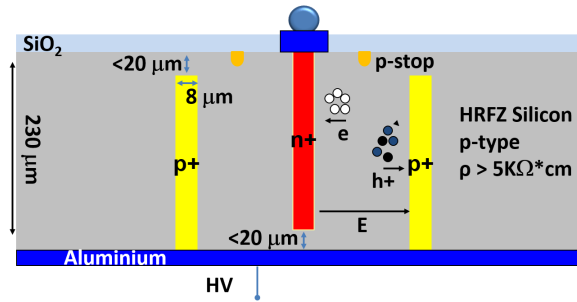
For the IT, 3D sensors are requested to have a good spatial resolution to cope with the increased pileup, and also a high radiation hardness to face the higher expected fluence. All this, while compromising the smallest volume possible in order to fit inside the IT, reducing as much as possible its non sensitive part.

For the extreme track density, a pixel cell size reduction by a factor of 6 with respect to the current CMS pixel detector is necessary. Two geometries are being considered: the rectangular  $25 \times 100 \mu\text{m}^2$  and the squared  $50 \times 50 \mu\text{m}^2$ , whose layouts are shown in Fig. 3.2, from both FBK and CNM manufacturers. To reduce the amount of material inside the detector, sensors with around  $150 \mu\text{m}$  active thickness are considered. A reduced bulk volume also seeks to minimize multiple scattering, making the tracker light enough to interfere the least with the particle tracks and get the most accurate momentum measurement. To deal with high fluence levels, these sensors must present a ratio between signal and threshold high enough at a fluence of  $2 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$  to guarantee good detection efficiency.

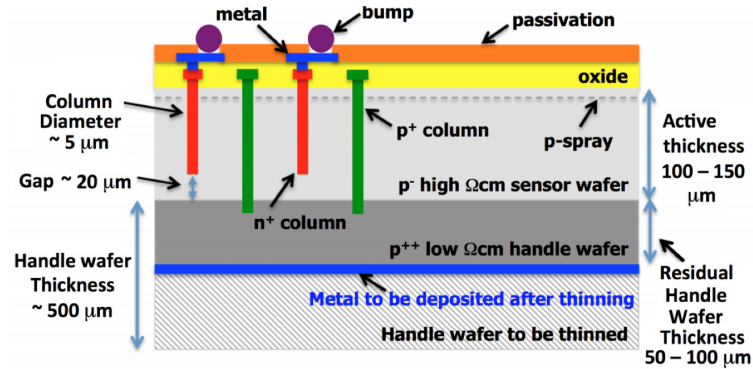
The sensors of my study are pixelated CNM and FBK 3D devices. Both transverse cut representations are shown in Fig. 3.1. The electrodes are columns that penetrate the sensor bulk perpendicular to its surface. The PN junction is located at the boundary between the N column (in red) and the P bulk. The P columns are the ohmic contacts, represented in yellow in the CNM designs and green in the FBK design. The electric field lines go towards them, starting from the N columns, making possible that electrons drift towards the PN junction,



(a) Single side Si-Si CNM 3D sensor



(b) Double side CNM 3D sensor



(c) Single side Si-Si FBK 3D sensor

**Fig. 3.1** Transverse cut of FBK and CNM 3D sensors. N-type columns in red are located at the pixel centers and penetrate the bulk without completely going through. P-type columns in yellow (CNM) or green (FBK) are the ohmic contacts at the pixel corners. P-type columns traverse the whole active bulk in the single side designs. In the double side design all the columns have the same length. The signal is extracted from the N-type columns through the bump pads.

to be collected there. The N column is therefore connected with a metal to a bump pad for subsequent bump-bonding. The bump-bonding connects each pixel of the sensor to a pixel channel of the readout chip. As a reminder, these are hybrid detectors, where sensor and readout electronics are independent devices.

The difference between the *single side* and *double side* designs is that in the former, both N and P columns are etched from the same wafer side; while in the latter, N columns are etched from the front side and P columns from the back. Since the double side technology requires photolithographic processes on both sides of the wafer, its production is more complex.

The single side design presents a highly doped  $P^+$  layer, with low resistivity. It connects all the P columns without touching the N type ones. During the fabrication process, over this low resistivity support wafer, another wafer with high resistivity is welded to create the active layer. All the columns are built from the surface of the high resistance wafer. The P columns are lengthen more than the N ones in order to make them reach the support wafer. In this way, all the P columns are connected by the support wafer, whereas the front surface connects the N columns.

Both single side CNM and FBK designs are silicon on silicon (Si-Si), due to this silicon layers arrangement. There are other designs, like silicon on insulator SOI, where a  $1\text{ }\mu\text{m}$  oxide layer is grown between the support and active wafers to electrically insulate them.

In the double side technology, no columns traverse the whole bulk since the P columns are already all connected from the wafer back side. In this design, a lowly doped and homogeneous substrate, with high resistivity and thicker than the previous design, is traversed by the P columns coming from the wafer back side, and by the N columns coming from the front.

| DUT     | Manuf. | Tech | Geo [ $\mu\text{m}^2$ ] | $\Phi$ [ $\text{n}_{\text{eq}}/\text{cm}^2$ ] | ROC      | $d_t$ [ $\mu\text{m}$ ] | $d_a$ [ $\mu\text{m}$ ] | $\varnothing$ [ $\mu\text{m}$ ] | $E$ [GeV] | Beam      |
|---------|--------|------|-------------------------|-----------------------------------------------|----------|-------------------------|-------------------------|---------------------------------|-----------|-----------|
| W3-3-2  | FBK    | SS   | $25 \times 100$         | $0 \text{ \& } 10^{16}$                       | RD53A    | 200                     | 130                     | 5                               | 120       | $p^+/\pi$ |
| W91-1-3 | FBK    | SS   | $50 \times 50$          | $0 \text{ \& } 10^{16}$                       | RD53A    | 200                     | 130                     | 5                               | 120       | $p^+/\pi$ |
| W7-3-1  | CNM    | SS   | $25 \times 100$         | 0                                             | RD53A    | 350                     | 150                     | 8                               | 6         | $e^-$     |
| W7-1-1  | CNM    | SS   | $50 \times 50$          | 0                                             | RD53A    | 350                     | 150                     | 8                               | 6         | $e^-$     |
| 332     | CNM    | DS   | $50 \times 50$          | 0                                             | ROC4SENS | 230                     | 230                     | 8                               | 5.6       | $e^-$     |

**Table 3.1** Summary of the sensors employed in the studies of this thesis. The information provided is the following: name of the tested DUT, its manufacturer, if the technology is single-sided (SS) or double-sided (DS), its pixel size geometry, the irradiation state  $\Phi$  at which it was measured (0 when just fresh and specifying the value of the target fluence when irradiated), the type of readout chip (ROC) to which it was connected, the total sensor thickness  $d_t$ , the active thickness  $d_a$ , the columns diameter  $\varnothing$ , the energy  $E$  of the test beam particles with which the DUT was tested and the type of beam particles (*Beam*).

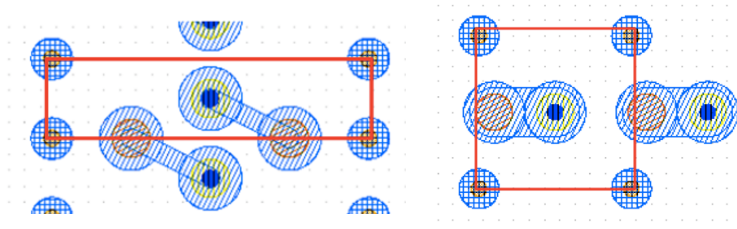
In the single side CNM sensors (production run 11119), the low resistivity support (also called handle) wafer has a thickness of  $200\text{ }\mu\text{m}$ . The high resistivity active wafer has a thickness of  $150\text{ }\mu\text{m}$ . The N-type columns have a depth of  $130\text{ }\mu\text{m}$ , the P-type traverse the



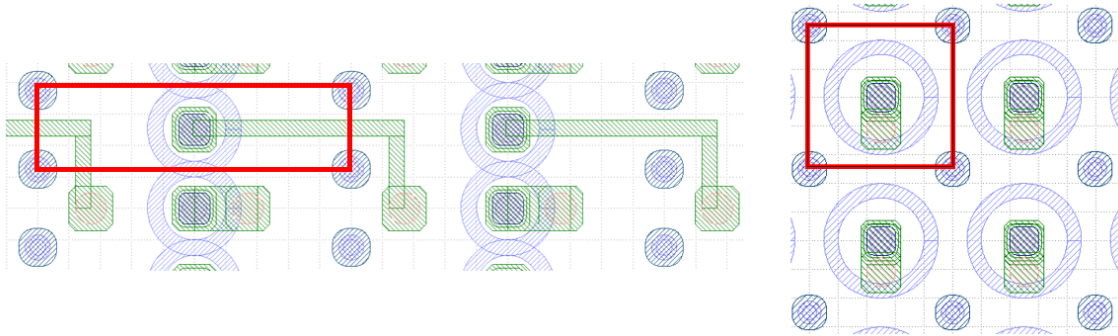
whole active bulk and all the columns have a diameter of  $8\text{ }\mu\text{m}$ . The double side CNM sensors have an active thickness of  $230\text{ }\mu\text{m}$ , all N and P-type columns have a length around  $210\text{ }\mu\text{m}$  and the same  $8\text{ }\mu\text{m}$  diameter.

The physical thickness of the studied FBK sensors is  $200\text{ }\mu\text{m}$ , from which  $130\text{ }\mu\text{m}$  are active. The handle wafer has a thickness of  $70\text{ }\mu\text{m}$ . The columns have a diameter around  $5\text{ }\mu\text{m}$ . While the P-type columns go through the whole bulk, the N-type ones have a length of  $110\text{ }\mu\text{m}$ .

Table 3.1 displays the summary of the sensors employed in this study, together with their specifications and conditions during the test beams. We characterized sensors with two pixel geometries: the rectangular  $25\times 100\text{ }\mu\text{m}^2$  (1E)<sup>1</sup>, and the squared  $50\times 50\text{ }\mu\text{m}^2$ . Figure 3.2(a) shows the pixel layout of the FBK 3D sensors, where the pixel is represented by the red polygon. The collector electrode (the N-type column) is located at its center while the ohmic contacts (the P-type columns) are at the corners. The bump pad opening is drawn with big red circles connected to the N-columns through metal paths in light blue.



(a) FBK 3D sensor

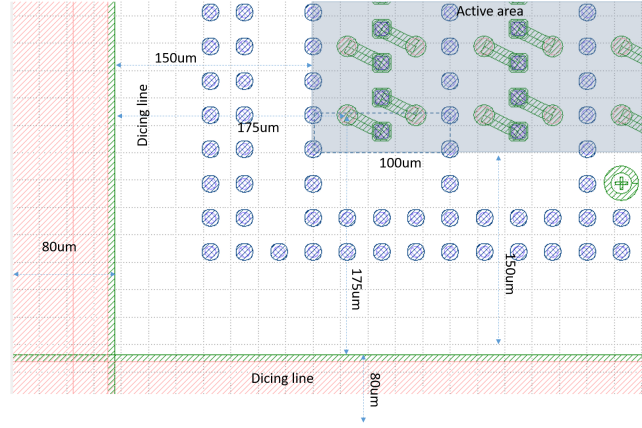


(b) CNM 3D sensor. The  $50\times 50\text{ }\mu\text{m}^2$  layout represents both single and double side designs.

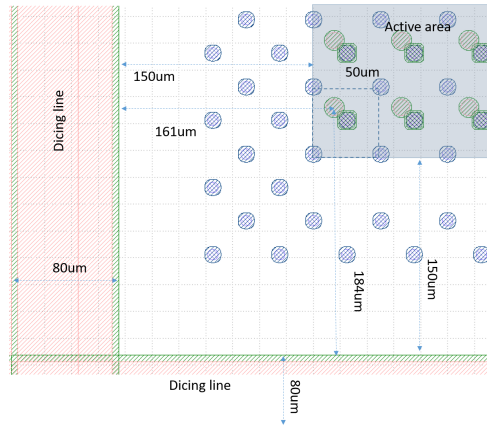
**Fig. 3.2** Pixel cell layouts for the  $25\times 100\text{ }\mu\text{m}^2$  (left) and  $50\times 50\text{ }\mu\text{m}^2$  (right) geometries of the characterized 3D sensors. Each red polygon identifies one pixel.

<sup>1</sup>The 1E notation indicates that this  $25\times 100\text{ }\mu\text{m}^2$  geometry has just one electrode per pixel, against another design (2E) with two collecting structures in each pixel. Although we have also tested 2E sensors, since CMS is not considering them anymore, I am not presenting them in this thesis.

In the case of the CNM 3D sensors, the pixel layout matrix of  $2 \times 2$  pixels is shown in Fig. 3.2(b). Here the red polygon identifies one pixel too. For the  $50 \times 50 \mu\text{m}^2$  geometry, both manufacturers go for very similar designs, which is the same for both single and double sided characterized CNM sensors. However, the  $25 \times 100 \mu\text{m}^2$  geometry has a different routing connecting the N-columns to the electronics; in the CNM design it is done by alternating an L-shape routing with a straight routing like the one used for the  $50 \times 50 \mu\text{m}^2$ .



(a)  $25 \times 100 \mu\text{m}^2$  geometry.



(b)  $50 \times 50 \mu\text{m}^2$  geometry.

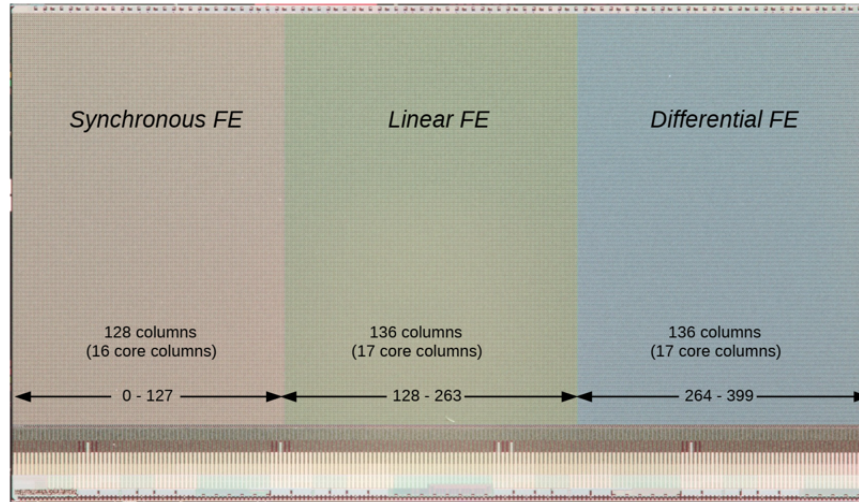
**Fig. 3.3** CNM 3D sensor bottom left corner for each pixel geometry. The dicing edge and three lines of ohmic contacts prevent the depletion region to get to the sensor edge. Layouts from CNM.

For small pixel sizes, like the two being considered, the sensors are intrinsically resistant to radiation. They can be operated at very low bias voltages due to the proximity of the columns. There is no biasing structure. These sensors do not have any guard ring, instead, three lines of ohmic contacts are placed along the periphery, providing a separation of  $150 \mu\text{m}$  between the outermost pixels and the sensor physical edge. This is represented in Fig. 3.3 for

both  $25 \times 100 \mu\text{m}^2$  and  $50 \times 50 \mu\text{m}^2$  geometries. The three lines of ohmic contacts substitute the guard ring, with the purpose of attenuating the electric field. In this way, the depletion region never reaches the dicing edge, where the crystalline lattice is full of defects that make this region much more conducting than the sensor bulk. This mess in the crystalline lattice is caused by the cuts performed on the original wafer to separate (dice) each of the sensors on it.

### 3.1.2 Readout ASIC

The 3D sensors were bump-bonded to the RD53 collaboration pixel readout ASIC<sup>2</sup>: the RD53A readout chip [90]. The RD53A ROC is a prototype demonstrator chip for the CMS and ATLAS collaborations. It demonstrates the applicability of the 65 nm CMOS technology in high energy physics. It can be self triggered and also externally triggered, and stores the time-over-threshold of signals with 4 bit accuracy. The active pixel matrix has  $400 \times 192$  squared pixels of  $50 \times 50 \mu\text{m}^2$  dimensions. The ROC has three analogue front-end (FE) flavors: synchronous SYNC, linear LIN and differential DIFF, shown in Fig. 3.4. The three of them were implemented together with the purpose of testing different designs. While the CMS collaboration chose to use the LIN-FE, ATLAS chose the DIFF-FE due to operation preferences. Each of the three designs consist of matrices with different analog circuitries.

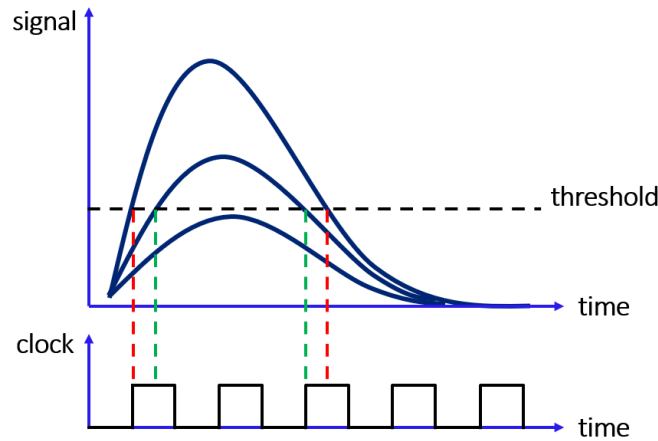


**Fig. 3.4** Schematic of the RD53A chip showing the pixel regions occupied by each of the three analogue front-ends.

<sup>2</sup>ASIC: Application specific integrated circuit

My team and I collected data during the test beams using the LIN and SYNC FEs. Only results with the LIN FE are presented in this thesis. For non-irradiated chips a threshold below 1000 electrons was achieved. The RD53A ROC bump-bond pads were not staggered. Due to the  $50\text{ }\mu\text{m}$  ROC pitch, for  $25 \times 100\text{ }\mu\text{m}^2$  pixel sensors, the bump bond pads are placed on the pixel boundaries. Certain metal routings are necessary for this pixel sensor geometry to be bump-bonded to the chip, as shown in Fig. 3.2.

In the RD53A chip, charge is digitized using the Time over Threshold (ToT) method, that features low power and minimal required circuitry. The ROC has an analog to digital converter (ADC) with a pixel amplifier which is a charge integrator, followed by a threshold discriminator. The ToT method measures the time that the signal is above the discriminator threshold using a counter running with a constant frequency clock, as represented in Fig. 3.5.



**Fig. 3.5** Calculation of the signal in ToT units. Three signals are exemplified here: the higher one registers 2 clock cycles while the signal is over the threshold value, therefore the measured ToT is 2 (red), the middle registers 1 (green), and the last one does not exceed the threshold.

The RD53A chip stores 4 bits per hit per pixel at  $75\text{ KHz/pixel}$  input hit rate and  $12\text{ }\mu\text{s}$  latency. The digitization of charge uses a 4-bit Time-over-Threshold (ToT) linear ADC conversion method. The dynamic range is 16 counts, although the highest ToT value is reserved. The second highest ToT value includes over flow for large deposited charge (discriminator still above threshold when counter reaches maximum). Since the stored bits can be compressed, the number of ADC and stored bits do not have to match. The hit rate limits the discharge rate. A non-negligible probability for a second hit to arrive while the first hit is still discharging gives rise to in-pixel pileup, which causes the second hit to be lost and the first hit to have a wrong charge measurement. This in-pixel pileup must be  $<1\%$  for

accurate track and vertex reconstruction at high luminosity. The translation of time into bits depends on the counting rate.

We have also taken data with the ROC4SENS generic pixel readout chip [91], developed by the Paul Sherrer Institut (PSI) [92] and fabricated using a 250 nm CMOS process with radiation tolerant design. This readout chip, developed with the purpose to serve research and development activities, is widely used for testing at universities and research centers. It applies no threshold and its output is analogue. This ROC has no zero-suppression and reads out the charge with an 8 bit resolution, this is 32 times better than the RD53A. However, the ROC4SENS data taking time is longer and its radiation tolerance is not as good as the one of the RD53A ROC.

The first study we carried out with small-cell 3D sensors used double-sided n-on-p 3D sensors readout with ROC4SENS. These sensors were fabricated at IMB-CNM, and we tested them in a test beam at DESY in 2019. Those results, which can be accessed in our paper at [27], are as well summarized in the next chapter.

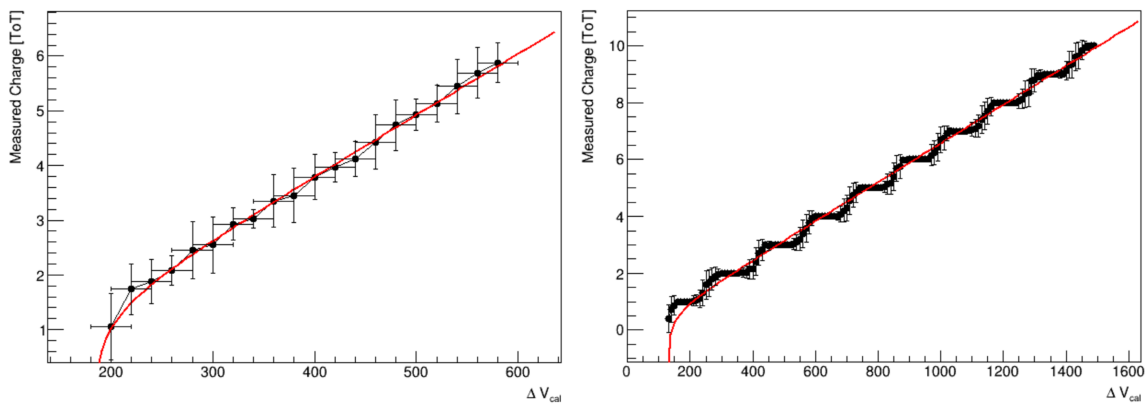
### 3.1.3 Charge injection calibration process

When the RD53A ROC reads the charge collected by the sensor, it is given in Time over Threshold (ToT) units (whose meaning is explained in Section 3.4.3). However, this format is not relevant from the physical point of view, and using it for comparison with other measurements is complicated. Consequently, the translation into a number of electrons is a critical step. To do so, the ROC can perform a calibration process. Through it, the ToT units are converted into electrons, pixel by pixel.

A ROC specialised calibration circuit injects known amounts of electrons to each of the pixels and the ROC response is recorded, determining the equivalence between the read ToT units and the known electrons. The user chooses the values the ROC must inject, in digital units, defined as  $\Delta V_{\text{cal}}$ , equivalent to certain amounts of electrons (one unit of  $\Delta V_{\text{cal}}$  corresponds roughly to ten electrons). The ROC transforms those  $\Delta V_{\text{cal}}$  into voltage signals  $V_s$  (this is, analog units) through a Digital to Analog Converter (DAC), charging a capacitor. The  $V_s$  value per unit of  $\Delta V_{\text{cal}}$  has been measured to be  $0.197 \pm 0.004$  mV/ $\Delta V_{\text{cal}}$  [93], which constitutes the first calibration of the process. Applying known voltages  $V_s$  across a known capacitance ( $C = 8.21 \pm 0.04$  fF) [93] allows us to determine the charges  $Q$  ( $10.1 \pm 0.2 e / \Delta V_{\text{cal}}$ ) injected into the calibration circuit. The capacitor starts to accumulate charge until it stores the maximum value, injecting it to the normal readout pixel of the chip, generating the corresponding ToT signal, like the one that would come from a detecting sensor pixel. The

conversion from  $\Delta V_{cal}$  to electrons is done through Eq. (3.1), with an associated error around  $12 e^-$ .

$$Charge[e^-] = 10.1[e^-/\Delta V_{cal}] * \Delta V_{cal} + 50[e^-] \quad (3.1)$$



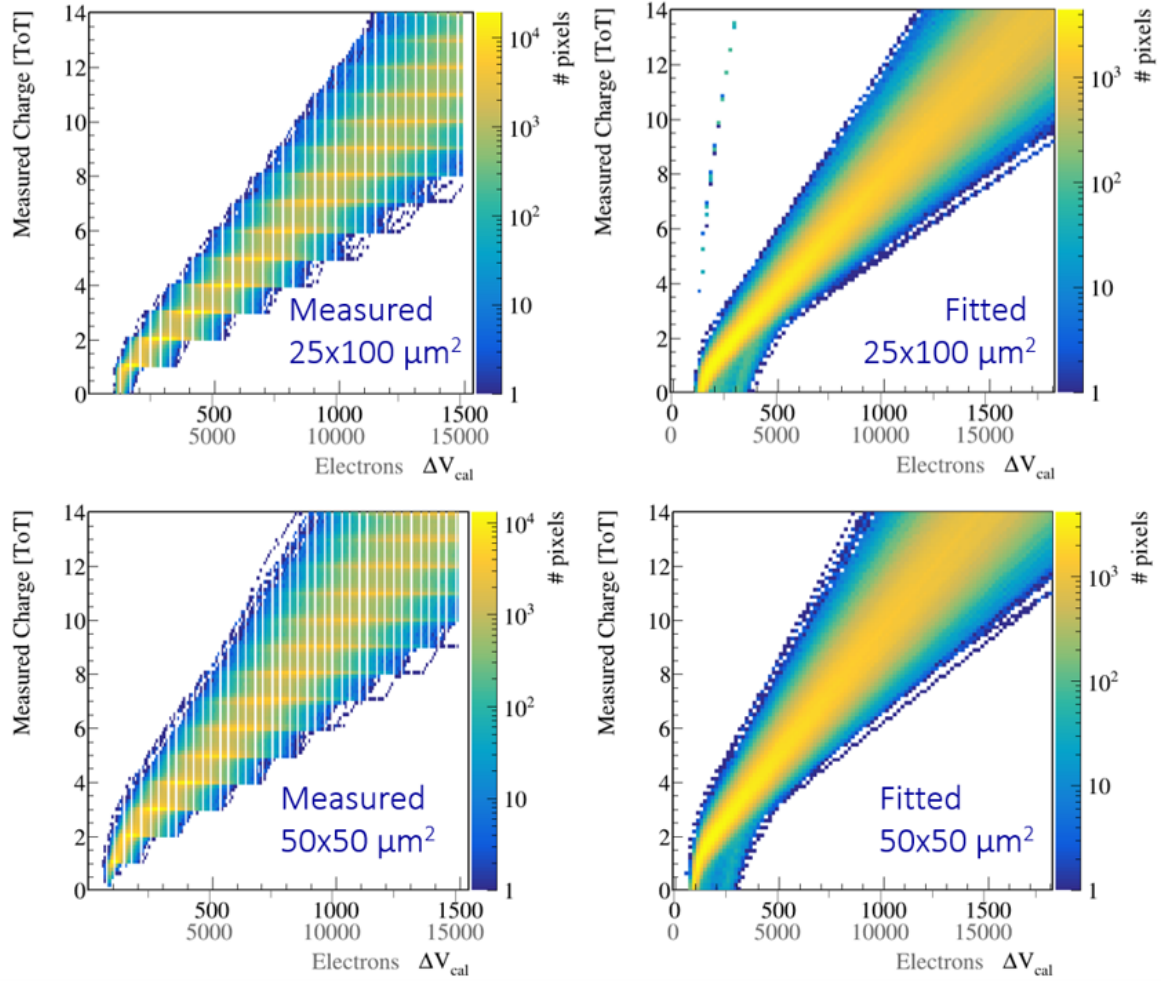
**Fig. 3.6** One pixel charge calibration curve. Measured from a  $25 \times 100 \mu m^2$  sensor, over two different ranges. The sensor on the left is an irradiated FBK 3D sensor and the one the right is a CNM fresh 3D sensor. The zig-zag behaviour is a consequence of the ToT quantification in 4 bits.

For different  $\Delta V_{cal}$  injections to each pixel, the ToT response is expected to have a shape similar to the plots in Fig. 3.6. For low values of  $\Delta V_{cal}$ , the signal response presents an asymptotic behaviour due to the presence of an activation threshold. In an intermediate range, it stabilises and reaches a linear dependence. For high signals a saturation regime is reached. Figure. 3.6 shows this pixel response over different ranges of  $\Delta V_{cal}$  values. On the left the pixel response is shown over a short range of low  $\Delta V_{cal}$  values, and on the right over a wider range assuring the full curve is measured. In this way, the slope of the linear zone constitutes the searched calibration factor. To best fit these curves, it is necessary to select a range of values over which the linear behaviour dominates. In this case, the curve on the right has a wider range over the linear response, being less affected by the pixel activation.

Although it is more visible on the right plot, both calibration curves show a zig-zag increase. This happens as a consequence of the ToT quantification in 4 bits, which means that only 16 values are possible, setting a threshold for each ToT value.

This charge injection per pixel is repeated a hundred times, getting a distribution of values relating  $\Delta V_{cal}$  and ToTs for just one pixel. This is performed for all the pixels, resulting in a plot relating the DAC unit signal and the ToT signal like the ones shown on the left of Fig. 3.7, for the two pixel geometries. In the measured calibration curves, the distribution looks discontinuous, as a consequence of the 4 bit quantification, leaving those gaps in the distributions. The plots on the right are the fitted response. The fitted curves follow the





**Fig. 3.7** Charge calibration curves measured over 100 injections on a  $25 \times 100 \mu\text{m}^2$  and a  $50 \times 50 \mu\text{m}^2$  fresh CNM 3D sensor, on the left. Their corresponding fits on the right.

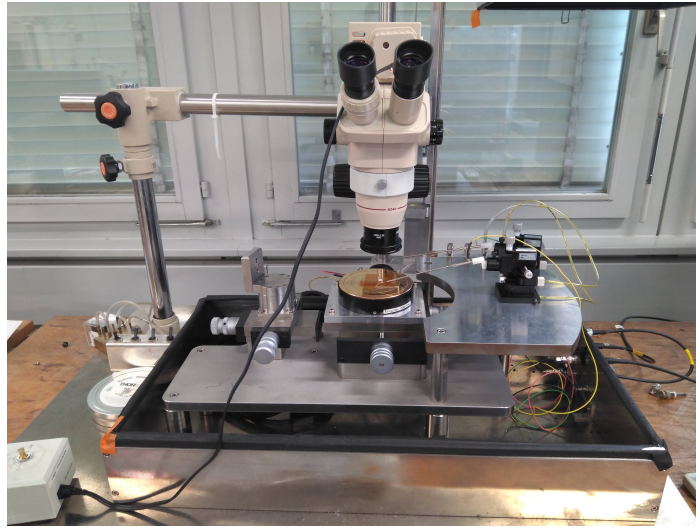
relation in Eq. (3.2), with  $x$  representing the charge input in  $\Delta V_{\text{cal}}$  units and  $F_{\text{ToT}}(x)$  the signal response in ToT units.

$$F_{\text{ToT}}(x) = A_{\text{ToT}} \cdot x + B_{\text{ToT}} - \frac{C_{\text{ToT}}}{x - T_{\text{ToT}}} \quad (3.2)$$

Here, the two regimes are considered in this model: the pixel activation or threshold and the linear dependency. The free parameters  $A_{\text{ToT}}$  and  $B_{\text{ToT}}$  are the gain and offset of the linear part, while  $C_{\text{ToT}}$  and  $T_{\text{ToT}}$  describe the curvature and asymptotic threshold [94]. Therefore, the calibration consists in fitting the measured responses to the Eq. (3.2) and obtaining the value of those parameters for each pixel.

## 3.2 DUT basic operating information: IV/CV setup

To define the DUT operation parameters and optimal input ranges, necessary to carry further studies like test beams, it is useful to measure macroscopic quantities such as capacitance  $C$  and leakage current  $I$  for different bias voltages  $V$ . As stated in Chapter 2, the sensor depletion width increases with the reverse bias voltage applied, leading to the increase of the sensitive volume and the reduction of the detector capacitance. For a charged particle traversing the detector, this increases the signal charge and reduces the electronic noise (see Section 3.4.3). Capacitance as a function of the applied bias voltage ( $C$ - $V$ ) is measured to identify the depletion voltage, as well as when type inversion processes start. It can also be used to analyze the doping profiles of semiconductor devices since dopant concentration affects the width of depletion region (see Eq. (2.25) in Chapter 2). Since the fabrication and dicing processes do not ensure full sensors quality, these fundamental properties have to be evaluated prior to the full sensor study. In order to determine the noise at the input of the readout electronics, the leakage current and the capacitance are the most critical parameters.



**Fig. 3.8** Picture of the IV/CV setup in the laboratory of the SSD CERN group. The chuck is the round ochre plate in the center under a sensor. Two probing needles -not connected to the sensor- are coming from the right side. The needles are attached to the rest of the structure which allows their operation over the vacuum table, assuring their steadiness during the measurements. The microscope and light source on top allows the correct connection of the probing needles on the sensor. All the setup is connected to the high voltage sources and PC for data taking.

The measurements of these quantities are performed using the IV/CV setup shown in Fig. 3.8. In the CV/IV setup, the sensor is placed on a chuck and kept in place with the suction generated by a vacuum pump. The chuck is both used for the cooling as well as to



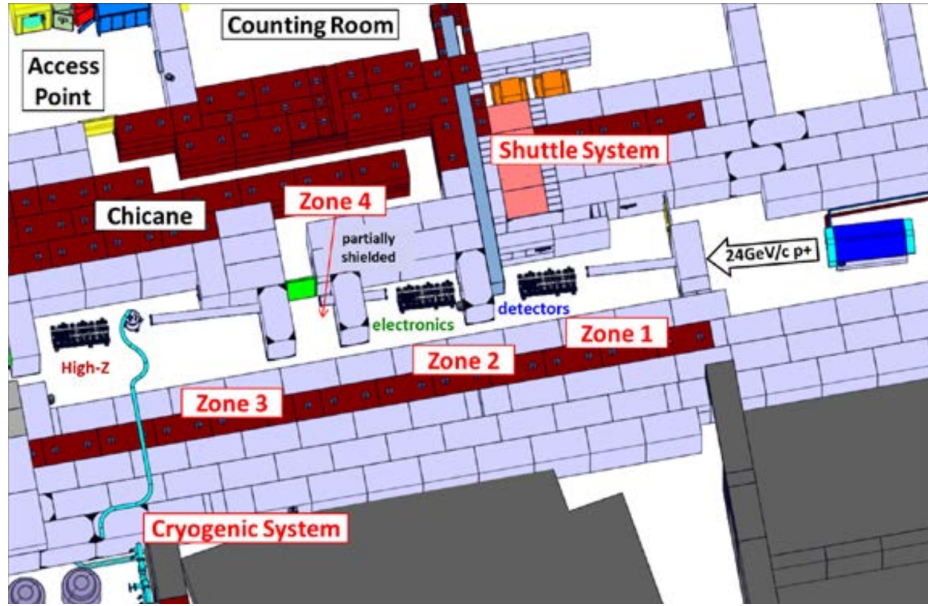
apply the bias voltage to the metallized backside contact of the sensor. Before dicing the 3D pixel sensors, a temporal metal is present over the whole wafer to connect to ground during the characterizations. This metal is removed before the dicing. The total leakage current and capacitance of the entire sensor is measured this way. Values per pixel are calculated by dividing these values among the sensor pixel number.

### 3.3 DUT fluence degradation: IRRAD facility

Under the same operating conditions, fresh sensors performance completely differs from that observed after exposure to radiation for many years. In consequence, to ensure that a sensor can survive a certain fluence or to assess the required operating conditions for an optimal performance after damage, irradiation campaigns are key. In those tests, high intensity beams are used to produce accelerated damage on the devices and allow to reach fluence levels equivalent to years inside a big experiment like CMS, in a much shorter time period. Irradiation campaigns normally take from days to few weeks, depending on the facility and the target fluence. Nowadays, there are plenty of facilities carrying out irradiations; in the case of the sensors studied in this thesis, the irradiations took place in the CERN IRRAD facility [95].

The IRRAD proton facility is located on the T8 beam-line at the CERN PS East Hall. This beam-line is shared between two facilities: the IRRAD proton facility is located upstream while the CERN High Energy Accelerator Mixed-Field (CHARM) facility is implemented downstream.

In IRRAD, a primary proton beam with a momentum of 24 GeV/c is extracted from the PS ring and hits directly on the samples to be irradiated. The facility is subdivided, as shown in Fig. 3.9, in three zones according to the nature of the samples. In between each irradiation zone, a separation wall 80 cm thick (with a hole to allow the beam to pass through) is placed in order to reduce the radiation background during irradiation and to minimize the ambient equivalent dose to the personnel during the access to the area. Sections of vacuum beam-pipes are installed in the space between the irradiation systems, in order to further reduce the secondary radiation produced by the proton beam interaction with air. During nominal operation, around  $5 \times 10^{11}$  protons are delivered every 10 seconds in average, in 400 ms long spills. The beam spot features a Gaussian shape with a FWHM ranging from  $12 \times 12 \text{ mm}^2$  to  $20 \times 20 \text{ mm}^2$ , depending on the irradiation zone. In the zone with the most focused beam spot, a fluence of  $10^{16} \text{ p/cm}^2$  is achieved in roughly two weeks of irradiation (calculated based on data from irradiation run 2017) [97].

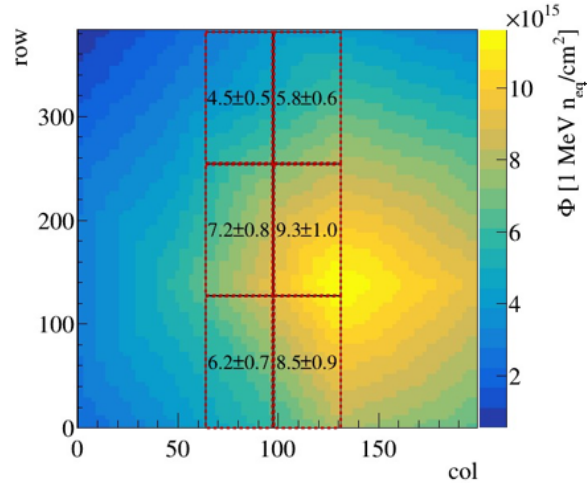


**Fig. 3.9** Detailed layout of the IRRAD proton facility. Figure from [96].

During October 2018, we carried out two test beam campaigns with irradiated FBK 3D and planar sensors. These test beams took place at the North Area of the CERN SPS, with a 120 GeV proton beam energy. Before the test beams, the sensors were sent to be irradiated to IRRAD. The target fluence was  $1 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$  (1 MeV). The reason for this target fluence is because a long technical stop after run 5 of the HL-LHC is expected. By that point, the sensors will be replaced by new ones, after reaching a value of  $1.88 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ . In order to check the radiation resistance, we have performed several fluence steps, and until now the maximum fluence we have tried on the sensors is  $1 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ . The replacement after run 5 is mandatory, however not because of the sensor but due to the readout chip. By the end of run 6, the expected total ionizing dose will be 1.91 GRad, much superior to the 500 MRad maximum radiation tolerance of the ROC. Nevertheless, studies at the final value of the fluence are taking place at the moment, to further demonstrate the sensor radiation tolerance.

During the irradiation campaign, the sensors were not homogeneously irradiated along their whole surface. Therefore, a dedicated study to estimate the received fluence at several sensor sections was carried out [98]. The study extracts the irradiation beam profile in an aluminium foil used to calculate the dosimetry (see in Fig. 3.10) and extrapolates it to each sensor.

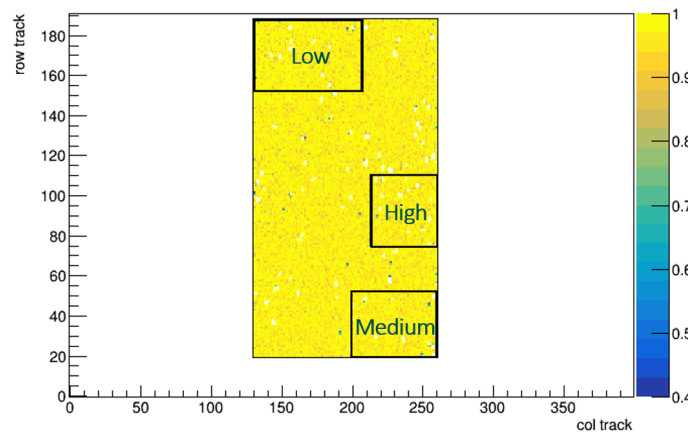
Three regions of interest on the LIN-FE have been defined, as shown in Fig. 3.11. Two of them are chosen close to the center of the irradiation beam and another one with the lowest



**Fig. 3.10** Beam profile plot superposing the RD53A linear front-end with six estimations of the fluence over it, in  $n_{eq}/cm^2$ , as a function of pixel row and column number.

achieved irradiation. Over these regions, the value of the fluence remains the most constant possible while keeping enough statistics to make charge and efficiency studies. These zones are named ‘Low’, ‘Medium’ and ‘High’ fluence regions, whose fluence estimated values are  $4 \times 10^{15} n_{eq}/cm^2$ ,  $8.5 \times 10^{15} n_{eq}/cm^2$  and  $10^{16} n_{eq}/cm^2$ , respectively.

The fact of having a non homogeneously irradiated DUT also signified an opportunity to study the sensor behaviour at different fluences, but in exactly the same conditions, on the very same module. Consequently, effects like differences in annealing are avoided, and external parameters like the bias voltage are guaranteed to be fully identical. In this manner, the effects due to just sensor damage can be investigated, excluding any other type of effect.



**Fig. 3.11** Efficiency map of the linear front-end, as a function of pixel row and column for a  $50 \times 50 \mu m^2$  FBK 3D sensor at operating conditions. The three under study fluence zones ( $4 \times 10^{15} n_{eq}/cm^2$ ,  $8.5 \times 10^{15} n_{eq}/cm^2$  and  $10^{16} n_{eq}/cm^2$ ) are drawn.

## 3.4 Full DUT study: Test beam campaign

A *test beam* is the data taking process during which the DUTs are operated inside a beam of minimum ionizing particles. The response is recorded and further studied. A test beam setup, like the one shown in Fig. 3.12(a), is composed by an amount of complex interconnected systems.

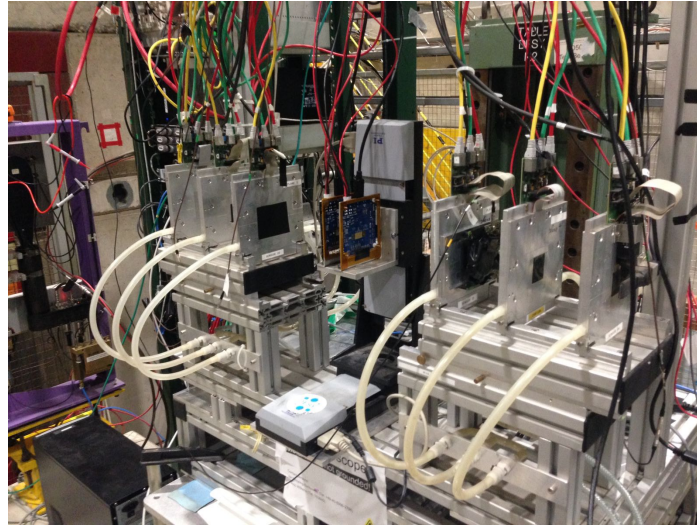
### 3.4.1 Test beam setup

The sensor characterisation was performed in several test beams in the North Area of the CERN Super Proton Synchrotron (SPS), at the Preveessin site. Here, we use a beam of pions and protons with energies of 120 GeV. Apart from CERN, there are other facilities where test beams can be performed, using other particles and lower energies. We carried out several test beams at the German electron synchrotron DESY (Deutsches Elektronen-Synchrotron), with 6 GeV electrons, in Hamburg.

The setup shown by Fig. 3.12(a) is the typical one we build in the test beam area. Here, pions and protons arrive with energies of 120 GeV and a maximum particle intensity of  $2 \times 10^8$  particles per spill. This beam composition is ideal for the characterisation of sensors for the CMS Inner Tracker since the charged hadron component (mainly charged pions) is dominating in the pixel layers. In this picture, the beam comes from the left, impacting on the six square metal shapes (part of the beam telescope reconstructing particle tracks) and two blue cards (DUTs). To correlate in time the data from the beam telescope and the DUTs, a time reference sensor (REF) based on a planar hybrid pixel sensor with the FE-I4 readout chip is placed on the back side of the fourth beam telescope plane.

Figure 3.13 shows a schematic view of the experimental setup used for the test beams, with all the main components. The beam telescope is an arrangement of several planes of sensors placed parallel one behind the other. They detect the particles from the beam along several points in space to reconstruct their tracks. The telescope used at CERN is an AIDA-type beam telescope<sup>3</sup>, consisting of six Mimosas26 planes [102]. The sensitive area of each plane is divided in a two-dimensional pixel array. The smallest detecting unit, a pixel, identifies over the plane the position the particle passed through. The first three telescope

<sup>3</sup>The AIDA-type beam telescope is an outcome of the EUDET-project [99] with the goal of providing homogeneous and reliable components to perform beam test experiments. Apart from the aforementioned telescope, the EUDAQ [100] package as a generic DAQ software and the EU Telescope [101] package as a generic reconstruction software were also developed in the context of EUDET.



(a) Test beam setup at the North Area. Two fresh sensors (at the center of the photo) record the pass of the particle beam traversing them, at room temperature. Three telescope planes are placed at each side of the DUTs. At the top of the planes: connections for clock, sensor configuration and data. Coolant is provided through tubes. Everything is mounted on a robotic platform for alignment.

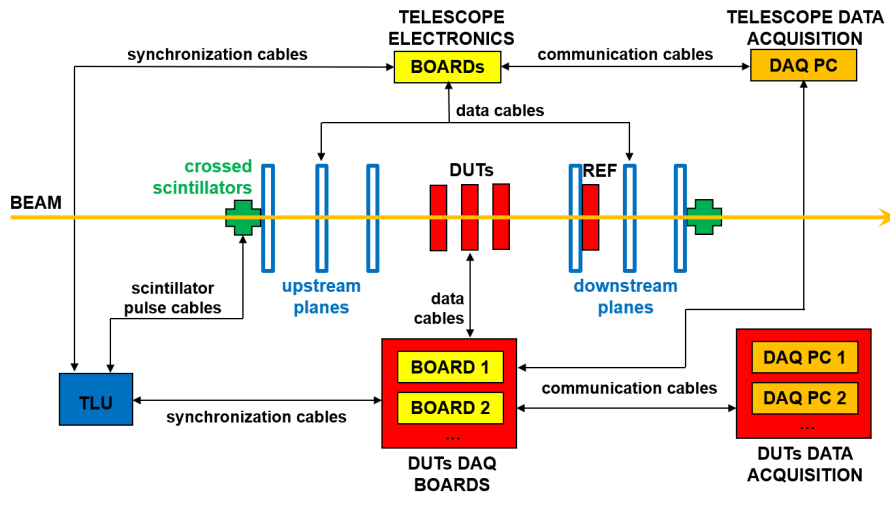


(b) Test beam area inside the CERN SPS North Area industrial ship.

**Fig. 3.12** Test beam pictures.

planes found by the particles passing by are called upstream planes, while the last three are the downstream planes.

The Trigger Logic Unit (TLU) fires the data acquisition process synchronising the pass of the spill of particles with the DAQ systems of the components in the setup: telescope



**Fig. 3.13** Test beam setup representation. The beam traverses the six Mimosa26 telescope sensors, grouped in upstream and downstream planes. The DUTs are placed between them, and the reference sensor (REF) after the fourth Mimosa26. The scintillators at the beginning and end of the telescope give the first trigger input to the Trigger Logic Unit (TLU) once they get coincidence inside their acceptance regions. The TLU triggers the data acquisition of the telescope, DUTs and REF sensor. This takes place at their corresponding DAQ boards, which constantly receive the sensors responses to the beam passing through, but they do not record it until getting the trigger. All the data are sent to the PCs for storage. Sketch adapted from Javier González Sánchez.

planes, DUT and REF. Four scintillators with photo-multiplier tubes (PMTs) are the input for the TLU. The scintillators are placed in pairs in front and behind the telescope set, and shadowing all the telescope, DUT and REF sensors, to assure spatial and time coincidence.

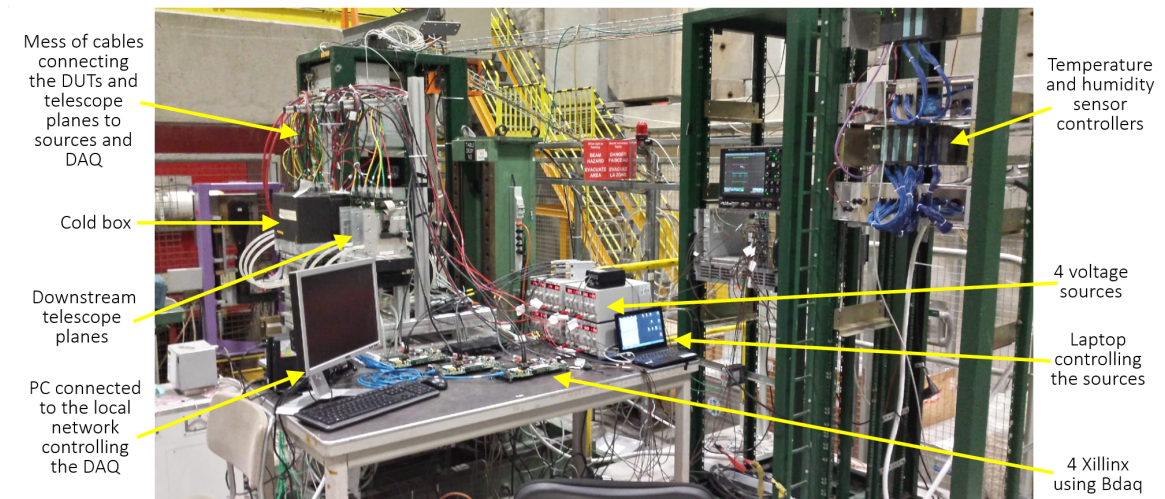
The TLU generates a trigger when it receives compatible signals from the scintillators, and uses a simple handshake protocol to maintain synchronization among the different detector systems. The detector systems assert busy signals on separate lines, which inhibit triggers from the TLU until all of the lines are cleared. No new triggers are sent by the TLU until all the sensors drop their busy-lines. This ensures sensors with different dead-times can be triggered and read out synchronously. Each trigger will define an *event*, where the collection of measured hits from all the sensors are stored together under the same event number. A collection of events taken with the same operating conditions of the setup is defining a *run*.

The Mimosa26 sensors from the telescope are read out continuously with a rolling-shutter mode, which means that the whole sensor surface is not read at the same time. The columns are readout in parallel, taking 16 cycles of an 80 MHz clock per row. The main part of the signal comes from beam particles which did not fire the acquisition process, but were



measured during the firing time frame of beam particles which did. This means that together with the signal of interest, many other beam particles are recorded, the so called pile-up.

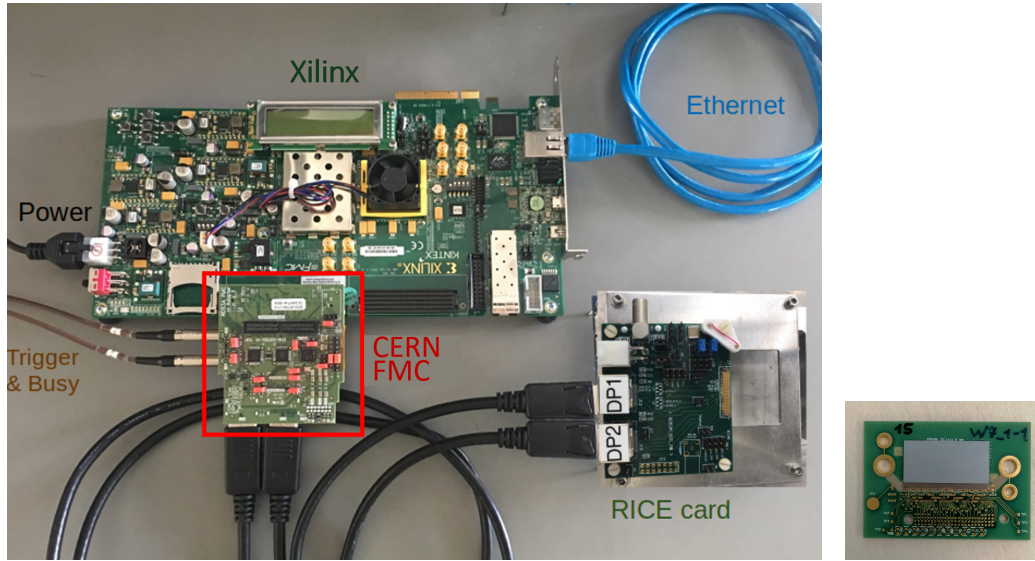
There are two main test beam setups to distinguish: one for fresh DUTs and another one for irradiated DUTs. Figure 3.12(a) is a picture of the former one, where the DUTs are visible, operated at room temperature and in direct contact with the air and external light. On the other hand, Fig. 3.14 shows the case of irradiated samples, placed inside a cold box.



**Fig. 3.14** Test beam setup at the North Area of CERN SPS for irradiated samples inside a cold box.

As explained in Section 2.4, in irradiated sensors the leakage current has a strong dependence with temperature. Keeping the sensor response stable leads to the necessity of operating the sensors at low temperatures, isolated inside a cold box. This space is equipped with temperature and humidity sensors and has a cavity where dry ice is placed to cool down to values around  $-30^{\circ}\text{C}$ . The humidity is also reduced with a flux of Nitrogen going inside the box to avoid condensation, which would damage both the sensor and the readout chips. Two fans inside the box constantly move the air and the injected Nitrogen to ensure the whole volume is homogeneous and all the DUTs experience exactly the same conditions. The box also prevents external light to reach the DUTs while being operated, whose effect is also highly noticeable in irradiated samples.

Apart from this difference in the setup for fresh and irradiated samples, the rest of components in the test beam area is the same. Their goal is to synchronize among each other to collect and transmit the DUTs detected signal to a storage computer for its processing. The sensor itself reacts to the charged particles which go through it, as explained in Chapter 2, but this reaction needs to be translated into interpretable information through readout electronics.



(a) Xilinx board equipped with the software that controls the ROC through PC commands. Cables and intermediate cards end at the RICE card. (b) Irradiation card with sensor and ROC.

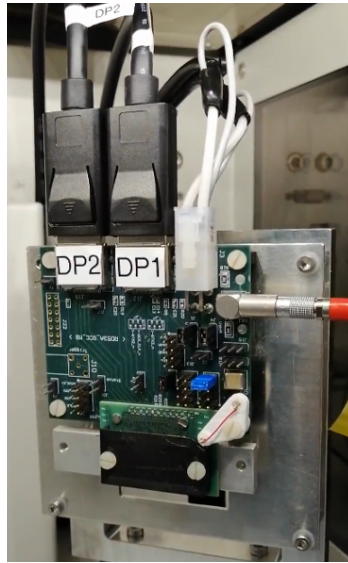
**Fig. 3.15** Readout electronics components chain. The Ethernet cable connects a PC with the Xilinx board and this one with the rest of the cards until the RICE card, that is afterwards connected with the irradiation card on the right.

The DAQ components of the sensors bump-bonded to RD53A readout chips are shown in Fig. 3.15. The RD53A-sensor assembly is wire-bonded to a Single Chip Card (SCC), a PCB board with some functionalities and connectors, in order to facilitate the placement of the sensors in the experimental setup (telescope, radioactive source, etc). The SCC is connected with two Display Ports with the FPGA unit, programmed with the BDAQ53 [103] system to drive the acquisition. The FPGA used is a Xilinx KC705 board using a mezzanine card developed at CERN (CERN-FMC), which provides LEMO inputs/outputs for the TLU trigger and busy signals, and the Display Port sockets connected to the SCC for ROC command sending and data reading. The FPGA board is connected to the computer for data storage and run control through an ethernet cable.

Two SCC cards were used when testing the sensors, the Bonn card and the RICE card, named after the institutions that designed and developed them. In the case of the RICE card, the SCC is split in two components: a main PCB with all the sockets and extensions, and the irradiation card (Fig. 3.15(b)), a small PCB support just holding the ROC-sensor assembly which can be de-attached from the main SCC in order to be irradiated without the rest of the components.

A picture with the RICE SCC ready for data taking is shown in Fig. 3.16.





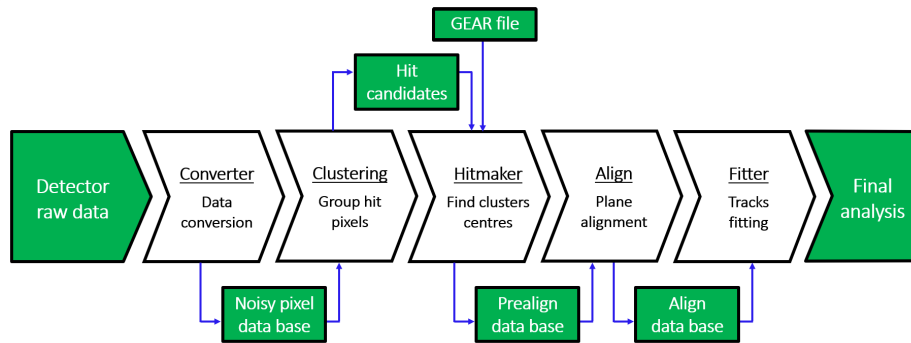
**Fig. 3.16** Picture of the RICE SCC card with the irradiation card connected on the bottom part. A black plastic cover protects the wirebonds to the ROC and avoids the effect of external light on the sensor.

### 3.4.2 Data analysis framework

Data obtained in CERN test beams are processed by using a generic pixel telescope data analysis framework: EUTelescope [101] [104]. It is integrated within the ILCsoft (ILC software) framework and built in the Marlin (Modular Analysis & Reconstruction for the linear collider) software package [105]. EUTelescope provides processors for the different reconstruction steps: converter, clustering, hitmaker, alignment and fitter, which are daisy-chained (modular structure). The final output is a ROOT<sup>4</sup> [106] ntuple with all the data in a suitable format for analysis.

An important input file for running the data analysis is the GEAR file. It contains the system geometry, this is the number of existing planes, their relative positions along the beam direction, rotations along the different axes (if any), the plane dimensions and thicknesses, or the number of pixels per plane and the pixel pitches. Likewise, processor files and steering files are tuned accordingly for each run and type of geometry in order to convert the data correctly. A short explanation of the function of each processor is given next and a scheme is given by Fig. 3.17.

<sup>4</sup>ROOT: framework for data processing, born at CERN. ROOT applications are used for analyzing Physics data and perform simulations.



**Fig. 3.17** Scheme of the flow of the reconstruction algorithm.

- **Converter:** The converter processor changes the raw data from the different detectors (telescope, DUTs and reference sensor) to Linear Collider Input/Output LCIO format, an event-based data format. During the converter step also the firing frequency of the pixels is computed. This is done checking how often a pixel sees a hit, on a pixel by pixel level and ultimately dividing this value by the number of investigated events. Those pixels with a firing frequency greater than what the user specifies in the configuration file — hot or noisy pixels — are determined and written out into a LCIO database. This noisy pixel database can then be used in following reconstruction processors.
- **Clustering:** The data are clustered in each sensor by identifying and grouping all pixels compatible to be created from the same particle (see Section 3.4.3 for details). Afterwards, those clusters containing a hot or noisy pixel are masked, using the cut calculated during the converter processor, to finally remove all the noisy clusters. This hot pixel suppression, reduces the number of clusters by a factor of 1.5 or 2 in the telescope planes, a valuable improvement in terms of CPU time consumption in the following steps. This processor creates a collection of clusters containing merely those free of noise.
- **Hitmaker:** Once all the clusters have been identified and the noisy ones have been removed, the hitmaker processor evaluates the cluster hit position of each cluster using a charge weighted center of gravity algorithm. The cluster hit positions are calculated as the signal weighted average positions and then translated from the local reference frame (coordinates related to the independent reference frame of each plane) to the external frame (a common reference frame for all the planes) using the GEAR file geometry description. Thus, a hit is defined as the signal measured in the weighted

center of gravity of a cluster. In other words, it is a potential candidate signal to have been originated by a beam particle.

In this processor, a pre-alignment step is also performed. Event by event, the global position of each hit is correlated with any other hit of a different sensor plane, in both X and Y coordinates. Using the fact that particles are mostly entering perpendicularly to each sensor plane, a first estimation of the relative positions of each plane can be extracted.

- **Alignment:** The pre-alignement carried out in the hitmaker is now used as a reference to further refine all the real plane positions in global coordinates. In this processor, using the hits previously obtained, tracks are reconstructed using a Kalman filter algorithm [107] (explained in the fitter processor description). The Millepede II<sup>5</sup> [108] algorithm is used to align the telescope, DUT and REF planes in an iterative procedure. This iterative process uses reconstructed tracks to minimize hit residuals after correcting for the real positions and rotations of each plane.
- **Fitter:** Once all the planes have been aligned, the ultimate fit is carried out, using only the information from the telescope planes and reference sensor, but not the DUTs, assuring the track fit is not biased with DUT hits. However, if there is any hit on the DUT within a compatible distance of the fitted track, the hit compatibility is added to the track, so afterwards it is possible to extract this information.

This final fitter processor, also uses a Kalman filter algorithm to generate a sharper fit. This algorithm is mathematically equivalent to a global least-squares minimization and it works in a two-step process of prediction and correction. First, estimations of the current state variables are produced, along with their uncertainties, error and/or random noise. When the outcome of the next measurement is observed, these estimates are updated using a weighted average, giving more weight to higher certainty estimates. In our code, the algorithm starts with a hit measured on the first plane. Its position on the plane is extrapolated to the second plane, assuming perpendicular particle incidence on the planes. A hit is searched on the second plane over a circular region of 500  $\mu\text{m}$  radius centered at the extrapolated position from the first plane hit. When found, a fit along the Z direction between these two points is defined. From the position found in the second plane, the same procedure is carried out with the third plane, and repeated until the last one. In this way, a sequence of segments connecting all the planes is

---

<sup>5</sup>Millepede is the method and software implementation developed in Hamburg University and DESY to solve the linear least squares problem with a simultaneous fit of all global and local parameters, irrespective of the number of local parameters

created. Since this is probably not a unique straight line traversing the planes, as a real particle would do, the second part of the Kalman filter consists on correcting the independent fits to make a global one. From the last plane, the same algorithm is used the other way back to connect the measured positions using the fits made before.

Unlike the fit carried out in the alignment step, during the fitter step, the maximum allowed distances between two hits along the planes for inclusion in track candidate are narrower.

The final output of the whole daisy-chained process is a ROOT ntuple containing four ROOT trees with different collections of data. These data is further post-processed [109] to obtain the parameters of the characterisation discussed in Section 3.4.3. Some examples of the kind of information obtained here are the sensor charge collection and its efficiency, both per pixel and also over its whole surface; the residual and cluster distributions, etc.

The data obtained from DESY test beams has been analyzed using a simpler and stand-alone code: tele-scope [110]. It incorporates in an unique executable the whole chain described before: raw data conversion, clustering, hit making, alignment, tracking and post-processing of final results. On the contrary than EUTelescope, the tele-scope code is not intended to be generic, and it was written explicitly for DESY test beam areas, with its particular telescope and reference DUTs.

### 3.4.3 Parameters for the characterisation

After the test beam campaign, once the first data processing explained in Section 3.4.2 has been carried out, the sensor data are interpretable and manageable. It is possible to assess sensor properties such as its clusters, efficiency, spatial resolution, collected charge or ratio between signal and noise. All of them need to be reconstructed from the test beam data. An explanation of their meaning and how they are obtained is given in this section.

For the purpose of clarification, during these studies, two types of readout chip were used: digital (RD53A) and analogue (ROC4SENS). Thus, the way of reconstructing the sensor signal on each is different.

#### Cluster

The most important parameter when analysing the data from a sensor is the cluster. This observable is the trace of a particle interacting with the detecting device. It is a group of

nearby pixels measuring a signal high enough to be distinguishable from noise fluctuations. The clustering process has two parts: cluster finding and cluster position estimation. The first part, to which I will refer from now on as just clustering or cluster identification, consists in pattern recognition to construct the clusters. The second one is the search of the position inside each found cluster domain where the particle most likely passed through, by calculating the charge-weighted mean position.

In pixel sensors, the clustering method identifies those pixels with a signal over a certain threshold that can have responded to the same particle. The clustering method in this context is partitional (clusters cannot be grouped inside another), not hierarchically distributed and exclusive (a pixel cannot belong to more than one cluster). In this way, when a pixel is included in a cluster it is removed from the list of available pixels, avoiding multiple inclusion.

The clustering algorithms fitting these descriptions and used with EUTelescope and the RD53A chip are the geometric clustering for the DUTs and reference sensor, and the sparse clustering for the telescope planes.

The geometric clustering algorithm uses the TGeo<sup>6</sup> based telescope and pixel layout description [111]. This algorithm performs a loop over all the activated pixel nodes following their spatial order on the sensor. For each activated pixel, this algorithm retrieves its position on the sensor and compares it with all the rest of activated pixels found for that event number and sensor. All those pixels satisfying proximity conditions (the pixels are neighbours and have at least one point in contact) are clustered together. To do this, the difference in X and in Y positions, as well as the time difference between the two pixels are calculated. The position difference squared values must be smaller than the squared value of the pixel size (the pixels touch each other) to be included in the same cluster. An example is given by Fig. 3.18 over part of a sensor matrix.

On the other hand, the sparse clustering algorithm is based on a proximity and minimum signal requirements. The user must provide a signal threshold for a pixel to be added to a cluster as well as a maximum distance in pixel units between two pixels to be in the same cluster. The algorithm performs two loops. The main one over all the pixels list in order to find pixels above the signal threshold. The vicinity loop, started every time a pixel over the threshold in the main loop is found, looks for pixels above the threshold and inside the maximum distance from the initial pixel. In this way, the pixels above the threshold are not

---

<sup>6</sup>A TGeo description is a model of each sensor constructed from the GEAR file, creating sensor nodes and loading the specified sensor layout into them. Each pixel is represented by a node, that is a volume positioned inside another. With this description, navigating through the sensor becomes simple.

|       | Column 1 | Column 2 | Column 3 | Column 4 |
|-------|----------|----------|----------|----------|
| Row 1 | (1,1)    | (2,1)    | (3,1)    | (4,1)    |
| Row 2 | (1,2)    | (2,2)    | (3,2)    | (4,2)    |
| Row 3 | (1,3)    | (2,3)    | (3,3)    | (4,3)    |
| Row 4 | (1,4)    | (2,4)    | (3,4)    | (4,4)    |

**Fig. 3.18** Representation of a section of a sensor pixel matrix, where four pixels measure a signal over a certain threshold. The red pixel represents the studied pixel during one of the geometric cluster finding algorithm loops. Green pixels are other nearby activated pixels satisfying the time requirement. The geometric cluster algorithm groups all these colored pixels in the same cluster since they are in contact.

required to be adjacent neighbours to merge them into a cluster. The actual spatial separation cut is the distance in pixel indices squared.

When using the tele-scope framework to analyze the test beam data taken in DESY test beams, we used the next-neighbour topological clustering. This algorithm, as in the geometric clustering of EUTelescope, goes through a list with the activated pixels. However, the pixels here are compared with each other by inspecting their column and row numbers in the sensor. Evaluating if two activated pixels can be inside the same cluster is done by checking that their separation is less than one column and one row. In this way, we consider for the cluster those pixels surrounding the activated pixel under test, this is, all those touching at least in one point. The rest of the algorithm is the same as the geometric clustering in EUTelescope, therefore the same clustering results are obtained with both of them.

Once the cluster identification has been carried out, other parameters can be derived, like the cluster size or the cluster charge, as explained next in the subsequent subsections.

### Cluster charge

The cluster charge is the sum of the charges of all the pixels composing the cluster.

If we have sufficient track statistics, the cluster charge distribution is expected to follow a Landau distribution.

There is an analytical approximation to the Landau: the Moyal distribution [112], that defines the ionization energy loss for fast charged particles and the number of produced

charge carrier pairs. Its probability density function is given by Eq. (3.3), where  $\mu$  is a location parameter (related to the position of the distribution) and  $\sigma$  a scale factor (related to the width of the distribution). Both the mean and the sigma of the distribution are expressed through these parameters, which are the first and second Moyal cumulants [113]: assuming that our observed data set are described by the Moyal distribution, a maximum likelihood method is used to estimate  $\mu$  obtaining Eq. (3.4), where the mean value of the charge  $\mu$  and the sigma  $\sigma$  of the distribution are related [114].

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp \left[ -\frac{1}{2} \left( \frac{x-\mu}{\sigma} + e^{-\frac{x-\mu}{\sigma}} \right) \right] \quad (3.3)$$

$$\langle \mu \rangle = -\sigma \ln \left( \frac{1}{N} \sum_1^N e^{\frac{-x_i}{\sigma}} \right) = -\sigma \ln \left( \langle e^{\frac{-x_i}{\sigma}} \rangle \right) \quad (3.4)$$

For each bin, the exponent mean value is calculated from all the accumulated entries. This mean value of  $\exp(\frac{-x_i}{\sigma})$  constitutes the estimation of  $\mu$ . Once the  $\sigma$  of the ToT charge distribution is checked out, the charge MPV  $\langle \mu \rangle$  is obtained through Eq. (3.4), associating an MPV of the mean charge to each bin.

## Hit

Once the clusters on a sensor have been identified, they are used to derive the hit positions, using a charge weighted center of gravity algorithm. This position in the sensor, along with the total charge of the cluster, associated to this position, is what is called a hit: the observable of a particle in the sensor.

## Hit efficiency

The hit detection efficiency quantifies the sensor ability to respond when a particle passes through. It gives the probability of detecting a particle passing through the sensor. The hit efficiency  $\varepsilon$  and its error  $\sigma_\varepsilon$  are calculated for the DUTs according to Eq. (3.5).

$$\varepsilon = \frac{N_{ht}}{N_t} \text{ and } \sigma_\varepsilon = \sqrt{\varepsilon(1-\varepsilon)/N_t} \quad (3.5)$$

Where  $N_t$  denotes the number of in-time tracks reconstructed in the beam telescope passing the fiducial volume of the DUT and detected in the reference sensor, and  $N_{ht}$  denotes the number of those tracks with an associated hit measured in the DUT. The track is associated

to a hit if the distance of the projected position of the track on the DUT plane and the measured hit is below 500  $\mu\text{m}$  radius. If the spatial resolution of the reference telescope is smaller than the size of pixels on the DUT, not only the global efficiency of the sensor can be measured, but also the in-pixel efficiency. This is the hit detection efficiency depending on where the track intercepts with the sensor within a pixel, i.e. close to the center, edge, or corner of the pixel.

### Spatial resolution

The position resolution is the main parameter of a vertex or tracking detector. This magnitude depends on various factors, some due to physics constraints (statistical fluctuations of the energy loss or diffusion of charge carriers) and some due to the system design, like the binary readout (threshold counter) or readout of analogue signal value, the distance between pixels (pixel pitch) or the already mentioned signal-to-noise ratio.

From the difference between the hit position measured by the DUT and the hit position estimated by extrapolating a track reconstructed by the telescope to the DUT plane, the residual is obtained, i.e., the position difference between the measured hit and its estimation. The RMS of the residual distribution represents the total spatial resolution  $\sigma_{total}$ , which has two main contributions: the telescope resolution and the DUT resolution. The tracking resolution of the telescope  $\sigma_{telescope}$  can be estimated independently and with dedicated studies [115]. The intrinsic detector resolution  $\sigma_{DUT}$  is the magnitude of interest as it is the minimum distance between two particles the DUT is able to distinguish. The intrinsic DUT resolution is therefore calculated as Eq. (3.6).

$$\sigma_{DUT} = \sqrt{(\sigma_{total})^2 - (\sigma_{telescope})^2} \quad (3.6)$$

During a test beam, in order to determine the DUT resolution, we place it as close as physically possible to the upstream telescope group of planes. The upstream planes track is extrapolated to the plane of the DUT taking into account multiple scattering by using, when needed, the General Broken Lines (GBL) formalism [116], and the distance to the DUT hit position is computed. This is the case in test beams at DESY, where multiple scattering has an important contribution.

In a detector, the spatial resolution along one dimension  $\sigma$  is proportional to the readout pitch  $p$ , following the relation  $\sigma_{DUT} = \frac{p}{\sqrt{12}}$ . This expression is the result of a binary read-out and assuming the threshold is adjusted such that only one pixel records a hit when a particle



passes by, only tracks passing between  $-p/2$  and  $p/2$  will give a hit on the pixel centred at 0, and the detector gets a uniform density of tracks ( $D(x) = 1$ ). In this way, the average difference between the real impact position  $x_r$  and the measured impact position  $x_m = 0$  is given by Eq. (3.7).

$$\sigma_{DUT}^2 = \frac{\int_{-p/2}^{p/2} (x_r - x_m)^2 D(x_r) dx_r}{\int_{-p/2}^{p/2} D(x_r) dx_r} = \frac{\int_{-p/2}^{p/2} x_r^2 \cdot 1 \cdot dx_r}{\int_{-p/2}^{p/2} 1 \cdot dx_r} = \frac{p^2}{12} \quad (3.7)$$

Charge sharing is usually beneficial for the spatial resolution of the detector. If multiple pixels fire, the track position can be estimated weighting the deposited charge in each pixel. As more information is added, the track position estimation is improved far beyond the intrinsic binary resolution.



# Chapter 4

## Experimental results. Sensor characterisation and fulfillment of the CMS IT requirements

This chapter starts with the determination of the sensors per-pixel capacitance, depletion voltage and dark current, from which the DUT operating conditions are determined.

Afterwards, we analyze the data taken in different test beams and discuss the results concerning radiation tolerance and its impact on the charge collection efficiency, the spatial resolution, the pixel size improvement, the charge sharing between neighbouring pixels, the residuals shape, the cluster size or the response at several particle beam incidence angles, as well as bias voltages and fluences. Each section focuses on a particular study to show the sensor performance and suitability. Two main sections are dedicated to efficiency and position resolution results. After that, another section further investigates the power dissipation. In the Appendix, other interesting topics like cluster breaking or the presence of a bias dot structure are covered.

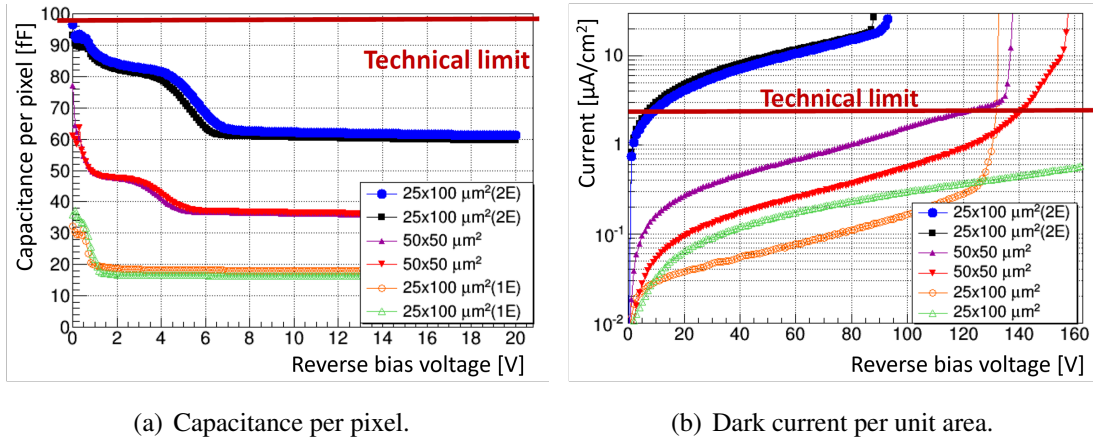
### 4.1 Electrical and thermal characterisation. Determination of operation parameters

In order to study the electrical characteristics of 3D pixels, CNM small pad-like sensors with single side technology were produced in the same wafers as the W7-3-1 and W7-1-1 sensors of Table 3.1. Both pixel sizes  $50 \times 50 \mu\text{m}^2$  and  $25 \times 100 \mu\text{m}^2$  were tested. These sensors

contain just  $50 \times 50$  3D pixels, but all the electrodes (n-type columns) are connected via an aluminum metallization. All the pixels have been turned into one pad. In this way, although the spatial resolution of pixel sensors is not achieved, pixels in a pad or in a standard 3D sensor are otherwise electrically identical, so the electrical characterisation performed over them gives the same information. Several IV and CV measurements were performed over the samples in order to determine the depletion voltage, the leakage current and the power consumption.

Depletion bias voltages were found to be just a few volts before irradiation, considerably lower than for typical planar pixel sensors. At 10-20 V the squared geometry is fully depleted, while the rectangular one at 5-15 V. Below this value, results are expected to present a lower charge collection efficiency since there will exist less sensitive regions. The per-pixel capacitance is almost 40 fF in the squared pixel geometry and 20 fF in the rectangular one. Always lower than the technical limit. After irradiations up to  $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ , the operating bias voltage increases to 100-200 V.

At a voltage of 20 V and a temperature of  $-20^\circ\text{C}$ , the dark current per unit area varies from  $40 \text{ nA}/\text{cm}^2$  (rectangular pixel geometry) to  $300 \text{ nA}/\text{cm}^2$  (squared pixel geometry). This is below the acceptance criteria of  $2.5 \mu\text{A}/\text{cm}^2$  for the geometries under consideration. After irradiation up to a fluence of  $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ , the dark current increased up to values around 4 nA per pixel at the same temperature.



**Fig. 4.1** Electrical properties as a function of the reverse bias voltage for several unirradiated  $50 \times 50 \mu\text{m}^2$  and  $25 \times 100 \mu\text{m}^2$  pitch 3D single side pad-like CNM sensors. The rectangular geometry with two electrodes is included in blue and black although it is not of interest in this thesis. Temperature was  $20^\circ\text{C}$  during the CV and  $-20^\circ\text{C}$  during the IV. Plots adapted from CNM.

These results were obtained from the IV and CV electrical characterisations, like the examples shown in Fig. 4.1(a) and Fig. 4.1(b). The CV characterisation is the total capacitance

measurement as a function of the applied bias voltage. The measurement in Fig. 4.1(a) was done at room temperature (20°C) over several fresh samples, in a range of bias voltages between 0 and 20 V. The IV characterisation is the measurement of current as a function of the reverse bias voltage. The example of Fig. 4.1(b) was carried out at around -20°C in order to keep the dark current at a stable value while measuring it, on account of its dependence with temperature (see Chapter 2). In particular, this value was chosen given that the sensors will be operated inside the tracker at approximately this temperature. A similar behaviour is expected in FBK sensors.

These magnitudes were measured for both fresh and irradiated sensors, and thanks to this data, the test beam campaigns were carried out with a better knowledge and understanding of the necessary operating conditions. In addition, these studies prove that the electrical requirements to operate the 3D sensor technology at ideal conditions are barely demanding.

## 4.2 Test beam characterisation: Hit efficiency

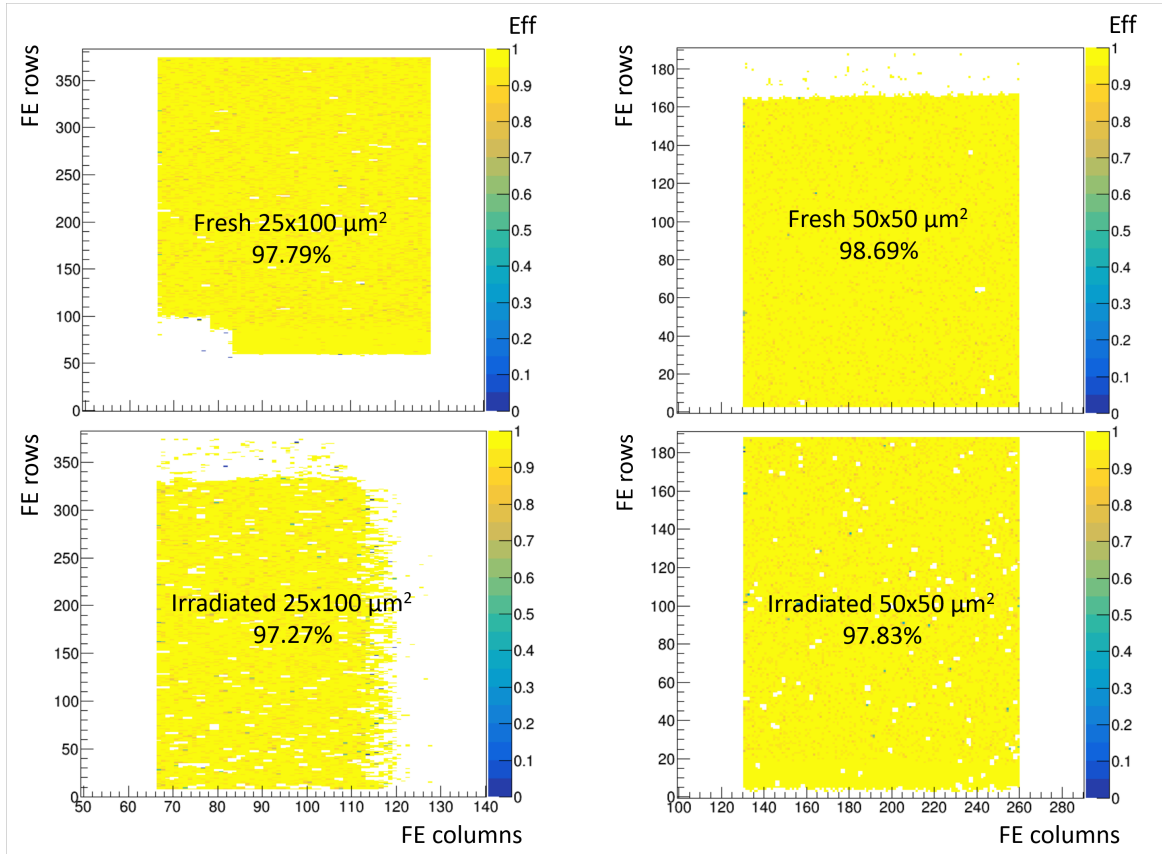
The hit efficiency of unirradiated (or fresh) sensors is presented in order to study their expected behaviour at the beginning of its operation inside the tracker. The sensors resistance to radiation is also checked by studying the efficiency change after irradiation. In this way, the change in efficiency after years of operation inside CMS can be emulated and tested too.

Apart from the global response of the DUT, pixel cell map studies have been performed to check the efficiency behaviour inside the pixel. At normal incidence, the efficiency pixel cell maps will differ from the ones obtained when the particles reach the sensor at an angle, as will be the case most of the time inside CMS. This is a worst case scenario situation. However, normal incidence allows to sample small, localized regions of the sensors, and therefore provides certain information about the sensor structure that allows to better understand the system. Moreover, the particular response inside a quarter of pixel can be analyzed by testing several points along it. This gives a view of the dependence with position and the effect of sensor structures on the efficiency.

### 4.2.1 Global sensor response

A study of the entire LIN-FE region is carried out to check how the efficiency depends on the position. For this study, data from  $25 \times 100 \mu\text{m}^2$  and  $50 \times 50 \mu\text{m}^2$  FBK 3D sensors (W3-3-2 and W91-1-3 in Table 3.1) has been used, before and after irradiation (at  $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$

target fluence). Normal incidence is considered in all the cases. Operation is done at room temperature for the fresh DUTs, while the post-irradiation measurements were taken at  $-36^{\circ}\text{C}$ . The reason for this low temperature is the limiting test beam setup: the DUTs were cooled down using dry ice inside a cold box, the thermal contact with the modules was not as good as it will be inside CMS and there is a lot of heat to dissipate. Figure 4.2 shows two-dimensional efficiency maps over the LIN-FE region of both sensors before and after irradiation. The data are in the middle of the FE columns range, as the linear is between the other FEs (shown in Fig. 3.4), whose empty spaces have been cropped from these plots. Each pixel geometry sensor has a way to connect to the ROC channels, explaining the different row and column numbers of Fig.4.2.



**Fig. 4.2** Top row: efficiency 2D maps of fresh  $25 \times 100 \mu\text{m}^2$  (left) and  $50 \times 50 \mu\text{m}^2$  (right) FBK 3D sensors operated at 5 V and 15 V respectively and tuned thresholds around 1000 electrons. Bottom row: same sensors after irradiation ( $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$  target fluence) tested at  $-36^{\circ}\text{C}$  temperature and operated at 125 V and 151 V. Global efficiencies are displayed with an error of a 0.03% (rectangular geometry) and 0.02% (squared one). Just the LIN-FE part is displayed, which corresponds to different rows and columns for each pixel geometry sensor. The lack of entries at the top, right or bottom sides of the linear front-end region is just due to a misalignment between the DUT and the scintillators during the test beam. Those hits out of the trigger acceptance region are consequently masked.

The top part of Fig. 4.2 shows the efficiency maps of both rectangular and squared pixel sensors before irradiation. The bottom plots correspond to their response after the non homogeneous irradiation performed on them (see Section 3.3 for details about this irradiation).

Before irradiation, global efficiency values of  $97.79 \pm 0.03\%$  ( $25 \times 100 \mu\text{m}^2$  DUT) and  $98.69 \pm 0.02\%$  ( $50 \times 50 \mu\text{m}^2$  DUT) are achieved at perpendicular incidence. The sensor response is constant and independent of the position. Brand new sensors function in an optimal way when operated at room temperature and with applied bias voltages of just 5 V (in the case of the rectangular pixel geometry) and 15 V (for the squared pixel geometry). In both cases a threshold around 1000 electrons was applied.

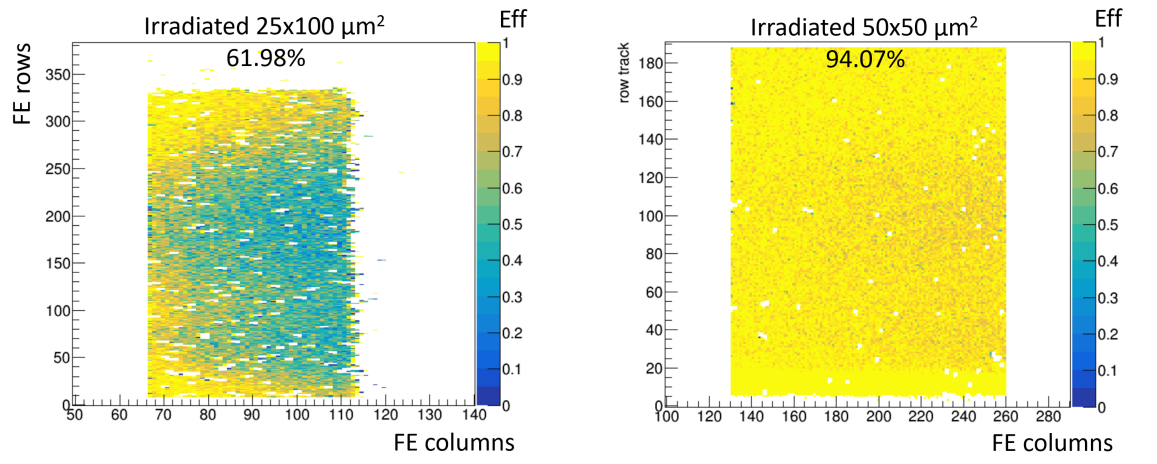
The irradiated DUTs were operated at the optimal bias voltages of 125 V and 151 V, respectively, and with increased thresholds in order to deal with the higher noise. Therefore, the first effect of irradiation damage is the necessity to operate at low temperatures to minimize leakage current and increase the bias voltage to fully deplete the bulk, as expected. Global efficiencies of  $97.27 \pm 0.03\%$  ( $25 \times 100 \mu\text{m}^2$  DUT) and  $97.83 \pm 0.02\%$  ( $50 \times 50 \mu\text{m}^2$  DUT) at perpendicular incidence are found now, meaning that the efficiency is barely affected after irradiation up to fluences of  $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ .

Both before and after irradiation, the whole sensor reaches the maximum achievable efficiency at normal incidence, as it will be explained later.

### Low bias voltage study

The sensors irradiated at the IRRAD facility received a non-homogeneous fluence due to an irradiation beam size smaller than the LIN-FE region and an imperfect alignment with respect to the beam. Although this was not done intentionally, it offers the opportunity to study, within a single sensor, areas of different fluence, as explained in Section 3.3. Since the dosimetry information by itself was not sufficient to obtain an approximate determination of the fluence received along different sensor regions, a dedicated study was performed combining the dosimetry and the sensor response information [98].

When operated at full depletion bias voltage, the sensor response is essentially insensitive to fluences up to  $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ . In order to see the effects of radiation damage, we therefore need to operate the sensors at low bias voltages, so that they are not fully depleted. An unusually low bias voltage value of 44 V is used for the rectangular sensor in Fig. 4.3, while for the squared geometry a less extreme value of 99 V was applied.



**Fig. 4.3** Efficiency 2D maps of irradiated  $25 \times 100 \mu\text{m}^2$  (left) and  $50 \times 50 \mu\text{m}^2$  (right) FBK 3D sensors, at unusually low bias voltages (44 V and 99 V).

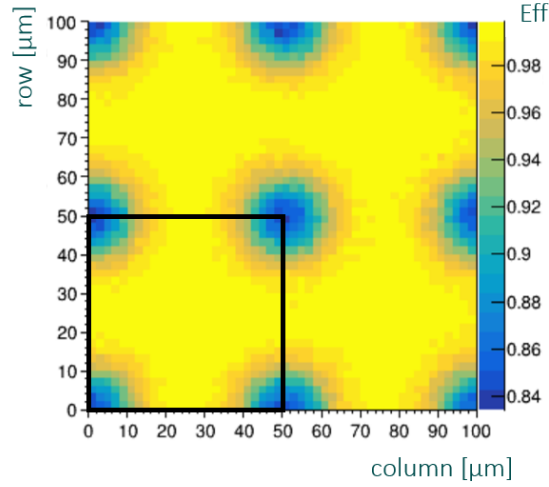
At these low bias voltages the efficiency significantly varies with the fluence. In Fig. 4.3, the sensor efficiency globally drops to 61.98% in the rectangular sensor. The differently irradiated areas can now be distinguished. The greenish area on the right side of this map represents the area where the irradiation beam impacted during the irradiation campaign. The sensor is more damaged there, leading to an efficiency drop. The rest of the FE, further from the irradiation beam position, presents a better performance, with values between 50 and 80%, which is not so bad considering that this data was taken in the worst possible conditions: highly irradiated sensor, at low bias voltage, far from depletion, and with particles impacting perpendicularly to the sensor. In the case of the squared pixel DUT, the bias voltage is not so low, and the global efficiency experiences a softer fall to just 94.07%. Even in these non optimal conditions, the response of the sensor is quite homogeneous and the efficiency is still high. However, the effect of radiation is slightly noticeable, since some pixels on the lower right part show around 85% efficiency.

#### 4.2.2 Full front-end pixel cell maps

The 3D sensors fabricated by CNM were first studied in a test beam before irradiation. We checked their performance in October 2019, using an electron beam of 4.8 GeV energy at the DESY electron synchrotron, in Hamburg, Germany. The DUTs are the W7-3-1 ( $25 \times 100 \mu\text{m}^2$ ) and W7-1-1 ( $50 \times 50 \mu\text{m}^2$ ) of Table 3.1.

Figure 4.4 shows one of the efficiency results in a four pixel cell map. The pixel cell map summarizes the response of all the pixels by calculating the position, within the cell,





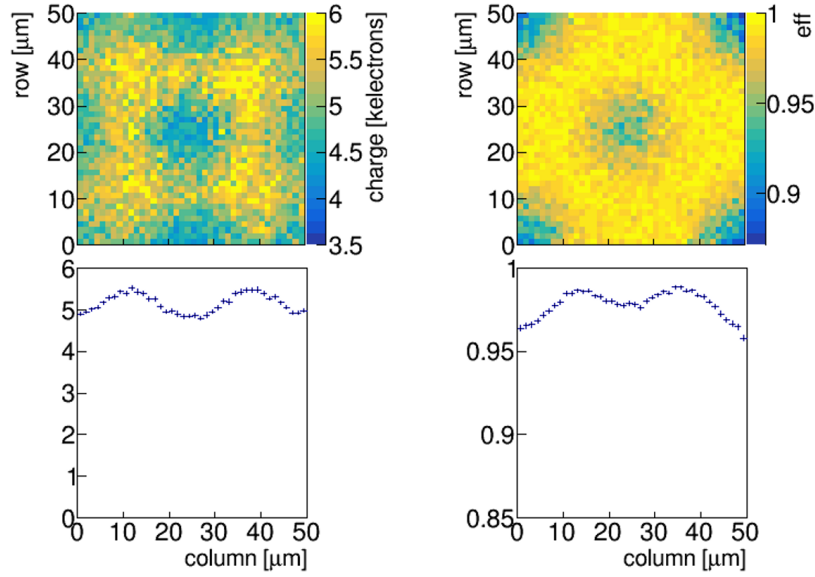
**Fig. 4.4** Efficiency for the CNM  $50 \times 50 \mu\text{m}^2$  geometry, over a four pixel cell map, before irradiation, at 5 V and normal incidence. The black square demarcates a single pixel.

module the cell pitch over each direction. Depending on the purpose of the study,  $1 \times 1$ ,  $2 \times 2$  or bigger pixel cell maps will be presented. This data is shown in Fig. 4.4 for the  $50 \times 50 \mu\text{m}^2$  geometry (sensor W7-1-1), at 5 V, normal incidence and room temperature. The ROC was calibrated at a 2280 electron threshold. The black square represents one pixel. In these pixel cell maps, the horizontal and vertical axes are respectively called *column* and *row* to refer to the direction being considered over the sensor surface. This direction is dependant on the directions over the LIN-FE, differentiated in columns and rows, as shown in the previous section 2D maps.

This sensor presents a  $97.52 \pm 0.03\%$  global efficiency at perpendicular incidence, reaching full efficiency in the regions between P-columns. Some particles traverse the P-columns, and since few charge carriers are generated in there, the efficiency drops. At the N-columns, which are shorter than the active sensor thickness, the depleted region below the column is enough to create charge carriers above the pixel thresholds, therefore no efficiency loss is observed.

After irradiation, the one-pixel cell maps<sup>1</sup> regarding collected charge and efficiency at normal incidence from the whole FE are the ones of Fig. 4.5. The bottom plots are the profiles over the sensor direction that corresponds to the FE columns. A slight charge collection reduction is observed at the columns and the efficiency mean values are found to be always higher than 95%.

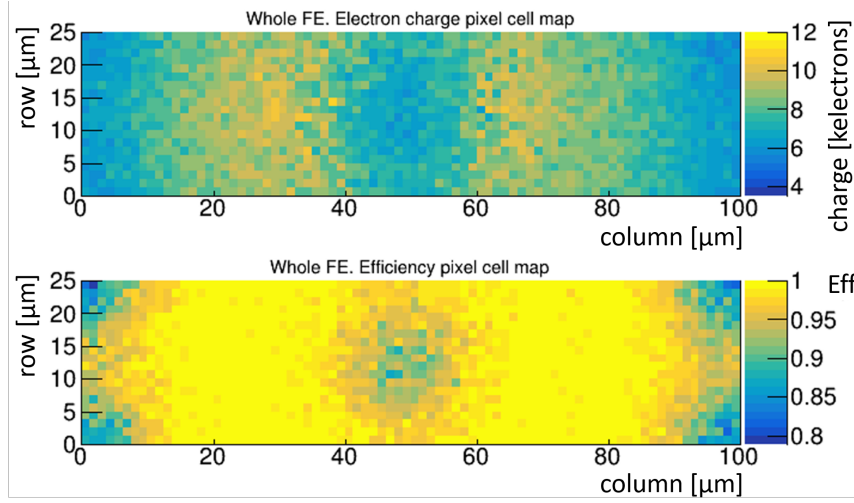
<sup>1</sup>These plots mix regions with different irradiations, so they are shown just to illustrate the general behaviour along the pixel. Since these are the only plots about irradiated results that present a lot of statistics, they are interesting to study.



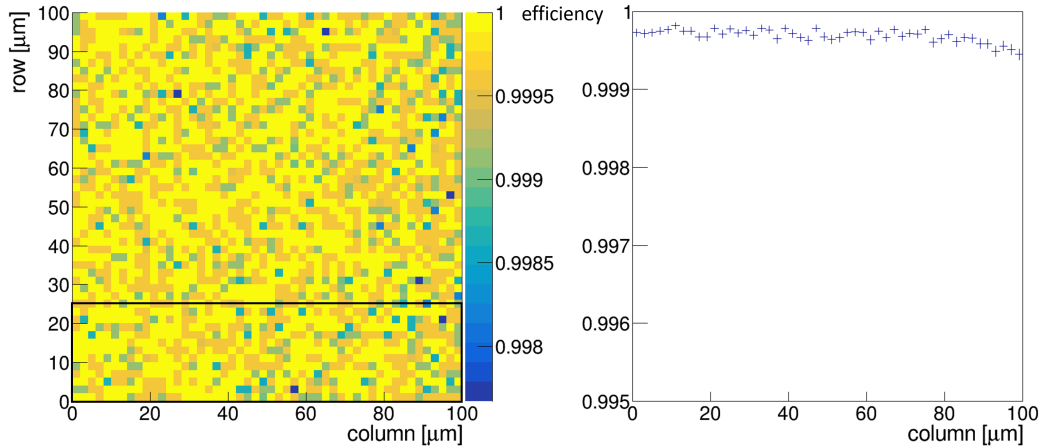
**Fig. 4.5** Collected charge (left) and efficiency (right) summaries over one pixel of the whole irradiated FE region of the squared FBK sensor at normal incidence and 151 V. Since the calibration for irradiated sensors is not optimal, the absolute charge scale is not known with high precision, but relative charge comparisons can still be made, as explained in the text.

In contrast to the scenario before irradiation, the efficiency drops near the N-columns at normal incidence. The N-columns have 20  $\mu\text{m}$  of active medium below them, where carriers can be generated. At perpendicular incidence, this leads to a drop of the collected charge when the incident particle passes over the N-columns, as shown in the left plot of Fig. 4.5. Nonetheless, while these 20  $\mu\text{m}$  of active bulk between the column end and the sensor surface create enough charge to activate the pixel—and therefore keep full efficiency—in a fresh sensor, this is not true anymore after irradiation. The increased thresholds applied in the FE to deal with larger noise, along with the reduced collected charge due to trapping in the bulk, increase the probability of not generating enough charge to reach the pixel activation threshold. This leads to a drop both in the charge and efficiency. Regarding the charge collection, the calibrations performed over the irradiated DUTs are not completely understood. This means that there are some parameters of the chip tuning that we had not mastered yet and may have biased the results.

For the rectangular pixel geometry, the equivalent plots are shown in Fig. 4.6. Global efficiency values similar to the square pixels are obtained. Due to the small pitch in the short side and the asymmetry of the geometry, the charge and efficiency distributions are different, but the drops are explained by the same reasoning. In this geometry, the shorter distance between ohmic contacts along the row side extends the charge collection drops.



**Fig. 4.6** Collected charge (top plot) and efficiency (bottom plot) summaries over one-pixel cell map of the whole irradiated FE region of the rectangular FBK sensor at normal incidence and 125 V. Since the calibration for irradiated sensors is not optimal, the absolute charge scale is not known with high precision, but relative charge comparisons can still be made.



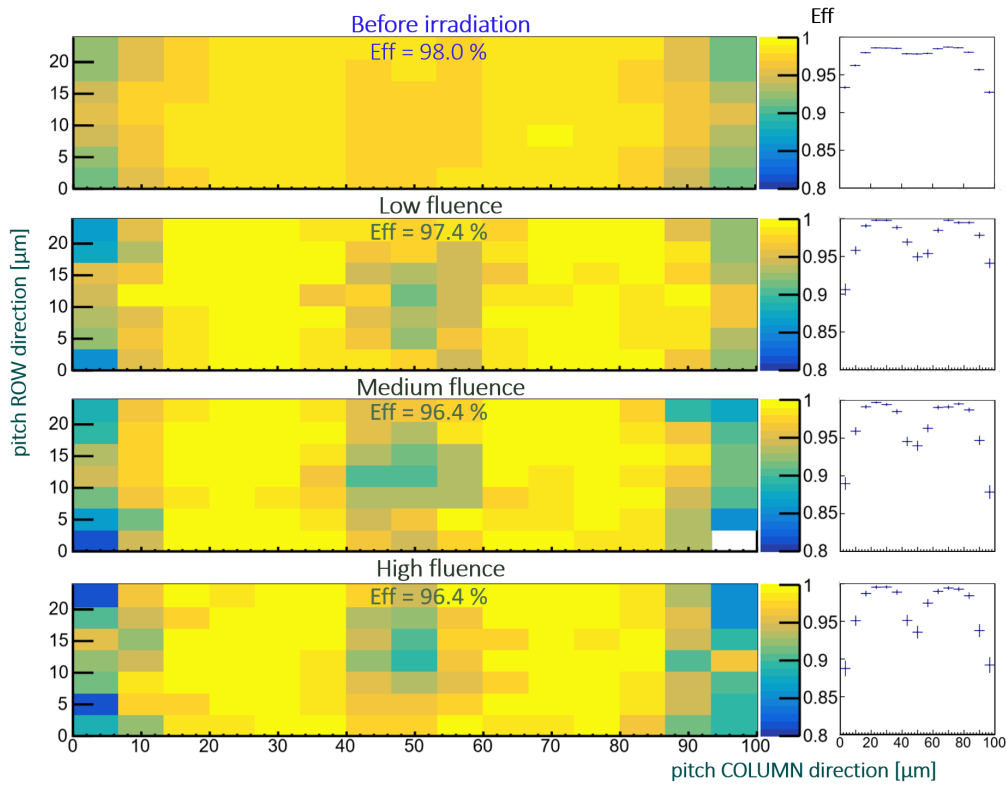
**Fig. 4.7** Efficiency four pixel cell map of a  $25 \times 100 \mu\text{m}^2$  CNM fresh 3D sensor tilted  $34^\circ$  along the  $100 \mu\text{m}$  side with respect to the particle beam. Bias voltage of 19 V using a 1448 electron threshold. Profile over the  $100 \mu\text{m}$  side on the right. Note the efficiency scale, starting from very high values (over 0.995) in both figures. The black rectangle represents one pixel.

At normal incidence, both geometries show the intercolumnar regions highly efficient even with the high fluence values reached on the sensors. However, as repeatedly observed, there is a drop at the region over the columns. When tilting the sensors, the effect of the columns disappears since all the particles necessarily go through both column and active bulk. This is demonstrated by Fig. 4.7, displaying the efficiency over four pixels of a fresh CNM 3D sensor at angular incidence. The black rectangle demarcates one pixel. This sensor was

tilted  $34^\circ$  along its  $100\ \mu\text{m}$  side with respect to the particle beam. As represented, the column structure is no longer distinguishable and the sensor response becomes homogeneous. The high efficiency obtained at normal incidence in the inter-electrode space is now registered all over the pixel area, extremely close to 100%. After irradiation, the intercolumnar high efficiency values achieved at normal incidence are also found at the column positions when tilting.

### 4.2.3 DUT response per fluence region

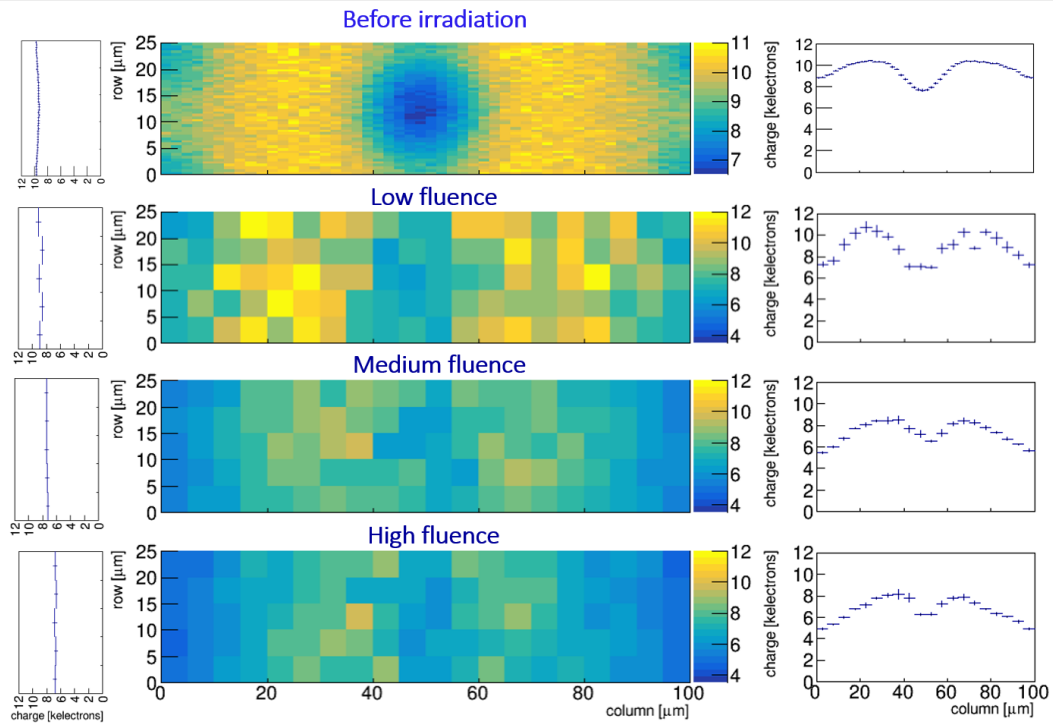
When operating the irradiated  $25 \times 100\ \mu\text{m}^2$  sensor at  $-36^\circ\text{C}$  temperature in test beam, at full depletion bias and with particles at normal incidence, the plots of Fig. 4.8 and Fig. 4.9 are obtained. Before irradiation the conditions are the same, except for the lower bias voltage (5 V) and the temperature (room temperature). For this sensor, full depletion is achieved with just 5 V before irradiation. Once highly irradiated, the depletion voltage increases to a few hundreds of volts.



**Fig. 4.8** Efficiencies of a  $25 \times 100\ \mu\text{m}^2$  3D sensor when fresh at 5 V and its three fluence zones after irradiation operated at 125 V. Single pixel cell maps on the left and their profiles over the long pitch direction on the right. All the plots are FBK sensors.

As represented in Fig. 4.8, before irradiation, the global efficiency is 98%, while after irradiation the efficiency is still measured to be above 96%. Before irradiation, the efficiency is more homogeneous along the pixel area. The drop from the PN junctions to the ohmic contacts is just 6%, while when irradiated this drop increases to 10% for the low fluence or 12% for the highest fluence. In general terms, the efficiency is largely unaffected by radiation damage up to  $10^{16}$   $n_{eq}/cm^2$ .

Before irradiation, the efficiency does not decrease at the PN junctions since the reduced amount of active bulk is enough to maintain full efficiency. Once irradiated, the higher trapping probability reduces the efficiency.



**Fig. 4.9** Calibrated collected charge in a non-irradiated  $25 \times 100 \mu m^2$  CNM 3D sensor at 5 V and the fluence zones of the irradiated FBK sensor operated at 125 V. Single pixel cell maps on the left and their profiles over X direction on the right. Since the calibration for irradiated sensors is not optimal, the absolute charge scale is not known with high precision, but relative charge comparisons can still be made.

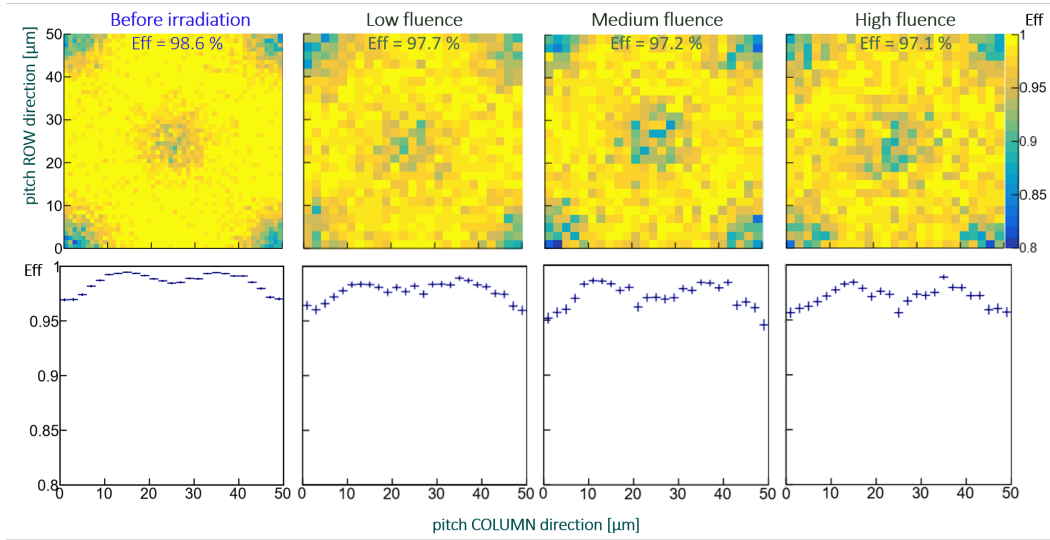
Charge collection decreases with fluence as expected (Fig. 4.9). This is especially noticeable at the ohmic columns where the sensor is not fully depleted with increasing irradiation. The reduced sensitive volume at the PN junctions reduces the amount of collected charge, although less than at the ohmic contacts.

In the case of the  $50 \times 50 \mu\text{m}^2$  geometry the conclusions are similar, as shown by Fig. 4.10. Here, the results before irradiation were taken at room temperature, with an applied bias voltage of 15 V, measuring a global efficiency of over 98%. For the irradiated sensor, during the test beam campaign, the applied bias voltage was increased to 151 V, while temperature was lowered to  $-36^\circ\text{C}$  inside a cooling box. The global efficiency remains above 97%, almost constant with fluence.

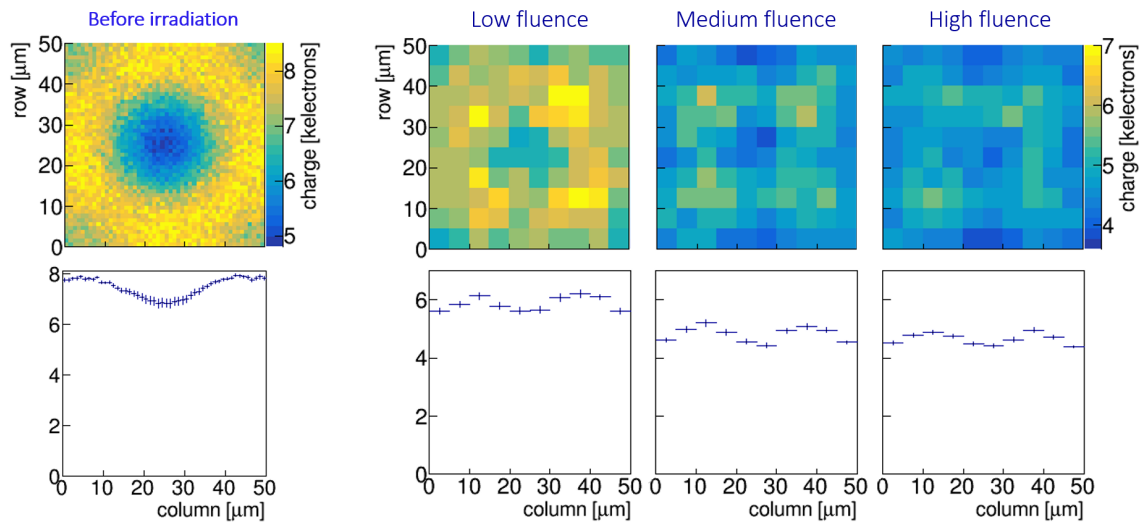
When studying the charge, likewise in the rectangular geometry plots, the fresh sensor charge collection is the one of a CNM DUT while all the other plots, both efficiency and charge in Fig. 4.10 are FBK DUTs. This selection is due to the lack of calibrations for the FBK fresh modules. In Fig. 4.10(b) the diagonal distribution of the charge is less clear, and the value of the charge decreases with the fluence. This result leads to the conclusion that the radiation damage decreases the signal. This fact is a consequence of trapping. The more radiation damage, the more traps along the sensor bulk and the more probable it is for the charge carriers to get trapped. These plots in Fig. 4.10(b) show a  $50 \times 50 \mu\text{m}^2$  CNM 3D sensor before irradiation, operated at 5 V effective bias voltage. The three fluence regions come from an irradiated  $50 \times 50 \mu\text{m}^2$  FBK 3D sensor operated at 151 V.

Paying attention to the charge profiles over the pixel column direction, one thing is constant: the slight drop at the columns position and the better collection in the intercolumnar regions. If comparing values of the charge, the first thing to mention is that the expected collected charge is not achieved: for a  $150 \mu\text{m}$  silicon sensor bulk, assuming an electron-hole pair production of 76 pairs per micron, the CNM sensor should collect a maximum value around  $11.4 \text{ ke}^-$  and with its  $130 \mu\text{m}$  thickness, the FBK should measure something close to  $9.8 \text{ ke}^-$ . This means that the calibration is not giving the correct transformation into electron units. There are some parameters of the chip tuning that we have not mastered yet and may bias the results. The same behaviour has been measured for rectangular pixel sensors from both manufacturers, but in that case measuring more charge than physically possible. However, considering the shown units as arbitrary values, the comparison between qualitative behaviours among all the plots in Fig. 4.10(b) is still completely fair. Furthermore, both qualitative and quantitative comparisons between the three irradiated areas is also reliable since the ROC tuning parameters are exactly the same for the three of them. With the calibration, even if the values in electron units are not the real one, the relative behaviour among pixels is surely standardized.

After irradiation, there is a higher charge collection between the PN junction and the ohmic contact due to a higher electric field, which reduces the trapping probability. The



(a) Efficiency pixel cell maps and profiles for the FBK non-irradiated sensor and its three regions after irradiation.



(b) Collected charge pixel cell maps and profiles for the non-irradiated CNM sensor and the three fluence regions of the FBK irradiated DUT.

**Fig. 4.10** Efficiency and collected charge when applying 15 V to the non-irradiated and 151 V to the irradiated  $50 \times 50 \mu\text{m}^2$  3D sensor. In each case, single pixel cell maps are displayed on the top and their profiles over X direction on the bottom. The charge values after irradiated can not be trusted, only relative comparison can be done, since their calibration is not optimal, as explained in the text.

irradiated pixel cell maps in Fig. 4.10(b) show how the pattern changes from a circle centered at the PN junction which seems to transform into an 'X' as the fluence increases.

As a summary of these results: a big point in favor of the capability of 3D sensors to fit in the upgraded CMS Inner Tracker has been made. Even after irradiation, the sensors present a high efficiency, with total global values always higher than 97%, and even getting 99% efficiency in the regions between columns. Good charge collection is observed and radiation damage, up to  $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ , does not significantly affect sensor performance. All this at the most inconvenient particle beam incidence (perpendicular) which will not be the case for most tracks in CMS. The operating bias voltage never exceeded two hundred volts, ensuring low power dissipation for optimal operation.

### Special case: Under depletion conditions

The present further study was carried out with the same DUTs, but in the worst possible conditions: highly irradiated, at normal incidence, and at an unusually low bias voltage. The expected sensor response can not be worse, but in this way the effects of the irradiation—which we want to study—are very noticeable.

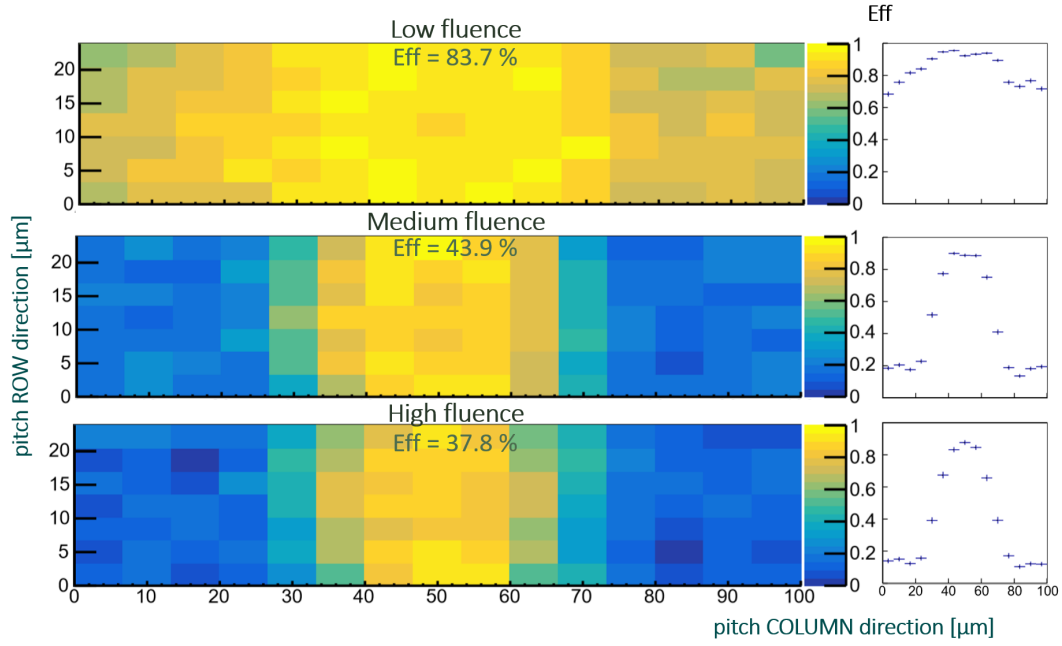
Applying an unusually low bias voltage, the sensor is only depleted, at best, around the PN junctions, the pixel centers. Under-depleted 3D sensor pixels provide with a method to study the effects of irradiation inside the pixel. In Fig. 4.11 and Fig. 4.12 the efficiency and charge collection of the  $25 \times 100 \mu\text{m}^2$  sensor, are shown when just 44 V are applied. From top to bottom, in both figures, the one pixel cell maps of the low, medium and high LIN-FE fluence regions are displayed. One should keep in mind that the response obtained here is the worst possible on account of the small depletion region, perpendicular particle incidence and high irradiation.

In the efficiency pixel cell maps of Fig. 4.11, the irradiation effect is clearly noticeable. The sensor region with the lowest fluence presents the highest efficiency (84%). As fluence is increased, the depleted volume is reduced and the efficiency drops: 44% for the medium fluence, and 38% for the highest one. The depletion volume around the PN junction is clearly visible in the projections over the X dimension, shown on the right.

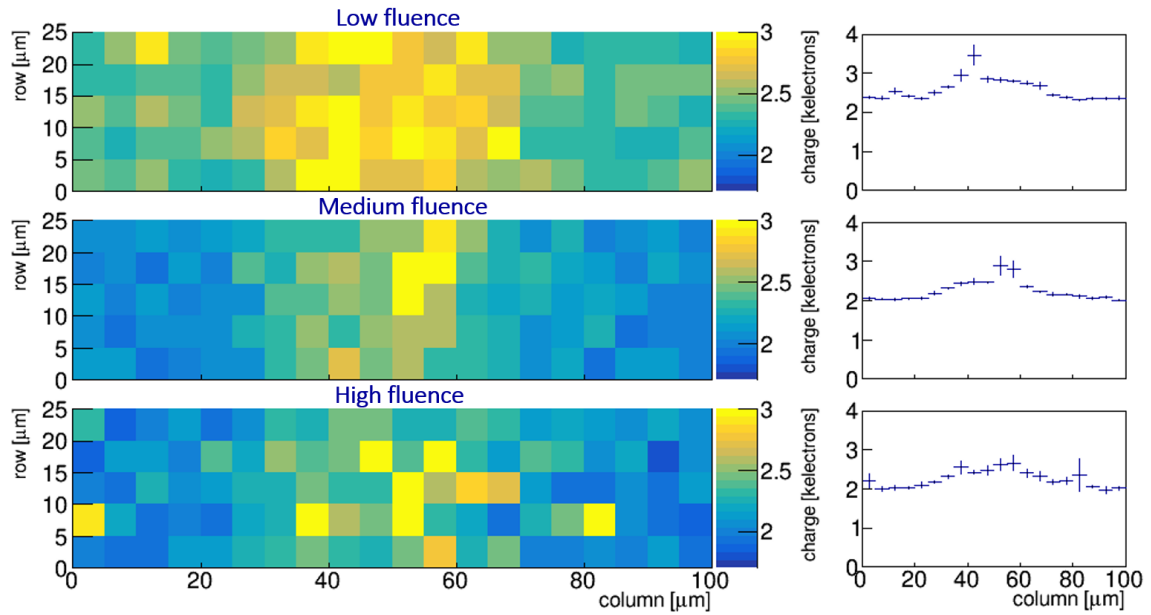
In terms of charge collection (Fig. 4.12), at the regions where depletion is achieved the signal decreases with fluence due to higher trapping probability. In the under-depleted regions, charge collection is dominated by diffusion, and therefore, the effect of the fluence is barely noticeable there.

For the squared pixel geometry irradiated 3D sensor, the charge collection at a low bias voltage is the one shown by Fig. 4.13. In this case, the applied effective bias was 99 V, a bit superior than in the case of the rectangular geometry. The highest charge collection happens

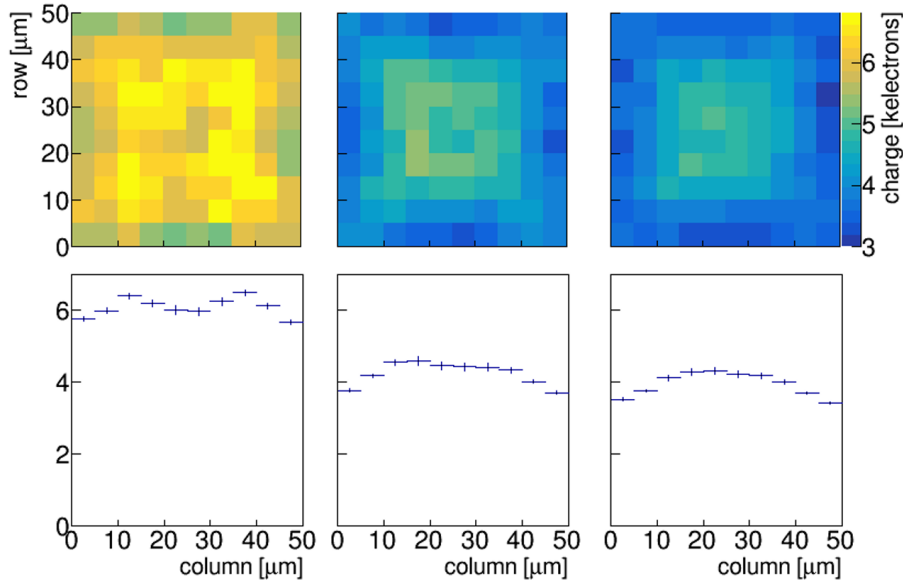




**Fig. 4.11** Efficiency pixel cell maps in the three different fluence regions of the  $25 \times 100 \mu\text{m}^2$  FBK 3D sensor at 44 V low bias voltage. Single pixel cell maps on the left and their profiles over the X direction on the right.



**Fig. 4.12** Calibrated collected charge pixel cell maps in the three fluence regions of a  $25 \times 100 \mu\text{m}^2$  FBK 3D sensor at 44 V low bias voltage. Single pixel cell maps on the left and their profiles over the X direction on the right. The charge values after irradiated can not be trusted, only relative comparison can be done, since their calibration is not optimal, as explained in the text.



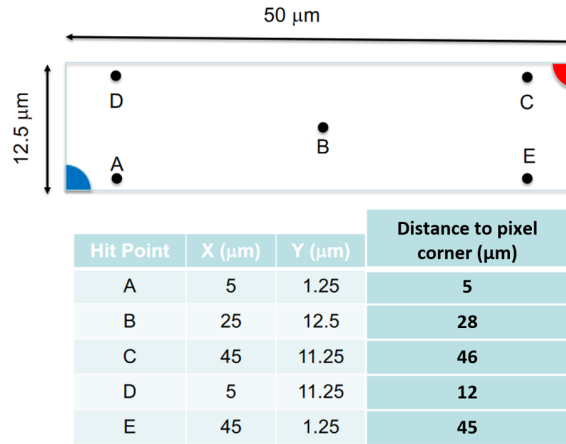
(a) Calibrated collected charge pixel cell maps in the three fluence regions.

**Fig. 4.13** Charge collection of a  $50 \times 50 \mu\text{m}^2$  3D sensor at 99 V low bias voltage and normal incidence. Single pixel cell maps on the left and their profiles over the X direction on the right.

along the diagonals of the pixel, following the electric field lines. The effect of the fluence is clear, reducing the charge collection. At the lowest fluence, the profile over the X direction shows how the charge collection drops at the columns because of the normal incidence. Maximum charge collection again happens at the regions between columns. For the higher irradiances, charge collection becomes so inefficient that the drops at the PN junctions are no longer distinguishable: the active  $20 \mu\text{m}$  below the column are no longer critical. The drop near the ohmic contacts remains since the electric field is less intense and the bulk is even further from depletion.

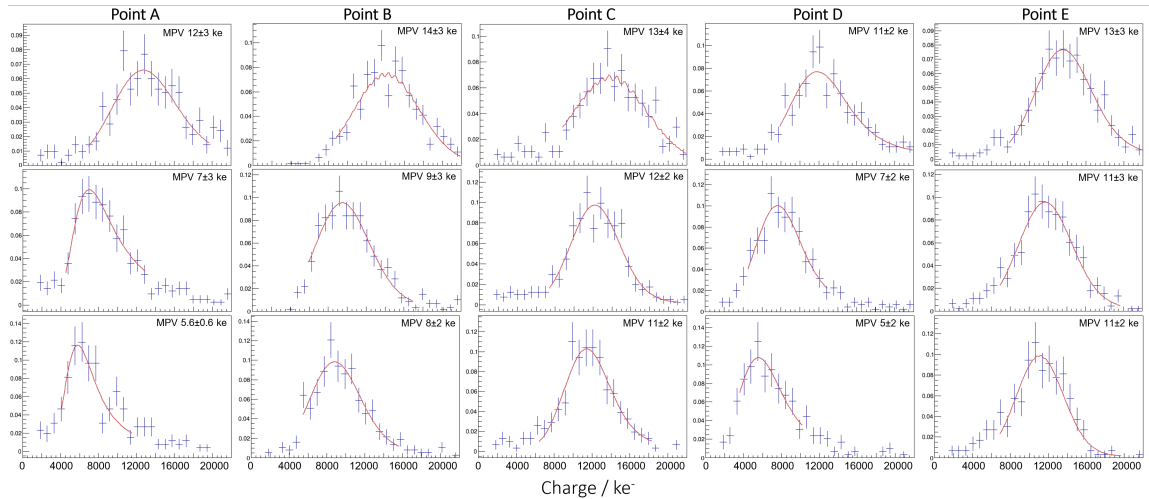
#### 4.2.4 Study over several points along a pixel quarter

Monitoring the behavior of several points along the pixel, the homogeneity of the pixel response can be tested and the effect of this 3D structure on the charge collection can be quantified. The red quarter circle in Fig. 4.14 represents the center of the pixel (N-type column or PN junction), while the blue one is a pixel corner (P-type column or ohmic contact). The sensors in this study are W91-1-3 ( $50 \times 50 \mu\text{m}^2$ ) and W3-3-2 ( $25 \times 100 \mu\text{m}^2$ ) of Table 3.1. For the sake of simplicity the results of only one pixel geometry are included in this thesis.



**Fig. 4.14** Points studied along a quarter of pixel and their positions in  $X$  and  $Y$  coordinates on the pixel, taking the pixel corner in blue as origin.  $25 \times 100 \mu\text{m}^2$  geometry.

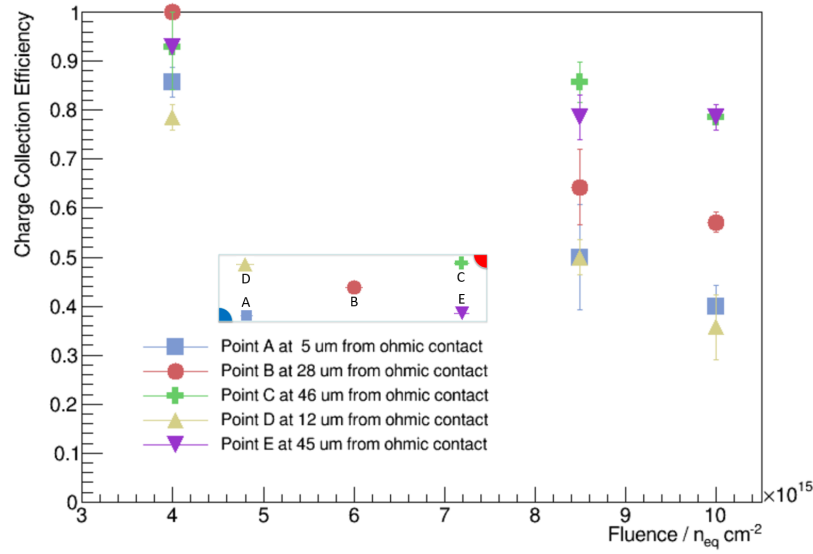
The points under study, or *hit points*, are labeled as A, B, C, D and E and have a radius of  $2.5 \mu\text{m}$ . Their exact positions can be consulted on Fig. 4.14, taking the ohmic contact as the origin of coordinates. The sensor columns radius is around  $4 \mu\text{m}$ . The positions of the hit points were chosen to study the areas close to the sensors columns, as well as those far from them, selecting regions under the effect of intense and weak electric field.



**Fig. 4.15** Charge collection distributions, in electrons, of each quarter pixel hit points at low fluence (top row), medium fluence (middle row) and high fluence (bottom row).  $25 \times 100 \mu\text{m}^2$  irradiated FBK 3D sensor. The charge values should be only considered as a relative comparison among them, not as absolute.

For each hit point, the calibrated charge distributions were obtained and fitted with a Landau⊗Gaussian convolution, as shown in Fig. 4.15. The most probable values of the

Landau were computed, using the sigma of the Gaussian of the charge distributions as its associated error. These plots clearly show the displacement of the distribution peaks at every hit point when the fluence increases. Relative charge collection efficiencies are calculated taking the point of highest charge collection as reference. This is point B (in the middle of the pixel quarter) at low fluence. Since all the charge values come from the same sensor in the same conditions, no further normalisations to compensate for the chip tuning are required.



**Fig. 4.16** Charge collection efficiency as a function of the fluence and the position on the pixel quarter for the  $25 \times 100 \mu\text{m}^2$  geometry FBK 3D sensor. All the points are normalized with respect to point B at low fluence.

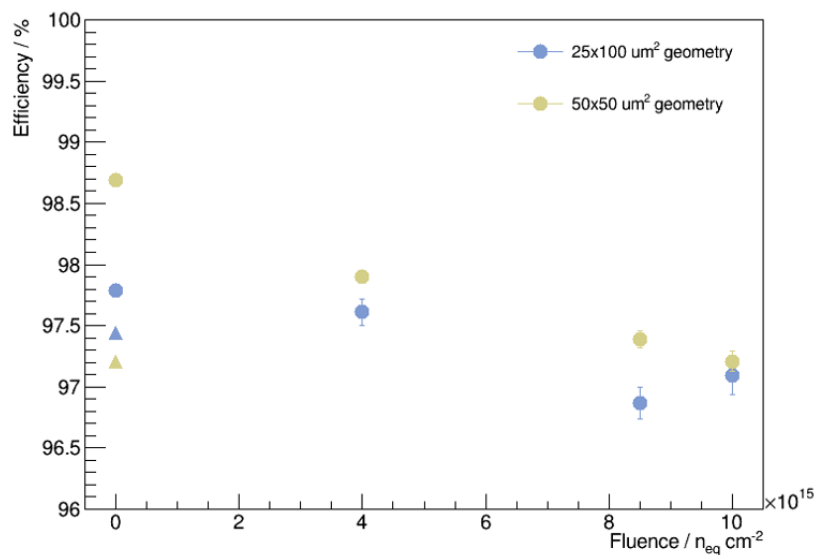
The summary of the charge collection efficiency for each hit point and fluence is presented in Fig. 4.16 for the rectangular geometry. In general terms, as the fluence increases the charge collection efficiency drops, and the differences in charge at the different hit positions become more pronounced. Normalization is performed with respect to point B at low fluence. Figure 4.16 shows that the regions of higher electric field and closer to the collecting electrode (C and E) collect more charge than the rest. With an increasing irradiation, the points further from the PN junction (A and D) collect less and less charge, and always less than the rest of points. The longer distance to the collecting electrode reduces the efficiency due to the higher trapping probability. In addition, since the depletion process starts at the PN junctions and extends towards the ohmic contacts as the bias voltage increases, regions near points A and D are more likely to be under-depleted as the fluence rises.

Point B, in the pixel center is the point with the highest charge collection at the lowest fluence and for higher irradiances remains in an intermediate value of the efficiency with

respect to the rest of points. Points C and E get always similar charge collection since they belong to the region closer to the PN junction, the one that is kept depleted even at the high irradiation. In addition, they are almost not affected by trapping because they are also very close to the collecting electrode. At the regions close to the PN junctions, from the low fluence to the high fluence, just a 20% relative charge collection efficiency is lost. As previously shown, this does not have a big impact on the global hit efficiency.

#### 4.2.5 Summary of the hit efficiency dependency with fluence

In global terms, the behaviour of the efficiency in terms of the fluence is the one given by Fig. 4.17, for both pixel geometries at normal incidence. The rectangular geometry is displayed in blue and the squared one in yellow. All the circles represent FBK sensors. Before irradiation, they were operated at 1 V (rectangular pixel sensor) and 15 V (squared one). After irradiation, the applied bias voltages were increased to 125 V and 151 V, respectively. With triangles, another set of measurements from CNM DUTs before irradiation is included. This set of values corresponds to 3D sensors operated at different bias voltages: 20 V in the case of the  $25 \times 100 \mu\text{m}^2$  pixel sensor and 5 V for  $50 \times 50 \mu\text{m}^2$ . By comparing these values, the effect of the bias voltage is tested.



**Fig. 4.17** Efficiency as a function of the fluence for rectangular and squared 3D sensors at normal incidence. FBK sensors operated fresh at 1 V and 15 V, respectively, and irradiated at 125 V and 151 V are represented with circles. Fresh CNM sensors at 20 V and 5 V are shown with triangles. CNM sensors have a smaller acceptance since the columns diameter is bigger than in FBK DUTs, leading to lower global efficiencies.

From the two measurements of the  $50 \times 50 \mu\text{m}^2$  geometry before irradiation (5 V yellow triangle and 15 V yellow circle), the effect of the bias voltage is clear. For this geometry, at 5 V the sensor is already more than 97% efficient, however, by increasing the bias voltage just 10 V, the efficiency improves and exceeds the 98.5%, in global terms.

In the case of the  $25 \times 100 \mu\text{m}^2$  geometry, for both bias voltages of 20 V (blue triangle) and just 1 V (blue circle), the efficiency is around the 97.5%. This response confirms that the rectangular geometry reaches depletion at bias voltages as low as only 1 V and increasing the bias voltages does not lead to any significant improvement in the performance. Nonetheless, the DUT at higher bias voltage is a 0.4% less efficient. This counter-intuitive conclusion finds its explanation in the fact that the sensor at 20 V is the CNM DUT, whose columns diameter is  $8 \mu\text{m}$ , while the DUT at 1 V is an FBK DUT, whose columns diameter smaller ( $5 \mu\text{m}$ ). Therefore, although both in the depletion regime, the DUT at 20 V presents a 3% smaller acceptance, leading to a slight reduction in the efficiency, at normal incidence. Here the worst case scenario is considered, since inside the CMS IT the sensors will always face a certain angle. And with just a slight angular incidence the efficiency is recovered all over the sensor.

The efficiency drops from a 98.69% maximum global efficiency value, to a 97.09%. From the fresh sensor, to the high irradiation situation, less than a 2% efficiency is lost, confirming the high radiation tolerance of 3D sensors.

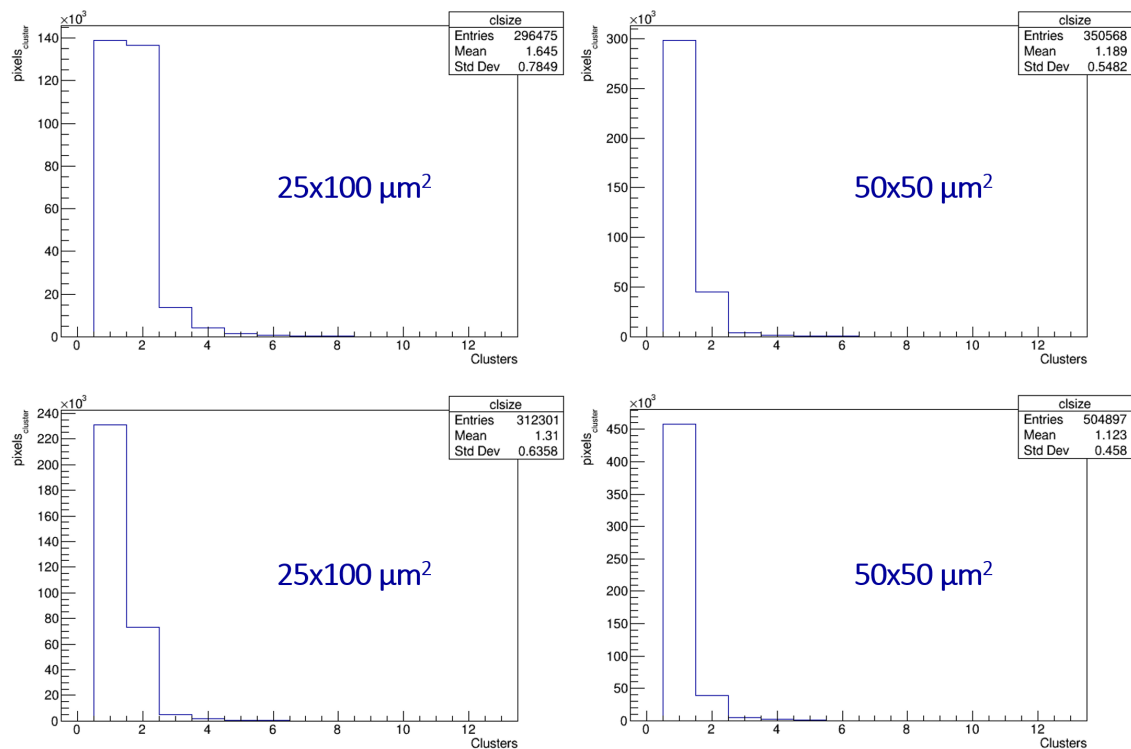
### 4.3 Test beam characterisation: Pixel resolution

The 3D sensors have proven to be close to 100% efficient, while working with safe power consumption, after the highest level of irradiation measured until the moment. However, the effect of the fluence on the position resolution is another important question. In order to answer it, a study of the cluster size and the resolution dependence with fluence is performed in the present section, at several particle incidence angles. Investigation of the two types of pixel geometries  $25 \times 100 \mu\text{m}^2$  and  $50 \times 50 \mu\text{m}^2$  will show the response quality of the new reduced pixel sizes.

#### 4.3.1 Cluster size distributions

The cluster size gives a measurement of the number of pixels sharing the detection of a particle. Cluster size measurements represent the amount of pixels collecting charge due

to the same track. At normal incidence, a main big contribution of clusters of size one are expected. Clusters of size two or three will represent a small but not negligible portion of the sample since there is always some scattering that makes tracks get to the sensor with a certain angle, touching more than one pixel. In addition, part of the charge generated at the pixel borders or close to them will drift to different pixels depending on the intensity of the electric field. In any case, at normal incidence cluster size one will definitely dominate the spectrum.



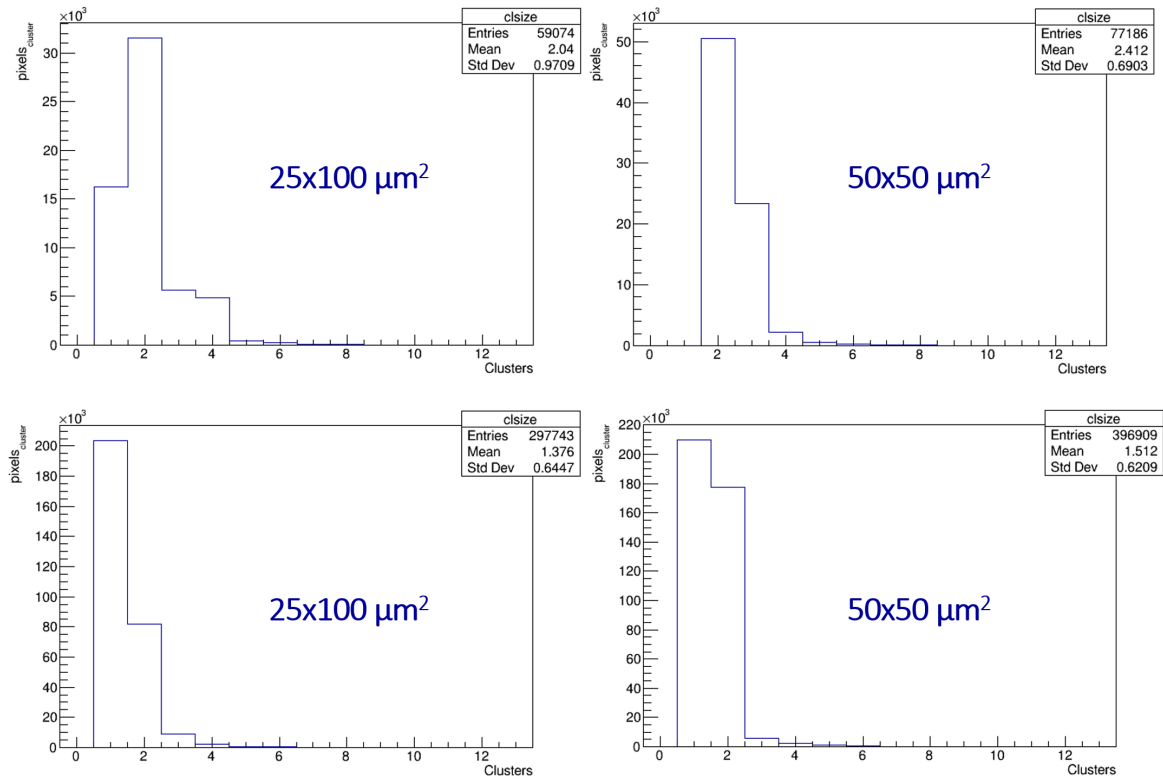
**Fig. 4.18** Cluster size distribution at normal incidence for both pixel geometries: rectangular on the left and squared on the right. Top plots are obtained from fresh DUTs at 1 V (rectangular) and 15 V (squared) effective bias voltages. Bottom plots correspond to the whole surface of the non homogeneously irradiated sensors, at 125 V and 151 V effective bias voltages.

The cluster size distributions shown by Fig. 4.18 correspond to 3D sensors at normal incidence. The two on the left are the plots of the  $25 \times 100 \mu\text{m}^2$  pixel geometry and those on the right correspond to the  $50 \times 50 \mu\text{m}^2$  geometry. The top plots correspond to each geometry before irradiation, while the bottom plots are those from the non homogeneously irradiated samples. Although considering the whole sensor surface means that different fluences are mixed, this plot provides with a general overview of the cluster size after irradiation.

The rectangular and squared DUTs before irradiation are operated here at 1 V and 15 V effective bias voltage, while the irradiated samples were measured at 125 V and 151 V.

In all of these plots, clusters of size 1 dominate. In the case of the rectangular geometry before irradiation, cluster size 2 is as well found as a result of the far from over-depletion situation in which this sensor was measured. This will be further explained with the pixel cell maps. The squared geometry presents a stronger domination of clusters of size 1. This slight difference could be related to geometrical reasons. In the squared geometry all the pixel borders are separated the same distance, while in the rectangular one the shorter side will find a higher charge sharing and bigger cluster sizes.

Before and after irradiation, the situation remains similar, no special changes are noticed. The effect of the fluence is not observed with the fluence at normal incidence.



**Fig. 4.19** Cluster size distribution at angular incidence tilting along the horizontal axis. Rectangular pixel geometry on the left and squared on the right. Top plots are obtained with fresh DUTs, tilted  $34^\circ$  and with effective bias voltages of 2 V (rectangular pixel DUT) and 35 V (squared pixel DUT). Bottom plots correspond to the whole surface of the non homogeneously irradiated sensors:  $25 \times 100 \mu\text{m}^2$  tilted  $38^\circ$  at 76 V effective bias, and  $50 \times 50 \mu\text{m}^2$  tilted  $21^\circ$  and at 120 V effective bias.

Examining the same DUTs in the same conditions but at an angular incidence, the results in Fig. 4.19 are gathered. The rectangular and squared DUTs before irradiation are operated here at 35 V and 2 V effective bias voltage, while the irradiated samples were measured at 76 V and 120 V. The chosen incidence angles for each pixel geometry are those at which



the tracks ideally activate two pixels. For the rectangular pixel sensors it would have been interesting to tilt along the short pitch, however due to test beam mechanical constraints it could only be done along the 100  $\mu\text{m}$  pixel direction.

The first change with respect to normal incidence is that the cluster size has grown. The dominant cluster size is 2 before irradiation due to the angle with which the particles cross the sensor, highly probably firing 2 pixels. However, when irradiated, this shift is less clear, meaning that both cluster sizes 1 and 2 are largely found.

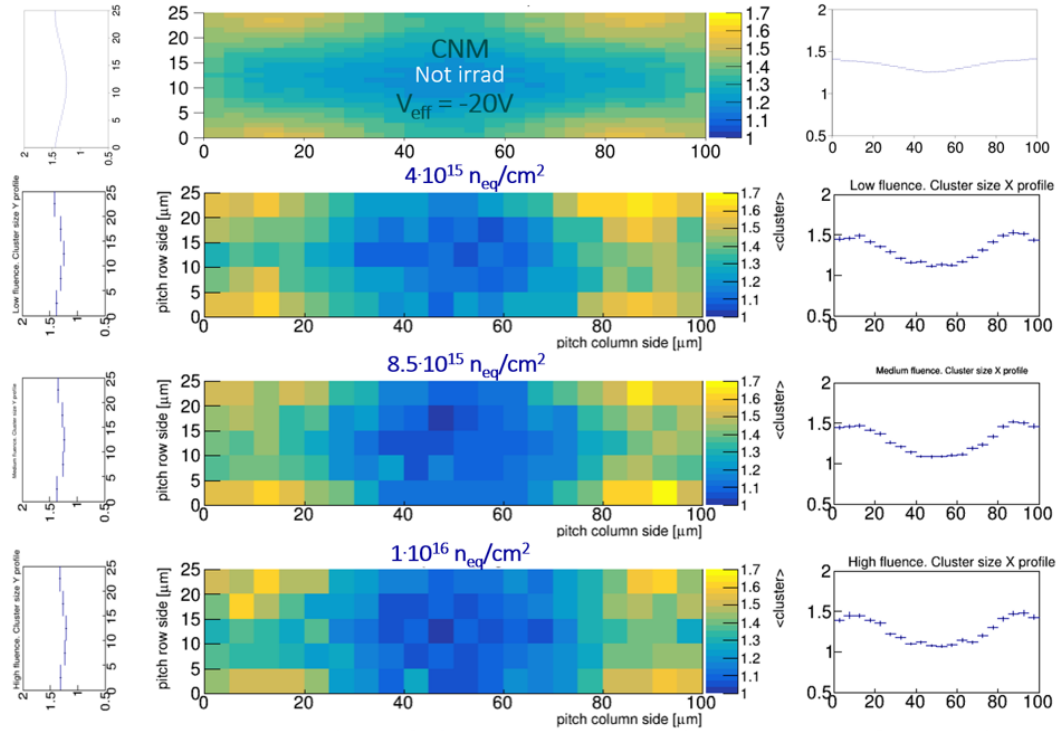
Apart from the geometry fact, it is important to notice that the squared geometry was operated at a higher value of the bias voltage and at  $21^\circ$  instead of  $38^\circ$ .

### 4.3.2 Cluster size at normal incidence

At normal incidence, the cluster size is mainly defined by the electric field lines direction and the electric field intensity. Particles reaching the sensor at normal incidence and passing close to the center of a pixel generate charge carriers that will probably be entirely collected by that very pixel. However, the closer to a pixel border, the stronger effect of the neighbouring pixels on the cluster size. The present section shows cluster size studies with the particle beam reaching the sensor at normal incidence. The plots of Fig. 4.20 show the average cluster size before irradiation and at  $4 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ ,  $8.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$  and  $1 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ .

The top plot in Fig. 4.20 shows the pixel behaviour of the whole LIN-FE of a non irradiated CNM sensor. The rest of maps show each of the defined fluence regions of the LIN-FE of an irradiated FBK sensor. The different size between the irradiated sensor investigated areas and the fresh sensor full area is the reason why the chosen bin size differs: there is far less statistics in each fluence region plot than in the fresh sensor plot. The profiles over the horizontal side (columns) are shown on the right while the profiles over the vertical direction (rows) are shown on the left.

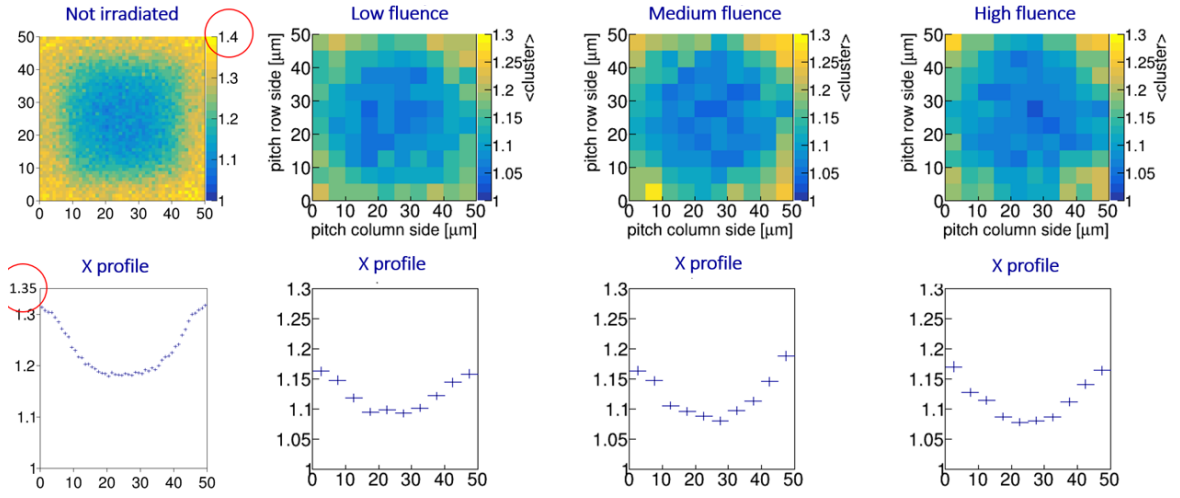
As expected, clusters of size 1 are found at the pixel center while bigger sizes are found closer to the border. In the inter-pixel region close to the ohmic contacts charge diffusion has a larger effect. Here the electric field is less intense and its lines are parallel to the pixel border, which results in a larger cluster size. At larger fluence the charge sharing is reduced in this region on account of the increase of traps, making diffusion more difficult to happen. In the region between pixels and far from the ohmic contacts, the electric field is higher as a consequence of the electrodes taking all the charge. In this way, around the border, the effect of very low charge sharing is found far from the ohmic columns, creating smaller clusters in particular when irradiated.



**Fig. 4.20** Average cluster size pixel cell maps for a fresh CNM sensor and the three fluence regions of an irradiated FBK sensor.  $25 \times 100 \mu\text{m}^2$  pixel geometry at normal incidence. Fresh CNM sensor operated at 20 V, while irradiated FBK sensor at 125 V.

In general terms, a slight difference before and after irradiation is observed in the cluster size. In all the situations a smaller cluster size can be found at the PN junction and a drop happens at the exact position of the ohmic contacts when irradiated, because of lower pixel activation.

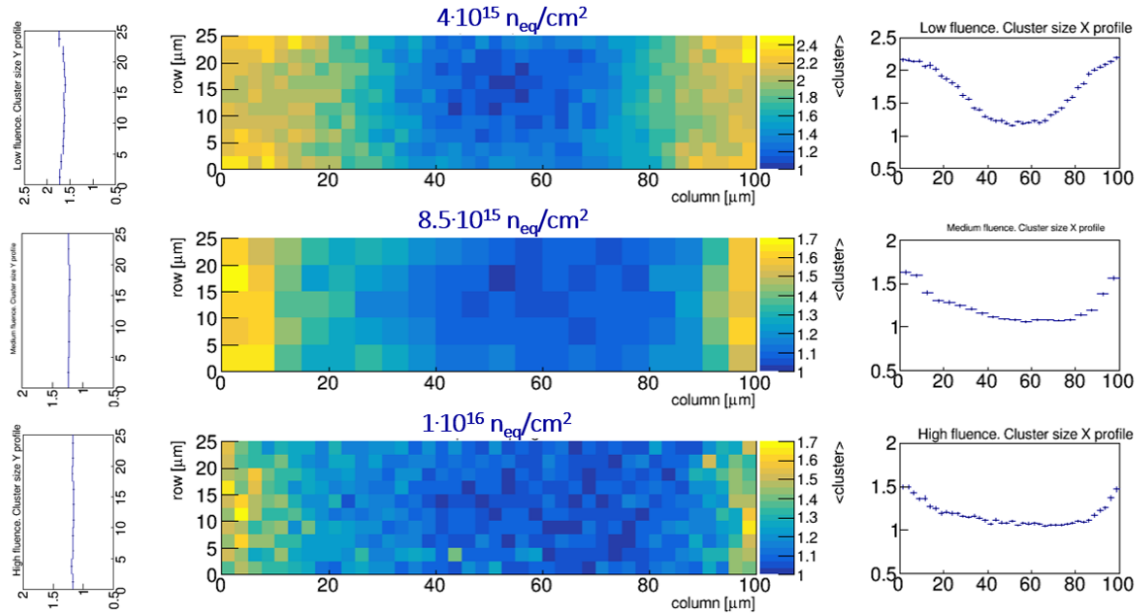
In the case of the  $50 \times 50 \mu\text{m}^2$  geometry, the same results comparing the whole LIN-FE of the fresh sensor and the three fluence regions of the irradiated one are shown in Fig. 4.21. Charge sharing around the whole pixel is present in the fresh sensor. There is a bigger charge sharing and bigger cluster size before irradiation. An important fact is the possibility of having operated this squared sensor before irradiation not fully depleted. This would explain the big difference between the before and after irradiation cases, which does not happen in the rectangular geometry. Since in the squared geometry there is symmetry in both directions, there is less charge sharing in vertical in the  $50 \times 50 \mu\text{m}^2$  geometry than in the rectangular one, since the charge is driven to the pixel center. Here again, the cluster size depends on the direction of the electric field and on its intensity. The cluster size remains constant for the three values of the fluence, both its distribution along the pixel and its value.



**Fig. 4.21** Cluster size pixel cell maps for a fresh CNM sensor and the three fluence regions of an irradiated FBK sensor.  $50 \times 50 \mu\text{m}^2$  pixel geometry at normal incidence. Fresh CNM sensor operated at 5 V, while irradiated FBK sensor at 151 V.

### 4.3.3 Cluster size at angular incidence

Tilting the DUT respect to the particle beam direction increases the cluster size, as shown by Fig. 4.22 for the irradiated rectangular geometry  $38^\circ$  tilted along the long pixel side.



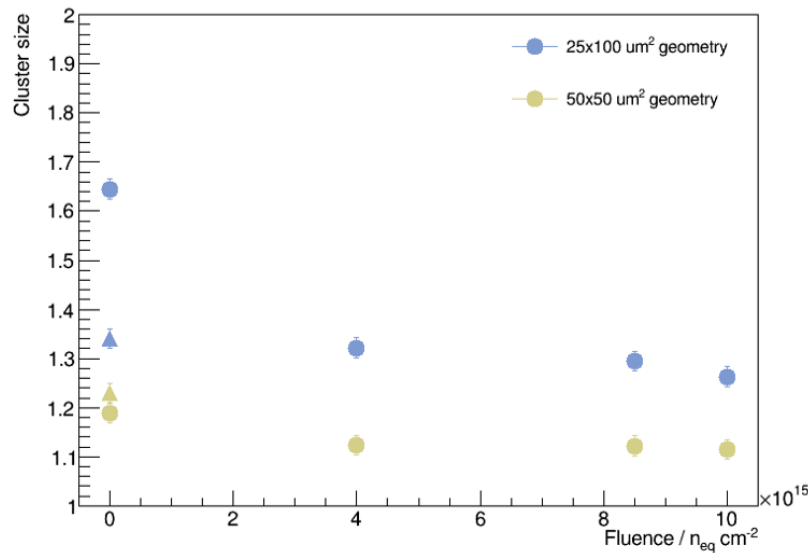
**Fig. 4.22** Cluster size pixel cell maps of each fluence region of rectangular geometry irradiated FBK sensor and profiles over each pixel direction. Run at  $38^\circ$  particle beam incidence and applied bias voltage of 125 V.

Comparing with normal incidence, the absolute value of the charge sharing has increased. Tracks close to the pixel borders deposit charge in two pixels instead of one, due to the incidence angle. This effect is reduced with the fluence, probably because the charge collected by the neighbouring pixel is low, and not enough for growing thresholds.

Mean values, given by the profiles over the Y direction, on the left of the pixel cell maps, lead to conclude that the mean value of the cluster size is reduced with fluence, in average terms, getting more homogeneous with position when more irradiated. The profiles over the X direction or long pixel side clearly show how cluster size one dominates more and more with fluence, which means that the charge sharing decreases.

#### 4.3.4 Summary of the cluster size dependency with fluence

Figure 4.23 summarizes the cluster size dependence with the fluence for both 3D sensors rectangular (blue) and squared (yellow) pixel size geometries. The circles represent FBK sensors. Before irradiation, they were operated at 1 V (rectangular) and 15 V (squared). After irradiation, the applied bias voltages were 125 V and 151 V. Another set of measurements with CNM sensors before irradiation is included with triangles, operated at 20 V (rectangular) and 5 V (squared). In this way, the effect of the bias voltage is also brought to comparison.

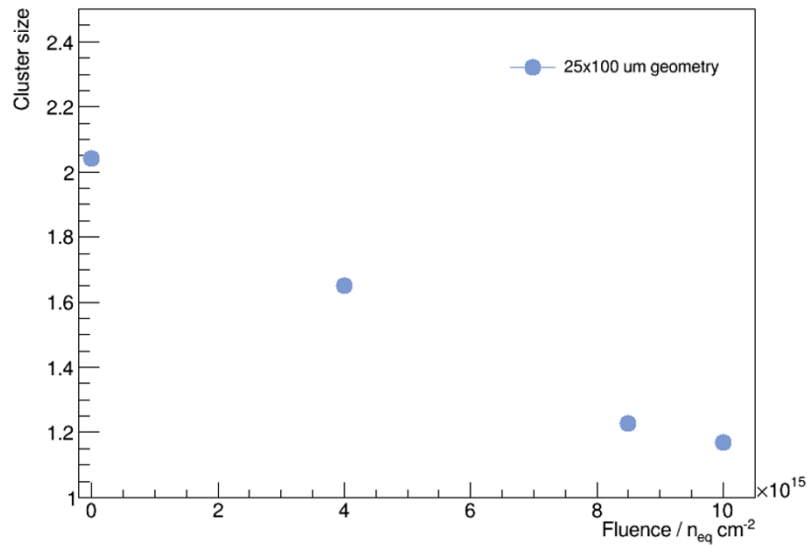


**Fig. 4.23** Average cluster size as a function of fluence at normal incidence for rectangular and squared 3D sensors. FBK sensors operated fresh at 1 V and 15 V, respectively, and irradiated at 125 V and 151 V are represented with circles. Fresh CNM sensors at 20 V and 5 V are shown with triangles.

In general terms, smaller clusters are found in the squared geometry, although the difference between the two geometries is just around 0.2. The average cluster size hardly changes with fluence for both square and rectangular pixels.

The higher average cluster size for the fresh rectangular FBK sensor is most likely due to an effective bias voltage of just 1 V, while the other  $25 \times 100 \mu\text{m}^2$  sensor was operated at 20 V. Comparing the two fresh squared sensors, the sensor at 5 V (yellow triangle) shows a bigger average cluster size than the sensor at 15 V (yellow circle). In this case the difference is less dramatic because the voltage difference is smaller and both voltages are in the depleted regime. Increasing the bias voltage above full depletion leads to higher electric fields, in which the charge carriers collection time can be significantly reduced.

Summarizing the cluster size behaviour with fluence at angular incidence, Fig. 4.24, shows how the cluster size decreases as the sensor gets more irradiated, when operated at  $38^\circ$  beam particle incidence. For this plot, the rectangular geometry tilted along its  $100 \mu\text{m}$  side is considered.

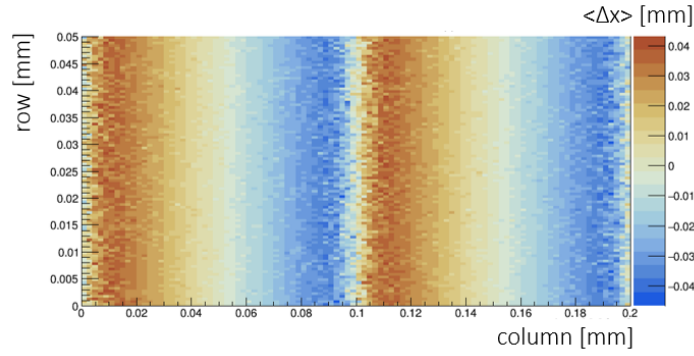


**Fig. 4.24** Average cluster size as a function of fluence at  $38^\circ$  incidence for the rectangular irradiated FBK 3D sensor.

#### 4.3.5 Residual pixel cell maps of the whole DUT surface response

The residuals study can be performed over each of the pixel directions. This is, for each pixel, the distance in horizontal and vertical between the hit on the DUT and the position of the reconstructed track can be calculated. In principle, the same residuals pattern is expected,

along both directions, something like the one shown in Fig. 4.25. This plot is an example of the horizontal residuals of a  $25 \times 100 \mu\text{m}^2$  sensor, in a  $2 \times 2$  pixel matrix.

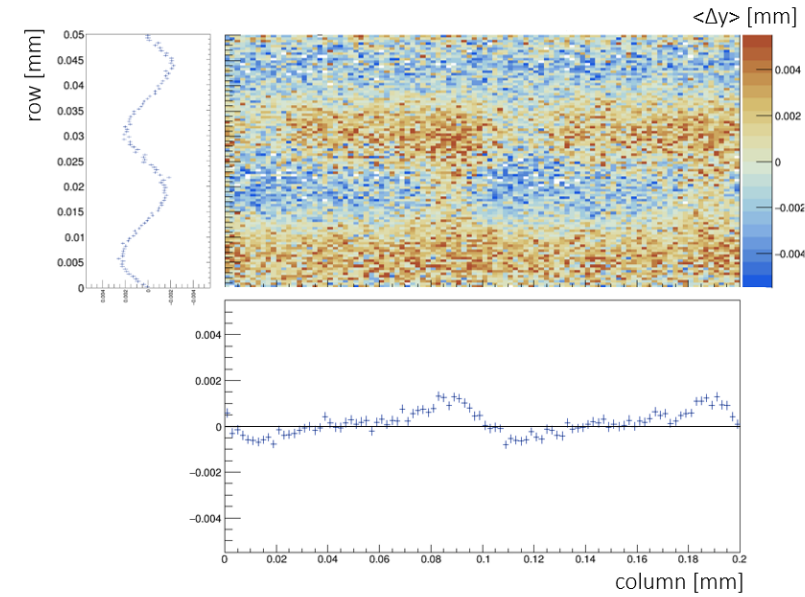


**Fig. 4.25** Four-pixel cell map of the horizontal residuals of an irradiated 3D  $25 \times 100 \mu\text{m}^2$  sensor. Normal incidence and effective bias voltage of 125 V, at  $-36^\circ\text{C}$ .

The chosen color palette to plot residuals is the ROOT kLightTemperature, different to the rest of plots in this thesis (ROOT kBird) with the purpose of giving the zero residual a neutral color, while extreme values in both directions have powerful colors, providing with a better understanding of the position dependence. As expected, the centre of a pixel records zero residual since the track and hit positions on the DUT coincide, therefore the difference is null. At the pixel border, the residual is also zero, since a particle there induces a similar signal in two neighboring pixels, and the DUT hit is reconstructed very close to the extrapolated track position. As we move away from those points, the absolute value of the residual grows, finding its maximum at few microns from the pixel borders.

However, for the same sensor, the vertical residuals we measured are the ones shown in Fig. 4.26, and a different pattern is observed. If projecting them over the axes, we find the already explained and expected behaviour along the vertical direction, but not over the horizontal. Odd and even pixels show a different behaviour with their neighbours. This is the result of a single hit inducing current on different pixels, not only in the one it belongs to. This current induction or cross-talk is due to the presence of metal routings on the surface of rectangular sensors, following an odd-even asymmetric layout along the horizontal coordinate, as shown in the  $25 \times 100 \mu\text{m}^2$  pixel sensor of Fig. 3.2(a), in Chapter 3. Recall that these routings are necessary to match the rectangular pixel geometry with the square readout ASIC geometry for bump-bonding.

In this way, hits around the bottom part of the left half of the pixel marked in red in Fig. 3.2(a), induce a current not only in the pixel they impacted, but also in the pixel under it. Therefore the residuals along the vertical coordinate suffer an asymmetry due to the



**Fig. 4.26** Residuals over the sensor vertical direction, as a function of both its horizontal and vertical coordinates. On the bottom and left side, the projections over the axis are shown. Irradiated 3D  $25 \times 100 \mu\text{m}^2$  sensor at normal incidence and an effective bias voltage of 125 V, at  $-36^\circ\text{C}$ .

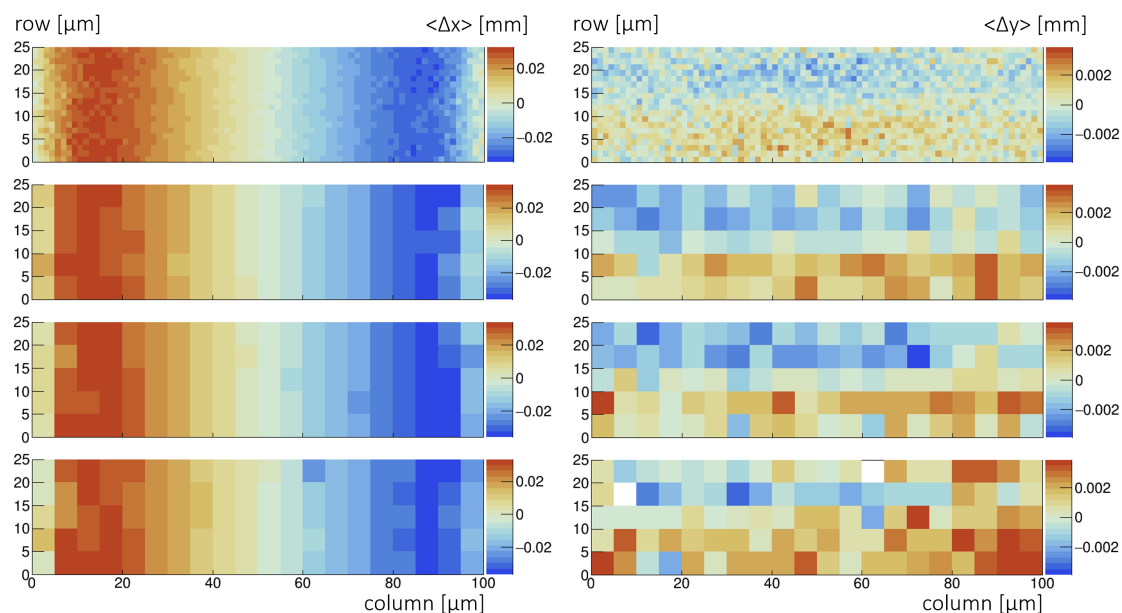
metallizations distribution. Nevertheless, the residuals suffer a total increase of only around  $2\text{--}3 \mu\text{m}$  in limited pixel regions. The effect of crosstalk therefore does not represent a serious problem for this geometry in 3D sensors.

### 4.3.6 Residual pixel cell maps of each fluence region

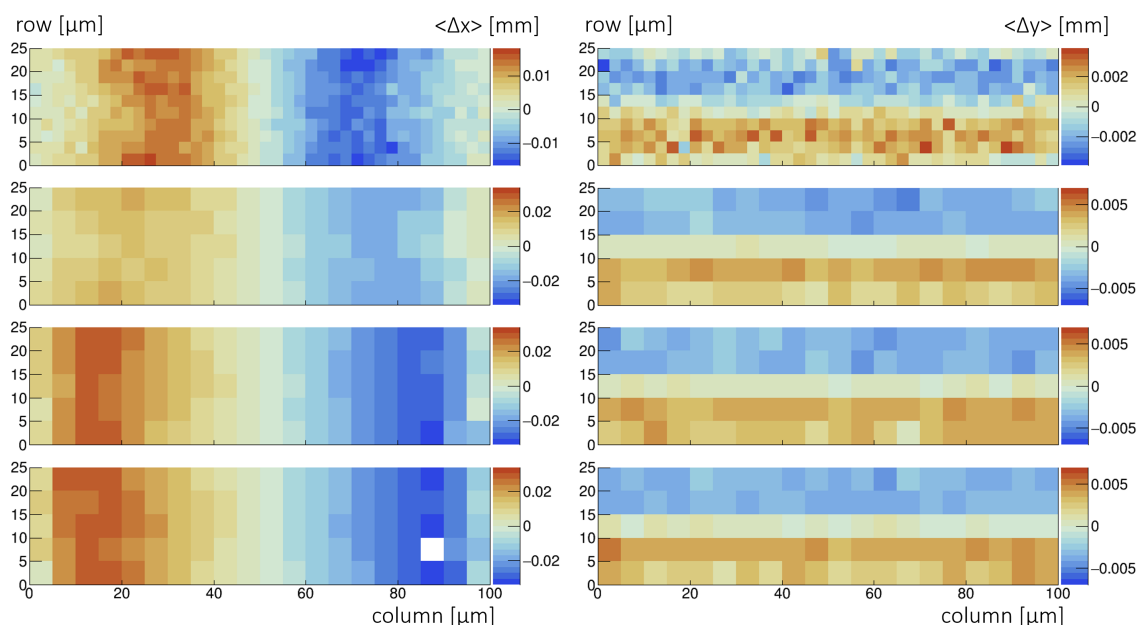
The study of the residuals provides with a way of estimating the spatial resolution of the sensor. Residual distributions as a function of the pixel position at normal incidence for the rectangular pixel geometry are the ones shown by Fig. 4.27.

When tilting the sensor, the residual pixel cell maps for both directions are the ones obtained in Fig. 4.28. Here, the residual values along X, which is the tilted side, got reduced with respect to normal incidence and the maximum values got displaced. The higher residual values get closer to the pixel center when tilting. The charge sharing region grows from the borders to the pixel center, meaning that the residuals improvement takes place before. The profiles over the direction of interest of all these plots are shown in Figure 4.29 for a more quantitative comparison.

In the profiles of Fig. 4.29 both pixel directions of both residuals of the  $25 \times 100 \mu\text{m}^2$  FBK 3D sensor are represented. Blue columns are the residuals at normal incidence, while



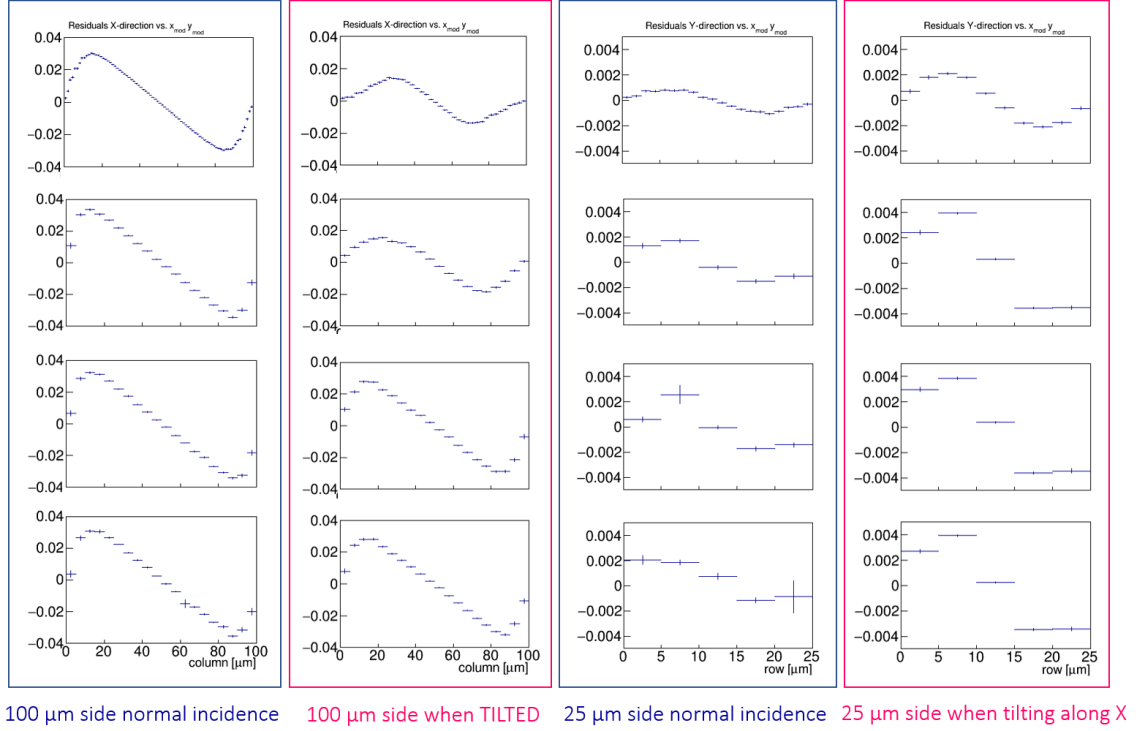
**Fig. 4.27** Residuals over the X (on the left) and Y (on the right) directions of a rectangular FBK DUT at normal incidence. Each row is dedicated to each fluence situation under study. From top to bottom: before irradiation,  $4 \times 10^{15}$  n<sub>eq</sub>/cm<sup>2</sup>,  $8.5 \times 10^{15}$  n<sub>eq</sub>/cm<sup>2</sup> and  $1 \times 10^{16}$  n<sub>eq</sub>/cm<sup>2</sup>. The fresh sensor cell map summarizes the whole DUT, while the irradiated plots correspond to smaller regions.



**Fig. 4.28** Residuals over the X (on the left) and Y (on the right) directions of a rectangular FBK sensor before and after irradiation (at the three fluences values), at 34° incidence for the fresh sensor and 38° for the irradiated one.



the pink ones are those at  $34^\circ$  in the case of fresh sensors and  $38^\circ$  for irradiated ones, both along the long pixel side. Here again, the three fluence regions of the irradiated sensor are considered independently.



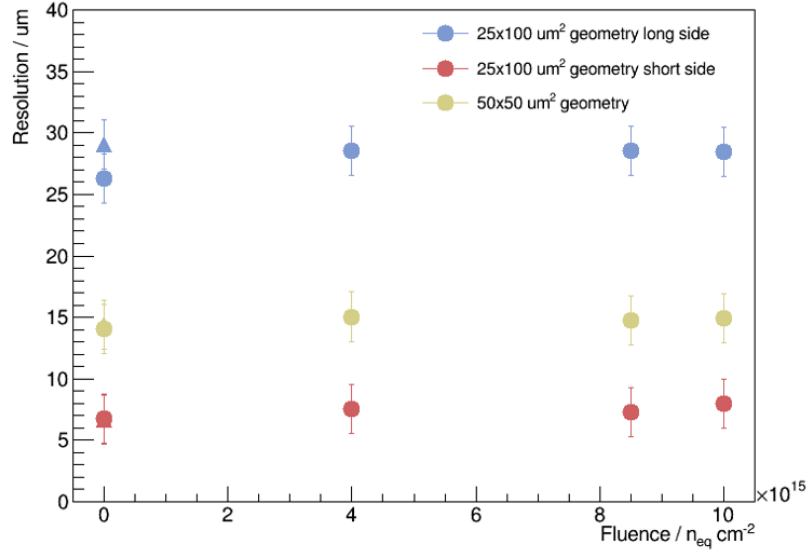
**Fig. 4.29** Residuals profiles over the X and Y directions of a rectangular FBK sensor before and after irradiation (at the three fluences values). Normal and angular incidences are considered.

### 4.3.7 Resolution dependency with the fluence

The intrinsic DUT resolution  $\sigma_{DUT}$  can be obtained from the residual distribution since this has a contribution from both the telescope track resolution, whose value is known, and  $\sigma_{DUT}$ . As already explained in Chapter 3,  $\sigma_{DUT}$  is calculated through Eq. (3.6).

The sensor resolution as a function of fluence is shown in Fig. 4.30. The resolution of the telescope at CERN SPS, which is  $7 \mu\text{m}$ , has been subtracted in quadrature. The rectangular pixel geometry is split over its two different lengths while just one side of the squared geometry is presented, for obvious reasons.

For the before irradiation situation, two bias voltages are considered for each point: in circles the FBK fresh sensors at 1 V ( $25 \times 100 \mu\text{m}^2$  geometry) and 15 V ( $50 \times 50 \mu\text{m}^2$  geometry) and in triangles the CNM fresh sensors at 20 V ( $25 \times 100 \mu\text{m}^2$  geometry) and 5 V ( $50 \times 50 \mu\text{m}^2$  geometry).



**Fig. 4.30** Position resolution dependence with fluence for each sensor direction at normal incidence. In circles all FBK sensors. For the before irradiation case, another set of values from CNM sensors is displayed with triangles.

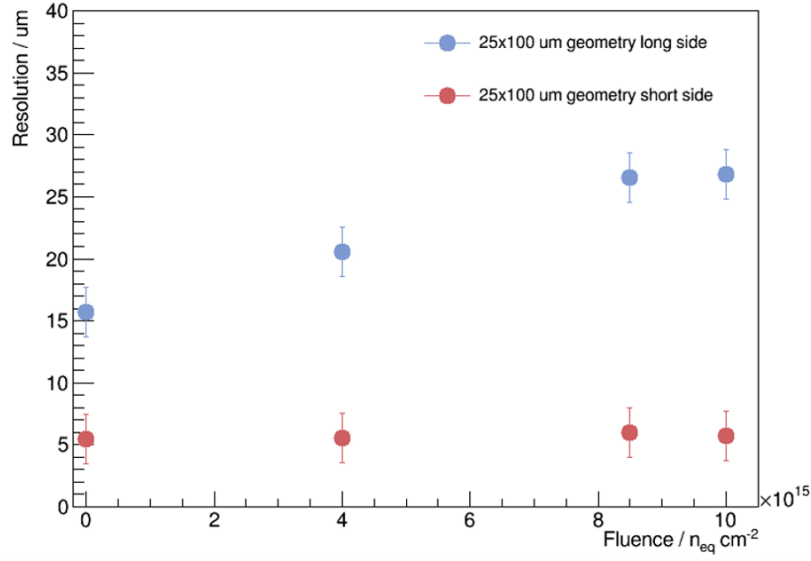
geometry). The rest of points correspond to the different fluence regions of the irradiated FBK DUTs at 125 V ( $25 \times 100 \mu\text{m}^2$  geometry) and 150 V ( $50 \times 50 \mu\text{m}^2$  geometry).

Comparing the points before irradiation, the two bias voltages considered per geometry present basically the exact same resolution. The blue triangle is slightly higher because this sensor was not fully depleted. At normal incidence, the sensor resolution is binary, as expected, and has no dependency with the fluence. This is a consequence of the particle impact equiprobability in the pixel area, given by  $\sigma_{DUT} = \frac{p}{\sqrt{12}}$ , as explained in Chapter 3.

When tilting the rectangular pixel sensor over its long side ( $100 \mu\text{m}$ ), the resolutions plot for both sensor sides is the one in Fig. 4.31. Since the short side is not facing any tilt, the resolution is not notably affected by this change. However, the side suffering the inclination shows a clear improvement of the binary resolution, which degrades with fluence. This is expected since the trapping probability increases, the charge losses grow and more hits are likely to get lost, leading to cluster population reductions from size 2 to size 1 (with worse resolution), in that coordinate.

### 4.3.8 Extended study over further incidence angles

In order to determine the sensor spatial resolution, the double side CNM 3D sensor (332 in Table 3.1) was placed as close as physically possible to the upstream telescope group of



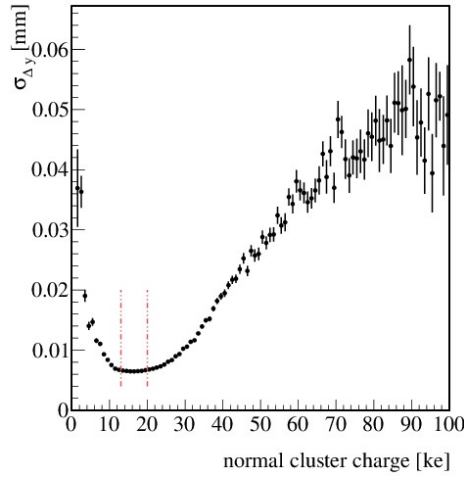
**Fig. 4.31** Position resolution as a function of the fluence for each rectangular pixel sensor direction, tilting  $34^\circ$  (fresh sensor) and  $38^\circ$  (irradiated values) over the long side.

planes, during the DESY test beam. The upstream planes reconstructed track is extrapolated to the plane of the DUT taking into account multiple scattering by using the General Broken Lines (GBL) formalism [116] and the distance to the DUT hit position is computed. In this way the residual, or distance between these two points on the DUT surface, is calculated.

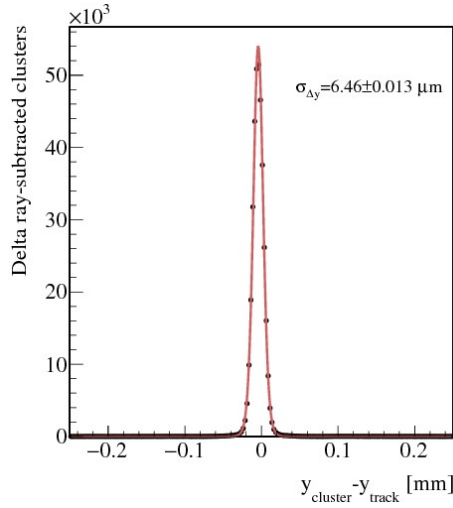
Only DUT clusters matched to a telescope track and to the reference sensor are used. In addition, only clusters which have a charge close to the Landau most probable value are used. This cut in charge rejects delta rays produced in the sensor which would severely affect the position resolution, since delta electrons produced at the point of incidence typically travel a long distance inside the sensor, producing very large clusters of large charge and with a centroid far away from the track incidence point. Fig. 4.32 shows the residual width as a function of cluster charge, where the deterioration at large charge due to delta rays can be seen.

The optimal DUT resolution is calculated using clusters from  $12^\circ$  incidence tracks after rejecting delta rays. The residual distribution between the telescope track projection and the cluster center has a width of  $6.46 \mu\text{m}$ , as shown in Fig. 4.33. After subtracting in quadrature the telescope resolution evaluated with the GBL formalism, the DUT resolution at  $12^\circ$  incidence is found to be  $3 \mu\text{m}$ .

The resolution has been studied as a function of incidence angle. The resolution is expected to be close to the binary resolution at perpendicular incidence ( $14.4 \mu\text{m}$  for a pitch

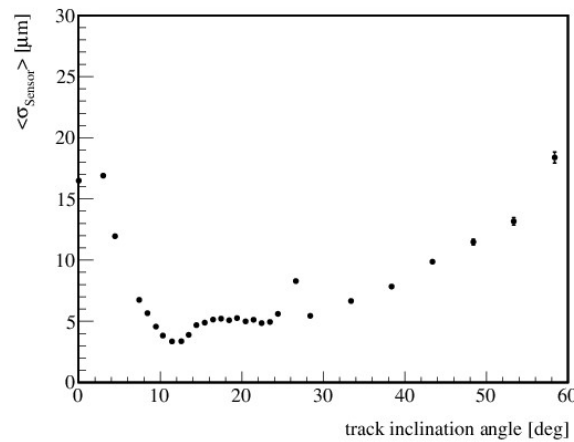


**Fig. 4.32** Residual width as a function of cluster charge. Only clusters with charge in the region inside the dashed lines are used for the DUT resolution measurement. The resolution deterioration at large charge is due to the influence of delta rays.



**Fig. 4.33** Residual distribution for 12° incidence for clusters matched to a telescope track after delta ray rejection. The width has a contribution from the telescope resolution and from the DUT resolution.

of 50  $\mu\text{m}$ ), and improve with charge sharing as the cluster size increases, reaching an optimal value at the arctangent of the pitch to thickness ratio (12° for these sensors). Figure 4.34 shows the DUT resolution as a function of incidence angle.



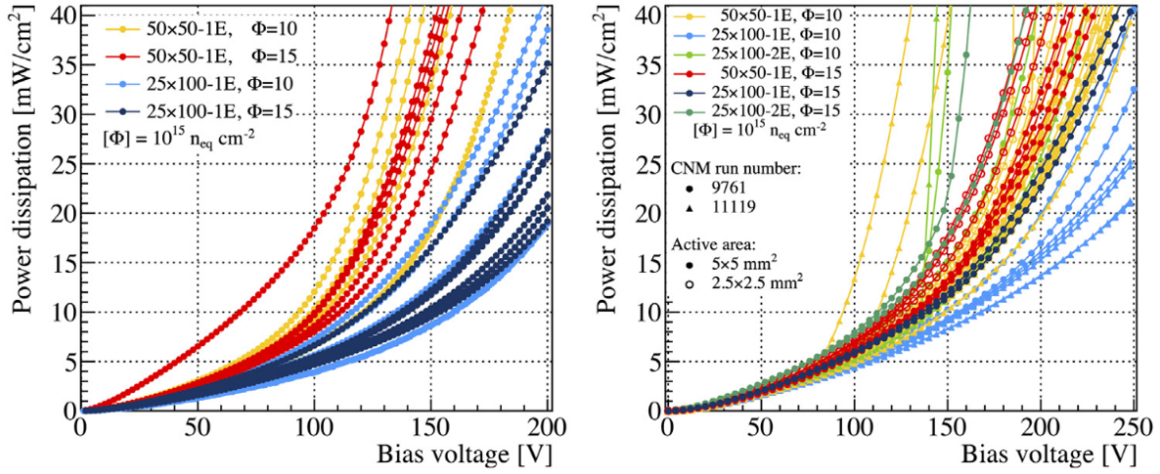
**Fig. 4.34** DUT resolution as a function of track incidence angle.

## 4.4 Power dissipation

Highly irradiated sensors generally present a large leakage current. This requires a powerful cooling system to prevent sensors from going into thermal runaway. The 3D sensors present an operational advantage because, thanks to a lower bias voltage, they dissipate less power and are therefore safer—from a thermal dissipation point of view—for the innermost IT regions. The present section represents a compendium of the different studies accomplished on different samples by several groups apart from IFCA.

Figure 4.35 shows a summary of the power dissipation of 3D diodes after irradiation, operated with the RD53A ROC. The DUTs were irradiated up to  $1.5 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$  with neutrons and suffered an annealing of 7 days at room temperature before the IV tests at  $-25^\circ\text{C}$  that lead to these results. The chips annealing was 3-4 days.

A higher current is measured for pixel cell designs with larger inter-electrode distances, especially for the  $25 \times 100 \mu\text{m}^2$ -2E. No significant difference is observed in the power dissipation between  $50 \times 50 \mu\text{m}^2$  and  $25 \times 100 \mu\text{m}^2$  sensors at this irradiation level for the operational voltage ranges between 80 and 150 V where more than 96% efficiency is reached. Results of the RD53A irradiated with protons are compatible with the measurements of diodes irradiated with neutrons given the uncertainties in the annealing times and irradiation levels. A few diodes and RD53A sensors show a larger power dissipation before 100 V due to an early breakdown.



**Fig. 4.35** Power dissipation as a function of the bias voltage, at  $-25^{\circ}\text{C}$  reference temperature, of different pixel geometry diodes from FBK (left) and CNM (right), after neutron irradiation. Picture extracted from [117].

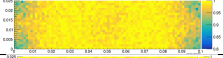
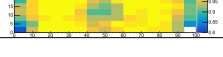
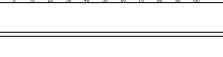
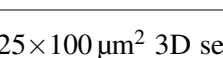
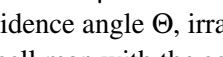
## 4.5 Summary

In the present section, a summary table with the main results is presented for the two pixel geometries of the tested 3D pixel DUTs. The different DUTs are distinguished by their name (which leads to all the specifications in Table 3.1). The conditions during the data takings are given: by the particle beam incidence angle  $\Theta$  during the test beams, the irradiation fluence  $\Phi$  in  $\text{n}_{\text{eq}}/\text{cm}^2$  units and the bias voltage  $V_{\text{bias}}$ .

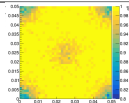
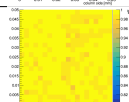
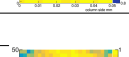
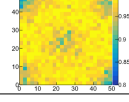
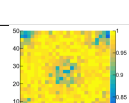
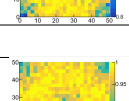
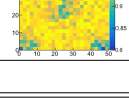
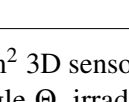
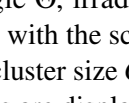
The most important results are summarized here, by providing the global efficiency  $Eff$ , the hit position resolutions  $\sigma$ —which in the case of the rectangular geometry are specified for each of the sensor pixel directions (long  $\sigma_l$  and short  $\sigma_s$  sides)—, the average cluster size  $CS$  and the power consumption  $P$  ( $\pm 0.2 \text{ mW}/\text{cm}^2$ ) at the specified temperature  $T$ .

The values of the power consumption are the ones obtained during the measurement of the DUTs during electrical characterisation before the test beam, in the case of fresh samples, and the operation parameters during the test beam, for the irradiated ones. The temperatures given are a rough estimation, in particular for irradiated sensors, since it was very complicated to measure the actual temperature in the sensor inside the cold box. The measurement of a region inside the cold box relatively close to the sensors is provided.

In the case of the hit position resolutions along each pixel side (just one in the squared geometry), the contribution of the telescope has been subtracted, which has been estimated to be around  $7 \mu\text{m}$  for those measurements taken at CERN SPS test beams.

| DUT    | $\Theta$ [°] | $\Phi$ [n <sub>eq</sub> /cm <sup>2</sup> ] | $V_{\text{bias}}$ [V] | $Eff$ [%]   | Efficiency pixel cell map                                                         | $\sigma_1$ [μm] | $\sigma_s$ [μm] | $CS$ | $P$ [mW/cm <sup>2</sup> ] | $T$ [°C] |
|--------|--------------|--------------------------------------------|-----------------------|-------------|-----------------------------------------------------------------------------------|-----------------|-----------------|------|---------------------------|----------|
| W3-3-2 | 0            | 0                                          | 15                    | 97.79 ±0.03 |  | 17              | 9               | 1.6  | 0.1                       | 20       |
| W3-3-2 | 34           | 0                                          | 15                    | 99.37 ±0.03 |  | 16              | 5               | 2.0  | 0.1                       | 20       |
| W7-3-1 | 0            | 0                                          | 15                    | 97.44 ±0.10 |  | 17              | 9               | -    | 0.5                       | 20       |
| W3-3-2 | 0            | 4×10 <sup>15</sup>                         | 125                   | 97.61 ±0.11 |  | 22              | 9               | 1.3  | 41.1                      | -36      |
| W3-3-2 | 38           | 4×10 <sup>15</sup>                         | 125                   | 91.53 ±0.15 |  | 21              | 6               | 1.7  | 41.1                      | -36      |
| W3-3-2 | 0            | 8.5×10 <sup>15</sup>                       | 125                   | 96.87 ±0.13 |  | 27              | 9               | 1.3  | 41.1                      | -36      |
| W3-3-2 | 38           | 8.5×10 <sup>15</sup>                       | 125                   | 91.51 ±0.17 |  | 27              | 6               | 1.2  | 41.1                      | -36      |
| W3-3-2 | 0            | 10×10 <sup>15</sup>                        | 125                   | 97.09 ±0.15 |  | 28              | 9               | 1.3  | 41.1                      | -36      |
| W3-3-2 | 38           | 10×10 <sup>15</sup>                        | 125                   | 88.04 ±0.18 |  | 27              | 6               | 1.2  | 41.1                      | -36      |
| ±1     |              |                                            |                       |             |                                                                                   | ±2              | ±2              | ±0.1 | ±0.2                      | ±5       |

**Table 4.1** Summary of the results of the 25×100 μm<sup>2</sup> 3D sensors characterisation. The displayed data are: the DUT name, particle beam incidence angle  $\Theta$ , irradiation state  $\Phi$ , operating voltage  $V_{\text{bias}}$ , global efficiency  $Eff$ , efficiency one-pixel cell map with the scale starting in 80% efficiency, position resolution along the long pixel side  $\sigma_1$  and along the short one  $\sigma_s$ , average cluster size  $CS$  and the power consumption  $P$  at the given temperature  $T$ . Some associated errors are displayed at the last row.

| DUT     | $\Theta$ [°] | $\Phi$ [n <sub>eq</sub> /cm <sup>2</sup> ] | $V_{\text{bias}}$ [V] | $Eff$ [%]   | Efficiency pixel cell map                                                           | $\sigma$ [μm] | $CS$ | $P$ [mW/cm <sup>2</sup> ] | $T$ [°C] |
|---------|--------------|--------------------------------------------|-----------------------|-------------|-------------------------------------------------------------------------------------|---------------|------|---------------------------|----------|
| W91-1-3 | 0            | 0                                          | 15                    | 98.69 ±0.02 |  | 14            | 1.2  | 1.7                       | 20       |
| W91-1-3 | 34           | 0                                          | 15                    | 99.31 ±0.03 |  | 11            | 2.4  | 1.7                       | 20       |
| W7-1-1  | 0            | 0                                          | 5                     | 97.52 ±0.03 |  | 2             | 0.1  | 8.9                       | 20       |
| W91-1-3 | 0            | 4×10 <sup>15</sup>                         | 150                   | 97.90 ±0.06 |  | 15            | 1.1  | 14.5                      | -35      |
| W91-1-3 | 21           | 4×10 <sup>15</sup>                         | 150                   | 98.76 ±0.05 |  | 11            | 1.6  | 14.5                      | -35      |
| W91-1-3 | 0            | 8.5×10 <sup>15</sup>                       | 150                   | 97.39 ±0.07 |  | 15            | 1.1  | 14.5                      | -35      |
| W91-1-3 | 21           | 8.5×10 <sup>15</sup>                       | 150                   | 96.54 ±0.10 |  | 11            | 1.5  | 14.5                      | -35      |
| W91-1-3 | 0            | 10×10 <sup>15</sup>                        | 150                   | 97.21 ±0.08 |  | 15            | 1.1  | 14.5                      | -35      |
| W91-1-3 | 21           | 10×10 <sup>15</sup>                        | 150                   | 95.18 ±0.11 |  | 11            | 1.4  | 14.5                      | -35      |
| ±1      |              |                                            |                       |             |                                                                                     | ±2            | ±0.1 | ±0.2                      | ±5       |

**Table 4.2** Summary of the results of the 50×50 μm<sup>2</sup> 3D sensors characterisation. The displayed data are: the DUT name, particle beam incidence angle  $\Theta$ , irradiation state  $\Phi$ , operating voltage  $V_{\text{bias}}$ , global efficiency  $Eff$ , efficiency one-pixel cell map with the scale starting in 80% efficiency, position resolution  $\sigma$  along one of the pixel sides, average cluster size  $CS$  and the power consumption  $P$  at the given temperature  $T$ . Some of the associated errors are displayed at the last row.





# Conclusions

By the end of 2027, the HL-LHC will start operating with an instantaneous luminosity of  $7.5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ , five times more than the current one. After about 12 operation years, it will reach an integrated luminosity around  $4000 \text{fb}^{-1}$ , more than ten times the LHC. This upgrade entails decisive upgrades of its colliding experiments. The innermost CMS detector, the Inner Tracker, will require sensors and components able to measure the primary interaction vertex and secondary vertices from decay particles coming from the collisions, within a high track density environment, and with demanding radiation conditions, constraining material and economic budget, and yield limitations, among others.

After describing the CMS detector, this thesis has focused on the Inner Tracker, where the highest levels of radiation will take place:  $3.5 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ , with a total ionizing dose of 1.91 Grad. Consequently, the detection technology there must be highly radiation tolerant. The high luminosity leads to the necessity of sensors with good spatial resolution and fast detection. Different pixel geometries are under consideration, reducing the pixel size by a factor of 6 with respect to the technologies prior to the upgrade. Electronic and durability constraints complete the variety of requirements.

The Physics behind the detecting technology suitable for this environment is explained, introducing silicon sensors as the best option. The state of the art leads to assert the 3D technology as an appropriate candidate for the CMS IT upgrade, as this thesis demonstrates.

In order to check the 3D technology suitability, both FBK and CNM samples have been tested with the ROC4SENS and RD53A readout chips. With both pixel geometries  $25 \times 100 \mu\text{m}^2$  and  $50 \times 50 \mu\text{m}^2$ , several test beams at the CERN SPS and DESY took place in the last years. There, the samples were characterised in the most alike environment to the one inside CMS. Many studies have been performed in terms of fluence, temperature, particle beam angle incidence, bias voltage, geometry or humidity.

The results prove that 3D sensors truly constitute an appropriate solution for the CMS Inner Tracker. As presented, radiation damage up to  $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$  does not significantly

affect sensor performance. Before and after irradiation, the sensors are highly efficient, exceeding the 96% in operating conditions even at normal incidence. Good charge collection is maintained at large fluences. At normal incidence, high charge collection is achieved and efficiency reaches 100% in the inter-columnar regions. When particles reach the sensor with an angle—as happens inside the CMS IT—the sensor response becomes homogeneous, losses in charge and efficiency are recovered and the column structure completely disappears from the pixel cell maps. Efficiency is maintained after different irradiations, establishing that 3D sensor response is not degraded with fluences at least up to  $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ .

The operating conditions are barely demanding. With a depletion voltage in the order of 10-20 V, before irradiation, and around 100-200 V at high fluence, the operation voltage remains low even in the worst case scenarios and it is highly competitive with respect to other technologies. The power consumption in 3D sensors is always below  $10 \text{ mW}/\text{cm}^2$  at operating conditions, even after irradiation.

The non-homogeneous irradiation of the sensor provided with the opportunity of studying the same sensor under identical conditions as a function of fluence only: same bias voltage, temperature, humidity, readout chip settings, etc. This fluence-only study compared three values of fluence on the same sensor:  $4 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ ,  $8.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$  and  $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ . Differences in charge collection at the PN junctions and ohmic contacts, effects due to depletion changes when increasing the fluence, and the slight reductions in charge collection and efficiency with sensor damage were all observed. Since fluence do not significantly affect sensor performance, with bias voltages over the depletion voltage, only with extremely and atypical low bias voltages the response degradation with the fluence can be checked.

Regarding the inside pixel studies, through quarter pixel cell maps of charge collection and efficiency distributions, the detailed response has been stated as a fluence function. High charge collection and high efficiency have been obtained. In the case of the  $50 \times 50 \mu\text{m}^2$  geometry, there is a homogeneous behaviour along the sensor, even when irradiated. On the other hand, the  $25 \times 100 \mu\text{m}^2$  sensor showed a less homogeneous response along the quarter of pixel and a less clear tendency with fluence.

In addition, for the rectangular geometry the effects of metallizations and connections with the readout chip through the bump-bounds—crosstalk effects— have been pointed out with residual maps. While the residuals along the pitch column direction show no crosstalk effects due to the absence of metallizations along this direction, along the pitch row direction it has been measured an L-shape patron. This crosstalk effect, although existent in some designs (and consequence only of the bonding matrix to the ROC), leads to a negligible effect on the detector resolution of just 2-3  $\mu\text{m}$  in small, localized areas of the sensor.

All these results have proven that the 3D pixel sensor technology is a good choice for the CMS IT upgrade, with outstanding results obtained from their full characterisation. Future activities take into account irradiations to  $2 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$  to further extend this characterisation.



# References

- [1] A.B. Arbuzov. Quantum Field Theory and the Electroweak Standard Model. (arXiv:1801.05670):1–34. 35 p, Jan 2018. 35 pages.
- [2] P. B. L. Evans. Lhc machine. *J. Instrum.*, 3 (S08001), 2008. <http://dx.doi.org/10.1088/1748-0221/3/08/S08001>.
- [3] 11 curiosidades sobre el Gran Colisionador de Hadrones del CERN. [https://www.nationalgeographic.com.es/ciencia/grandes-reportajes/11-cosas-que-no-sabias-sobre-lhc-ern\\_13139/2](https://www.nationalgeographic.com.es/ciencia/grandes-reportajes/11-cosas-que-no-sabias-sobre-lhc-ern_13139/2), [Accessed: 2019.10.01].
- [4] <https://cds.cern.ch/record/1621583>, [Accessed: 2019.10.01].
- [5] <https://supercoolpics.com/vnutri-bolshogo-adronnogo-kollajder/>, [Accessed: 2019.11.01].
- [6] <https://home.cern/science/engineering/accelerating-radiofrequency-cavities>, [Accessed: 2020.02.26].
- [7] <https://cds.cern.ch/record/1997424?ln=es>, [Accessed: 2020.02.26].
- [8] [https://www.lhc-closer.es/taking\\_a\\_closer\\_look\\_at\\_lhc/0.lorentz\\_force](https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.lorentz_force), [Accessed: 2020.02.26].
- [9] [https://www.lhc-closer.es/taking\\_a\\_closer\\_look\\_at\\_lhc/0.magnetic\\_multipoles](https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.magnetic_multipoles), [Accessed: 2020.02.26].
- [10] S Boreham, M Brice, P Ginter, C Marcelloni, and M Hoch. Photos from the CMS Photo Book, Aug 2008. <http://cds.cern.ch/record/1344500>, [Accessed: 2020.09.09].
- [11] Maximilien Brice (CERN). Amanecer del large hadron collider. <https://observatorio.info/2008/02/amanecer-del-large-hadron-collider/>, [Accessed: 2019.12.01].
- [12] The Daily Galaxy via University of Copenhagen Niels Bohr Institute. Cern lhc reveals: “the universe a billionth of a second after the big bang”. <https://dailygalaxy.com/2016/04/cern-lhc-reveals-the-universe-a-billionth-of-a-second-after-the-big-bang-weekend-feature/>, [Accessed: 2020.01.24].
- [13] CERN. Otro ángulo del electroimán del lhcb. <https://www.agenciasinc.es/Multimedia/Fotografias/Otro-angulo-del-electroiman-del-LHCb>, [Accessed: 2020.01.24].

- [14] CERN Collaboration. Compact muon solenoid experiment. <https://home.cern/science/experiments/cms>, [Accessed: 2019.12.01].
- [15] CMS Collaboration. Schema of a section cut of cms. <https://cms.cern/>, [Accessed: 2019.12.01].
- [16] Schema of a section cut of cms. <https://slideplayer.com/slide/11189499/>, [Accessed: 2019.12.01].
- [17] Michael Hoch. Installation of the world's largest silicon tracking detector in the CMS experiment. Installation du plus grand détecteur de trace au silicium au sein de l'expérience CMS, Dec 2007. <http://cds.cern.ch/record/1075944>, [Accessed: 2020.09.09].
- [18] Márton Bartók. Simulation of the Dynamic Inefficiency of the CMS Pixel Detector. *JINST*, 10(arXiv:1411.6770. 05):C05006. 6 p, Nov 2014.
- [19] CMS Collaboration. The Phase-2 Upgrade of the CMS Tracker. Technical Report CERN-LHCC-2017-009. CMS-TDR-014, CERN, Geneva, Jun 2017.
- [20] CMS Collaboration. Cms tracker information. <http://cms.cern/detector/identifying-tracks>, [Accessed: 2020.02.27].
- [21] I Béjar Alonso, O Brüning, P Fessia, L Rossi, L Tavian, and M Zerlauth. *High-Luminosity Large Hadron Collider (HL-LHC): Technical design report*. CERN Yellow Reports: Monographs. CERN, Geneva, 2020.
- [22] CERN Collaboration. Lh-lhc project schedule (january 2020). <https://project-hl-lhc-industry.web.cern.ch/content/project-schedule>, [Accessed: 2020.01.24].
- [23] CERN. What is hilumi? <http://hilumilhc.web.cern.ch/>, [Accessed: 2020.02.20], Information about the High Luminosity Upgrade of the LHC.
- [24] L. Bejar Alonso, I.; Rossi. Hilumi lhc technical design report: Deliverable: D1.10. Technical report, CERN, 2015.
- [25] Apollinari G., Béjar Alonso I., Brüning O., Fessia P., Lamont M., Rossi L., and Tavian L. *High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V. 0.1*. CERN Yellow Reports: Monographs. CERN, Geneva, 2017.
- [26] Zhengcheng Tao. Level-1 Track Finding with an all-FPGA system at CMS for the HL-LHC. Technical Report arXiv:1901.03745, Jan 2019. \* Temporary entry \*.
- [27] E. Currás, J. Duarte-Campderrós, M. Fernández, A. García, G. Gómez, J. González, R. Jaramillo, D. Moya, I. Vila, S. Hidalgo, M. Manna, G. Pellegrini, D. Quirion, D. Pitzl, A. Ebrahimi, T. Rohe, and S. Wiederkehr. Study of small-cell 3d silicon pixel detectors for the high luminosity lhc. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 931:127 – 134, 2019.

- [28] Karl Aaron Gill. Hgcal project overview. <https://indico.cern.ch/event/909689/>, [Accessed: 2020.04.22].
- [29] Arabella Martelli. The cms hgcal detector for hl-lhc upgrade, 2017.
- [30] CMS Collaboration. TECHNICAL PROPOSAL FOR A MIP TIMING DETECTOR IN THE CMS EXPERIMENT PHASE 2 UPGRADE. Technical Report CERN-LHCC-2017-027. LHCC-P-009, CERN, Geneva, Dec 2017. This document describes a MIP timing detector for the Phase-2 upgrade of the CMS experiment, in view of HL-LHC running.
- [31] R Brun, R Hagelberg, M Hansroul, and J C Lassalle. *Simulation program for particle physics experiments, GEANT: user guide and reference manual*. CERN, Geneva, 1978.
- [32] Collaboration CMS. A MIP Timing Detector for the CMS Phase-2 Upgrade. Technical Report CERN-LHCC-2019-003. CMS-TDR-020, CERN, Geneva, Mar 2019.
- [33] DONALD E. GROOM, NIKOLAI V. MOKHOV, and SERGEI I. STRIGANOV. Muon stopping power and range tables 10 mev–100 tev. *Atomic Data and Nuclear Data Tables*, 78(2):183 – 356, 2001.
- [34] Lev Davidovich Landau. On the energy loss of fast particles by ionization. *J. Phys.*, 8(4):201–205, 1944.
- [35] Robert F. Pierret. *Advanced Semiconductor Fundamentals*, volume VI. Addison-Wesley Longman Publishing Co., Inc., USA, second edition, 1987.
- [36] J.P. Colinge and C.A. Colinge. *Physics of Semiconductor Devices*. Physics of semiconductor devices. Springer US, 2007.
- [37] S. M. Sze and Kwok K. Ng. *Physics of Semiconductor Devices*. J. Wiley Sons, third edition, 1985.
- [38] Frank Hartmann. *Evolution of Silicon Sensor Technology in Particle Physics*, volume 275 of *Springer Tracts in Modern Physics*. Springer, 2017.
- [39] Charles Kittel. *Introduction to Solid State Physics*. Wiley, 8 edition, 2004.
- [40] Y. Yoshida and G. Langouche. *Defects and Impurities in Silicon Materials: An Introduction to Atomic-Level Silicon Engineering*. Lecture Notes in Physics. Springer Japan, 2016.
- [41] Hans-Günther Moser. Silicon detector systems in high energy physics. *Progress in Particle and Nuclear Physics*, 186-237 (2009), 63, 07 2009.
- [42] E. Fretwurst, G. Lindstrom, J. Stahl, and I. Pintilie. Radiation damage in silicon detectors caused by hadronic and electromagnetic irradiation. In *9th European Symposium on Semiconductor Detectors: New Developments in Radiation Detectors*, 11 2002.
- [43] Michael Moll. Displacement damage in silicon detectors for high energy physics. Displacement Damage in Silicon Detectors for High Energy Physics. *IEEE Trans. Nucl. Sci.*, 65:1561–1582. 22 p, 2018.

- [44] Ian (ed.) Dawson. Radiation effects in the LHC experiments: Impact on detector performance and operation, March 2021.
- [45] A. Vasilescu and G Lindstroem. Displacement damage in silicon, on-line compilation. <https://rd50.web.cern.ch/niel/>, [Accessed: 2021.06.09].
- [46] J. Van Zeghbroeck. *Principles of Semiconductor Devices*. Bart Van Zeghbroeck, 2011.
- [47] R. Wunstorf, H. Feick, E. Fretwurst, G. Lindström, G. Lutz, C. Osius, R.H. Richter, T. Rohe, A. Rolf, and P. Schlichthärle. Damage-induced surface effects in silicon detectors. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 377(2):290 – 297, 1996. Proceedings of the Seventh European Symposium on Semiconductor.
- [48] Maurice Garcia-Sciveres and Norbert Wermes. A review of advances in pixel detectors for experiments with high rate and radiation. *Reports on Progress in Physics*, 81(6):066101, May 2018.
- [49] S.I. Parker, C.J. Kenney, and J. Segal. 3d — a proposed new architecture for solid-state radiation detectors. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 395(3):328–343, 1997. Proceedings of the Third International Workshop on Semiconductor Pixel Detectors for Particles and X-rays.
- [50] A. García Alonso, E. Currás, J. Duarte-Campderrós, M. Fernandez, G. Gomez, J. Gonzalez, E. Silva, I. Vila, R. Jaramillo, M. Meschini, R. Ceccarelli, M. Dinardo, S. Gennai, L. Moroni, D. Zuolo, N. Demaria, E. Monteil, L. Gaioni, A. Messineo, G.-F. Dalla Beta, R. Menicino, M. Boscardin, S. Hidalgo, Á. Merlos, G. Pellegrini, D. Quirion, and M. Manna. Test beam characterization of irradiated 3d pixel sensors. *Journal of Instrumentation*, 15(03):C03017–C03017, mar 2020.
- [51] L. Rossi. Pixel detectors hybridisation. *Nucl. Instrum. Meth. A*, 501:239–244, 2003.
- [52] D.M.S. Sultan, G.-F. Dalla Betta, R. Mendicino, M. Boscardin, S. Ronchin, and N. Zorzi. First production of new thin 3d sensors for HL-LHC at FBK. *Journal of Instrumentation*, 12(01):C01022–C01022, jan 2017.
- [53] B. et al. Abbott. Production and Integration of the ATLAS Insertable B-Layer. *JINST*, 13:T05008. 90 p, Mar 2018. 90 pages in total. Author list: ATLAS IBL Collaboration, starting page 2. 69 figures, 20 tables. Published in Journal of Instrumentation. All figures available at: <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/PIX-2018-001>.
- [54] B. Abbott et al. Production and integration of the ATLAS insertable b-layer. *Journal of Instrumentation*, 13(05):T05008–T05008, may 2018.
- [55] M Capeans, G Darbo, K Einsweiler, M Elsing, T Flick, M Garcia-Sciveres, C Gemme, H Pernegger, O Rohne, and R Vuillermet. ATLAS Insertable B-Layer Technical Design Report. Technical report, Sep 2010.



- [56] Yosuke Takubo. Operational Experience and Performance with the ATLAS Inner Detector at the Large Hadron Collider at CERN. Technical report, CERN, Geneva, Nov 2020.
- [57] G. Balbi, M. Barbero, R. Beccherle, M. Bindi, P. Breugnon, P. Butti, D. Cinca, J. Dickinson, D. Ferrere, D. Fougeron, M. Garcia-Sciveres, J. Garcia Pascual, A. Gaudiello, C. Gemme, N. Giangiacomi, T. Hemperek, L. Jeanty, O. Kepka, M. Kocian, K. Lantzs, P. Liu, C. Martin, A. Mekkaoui, M. Menouni, K. Potamianos, A. Rozanov, Y. Takubo, and M. Wensing. Measurements of Single Event Upset in ATLAS IBL. *JINST*, 15:P06023. 30 p, Apr 2020. 30 pages with 32 figures.
- [58] The ATLAS IBL collaboration. Prototype ATLAS IBL modules using the FE-i4a front-end readout chip. *Journal of Instrumentation*, 7(11):P11010–P11010, nov 2012.
- [59] M. Obertino, A. Solano, E. Alagoz, J. Andresen, K. Arndt, G. Bolla, D. Bortoletto, M. Boscardin, R. Brosius, M. Bubna, G.-F. Dalla Betta, F. Jensen, A. Krzywda, A. Kumar, S. Kwan, C.M. Lei, D. Menasce, L. Moroni, J. Ngadiuba, I. Osipenko, L. Perera, M. Povoli, A. Prosser, R. Rivera, I. Shipsey, P. Tan, S. Terzo, L. Uplegger, S. Wagner, A. Vilela Pereira, and M. Dinardo. Performance of cms 3d silicon pixel detectors before and after irradiation. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 730:33–37, 2013. Proceedings of the 9th International Conference on Radiation Effects on Semiconductor Materials Detectors and Devices.
- [60] Fabio Ravera. 3D silicon pixel detectors for the CT-PPS tracking system, 2017. Presented 16 Jun 2017.
- [61] Fabio Ravera. The CT-PPS tracking system with 3D pixel detectors. *JINST*, 11(11):C11027, 2016.
- [62] Fabio Ravera. The CT-PPS project: detector hardware and operational experience. *PoS, Vertex* 2017:015, 2018.
- [63] M G Albrow, R B Appleby, M Arneodo, G Atoian, I L Azhgirey, R Barlow, I S Bayshev, W Beaumont, L Bonnet, A Brandt, P Bussey, C Buttar, J M Butterworth, M Carter, B E Cox, D Dattola, C Da Via, J de Favereau, D d'Enterria, P De Remigis, A De Roeck, E A De Wolf, P Duarte, J R Ellis, B Florins, J R Forshaw, J Freestone, K Goulianos, J Gronberg, M Grothe, J F Guion, J Hasi, S Heinemeyer, J J Hollar, S Houston, V Issakov, R M Jones, M Kelly, C Kenney, V A Khoze, S Kolya, N Konstantinidis, H Kowalski, H E Larsen, V Lemaitre, S L Liu, A Lyapine, F K Loebinger, R Marshall, A D Martin, J Monk, I Nasteva, P Nemegeer, M M Obertino, R Orava, V O'Shea, S Oryn, A Pal, S Parker, J Pater, A L Perrot, T Pierzchala, A D Pilkington, J Pinfold, K Piotrkowski, W Plano, A Poblaguev, V Popov, K M Potter, F Roncarolo, A Rostovtsev, X Roubly, M Ruspa, M G Ryskin, A Santoro, N Schul, G Sellers, A Solano, S Spivey, W J Stirling, D Swoboda, M Tasevsky, R Thompson, T Tsang, P Van Mechelen, A Vilela Pereira, S J Watts, M R M Warren, G Weiglein, T Wengler, S N White, B Winter, Y Yao, D Zaborov, A Zampieri, M Zeller, and A Zhokin. The FP420 r&d project: Higgs and new physics with forward protons at the LHC. *Journal of Instrumentation*, 4(10):T10001–T10001, oct 2009.

- [64] G.-F. Dalla Betta, M. Boscardin, G. Darbo, R. Mendicino, M. Meschini, A. Messineo, S. Ronchin, D.M.S. Sultan, and N. Zorzi. Development of a new generation of 3d pixel sensors for hl-lhc. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 824:386–387, 2016. Frontier Detectors for Frontier Physics: Proceedings of the 13th Pisa Meeting on Advanced Detectors.
- [65] J. Duarte-Campderros, E. Currás, M. Fernández, G. Gómez, A. García, J. González, E. Silva, I. Vila, R. Jaramillo, M. Meschini, R. Ceccarelli, M. Dinardo, S. Gennai, L. Moroni, D. Zuolo, L. Demaria, E. Monteil, L. Gaioni, A. Messineo, G.F. Dalla Betta, R. Mendicino, M. Boscardin, S. Hidalgo, A. Merlos, G. Pellegrini, D. Quirion, and M. Manna. Results on proton-irradiated 3d pixel sensors interconnected to rd53a readout asic. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 944:162625, 2019.
- [66] A. Lai. Timing characterisation of 3D-trench silicon sensors. *JINST*, 15(09):C09054, 2020.
- [67] Maria Manna, Chiara Grieco, Sebastian Grinstein, Salvador Hidalgo, Giulio Pellegrini, David Quirion, and Stefano Terzo. First characterisation of 3d pixel detectors irradiated at extreme fluences. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 979:164458, 2020.
- [68] Marta Baselga Bacardit. *Development of pixel detectors for the IBL and HL-LHC ATLAS experiment upgrade*. PhD thesis, Barcelona, Autonomia U., 1 2016.
- [69] G. Pellegrini, J.P. Balbuena, D. Bassignana, E. Cabruja, C. Fleta, C. Guardiola, M. Lozano, D. Quirion, and M. Ullan. 3D double sided detector fabrication at IMB-CNM. *Nucl. Instrum. Meth. A*, 699:27–30, 2013.
- [70] Leonardo Rossi, Peter Fischer, Tilman Rohe, and Norbert Wermes. *Pixel detectors: from fundamentals to applications*. Particle acceleration and detection. Springer, Berlin, 2006.
- [71] S Terzo, L Andricek, A Macchiolo, H G Moser, R Nisius, R H Richter, and P Weigell. Heavily irradiated n-in-p thin planar pixel sensors with and without active edges. *Journal of Instrumentation*, 9(05):C05023–C05023, May 2014.
- [72] Georg Steinbrueck. Development of planar pixel sensors for the CMS Inner Tracker at the High-Luminosity LHC. Technical report, CERN, Geneva, Feb 2020.
- [73] J. Weingarten, S. Altenheiner, M. Beimforde, Mathieu Benoit, M. Bomben, G. Calderini, C. Gallrapp, Minnu George, S. Gibson, Sebastian Grinstein, Z. Janoska, J. Jentsch, Osamu Jinnouchi, T. Kishida, Alessandro La Rosa, Vladyslav Libov, A. Macchiolo, G. Marchiori, Daniel Muenstermann, and T. Wittig. Planar pixel sensors for the atlas upgrade: Beam tests results. *Journal of Instrumentation*, 7, 04 2012.
- [74] Georg Steinbrueck. Development of planar pixel sensors for the CMS Inner Tracker at the High-Luminosity LHC. Technical report, CERN, Geneva, Feb 2020.

- [75] B. Pain, S. Mendis, R. Schober, R. Nixon, and E. Fossum. Low-power low-noise analog circuits for on-focal-plane signal processing of infrared sensors. In *Defense, Security, and Sensing*, 1993.
- [76] Christopher J. Kenney, Sherwood I. Parker, Vincent Z. Peterson, Walter J. Snoeys, James D. Plummer, and Chye Huat Aw. A Prototype monolithic pixel detector. *Nucl. Instrum. Meth. A*, 342:59–77, 1994.
- [77] R. Turchetta et al. A monolithic active pixel sensor for charged particle tracking and imaging using standard VLSI CMOS technology. *Nucl. Instrum. Meth. A*, 458:677–689, 2001.
- [78] B. Dierickx, G. Meynants, and D. Scheffer. Near-100% fill factor standard cmos active pixel. 1997.
- [79] Giacomo Contin, Leo Greiner, Joachim Schambach, Michal Szelezniak, Eric Anderssen, Jacque Bell, Mario Cepeda, Thomas Johnson, Hao Qiu, Hans-Georg Ritter, and et al. The star maps-based pixel detector. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 907:60–80, Nov 2018.
- [80] A. Dorokhov, G. Bertolone, J. Baudot, C. Colledani, G. Claus, Y. Degerli, R. De Masi, M. Deveau, G. Dozière, W. Dulinski, M. Gélin, M. Goffe, A. Himmi, Ch. Hu-Guo, K. Jaaskelainen, M. Koziel, F. Morel, C. Santos, M. Specht, I. Valin, G. Voutsinas, and M. Winter. High resistivity cmos pixel sensors and their application to the star pxl detector. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 650(1):174–177, 2011. International Workshop on Semiconductor Pixel Detectors for Particles and Imaging 2010.
- [81] I. Dario Caicedo Sierra. Radiation hardness and development of a large electrode dmaps design in a 150 nm cmos process. <https://indico.cern.ch/event/1029124/contributions/4411267/>, [Accessed: 2021.06.25].
- [82] P. Fernández Martínez. *Diseño, fabricación y optimización de detectores con multiplicación (LGAD) para experimentos de física de altas energías*. PhD thesis, Universitat Autònoma de Barcelona, 2014.
- [83] Imb-cnm. grupo de detectores de radiación.
- [84] E. Currás, Mar Carulla, M. Vignali, J. Duarte-Campderros, M. Fernández, D. Flores, A. García, G. Gómez, J. González, S. Hidalgo, R. Jaramillo, A. Merlos, M. Moll, G. Pellegrini, D. Quirion, and I. Vila. Inverse low gain avalanche detectors (ilgads) for precise tracking and timing applications. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, page 162545, 08 2019.
- [85] Andrea García Alonso. Study of silicon radiation sensors with integrated gain, 2017.
- [86] S. Ayyoub, C. Gee, R. Islam, S. M. Mazza, B. Schumm, A. Seiden, and Y. Zhao. A new approach to achieving high granularity for silicon diode detectors with impact ionization gain. 1 2021.

- [87] G. Paternoster, G. Borghi, Maurizio Boscardin, Nicolo Cartiglia, Maricel Ferrero, F. Ficorella, Federico Siviero, Alberto Gola, and Pierluigi Bellutti. Trench-isolated low gain avalanche diodes (ti-lgads). *IEEE Electron Device Letters*, PP:1–1, 04 2020.
- [88] G. Giacomini, W. Chen, G. D’Amen, and A. Tricoli. Fabrication and performance of ac-coupled lgads. *Journal of Instrumentation*, 14(09):P09004–P09004, Sep 2019.
- [89] V. Mikhaylov, F. Guber, A. Ivashkin, A. Kugler, V. Kushpil, S. Morozov, O. Svoboda, and P. Tlustý. Characterisation of sipm radiation hardness for application in hadron calorimeters at fair, cern and nica, 2020.
- [90] Maurice Garcia-Sciveres. The RD53A Integrated Circuit. Technical Report CERN-RD53-PUB-17-001, CERN, Geneva, Oct 2017.
- [91] Tilman Rohe. Roc4sens – a generic readout chip for sensor studies. <https://indico.cern.ch/event/663851/contributions/2788211>, [Accessed: 2020.06.29].
- [92] Paul sherrer institut. <https://www.psi.ch>, [Accessed: 2020.06.29].
- [93] Rd53a chip testing results – biases, dacs, adcs, sensors. <https://twiki.cern.ch/twiki/bin/viewauth/RD53/BiasesNDacs53A>, [Accessed: 2021.04.06].
- [94] Florian Michael Pitters, Niloufar Alipour Tehrani, Dominik Dannheim, Adrian Fiergolski, Daniel Hynds, Wolfgang Klempt, Xavi Llopert Cudie, Magdalena Munker, Andreas Matthias Nurnberg, Simon Spannagel, and Morag Jean Williams. Time and Energy Calibration of Timepix3 Assemblies with Thin Silicon Sensors. Nov 2018.
- [95] Blerina Gkotse, Maurice Glaser, Michael Moll, and Federico Ravotti. IRRAD: The New 24GeV/c Proton Irradiation Facility at CERN. (AIDA-2020-CONF-2016-006), Nov 2015.
- [96] Federico Ravotti, Blerina Gkotse, Maurice Glaser, Pedro Lima, Emanuele Matli, and Michael Moll. A New High-Intensity Proton Irradiation Facility at the CERN PS East Area. *PoS, TIPP2014:354*, 2014.
- [97] CERN Collaboration. Cern irradi proton facility. <https://ps-irrad.web.cern.ch/index.php>, [Accessed: 2020.04.15].
- [98] Jordi Duarte-Campderros. Study of 3d pixel sensors after non-uniform proton irradiation. [https://indico.cern.ch/event/813597/contributions/3727824/attachments/1989964/3317259/fluence\\_estimation\\_tredi2020\\_jdc.pdf](https://indico.cern.ch/event/813597/contributions/3727824/attachments/1989964/3317259/fluence_estimation_tredi2020_jdc.pdf), [Accessed: 2020.11.13].
- [99] Deutsches Elektronen-Synchrotron DESY. Eudet: Detector r&d towards the international linear collider. <https://www.eudet.org/>, [Accessed: 2020.07.08].
- [100] P. Ahlburg, S. Arfaoui, J.-H Arling, H. Augustin, D. Barney, M. Benoit, T. Bisanz, E. Corrin, D. Cussans, D. Dannheim, J. Dreyling-Eschweiler, T. Eichhorn, A. Fiergolski, I.-M Gregor, J. Grosse-Knetter, D. Haas, L. Huth, A. Irles, H. Jansen, J. Janssen, M. Keil, J.S. Keller, M. Kiehn, H.J. Kim, J. Kroll, K. Krüger, S. Kulis, J. Kvasnicka, J. Lange, Y. Liu, F. Lüticke, C. Marinas, P. Martinengo, A. Nurnberg, B. Paschen, H. Perrey, R. Peschke, D. Pitzl, D.-L Pohl, A. Quadt, T. Quast, F. Reidt, E. Rossi, I. Rubinsky, A. Rummler, H. Schreeck, P. Schütze, B. Schwenker, S. Spannagel,

- M. Stanitzki, U. Stolzenberg, T. Suehara, M. Suljic, G. Troska, M. Varga-Kofarago, J. Weingarten, and P. Wieduwilt. EUDAQ – A Data Acquisition Software Framework for Common Beam Telescopes. EUDAQ—a data acquisition software framework for common beam telescopes. *JINST*, 15:P01038. 30 p, Sep 2019. 11 figures.
- [101] I. Rubinskiy. Eutelescope. offline track reconstruction and dut analysis software. <https://pdfs.semanticscholar.org/5072/53550adab223998fc328659fdf054378e60a.pdf>, [Accessed: 2020.07.06].
- [102] CERN Collaboration. Mimosa telescope. <https://twiki.cern.ch/twiki/bin/view/MimosaTelescope/>, [Accessed: 2019.10.15].
- [103] M. Daas and M. Vogt. Bdaq53 readout hardware. <https://gitlab.cern.ch/silab/bdaq53/wikis/Hardware/Readout-Hardware>, [Accessed: 2019.11.20].
- [104] Michaela Queitsch-Maitland Edoardo Rossi Jan-Hendrik ArlingCyril Becot, Jan Dreyling-Eschweiler. Hands-on: Starting with eutelescope - no or passive dut. [https://indico.cern.ch/event/731649/contributions/3237171/attachments/1779014/2893880/BTTB7\\_EUTelescopeTutorial\\_Arling.pdf](https://indico.cern.ch/event/731649/contributions/3237171/attachments/1779014/2893880/BTTB7_EUTelescopeTutorial_Arling.pdf), [Accessed: 2020.07.06].
- [105] Marlin homepage. <http://ilcsoft.desy.de/marlin>, [Accessed: 2021.06.10].
- [106] CERN. Root data analysis framework. <https://ph-root-2.cern.ch/>, [Accessed: 2020.07.06].
- [107] Youngjoo Kim and Hyochong Bang. *Introduction to Kalman Filter and Its Applications*. 11 2018.
- [108] Hamburg University Volker Blobel. Millepede ii - draft manual, 2007. [https://www.desy.de/~kleinwrt/MP2/doc/html/draftman\\_page.html](https://www.desy.de/~kleinwrt/MP2/doc/html/draftman_page.html), [Accessed: 2020.09.23].
- [109] Jordi Duarte-Campderros. sps\_tb\_eutelizer: Test beam analysis and eutelescope configuration, April 2020.
- [110] DESY Daniel Piztl. tele-scope. <https://github.com/piztl/tele-scope/>, [Accessed: 2020.10.27], 2015.
- [111] ROOT Reference Guide. Tgeomanager class reference. <https://root.cern.ch/doc/master/classTGeoManager.html>, [Accessed: 2020.11.12].
- [112] Gauss Cordeiro, Juvêncio Nobre, Rodrigo Pescim, and Edwin Ortega. The beta moyal: a useful skew distribution. *International Journal of Research and Reviews in Applied Sciences*, 10:171–192, 02 2012.
- [113] Christian Walck. *Hand-book on statistical distributions for experimentalists*. 12 1996.
- [114] Talha Arslan, Sukru Acitas, and Birdal Senoglu. Estimation of the location and scale parameters of moyal distribution. *TWMS Journal of Applied and Engineering Mathematics*, pages 1–10, 07 2019.

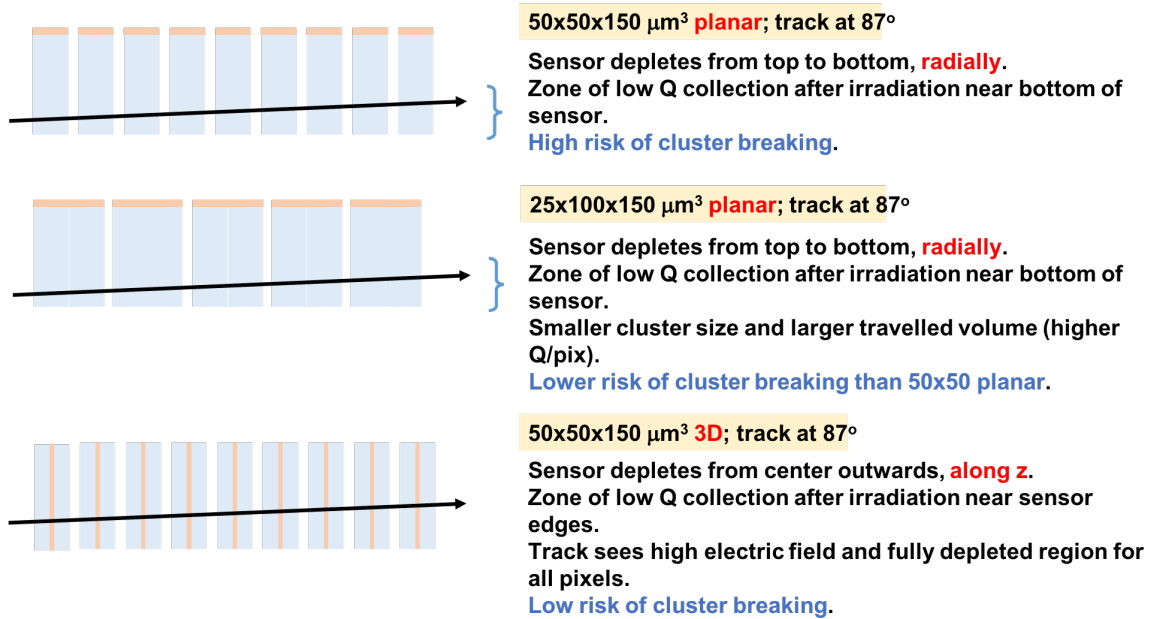
- [115] Hendrik Jansen, Simon Spannagel, Antonio Bulgheroni, Gilles Claus, Emlyn Corrin, David Cussans, Jan Dreyling-Eschweiler, Doris Eckstein, Thomas Eichhorn, Mathieu Goffe, Ingrid Gregor, Daniel Haas, C. Muhl, Hanno Perrey, Richard Peschke, Philipp Roloff, Igor Rubinskiy, and Marc Winter. Performance of the eudet-type beam telescopes. *EPJ Techniques and Instrumentation*, 3, 03 2016.
- [116] Claus Kleinwort. General broken lines as advanced track fitting method. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 673, 01 2012.
- [117] Stefano Terzo, Maurizio Boscardin, Juan Carlotto, Gian-Franco Dalla Betta, Giovanni Darbo, Ole Dorholt, Francesco Ficorella, Giuseppe Gariano, Claudia Gemme, Giulia Giannini, Sebastian Grinstein, Andreas Heggelund, Simon Huiberts, Angela Kok, Ozhan Koybasi, Alessandro Lapertosa, Magne Elk Lauritzen, Maria Manna, Roberto Mendicino, Hideyuki Oide, Giulio Pellegrini, Marco Povoli, David Quirion, Ole Myren Rohne, Sabina Ronchin, Heidi Sandaker, Md. Arif Abdulla Samy, Bjarne Stugu, and Leonardo Vannoli. Novel 3d pixel sensors for the upgrade of the atlas inner tracker. *Frontiers in Physics*, 9:2, 2021.
- [118] Georg Steinbrueck. Development of Novel Pixel Sensors for the CMS Upgrade for HL-LHC. Technical report, CERN, Geneva, Dec 2018.

# Appendix

This appendix presents further information regarding some other studies and topics of interest: cluster breaking and the bias dot structure.

## .0.1 Response at shallow angle: Cluster breaking

On account of the geometry of CMS, at its Barrel, particles approach the detector with grazing angles, which could be related with problems of cluster breaking.



**Fig. 36** Schema about risk of cluster breaking in planar sensors of  $50 \times 50$  and  $25 \times 100 \mu\text{m}^2$  geometries (top and centre pictures) and 3D sensors of  $50 \times 50 \mu\text{m}^2$  (bottom picture).

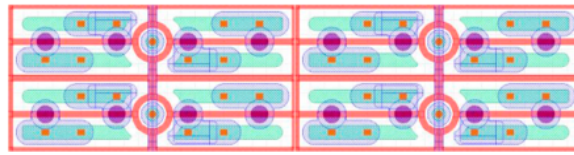
Cluster breaking is the separation of pixels in different clusters when all of them should belong to the same one. This happens when a particle goes through a set of pixels with a grazing angle, but for instance one of them does not get enough charge and therefore

constituting the separation between two clusters, which should have been only one. This happens when there are not depleted regions along its path.

Fig. 36 shows a representation of cluster breaking in planar and 3D sensors. In this technology, the direction in which the depletion happens is parallel to the sensor surface, instead of perpendicular as in the case of planar sensors. This effect is particularly positive in order to deal with problems like the cluster breaking.

## .0.2 Presence of a bias dot structure

The bias dot mechanism is used by some manufacturers for doing the quality control of sensors before releasing them. The biasing scheme potentially permits to test a pixel sensor fully depleted before bump-bonding to the readout chip. A bias dot is implanted common to four pixels [118]. However, the presence of this structure produces important effects in the charge collection.



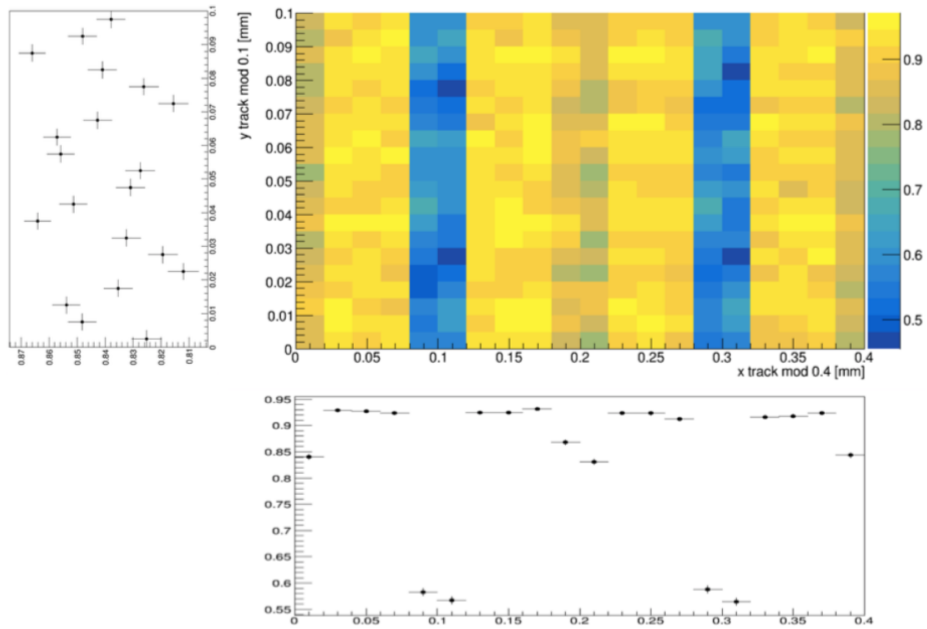
**Fig. 37** Pixel layout of a  $25 \times 100$  planar sensor with biasing structure. Representing 4x4 pixels are displayed, as in Fig. 38.

In order to study this structure, planar sensors with bias dot were characterized. Their pixel layout is the one shown in Fig. 37.

After checking the efficiency plots of irradiated planar sensors with bias dot, we discovered the distribution of the efficiency values along the surface of the sensor is not homogeneous. Instead, there is a special drop at the zones corresponding with the position of the biasing structure.

The summary of the efficiency over the whole sensor is given by Fig. 38, which shows a noticeable decrease of the efficiency, periodically every two pixels. Comparing this plot with the pixel layout of this kind of sensors (Fig. 37), it can quickly be deduced that the drop is exactly in the same position as the bias dot structure.





**Fig. 38** 4x4 pixel cell efficiency distribution of a  $25 \times 100$  planar sensor with bias dot and the projection over the two spacial directions.

