

Characterisation of silicon detectors for the LHCb Vertex Locator Upgrade

by

Sophie Elizabeth Richards

A dissertation submitted to the University of Bristol in accordance
with the requirements for award of the
degree of Doctor of Philosophy

in the
Faculty of Science
School of Physics

December 2017

Word count: 28,160



Abstract

The LHCb Vertex Locator must be upgraded in the next long shutdown of the LHC, starting at the end of 2018. This is due to the increased occupancy. The current silicon strip detector is being upgraded to a silicon pixel detector. The prototype sensors for this detector were tested thoroughly before a final design will be chosen. The testing was done with the Timepix3 Telescope, which was commissioned in the summer of 2014. The charge collected by the sensors and efficiency of the sensors were investigated. After maximum irradiation, of $8 \times 10^{15} \text{ 1 MeV } n_{eq}/\text{cm}^2$, the sensors must have a most probable value of collected charge of 6000 electrons before 1000 V or breakdown, whichever comes first. The sensors must also have a high efficiency at maximum irradiation of $8 \times 10^{15} \text{ 1 MeV } n_{eq}/\text{cm}^2$. All tested sensors reach these criteria. All sensors reach 6000 electrons between 600 V and 800 V and have a cluster finding efficiency of over 95% at the respective voltages. Overall, a 150 μm thick n -on- n silicon sensor with an implant width of 39 μm would be the best option for the LHCb Vertex Locator upgrade.

Declaration of authorship

I, Sophie Richards, declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

Signed:

Date:

Acknowledgements

I am very thankful for the support that I have received over the past four years.

First, I would like to thank Jaap. It was a pleasure to work with you. Thank you for all of your advice and guidance over the past years.

Secondly, all the support that I have had from my tea buddies Gen and Nicole. I am looking forward to the tea and adventures in the future.

My biggest support will always come from my family. I know that you are always by my side in everything that I do, even if you are across an ocean. Thank you for always believing in me.

I would also like to thank the LHCb VELO test beam crew. Thank you for the exciting experiences and the night shifts.

Finally, thank you to all of the members of the Bristol particle physics group. Working alongside all of you has been a great experience.

Author's contribution

The author's contribution to the work presented in this thesis are as follows :

The Timepix3 Telescope was commissioned in 2014, the author provided the run control which made sure that the run computer was able to communicate correctly with the SPIDR boards of the telescope. During the data taking with the Timepix3 telescope the shifts taken are where a lot of the data used in the thesis came from. The data taking in the lab was also done while out at CERN for the test beams. The main part of work can be seen below.

Chapter 7 : The charge collection and cluster finding efficiency of the prototype sensors before irradiation for the LHCb Vertex Locator upgrade.

Chapter 9 : The charge collection and cluster finding efficiency of the prototype sensors after irradiation for the LHCb Vertex Locator upgrade.

Chapter 10 : Edge finding of inhomogeneous irradiation profiles using the Sobel operator.

Contents

Abstract	iii
Declaration of authorship	v
Acknowledgements	vii
Author's contribution	ix
List of Figures	xv
List of Tables	xxi
1 Introduction	1
1.1 The Large Hadron Collider	2
Introduction	1
2 The LHCb Experiment	7
2.1 Tracking Detectors	9
2.1.1 The VELO	9
2.1.2 The TT	11
2.1.3 The T-stations	11
2.1.4 Track definitions	12
2.1.5 Tracking Performance Results	13
2.2 Particle Identification	14
2.3 The RICH Detectors	15
2.4 Calorimeters	15
2.5 Muon System	16
2.6 Trigger	17
2.7 The LHCb Upgrade	18
3 VELO Upgrade	19
3.1 The VELO upgrade	19
3.2 Constraints	19
3.3 Module Design	20
3.3.1 Micro-channel cooling	21

3.3.2	RF-foil	22
3.3.3	VeloPix	23
3.3.4	Sensor Design	24
3.4	Test beam program	24
4	Silicon Sensors	25
4.1	Particles and Matter	25
4.1.1	Energy Loss	25
4.2	Silicon Sensors	28
4.2.1	Semiconductors	28
4.2.2	Doping and the p-n junction	28
4.3	Signals	32
4.3.1	Time of Arrival and Time over Threshold	32
4.3.2	Timepix3 ASIC	33
4.3.3	Time walk	34
4.4	Sensor Configurations	35
4.4.1	Sensor Types	35
4.4.2	Inter-pixel Isolation	37
4.4.3	Edge designs	38
4.4.4	Prototype overview	38
5	Laboratory Tests of Prototype Sensors	41
5.1	Test Set-up	41
5.2	Current Voltage Scans	42
5.3	Equalisation	44
5.4	Test Pulse Calibration	45
5.5	Summary	47
6	Test beam assembly for testing of prototype sensors	49
6.1	Timepix3 Telescope	49
6.2	Telescope Tracking	50
6.2.1	Hit collection and clustering	51
6.2.2	Tracking	52
6.2.3	Alignment corrections of telescope	53
6.2.4	Pointing Resolution	54
6.3	Device under Test	55
6.4	Sensor Performance	56
6.5	Summary	62
7	Charge Collection and Efficiency Before Irradiation	63
7.1	Assemblies	63
7.2	Charge Collection	64
7.3	Cluster Finding Efficiency	67
7.4	Summary	68
8	Radiation Effects in Timepix3 Devices	71
8.1	Bulk Damage	71
8.1.1	Leakage Current	72

8.1.2	Thermal Runaway	73
8.1.3	Effective Doping	74
8.1.4	Charge Trapping	75
8.2	Surface Damage	76
8.3	Annealing of Radiation Damage	77
8.4	JSI Irradiation	79
8.5	General Sensor Performance after Irradiation	79
9	Charge Collection and Efficiency After Irradiation	83
9.1	Current-Voltage scan	83
9.2	Charge Collection	84
9.2.1	Annealing	86
9.3	In-Pixel Studies	87
9.4	Cluster Finding Efficiency	92
9.4.1	Pixel cluster finding efficiency in the corner	93
9.5	Summary	99
10	Inhomogeneous Irradiation and the Sobel Operator	101
10.1	KIT irradiation	101
10.2	Non uniform irradiation studies	103
10.3	Sobel Operator	104
10.4	Diagonal Bins	107
10.5	Summary	108
11	Conclusions	111
	Bibliography	115

List of Figures

1.1	<i>CERN Accelerator chain</i>	3
2.1	<i>The LHCb detector. The sub-detectors are the VELO, TT, IT, OT, RICH 1 and 2, ECAL, HCAL, and M1-M5. The interaction point is shown at $z = 0$ inside the VELO. Also shown are the sub-detector systems which will be discussed in this chapter.</i>	7
2.2	<i>Production angle of b and $\bar{b}$ mesons in the lab reference frame, using PYTHIA.</i>	8
2.3	<i>3-D model of LHCb VELO vacuum tank. The cooling and support system is shown on in the cut out on the left-hand side. The modules are also visible.</i>	9
2.4	<i>VELO Module rotated by 90°</i>	10
2.5	<i>Different tracks that occur in LHCb. All of the tracking detectors are shown here.</i>	12
2.6	<i>One-dimensional representation of the impact parameter also showing the decay time of the particle.</i>	13
2.7	<i>Impact parameter resolution in x as a function of $1/p_T$.</i>	13
2.8	<i>Track finding efficiency of long tracks in LHCb, as a function of momentum.</i>	14
2.9	<i>Reconstructed Cherenkov angle as a function of track momentum.</i>	15
2.10	<i>Schematic showing how the signal is deposited in different parts of the calorimeter.</i>	16
3.1	<i>A VELO upgrade module showing the average number of tracks per ASIC per bunch crossing.</i>	20
3.2	<i>Fluence as a function of the radius per delivered fb^{-1} for two sensors at different z positions.</i>	21
3.3	<i>Schematic of an upgrade VELO module.</i>	21
3.4	<i>Schematic of the cross-section of a upgraded module, with VeloPix ASICs, micro-channel cooling, and bond wires (not to scale).</i>	22
3.5	<i>A drawing of the microchannel cooling channels.</i>	23
4.1	<i>Stopping power in liquid, hydrogen, gaseous helium, carbon, aluminium, iron, tin and lead.</i>	26
4.2	<i>Fitted charge distribution of a $200\text{ }\mu\text{m}$ thick silicon sensor.</i>	27
4.3	<i>A charged particle travelling through a partially depleted silicon sensor.</i>	31
4.4	<i>Operation modes of the Timepix3 ASIC</i>	32
4.5	<i>Schematic for one pixel and super pixel of a Timepix3.</i>	33
4.6	<i>Sketch of time walk effect.</i>	34

4.7	<i>Time walk as a function of charge at 200V for a 200 μm thick silicon sensor bump bonded to a Timepix3 ASIC.</i>	35
4.8	<i>Sketch of a n-on-p type silicon sensor, with silicon oxide layer</i>	36
4.9	<i>Different edge designs to reduce the electric field at the edge of the sensors, using guard rings (left) or active edges (right).</i>	38
5.1	<i>Picture of laboratory setup of vacuum tank at CERN, showing the Peltier cooler and Kapton connectors.</i>	42
5.2	<i>Example of an IV scan.</i>	43
5.3	<i>Breakdown voltages for unirradiated sensors, each bar represents a separate sensor.</i>	43
5.4	<i>Results of the threshold distributions during and after the equalisation procedure, the red distributions shows the pixel baselines when the trim DAC is set to zero and the blue distribution is the equivalent when the trim DAC is set to fifteen. The black distribution shows the threshold dispersion after equalisation.</i>	45
5.5	<i>Example of calibration curve from a pixel showing the connection of time over threshold to electrons.</i>	46
5.6	<i>Magnification of the non-linear section of the example calibration curve shown in the previous figure.</i>	46
6.1	<i>The Timepix3 Telescope with the 8 telescope planes distributed evenly over two arms with the DuT in the middle. The SPIDR boards that are needed for the Timepix3 ASIC are also visible.</i>	50
6.2	<i>The global and local reference planes for the Timepix3 Telescope.</i>	51
6.3	<i>Four example tracks in the Timepix3 telescope.</i>	52
6.4	<i>χ^2 for the tracks of the Timepix3 Telescope.</i>	53
6.5	<i>Residual in x, showing misalignment with the non-zero mean.</i>	54
6.6	<i>Residuals in x and y for one telescope plane, both integrated over the chip and as a function of position.</i>	55
6.7	<i>Pointing resolution of the Timepix3 telescope in the x direction.</i>	56
6.8	<i>Time residual for a 200 μm thick n-on-p sensor operated at 300V.</i>	57
6.9	<i>Residual for x and y for a 200 μm thick n-on-p sensor operated at 300V.</i>	57
6.10	<i>Cluster size distribution a 200 μm thick n-on-p sensor operated at 300V</i>	58
6.11	<i>Track intercept coordinates for clusters made of (a) one, (b) two, (c) three and (d) four pixels for a 200 μm thick n-on-p sensor operated at 300V.</i>	59
6.12	<i>Resolution distribution of a 200 μm thick n-on-p sensor as a function of bias voltage.</i>	59
6.13	<i>Most probable collected charge at the edge of non-irradiated sensors. The edge of the pixel matrix starts at 0 μm.</i>	60
6.14	<i>Charge distribution for a 200 μm thick silicon sensor irradiated to the maximum fluence (see chapter 8), with a most probable value of 7666 electrons.</i>	61
6.15	<i>Distribution of MPV values, from which the error on the MPV can be extracted.</i>	61
7.1	<i>Fitted Charge distribution for assembly S8 at 300V.</i>	64
7.2	<i>Collected charge for assembly S8 as a function of bias voltage.</i>	65

7.3	Collected charge as a function of bias voltage for the sensors before irradiation. The 200 μm thick n-in-p from Hamamatsu sensors are displayed in green; the 200 μm thick Micron sensors are displayed in blue and the 150 μm thick Micron sensors are shown in purple.	65
7.4	Most probable value of collected time over threshold counts for sensors before irradiation.	66
7.5	Conversion for time over threshold units to electrons before irradiation.	67
7.6	Spacial requirements for cluster finding efficiency	68
7.7	Cluster finding efficiency as a function of the bias voltage for the unirradiated sensors. The 200 μm thick n-in-p from Hamamatsu sensors are displayed in green; the 200 μm thick Micron sensors are displayed in blue and the 150 μm thick Micron sensors in purple.	69
8.1	Leakage current in silicon detectors, produced by various processes, as a function of fluence. FZ refers to float-zone silicon, CZ refers to Czochralski silicon, and EPI refers to epitaxial silicon. The current is measured after controlled annealing, which is discussed in more detail in section 8.3	72
8.2	Leakage current in the current VELO as a function of z coordinate after 1.20 fb^{-1} , normalised to 0°C . The data is in agreement with the predictions (shown as the shaded region). The two halves of the VELO are known as the A and C sides.	73
8.3	Variation of the depletion voltage and the effective doping concentration as a function of fluence.	75
8.4	Fluence dependence of effective trapping rate for neutron irradiated assembly for electrons (a) and holes (b).	76
8.5	Leakage current damage rate, α , versus annealing time at different temperatures.	78
8.6	N_{eff} as a function of annealing time for a sensor irradiated to $1.4 \times 10^{14} \text{ cm}^{-2}$	78
8.7	Cluster size distribution for a 200 μm thick n-in-p sensor with a 39 μm implant operated at 700V.	80
8.8	Coordinates of the track intercept for one (a), two (b), three (c) and four (d) pixel clusters for an irradiated 200 μm thick n-on-p sensor operated at 700V.	80
8.9	X and Y residuals for a 200 μm thick n-in-p sensor with a 39 μm implant operated at 700V.	81
9.1	Measured breakdown voltages, or high voltage limit, for irradiated sensors, each bar is a separate sensor	84
9.2	Most probable collected charge for assembly S22 after irradiation as a function of absolute voltage.	85
9.3	Most probable number of collected electrons for sensors irradiated at JSI. The red dotted line shows most probable value of collected charge of 6000 electrons. The Hamamatsu sensors are displayed in green; the 200 μm thick Micron sensors are displayed in blue and the 150 μm thick Micron sensors are shown in purple	86
9.4	Most probable number of collected charge in electrons for sensors irradiated at JSI before and after annealing.	87

9.5	An example pixel divided into 5×5 regions for in-pixel studies. The yellow shaded section represents the area covered by a $35 \mu\text{m}$ implant, while the orange shaded area represents the additional area covered by the $39 \mu\text{m}$ implant. The red and green regions represent areas that are completely covered by the implant, regardless of which size is used. The blue region is selected for study as it sits on the pixel edge.	88
9.6	Charge distributions for the red, blue, and green regions of a pixel (see main text for explanation) on a $200 \mu\text{m}$ thick n-in-p sensor with a $35 \mu\text{m}$ implant at 300V before irradiation.	88
9.7	Cluster size distributions for the red, green and blue regions of a pixel (see main text for explanation) on a $200 \mu\text{m}$ thick n-in-p sensor with a $35 \mu\text{m}$ implant at 300V before irradiation.	89
9.8	Collected charge distributions for three different regions on a pixel on S22, a $200 \mu\text{m}$ thick n-in-p sensor with a $35 \mu\text{m}$ implant operated at 900V. . .	90
9.9	Collected charge distributions for three different regions on a pixel on S17, a $200 \mu\text{m}$ thick n-in-p sensor with a $39 \mu\text{m}$ implant operated at 900V. . .	90
9.10	Cluster size distributions for three different regions on a pixel on S22, a $200 \mu\text{m}$ thick n-in-p sensor with a $35 \mu\text{m}$ implant operated at 900V. . . .	91
9.11	Cluster size distributions for three different regions on a pixel on S17, a $200 \mu\text{m}$ thick n-in-p sensor with a $39 \mu\text{m}$ implant operated at 900V. . . .	92
9.12	Overall Efficiency for sensors irradiated at JSI.	93
9.13	Efficiency for sensors irradiated at JSI, focussing on the efficiency region above 90%.	93
9.14	In-pixel efficiency for for the four-pixel area on S24 at 500V.	94
9.15	Profile along the diagonal of a four pixel efficiency for assembly S24. . . .	95
9.16	Example of fitted profile along the diagonal of a four pixel efficiency for S24 at 500V.	96
9.17	Location of the efficiency minimum for all irradiated sensors.	97
9.18	Width of of the inefficient area for all irradiated sensors.	97
9.19	Efficiency for area under the implant for sensors irradiated at JSI.	98
9.20	Corner efficiency as a function of absolute voltage for sensors irradiated at JSI.	98
10.1	Fluence profile at KIT with overlaid outline of a single-chip sensor.	102
10.2	Original charge distribution (left) for one section at 400 V and after a coarse rebinning (right). The estimated most probable value of collected charge is 10365 electrons.	103
10.3	Most probable value of associated clusters across the sensor at 400 V for a single chip assembly irradiated to maximum fluence of $4 \times 10^{15} \text{ 1 MeV } n_{\text{eq}}/\text{cm}^2$	104
10.4	Simulation of non-uniform irradiation (left) and the output of the Sobel operator using a 3×3 kernel and applied to the simulated data (right). The transition areas are identified as the light blue lines in the right-handed distribution.	106
10.5	The output of the Sobel operator using a 3×3 kernel applied to single-chip assemblies at 400V irradiated to a maximum fluence of $4 \times 10^{15} \text{ 1 MeV } n_{\text{eq}}/\text{cm}^2$. The distributions has been limited to the specific area of interest.	107

-
- 10.6 *The output of the Sobel operator using a 5×5 kernel applied to single-chip assemblies at 400V irradiated to a maximum fluence of 4×10^{15} 1 MeV n_{eq}/cm^2 . The distributions has been limited to the specific area of interest.* 107
- 10.7 *Most probable value of collected charge as a function of diagonal bin number for the single-chip assemblies at 400V irradiated to a maximum fluence of 4×10^{15} 1 MeV n_{eq}/cm^2 . This is shown for two areas of interest. . . .* 108

List of Tables

4.1	<i>Table of the assemblies tested. The assembly IDs that start with 'S' are a single assembly and the 'T' refers to triple assemblies in which three sensors are attached together.</i>	39
10.1	<i>Irradiation protocol used for the single-chip assemblies at KIT, fluence is expressed in $1 \text{ MeV } n_{eq}/\text{cm}^2$.</i>	102

Chapter 1

Introduction

The goal of particle physics is to understand the building blocks of matter and their interactions, which are described by the fundamental forces. The current theory that explains the fundamental particles and forces is known as the Standard Model. Over time the Standard Model has been tested and has become well established. The discovery of the Higgs Boson was the latest discovery that supported the Standard Model[1]. The Standard Model does not answer some remaining questions, like the absence of antimatter in our universe[2]. These questions are being investigated.

Experiments in particle physics are undertaken to verify the properties of the Standard Model and look for physics beyond the Standard Model. Particles are collided at high energies to examine new theories and discover new particles. The Large Hadron Collider (LHC), at CERN, is colliding particles at a centre-of-mass energy of 13 TeV. There are many experiments at the LHC. Some are general purpose experiments for particle physics, and others have more focused areas of interest. One of these more focused experiments is LHCb, which focuses mainly on B -physics.

One thing that sets B mesons apart is that they have long lifetimes. The long lifetime means that they can travel a measurable distance within the detector, thus they can be identified by looking for a vertex that is displaced with respect to the primary interaction vertex. This is known as a displaced or secondary vertex. A very precise vertex detector is needed to look for these displaced vertices and reconstruct the B mesons. LHCb has

collected data corresponding to an integrated luminosity of more than 7 fb^{-1} since its start in 2010, which includes Run 1 and Run 2. Run 1 is the years of data taking that span 2009 until 2013. Run 2 is the years of data that span 2015 until 2018. The LHC is looking to increase the data rates for the next run, Run 3, which will start in 2020 and end in 2023. During the next LHC shutdown, which starts the end of 2018, LHCb is scheduled to be upgraded.

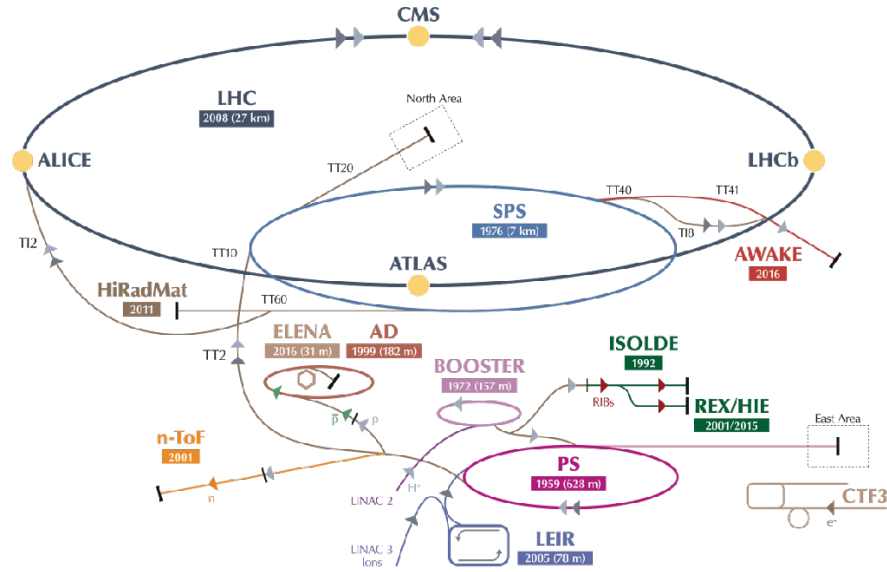
The tracking detectors must be upgraded to be able to cope with the higher data rates. The current vertex detector, Vertex Locator, is being upgraded from a silicon strip detector to a silicon pixel detector. The silicon pixel detector allows for improved particle tracking for Run 3. At the end of Run 3 the sensors are expected to collect a maximum fluence of $8 \times 10^{15} \text{ 1 MeV } n_{eq}/\text{cm}^2$. This means that the silicon sensors must be radiation hard. They must also maintain a high cluster finding efficiency at this level of radiation. A critical part of the Vertex Locator upgrade is the silicon sensor. The sensors will be either $200 \text{ }\mu\text{m}$ thick or $150 \text{ }\mu\text{m}$ thick segmented with a $55 \text{ }\mu\text{m}$ pitch.

1.1 The Large Hadron Collider

The European Organization for Nuclear Research (CERN) [3] has been the world leading institute in particle physics since its start in 1954. There have been many important discoveries, including the W, Z, and Higgs bosons.

To examine new theories and to produce new particles, particles must be collided at high energies. The Large Hadron Collider (LHC), CERN's flagship, is the largest particle collider in the world. The LHC is a circular accelerator with a 27 km circumference. The LHC accelerates protons. The proton-proton collider is designed to deliver the highest centre-of-mass energy of 13 TeV.

The protons need a minimum energy to be successfully injected into the LHC. A whole chain of accelerators is used to reach this threshold energy. The accelerator chain is shown in figure 1.1. The protons are accelerated by a linear accelerator (LINAC 2), before going into a booster ring. The protons are then accepted into the Proton Synchrotron (PS), the first large-scale accelerator on the way to the LHC. The protons

Figure 1.1: *CERN Accelerator chain*

are then accelerated further before being transferred to the Super Proton Synchrotron (SPS). Particle beams can then be delivered to test beam areas located in the North Area by the SPS. After the SPS the protons get injected into the LHC where they get their final boost to collision energies, which has a maximum of 13 TeV. When the protons are at collision energy, there are four main points where they are made to collide: ATLAS, CMS, LHCb, and ALICE. The protons collide at these points every 25 ns. These experiments are described below.

ALICE Experiment

A Large Ion Collider Experiment (ALICE) is a detector optimised to study heavy ion collisions at the LHC. ALICE focuses on strongly interacting matter at extreme energy densities. This is where quark-gluon plasma forms, a state of matter where the quarks are separated from their bond with the gluons. When there are lead-lead collisions at the LHC, the collisions are every 100 ns[4].

CMS Experiment

The Compact Muon Solenoid (CMS) is one of two general purpose detectors at the LHC. Their main goals are to explore physics at high energy scales and study the properties of the Higgs Boson. CMS has a lot of other physics programs, some being, searching for extra dimensions and particles that could be responsible for dark matter[5].

ATLAS Experiment

A Toroidal LHC ApparatuS (ATLAS) is the other general purpose detector at the LHC. It has the same goals as CMS but has different technical solutions and magnet. ATLAS is also looking for a dark matter candidate. Having the same goals as CMS provides checks on physics results[6].

LHCb experiment

The LHCb experiment studies B -physics in proton-proton collisions at the LHC. It focuses on rare decays of charm and beauty hadrons and CP violation. The structure of the LHCb detector will be described in chapter 2.

CP violation is the violation of charge conjugation (C) and of parity (P). Charge conjugation is changing a particle to an antiparticle. Parity is equivalent to a particle reflected across a plane and rotated by 180° . CP violation could describe the matter-antimatter asymmetry of the universe. The heavy B -mesons provide the ideal environment for precision measurements of CP violation.

This thesis focuses on the charge collection and cluster finding efficiency of the prototype sensors. The prototype sensors are designed to the requirements for the upgrade of the LHCb Vertex Locator. Chapter 2 introduces CERN and the LHCb experiment. The upgrade of the LHCb Vertex Locator is discussed in detail in Chapter 3. Silicon sensors are talked about in Chapter 4. Prototype sensors were tested thoroughly in a lab and test beams. Chapter 5 discusses the testing of the prototype sensors in the lab. The Timepix3 telescope in Chapter 6 is needed for testing the prototype sensors

in test beams. The charge collection and cluster finding efficiency of the non-irradiated prototype assemblies are discussed in Chapter 7. Then the effects of radiation damage are discussed in Chapter 8. The charge collection and cluster finding efficiency for the irradiated prototype sensors are discussed in Chapter 9. A Sobel operator was used in Chapter 10 to find edges of a non-uniform radiation profile on prototype sensors.

Chapter 2

The LHCb Experiment

LHCb, shown in figure 2.1, is a forward arm spectrometer which has a horizontal angular coverage of 10 to 300 mrad and a vertical coverage of 250 mrad; both with respect to the incoming proton beams. The reason for this is that $b\bar{b}$ pair production at the LHC

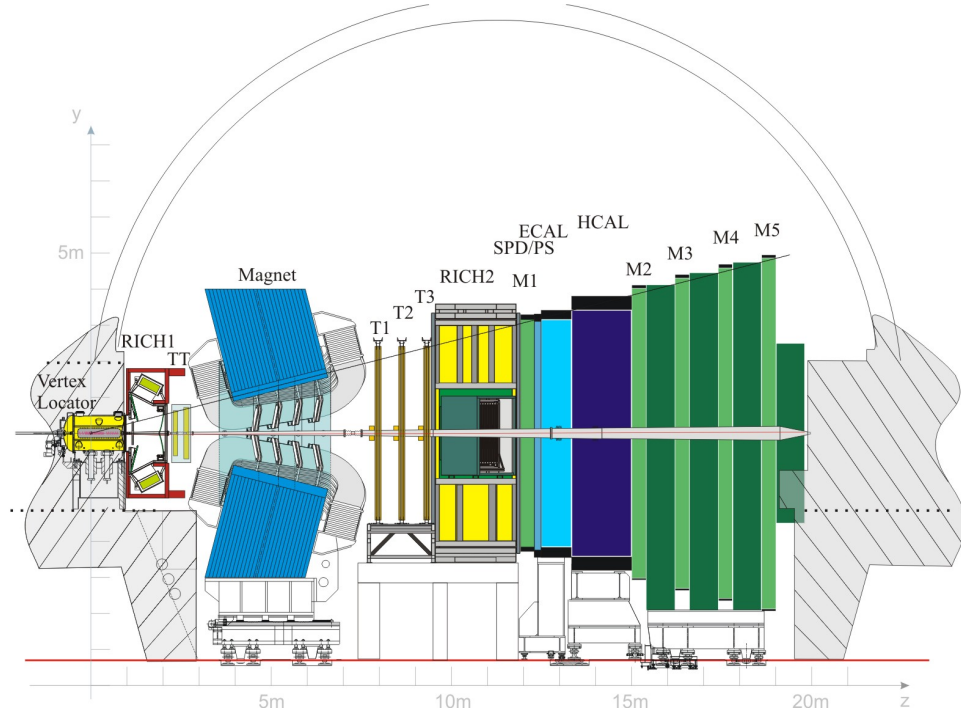


Figure 2.1: The LHCb detector. The sub-detectors are the VELO, TT, IT, OT, RICH 1 and 2, ECAL, HCAL, and M1-M5. The interaction point is shown at $z = 0$ inside the VELO. Also shown are the sub-detector systems which will be discussed in this chapter.

is highly peaked in the forward and backward directions, as seen in figure 2.2.

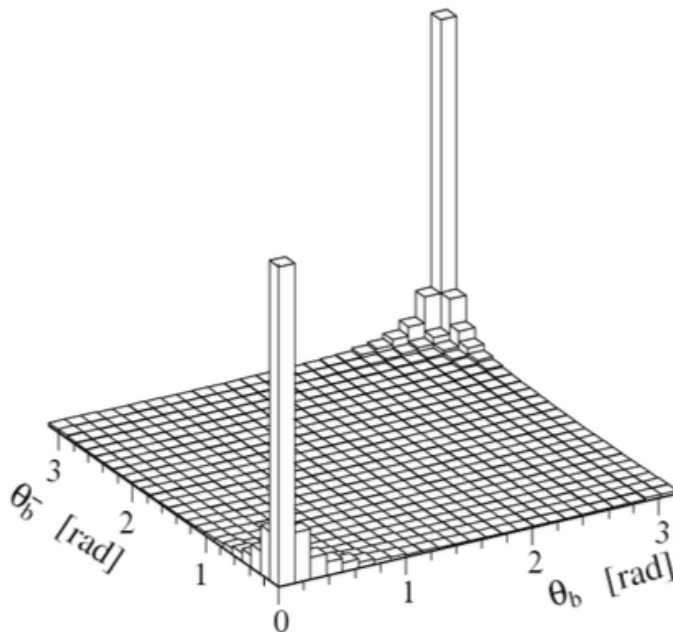


Figure 2.2: *Production angle of b and $\bar{b}$ mesons in the lab reference frame, using PYTHIA[7].*

The detector only covers 2% of the solid angle, but it does cover approximately 27% of b quark pairs that are produced[8]. The LHCb experiment collected data corresponding to an integrated luminosity of 3 fb^{-1} during the first years. After being shut down for two years, LHCb is collecting data again and has collected data corresponding to a total integrated luminosity of 7 fb^{-1} since 2010. It is currently operating at an instantaneous luminosity of $L = 4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. This luminosity will provide an average of 1.62 proton-proton collisions per bunch crossing.

The LHCb detector is made up of many different sub-detectors, as seen in figure 2.1. Closest to interaction point is the Vertex Locator, VELO (see section 2.1.1), which allows for excellent vertex resolution of decaying particles. Next is the RICH detector (see section 2.3), whose role is particle identification. Next is the TT (see section 2.1.2), which is used for triggering. After the magnet are the three tracking stations, T1, T2, and T3. These are made up of two different trackers, IT and OT, (see section 2.1.3). Next is another RICH detector. Then are the ECAL and HCAL (see section 2.4). These are important for the particle momentum. Lastly, there are the muon chambers, M1-M5,

which identify the muons present in B decays (see section 2.5).

2.1 Tracking Detectors

The tracking detectors are made up of the Vertex Locator (VELO), the Trigger Tracker (TT) and T-stations.

2.1.1 The VELO

The Vertex Locator is designed to reconstruct the production and decay vertices of b and c quark hadrons. The detector has to be close to the interaction point for precise measurements of the decay vertices. It must therefore have high spatial resolution and minimal material to decrease the amount of multiple scattering from the particles. The

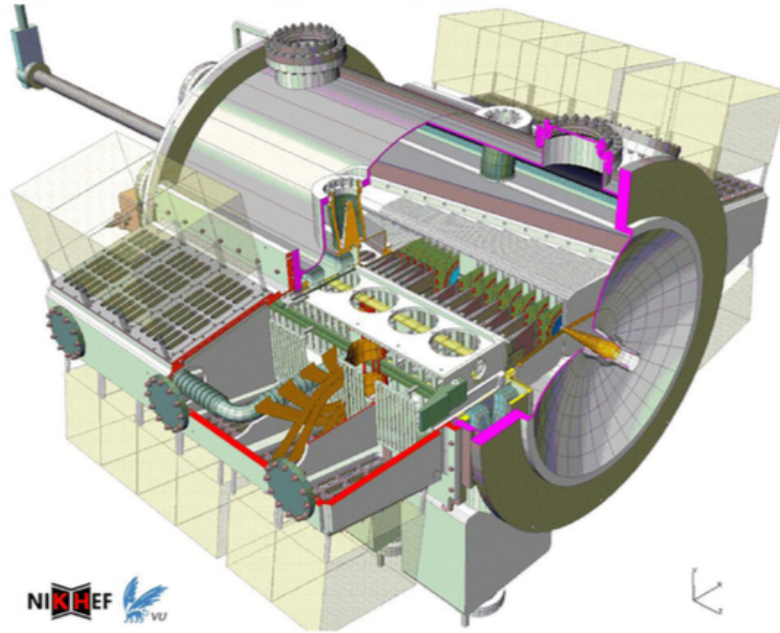


Figure 2.3: 3-D model of LHCb VELO vacuum tank. The cooling and support system is shown on in the cut out on the left-hand side. The modules are also visible[9].

detector has a specific design for these requirements. It is a silicon strip detector oriented perpendicular to the beam axis. The VELO modules are separated from the beam vacuum by a corrugated 300 μm Radio Frequency (RF) foil. This shields the modules from beam induced RF signals. There are two halves of the detector on a mechanical

stage so they can be retracted during beam injection and be moved back in when stable beams are achieved. This allows the closest active module to be 8.2 mm from the interaction point[10]. Figure 2.3 shows a 3-D model of the LHCb VELO. Every single module consists of two silicon strip sensors on opposite sides of the printed circuit board, which contains the active components of the sensor readout. This is seen in figure 2.4.

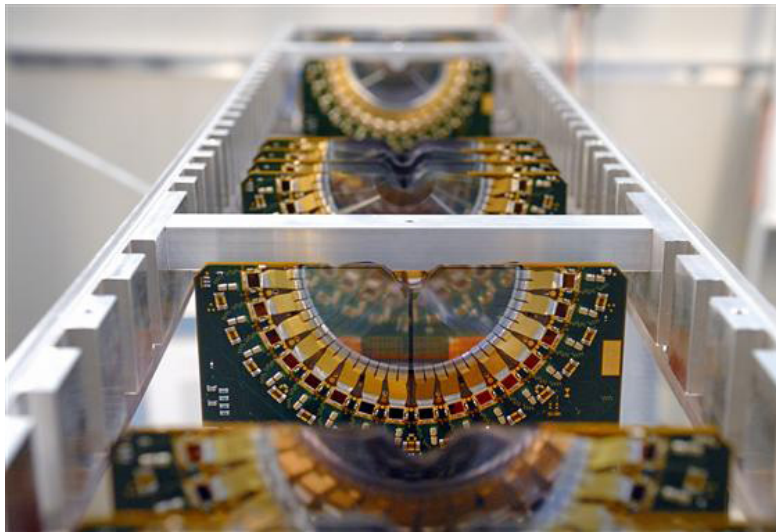


Figure 2.4: *VELO Module rotated by 90°*

Each sensor has strip implants on it, which either have a radial or circular pattern. Each module has both types of sensors; this allows one measurement point from the radial and circular sensors. The Vertex Locator has a best hit resolution of $4\text{ }\mu\text{m}$ [10]. The readout chips are located around the sensor edge and mounted on the PCB connected by a pitch adapter to the metal readout lines patterned on the sensor. Thermal connectors are located on the top of the carbon fibre support. They act as a heat sink which cools the PCB. The cooling system is a bi-phase CO_2 system. The sensors are operated between -10°C and 0°C to minimize the effects of radiation damage, see section 8.1.1[11].

The VELO reconstruction is done by measuring the decay times, offline, and the distance of closest approach, the impact parameter, with respect to the primary vertex, used in the trigger.

2.1.2 The TT

After the Vertex Locator, the next tracking detector is the TT. The information from the TT is used for trigger decisions. It also is used for the reconstruction of long-lived particles that decay outside the acceptance of the VELO. The detector has four planes of silicon strip sensors. They are orientated at angles of 0° , 5° , -5° and 0° with respect to the vertical. The different orientations allow for more information about the track. The sensors have a pitch of $183\ \mu\text{m}$ and are p -doped implants on a $500\ \mu\text{m}$ thick n -type silicon. The spatial resolution is approximately $50\ \mu\text{m}$ [12].

2.1.3 The T-stations

After the particles travel through the magnet, there is another set of three tracking stations: T1, T2, and T3, which are collectively referred to as the T-stations. Each of the T-stations are made up of an inner tracker and an outer tracker. The Inner Tracker, IT, is closest to the beam pipe and has the same setup as the TT. The four silicon strip sensors are orientated at angles of 0° , 5° , -5° , and 0° with respect to the vertical. There are two different sensor thickness, $320\ \mu\text{m}$ above and below the beam, and $410\ \mu\text{m}$ to the left and right. All four sensors have a constant pitch of $198\ \mu\text{m}$. The resulting resolution is approximately $50\ \mu\text{m}$ [12].

The Outer Tracker, OT, covers the large region outside the acceptance of the IT. The OT consists of tracking planes made of straw tubes. The straw tube planes of the OT are arranged in sets of four per station with angles of 0° , 5° , -5° , and 0° with respect to the vertical on the central planes. The straw tubes are made up of $4.9\ \text{mm}$ diameter cylindrical gas tubes, with a $25.4\ \mu\text{m}$ thick gold-plated tungsten wire running through the centre. The tubes are filled with a gas mixture of 70% Ar and 30% CO_2 . The spatial resolution of the OT is $\sim 200\ \mu\text{m}$ [13].

2.1.4 Track definitions

Figure 2.5 show the different tracks that can occur in LHCb. An ideal track is one that starts in the VELO and continues through the whole detector, i.e. long track.

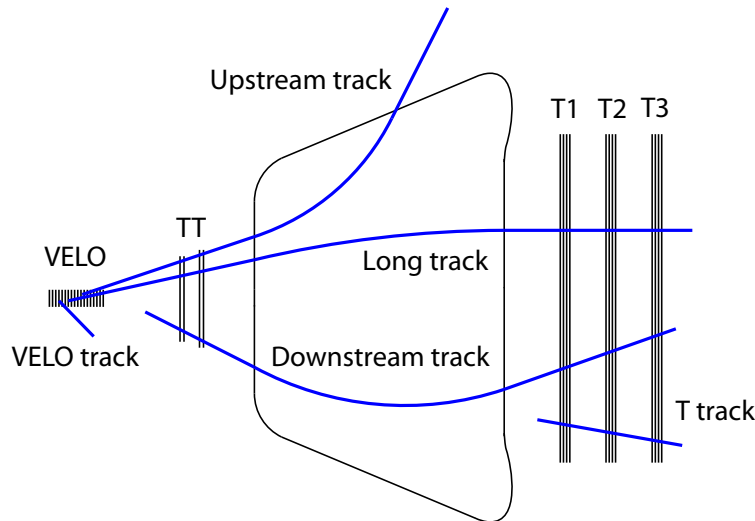


Figure 2.5: *Different tracks that occur in LHCb. All of the tracking detectors are shown here.*

Track reconstruction is done by combining the information from all of these tracking detectors. The tracks that have a hit in all of the sub-detectors are labelled "long tracks". An upstream track has hits only in the VELO and the TT. A downstream track has hits in the TT and T-stations. A T track just has hits in the T-station. The final type of track is referred to as a VELO track; this type of track only has hits in the Vertex Locator. LHCb uses two different sequences to reconstruct tracks. The first starts with the information from the VELO and looks forward through the subsequent sub-detectors to find the rest of the hits associated with the track. The second sequence begins with some of the smaller tracks, such as a VELO track and T track, and tries to match the trajectories of tracks in the remaining trackers. The track finding efficiency for these two methods, is above 90% for particle momentum between 0 and 200 GeV/c[14].

2.1.5 Tracking Performance Results

The track finding efficiency and the impact parameter resolution are important criteria of the tracking performance. The impact parameter is the closest distance between the primary vertex and the decay vertex, as shown in figure 2.6.

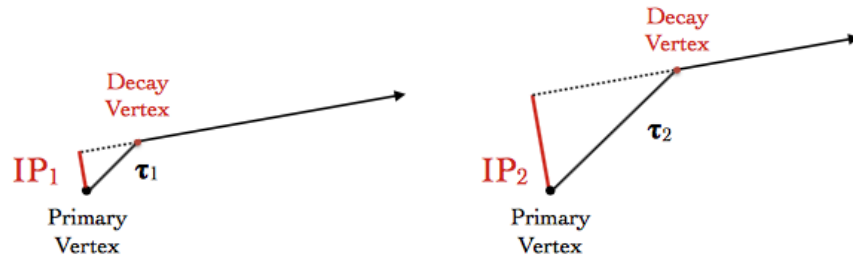


Figure 2.6: *One-dimensional representation of the impact parameter also showing the decay time of the particle*[15].

If a track has a large impact parameter then the track is created by a long-lived particle that decays within the detector. Figure 2.7 shows the impact parameter resolution in the x -direction as a function of the inverse of the transverse momentum, p_T . The impact parameter plays a key role in the high-level trigger, as described in section 2.6. Large impact parameters are favoured in the high-level trigger.

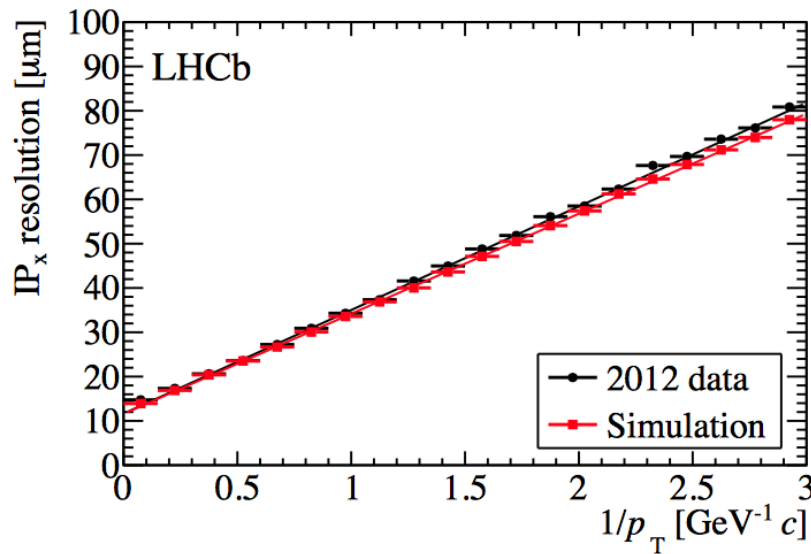


Figure 2.7: *Impact parameter resolution in x as a function of $1/p_T$* [16].

The track finding efficiency is the probability of a charged particle traversing all of the tracking sub-detectors being reconstructed correctly. The current track finding efficiency for long-lived tracks is about 96%, as shown in figure 2.8.

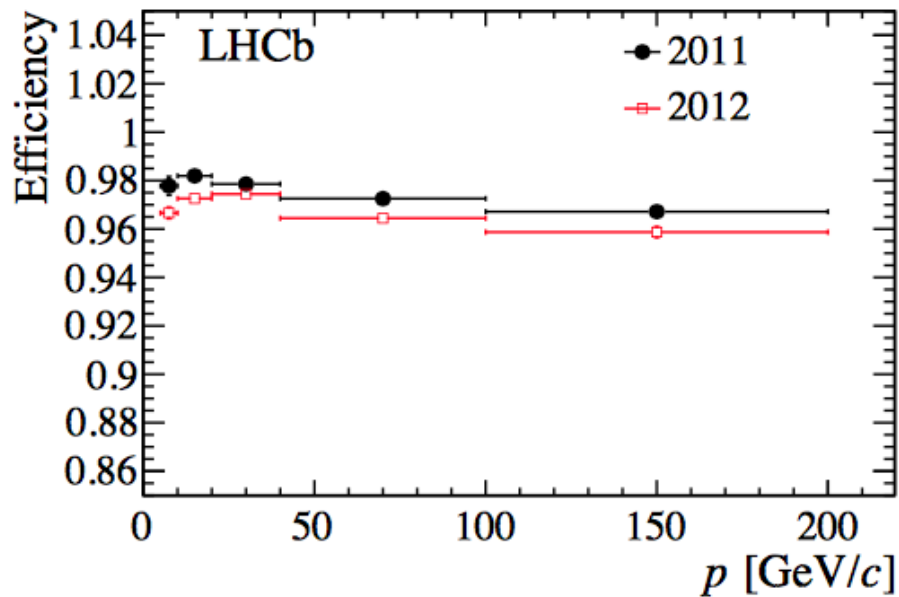


Figure 2.8: *Track finding efficiency of long tracks in LHCb, as a function of momentum*[14].

2.2 Particle Identification

In B -physics, particle identification is of paramount importance. To achieve this, a Cherenkov detector is placed in front of the magnet (RICH1) and another (RICH2) behind the tracking stations each serving a different momentum range[17]. The calorimeter system, includes an Electromagnetic calorimeter, ECAL, the Hadronic Calorimeter, HCAL, the Pre-shower (PS) and the Scintillating Pad Detector (SPD)[18]. To identify muons, there are then five muon stations (M1 to M5)[19].

2.3 The RICH Detectors

When a relativistic charged particle enters an optically denser material, it emits electromagnetic radiation that is seen as a cone of light. This cone of light has an opening angle that is dependent on the particle its velocity and the refractive index of the material. To identify the particle, the opening angle measurement is combined with a momentum measurement from the tracking. Due to the different particle masses, each particle type follows its own trajectory in opening angle - momentum space. This is illustrated in figure 2.9, where the Cherenkov angle is plotted as a function of the track momentum in C_4F_{10} . As long as the particle momenta are below ~ 65 GeV/c for a C_4F_{10} filled RICH, particles can be identified easily.

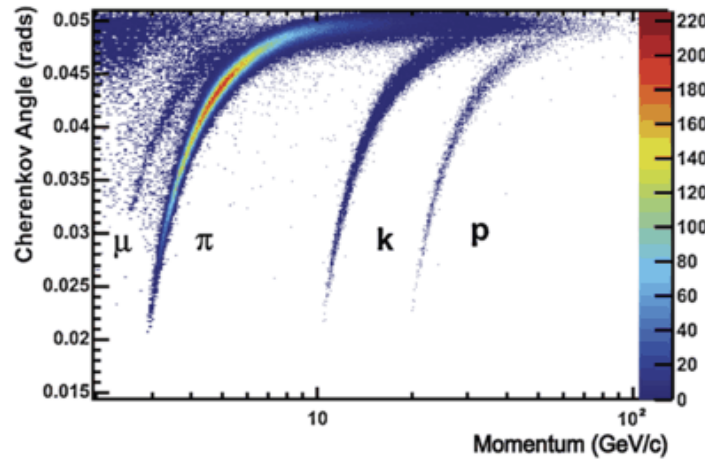


Figure 2.9: *Reconstructed Cherenkov angle as a function of track momentum*[17].

At high momenta, the ability to identify particles is lost due to opening angle saturation. There are two RICH detectors in the LHCb experiment, RICH 1, which is before the magnet, and RICH2, which is after the magnet. RICH 1 covers the particle identification at low momentum, while RICH 2 covers particle identification at higher momenta. RICH 1 covers a range of 2 - 60 GeV/c and RICH 2 covers 15 to ~ 100 GeV/c.

2.4 Calorimeters

The calorimeter system is designed to measure particle energies. Four main sub-detectors make up the calorimeter system: The Electromagnetic Calorimeter (ECAL), the Hadronic

Calorimeter (HCAL), the Scintillating Pad Detector (SPD) and the Pre-Shower (PS). They are used in coincidence to distinguish between photons, electrons and hadrons at the trigger level. The Scintillating Pad Detector is used to identify charged particles before they produce showers in the calorimeter, which allows for the separation of electrons and photons. The Pre-Shower identifies electromagnetic particles. The ECAL measures the energy of the electromagnetic showers while the HCAL measures the energy of the hadronic showers. Figure 2.10 shows the where the energy is deposited for different particle types in the different calorimeters.

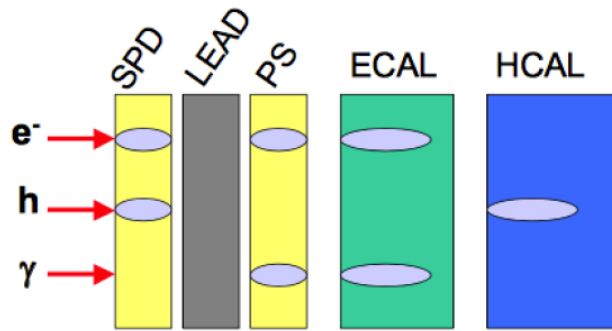


Figure 2.10: *Schematic showing how the signal is deposited in different parts of the calorimeter.*

The SPD and PS are built out of scintillating pads that use wavelength shifting fibres that transmit the light to Multi-Anode Photomultipliers. The detectors are also separated by a 15 mm thick lead converter. The Electromagnetic Calorimeter has 2 mm thick lead tiles intermixed with 4 mm of scintillating pads; these are read out with wavelength shifting fibres connected to phototubes. The Hadronic Calorimeter uses alternating iron and scintillator and has a depth of 5.6 interaction lengths. The Electromagnetic Calorimeter has a thickness of 25 radiation lengths.

2.5 Muon System

Muons are present in the final stages of many states of CP sensitive B meson decays. Therefore, the muon detection at LHCb is very important. There are five muon stations at LHCb, one is in front of the calorimeter, and the other four are at the back of the

detector. Only muons¹ manage to traverse the calorimeter. The muon system is mostly made of Multi-Wire Proportional Chambers (MWPC). The central region of the first muon chamber has Gas Electron Multiplier (GEM) detectors. The MWPC consist of gas volumes containing thin wires. When the muons interact with the gas in the detectors, they create free electrons which drift toward the wires. The GEM uses thin metal foils with holes to start the electron avalanche.

2.6 Trigger

Proton bunches at the LHC arrive every 25 ns. There is too much data registered from all of the sub-detectors of LHCb to read out all of the information between the bunches. A trigger system is therefore needed to ensure that only the output from interesting events is stored. All of the sub-detectors that make up the LHCb detector use an external trigger. The trigger consists of two levels, the first level trigger, L0, and the high-level trigger, HLT[20]. The first level trigger is a hardware trigger that looks for large energy deposits in the calorimeters or the presence of a moderately energetic muon in the muon system. Muons are part of the final states of the decays of many B mesons, so it makes sense to start by looking for their presence in the trigger.

The decision from the L0 trigger is distributed to the remaining sub-detectors, and the data for that bunch crossing is sent to the electronics for pre-processing. The efficiency for the L0 trigger is 89%[21]. The data must be reduced further before it can be stored. This is done by the high-level trigger. The high-level trigger reviews the data looking for long tracks, that pass through all tracking stations. The high-level trigger is looking for well-fitted tracks with sufficient momentum, and large impact parameters. This final data is stored for physics analysis.

¹Neutrinos also make it through the calorimeter, but the cross section for neutrino interaction with the detector is so small that they can safely be ignored.

2.7 The LHCb Upgrade

LHCb has collected data corresponding to an integrated luminosity of over 7 fb^{-1} since 2010. The LHCb detector is being upgraded in the next long shut down of the LHC, starting at the end of 2018. The upgrade is essential to profit from the higher luminosity of the LHC. There are many aspects of LHCb that need to be upgraded, including the particle identification, trackers, and the trigger. The VELO is a major upgrade scheduled to take place. The VELO is one of the major upgrade projects scheduled to take place and will be discussed in more detail in Chapter 3.

Chapter 3

VELO Upgrade

During the next long shutdown of the LHC, LHCb will be upgraded. The VELO must be replaced to cope with the higher luminosity. A silicon pixel detector will replace the current Vertex Locator. The following chapter focuses on the design of the components of the LHCb Vertex Locator Upgrade.

3.1 The VELO upgrade

The changes that are happening to the VELO are significant. Almost all of the existing components within the VELO are going to be replaced. This includes new cooling and a new Radio-Frequency box; a new module has also been designed. The new module includes a new ASIC capable of dealing with higher occupancy. The increased occupancy requires a higher segmented area. This is achieved by upgrading to a pixel detector using VeloPix ASIC, which are based on the existing Timepix3 ASIC[22].

3.2 Constraints

The new VELO is going to have to cope with the increased data rates and increased amounts of radiation. In Run 1 the average number of hits per pp -collision was approximately 5,000. After the upgrade, the modules are going to be 3.1 mm closer to the

beam than previously. In Run 3 the average number of hits per event is expected to be 7,300 [8].

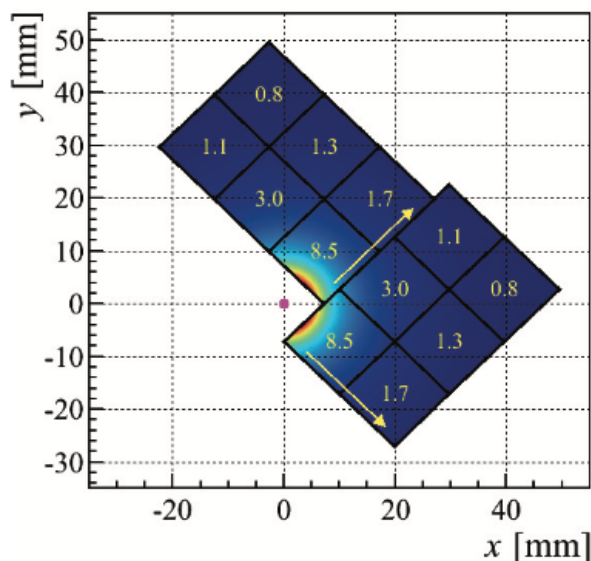


Figure 3.1: A *VELO* upgrade module showing the average number of tracks per ASIC per bunch crossing.

Figure 3.1 shows the average number of tracks traversing each of the VeloPix ASICs for each bunch crossing for a single module. The maximum number of tracks that cross the ASIC per bunch crossing is 8.5 hits, whereas the minimum is less than 1 per bunch crossing.

The estimated integrated radiation dose per fb^{-1} will increase by a factor of 2.5. Figure 3.2 shows how the fluence varies with the z position. Near the centre of the interaction region, where $z = 0$ mm, the expected fluence is 1.5 times greater than that of the downstream sensor where $z = 700$ mm. At the end of Run 3 the maximum fluence is expected to be $8 \times 10^{15} \text{ 1 MeV n}_{eq}/\text{cm}^2$ for the modules closest to the beam.

3.3 Module Design

The VELO is being upgraded to a silicon pixel detector using the VeloPix ASIC; a schematic of the design is shown in figure 3.3. The modules have four silicon sensors that

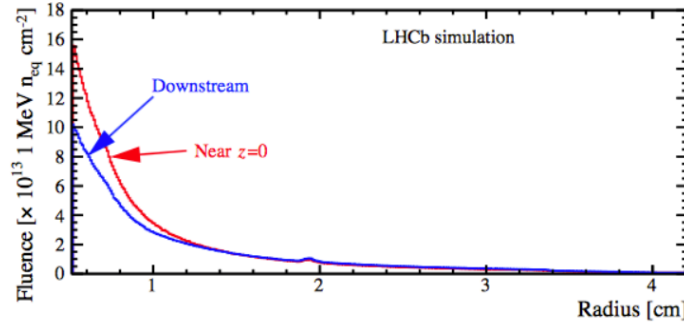


Figure 3.2: *Fluence as a function of the radius per delivered fb^{-1} for two sensors at different z positions [8].*

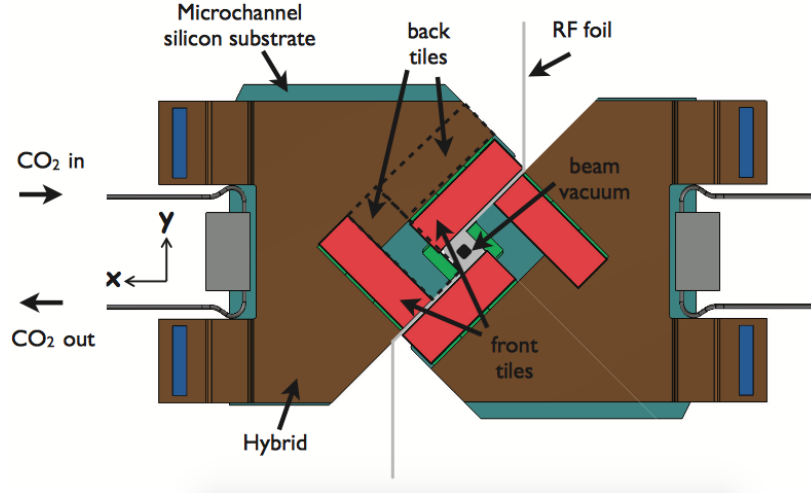


Figure 3.3: *Schematic of an upgrade VELO module.*

cover an area of $42.46 \text{ mm} \times 14.08 \text{ mm}$ each and the size of the pixels is $55 \mu\text{m} \times 55 \mu\text{m}$. The detector consists of 52 modules. Each module has 4 sensor tiles with two on either side of the module. The Radio Frequency foil is a thick aluminium foil that separates the modules from the primary beam vacuum (see section 3.3.2). The cross-section of the module is shown in figure 3.4. Here the overhang of the silicon sensors and VeloPix ASICs is visible. The etched micro-channel cooling is visible in the silicon substrate.

3.3.1 Micro-channel cooling

The main power dissipation in the modules comes from the ASICs. The expected heat dissipation for each ASIC is 3 W. The ASICs are placed in between the sensors and the cooling substrate, so the sensors are cooled through the ASICs. If the sensors are not

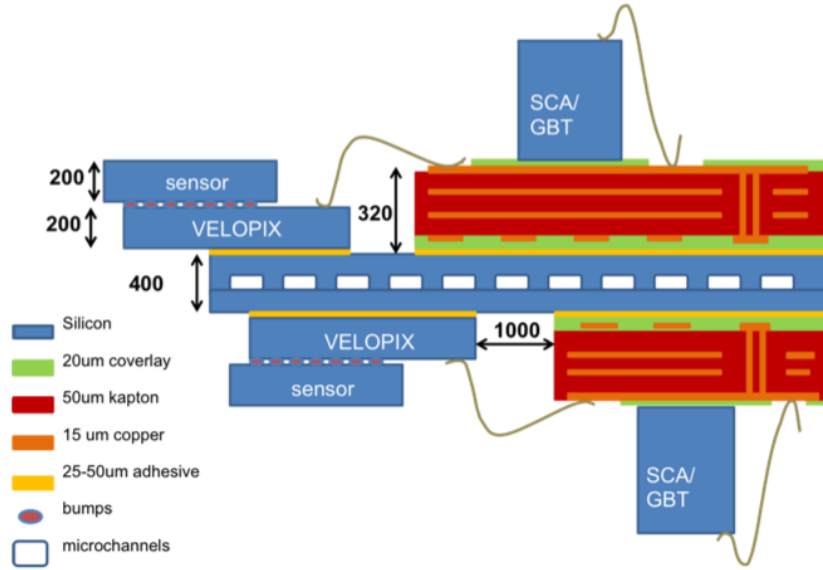


Figure 3.4: *Schematic of the cross-section of a upgraded module, with VeloPix ASICs, micro-channel cooling, and bond wires (not to scale) [8].*

cooled then the power dissipation can cause thermal runaway (see section 8.1.2). To prevent thermal runaway, the sensors need to be cooled to below -20°C [8]. This is most important for the innermost region of the sensor, where the most radiation damage is expected.

The cooling of the sensors is going to be done through micro-channel cooling. The micro-channels are etched into the 400 μm thick silicon substrate with channels of $200 \mu\text{m} \times 120 \mu\text{m}$. Due to the same materials being used there will be no deformation of the module during thermal cycles. Figure 3.5 shows a drawing of the etched microchannels. The microchannels follow a curved design that covers most of the sensor.

3.3.2 RF-foil

The RF-foil separates the beam vacuum from the secondary vacuum and shields the modules from the electromagnetic interference from the beam. The RF-foil also guides the mirror currents of the beam. The foil can have a maximum thickness of 250 μm as it is the main contributor to the material budget. A low material budget is better for

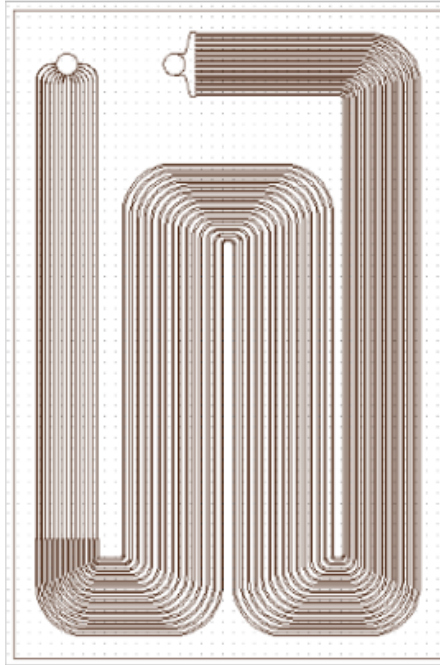


Figure 3.5: A drawing of the microchannel cooling channels [23].

less multiple scattering. Particles can end up traversing the RF-foil multiple times due to the corrugated shape. Tracks with a low relative angle to the beam cross the RF-foil more than the tracks with a high relative angle to the beam.

3.3.3 VeloPix

VeloPix [24] is a new-front end ASIC designed by CERN and Nikhef for the VELO upgrade. It has been derived from the Medipix family of ASICs [25]. VeloPix is a hybrid pixel chip with 256×256 square pixels, each with a $55 \mu\text{m}$ pitch. It is built in 130 nm CMOS technology. As mentioned in section 3.2, the number of events per bunch crossing is going to increase after the upgrade. The raw data that is read out from the VELO modules must be reduced in some way to deal with the increase in data. In order to achieve this, it was decided that the ASIC should be binary and should use a data-driven readout. The data is readout in super pixels. These super pixels are fixed regions of 2×4 pixels for which the data is sent off together. The output of the super pixel includes the bunch crossing ID, so it is known which bunch crossing the hit is associated with. The output also includes the location of the super pixel and which one

of those pixels went over the threshold. The data is reduced by about 30% using this format.

3.3.4 Sensor Design

The VELO sensors are designed around a baseline option of a 200 μm thick, *n-on-p* silicon sensor with a guard ring size of 450 μm . The variations are in the thickness, implant width and sensor type. The sensor types being tested are *n-on-p* and *n-on-n* type silicon. There are three implant widths of 35 μm , 36 μm , and 39 μm , and two thicknesses of 200 μm and 150 μm . Results are shown in Chapters 7 and 9.

3.4 Test beam program

All of the variations need to be tested before a final design for the VELO sensor can be decided upon. As the VeloPix chip was only being developed while the sensor study program was taking place, the silicon detectors were mounted on the Timepix3 ASIC. The Timepix3 ASIC is described in more detail in section 4.3.2. The variations in silicon sensors are tested using the Timepix3 telescope, at the SPS at CERN, discussed in more detail in Chapter 6.

Chapter 4

Silicon Sensors

Silicon microstrip detectors were first developed for use in particle physics by Heijne et al. [26]. Silicon sensors are the detector of choice for high precision tracking in high occupancy environments. In this chapter, first, the interaction mechanisms of charged particles with the silicon are reviewed. Next, the basic characteristics of silicon sensors are discussed. Finally, the Timepix3 ASIC's signal acquisition is described.

4.1 Particles and Matter

4.1.1 Energy Loss

When charged particles traverse matter, they lose energy mainly through inelastic collisions with atomic electrons. The Bethe-Bloch equation, equation 4.1 below, [27] describes the average energy loss per unit thickness or stopping power, $\langle dE/dx \rangle$, of charged particles in units of $\text{MeV g}^{-1} \text{ cm}^2$.

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi N_A r_e^2 m_e c^2}{\beta^2} \frac{Z}{A} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \quad (4.1)$$

where N_A is Avogadro's number, r_e is the electron radius, A and Z are the atomic mass and atomic number of the material, z is the charge of the particle, β is the ratio of the velocity of to the speed of light, γ is the Lorentz factor, $m_e c^2$ the rest mass of the

electron, T_{max} is the maximum kinetic energy that can be transferred to a free electron in a single collision, I is the mean excitation energy in electron volts and $\delta(\beta\gamma)$ is the density effect correction to the ionization energy loss [28].

The energy loss depends on the momentum of the particle. When the energy increases the stopping power of an ionising particle drops until it reaches a minimum, as can be seen in figure 4.1. At this minimum, the particle is said to be a minimum ionising particle. After this point, there is a small rise in the stopping power, which eventually flattens out due to the density effect. Minimum ionising particles form a vital benchmark as they result in the minimum signal that a given charged particle can generate in a silicon sensor.

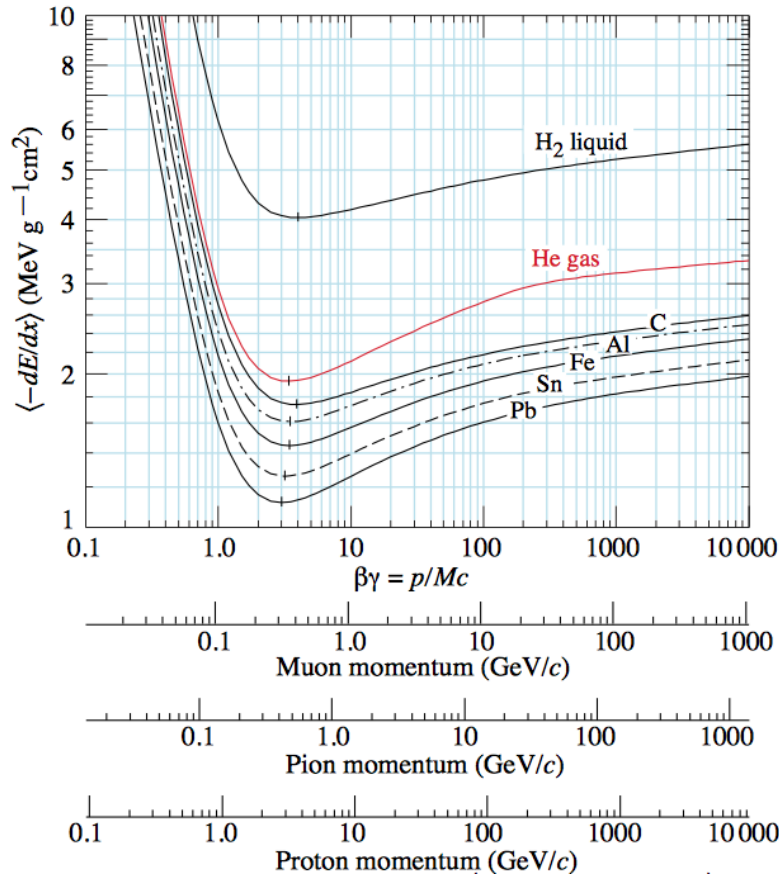


Figure 4.1: Stopping power in liquid, hydrogen, gaseous helium, carbon, aluminium, iron, tin and lead [27].

The Bethe-Bloch equation describes the average energy loss in a material. However, energy loss is a stochastic process. The energy loss distribution for a charged particle traversing a thin absorber containing an infinite number of free electrons was first

calculated by Landau [29].

The energy loss distribution resembles a Gaussian distribution with a long tail towards large energy losses. The tail is due to so-called " δ electrons". These are electrons that have so much energy transferred to them that they act like charged particles traversing the material. Silicon sensors with a thickness between 32 - 1040 μm are considered thin absorbers [30], for which the most probable value (MPV) of the energy loss is given by:

$$MPV = \xi \left[\ln \frac{2m_e c^2 \beta^2 \gamma^2}{I^2} + \ln \frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma) \right] \quad (4.2)$$

with

$$\xi = \frac{4\pi N_A r_e^2 m_e c^2}{2} \left\langle \frac{Z}{A} \right\rangle \frac{x}{\beta^2} \quad (4.3)$$

where j is a constant with a measured value of 0.200, and the density effect correction has been added by Bichsel [31]. For thick absorbers, the distribution changes from a skewed distribution to a Gaussian distribution. For thin absorbers the measured energy loss distributions can be described by a Landau distribution convoluted with a Gaussian. The Gaussian takes into account the effects of charge sharing and noise. The detector performance is evaluated in terms of the most probable value of collected charge.

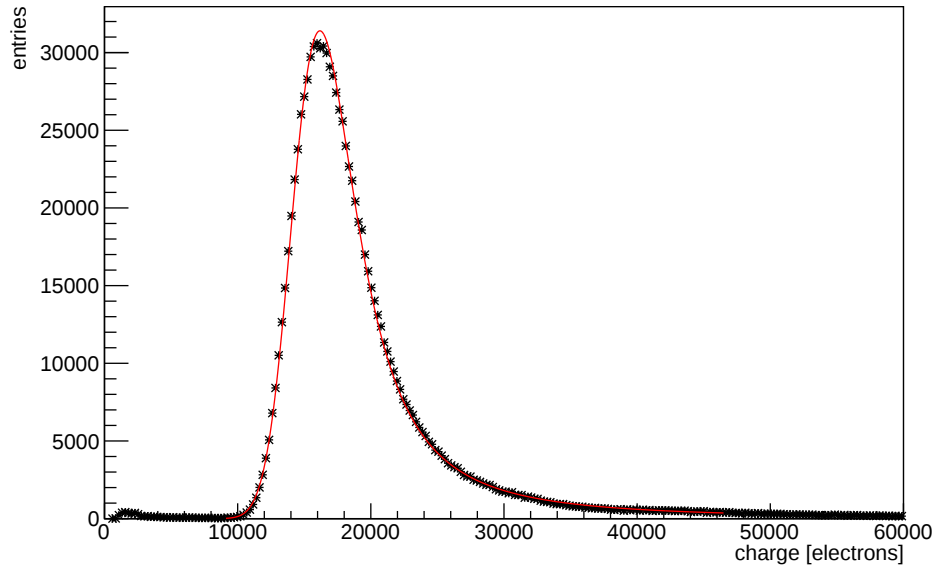


Figure 4.2: *Fitted charge distribution of a 200 μm thick silicon sensor.*

Figure 4.2 shows a fitted collected charge distribution for a 200 μm thick silicon sensor. The most probable value of collected charge is expected to be between 76 and 80 electron hole pairs per micron of silicon traversed [32, 33]. This corresponds to an expected most probable value between 15,200 electrons and 16,000 electrons. The most probable value from the fit is 15,600 electrons with an error of 13 electrons. The determination of the fit errors is discussed in more detail in Section 6.4.

4.2 Silicon Sensors

When a charged particle interacts with a silicon sensor, the liberated charge must be collected and converted into a signal. The principles of design and operation of a silicon sensor are explained in this section.

4.2.1 Semiconductors

The band gap in a solid state material is the energy gap between the valence and conduction bands. The band gap in semiconductors is smaller than in insulators, whereas in conductors the bands overlap. In semiconductors, electrons that have enough thermal energy can be excited across the band gap. When this excitation happens, holes are left where the electrons used to be.

Silicon, which has four valence electrons, is one of the most commonly used semiconductors. The four electrons combine with neighbouring electrons to form covalent bonds. The electrons can easily move from the valence band to the conduction band when the semiconductor is at room temperature. When this happens, mobile electron-hole pairs are formed. Silicon has an intrinsic carrier concentration is in the order of 10^{10} cm^{-3} at 300 K.

4.2.2 Doping and the p-n junction

Addition of impurities to the silicon is known as doping. When a silicon atom is replaced with an atom with five valence electrons, it is known as *n*-type doping. Only four of

the five electrons can form a covalent bond with neighbouring silicon atoms. The fifth is only very lightly bound to the donor and can therefore escape and move freely through the material. If the silicon is replaced with an atom that has three valence electrons, it is known as *p*-type doping. The missing covalent bond creates a mobile hole, known as an acceptor, that could be filled with an electron from a neighbouring atom.

When an *n*-type and a *p*-type doped semiconductor are joined a *p-n* junction is created. Electrons are attracted to the *p* region while holes are attracted to the *n* region. An electric field is created by the formation of the two space charge regions, which counteracts the diffusion. The electric field results in a region free of mobile charge carriers, which is known as the depletion region. For radiation detectors, this depletion region is the most important feature of the *p-n* junction. The width of the depletion region, x , can be extended by application of a potential, V . The width can be calculated by solving Poisson's equation:

$$\frac{d^2V}{dx^2} + \frac{Ne}{\epsilon_0\epsilon_{Si}} = 0 \quad (4.4)$$

where N is the doping concentration, e is the charge of the electron in Coulombs and ϵ_0 and ϵ_{Si} are the permittivity of free space and the relative permittivity of silicon, respectively. When equation 4.4 is integrated the electrostatic potential obtained is given by:

$$V(x) = \begin{cases} V_n(x) = V_n - e\frac{N_d}{2\epsilon_0\epsilon_{Si}}(x - x_n)^2 & \text{for } 0 \leq x \leq x_n \\ V_p(x) = V_p + e\frac{N_a}{2\epsilon_0\epsilon_{Si}}(x + x_p)^2 & \text{for } -x_p \leq x \leq 0 \end{cases} \quad (4.5)$$

where V_n and V_p are the electrostatic potentials and x_n and x_p are the depletion widths on the *n*- side and *p*-side, respectively. When V_n is equal to V_p the potential difference between the unbiased *n* and *p* regions is equal to [34] :

$$V_{bi} = \frac{kT}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right) \quad (4.6)$$

where k is the Boltzmann constant, T is the temperature in Kelvin, n_i is the intrinsic carrier concentration and N_d and N_a are the concentrations of the donors and acceptors. There is no free charge in the depletion region so

$$N_d x_n = N_a x_p \quad (4.7)$$

When equation 4.5 and 4.6 are combined using the relation given in equation 4.7, they give the total depletion width, X , as

$$X = \sqrt{\frac{2\epsilon_0\epsilon_{Si}V_{bi}}{e}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)} \quad (4.8)$$

When a charged particle travels through the depletion region, the liberated electrons will drift towards the n - side and the holes will drift towards the p - side. A sketch of this process can be seen in figure 4.3. The grey shaded area is the area of the sensor that is not depleted. The green area is the p^+ backplane, the blue dots are the n^+ electrodes, which can also be referred to as implants. The backplane and implants are needed so that a bias can be applied of the silicon sensor. These implants are the charge collection region in each of the pixels. In the non-depleted region the electrons (filled circles) and holes (empty circles) do not drift toward the respective implants. The charge carriers that drift to the implants induce a signal there. The charge only has a net movement in the depleted region.

To extend the p - n junction a reverse bias, V_b , is applied across the p - n junction. This potential adds to the built-in voltage in equation 4.8, which then becomes:

$$X = \sqrt{\frac{2\epsilon_0\epsilon_{Si}(V_b + V_{bi})}{e}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)} \quad (4.9)$$

This shows that the depletion width increases by the square root of the applied bias voltage. The sensors that will be installed into the VELO Upgrade have an asymmetrical p - n junction. This means that there is a high doped n^+ implant in a low doped p bulk. In the n -on- p sensor the depletion width starts from the n^+ implant. The asymmetric

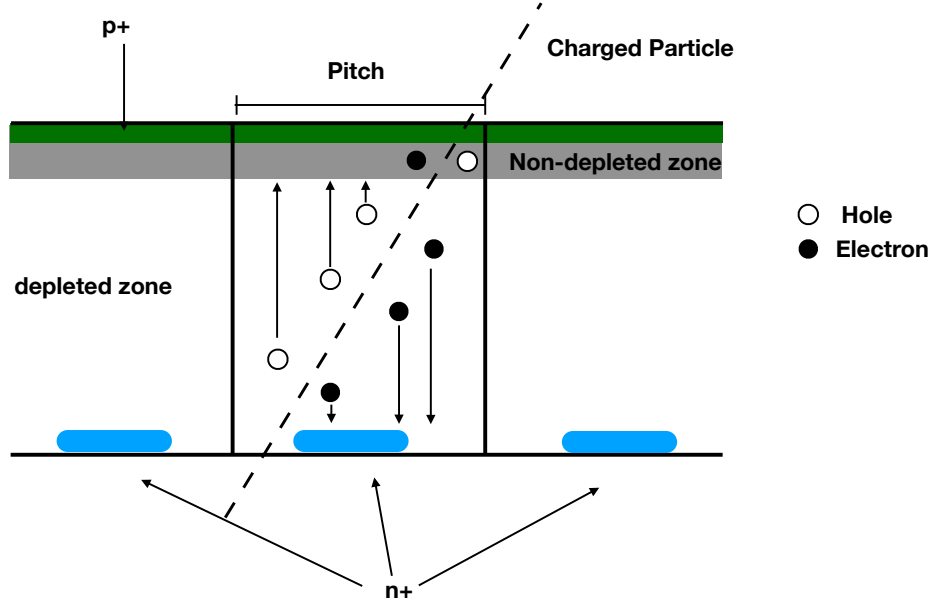


Figure 4.3: A charged particle travelling through a partially depleted silicon sensor.

p - n junction has a depletion width of

$$X \approx \sqrt{\frac{2\epsilon_0\epsilon_{Si}}{eN_a}(V_b + V_{bi})} \quad (4.10)$$

When the depletion width equals the detector thickness, the detector is fully depleted. The voltage at which this occurs is known as the depletion voltage.

The passing of a particle through a diode, such as the p - n junction described here, can be identified by measuring the deposited charge. By segmenting the sensor the location of the point where the particle crossed the sensor can be more accurately determined. A sensor segmented into multiple electrodes along one axis (known as strips) will yield position information perpendicular to the electrode orientation. Two-dimensional position information can be obtained by segmenting the electrodes along two axes. This two-dimensional segmentation is referred to as a pixel, and the whole structure as a pixel sensor.

4.3 Signals

As described in the previous section, the free moving charge carriers in the depletion region induce a signal on the electrodes, which is observed as a short current pulse. This signal is then read out by an Application Specific Integrated Circuit or ASIC. The ASIC that is used in the results here, known as the Timepix3, is in the same family of chips as the Medipix [35].

4.3.1 Time of Arrival and Time over Threshold

The Timepix3 can measure both the time of arrival and time over threshold simultaneously. The time over threshold is a proxy for the collected charge, as described in section 5.4. Figure 4.4 shows the operational principle of the pixels. The current pulse is shaped into the pulse sketched in figure 4.4. When the analogue shaped pulse passes

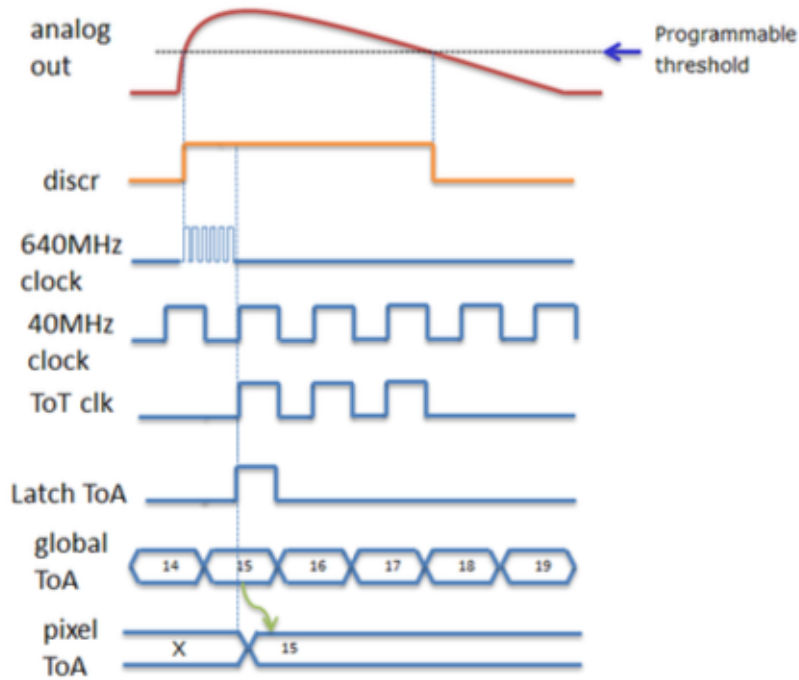


Figure 4.4: *Operation modes of the Timepix3 ASIC*

a set threshold, the number of clock pulses of the 640 MHz clock is counted until the

next rising edge of the 40 MHz clock. This gives the time of arrival. Next, the time when the pulse passes back across the threshold is determined, which gives the time over threshold. The time over threshold depends on the amplitude of the original current pulse. Thus the measurement of the time over threshold allows the determination of the amount of deposited charge. Using a calibration, this can be converted into a signal in electrons. The calibration is discussed in section 5.4.

4.3.2 Timepix3 ASIC

The Timepix3 ASIC [22] is designed in 130 nm CMOS technology and has a matrix of 256×256 square pixels each with a pitch of $55 \mu\text{m}$. There are 8 pixels, organised in a 2×4 configuration that make up a super pixel. Figure 4.5 shows the schematic of one pixel and a super pixel. The signal induced current is integrated and discharged by the pre-amplifier. The pre-amplifier needs a certain amount of time to discharge. The pre-amplifier output is compared to the threshold value. The global threshold is commonly distributed to all pixels. It can be tuned locally with a 4-bit trim DAC during the equalisation, using the procedure discussed in section 5.3. The analogue front end synchronises hits to the on-pixel clock, and local clock gating reduces the power consumption of inactive pixels. The data from the super pixel is read out in one packet.

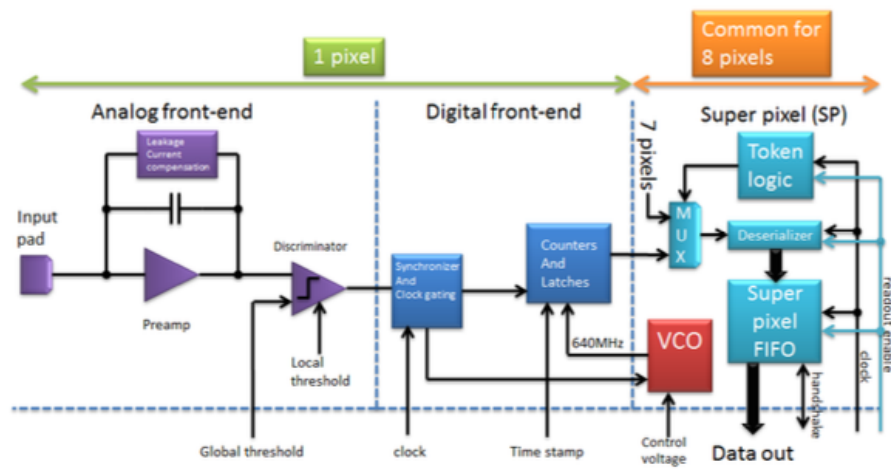


Figure 4.5: Schematic for one pixel and super pixel of a Timepix3 [22].

The Timepix3 has a zero suppression scheme that minimises that time that is needed to read the data. This scheme only reads out the pixels that register a hit. The time of arrival is typically measured with a 14-bit register that can be extended by 4 bits to reach a timing resolution of 1.56 ns. The maximum hit rate of the Timepix3 is 80 Mhits/s.

4.3.3 Time walk

Particles coming from the same bunch crossing should arrive at the same time. However, the time at which the signal reaches threshold depends on the magnitude of the induced pulse. This leads to the phenomenon known as time walk. Figure 4.6 illustrates this effect. As mentioned before, the Timepix3 simultaneously can measure time of arrival

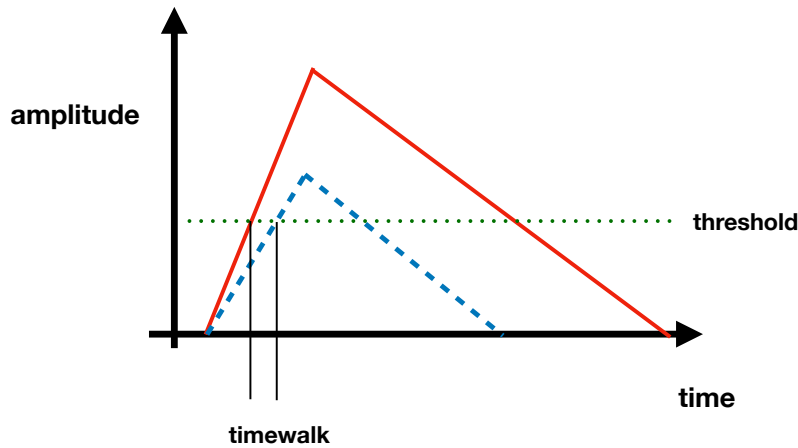


Figure 4.6: *Sketch of time walk effect.*

and time over threshold. This can be used to measure the time walk. This is done by plotting the difference between the time of the track, t_{track} , which is defined as the mean of the times at which the particle traversed the different planes of the telescope (see section 6.2.2), and the time of the hit, t_{hit} , which is the time of arrival of the hit, as a function of charge. Figure 4.7 shows an example of this sort of time walk distribution.

The profile is overlaid on the distribution, this is the mean of the distribution. For large charge values, the difference between the t_{track} and t_{hit} is small. For small charge values, there is a non-negligible time walk effect. The bunch crossing at LHCb is 25 ns; the time

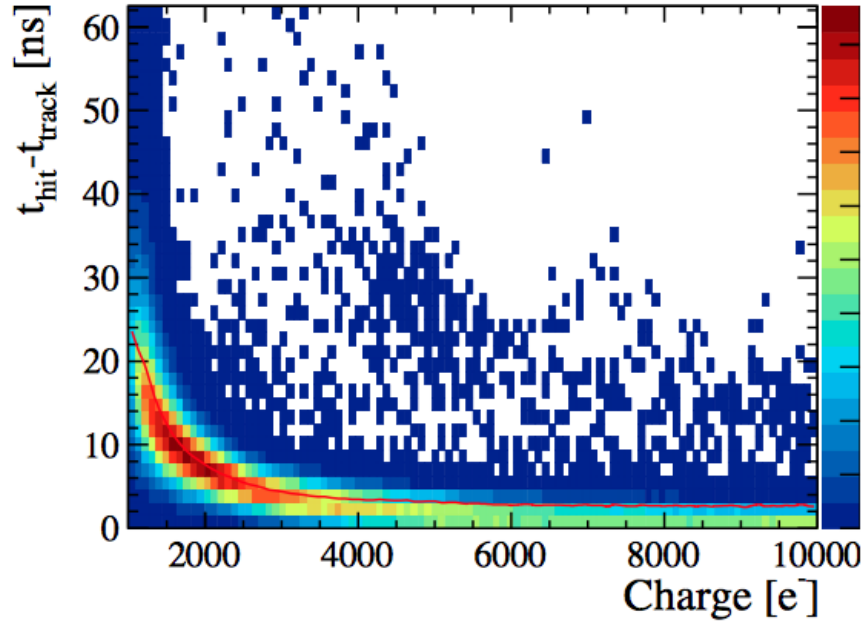


Figure 4.7: Time walk as a function of charge at 200V for a 200 μm thick silicon sensor bump bonded to a Timepix3 ASIC. The colour scale shows the number of entries at that point.

walk distribution shown here shows the majority of the hits having a difference in time less than 25 nanoseconds. As discussed in section 9.2 the expected minimum signal to register a hit is 6000 electrons. Hence, all clusters will be assigned to the correct bunch crossing. Pulse height information on the neighbouring pixels might arrive in the next bunch crossing.

4.4 Sensor Configurations

4.4.1 Sensor Types

The p -on- n type is the most commonly used type of sensor. The depletion region of this type starts from the p^+ regions and extends toward the backplane of the sensor. The electrons in the sensor drift towards the backplane of the sensor while the holes drift towards the p^+ electrodes, also known as implants. This type of detector has the

advantage that already for a very small bias voltage, the p^+ strips are insulated from each other. Hence, even if this sensor would not be fully depleted, it will operate as a good detector. There are, however, two major drawbacks with this sensor type. First, as the detector collects holes, which have a factor of approximately three smaller mobility compared to electrons, the signal will be about 3 times smaller. Secondly, when a p -on- n type sensor is exposed to a radiation dose of more than about $10^{13} \text{ 1 MeV n}_{eq} \text{ cm}^{-2}$ the depleted region starts from the backplane not the electrodes. This means that the detector needs to be operated at full depletion, otherwise the p^+ electrodes are no longer insulated and charge of the hits is resistively shared between the strips, making position reconstruction basically impossible and resulting very low efficiencies. Radiation damage is discussed in Chapter 8.

The radiation softness of p -on- n type sensors makes them unsuitable for use in the VELO and that other sensor types must therefore be used.

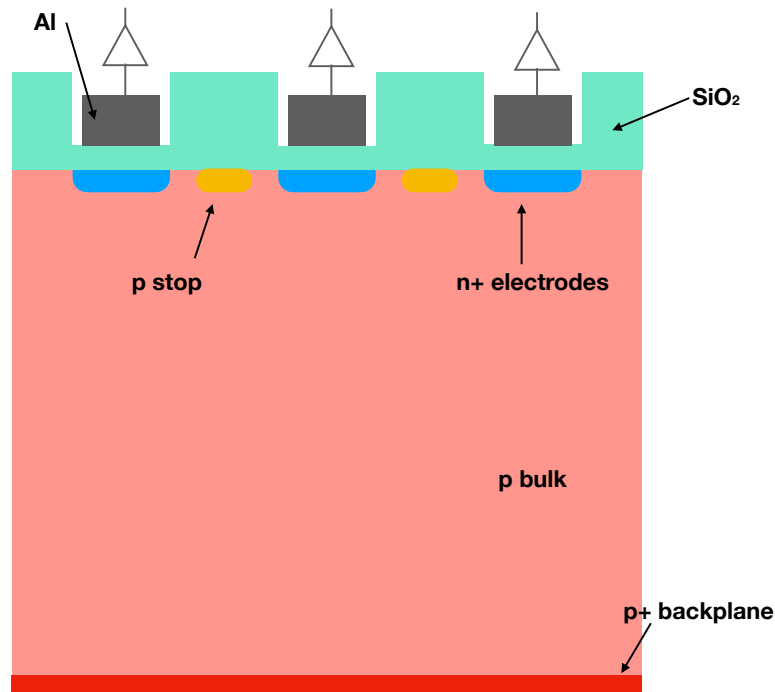


Figure 4.8: Sketch of a n -on- p type silicon sensor, with silicon oxide layer

For the LHCb VELO upgrade two types of sensor designs were looked at: The n -on- p and n -on- n types. The n -on- p type uses a p^+ bulk with n -type implants. As discussed in chapter 8, this type of sensor is more radiation hard than the p -on- n type discussed

above. It has a further advantage in that electrons, rather than holes, are collected, resulting in a larger induced signal. The amount of charge that gets trapped is also smaller, which means that less charge is lost after the crystal becomes damaged. It can also be operated partially depleted as the implants are insulated. For the *p-on-n* type of sensor the depletion zone starts at the pixel implants. In an *n-on-n* type sensor, the n^+ electrodes collect electrons and the depletion zone starts at the backplane, which means that it has to be operated at full depletion. However, irradiation causes the bulk to undergo type inversion. When this happens it makes the sensor behave as if it were an *n-on-p* type sensor. After type inversion takes place the depletion area starts from the electrodes. Figure 4.8 shows a *n-on-p* type sensor with a silicon oxide layer. The silicon oxide layer is used as a masking layer for etching or cleaning the silicon surface. This layer is where a lot of charge can be trapped especially when the sensor is highly irradiated. A *n-on-n* type sensor is the same concept just with the *p* bulk changed to *n* bulk.

4.4.2 Inter-pixel Isolation

To reconstruct the position of the traversing particles, the electrodes need to be insulated from each other. This occurs as long as there is a *p-n* junction. However, in *n-on-n* detectors, there is no *p-n* junction between the implants and the bulk until type inversion. This means that other techniques must be used to ensure that the electrodes are isolated. There are two different types of isolation technique, known as *p-stop* and *p-spray*, that can be used to prevent an electron accumulation layer forming below the silicon oxide layer during irradiation. The *p-stop* technology uses a blocking electrode to stop the formation of the accumulation layer. The *p-spray* technology involves placing a thin layer of *p*-doped silicon beneath the silicon oxide. The *p-stop* technique with a high dose of p^+ results in a good isolation between the electrodes. On the other hand *p-spray* has a very good high voltage performance due to a reduction in the electric field lines in the sensor. Another advantage is the *p-spray* technique takes one less photolithographic step. Both the *p-stop* and *p-spray* techniques are used in the prototype sensors tested for the upgrade.

4.4.3 Edge designs

The sensors are cut out of a large wafer. These cut edges are rough and could provide conductive paths around the outside of the sensor. To avoid this and a high electric field at the edge, guard rings are implemented. Guard rings are used at the edge of the sensor to slowly drop and terminate the potential. The guard rings result in a $500\text{ }\mu\text{m}$ inactive area at the edge of the sensor. This leads to multiple Coulomb scattering and also prevents the placement of sensors close to the beam. A smaller area around the edge of the sensor is therefore desirable. An alternative is the use of so-called active edge sensors. Active edge sensors are etched and doped [36]. Figure 4.9 shows the differences in the edge designs. It can be seen that the inactive area is reduced to between 20 and $50\text{ }\mu\text{m}$ when using active edge sensors. However, the doping of the edge of the sensor distorts the electric field lines. The collected charge for different guard rings designs is discussed in section 6.4. The doped edge design was not pursued in the prototype sensors tested in this thesis.

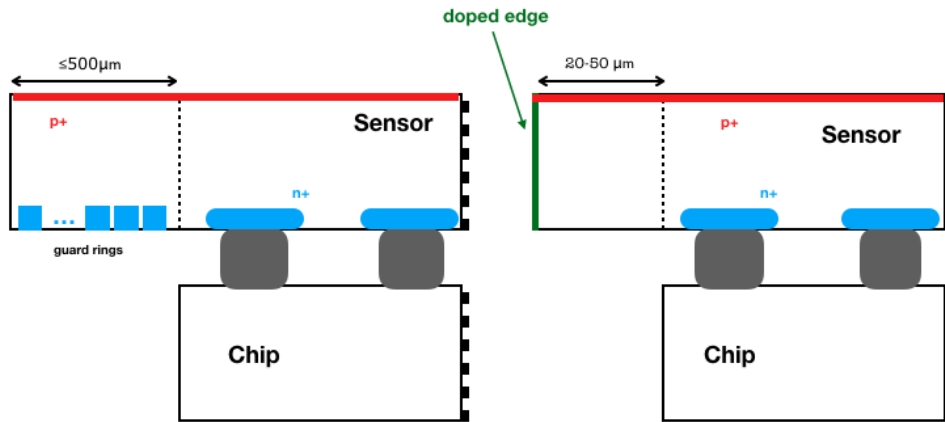


Figure 4.9: Different edge designs to reduce the electric field at the edge of the sensors, using guard rings (left) or active edges (right).

4.4.4 Prototype overview

A number of different sensor variations were tested for use in the VELO upgrade. The two manufactures that supplied the sensors was Hamamatsu and Micron. The type of silicon, size of the implant, and thickness were all varied. Hamamatsu only supplied 200

μm thick silicon but had many different implant sizes. Micron supplied both 200 μm thick silicon sensors and 150 μm thick silicon sensors. Micron also provided *n-on-p* and *n-on-n* type silicon. They were tested in the laboratory, as discussed in Chapter 5, and in a test beam, as discussed in Chapter 6. An overview of the assemblies that were used in the testing and which are described in Chapters 7 and 9 are listed table 4.1.

Assembly ID	Thickness [μm]	Sensor Type	Manufacturer	Implant Width [μm]	Depletion Voltage [V]
S6	200	<i>n-on-p</i>	Hamamatsu	39	~ 130
S8	200	<i>n-on-p</i>	Hamamatsu	35	~ 130
S11	200	<i>n-on-p</i>	Hamamatsu	39	~ 130
S17	200	<i>n-on-p</i>	Hamamatsu	35	~ 130
S18	200	<i>n-on-p</i>	Hamamatsu	35	~ 130
S20	200	<i>n-on-p</i>	Hamamatsu	35	~ 130
S22	200	<i>n-on-p</i>	Hamamatsu	39	~ 130
T2	200	<i>n-on-p</i>	Hamamatsu	35	~ 130
S23	200	<i>n-on-p</i>	Micron	36	~ 40
S24	200	<i>n-on-p</i>	Micron	36	~ 40
S25	200	<i>n-on-p</i>	Micron	36	~ 40
T15	200	<i>n-on-p</i>	Micron	36	~ 40
S27	150	<i>n-on-n</i>	Micron	36	~ 40
S29	150	<i>n-on-n</i>	Micron	36	~ 40
S30	150	<i>n-on-p</i>	Micron	36	~ 40
S31	200	<i>n-on-n</i>	Micron	36	~ 40
S33	150	<i>n-on-n</i>	Micron	36	~ 40

Table 4.1: *Table of the assemblies tested. The assembly IDs that start with 'S' are a single assembly and the 'T' refers to triple assemblies in which three sensors are attached together.*

Chapter 5

Laboratory Tests of Prototype Sensors

Before the prototype sensors were placed in a test beam, a number of tests were performed on the sensors in the lab. Each wire-bonded assembly was required to have an IV measurement up to break down, threshold equalisation of the ASIC and a time over threshold calibration, all of which are described below.

5.1 Test Set-up

The sensors were placed in a vacuum tank for all testing procedures, as can be seen in figure 5.1. The assemblies needed to be tested in both dry air and in a vacuum. The irradiated sensors needed to be kept cool during the tests. Since the VELO sensors will be operated at around -22°C and in a vacuum, the sensors were tested under the same conditions. For practical reasons, unirradiated sensors, which do not require significant cooling to operate, were tested in dry air at 15°C . The Timepix3 was controlled and read out using the Speedy PIXel Detector Readout, SPIDR [37]. The SPIDR was used in both the lab tests and the test beam. A SPIDR board consists of a Xilinx Artix7 FPGA and a 10 Gb ethernet optical connection to handle the high rates of the Timepix3.

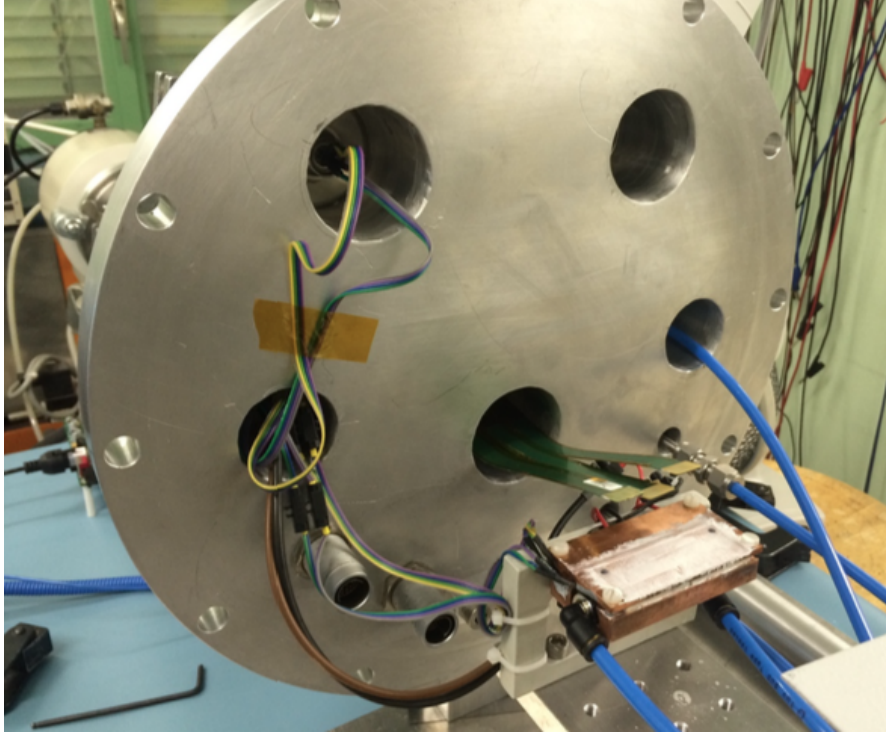
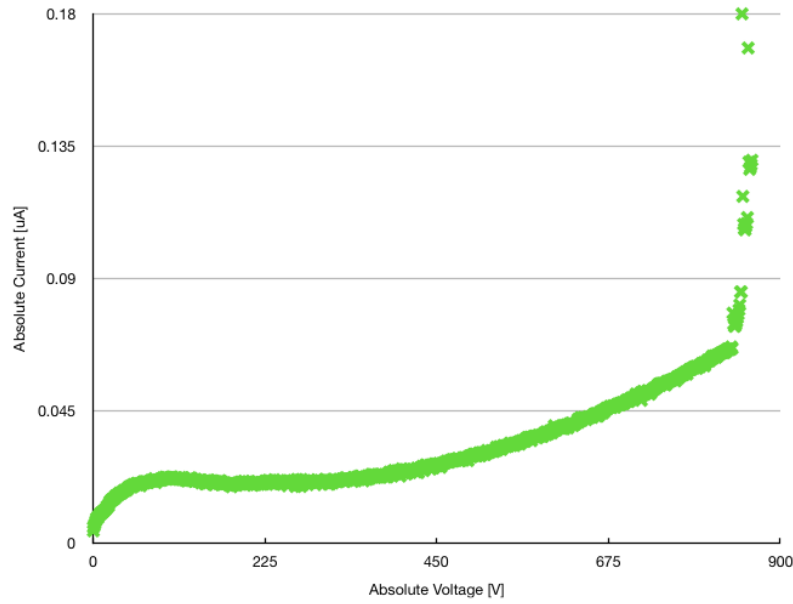


Figure 5.1: *Picture of laboratory setup of vacuum tank at CERN, showing the Peltier cooler and Kapton connectors.*

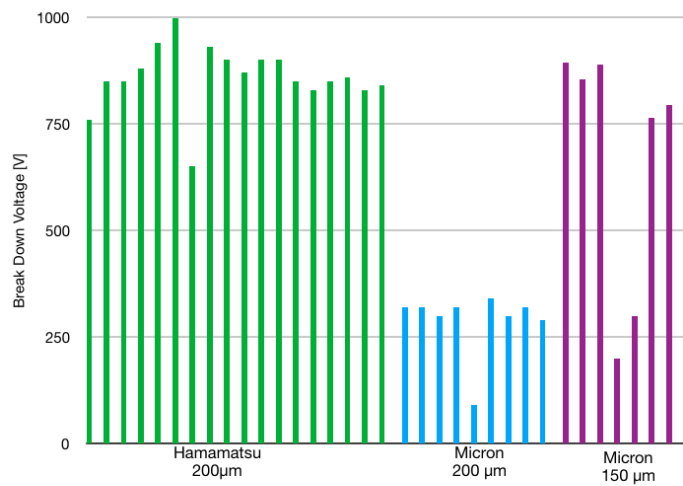
5.2 Current Voltage Scans

To check that the leakage current is of an acceptable level, to find the depletion voltage, and to determine the high voltage tolerance of the sensors, an IV scan is made. Since the foreseen power supplies for the VELO upgrade can provide a maximum voltage of 1000 V, all sensors are tested up to that value. Even after the highest radiation dose, sensors must either fully deplete before 1000 V or, at least, not breakdown before 1000 V [8]. The IV scan was taken in 1V steps with a 2-second delay between the steps to allow the current to settle so an accurate reading could be made. An example of one the output of these IV scans can be seen in figure 5.2.

Initially, the current increases until full depletion is reached. For the example sensor in figure 5.2 that occurs around 130 V. After that, the leakage current stays relatively constant, until breakdown occurs, after which a large increase in current is observed. The corresponding voltage is referred to as the breakdown voltage. For the sensor in figure 5.2 the breakdown voltage is around 870 V. Figure 5.3 shows the breakdown voltage for different unirradiated sensors tested in dry air. The Hamamatsu sensors are displayed

Figure 5.2: *Example of an IV scan.*

in green, the Micron sensors that have a thickness of 200 μm are shown in blue and the 150 μm thick Micron sensors are shown in purple.

Figure 5.3: *Breakdown voltages for unirradiated sensors, each bar represents a separate sensor.*

Before irradiation, the sensors need to be operated safely above the depletion voltage but below breakdown. The unirradiated Hamamatsu and the 150 μm thick Micron sensors develop large currents and instabilities between 750 and 950 V. The 200 μm thick Micron

sensors break down at approximately 300 V. The depletion voltage of the Hamamatsu sensors is approximately 130 volts, while the Micron sensors have a depletion voltage of approximately 40 volts. Hence, for all sensors, there is a comfortably large range above depletion and below breakdown in which the sensors can be operated. All of the assemblies tested before irradiation we found to be viable for further testing. The current-voltage scans for the sensors after irradiation are shown in section 9.1.

5.3 Equalisation

The sensors have a coarse threshold and fine threshold that can be set for each pixel, as was described in section 4.3.2. The fine threshold mitigates the pixel-to-pixel variation in gain. An equalisation procedure is performed to acquire the optimal setting for the fine threshold using a 4-bit trim DAC. This procedure measures the baseline level of the amplifier by scanning the global threshold while recording the number of noise hits in each pixel. The scan is performed twice for each pixel, once with the trim DAC at zero, the lowest fine threshold, and once with the trim DAC at fifteen, the highest fine threshold.

Figure 5.4 shows the distributions of these pixel baselines. The blue distribution is the baseline when the trim DAC is set to zero and the red distribution shows the baselines when the trim DAC is set to fifteen. From the two results for each pixel, an optimal setting is obtained for that pixel by linear interpolation. Figure 5.4 show the results of the equalisation. After tuning the trim DACs, the final distribution is much narrower which reduces the noise of the Timepix3 due to threshold dispersion.

If the threshold level of a pixel cannot be adjusted to the same level as the surrounding pixels, then it is masked. The number of masked pixels is typically less than 1% of all of the pixels in the sensor.

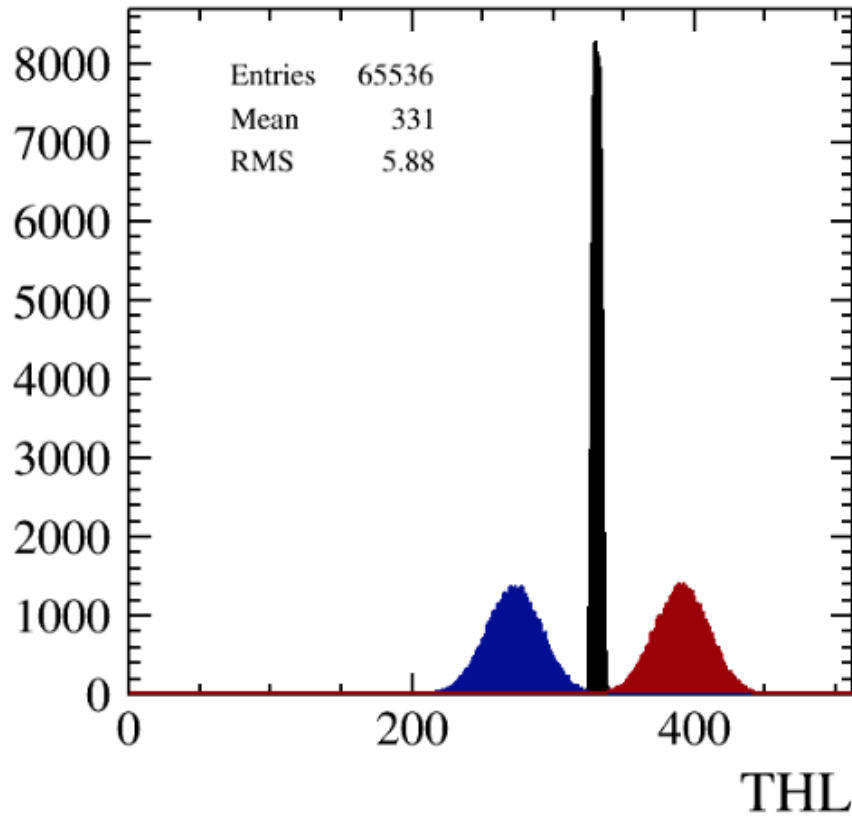


Figure 5.4: *Results of the threshold distributions during and after the equalisation procedure, the red distributions shows the pixel baselines when the trim DAC is set to zero and the blue distribution is the equivalent when the trim DAC is set to fifteen. The black distribution shows the threshold dispersion after equalisation.*

5.4 Test Pulse Calibration

The Timepix3 ASICs register the signal in the form of time over threshold counts, as discussed in section 4.3.1. To convert the time over threshold into the equivalent input signal in electrons a calibration procedure is carried out. Each pixel has an integrated test pulse circuit, which includes a switched capacitor. An external voltage step is applied to the capacitor, and thus a known amount of charge is injected, and the pixel's response is measured in time over threshold, ToT. This procedure is carried out multiple times, varying the magnitude of the voltage step each time [38]. The measured ToT for a given injected charge can vary from pixel to pixel because of variations in the discharge current across the pixel matrix. The calibration curve is determined for each pixel using the data from this procedure. An example is shown in figure 5.5.

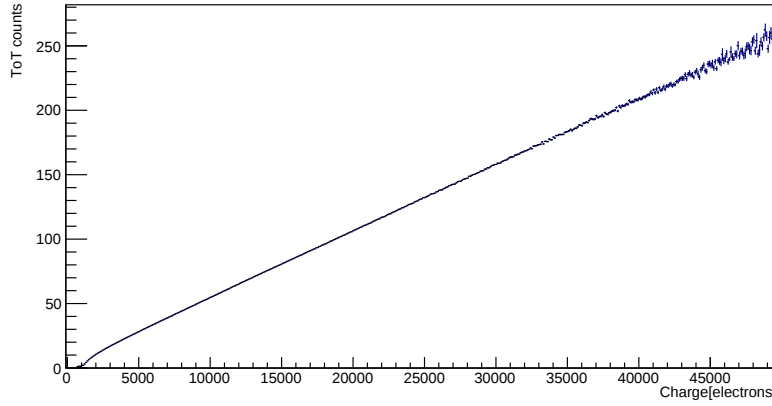


Figure 5.5: *Example of calibration curve from a pixel showing the connection of time over threshold to electrons.*

Figure 5.5 shows an example of a calibration curve from a pixel, this shows the time over threshold value and the corresponding electron value. There is a linear section, which occurs for values above 2000 e^- , and a non-linear section. This latter part is shown in more detail in figure 5.6 and is close to the detector threshold.

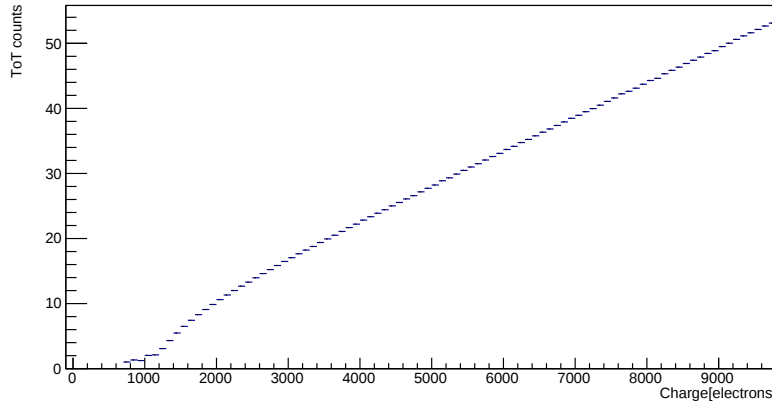


Figure 5.6: *Magnification of the non-linear section of the example calibration curve shown in the previous figure.*

All of the prototype assemblies have a per-pixel calibration performed, both before and after irradiation. The resulting calibration curves can be described by the following expression [39]:

$$ToT(q) = g \cdot q + ToT_o - \frac{c}{q - t} + o \quad (5.1)$$

where q is the amount of charge injected, g is the gain, o is the offset, ToT_o is the original time over threshold value, t is the threshold, and c is a fit parameter that describes how quickly the transition from the non-linear section to the linear section occurs.

5.5 Summary

The ultimate method of testing a sensor is to make use of a test beam setting to understand its performance with real particles. However, before a sensor can be tested using a particle beam, it must first be characterised and calibrated in the lab. Even after being subjected to the highest radiation dose, sensors need to fully deplete at an applied voltage of less than 1000 V or at least not breakdown before 1000 V, in order to be considered acceptable for use in the VELO upgrade. The depletion voltages before irradiation for the Hamamatsu sensors are approximately 130 V, and for those manufactured by Micron are approximately 40 V. The breakdown voltages before irradiation for the Hamamatsu sensors range between 650 V and 1000 V, while the 150 μm thick Micron sensors breakdown between 750 and 950 V. The 200 μm thick Micron sensors breakdown at approximately 300 V. Hence, for the majority of the sensors considered, there is a comfortably large voltage range above the depletion voltage and below the breakdown voltage, in which the sensors can be operated. After the IV scan was performed, the equalisation procedure was carried out to find the optimal per pixel fine threshold settings. Finally, a test pulse calibration scan was performed to obtain a per pixel calibration. The calibration converts time over threshold counts into the equivalent signal in electrons for each pixel.

Chapter 6

Test beam assembly for testing of prototype sensors

The prototype silicon sensors for the VELO upgrade need to be thoroughly tested before an optimal design is chosen and they are mass produced. The prototype sensors have different thicknesses, doping profiles, implant widths, and edge designs, as described in section 4.4. After characterisation and calibration in the lab, the sensors need to be tested for charge collection, position resolution and efficiency. To achieve this, the sensors were placed in the 180 GeV beam of protons and pions provided by the SPS at CERN, where the position and time information for the particles fired through the sensors was reconstructed using the Timepix3 telescope.

6.1 Timepix3 Telescope

The Timepix3 telescope is based on the TimePix telescope [40]. The Timepix3 telescope consists of 8 Timepix3 ASICs bump-bonded to 300 μm -thick silicon sensors equally divided over two arms [41]. The Device under Test (DuT) is placed in between the two arms of the telescope where the pointing resolution is better than 2 μm , as discussed in section 6.2.4 [40]. The set up is shown in figure 6.1. The Timepix3 telescope uses SPIDR boards [37] to readout the Timepix3 ASICs. The SPIDR boards were developed

to exploit all of the capabilities of the Timepix3 chip including a high data output of 80 MHits per chip per second.

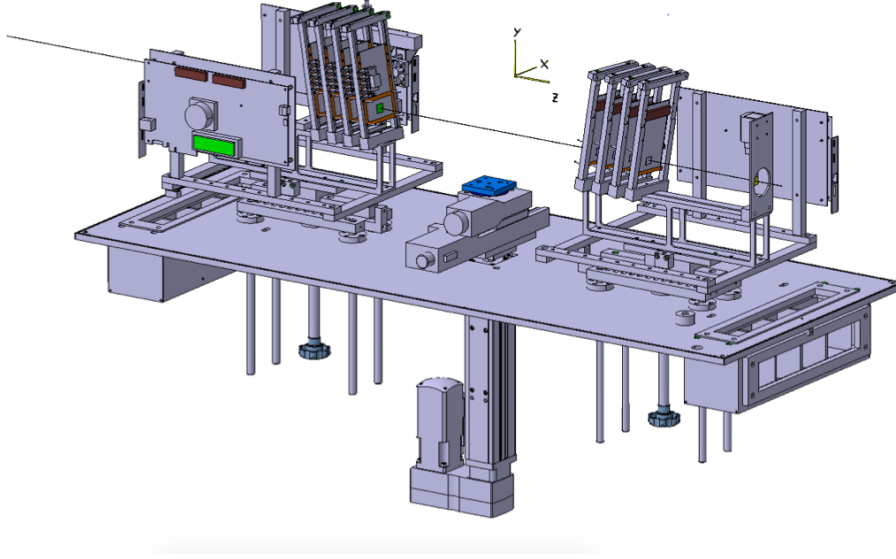


Figure 6.1: *The Timepix3 Telescope with the 8 telescope planes distributed evenly over two arms with the DuT in the middle. The SPIDR boards that are needed for the Timepix3 ASIC are also visible.*

The global reference frame of the telescope (x, y, z) is defined as $(0, 0, 0)$ at the bottom left hand corner of the upstream most telescope plane shown in figure 6.2. The Z direction is along the beam axis, perpendicular to the XY plane. The row number of the pixel matrix corresponds to the y coordinate, and the column number of the pixel matrix is the x coordinate. The telescope planes are placed along the beam axis at fixed intervals. They are rotated by 9° around both the x and y global direction to get the optimal spatial resolution [40].

6.2 Telescope Tracking

To reconstruct the position of the point at which the particle traverses the Device under Test, the particle trajectory or track has to be reconstructed using the Telescope. When a particle passes through a sensor it generates a signal. When the signal in an individual pixel exceeds the threshold a hit is registered in that pixel; multiple hits then create a cluster. A particle will generate clusters in all the sensors it traverses. Combining all the clusters from the same particle allows the track to be reconstructed and thus the

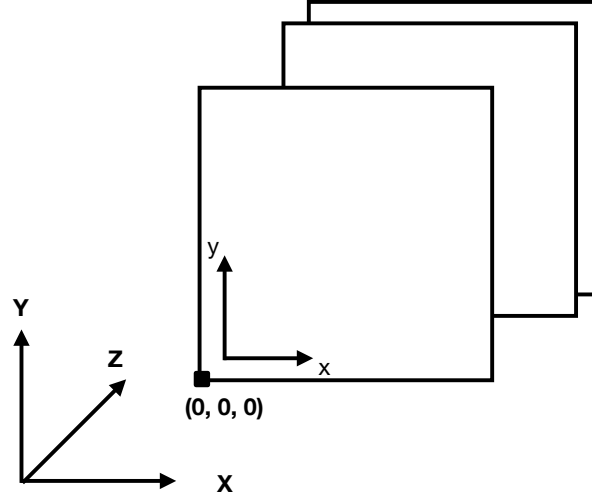


Figure 6.2: The global and local reference planes for the Timepix3 Telescope.

position where the particle traversed the DuT to be determined. The track fitting procedure is performed with the purpose built offline software package *KEPLER*, based on the *GAUDI* framework[42]. As the detectors are not perfectly aligned they must be aligned offline first. The procedure through which tracks are reconstructed and the detectors aligned is explained in detail in the next sections.

6.2.1 Hit collection and clustering

When a pixel registers a signal above the set threshold, a hit is registered. The collected hits are ordered in time using the recorded time stamp information, which has nanosecond precision. The first hit in recorded time is referred to as the seed pixel. A clustering algorithm loops over the neighbouring pixels for each pixel hit. If a neighbouring pixel is within a time window surrounding the seed pixel of 100 nanoseconds, the hit is added to the cluster. The time stamp of the cluster is the time stamp that is associated with the earliest hit. The time over threshold for each hit in the cluster is converted to a number of electrons using the calibration described in section 5.4. The cluster charge is then the sum of all the charges of the constituent hits. The size of the cluster is defined as

the number of pixels that make up the cluster. Each telescope plane will have a typical cluster size of around 3 pixels due to the angle of the telescope planes.

The position of the cluster is found using the centre-of-gravity method given in equation 6.1. The reconstructed cluster position is the charge-weighted average position of all the pixels in a cluster.

$$x_{cluster} = \frac{\sum x_i S_i}{\sum S_i} \quad (6.1)$$

where x_i is the x -coordinate of the pixel and S_i its signal. The same procedure is done for the y -coordinate as well.

6.2.2 Tracking

Track reconstruction is based on the timing information of the cluster. The tracking starts on the first plane and looks to the next plane for a cluster within 10 ns of the first cluster. These two clusters become the track seed. The track seed is extrapolated to the next plane, excluding the device under test, looking for a cluster within a cone with an opening angle of 0.01 radians and the 10 ns time window. Providing a cluster is found on each subsequent plane, this process continues until all planes have been considered. A complete track has a registered cluster on all of the planes.

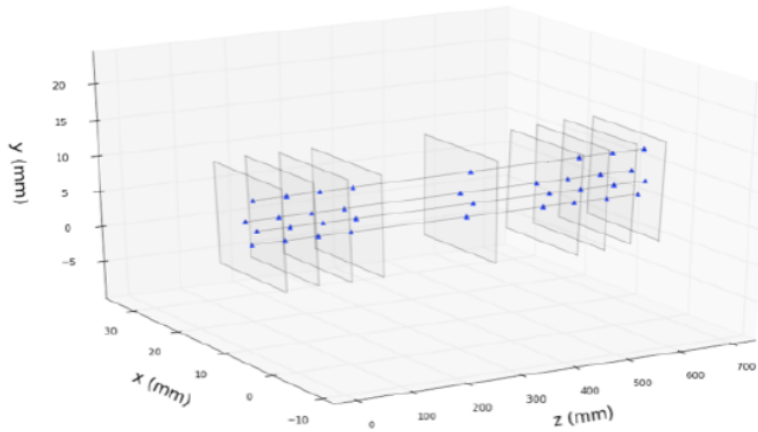


Figure 6.3: Four example tracks in the Timepix3 telescope.

An example of four tracks reconstructed in the telescope can be seen in figure 6.3. Here all of the telescope planes are shown with tracks traversing each plane. Next, the clusters are fitted with a straight line. The χ^2/ndof distribution for the tracks reconstructed in the Timepix3 telescope is shown in figure 6.4. The majority of the tracks have a χ^2/ndof under 2, meaning the straight line fit is a good way of describing these tracks.

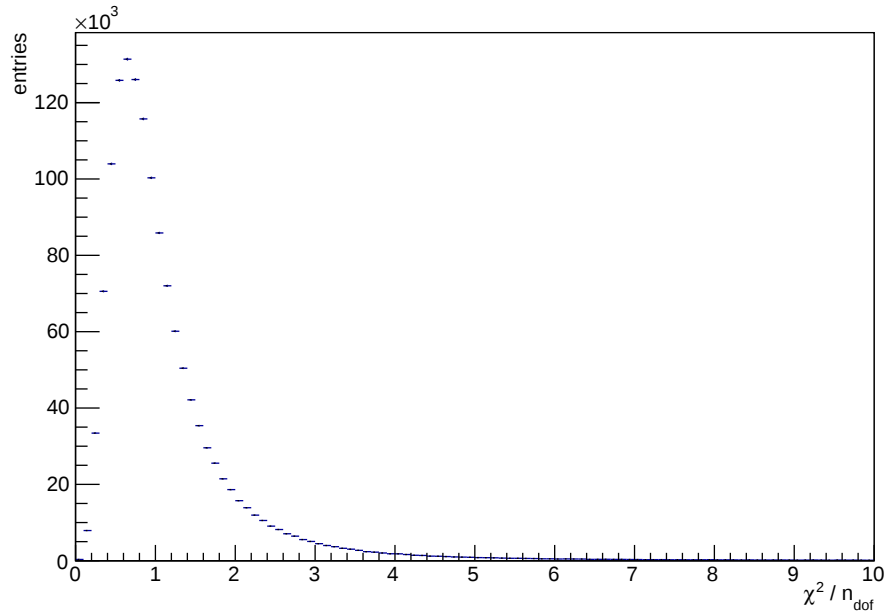


Figure 6.4: χ^2 for the tracks of the Timepix3 Telescope.

6.2.3 Alignment corrections of telescope

The telescope modules and DUT are mounted by hand in the telescope. Hence, their precision is only known to within a few hundred μm precision. As the expected hit precision of the module is of the order of 20 μm , this alignment precision is not sufficient. Hence, the actual positions and rotations of the modules need to be found and corrected. This procedure is known as alignment. First, the alignment of the telescope has to be performed. Misalignment is seen first in the residual distribution, which shows the difference between the predicted track position and the calculated cluster position. An example of a misaligned residual in x is shown for a telescope plane in figure 6.5. The misalignment becomes evident as the mean of the residual distribution is not centred around zero. The Timepix3 telescope alignment uses a data sample of the order of 10^4

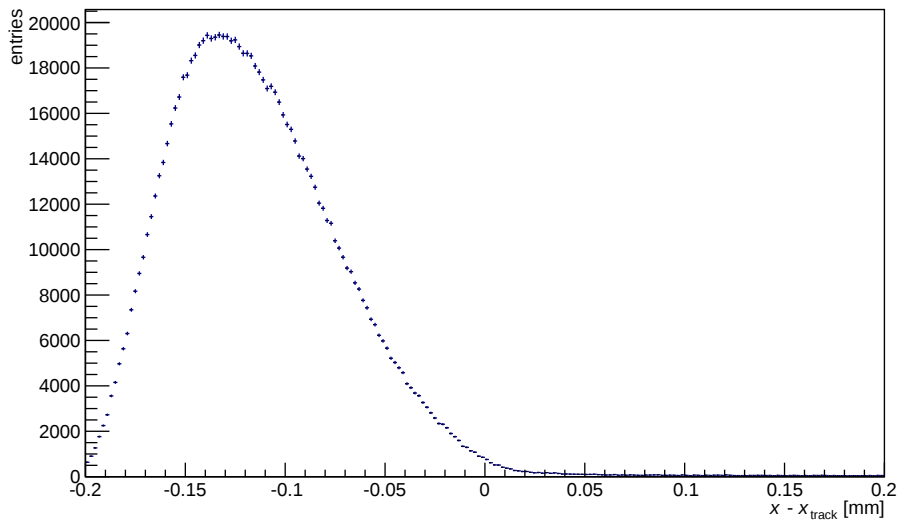


Figure 6.5: *Residual in x , showing misalignment with the non-zero mean.*

tracks. The alignment is based on the Millipede algorithm [43], which uses a linear least squares fit to optimise three rotation angles and three offset parameters for each plane. In the alignment procedure clusters with a size of less than five pixels are used. After completion of the alignment process all clusters are available for analysis. After alignment, a quality check is performed by looking at the residuals and the residual versus the global position on the sensor. Figure 6.6 shows an example of these checks after a successful alignment. The residual distributions are symmetric around 0 and the residuals do not show any dependence on the global position. The residual width is very stable across all telescope planes. The error on each of the planes is $0.15\mu\text{m}$, by estimating the variation of the residual across the plane.

6.2.4 Pointing Resolution

The pointing resolution uses the same process as the TimePix telescope [40]. When particles traverse the detector, they undergo multiple scattering leading them to change their direction. Furthermore, the hit positions are reconstructed with a finite precision due to the pixel size. As a consequence, there is an uncertainty in the measurement of the coordinates of the point where the particle traversed the DUT. This uncertainty is known as the pointing resolution. It is dependent on the intrinsic resolution of the

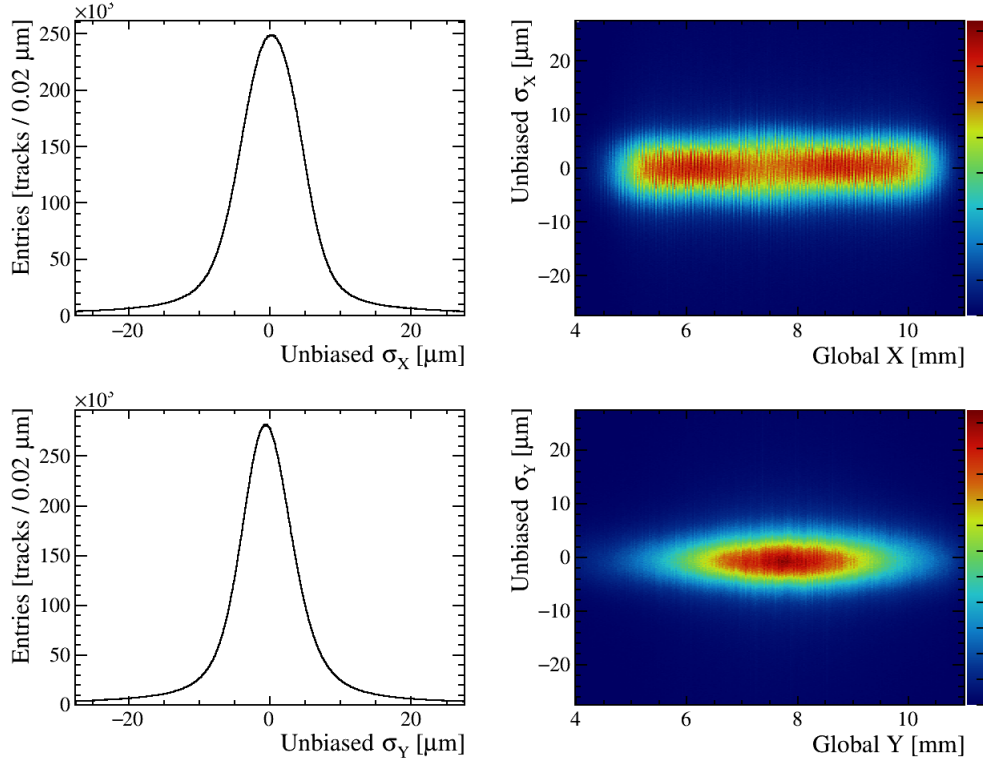


Figure 6.6: *Residuals in x and y for one telescope plane, both integrated over the chip and as a function of position.*

sensor, the z position, the number of telescope planes, the particle momentum and the radiation length of the material. The pointing resolution is calculated from the test beam data and a Monte Carlo simulation which is similar to the one used with the TimePix telescope [40]. In the simulation tracks are propagated through the detectors, taking into account the effects of multiple scattering. Having done this, uncertainties are assigned to each hit based on the measured detector resolution of the plane. After fitting tracks to the simulated clusters, the extrapolated position on the DUT is compared to the actual position and the pointing resolution is extracted. Figure 6.7 shows the expected track resolution as a function of Z . It demonstrates that the pointing resolution between the telescope arms is below $2 \mu\text{m}$.

6.3 Device under Test

After the telescope tracking is performed the device under test must also have its manual alignment corrected in the same way as the telescope. The tracks that are reconstructed

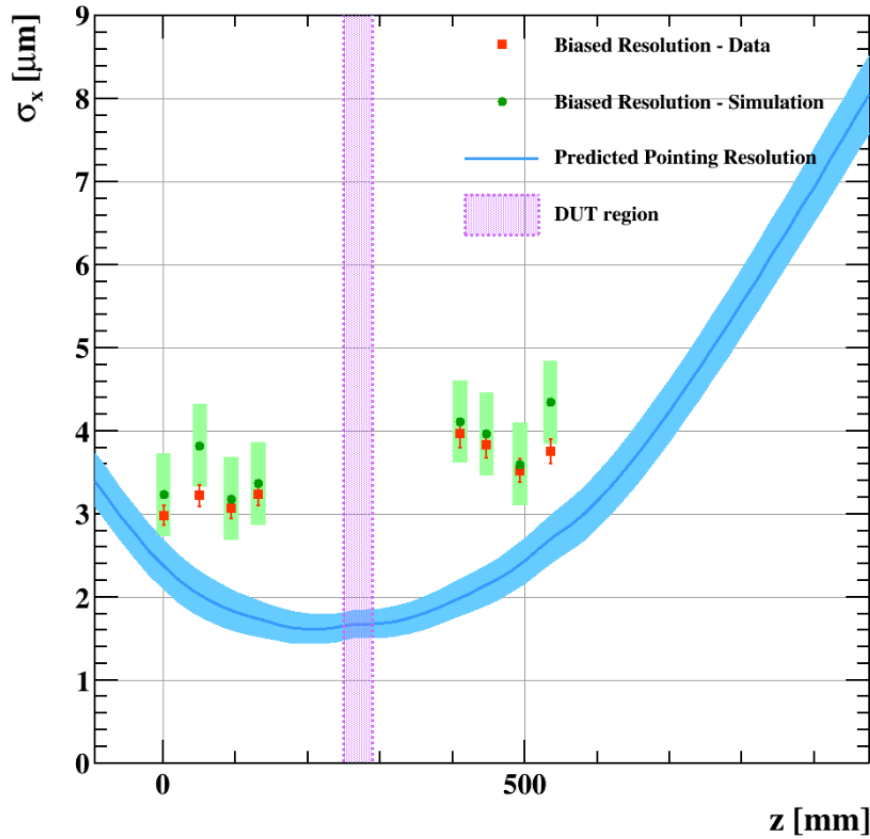


Figure 6.7: *Pointing resolution of the Timepix3 telescope in the x direction*[44].

using the telescope are extrapolated to the Z position of the DuT. The procedure used to align the telescope modules is then used to align the DuT. A cluster is associated with a track using both timing and spatial information. Figure 6.8 shows the time residual for an example device under test. The cluster must be within 50 ns of the track on the device under test. Figure 6.9 shows the residual in both x and y for a 200 μm thick n -on- p sensor operated at 300 V. Clusters are sought within a 220 μm diameter circle, centred around the track. The box shape of the residual is due to the majority of the clusters being one-pixels clusters. The residual value of one pixel clusters is a constant.

6.4 Sensor Performance

After the device under test has been aligned, the analysis can be performed. The tracks going through the telescope pass through the device under test. The same clusters and tracks that are used for the alignment are only a subset of the information used to gather

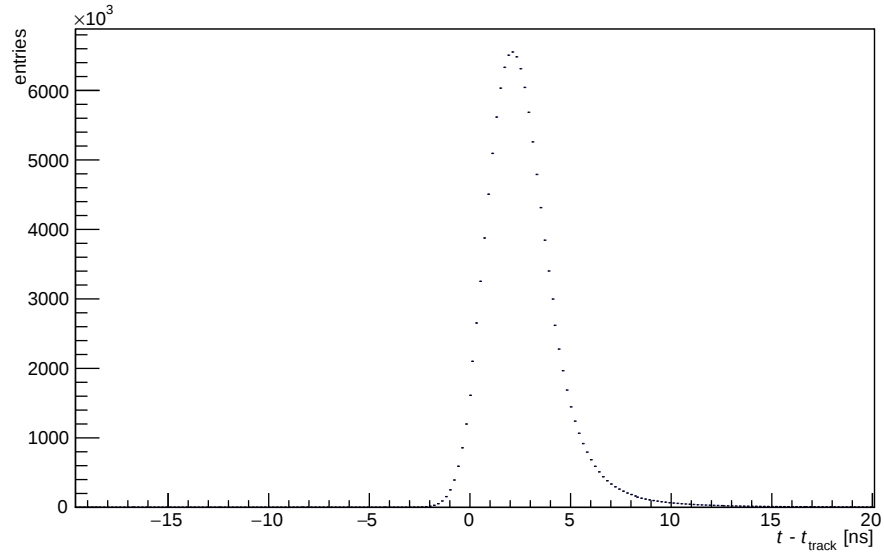


Figure 6.8: Time residual for a 200 μm thick *n-on-p* sensor operated at 300V.

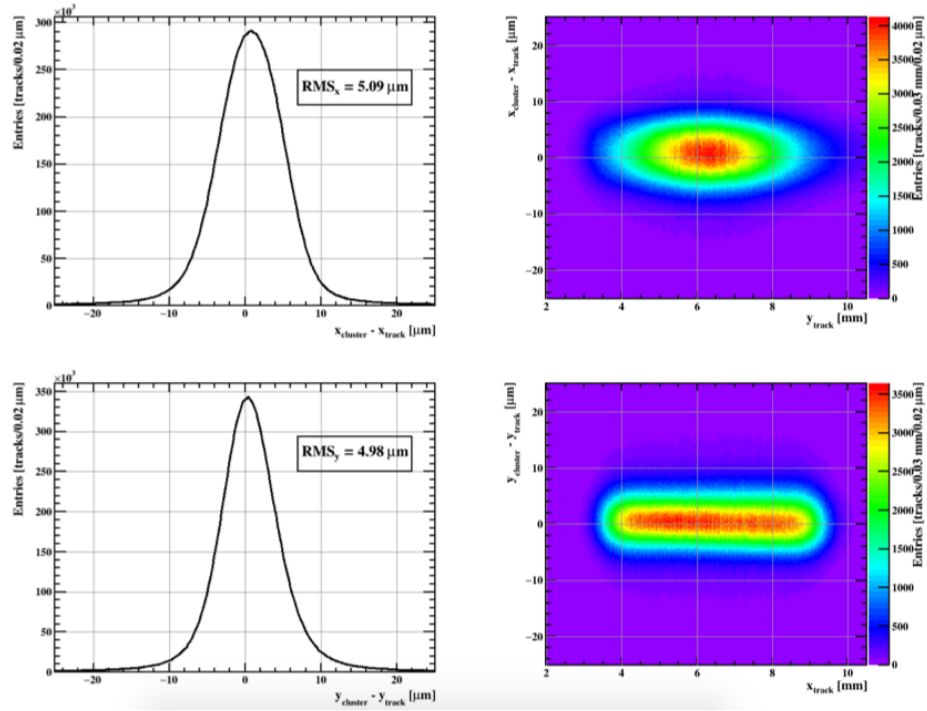


Figure 6.9: Residual for x and y for a 200 μm thick *n-on-p* sensor operated at 300V.

information about the sensor. Those hits that are above threshold can be converted from time over threshold counts to a number of electrons, as discussed in section 4.1.1.

When a particle crosses the sensor with a trajectory perpendicular to the sensor plane, the size of the cluster depends on where the particle crosses the pixel. Figure 6.10 shows the distribution of cluster sizes for a 200 μm thick *n-on-p* sensor operated at 300 V.

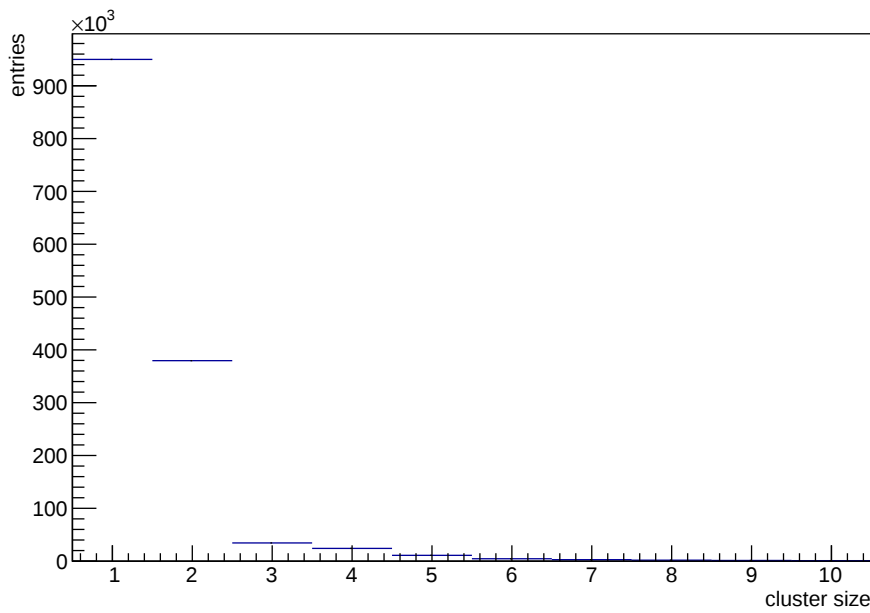


Figure 6.10: Cluster size distribution a 200 μm thick *n-on-p* sensor operated at 300V

The implant occupies the majority of the pixel and the implant is much larger than the charge cloud, which means that all the charge is collected by a single pixel for most hits. This means that the hit does not have a high enough signal in the neighbouring pixels to actually register as a hit. Particles that pass through the corner or the edges of the pixel, however, will result in a hit with a large enough signal that is will be shared between multiple pixels. This can be seen in figure 6.11, where the track intercept is plotted for different cluster sizes.

It is clear that one pixel clusters are most likely to occur in the centre of the pixel. Two-pixel clusters are most likely to happen when the particle crosses close to the pixel edge. Three- and four-pixel clusters are most likely to happen in the corner of a pixel, where more of the signal can cross the threshold in the neighbouring pixels. The cluster size does not vary much with the applied bias voltage.

The resolution of the sensor is dependent on the reconstruction of the track at its associated cluster position. The resolution as a function of the bias voltage is shown in figure 6.12. The minimum resolution occurs when the sensor reaches full depletion. The resolution of the sensor worsens when the sensor is over-biased. There is no dependence on the sensor thickness or the implant width.

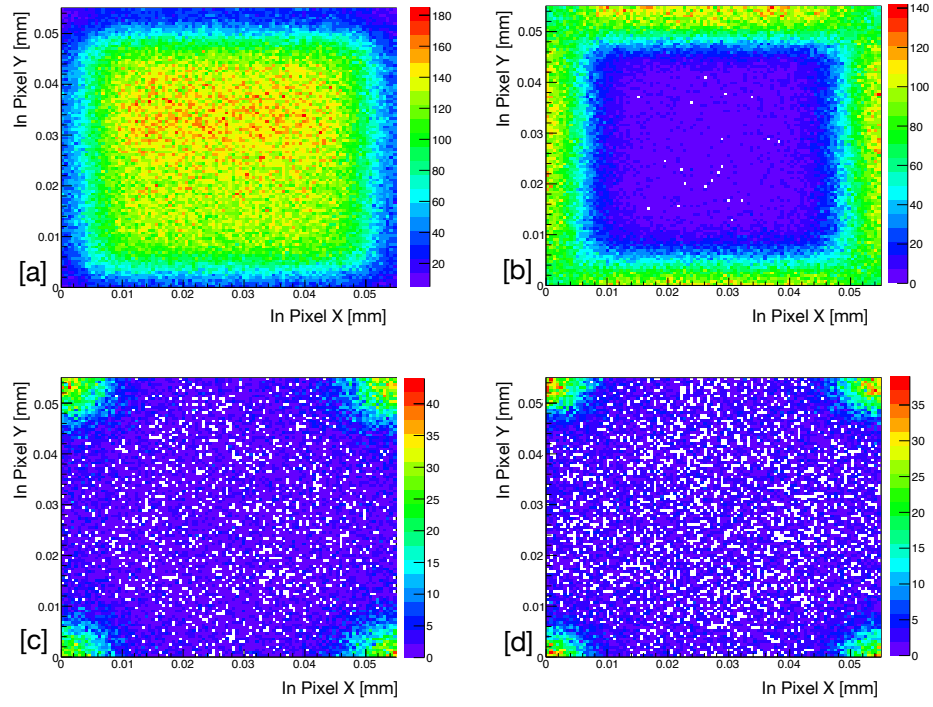


Figure 6.11: Track intercept coordinates for clusters made of (a) one, (b) two, (c) three and (d) four pixels for a 200 μm thick n-on-p sensor operated at 300V.

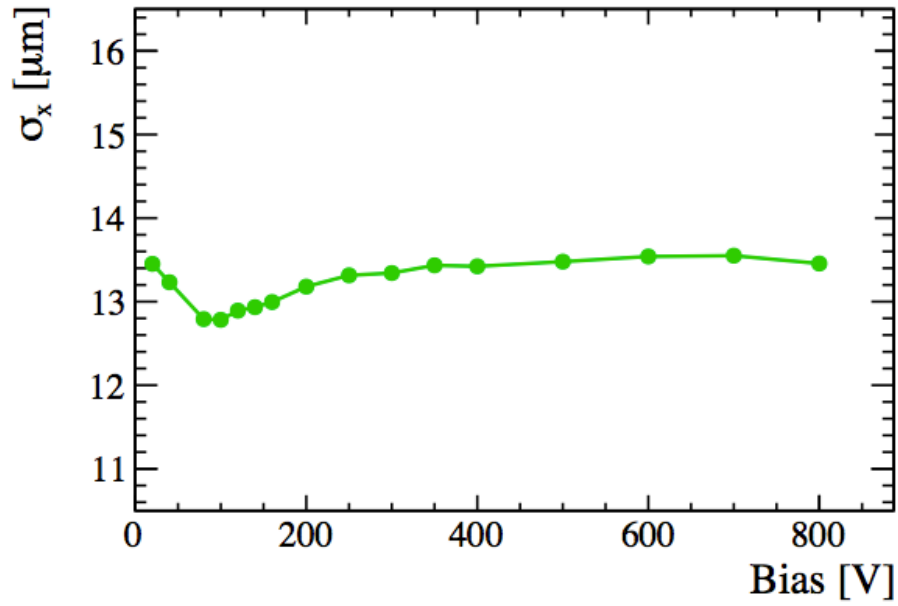


Figure 6.12: Resolution distribution of a 200 μm thick n-on-p sensor as a function of bias voltage [44].

At the edge of the sensor guard rings are used, as discussed in section 4.4.3. The collected charge at the edge of the sensor, as observed for different sensors before irradiation, are shown in figure 6.13. In the figure, the Hamamatsu sensors are displayed in green; the 200 μm thick Micron sensors are displayed in blue and the 150 μm thick Micron sensors are shown in purple. The sensors that collect significant charge outside the active area

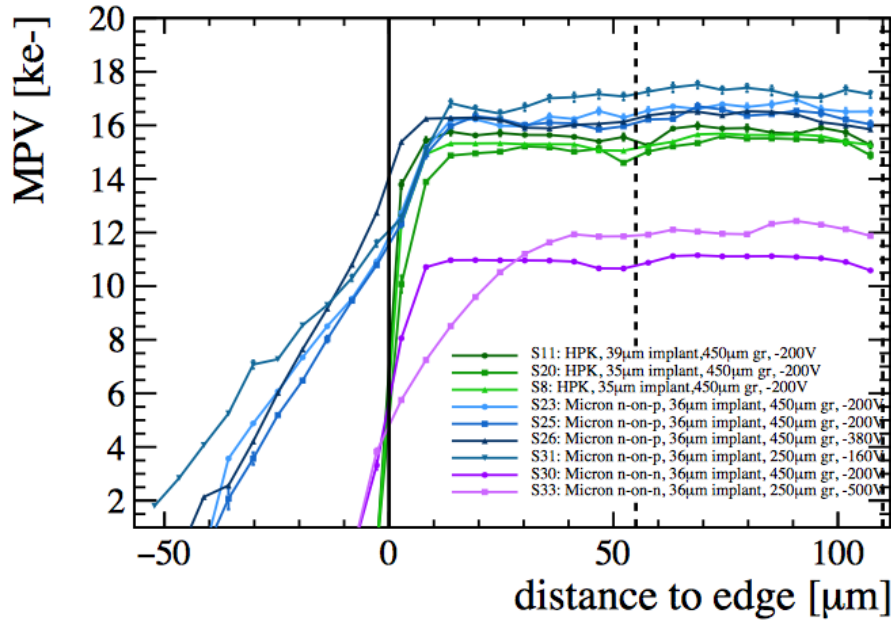


Figure 6.13: *Most probable collected charge at the edge of non-irradiated sensors. The edge of the pixel matrix starts at 0 μm [45].*

are the 200 μm thick n-on-p Micron sensors. The 150 μm thick sensors do not collect full charge in the first pixel on the edge. The edge of the sensor is very important in the VELO upgrade. This is due to the edge of the modules experiencing the highest occupancy, as was discussed in section 3.2. If the edge design of the upgraded sensor added to the increase in occupancy, as the 200 μm thick n-on-p Micron sensors appear to, it should mean that the resolution on the measurement of points closest to the beam will decrease.

An example of a fitted charge distribution is shown in figure 6.14 for an irradiated sensor; this will be discussed in section 8.4. The parameters of the fit to the charge collection distribution are varied one by one to find the error on the most probable value of collected charge. For each of these variations, the fit is performed on a given charge distribution. Next, the most probable value of collected charge distribution is fitted with

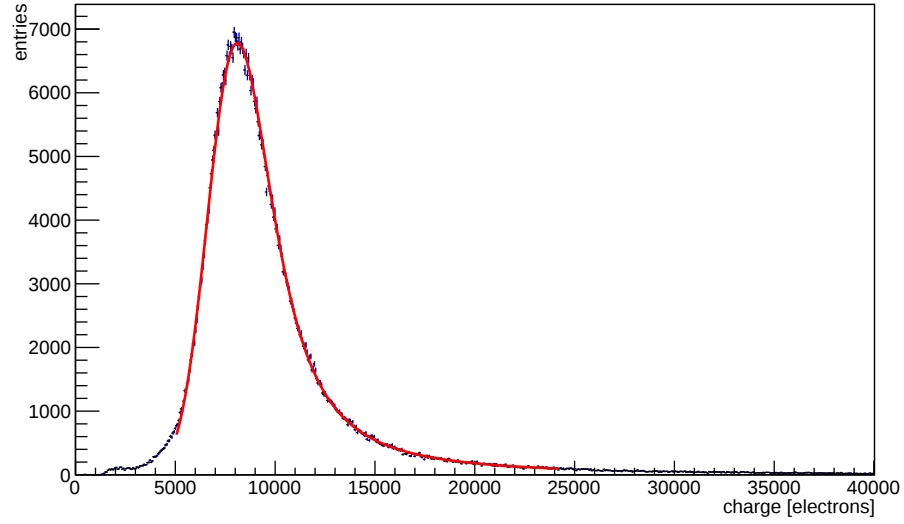


Figure 6.14: Charge distribution for a 200 μm thick silicon sensor irradiated to the maximum fluence (see chapter 8), with a most probable value of 7666 electrons.

a Gaussian to determine the error. The most probable value distribution is shown in figure 6.15 and gives an error of 13 electrons.

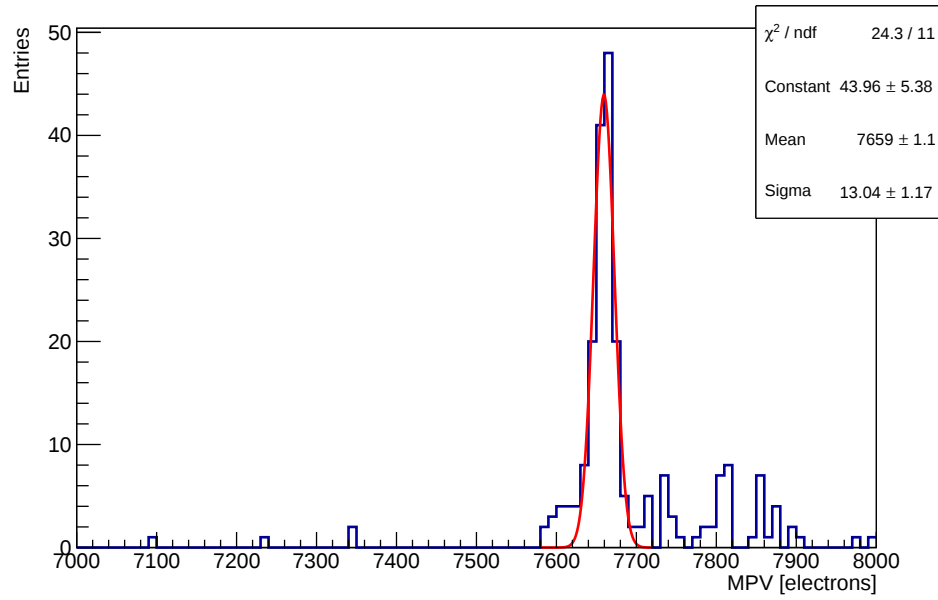


Figure 6.15: Distribution of MPV values, from which the error on the MPV can be extracted.

6.5 Summary

The Timepix3 telescope is the key part of the assembly used to study the prototype sensors in the test beam. The pointing resolution at the centre of the telescope is below $2\text{ }\mu\text{m}$, which allows the sensors to be studied with sub-pixel precision. The Timepix3 telescope allows for the simultaneous measurements of time of arrival and time over threshold. This permits the association of clusters with tracks to be performed using both time and spatial information. Many properties of the device under test are considered. The resolution shows that operating the sensors too far above their depletion voltage degraded the position resolution. The track intercept on the device under test shows mainly one-pixel clusters. The two-, three-, and four-pixel clusters are predominantly formed on the edges and at the corners of pixels. The edge design of the sensor is not dependent on the width of the guard ring but is dependent on the guard ring design of each manufacturer.

Chapter 7

Charge Collection and Efficiency Before Irradiation

One of the most important performance parameters of a sensor is the efficiency with which it detects particles. For a Timepix3 sensor to detect a particle, the signal in a given pixel must exceed the set threshold. Therefore, it is important to study the amount of charge collected by a pixel when a charged particle passes through it. To do this, a test beam programme was undertaken to investigate prototype sensors as part of the VELO upgrade. These prototype sensors were evaluated using the Timepix3 telescope which is discussed in Chapter 6.

7.1 Assemblies

All of the assemblies tested are Timepix3 ASICs bump-bonded to a sensor manufactured by either Hamamatsu or Micron. All of the Hamamatsu sensors were produced from a single 200 μm thick wafer of *n-on-p* type silicon. The Micron sensors came from two different wafers, a 200 μm thick *n-on-p* wafer and a 150 μm thick *n-on-n* wafer. The assemblies are discussed in more detail in Section 4.4. Every assembly was equalised and calibrated in the lab before it was used in the test beam. These procedures are discussed in more detail in Chapter 5.

7.2 Charge Collection

As discussed in chapter 4, when charged particles travel through material, Coulomb interactions take place between the particle and the electrons in the material. This leads to ionisation. A minimum ionising particle will generate a most probable charge between 76 and 80 electron-hole pairs per micron of traversed silicon[32] [33]. As was discussed previously, the collected charge is measured in terms of time over threshold units. After applying the calibration constants, discussed in section 5.4, the signal in time over threshold units is converted to a signal expressed as a number of electrons. For a 200 μm silicon sensor the equivalent signal would be between 15,200 electrons and 16,000 electrons. The charge distribution can be described by a Landau convoluted with a Gaussian. Figure 7.1 shows the fitted charge distribution for the assembly S8 biased at 300 V. From the fit, the most probable value of collected charge of $15,630 \pm 13$ electrons.

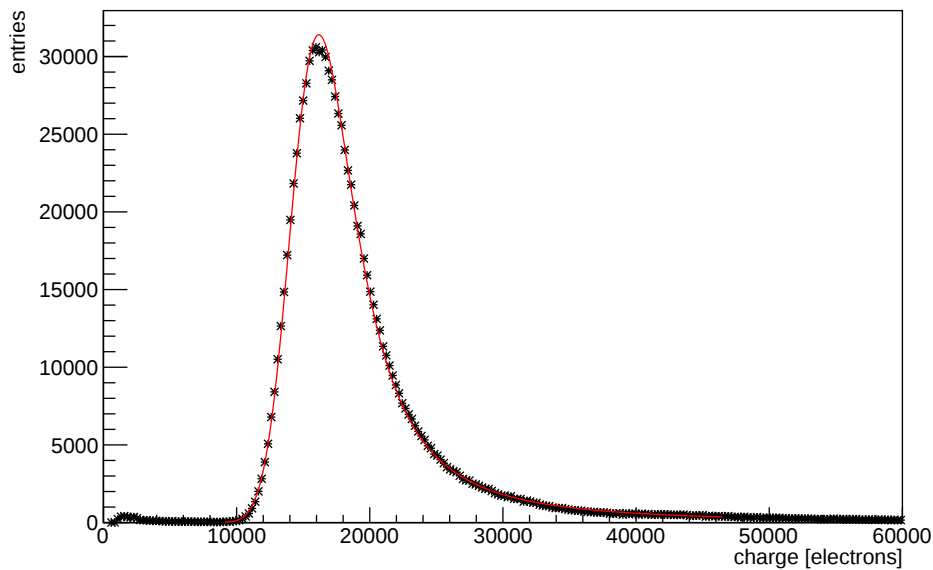


Figure 7.1: *Fitted Charge distribution for assembly S8 at 300V.*

As discussed in section 4.2.2, the signal is proportional to the width of the depletion layer. Hence, the amount of generated charge is dependent on the square root of the bias voltage, as can be seen in equation 4.8. When the depletion width is equal to the sensor thickness, full depletion of the sensor is reached. Figure 7.2 shows the collected charge for assembly S8, a 200 μm n -on- p sensor from Hamamatsu, as a function of the

applied bias voltage. The assembly fully depletes at around 130 volts, where there is a plateau of collected charge of around $15630 \pm 13 e^-$, as expected from the fit of the charge distribution for this sensor described above.

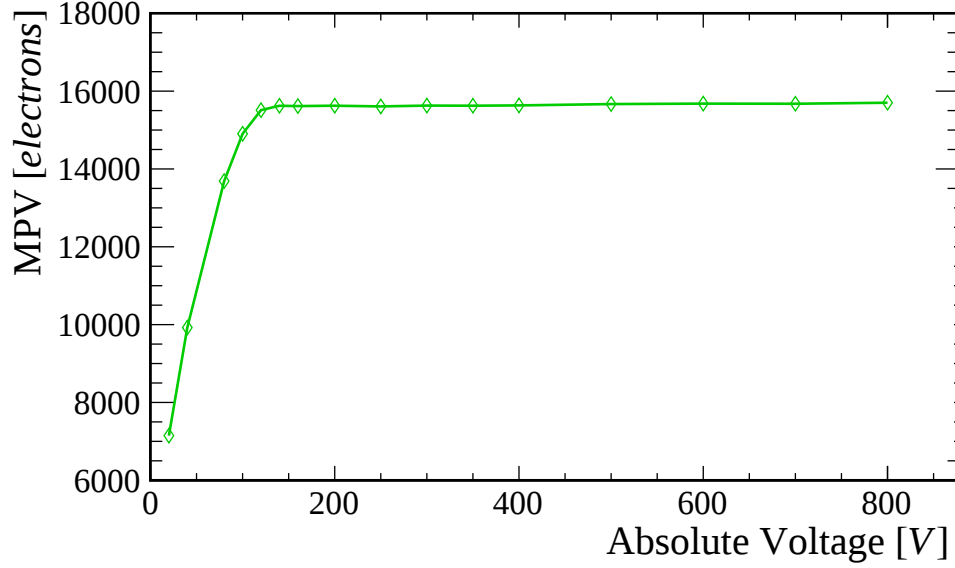


Figure 7.2: Collected charge for assembly S8 as a function of bias voltage.

Twelve sensors were tested. Their details are listed in Table 4.1. Figure 7.3 shows the charge collected in number of electrons as a function of the bias voltage for the unirradiated sensors. The Hamamatsu sensors are displayed in green. Based on their

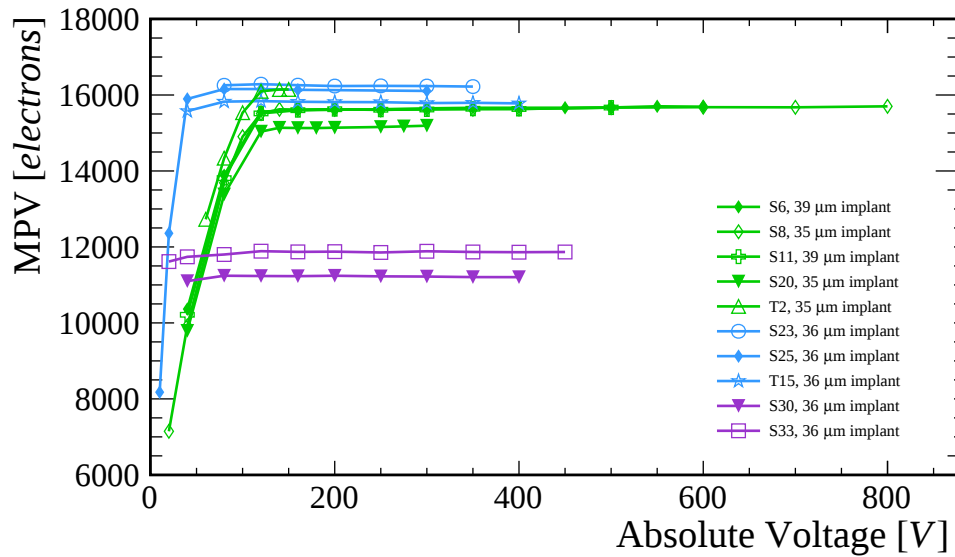


Figure 7.3: Collected charge as a function of bias voltage for the sensors before irradiation. The $200 \mu\text{m}$ thick n-in-p from Hamamatsu sensors are displayed in green; the $200 \mu\text{m}$ thick Micron sensors are displayed in blue and the $150 \mu\text{m}$ thick Micron sensors are shown in purple.

thickness, the collected charge for a fully depleted sensor is expected to be approximately 16,000 electrons. The 200 μm thick Micron sensors are displayed in blue. The 150 μm thick Micron sensors, which are expected to collect approximately 12,000 electrons at full depletion, are shown in purple.

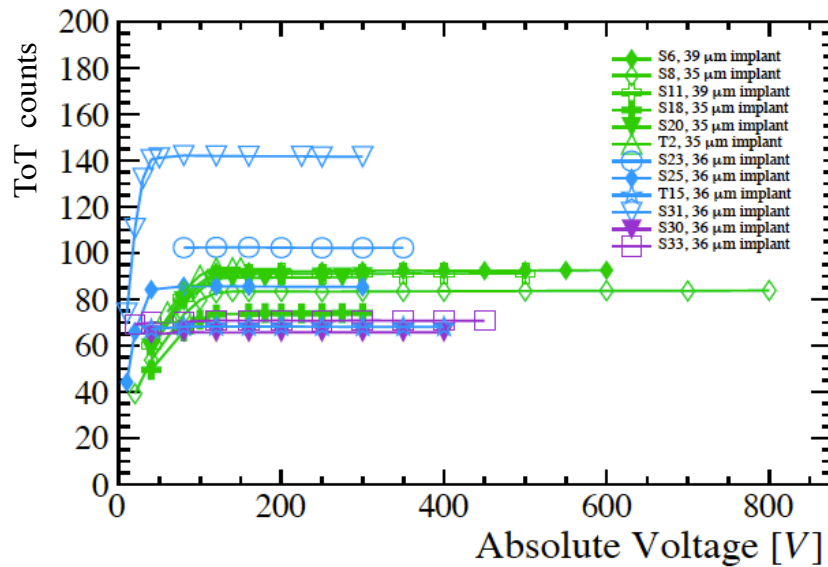


Figure 7.4: *Most probable value of collected time over threshold counts for sensors before irradiation.*

All 200 μm -thick assemblies collect around 16,000 electrons with two exceptions: S31 and S18. S31 is collecting more charge than expected, which is also seen in the original time over threshold data. Assembly S18 is collecting less charge than expected for a 200 μm thick detector. Figure 7.4 shows that the sensor collects less signal in time over threshold even though the calibration curve for S18 is very similar to S8 as seen in figure 7.5.

The two 150 μm thick detectors collect the expected amount of charge of between 11,400 electrons and 12,000 electrons.

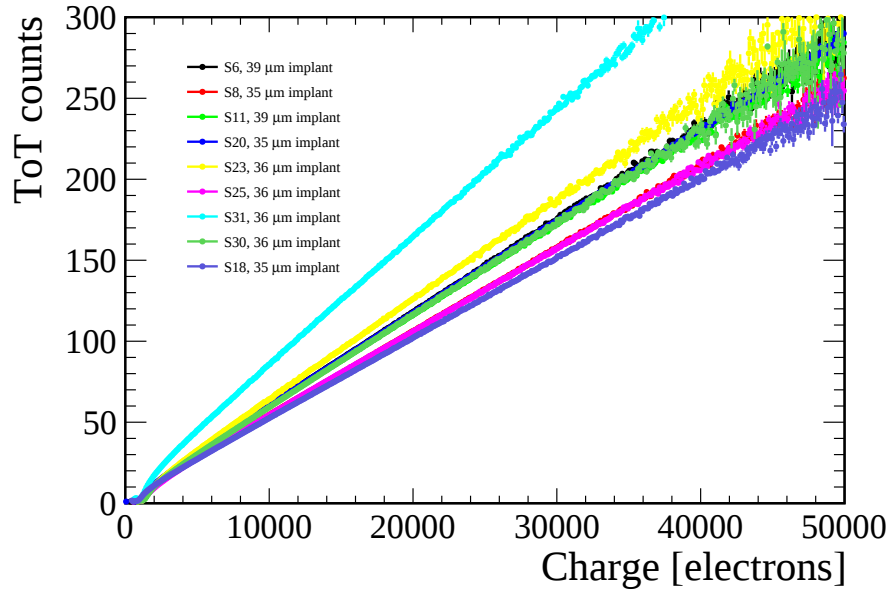


Figure 7.5: Conversion for time over threshold units to electrons before irradiation.

7.3 Cluster Finding Efficiency

The cluster finding efficiency is one of the most important performance parameters of a sensor. The cluster finding efficiency of an assembly is defined as the probability of finding a cluster given the presence of a track. To detect a cluster the pixel signal needs to exceed a set threshold, which for non-irradiated sensors was chosen to be 1000 electrons. The tracks are reconstructed with the device under test masked, as discussed in Section 6.3. The cluster must be within 10 ns and a 220 μm diameter circle of the track intercept. Figure 7.6 illustrates this.

The efficiency, ε , is defined as the ratio of the number of matched clusters, N_e , and the total number of reconstructed track candidates, N_t . The error on the efficiency, σ_ε , is dependent on the total reconstructed track candidates and the number of tracks. It is given by:

$$\sigma_\varepsilon = \sqrt{\frac{\varepsilon(1 - \varepsilon)}{N_t}} \quad (7.1)$$

The number of tracks considered, N_t , affects σ_ε . The more tracks considered, the lower the error. One million tracks are considered when calculating the efficiency.

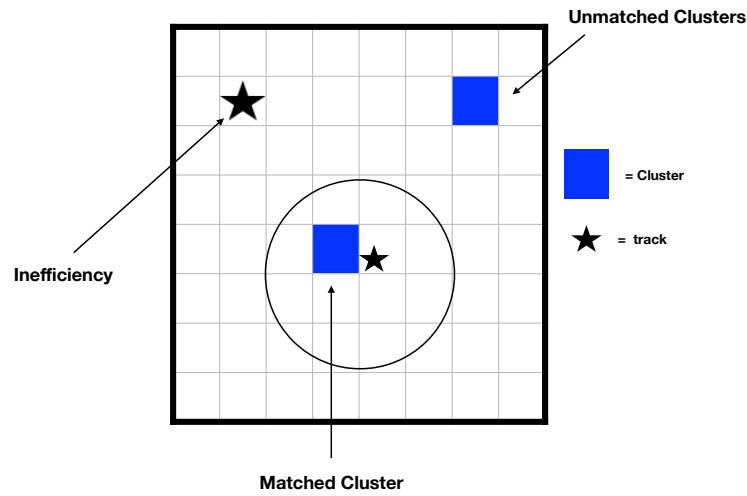


Figure 7.6: *Spacial requirements for cluster finding efficiency*

According to the Technical Design Report, TDR [8], the sensors efficiency within the pixel must be above 99% before irradiation. Figure 7.7 shows the cluster finding efficiency of the unirradiated assemblies. The 200 μm thick *n-on-p* sensors from Hamamatsu are displayed in green; the 200 μm thick Micron sensors are displayed in blue and the 150 μm thick Micron sensors in purple. The figure shows that all unirradiated assemblies are 99.9% efficient even before the sensors are fully depleted. The depletion voltages for the Hamamatsu sensors are about 130 V, whilst they are about 40 V for the Micron sensors (see table 4.1).

7.4 Summary

The cluster finding efficiency is one of the most important performance parameters of a sensor. When a Timepix3 sensor detects a particle, the signal must exceed a set threshold. Therefore, the collected charge is also an important subject to study as it will affect hit identification and therefore the cluster finding efficiency. The sensors were placed in a test beam in order to study these quantities. A 200 μm *n-on-p* silicon sensor is expected to collect approximately 16,000 e^- when fully depleted. There are two sensors that did not perform as expected in this regard. One collects more charge than expected, while another collects too little charge than expected. A 150 μm *n-on-n*

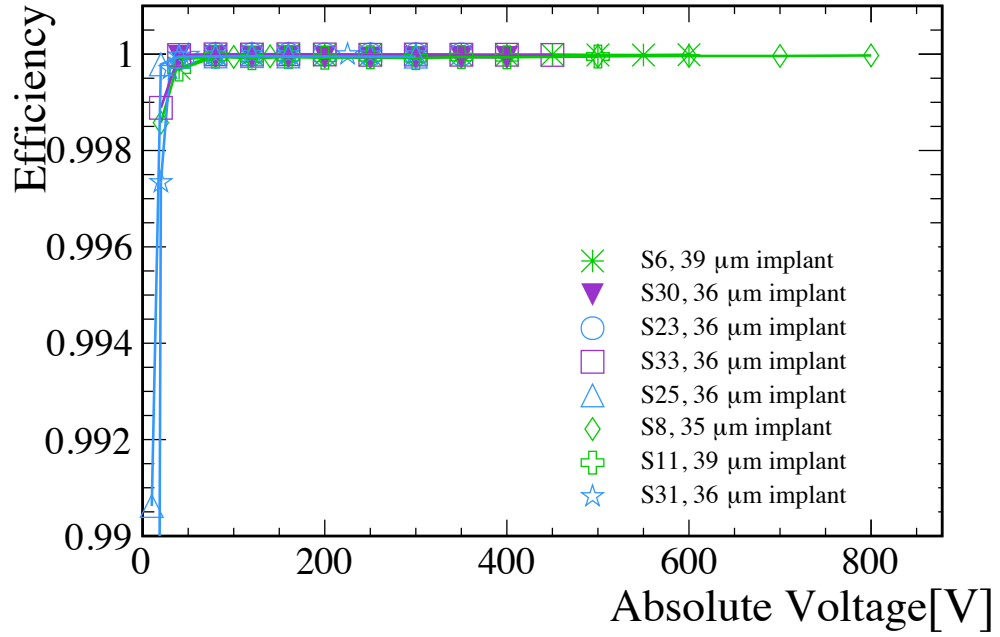


Figure 7.7: Cluster finding efficiency as a function of the bias voltage for the unirradiated sensors. The 200 μm thick *n-in-p* from Hamamatsu sensors are displayed in green; the 200 μm thick Micron sensors are displayed in blue and the 150 μm thick Micron sensors in purple.

silicon sensor is expected to collect approximately 12,000 e^- at full depletion. According to the TDR, the sensors must have a in-pixel efficiency of 99%. All the sensors studied were found to be 99.9% efficient even before the sensor was fully depleted. This means that the requirement described in the TDR is met in all cases.

Chapter 8

Radiation Effects in Timepix3 Devices

The exposure to a flux of particles, irradiation, causes defects in the assemblies. There are two different types of damage that can happen: Bulk damage and surface damage, both of which are described here. The radiation facility where the prototype sensors were irradiated is presented. At the end of the chapter the performance of the sensors after irradiation is presented.

8.1 Bulk Damage

When irradiating a silicon detector, one type of damage that occurs is bulk damage. Bulk damage occurs when an atom is displaced out of its lattice position by a high energy particle. This is known as a point defect. In some cases so much energy is transferred to the displaced atom that it is then able to displace other atoms. This leads to a cluster of point defects [46]. As photons are massless, only very rarely do they transfer enough momentum to displace even a single atom. Hence, photons will only cause point defects, at most. Neutrons, on the other hand, are most likely to cause cluster defects. Electrons and charged hadrons cause both point and cluster defects. The defects lead to additional energy levels in the band gap. These levels primarily have energies just

above the valence band and hence act as acceptors. This leads to an effective p -type doping occurring as a result of irradiation. The additional levels also trap electrons moving in the conduction band and holes moving in the valence band. These electrons and holes may be released later or can recombine, but the time constants for carrier escape are such that these charge carriers no longer contribute to the collected signal in an event. Furthermore, the intermediate levels will increase the thermal generation of mobile charge carriers significantly as the electron no longer needs to gain the full band gap energy to move from the valence to the conduction band, but can instead overcome the energy gap by first being excited to an intermediate level and then from there, maybe through several intermediate steps, to the conduction band. This leads to a much higher leakage current.

8.1.1 Leakage Current

Defects in the bulk increase the leakage current. It has been empirically found that the leakage current scales linearly with the 1 MeV neutron equivalent fluence [47]:

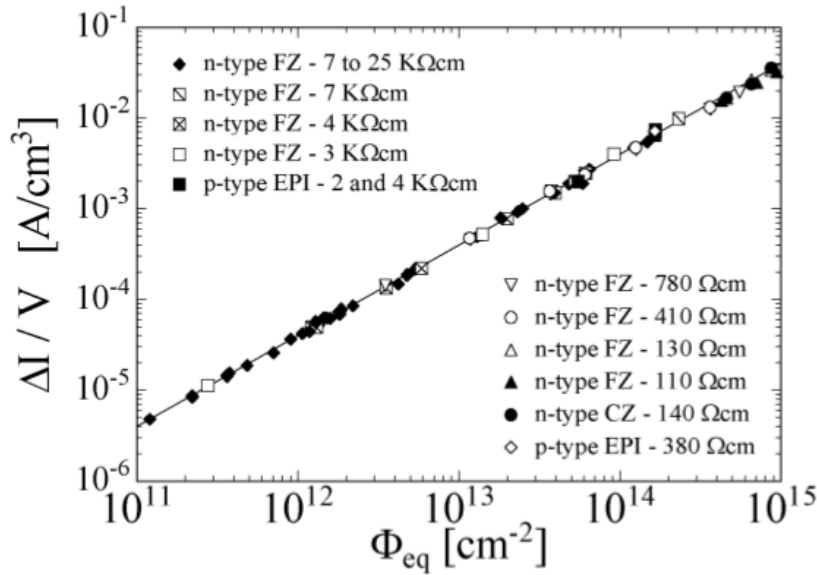


Figure 8.1: Leakage current in silicon detectors, produced by various processes, as a function of fluence. FZ refers to float-zone silicon, CZ refers to Czochralski silicon, and EPI refers to epitaxial silicon. The current is measured after controlled annealing, which is discussed in more detail in section 8.3 [47].

$$I = \alpha \Phi_{eq} V \quad (8.1)$$

where I is the leakage current, α is the current-related damage rate, Φ_{eq} is the fluence, and V is the active volume, as shown in figure 8.1. The damage rate is not dependent on the material type, process technology, or the type of particle that causes the irradiation¹ [48].

The expected leakage current for the current VELO is shown in figure 8.2. The radiation damage in the VELO depends on z , where the highest dose is observed at $z=0$, i.e. the nominal beam interaction point. There are uncertainties on the leakage current prediction, that come from the annealing (see section 8.3) and fluence prediction. The predictions are shown by the shaded region.

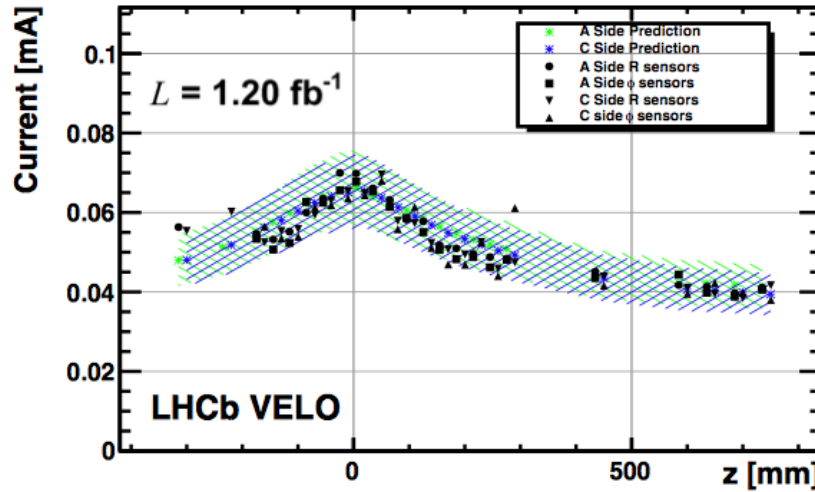


Figure 8.2: Leakage current in the current VELO as a function of z coordinate after 1.20 fb^{-1} , normalised to 0°C . The data is in agreement with the predictions (shown as the shaded region). The two halves of the VELO are known as the A and C sides [49].

8.1.2 Thermal Runaway

The leakage current is dependent on the temperature of the sensor [50]:

$$I(T) \propto T^2 \exp\left(-\frac{E_g}{2kT}\right) \quad (8.2)$$

¹The type of particle does not matter but the energy does.

where E_g is the band gap energy, T is temperature in Kelvin, and k is the Boltzmann constant [51]. When the leakage current increases the power dissipation also increases. If the heat is not removed, then the increase in power dissipation leads to an increased temperature and therefore an increased leakage current. The rise in temperature will lead again to a rise in leakage current, which will lead to a rise in temperature and so on. This could cause the sensor to become thermally unstable. This is known as *thermal runaway* [52]; to avoid this, the sensors have to be cooled. The VELO will be kept at a temperature of -22°C to keep the leakage current of the sensors low enough.

8.1.3 Effective Doping

The silicon sensors are essentially segmented, reverse biased diodes that rely on doping profiles, as discussed in section 4.4.1. As mentioned above, bulk damage can lead to donor removal and acceptor generation. The difference between the number of donor and acceptor-like states is defined as the effective doping, N_{eff} . When a sensor is irradiated defects mainly act as acceptors, and thus the effective doping is changed. According to equation 4.9 the depletion voltage is dependent on the number of acceptors and donors. Rewriting 4.9 yields

$$V_{dep} = \frac{e}{2\epsilon_0\epsilon_{Si}} \left| \frac{N_a + N_d}{N_a N_d} \right| X^2 \quad (8.3)$$

where V_{dep} is the depletion voltage of the sensor. In n-bulk the increase in the number of acceptors counteracts the original n -type doping and thus N_{eff} decreases, which lowers the full depletion voltage as shown in figure 8.3.

At some point, the n -type material turns into p -type material. To make functional detectors of p -on- p type they need to be operated fully depleted as explained in section 4.4.1. With more irradiation, the material becomes more and more p -type and thus $|N_{eff}|$ increases further, leading to a higher full depletion voltage. As a result the full depletion voltage increases with dose and thus at some point will exceed the maximum allowable 1000 V. At that point the sensors will not be fully depleted, and the strips are no longer insulated, rendering the detector useless. For these reasons, the VELO upgrade has chosen to investigate only n -on- p and n -on- n prototypes. In n -on- p sensors,

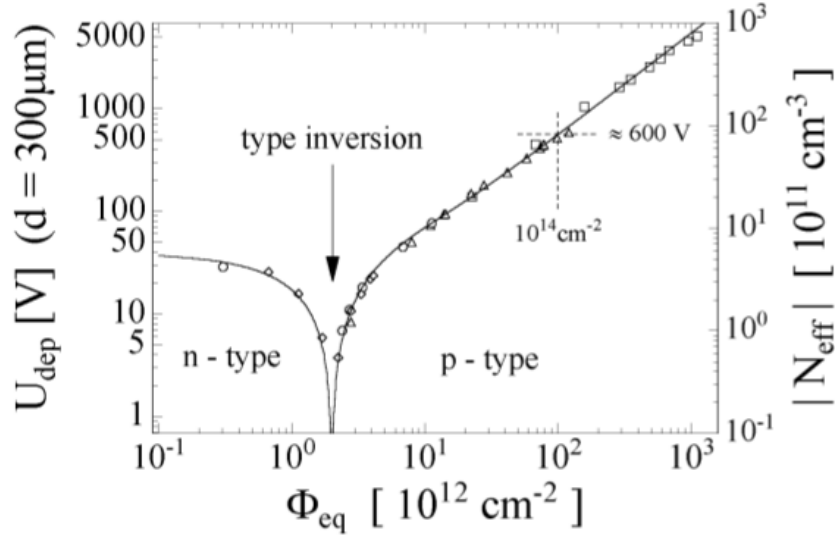


Figure 8.3: Variation of the depletion voltage and the effective doping concentration as a function of fluence [47].

the p -bulk just becomes more heavily p -type doped, which does lead to an increase in the full depletion voltage, but as the junction occurs at the strip side where the pn -junctions are, they will still operate effectively, even if only partially depleted. Similarly, the n -on- n sensors will initially need to be operated at full depletion, but at some point the bulk will type invert and the sensor will become an n -on- p device.

8.1.4 Charge Trapping

As already discussed, the defects in the material lead to intermediate levels in the band gap. These levels can trap signal charge, which, in turn, reduces the amount of collected charge. The amount of trapping depends on the fluence and can be described by $1/\tau$ [ns^{-1}], or the trapping rate and τ is the trapping time. Electrons or holes are captured and then released with some time delay. If the signal charge is trapped and released too late for efficient detection, the collected signal will be reduced. The trapping rate can be written as

$$\frac{1}{\tau_c} = \beta_c \Phi \quad (8.4)$$

where τ is the trapping time, c is the type of charge carrier, Φ is the fluence in cm^{-2} , and β_c is a fit parameter in cm^2/ns . The effective trapping rate is different for electrons

and holes. The trapping rate as a function of fluence for a neutron irradiated sample is shown in figure 8.4. For a neutron-irradiated sensor the fit parameter for electrons, β_e , is $4.1 \times 10^{-16} \text{ cm}^2/\text{ns}$ and the fit parameter for holes, β_h , is $6.0 \times 10^{-16} \text{ cm}^2/\text{ns}$ [53]. The

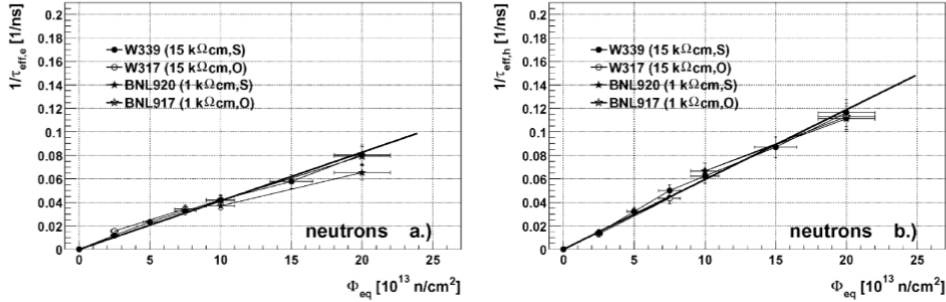


Figure 8.4: Fluence dependence of effective trapping rate for neutron irradiated assembly for electrons (a) and holes (b) [53].

capture cross section for the traps depends on the velocity of the charge carriers. With a higher bias voltage the carriers move faster, induce more signal on the collecting implant and therefore have a lower probability of being captured. The probability of captured charge carriers escaping is proportional to $e^{\Delta E/kT}$, where ΔE is the difference in energy. Hence, if the trap energy level is very close to the conduction band, electrons can escape early enough to contribute to the collected signal. For deeper traps, the charge will be released too late and less charge is collected [28].

8.2 Surface Damage

The silicon-oxide interface and the oxide are affected by a different type of radiation damage. The silicon-oxide interface is already irregular, meaning that the displacement of one atom does not have the same effect as if it was the bulk. However, ionisation causes permanent defects to the interface [54]. Charged particles will generate electron-hole pairs not only in the silicon bulk but also in the silicon oxide. The electrons can escape the oxide. However, the hole mobility in the oxide is very small. This leads to the oxide becoming charged. A positive charge density caused by the surface damage can short circuit the n^+ electrode on a n -on- p sensor. This could cause the charge that is collected to spread over multiple pixels and result in a lower spatial resolution and

efficiency. Both the p -stop and p -spray techniques provide protection through insulation between the pixels (see section 4.4.2).

8.3 Annealing of Radiation Damage

A displaced atom can return to its original lattice position or change into a more stable defect with different properties. For these processes to take place the atoms have to overcome energy barriers. The transition probability for these barriers, and thus the rate, depends on the temperature. Hence, when irradiated sensors are kept at a high temperature they will tend to self-repair some of the damage. This process is called annealing. The annealing follows an exponential behaviour:

$$N_d(t) = N_d(0)e^{-\frac{t}{\tau}} \quad (8.5)$$

with

$$\tau(T) \propto e^{\frac{E_a}{kT}} \quad (8.6)$$

where N_d is the number of defects, E_a is the activation energy, k is the Boltzmann constant, and T is the temperature in Kelvin. Thus, in an irradiated sensor the leakage current anneals with time and the effects of the annealing are temperature dependent, as shown in figure 8.5. However, it should be noted that annealing may not always be beneficial for detector performance. This is due to an increase in the depletion voltage after the initial annealing can be bad for the detectors. This is referred to as reverse annealing. After annealing the effective doping concentration can be described as a function of time, doping concentration before irradiation, and fluence, as described in equation 8.7.

$$N_{eff} = N_{eff,\phi=0} - [N_a(\phi, T_a, t) + N_C(\Phi) + N_Y(\phi, T_a, t)] \quad (8.7)$$

This is known as the Hamburg model [55]. This model is dependent on the short term annealing, N_a , the stable damage, N_C , and the reverse annealing term, N_Y . The short term annealing is observed over a period of the order of hours after irradiation has taken

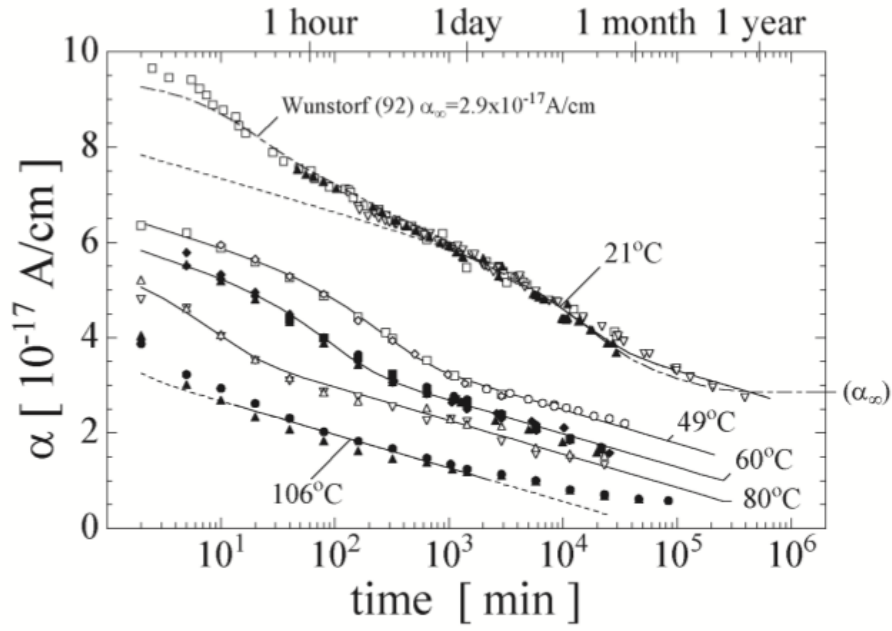


Figure 8.5: Leakage current damage rate, α , versus annealing time at different temperatures [47].

place. This is observed as a decrease of depletion voltage. This annealing is caused by the change in effective doping concentration. The n - to p -type inversion in the bulk means positive charge is removed. Figure 8.6 shows N_{eff} as a function of annealing time.

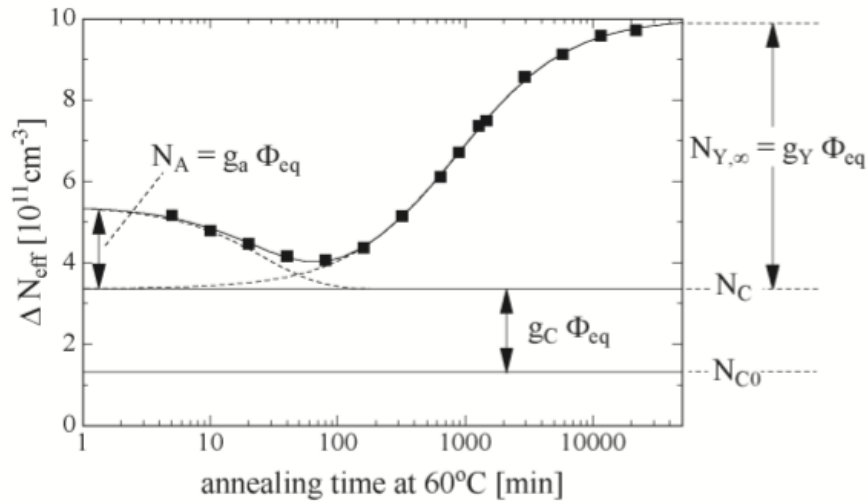


Figure 8.6: N_{eff} as a function of annealing time for a sensor irradiated to $1.4 \times 10^{14} \text{ cm}^{-2}$ [47].

N_{eff} reaches a minimum at the end of the short-term annealing, which is represented

by the stable damage, N_C . Stable damage is independent of temperature and time; it is only dependent on the fluence. Reverse annealing, N_Y , occurs at the end of the short-term annealing. During reverse annealing, the space charge of the type inverted sensor becomes more negative. This leads to an increase in the depletion voltage.

The LHCb detector is intended to run for many years, so reverse annealing is a problem for both the current and the upgraded VELOs. If the sensors are kept at room temperature for weeks, then the depletion voltage will increase.

8.4 JSI Irradiation

To test the effects of radiation damage on the prototype sensors they were irradiated at JSI. JSI has a 250kW TRIGA Mark II reactor. It is a light water pool type reactor that is cooled by natural convection [56]. This reactor was used to uniformly irradiate some of the Timepix3 assemblies with neutrons to a maximum expected fluence for the innermost detector in the upgraded VELO of $8 \times 10^{15} \text{ 1 MeV n}_{eq}/\text{cm}^2$. There was no cooling for the assemblies during irradiation or transport from the facility. After arriving at CERN, some sensors were placed in a controlled annealing environment for 80 minutes at 60°C. Some sensors were characterised before and after the annealing process.

8.5 General Sensor Performance after Irradiation

After irradiation, the sensors were placed into the Timepix3 telescope and characterised in the same way as they were before irradiation (see section 6.4). The hits that exceed the threshold are converted into electrons using the appropriate time over threshold to electron calibration, as described in section 4.1.1. The size of the resulting clusters is given by the number of pixels whose signal crosses the threshold, as shown in figure 8.7. The majority of the clusters are one-pixel clusters; this is due to the particle crossing at right-angles to the sensor plane and the lower generated signal due to partial depletion and less efficient charge collection. All of these effects will combine to reduce the probability that neighbouring pixels will collect enough signal to exceed the threshold. This

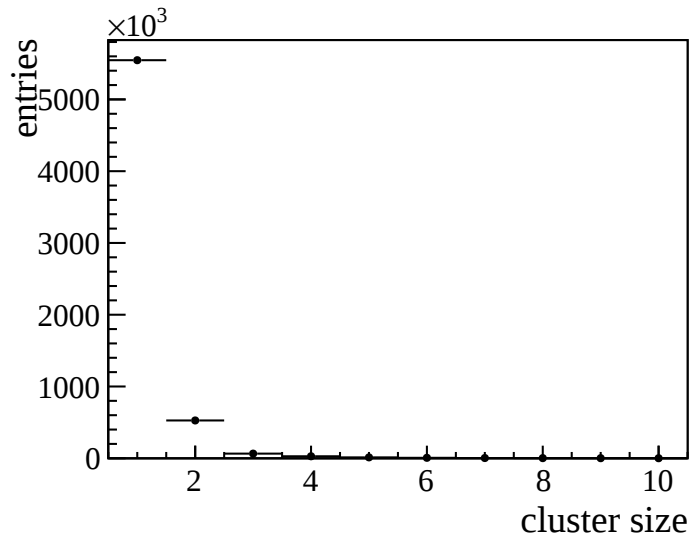


Figure 8.7: Cluster size distribution for a 200 μm thick n -in- p sensor with a 39 μm implant operated at 700V.

leads to a decrease in two-pixel and larger clusters. The fraction of one-pixel clusters before irradiation is 67% while after irradiation it is 89%. This is reflected in the location of hits resulting in two, three, and four-pixel clusters. Figure 8.8 shows the track

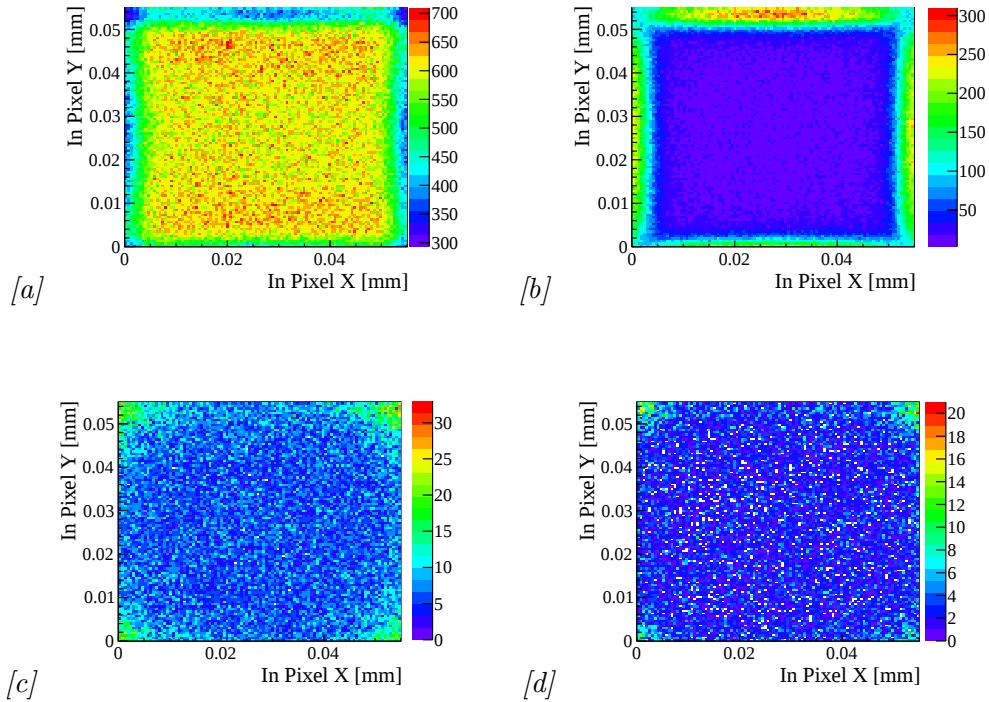


Figure 8.8: Coordinates of the track intercept for one (a), two (b), three (c) and four (d) pixel clusters for an irradiated 200 μm thick n -on- p sensor operated at 700V.

intercept for one, two, three, and four pixel clusters. The one-pixel clusters display a

slight bowing on the edges of the implant compared to the corresponding distributions for the unirradiated sensors. This is also seen on the edges of the two pixel cluster distribution. The region of the three and four pixel clusters covers a smaller area of the pixel compared to what was observed before irradiation (see figure 6.11). The sensor shown here is not operated at full depletion because none of the sensors were able to reach full depletion before 1000 V. The residuals for a sensor irradiated to the expected

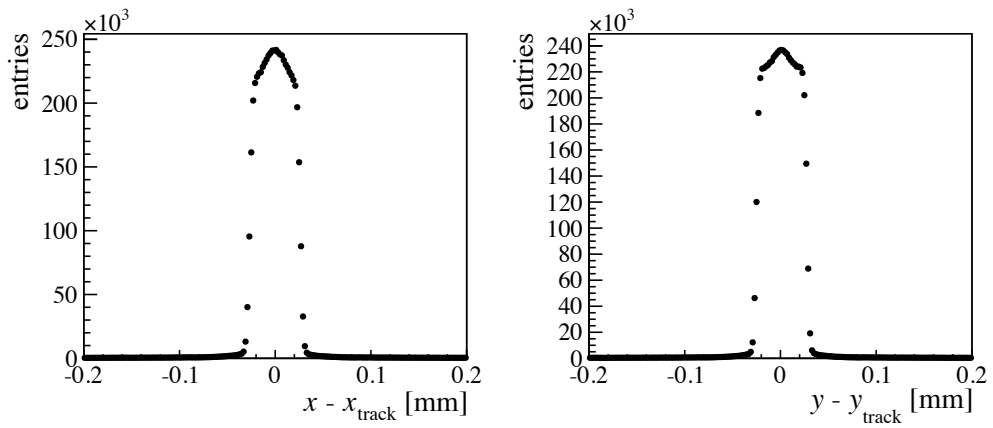


Figure 8.9: *X and Y residuals for a 200 μm thick n-in-p sensor with a 39 μm implant operated at 700V.*

maximum fluence are shown in figure 8.9. The resolutions of the irradiated sensors are not dependent on implant width or the thickness of the sensor. The optimal resolution for an unirradiated sensor is not reached for the irradiated sensors due to the sensors not being fully depleted.

A detailed study of the charge collection and the cluster finding efficiency observed after irradiation will be presented in Chapter 9.

Chapter 9

Charge Collection and Efficiency After Irradiation

A test beam programme was undertaken to investigate prototype sensors after irradiation as part of the VELO upgrade. These prototype sensors were evaluated using the Timepix3 telescope. Assemblies were sent to the JSI Institute in Ljubljana to be irradiated with reactor neutrons to a fluence of $8 \times 10^{15} \text{ 1 MeV n}_{eq}/\text{cm}^2$, the maximum expected fluence for the VELO after the upgrade [57]. A current voltage scan must be performed for each prototype sensor to determine their high voltage tolerance. The collected charge and cluster finding efficiency are also studied in this chapter.

9.1 Current-Voltage scan

Before the irradiated sensors are placed in test beam, a current-voltage, or, IV scan, with the same settings as were used prior to irradiation (see section 5.2), is performed to see how the sensors respond to the application of a high voltage. The sensors are expected to function at up to 1000 V. As can be seen in figure 9.1, three of the sensors breakdown before full depletion and before 1000V. In the figure, the Hamamatsu sensors are displayed in green; the 200 μm thick Micron sensors are displayed in blue and the 150 μm thick Micron sensors are shown in purple. All of the sensors that failed this test

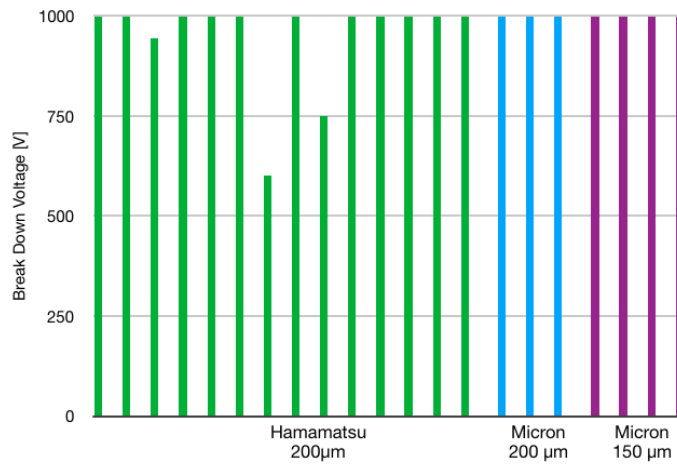


Figure 9.1: *Measured breakdown voltages, or high voltage limit, for irradiated sensors, each bar is a separate sensor*

are 200 μm thick Hamamatsu sensors. The current-voltage behaviour for the majority of the sensors reach the required of 1000 V before breaking down at full fluence.

9.2 Charge Collection

As discussed in chapter 8, when a sensor is irradiated it gets damaged. After the assembly is irradiated the damage to the silicon causes a change in the signal that is collected. The amount of collected charge was tested by placing the irradiated sensors as the device under test in the Timepix3 telescope that was described in chapter 6. The sensors were kept at -22°C using a Peltier cooler and water/glycol chiller. The analysis follows exactly the same procedure, the one described in section 7.2. Figure 9.2 shows the most probable value of the collected charge for irradiated assembly S22 as a function of the absolute voltage. This shows a different trend compared to that observed with the same assembly before irradiation. Before irradiation, it was observed that the most probable value of collected charge increases quickly with increasing voltage and becomes stable at around the full depletion voltage. After irradiation, the most probable value of collected charge appears to change almost linearly with voltage. As discussed in equation 8.3, the radiation damage leads to an increase in the full depletion voltage. Figure 9.2 shows that the assembly does not reach a plateau, meaning the assembly does not reach full depletion before 1000 V.

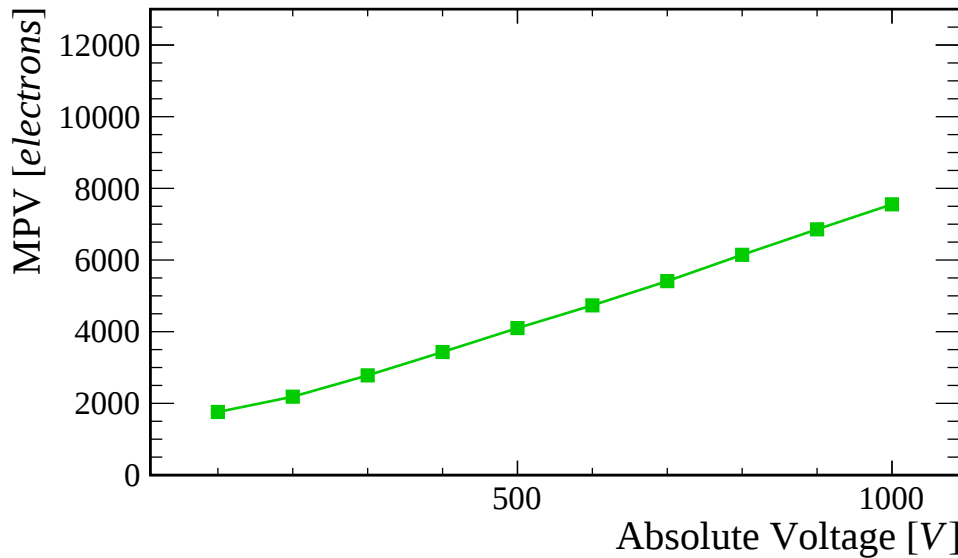


Figure 9.2: *Most probable collected charge for assembly S22 after irradiation as a function of absolute voltage.*

Figure 9.3 shows the charge collected for all assemblies irradiated at JSI. All of the sensors here have been irradiated to a fluence of $8 \times 10^{15} \text{ 1 MeV n}_{eq}/\text{cm}^2$. The Hamamatsu sensors are displayed in green; the 200 μm thick Micron sensors are displayed in blue and the 150 μm thick Micron sensors in purple.

Once the assemblies have been irradiated the dependence on the thickness and type disappears, and all of the sensors follow approximately the same trajectory. The collected charge does not reach a plateau for any of the sensors irradiated to maximum fluence. This indicates that only a fraction of the sensor is actually depleted at an absolute voltage of 1000 V. It can be concluded therefore that the width of the depletion region must be smaller than 150 μm as even the thinnest sensors do not fully deplete. All sensors collect approximately 8000 electrons at 1000 V. In an unirradiated sensor, this would correspond to a depletion depth of approximately 100 μm . As for irradiated sensors, only a fraction of the charge is collected which means that the actual depletion depth is between 100 and 150 μm .

According to the TDR, it is essential that the most probable collected charge for the assemblies after maximum irradiation must be at least 6000 electrons before 1000 V or breakdown, whichever comes first [8]. This is because it allows the thresholds to be set high enough to ensure that a real signal can be effectively distinguished from noise,

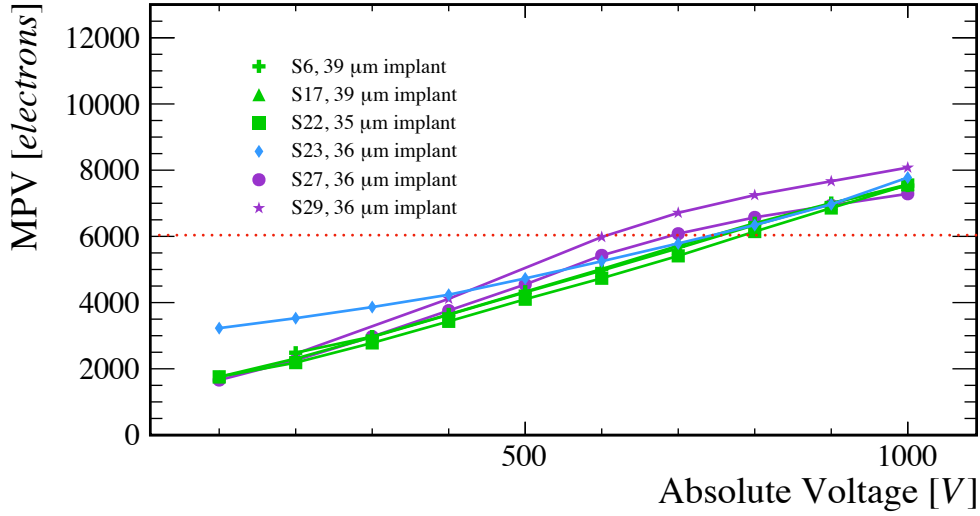


Figure 9.3: *Most probable number of collected electrons for sensors irradiated at JSI. The red dotted line shows most probable value of collected charge of 6000 electrons. The Hamamatsu sensors are displayed in green; the 200 μm thick Micron sensors are displayed in blue and the 150 μm thick Micron sensors are shown in purple*

whilst maintaining a good cluster finding efficiency. The range of voltages in which the sensors collect 6000 electrons ranges between 600 V and 800 V. The thinner sensors achieve this before the thicker sensors. This is because for the same voltage, the electric field in the thinner detector is higher. This leads to higher charge carrier velocities and thus higher induced signals and less trapping. These effects all lead to larger collected signals.

9.2.1 Annealing

Three of the JSI irradiated assemblies were annealed in a controlled situation for 80 minutes at 60°C. Figure 9.4 shows the collected charge before and after annealing. There is no noticeable difference between the charge collection before and after the controlled annealing. This might be because of the lack of cooling during transport. Without cooling during this period, it is possible that the sensors could have annealed during transport, i.e. before the set of measurements were taken.

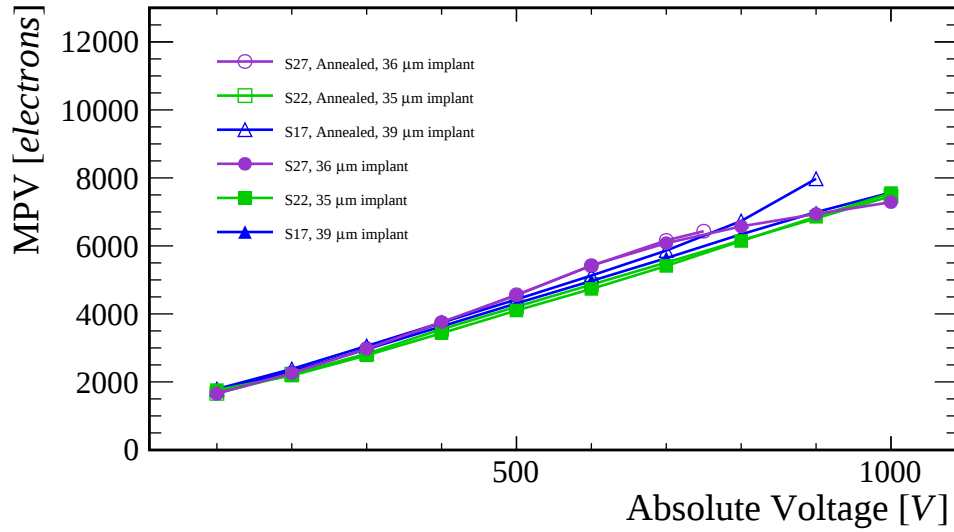


Figure 9.4: *Most probable number of collected charge in electrons for sensors irradiated at JSI before and after annealing.*

9.3 In-Pixel Studies

All the pixel sensors have a $55\ \mu\text{m}$ pitch with either a $35\ \mu\text{m}$, $36\ \mu\text{m}$ or $39\ \mu\text{m}$ square implant at the centre. It is interesting to study the differences in charge collection for tracks that traverse the implant and tracks that pass in-between implants. The Timepix3 telescope has a pointing resolution better than $2\ \mu\text{m}$, as was demonstrated in section 6.2.4. This allows for in-pixel studies to be performed for the device under test. To have enough information in the in-pixel bins, the pixel was divided into 5×5 areas, which corresponds to $11 \times 11\ \mu\text{m}$ bins. Figure 9.5 shows these different regions on the pixel. Three are studied in more detail. The green and red regions are completely covered by the pixel implant. It is therefore expected that they will collect the same charge and have the same efficiency. The blue region is at the edge of the pixel. For pixels with the smaller implant only a very small contribution from the implant is expected in this region. For pixels with the larger implant size, a larger contribution from the implant is expected.

The collected charge distributions before irradiation for these three regions for a $200\ \mu\text{m}$ thick n -in- p with a $35\ \mu\text{m}$ implant at $300\ \text{V}$ are shown in figure 9.6. The collected charge distributions for the red and green regions are very similar, as expected. In the corner of the pixel (the blue region), there is a very small contribution from the implant,

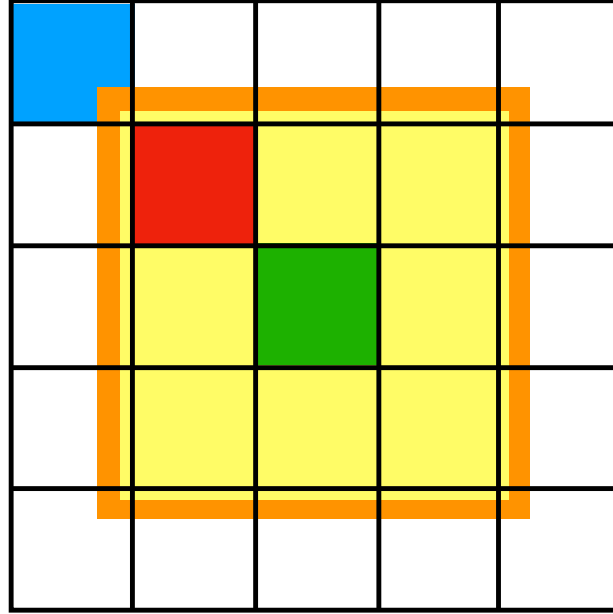


Figure 9.5: An example pixel divided into 5×5 regions for in-pixel studies. The yellow shaded section represents the area covered by a $35 \mu\text{m}$ implant, while the orange shaded area represents the additional area covered by the $39 \mu\text{m}$ implant. The red and green regions represent areas that are completely covered by the implant, regardless of which size is used. The blue region is selected for study as it sits on the pixel edge.

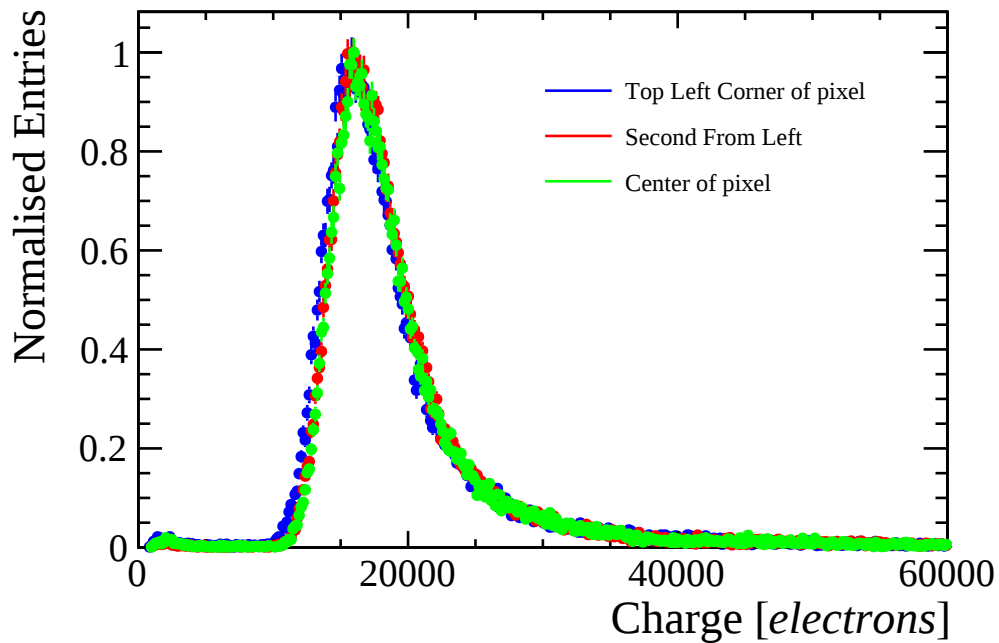


Figure 9.6: Charge distributions for the red, blue, and green regions of a pixel (see main text for explanation) on a $200 \mu\text{m}$ thick n-in-p sensor with a $35 \mu\text{m}$ implant at 300V before irradiation.

which is shown by the slight shift in the collected charge distribution. The fact that the three distributions are all very similar shows that for unirradiated sensors the charge collection in the corner is complete.

In the corner of the pixel there will be more charge sharing with neighbouring pixels. This means that the size of the clusters in this region should be larger than those in the centre of the pixel. Figure 9.7 shows the cluster size distributions for the three different regions. The corner regions does tend to have larger clusters than The red and blue regions represent areas that are completely covered by the implant, regardless of which size is used. The green region is selected for study as it sits on the pixel edge.

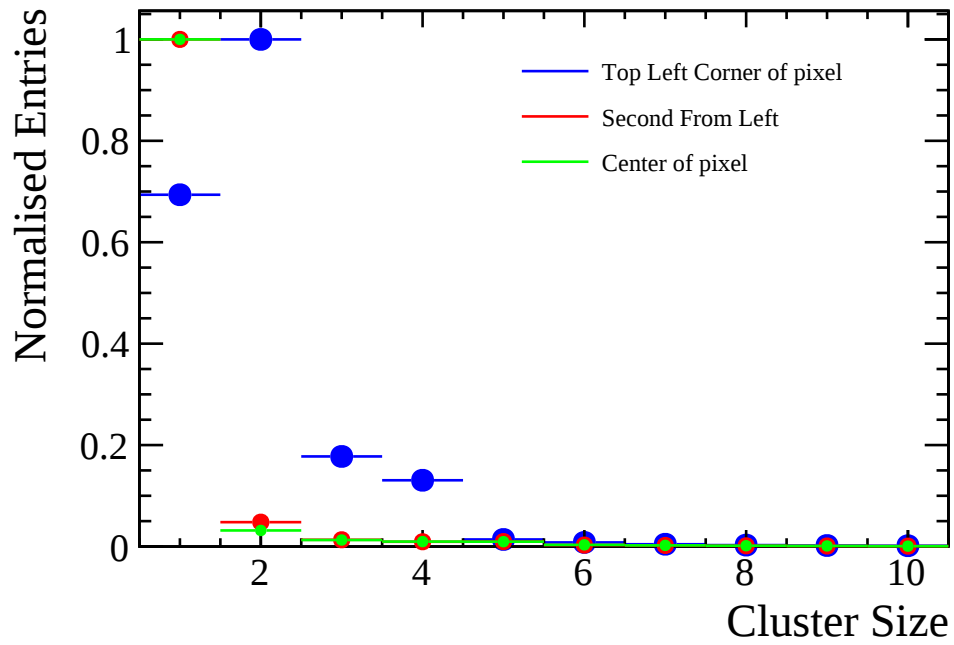


Figure 9.7: Cluster size distributions for the red, green and blue regions of a pixel (see main text for explanation) on a $200\ \mu\text{m}$ thick $n\text{-in-p}$ sensor with a $35\ \mu\text{m}$ implant at 300V before irradiation.

This behaviour will change after irradiation, as the damage to the sensor leads to less charge being collected. This mainly affects the corners of the pixel for two reasons. Firstly, the electric field in the corners is smaller and the field lines are bent towards the implant. This means that the charge carriers move more slowly, resulting in a smaller signal being induced on the implant. Secondly, the charge for hits on the corner of the pixel is shared over multiple pixels. Hence, the probability that the charge generated in one or more of the neighbouring pixels does not exceed the threshold is much higher

than for central hits, where one pixel receives all the charge. This will lead to lower cluster charges.

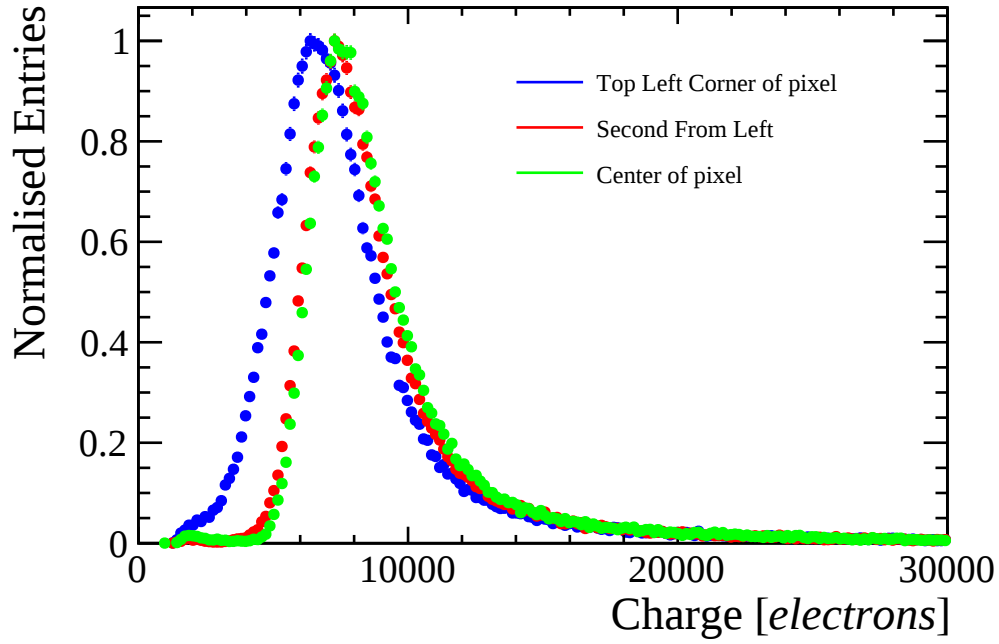


Figure 9.8: Collected charge distributions for three different regions on a pixel on S22, a $200\text{ }\mu\text{m}$ thick *n-in-p* sensor with a $35\text{ }\mu\text{m}$ implant operated at 900V .

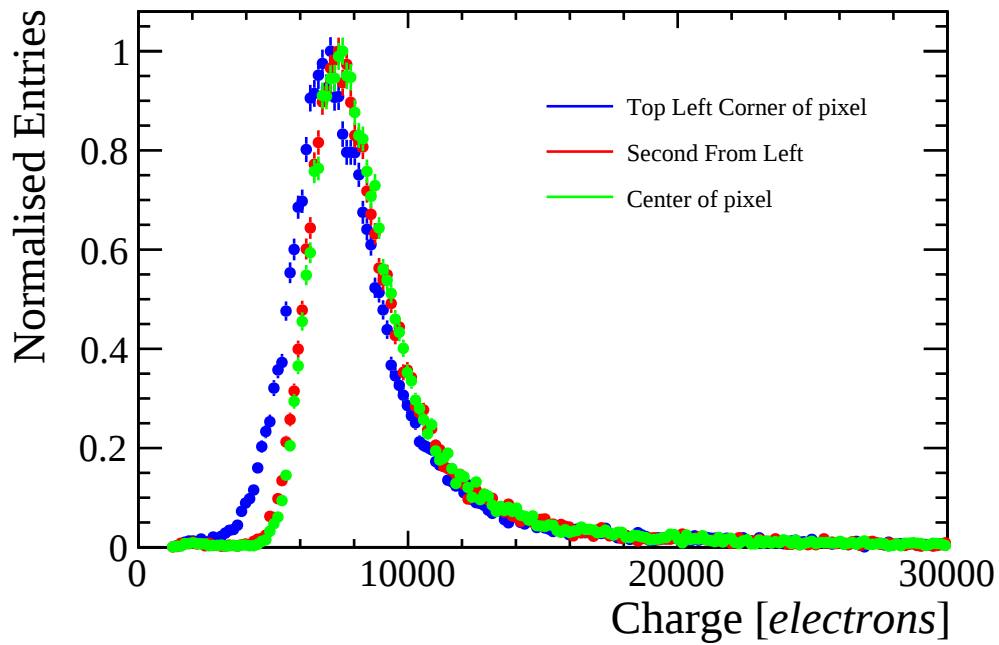


Figure 9.9: Collected charge distributions for three different regions on a pixel on S17, a $200\text{ }\mu\text{m}$ thick *n-in-p* sensor with a $39\text{ }\mu\text{m}$ implant operated at 900V .

This can be seen by looking at two different sensors with different implant sizes. Figures

9.8 and 9.9 show the charge distributions for S22 and S17, respectively. Both are 200 μm thick n -in- p sensors operated at 900 V. However, S22 has a 35 μm implant, while S17 has a 39 μm implant. The figures show that for the two central regions, the same amount of charge is collected by both sensors. The collected charge distributions for the corner regions, however, are different. For both sensors less charge is collected in the corner sections compared to the central sections. The result shows that more charge is lost in the corner of the sensor with the smaller implant compared to the sensor with the larger implant.

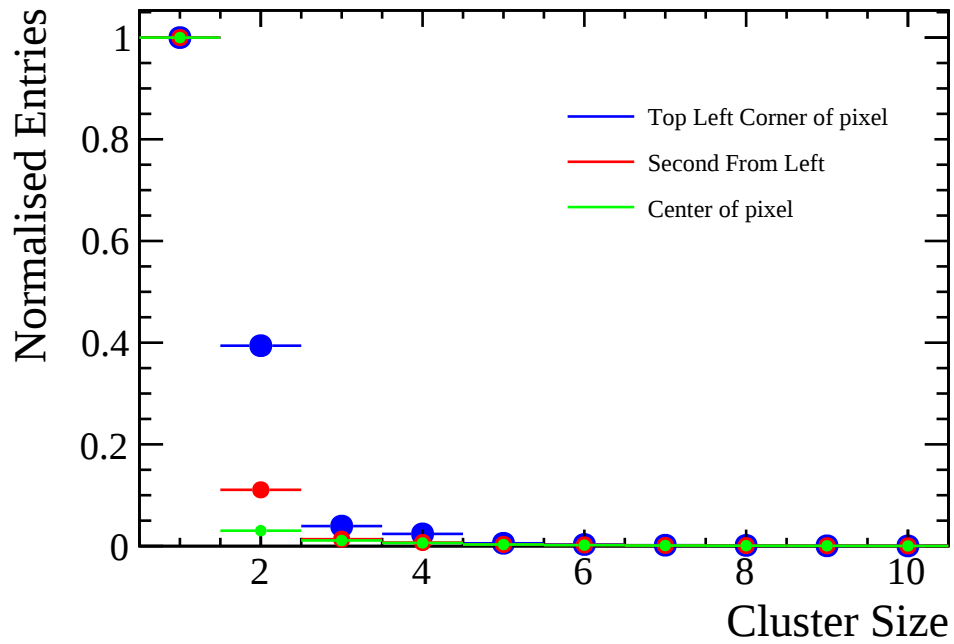


Figure 9.10: Cluster size distributions for three different regions on a pixel on S22, a 200 μm thick n -in- p sensor with a 35 μm implant operated at 900V.

The cluster size distributions are shown in figure 9.10 and figure 9.11, respectively. It is clear that larger clusters occur for hits at the edge of the pixel. The regions that covers the implant predominately have a cluster size of one. Compared to the unirradiated sensor, the cluster sizes in the corner region tend to be smaller. After irradiation, the cluster size distribution for the corner regions is the same for both implant sizes. This implies that the absolute charge collection is more efficient for hits in the corner for larger implants while the charge sharing is not significantly affected by the slightly different electric field configuration resulting from the different implant size.

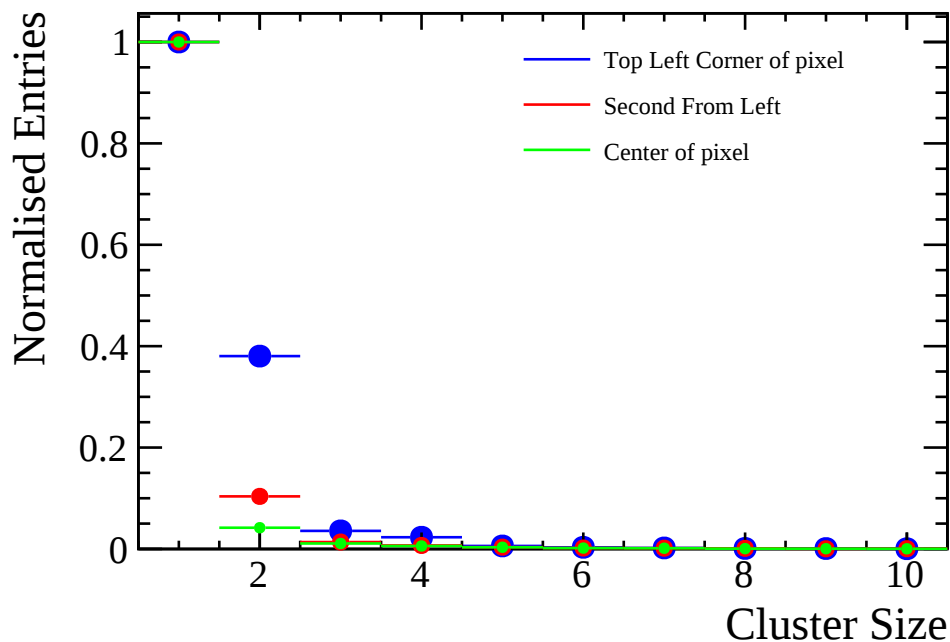


Figure 9.11: Cluster size distributions for three different regions on a pixel on S17, a 200 μm thick n -in- p sensor with a 39 μm implant operated at 900V.

9.4 Cluster Finding Efficiency

Less charge collected in the corner of the pixel could mean that the tracks that pass through the corner of the pixel might not result in an associated cluster, resulting in a decrease in cluster finding efficiency in the corner of the pixel compared to the region covered by the implant. This means that the efficiency will be affected by the damage caused by irradiation.

It is important that at maximum fluence the sensors remain efficient. The analysis described in section 7.2 was used to measure the cluster finding efficiency for irradiated sensors. Figure 9.12 shows the cluster finding efficiency for the assemblies that were irradiated at JSI as a function of the applied voltage. The Hamamatsu sensors are displayed in green, the 200 μm thick Micron sensors are displayed in blue and the 150 μm thick Micron sensors in purple. As expected, given that after irradiation the sensors collect a lot less charge for the same voltage than they did before irradiation, the efficiency after irradiation is reduced. However, after increasing the voltage, all sensors reach 98% efficiency before 1000V, as can be seen in figure 9.13. The TDR requirement that each sensor must collect at least 6000 e^- is a direct consequence of there being a minimum

required cluster finding efficiency.. Indeed, when the sensors collect a most probable signal of 6000 e^- , all of the sensors are over 95% efficient.

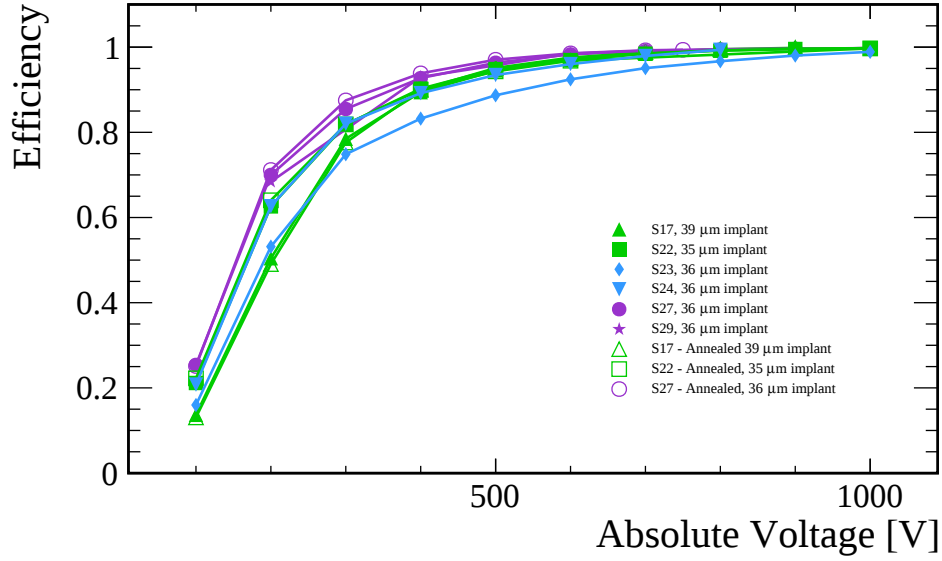


Figure 9.12: Overall Efficiency for sensors irradiated at JSI.

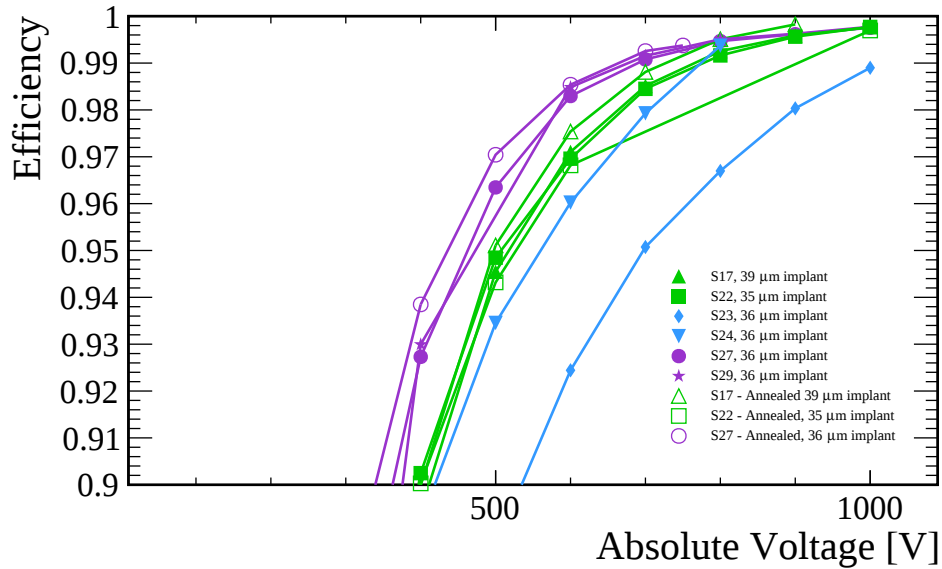


Figure 9.13: Efficiency for sensors irradiated at JSI, focussing on the efficiency region above 90%.

9.4.1 Pixel cluster finding efficiency in the corner

It has already been shown that the charge collected for hits in the corner of a pixel is less than that for hits in the centre. Therefore, it is expected that the cluster finding

efficiency in the corner of a pixel is less than the cluster finding efficiency in the centre. Thus, the overall efficiency for a full sensor could be reduced because of lower efficiencies in the corners of the pixel within a sensor. This is investigated further, by considering the whole sensor efficiency, which is normalised by two pixels in the x-direction and two pixels in the y-direction. This provides a four-pixel area that can be used to study the effects of the efficiency in the corners of adjoining pixels. The efficiency as a function of the track location is shown in figure 9.14. This shows the differences in the efficiencies between the implant and the surrounding areas. The areas in between the implants show lower efficiency.

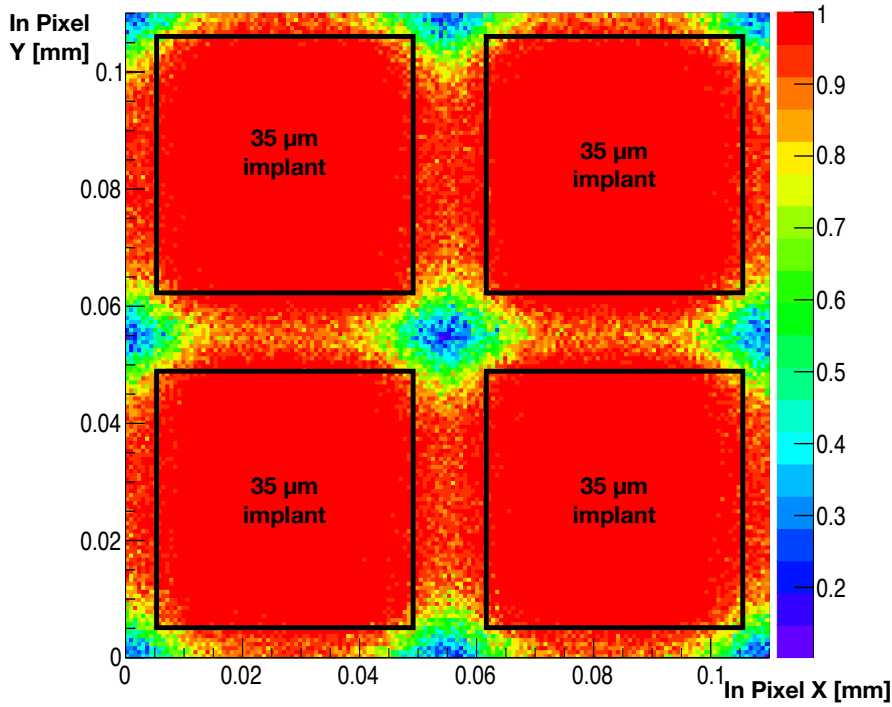


Figure 9.14: *In-pixel efficiency for for the four-pixel area on S24 at 500V.*

To look into the lower corner efficiencies, a profile along the diagonal of the in-pixel efficiency for the four-pixel area was plotted as a function of the x -coordinate and studied in more detail. The profiles for four different voltages for assembly S24, which has a $36 \mu\text{m}$ implant, are shown in figure 9.15. These results show that, as the voltage increases, the efficiency rises in the region under the implant. As the threshold is only $1000 e^-$ it is no surprise that the efficiency in the centre of the pixel is high, even at

just 200V. Furthermore, it can be seen that the efficiency in the corners improves much more slowly with voltage.

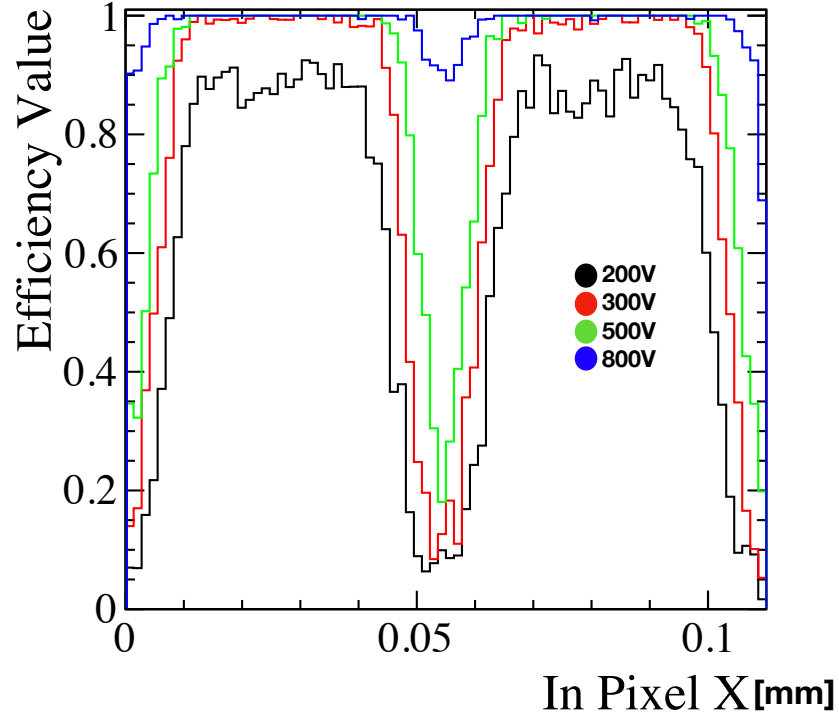


Figure 9.15: Profile along the diagonal of a four pixel efficiency for assembly S24.

To investigate this inefficient area between the implants, the profile was fitted with

$$Efficiency = P_0 - P_1 * (e^{-\lambda}) \quad (9.1)$$

with

$$\lambda = \frac{x - P_2}{P_3} \quad (9.2)$$

where P_n are the fit parameters, with P_0 representing the efficiency value at the implant, $P_0 - P_1$ representing the corner efficiency, P_2 representing the location within the pixel with the lowest efficiency and P_3 representing the full-width half maximum of the efficiency drop. An example of the use of this fit is shown in figure 9.16. The model describes the data well. The fit procedure was repeated for all irradiated sensors and all voltages.

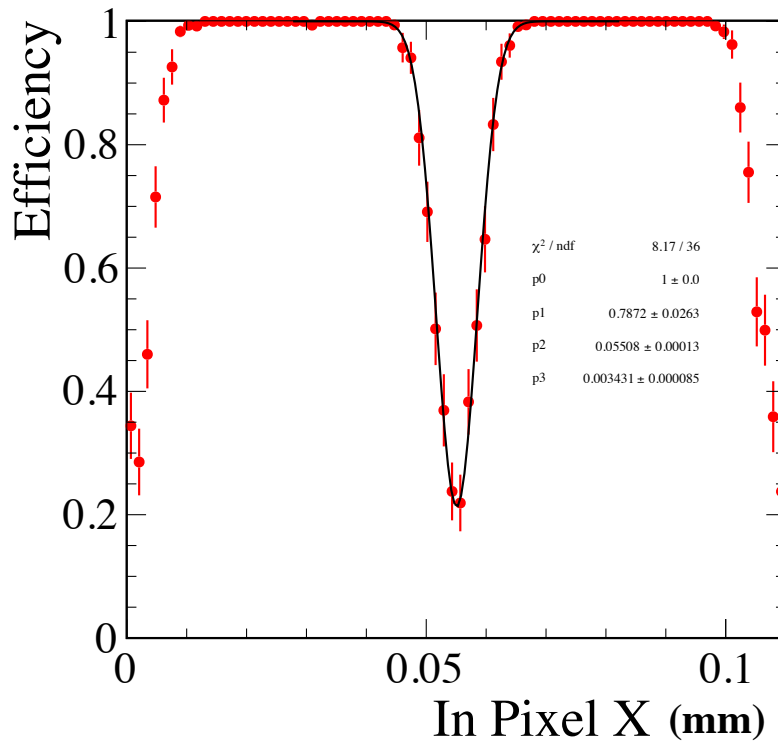


Figure 9.16: *Example of fitted profile along the diagonal of a four pixel efficiency for S24 at 500V.*

The efficiency in the area under the implant, P_0 , is expected to reach its maximum value at a lower voltage than the overall efficiency. The corner efficiency, $P_0 - P_1$, is expected to increase with voltage, but at a slower rate than the overall efficiency. P_2 is expected to be constant with varying voltage while P_3 expected to decrease when the voltage increases.

Figure 9.17 shows the x-coordinate extracted from the fits, or P_2 , for all sensors as a function of the voltage. As expected, the minimum efficiency occurs exactly at the boundary between two pixels. Furthermore, this x-coordinate of the minimum efficiency is not dependent on the thickness of sensor, voltage, or implant size. Figure 9.18 shows the full-width half maximum of the efficiency drop for all sensors as a function of the absolute voltage. The width of the inefficient area decreases with voltage and there is no significant dependence on the thickness of the sensors or implant size. The efficiency in the area over the implant is expected to reach its maximum value at a lower voltage than the overall efficiency will.

Figure 9.19 shows how the efficiency in the area of the implant changes with voltage. The

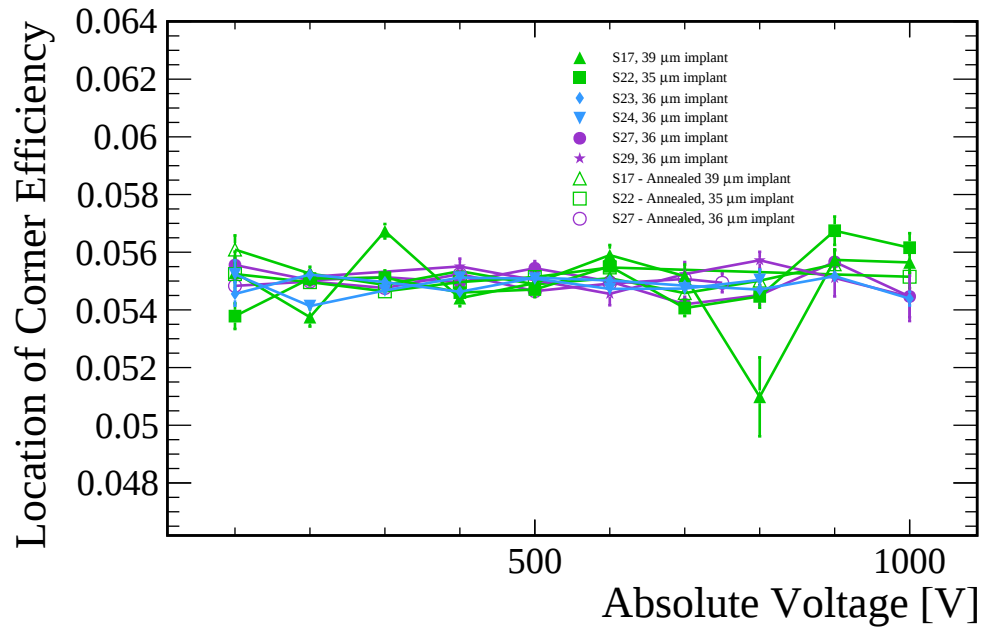


Figure 9.17: Location of the efficiency minimum for all irradiated sensors.

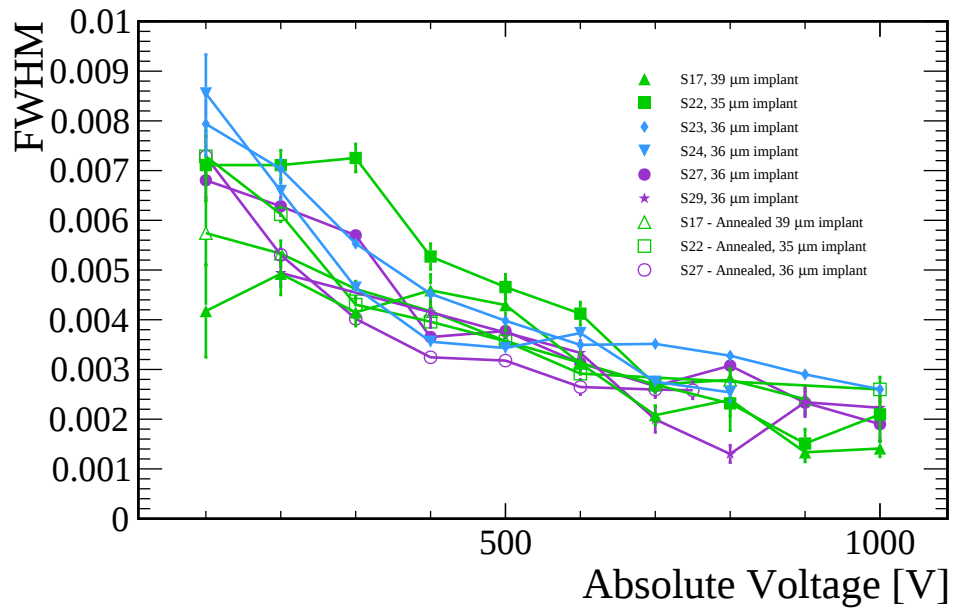


Figure 9.18: Width of the inefficient area for all irradiated sensors.

area underneath the implant is the most efficient part of the pixel. Hence, the efficiency here should be relatively high and should increase rapidly with voltage. This is indeed observed. The area under the implant is fully efficient from 400 V while for the full pixel full efficiency does not occur until 900 V. The corner efficiency is expected to increase with voltage but at a slower rate compared to the overall efficiency. The minimum efficiency for all sensors is shown as a function of the absolute voltage in figure 9.20.

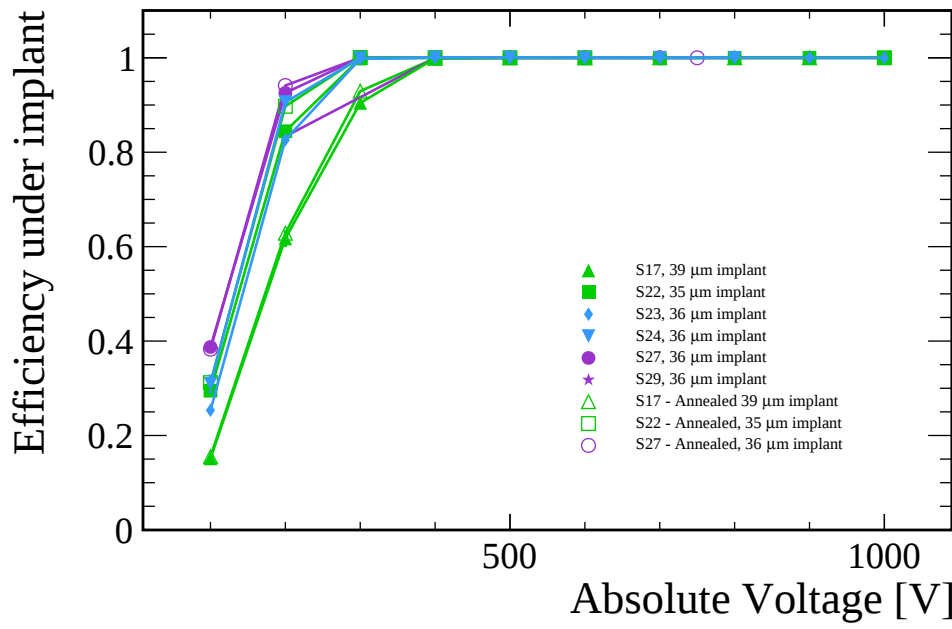


Figure 9.19: Efficiency for area under the implant for sensors irradiated at JSI.

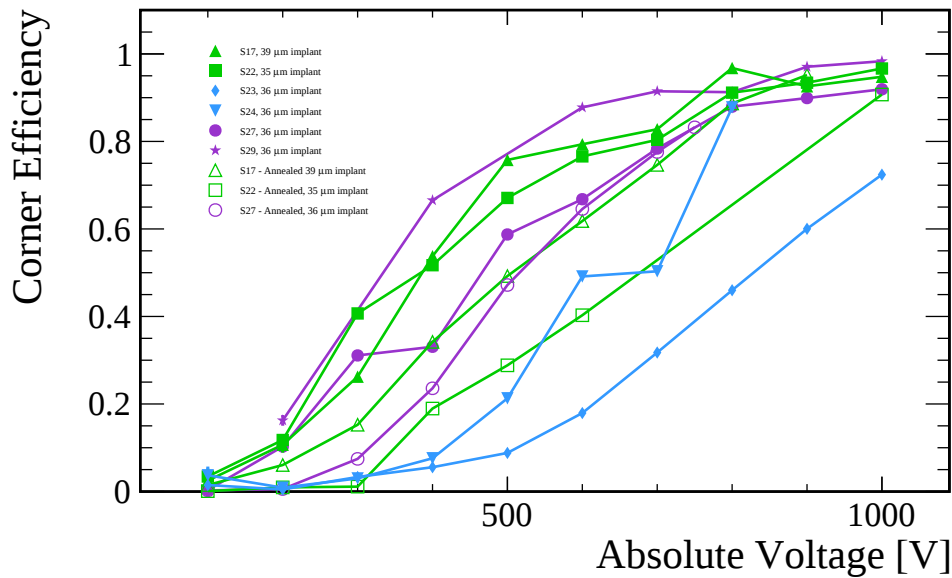


Figure 9.20: Corner efficiency as a function of absolute voltage for sensors irradiated at JSI.

The graph shows that the minimum efficiency increases only slowly as a function of the absolute voltage. There is no significant dependence on the implant width or detector thickness.

9.5 Summary

The sensors discussed in this section were all irradiated to $8 \times 10^{15} \text{ 1 MeV n}_{eq}/\text{cm}^2$, which is the maximum expected fluence for the VELO to have received by the end of Run 3. After irradiation, the sensors are able to collect the required minimum of 6000 electrons between 600 V and 800 V. At 1000 V the sensors collect around 8000 electrons. The sensors with larger implant widths collect more charge in the corners of the pixels than the sensors with smaller implant widths. By the point at which the sensors collect the required 6000 electrons, they are all 95% efficient. The 150 μm thick sensors reach 95% efficiency at a lower voltage than the 200 μm thick sensors. The efficiency is reduced by the loss of charge from the corner of the pixels. The minimum of the corner efficiency is located in-between the pixels. The implant width and thickness of the sensor do not have an effect on the corner efficiency of the sensor.

Chapter 10

Inhomogeneous Irradiation and the Sobel Operator

The measurements described in chapter 9 were performed after the sensors had been irradiated homogeneously with neutrons up to the maximum flux expected to be experienced by the upgraded VELO by the end of Run 3. To better understand the development of the sensor damage with dose and to study the effects of the non-uniform radiation profile that is expected to be experienced by the upgraded VELO, some sensors were deliberately irradiated so that they would end up with a non-uniform irradiation profile. This was done at KIT using low energy protons to create the required non-uniform radiation profile. The non-uniformly irradiated sensors were tested in the same way as the homogeneously irradiated sensors. The results of this study are reported here.

10.1 KIT irradiation

The results presented in chapter 9 demonstrate that the performance of all the sensors after receiving a dose of $8 \times 10^{15} \text{ 1 MeV n}_{eq}/\text{cm}^2$ is sufficient for operation of the VELO even after irradiation. These sensors are uniformly irradiated. However, the expected radiation profile for the upgrade is actually expected to be highly irregular (see section 3.2). To achieve this non-uniform radiation profile, some sensors were irradiated at

KIT. The KIT cyclotron provides protons with an energy of approximately 23 MeV. The fluence is known with an accuracy of $\pm 20\%$. During irradiation, the sensors are rotated by 45° with respect to the horizontal and cooled below -30°C [58]. Two single-chip $200\text{ }\mu\text{m}$ thick n -on- p sensors were irradiated with a planned profile, which is shown in figure 10.1 and table 10.1.

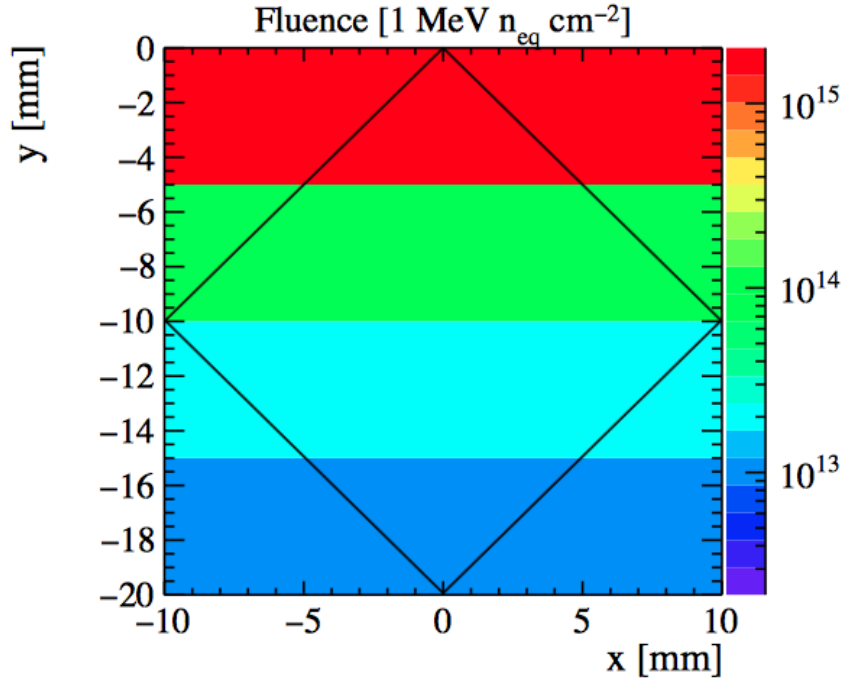


Figure 10.1: *Fluence profile at KIT with overlaid outline of a single-chip sensor.*

Line [mm]	Fluence/scan	Fluence
0 - 5	1.92×10^{15}	2.00×10^{15}
0 - 10	6.08×10^{13}	7.82×10^{13}
0 - 15	8.86×10^{12}	1.74×10^{13}
0 - 20	2.17×10^{12}	8.68×10^{12}
0 - 25	2.17×10^{12}	6.51×10^{12}
0 - 30	2.17×10^{12}	4.34×10^{12}
0 - 50	2.17×10^{12}	2.17×10^{12}

Table 10.1: *Irradiation protocol used for the single-chip assemblies at KIT, fluence is expressed in $1\text{ MeV } n_{eq}/\text{cm}^2$.*

The maximum fluence to which the two assemblies were exposed differ by a factor of two. The higher maximum fluence was achieved simply by sending one of the single-chip assemblies through the fluence scan twice. These sensors were then studied using the test beam set-up, so that the effects of non-uniform radiation damage could be studied.

Each sensor had a bias scan up to 1000 V performed using the Timepix3 telescope. Then, the charge collection as a function of the bias voltage and radiation dose was studied. The majority of the data collection was with the beam focussed on the most irradiated corner of the sensor.

10.2 Non uniform irradiation studies

To study the collected charge as a function of dose, it is of paramount importance to select areas of constant dose. This can either be done from the data or one has to rely on the mechanical alignment in both the irradiation set up and the test beam. Here a data driven method was used, which requires subdividing the sensor in bins of pixels. To maximise the sensitivity, the bins need to be kept as small as possible. It was not possible to use the method described in section 4.1.1 to extract the most probable signal in each bin, as the number of entries in each bin is too small to yield meaningful results. To avoid this problem, the signal distribution was instead coarsely binned, and the most probable signal estimated by calculating the centre of gravity of the highest bin with its two neighbours. Figure 10.2 shows an example to illustrate this method, along with corresponding estimate of the most probable value.

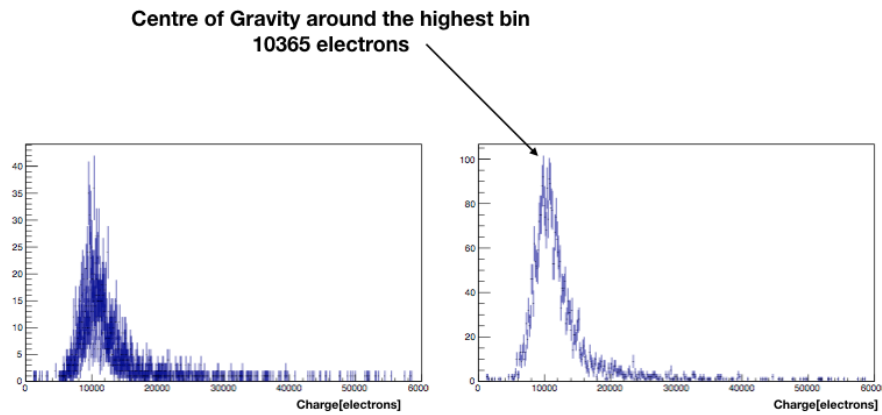


Figure 10.2: *Original charge distribution (left) for one section at 400 V and after a coarse rebinning (right). The estimated most probable value of collected charge is 10365 electrons.*

After finding the areas between the areas of constant radiation dose, bin ranges with the same radiation dose can be safely chosen.

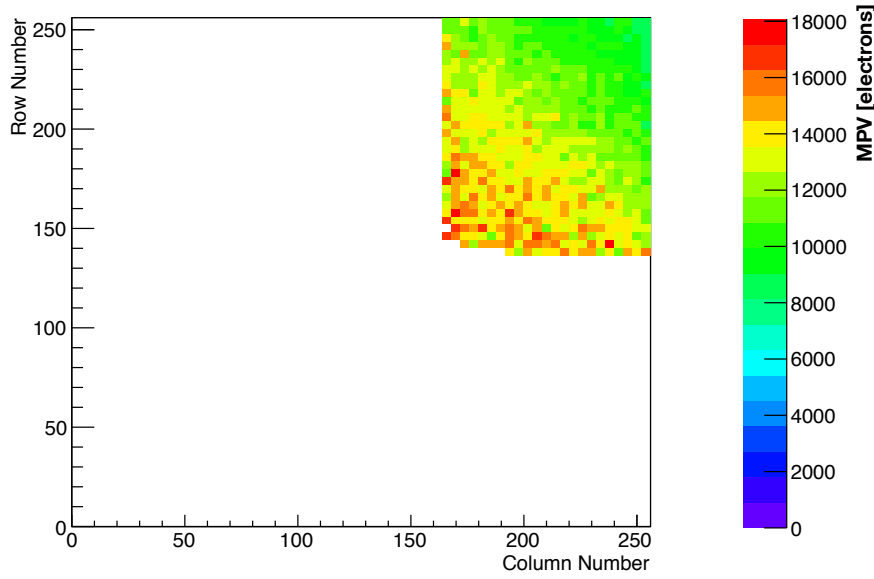


Figure 10.3: *Most probable value of associated clusters across the sensor at 400 V for a single chip assembly irradiated to maximum fluence of $4 \times 10^{15} \text{ 1 MeV } n_{eq}/\text{cm}^2$.*

Figure 10.3 shows the most probable signal of collected charge in the bins as a function of the column number and row number. As can be seen in figure 10.3 there are no visible steps in the most probable value distribution across the sensor.

Another way to find areas with the same dose is to assume that the sensor was placed into the beam at KIT at a perfect angle. Instead of dividing the sensor up into small square bins, diagonal bins can be used. This is when bins are orientated at the same angle as the beam at KIT, all of these bins have the same width but differing lengths.

10.3 Sobel Operator

Finding the transitions between areas of constant radiation dose is very important for this analysis. Although no transitions can be observed easily by eye, an edge finding analysis using the Sobel operator can be performed to identify them. The Sobel operator performs a two-dimensional spatial gradient on an image, which can be used to identify edges. A Sobel operator usually consists of two 3×3 kernels, one for the x direction, G_x ,

and one for the y direction, G_y , which are defined as follows:

$$G_x = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}$$

and

$$G_y = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix}$$

The Sobel operator can also be increased to a larger kernel. The kernels are combined together to produce the magnitude of the gradient

$$|G| = \sqrt{G_x^2 + G_y^2} \quad (10.1)$$

The larger kernel includes more of the surrounding area:

$$G_{x5} = \begin{bmatrix} -2 & -1 & 0 & 1 & 2 \\ -3 & -2 & 0 & 2 & 3 \\ -4 & -3 & 0 & 3 & 4 \\ -3 & -2 & 0 & 2 & 3 \\ -2 & -1 & 0 & 1 & 2 \end{bmatrix}$$

and

$$G_{y5} = \begin{bmatrix} -2 & -3 & -4 & -3 & -2 \\ -1 & -2 & -3 & -2 & -1 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 2 & 3 & 2 & 1 \\ 2 & 3 & 4 & 3 & 2 \end{bmatrix}$$

Before this analysis was applied to the test beam data, it first was tested on simulation. An example of the simulated data before and after the 3×3 Sobel operator was applied is shown in figure 10.4. The Sobel operator finds the transition areas clearly.

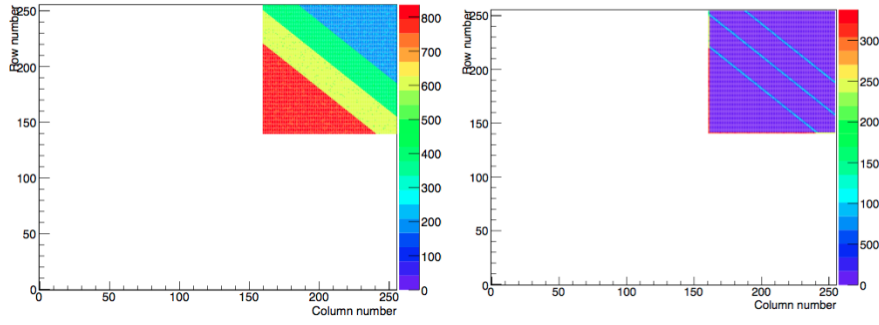


Figure 10.4: *Simulation of non-uniform irradiation (left) and the output of the Sobel operator using a 3×3 kernel and applied to the simulated data (right). The transition areas are identified as the light blue lines in the right-handed distribution.*

The Sobel operator is then applied to the corresponding test beam data. The results for data taken at a bias voltage of 400V after the Sobel operator has been applied are shown in figure 10.5 for a 3×3 kernel and figure 10.6 for a 5×5 kernel.

For the data from this particular sensor, the highest irradiated area received a dose of $4 \times 10^{15} \text{ 1 MeV n}_{eq}/\text{cm}^2$. This is half the dose received by the sensors presented in chapter 9. The full depletion voltage of p -type bulk sensors scales roughly linearly with dose, as can be seen from equation 8.3 and figure 8.3. The unirradiated sensors deplete at around 140 V and the highly irradiated sensors deplete at a voltage well over 1000 V. This means that the depletion voltage for this sensor at the highest dose is well over 570 V. Thus, the most highly irradiated area on the sensor presented here is only partially depleted at 400 V. Therefore, the radiation induced collected signal steps should be present.

No clear transitions are observed in the test beam data, regardless of whether a 3×3 or a 5×5 kernel is used. There are differences in the gradient but there are no distinct transitional steps. This means that the radiation profile is not as it was originally planned, otherwise the transitions would be apparent. As there are no transitional steps it is not possible to identify areas of constant radiation. This means that the study of the most probable value of collected charge as a function of bias voltage for areas of constant radiation dose is not possible.

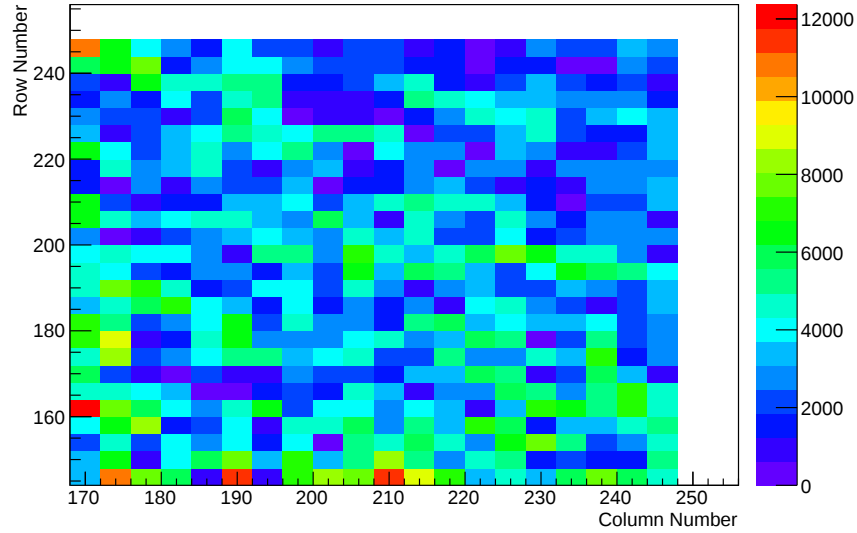


Figure 10.5: The output of the Sobel operator using a 3×3 kernel applied to single-chip assemblies at 400V irradiated to a maximum fluence of 4×10^{15} 1 MeV n_{eq}/cm^2 . The distributions has been limited to the specific area of interest.

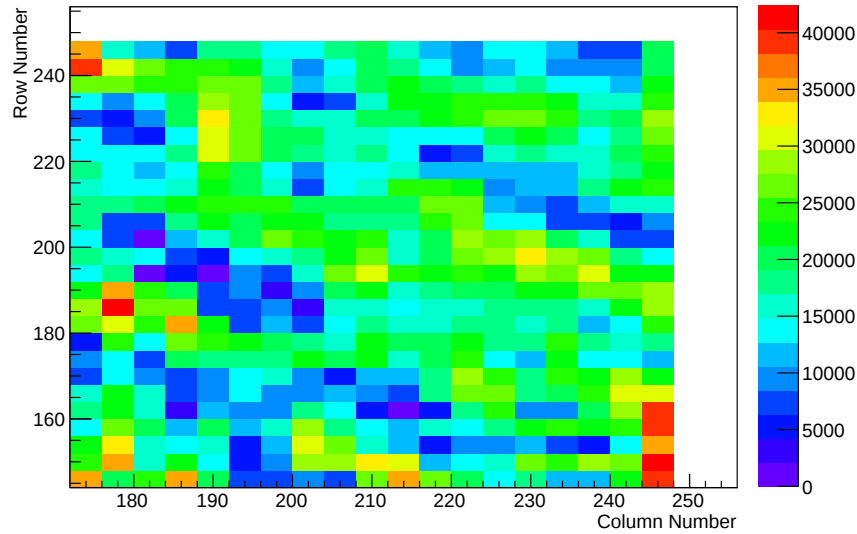


Figure 10.6: The output of the Sobel operator using a 5×5 kernel applied to single-chip assemblies at 400V irradiated to a maximum fluence of 4×10^{15} 1 MeV n_{eq}/cm^2 . The distributions has been limited to the specific area of interest.

10.4 Diagonal Bins

As discussed previously, diagonal bins can be used as an alternative. In this case, the width of the bins will be smaller than the expected bands of constant radiation. The data for each diagonal bin is fitted with a Landau convoluted with a Gaussian, as described in

section 4.1.1. The most probable value of collected charge is shown as a function of the bin number in figure 10.7. The bin numbering scheme starts with 0 in the upper-most

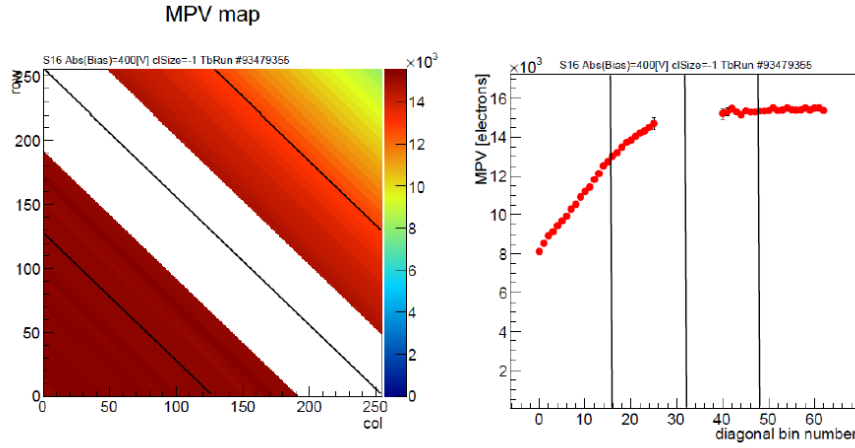


Figure 10.7: *Most probable value of collected charge as a function of diagonal bin number for the single-chip assemblies at 400V irradiated to a maximum fluence of 4×10^{15} $1 \text{ MeV } n_{eq}/\text{cm}^2$. This is shown for two areas of interest.*

right-hand bin of the left most figure. This is the area of maximum irradiation. The second area of constant radiation should start around bin number 26 if the fluence scan provided by KIT in table 10.1. In the first expected area of constant irradiation the most probable value appears to be decreasing where it is expected to be constant. This is inconsistent with the planned irradiation profile from KIT. Both this method and the Sobel operator show the inconsistency.

10.5 Summary

The measurements presented in chapter 9 were performed after irradiating the sensors homogeneously with neutrons until they had received the maximum flux that the upgraded VELO is expected to receive. To better understand the development of sensor damage with dose and to study the effects of a non-uniform radiation profile (expected in the upgraded VELO), some sensors were irradiated to have a specific non-uniform irradiation profile. The areas of with constant radiation dose were studied using two techniques: using a Sobel operator and relying on alignment. In both methods the most probable value of collected charge was observed to change across the sensor. This implies

that the irradiation profile is indeed inhomogeneous. Unfortunately it is not consistent with the originally-planned irradiation profile. Therefore, nothing conclusive can be said about the effects of varying the radiation dose. It is therefore not possible to produce a distribution of the most probable value of the collected charge as a function of bias voltage for areas of constant radiation. There are several possible explanations for this: It could be that the beam of radiation was insufficiently focussed; it is also possible that the areas chosen to receive a constant radiation dose were too narrow or it could be that the defects caused within the sensor have annealed in such a way that the radiation damage is no longer distinct enough to identify.

Chapter 11

Conclusions

A new Vertex Locator will be installed during the next long shutdown, which is planned to start at the end of 2018 and to run into 2020. The current silicon strip detector will be replaced by a new silicon pixel detector. It will be a hybrid pixel detector read out by the VeloPix chip. The VeloPix is an updated version of the existing Timepix3 chip. The key difference between the Timepix3 and the VeloPix is that the latter has binary readout while the former measures time over threshold and time of arrival for signals that exceed a set threshold. As the VeloPix was not available during the period in which the work documented here was performed, the Timepix3 was used to test the prototype sensors. The choice of the chip dictates the geometry of the detector; the chip is designed for $55\mu\text{m}$ pixels. The key design parameters that are still open are the detector type (n -on- n , n -on- p), the charge collection implant size and the sensor thickness. Several silicon detector designs have been tested thoroughly to make sure that they meet the requirements for Run 3.

Radiation damage is a major issue for the new VELO. It is vital that the sensors will maintain a hit finding efficiency above 95% even at the expected maximum fluence the new detector is expected to receive, which is $8 \times 10^{15} \text{ 1 MeV n}_{eq}/\text{cm}^2$. This corresponding to, at minimum, a most probable value for the signal of 6000 electrons at a bias voltage of 1000 V or less. Tests were undertaken both in the lab and with the Timepix3 telescope in test beam to study this and other requirements.

Before every prototype sensor is placed in a test beam environment, multiple tests are performed to obtain the correct operational settings. In the lab, every assembly went through an IV scan to confirm depletion voltage and breakdown voltage. After the highest irradiation dose was administered the sensors need to either continue to fully deplete or, at the very least, not breakdown before 1000 V. Before irradiation, the depletion voltages for the Hamamatsu sensors were found to be approximately 130 V. The Micron sensors were found to fully deplete at around 40 V. The breakdown voltages for the Hamamatsu sensors varied between 650 V and 1000 V. The 150 μm thick Micron sensors were found to break down between 750 and 950 V. The 200 μm thick Micron sensors broke down at approximately 300 V. Before irradiation, all sensors were confirmed as having a large voltage range between the depletion and breakdown voltages, in which the sensors could be operated and in which the performance would be good. After irradiation, no sensors reached full depletion before 1000 V, while three of them were found to break down before 1000 V. These three sensors are the 200 μm thick *n-in-p* silicon sensors manufactured by Hamamatsu. All three have a 35 μm implant.

The Timepix3 chip operates in a zero-suppressed mode, just like the VeloPix chip will. Thus only pixels whose signal exceeds a set threshold will be read out. The threshold is first set coarsely for the whole sensor using a global threshold and then individually for each pixel using a trim DAC, which allows the threshold for each individual pixel to be set much more finely. The optimal per pixel fine threshold settings are obtained using an equalisation procedure, which reduces the threshold dispersion. The Timepix3 measures the time over threshold as a proxy for the collected charge. In order to convert the signal in time over threshold units to the amount of collected charge in number of electrons, a test pulse calibration is performed on a pixel-by-pixel basis, the result of which may be used to perform the required conversion.

After the tests in the lab have been completed, the sensors are placed as the device under test in the Timepix3 Telescope, so that they may be studied in a test beam. The pointing resolution between the telescope arms was found to be better than 2 μm , which allows in-pixel studies to be performed, that is, the dependence of key performance parameters

on the coordinates of the point at which the particle impacts on an individual pixel can be investigated.

The focus of this thesis has been on the measurement of the charge collection and cluster finding efficiency for different sensors before and after irradiation. These two quantities are important because – Before irradiation, the 200 μm thick *n-in-p* silicon sensors were found to collect the expected 16,000 e^- when fully depleted. The 150 μm *n-in-n* thick silicon sensors also collected the expected 12,000 e^- at full depletion. All of the sensors were found to be more than 99.9% efficient before irradiation. The 55 μm pixels are much larger than the size of the charge cloud generated by a traversing particle. As a result the clusters on these sensors are mostly one-pixel clusters, which will yield a position resolution of 55 μm divided by the $\sqrt{12}$. The larger cluster sizes lead to a decrease in the position resolution. The position resolution of the sensor also depends on the applied bias voltage. The minimum resolution of 12.7 μm is when the sensor is fully depleted. When the sensor is over-biased the spatial resolution gets slightly worse, increasing to 13.5 μm . No dependence of the resolution on the pixel implant width is observed.

Some sensors were irradiated to the expected maximum fluence that the upgraded VELO is expected to receive, which is $8 \times 10^{15} \text{ 1 MeV } n_{eq}/\text{cm}^2$. After irradiation, all the sensors meet continue to the required 6000 electrons between bias voltages of 600 V and 800 V. At 1000 V the sensors collect around 8000 electrons. When the sensors are collecting the required 6000 electrons, they are all at least 95% efficient. The remaining inefficiency originates from the corners of the pixels. This is because the electric field is much lower in the corners, which enhances trapping and, due to charge sharing, makes it much less likely that the pixel, and more importantly, its neighbours, will collect enough signal to exceed the threshold. The implant width and thickness of the sensor do not significantly affect the corner efficiency of the sensor.

After irradiation, the sensors predominantly detect one-pixel clusters. This is due to the particle crossing at right-angles to the sensor plane and the lower generated signal resulting from partial depletion and hence, less efficient charge collection. The sensors with larger implants collect slightly more charge in the corners of the pixels than those with the smaller implants. Although this increase in charge collection at the corners

is not significant, it does not appear to affect the charge collection or cluster finding efficiency for the whole sensor.

The prototype sensors tested show that a 150 μm thick n -on- n silicon sensor with an implant width of 39 μm would be the best choice for the LHCb Vertex Locator upgrade. The largest implant width shows a small benefit in the charge collected in the corners of the pixels, but this has no effect on the efficiency. The larger implant covers more of the pixel, so less charge is lost at the edges and corners of the pixel. The thinner sensors have less multiple scattering due to less material. After irradiation at the maximum expected fluence, the thinner sensors do not perform worse than the thicker sensors, in terms of charge collection. The 150 μm thick sensors do reach a higher cluster finding efficiency at a lower voltage in comparison to the thicker sensors. This option is not available for the LHCb VELO upgrade due to the manufacturers specifications. Considering only the options that are available, the 200 μm thick n -on- p silicon sensor with the implant width of 39 μm would be the best option. This is due to more charge being collected in the corners of the pixels.

Bibliography

- [1] **ATLAS and CMS** Collaboration, G. Aad *et al.*, “Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments,” *Phys. Rev. Lett.* **114** (2015) 191803.
- [2] A. D. Sakharov, “Violation of CP Invariance, c Asymmetry, and Baryon Asymmetry of the Universe,” *Pisma Zh. Eksp. Teor. Fiz.* **5** (1967) 32–35. [Usp. Fiz. Nauk161,61(1991)].
- [3] “CERN.” www.cern.ch. Accessed: 2017-08-01.
- [4] **ALICE** Collaboration, K. Aamodt *et al.*, “The ALICE experiment at the CERN LHC,” *JINST* **3** (2008) S08002.
- [5] **CMS** Collaboration, S. Chatrchyan *et al.*, “The CMS Experiment at the CERN LHC,” *JINST* **3** (2008) S08004.
- [6] **ATLAS** Collaboration, G. Aad *et al.*, “The ATLAS Experiment at the CERN Large Hadron Collider,” *JINST* **3** (2008) S08003.
- [7] A. Sarti, “ B Physics at LHC,” in *Hadron collider physics. Proceedings, 19th Symposium, HCP2008, Galena, USA, May 27-31, 2008*. 2008. [arXiv:0809.0450](https://arxiv.org/abs/0809.0450) [hep-ex].
- [8] **LHCb** Collaboration, *LHCb VELO Upgrade Technical Design Report*. Geneva, Nov, 2013.
- [9] T. Szumlak and A. Obakowska-Mucha, “LHCb Vertex Locator: Performance and radiation damage in LHC Run 1 and preparation for Run 2,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **824** (2016) no. Supplement C, 59 – 61. <http://www.sciencedirect.com/science/article/pii/S0168900215015910>. Frontier Detectors for Frontier Physics: Proceedings of the 13th Pisa Meeting on Advanced Detectors.
- [10] R. Aaij *et al.*, “Performance of the LHCb Vertex Locator,” *JINST* **9** (2014) 09007, [arXiv:1405.7808](https://arxiv.org/abs/1405.7808) [physics.ins-det].

- [11] The LHCb Collaboration and others, “The LHCb Detector at the LHC,” *Journal of Instrumentation* **3** (2008) no. 08, S08005.
- [12] M. Needham, “Silicon Tracker simulation performance,” *LHCb note* (2003) .
- [13] **LHCb Outer Tracker Group** Collaboration, R. Arink *et al.*, “Performance of the LHCb Outer Tracker,” *JINST* **9** (2014) no. 01, P01002, [arXiv:1311.3893 \[physics.ins-det\]](#).
- [14] **LHCb** Collaboration, R. Aaij *et al.*, “Measurement of the track reconstruction efficiency at LHCb,” *JINST* **10** (2015) no. 02, P02007, [arXiv:1408.1251 \[hep-ex\]](#).
- [15] D. P. M. Hynds, L. Eklund, P. Soler, and C. Parkes, *Resolution studies and performance evaluation of the LHCb VELO upgrade*. PhD thesis, Glasgow University, Mar, 2015. Presented 27 Nov 2014.
- [16] T. L. Collaboration *et al.*, “LHCb detector performance,” *International Journal of Modern Physics A* **30** (2015) no. 07, 1530022.
- [17] M. Adinolfi *et al.*, “Performance of the LHCb RICH detector at the LHC,” *The European Physical Journal C* **73** (2013) no. 5, 2431.
- [18] **LHCb** Collaboration, S. Amato *et al.*, *LHCb calorimeters: Technical Design Report*. Technical Design Report LHCb. CERN, Geneva, 2000. <https://cds.cern.ch/record/494264>.
- [19] F. Archilli *et al.*, “Performance of the Muon Identification at LHCb,” *JINST* **8** (2013) P10020, [arXiv:1306.0249 \[physics.ins-det\]](#).
- [20] R. Aaij *et al.*, “The LHCb trigger and its performance in 2011,” *Journal of Instrumentation* **8** (2013) no. 04, P04022.
- [21] **LHCb** Collaboration, J. Albrecht, “The LHCb Trigger System: Present and Future,” *J. Phys. Conf. Ser.* **623** (2015) no. 1, 012003.
- [22] T. Poikela *et al.*, “Timepix3: a 65K channel hybrid pixel readout chip with simultaneous ToA/ToT and sparse readout,” *Journal of Instrumentation* **9** (2014) no. 05, C05013.
- [23] A. Nomerotski *et al.*, “Evaporative CO₂ cooling using microchannels etched in silicon for the future LHCb vertex detector,” *Journal of Instrumentation* **8** (2013) no. 04, P04004.
- [24] M. van Beuzekom *et al.*, “VeloPix ASIC development for LHCb VELO upgrade,” *Nuclear Instruments and Methods in Physics Research A* **731** (2013) 92–96.

- [25] M. Campbell *et al.*, “A readout chip for a 64x64 pixel matrix with 15-bit single photon counting,” *IEEE Transactions on Nuclear Science* **45** (1998) no. 03, 751–735.
- [26] E. Heijne *et al.*, “A silicon surface barrier microstrip detector designed for high energy physics,” *Nuclear Instruments and Methods* **178** (1980) 331 – 343.
- [27] **Particle Data Group** Collaboration, K. A. Olive *et al.*, “Review of Particle Physics,” *Chin. Phys.* **C38** (2014) 090001.
- [28] G. Lutz, *Semiconductor Radiation Detectors*. Springer, Munich, Germany, 1999.
- [29] L. Landau, “On the energy loss of fast particles by ionization,” *J. Phys.(USSR)* **8** (1944) 201–205.
- [30] J. Bak *et al.*, “Large departures from Landau distributions for high-energy particles traversing thin Si and Ge targets,” *Nuclear Physics B* **288** (1987) no. Supplement C, 681 – 716.
- [31] H. Bichsel, “Straggling in thin silicon detectors,” *Rev. Mod. Phys.* **60** (1988) 663–699.
- [32] F. Hartmann, “Evolution of Silicon Sensor Technology in Particle Physics,” *Springer Tracts Mod. Phys.* **231** (2009) 1–204.
- [33] C. Leroy and P.-G. Rancoita, *Silicon solid state devices and radiation detection*. World Scientific, Singapore, 2012.
- [34] H. Spieler, *Semiconductor Detector Systems*. Oxford science publications, 2005.
- [35] M. Campbell *et al.*, “Medipix Collaboration.”
<http://medipix.web.cern.ch/medipix/>. Accessed: 2017-09-05.
- [36] M. Bomben, A. Ducourthial, A. Bagolini, M. Boscardin, L. Bosisio, G. Calderini, L. D’Eramo, G. Giacomini, G. Marchiori, N. Zorzi, A. Rummler, and J. Weingarten, “Performance of active edge pixel sensors,” *Journal of Instrumentation* **12** (2017) no. 05, P05006.
- [37] J. Visser *et al.*, “SPIDR: a read-out system for Medipix3 and Timepix3,” *JINST* **10** (2015) no. C 12028, .
- [38] K. Akiba *et al.*, “Charged Particle Tracking with the Timepix ASIC,” *Nucl. Instrum.Meth.* **A 661** (2011) 51, [arXiv:1103.2739](https://arxiv.org/abs/1103.2739) [physics.ins-det].
- [39] J. Jakubek, “Precise energy calibration of pixel detector working in time-over-threshold mode,” *Nucl. Instrum. Meth.* **A 633** (2011) S262–S266.
- [40] K. Akiba *et al.*, “The Timepix Telescope for High Performance Particle Tracking,” *Nucl. Instrum.Meth.* **A 723** (2013) 47, [arXiv:1304.5175](https://arxiv.org/abs/1304.5175) [physics.ins-det].

- [41] K. Akiba *et al.*, “LHCb VELO Timepix3 Telescope,”.
- [42] M. Clemencic, H. Degaudenzi, P. Mato, S. Binet, W. Lavrijsen, C. Leggett, and I. Belyaev, “Recent developments in the LHCb software framework GAUDI,” *Journal of Physics: Conference Series* **219** (2010) no. 4, 042006.
- [43] V. Blobel, “Software alignment for tracking detectors,” *Nucl. Instr. Meth.* **A566** (2006) no. 1, 5 – 13.
- [44] E. Buchanan, *Yet to be decided*. PhD thesis, University of Bristol, 2018.
- [45] E. Dall’Occo, *Yet to be decided*. PhD thesis, Nikhef, 2018.
- [46] G. Lindström, “Radiation damage in silicon detectors,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **512** (2003) no. 1, 30 – 43. Proceedings of the 9th European Symposium on Semiconductor Detectors: New Developments on Radiation Detectors.
- [47] M. Moll, *Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties*. PhD thesis, Hamburg U., 1999.
- [48] G. Lindström, M. Moll, and E. Fretwurst, “Radiation hardness of silicon detectors a challenge from high-energy physics,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **426** (1999) no. 1, 1 – 15.
- [49] A. Affolder *et al.*, “Radiation damage in the LHCb Vertex Locator,” *Journal of Instrumentation* **8** (2013) no. 08, P08002.
- [50] **CERN-ROSE/RD48** Collaboration, M. Moll, E. Fretwurst, and G. Lindström, “Leakage current of hadron irradiated silicon detectors - material dependence,” *Nucl. Instrum. Meth.* **A426** (1999) 87–93.
- [51] **RD50** Collaboration, A. Chilingarov, “Generation current temperature scaling,” Tech. Rep. PH-EP-Tech-Note-2013-001, CERN, Geneva, Jan, 2013.
- [52] G. Beck and G. Viehhauser, “Analytic model of thermal runaway in silicon detectors,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **618** (2010) no. 1, 131 – 138.
- [53] G. Kramberger *et al.*, “Determination of effective trapping times for electrons and holes in irradiated silicon,” *Nucl. Instrum. Meth.* **A476** (2002) 645–651.
- [54] K. Iniewski, *Radiation Effects in Semiconductors*. CRC Press, 2010.

-
- [55] M. Moll, E. Fretwurst, G. Lindström, and CERN project RD48 (ROSE Collaboration), “Investigation on the improved radiation hardness of silicon detectors with high oxygen concentration,” *Nuclear Instruments and Methods in Physics Research A* **439** (2000) 282–292.
- [56] L. Snoj, G. Žerovnik, and A. Trkov, “Computational analysis of irradiation facilities at the JSI TRIGA reactor,” *Applied Radiation and Isotopes* **70** (2012) no. 3, 483 – 488.
- [57] “Jozef Stefan Institute.” <https://www.ijs.si/ijsw/JSI>. Accessed: 2017-07-19.
- [58] “Irradiation Center Karlsruhe.” http://www.etp.kit.edu/english/irradiation_center.php. Accessed: 2017-11-27.