Influence of Highly Ionising Events on the CMS APV25 Readout Chip

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ABSTRACT

The Compact Muon Solenoid (CMS) experiment is one of four large high energy physics experiments presently being constructed for operation at the Large Hadron Collider (LHC) facility at CERN, Geneva. The motivation for the LHC and its experiments is the large range of new physics expected at the TeV energy scale. The CMS Silicon Strip Tracker (SST) will play a major role in all physics searches, providing precision tracking within a hostile radiation environment. The SST readout system is based on the APV25 front-end chip, of which 73000 are needed to fully instrument the sub-detector.

It is essential for the SST readout system to be of the highest quality in order to maximise the physics performance of the sub-detector. Therefore, a production test station has been developed to screen wafers, each containing several hundred APV25 chips, prior to the integration of individual die into the final readout system. Several hundred wafers have already been screened and the number of chips identified to be fully functional and exhibit excellent performance corresponds to 70 % of the SST requirement. Analysis results are presented.

Inelastic nuclear collisions of hadrons incident on silicon sensors frequently generate highly ionising particles that can deposit as much energy within the sensor bulk as several hundred minimum ionising particles. These large signals can saturate the APV25 front-end chip, resulting in deadtime and introducing inefficiencies into the readout system. Analyses of beam test data that quantify the effect are presented. A change of a front-end component is shown to significantly reduce the induced inefficiencies, which are predicted to be at the sub-percent level for the final SST readout system. Subsequent Monte-Carlo studies have shown that the induced inefficiencies will have negligible effect on the tracking performance and $b$-tagging efficiency of the SST sub-detector.
To mum and dad.
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Chapter 1

The CMS Experiment at the LHC

1.1 Physics Motivation for the LHC

The Standard Model (SM) of particle physics is the theory of the fundamental electroweak and strong forces that govern the interactions between the most basic constituents of matter. The model has been remarkably successful since its conception in the 1970’s. The model has predicted the existence of a number of new particles, including the carriers of the weak force (the $Z$ and $W^\pm$ bosons) and has been rigorously tested experimentally to a high degree of accuracy. The only remaining SM particle that has yet to be observed experimentally is the Higgs boson, which provides the mechanism through which all particles acquire mass. Unfortunately, the SM does not provide an accurate prediction for the mass of the Higgs boson, although theoretical arguments provide an upper limit of $\sim 1 \text{ TeV}$. Hence, it is left to the experiments of the Large Hadron Collider (LHC) to search for the Higgs boson \cite{1, 2, 3, 4, 5, 6}.

In spite of its impressive success, the SM is not considered to be the ultimate description of nature. An appealing theoretical concept is that the electromagnetic, weak and strong forces are all manifestations of a single grand unified force, as described by a “Grand Unified Theory” (GUT). The reason for the different strengths of the forces at the energy scales probed by today’s accelerators is thought to be explained by the mechanism of ‘symmetry breaking’ at some higher energy scale. The most well-known example is the Higgs mechanism, which provides the explanation for the ‘broken symmetry’ exhibited by the electroweak theory. However,
problems arise when extrapolating from today’s knowledge at mass scales of a few hundred GeV to energy scales that existed in the early universe, \textit{i.e.} to energies of $10^{15}$ GeV and more. The theory of supersymmetry provides a theoretical solution to these conceptual problems by the introduction of supersymmetric partners to every known boson and fermion. These ‘sparticles’ are predicted to have masses at the TeV scale and so should be accessible to the Large Hadron Collider (LHC) [7].

Another question prominent in the field of particle physics is why the known universe is matter-dominated, given that matter and anti-matter were created in exactly equal quantities as the early universe cooled. The experimental observation of Charge-Parity (CP) violation during the decay of particles (implying a distinction of the weak force, which is responsible for decay, between matter and anti-matter) provides one mechanism for explaining this matter-antimatter disparity. Experimental evidence for CP violation has been observed through the different decay rates of neutral kaons, which contain the $s$ and $\bar{s}$ quarks, and also in neutral $B$-mesons, which contain the heavier $b$ and $\bar{b}$ quarks [8]. The high energy proton collisions provided by the LHC will be an abundant source of $B$-mesons [9].

Furthermore, the LHC program will also collide heavy ions (such as lead), which will result in very large centre-of-mass energies. Thus, the LHC will be able to replicate the conditions of the very early universe and generate quark-gluon plasmas, permitting a study of this previously unexplored state of matter [10].

1.1.1 LHC and its Experiments

The Large Hadron Collider will open up a new energy regime to particle physics, which will allow the study of a number of today’s outstanding physics issues, such as the origin of mass, supersymmetric particles, the possible substructure of quarks, and CP violation.

The observation of new and rare physics processes requires large centre-of-mass energies and high luminosities. Therefore, the LHC will collide proton bunches at a centre-of-mass energy of 14 TeV at a frequency of 40 MHz. The design luminosity of the machine is $10^{34}$ cm$^{-2}$ s$^{-1}$ which, coupled with the proton-proton inelastic cross section of $\sim$80 mb, results in a large $pp$ interaction rate of $\sim10^9$ events s$^{-1}$. 
1.1 Physics Motivation for the LHC

Figure 1.1: Predicted Standard Model Higgs cross sections at the LHC for various production processes, as a function of the Higgs mass.

The LHC will accommodate four major experiments, each optimised to exploit different physics processes accessible by the LHC. There are two ‘general purpose’ detectors designed primarily for Higgs searches: CMS (Compact Muon Solenoid) [11] and ATLAS (A Toroidal LHC Apparatus) [12]. Both detectors will provide precision tracking of charged particles, accurate energy measurements from large-coverage electromagnetic and hadronic calorimeters, and extensive muon tracking. The LHCb detector [13] is optimised for a study of CP violation and the ALICE detector (A Large Ion Collider Experiment) [14] is dedicated to studying the quark-gluon plasmas generated by heavy ion collisions.

1.1.2 Higgs Searches at the LHC

The mass of the Higgs is not predicted by the SM, but the self-consistency of the model up to an arbitrary energy scale imposes constraints on the Higgs mass: for a SM valid up to 1 TeV, the Higgs mass is confined to 55–700 GeV; at the GUT scale of $10^{19}$ GeV, the Higgs mass range narrows to 130–190 GeV [15].

The precision measurements of electroweak observables, such as $m_Z$ at the Large Electron Positron (LEP) collider, can also be used within the SM framework to impose further constraints on the Higgs mass. Fits to the electroweak data predict a most probable Higgs mass of $\sim 96$ GeV and an upper limit of $\sim 219$ GeV [16].
1.1 Physics Motivation for the LHC

Direct searches at LEP have provided a lower mass limit of 114 GeV [17] and the observation of a few candidate events, which favour a Higgs mass of 115.6 GeV [18]. Depending on its mass, there are a number of processes that can generate Higgs particles at the LHC, as illustrated in figure 1.1. The dominant production channel is gluon-gluon fusion. The available decay channels for the SM Higgs and their branching ratios are also mass dependent, as shown in figure 1.2. The favoured decay channels above and below a Higgs mass of \(\sim 140\) GeV are \(WW\) and \(bb\), respectively. The total decay width of the Higgs is small (<10 MeV) for Higgs masses below 140 MeV; beyond this mass, the real and virtual gauge boson channels open up and so consequently the width grows, reaching \(\sim 1\) GeV at the \(ZZ\) threshold \((2m_Z\approx 160\) MeV\). Below a mass of \(\sim 200\) GeV, the experimental mass resolution dominates the measured width; above this threshold, the LHC experiments can expect to measure the width to better than \(\sim 1\) %.

As highlighted above, the physics potential of the LHC is huge, but the search for evidence of the Higgs boson (either the Standard Model particle or its supersymmetric counterparts) has had the largest influence on the design of the CMS and ATLAS experiments at the LHC. Optimal detector performance is of paramount importance if the experiments are to observe the rare Higgs processes and the detector design...
has been driven by a number of “benchmark” processes. Two of these processes, $H \to \gamma \gamma$ and $H \to ZZ^{(*)} \to 4l^{\pm}$, are discussed below. Figure 1.3 shows the discovery $(5\sigma)$ luminosity for various Higgs decay channels as a function of Higgs mass. The two channels described below provide the highest sensitivity to a low mass Higgs ($\lesssim 2m_Z$). An integrated luminosity of $\mathcal{O}(10 \text{ fb}^{-1})$ is needed for full coverage of the low mass region, which corresponds to about 1 year of running at the initial “low” luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

**Di-photonic decay channel: $H \to \gamma \gamma$**

The $H \to b\bar{b}$ channel is the dominant decay channel in the low mass region, but the QCD background due to the $pp$ collisions will be overwhelming. The most promising signature for the Higgs boson with a mass of $m_H \lesssim 140 \text{ GeV}$ is the decay channel $H \to \gamma \gamma$, as highlighted in figure 1.3, even though the branching ratio for this channel is predicted to be only $2 \cdot 10^{-3}$. This channel provides a direct mass measurement, but has a large background, much of which is irreducible due to the $gg \to \gamma \gamma$ and $qq \to \gamma \gamma$ processes. The main reducible background is $\gamma + \text{jet}$, where the jet comprises a single $\pi^0$. The separation of $\gamma/\pi^0$ is achieved with a highly granular EM calorimeter, which can distinguish between the lateral development of the EM showers for the two particles. The irreducible background is smoothly
varying and can be accurately calibrated, hence the reconstructed mass peak is expected to be distinguishable from background.

The total decay width of the Higgs for this energy range is small, ($\sim 10$ MeV), and so the observed signal width will be entirely dominated by the mass resolution of the two photons. Therefore, in order to be sensitive to this decay channel, good photon energy and angular resolutions are required, necessitating a highly granular and uniform electromagnetic calorimeter.

**Four-lepton decay channel: $H \to ZZ^{(*)} \to 4l^{\pm}$**

The $H \to ZZ^{(*)} \to 4l^{\pm}$ is one of the most sensitive channels in the mass range $130 \lesssim m_H \lesssim 2m_W$. Leptons are easily identifiable and so the four high-$p_T$ leptons will provide a strong signature, as well as allowing a direct and precise mass measurement. This is important as the natural width of the Higgs in this mass range is small and detector resolution will dominate the observed width. Therefore, the channel requires high performance from all of the tracker, calorimeter and muon systems to be sensitive to the narrow width of the Higgs in this mass region. The $ZZ^{(*)}$ continuum provides an irreducible background and the reducible background is largely due to $Zbb$.

### 1.1.3 Experimental Challenges at the LHC

The LHC provides the high centre-of-mass energies and high luminosities required for discovery of new and rare physics processes, but this generates many difficulties for the experiments instrumenting the LHC machine. The large $pp$ cross section of $\sim 80$ mb at 14 TeV will result in $\sim 20$ interactions and a charged particle multiplicity of $\sim 1000$ per bunch crossing period. This hostile radiation environment impacts considerably on detector and readout design and trigger performance requirements [19, 20].

All front-end components of the readout system must operate without degradation in performance for the lifetime of the experiment; issues related to radiation damage are discussed further in section 1.4. Additionally, detectors are required to be highly granular and exhibit fast response times in order to minimise channel occupancy and pileup. Consequently, the readout systems are complex, with large
numbers of channels and usually some form of signal processing at the front-end. A strong magnetic field is required to provide the bending power for good momentum resolution of the highly energetic particles produced by “interesting” physics processes, which consequently confines the low momentum particles of minimum bias events to the inner Tracker region, further complicating the reconstruction of tracks and event topologies.

The trigger is a crucial component of the LHC experiments. Figure 1.4 plots the energy dependence of the cross section of various interesting processes, along with the total $pp$ cross section. The total inelastic cross section at 14 TeV centre-of-mass energy will be $\sim 80$ mb, resulting in a $pp$ collision rate of $\sim 10^9$ s$^{-1}$. These numbers compare with a cross section and production rate of $\sim 100$ fb and $10^{-3}$ s$^{-1}$, respectively, for the process $H \rightarrow \gamma\gamma$. Hence, the experiment requires a complicated set of
trigger selection rules to separate the rare, interesting physics processes from the superimposed “minimum bias” events. However, implementation of the selection rules and broadcasting the trigger decision to all subdetectors is not possible within 25 ns and so pipelined processing and readout is necessary on the front-end electronics. The trigger is required to reduce the $10^9$ $pp$ interactions s$^{-1}$ to around 100 Hz for manageable storage.

1.2 The Compact Muon Solenoid Experiment

The main goal of the ‘general purpose’ Compact Muon Solenoid detector [11, 21], illustrated in figure 1.5, is to provide experimental evidence for the Higgs boson. The detector design must be sufficiently sensitive to the various Higgs decay channels to provide full coverage over the mass range $\sim$100 GeV to $\sim$1 TeV. Due to the large hadronic background resulting from the $pp$ collisions, the detector is optimised for identification and precise momentum measurements of muons, electrons and photons over a large energy range and at high luminosity.

The design of the CMS detector is based around a 4 Tesla superconducting solenoid with a length of 13 m and an inner diameter of 5.9 m [22]. The solenoid comprises a large superconducting coil housed in a cryogenic system and cooled to a
temperature of 4.5 K using liquid helium. A large iron return yoke, within which the entire muon detector system is housed, is used to contain and return the magnetic field outside the solenoid. The strong magnetic field allows for a compact design of the surrounding muon spectrometer and provides the large bending power necessary for good momentum resolution of highly energetic charged particles resulting from the 14 TeV $pp$ collisions. The solenoid is sufficiently large to accommodate the calorimetry as well as the inner tracking subdetector.

The following subsections briefly describe the main detector components of the CMS experiment and the trigger (event selection) system.

1.2.1 Muon System

As well as providing muon identification and momentum measurement, the muon system [23, 24] also provides bunch crossing identification and trigger primitives that are used in the ‘Level-1’ trigger decision. In the hadron-dominated minimum bias events, muons are highly identifiable and provide strong signatures for interesting physics, such as the decay channels $H \to ZZ^{(*)} \to 4l$ and $H \to WW^{(*)} \to ll\nu\nu$. Hence, efficient muon identification and good momentum resolution down to low $p_T$ is necessary for sensitivity to these decay channels. Muon identification is improved further when the muon system is used in conjunction with the Tracker subdetector. The performance of the muon system is defined by the track reconstruction efficiency, momentum resolution and trigger efficiency. The transverse momentum measurement of the muon and Tracker systems combined is expected to exhibit an accuracy of better than 5 % for a muon momentum up to 1 TeV in the central rapidity region.

The entire muon system is accommodated in the iron return yoke for the magnetic field, which is strong enough to saturate 1.5 m of iron. The return yoke also acts as an absorber so that only muons fully traverse the muon system. The muon system comprises four stations in both the barrel and endcap regions, which are arranged such that each muon escaping the detector will traverse at least three stations.

In the barrel region, each station consists of twelve layers of Drift Tube chambers (DT). Each DT consists of parallel aluminium cathode plates with an anode wire located between the plates and stretched along the drift chamber length. The anode
wire pitch for adjacent DTs is 40 \mu m, and adjacent DTs are staggered by half a cell to allow coordinate and incidence angle measurements. The drift time is known to an accuracy of typically \pm 2 ns and the optimum spatial resolution is \pm 200 \mu m.

The endcap region is instrumented by Cathode Strip Chambers (CSC), with six CSCs per station (as opposed to twelve DTs in the barrel region). Each CSC consists of segmented cathode planes with interleaved anode wires running perpendicular to the cathode strips and provides coordinate information in both \( r \) and \( \phi \).

Resistive Plate Chambers (RPC) are used throughout the muon system and provide bunch crossing identification and a fast \( p_T \) measurement used in the trigger decision. A moderate spatial resolution is traded for an excellent time resolution of better than \pm 3 ns. An RPC consists of two parallel and closely spaced plastic plates with the chamber filled with gas. Avalanches generated by ionising particles are drifted by an electric field to collecting anode strips.

1.2.2 Calorimetry

The bore of the solenoid (5.9 m) is sufficiently large to accommodate both the electromagnetic (ECAL) and hadronic (HCAL) calorimeters. The positions of the calorimeters are conducive to high precision energy measurements as the coil does not interfere with their performance. Both calorimeters provide hermetic coverage up to large rapidities for accurate transverse energy and (indirect) missing transverse energy measurements.

The ECAL [25] design is tailored for optimal energy and angular resolutions in order to maximise the detector performance for a Higgs search via the \( H \to \gamma\gamma \) decay channel. As the natural width of the Higgs boson below \( \sim 2m_Z \) is small (\( \sim 10 \) MeV), the measured mass resolution in this region will be entirely dominated by the experimental resolution. Excellent mass resolution is required due to the large irreducible background for this channel, and optimal energy and angular resolutions require demand a highly granular and uniform ECAL.

The energy resolution of the ECAL is defined by the quadrature addition of three terms: the stochastic term, attributable to intrinsic shower fluctuations and the photostatistics of the photosensors; a noise term, which accounts for preamplifier and digitisation noise and pileup; and finally a constant term, which accounts for
systematics such as energy leakage due to the finite crystal length, inter-crystal calibration errors and non-uniform light collection along the crystal length. The limiting contribution is the constant term, which is 0.55 % (target value) for both the barrel and endcap regions. The energy resolution is better than 2 % for photon energies greater than 10 GeV.

The ECAL will consist of 74000 lead tungstate crystals. Electrons and photons entering the ECAL crystals will result in electromagnetic showers and the production of scintillation light. This light is collected by avalanche photodiodes in the barrel section and by vacuum phototriodes in the endcap regions. Lead tungstate has a very short radiation length of 0.89 cm and a small Molière radius of 2.0 cm, allowing a compact and highly granular detector to be constructed.

The performance of the HCAL [26] can be characterised by the jet-jet mass resolution and the missing transverse energy resolution. The mass resolution depends on the calorimeter resolution but also on the jet reconstruction algorithms and energy pileup.

The HCAL is a sampling calorimeter consisting of barrel, endcap and forward regions. The barrel and endcap regions are contained within the solenoid and comprise copper absorber layers interleaved with plastic scintillator tiles. Plastic wavelength-shifting fibers are used to collect the scintillation light. In the two forward regions, located ~6 m downstream from the endcap regions to provide hermetic coverage up to $\eta = 5$, use quartz fibres embedded in an iron absorber to sample the hadronic showers.

1.2.3 Tracking

The central tracking system will play a major role in all physics searches. The Tracker [27, 28, 29] allows reconstruction of the event topology through high precision tracking of charged particles and the reconstruction of secondary vertices resulting from neutral particles. The Tracker plays a prominent role in identifying electrons, taus and $b$-jets and provides momentum and impact parameter measurements. The Tracker is also used to calibrate the ECAL through $p/E$ matching.

\[ p_T = q r B, \]
\[ e = 0.2998 \text{ (GeV/c) T}^{-1} \text{ m}^{-1}. \]

The transverse momentum of a charge particle, $p_T$ [GeV/c], is given by the (non-relativistic) relation $p_T = q r B$, where $r$ [m] is the bending radius, $B$ [T] is the magnetic field strength and $q$ is the particle charge expressed in units of elementary charge $e = 0.2998$ (GeV/c) T$^{-1}$ m$^{-1}$. The bend orientation provides the charge polarity of the particle.
with electrons. A low material budget is necessary to minimise multiple scattering, conversion and Bremsstrahlung, which affects both the Tracker and ECAL performances.

The target performance of the Tracker is to reconstruct 98 % of muon tracks, 95 % of charged hadron tracks (with $p_T < 10$ GeV/c) and 90 % of high energy electron tracks, over the pseudo-rapidity range $\eta < 2.6$. The (transverse) momentum resolution of the Tracker is better than 7 % for momenta below 100 GeV and a pseudo-rapidity range of $\eta < 2.6$.

The Tracker occupies the central region of the detector, with a diameter of 2.6 m and a length of 6 m, and is implemented in two different detector technologies: silicon pixel and silicon microstrip detectors. The region closest to the interaction point, where the particle fluxes are highest, is instrumented by a silicon pixel detector comprising three barrel layers (at 4.3 cm, 7.2 cm and 11.0 cm) and two endcap layers (at 32.5 cm and 46.5 cm). The pixel detector is used in the immediate vicinity of the interaction point to provide ultra-fine two-dimensional spatial resolution and allow a very precise measurement of track impact parameters (important for $b$-jet identification) and accurate secondary vertex fitting. The detector will use pixels of dimensions $150 \times 150 \, \mu m^2$, providing a spatial resolution of $\sim 10 \, \mu m$ in the $r-\phi$ direction and about $15 \, \mu m$ in the $z$ direction. A total active surface of $\mathcal{O}(m^2)$ will be instrumented by $\sim 5 \cdot 10^7$ readout channels.

The pixel detector is surrounded by a silicon microstrip detector, known as the Silicon Strip Tracker (SST), which comprises four inner barrel (TIB), six outer barrel (TOB), three inner disk (TID) and nine endcap (TEC) layers, as shown in figure 1.6. The first two layers of both the TIB and TOB regions, along with a number of TID and TEC sensors, will be ‘double-sided’, consisting of two single-sided sensors mounted back-to-back, one tilted by an angle of 100 mrad with respect to the other, to provide two-dimensional spatial resolution. Sensors in the inner (TIB and TID) and outer (TOB and TEC) regions will have a thickness of 320 $\mu m$ and 500 $\mu m$, respectively. The strip pitch of the TIB (TOB) sensors is 80 $\mu m$ or 120 $\mu m$ (122 $\mu m$)

---

2Pseudorapidity, $\eta$, is an approximate measure of the rapidity of a relativistic particle and is a function of the particle production angle with respect to the beam axis: $\eta = -\ln[\tan(\frac{1}{2}\theta)]$.

3The thicker sensors will provide larger signals and so the strip length is correspondingly longer to reduce the number of sensors required to instrument the outer region. Consequently, this increases the noise, resulting in comparable S/N performance for both sensor thicknesses.
1.2 The Compact Muon Solenoid Experiment

or 183 μm) depending on the radial position of the sensor, and the TID and TEC sensors are trapezoidal with pitches in the range of 81–205 μm. These pitches will provide spatial resolutions in the range 23–60 μm. Due to this high granularity, the SST will have ~10^7 readout channels.

1.2.4 Event Selection

The CMS detector and its readout system generate huge volumes of data, which have to be reduced to a manageable level before being written to disk for later analysis [30, 31, 32].

The Level-1 trigger system uses local information provided by special hardware processors within the muon and calorimetry systems, which look for the presence of trigger objects, such as photons, leptons and jets. This local information is also pooled to allow global sums of (missing) transverse energy to be performed. A global Level-1 trigger decision is made within 1 μs for each bunch crossing and distributed to all subdetectors within 3.2 μs. This trigger latency has important consequences for the readout systems, as data must be stored in pipeline memories on front-end circuitry until the Level-1 trigger decision is made. The Level-1 trigger system reduces the 10^9 event rate to less than 100 kHz. The raw data generated per event is ~1 Mbyte, resulting in a data rate of up to 100 Gbyte s⁻¹, which is orders of magnitude higher than in any previous high energy physics experiment and demands state-of-the-art technology to perform massively parallel processing. Sophisticated
1.3 The Silicon Strip Tracker Readout System

1.3.1 Overview

The SST data acquisition (DAQ) system is based on an analogue front-end readout chip, known as the APV25 [33, 34, 35, 36], and analogue optical links [37]. The APV25 chip instruments the tracking sensors, both of which are mounted on a Front-End Module (FEM) along with a number of ancillary chips. Digitisation and processing of the analogue data is done by the Front-End Driver (FED) [38], which is external to the detector. Control of the readout system [39], in terms of system configuration, timing synchronisation and monitoring, is based around the Front-End Controller (FEC), the Communication and Control Unit (CCU) [40] and digital optical links [41]. A schematic of the Tracker DAQ and control systems is illustrated in figure 1.7.

There are a number of motivations for an analogue readout system: analogue readout will be able to take advantage of charge sharing, due to non-normal incidence.
and the Lorentz effect, resulting in improved spatial resolution; digitisation is not necessary on the front-end chips, hence their complexity and power requirements are reduced; the availability of analogue pulse height information is more conducive to system debugging and performance optimisation, which is an attractive feature for large-scale and complex readout systems.

1.3.2 The Data Acquisition Chain

Each Front-End Module houses a silicon strip sensor and a Front-End Hybrid (FEH), on which are mounted a number of APV25 and APVMUX (APV25 multiplexer) chips, a DCU (Detector Control Unit) chip and a PLL (Phase Locked Loop) chip [42]. The APV25 chip, described in detail below, is designed to amplify, store and process detector signals, and output analogue data containing pulse height and bunch crossing information. The APVMUX chip interleaves data from pairs of APV25 chips onto a single differential line. Electrical-to-optical conversion is performed and an edge-emitting laser transmitter drives the optical signals along a ∼100 m length of optical cable, at 40 MHz and a wavelength of 1310 nm, to the external Front-End Driver cards. The optical links provide the necessary high data transfer rates with minimal contribution to the material budget and immunity to electrical interference.

Each Front-End Driver card receives 96 channels (i.e. 192 APV25 chips) of optical multiplexed APV25 data, which are converted to electrical levels by p-i-n photodiodes and then sampled and digitised by a 10-bit commercial ADC at 40 MHz. The digitised data are subsequently processed by software algorithms running on Field Programmable Gate Array (FPGA) chips; the data are synchronised and re-ordered before pedestal and common mode corrections are applied. Finally, the data are zero-suppressed using simple ‘signal-finding’ algorithms before being transmitted via a fast S-Link interface [43] to a computer farm for further event filtering.

1.3.3 System Control and Monitoring

The Front-End Controller provides the interface with the global Timing, Trigger and Command (TTC) system [44], which distributes the LHC machine master clock

4See below for definitions of pedestal and common mode levels.
1.3 The Silicon Strip Tracker Readout System

Figure 1.8: (left) 200 mm silicon wafer containing 360 fully processed APV25 sites. (right) Schematic of the APV25 chip.

and Level-1 triggers to the Tracker front-end electronics.

Encoded clock and trigger information is distributed by the FEC via digital optical links to a serial network of CCUs within the detector. The CCUs redistribute electrical signals to PLL chips on the Front-End Module, which recover the clock and trigger signals used by local APV25 chips and allow for precise (timing) synchronisation of the front-end electronics throughout the Tracker. The FEC also provides the control interface to the front-end electronics, allowing configuration of the front-end electronics for optimum performance, and monitoring of environmental parameters such as temperature.

1.3.4 The APV25 Readout Chip

The APV25 chip is the first major chip of a high energy physics experiment to be fabricated in a 0.25 μm CMOS technology. APV25 chips are fabricated on 200 mm-diameter silicon wafers, with each wafer containing 360 fully-processed APV25 sites, as illustrated in figure 1.8. The high circuit density allows for 128 channels per chip and a long pipeline memory within dimensions of only 7.1 × 8.1 mm².

The most important feature of this technology is its intrinsic radiation tolerance, due to the small feature size and thin gate oxide (discussed further in section 1.4). In addition to radiation tolerance, the APV has to fulfil the important requirements of low noise and low power, driven by the need to discriminate small detector signals from background and to minimise cooling requirements and, consequently, the
1.3 The Silicon Strip Tracker Readout System

material budget. Low power consumption and noise levels have been realised with this technology.

The 40 MHz bunch crossing frequency at the LHC requires fast pulse shaping in order to provide bunch crossing identification and minimise pileup. This is difficult to achieve with low noise and power levels and so the APV25 chip uses a preamplifier with a relatively slow rise-time and then performs ‘deconvolution’ signal processing to constrain the signal to one bunch crossing [45, 46, 47].

APV25 Design Features

Figure 1.9 shows a schematic of a single APV25 channel. Each channel consists of an integrating preamplifier coupled to a shaping amplifier in order to produce a CR-RC pulse shape with a peaking time of 50 ns. The feedback resistors of both the preamplifier and shaper and bias currents and voltages are fully programmable to allow pulse shape optimisation. An unity gain inverter is included between the two stages that can be switched in or out so that the chip can be used to instrument either p-type or n-type substrate sensors.

The CR-RC pulse shape is sampled at 40 MHz into a 192-column pipeline memory. For each trigger received by the chip, the appropriate pipeline column is marked for readout and is not overwitten until the stored data samples have been output by the chip. The pipeline depth permits a (programmable) trigger latency of up to 4 μs, with 32 pipeline locations reserved for the buffering of events awaiting readout.

The chip can be operated in one of three modes: peak, deconvolution or multimode. In peak mode, only data from a single pipeline column, coinciding with the peaking time of the CR-RC pulse shape, are output. In deconvolution mode,
data samples from three sequential columns (bunch crossing periods) are weighted and summed by the analogue pulse shape processor (APSP) stage, which comprises a switched capacitor network. This weighted sum confines the signal to a single bunch crossing period by suppressing signals that are out-of-time with respect to the trigger. Multi-mode allows readout of peak-sampled data from three consecutive pipeline columns. The APSP stage is followed by a programmable gain stage and a multiplexer stage that provides 128:1 multiplexing onto a single line with differential current output.

Chip configuration is achieved via a two-wire serial interface [34] designed to conform to the Philips I\textsuperscript{2}C standard [48]. This interface\textsuperscript{5} provides access to the on-chip registers that store the parameter settings defining the chip operating modes as well as the bias voltages and currents used to tune the pulse shaping.

The chip also provides an internal calibration circuit that allows to test the functionality and performance of each channel by injecting charge into channels prior to the preamplifier stage. The performance of the amplifying stages, in terms of pulse shaping and channel gain, is assessed by performing a scan through a range of delays between the injection of the test pulse and triggering the chip. Both coarse (25 ns) and fine (3.125 ns) adjustments to the delay are possible, allowing a detailed image of the pulse shape to be reconstructed.

**APV25 Data Output**

The chip provides pulse height and bunch crossing information in the form of data frames, which are output for each trigger received by the chip. The overall data frame length is 7 \(\mu\)s and comprises 12 bits of binary information followed by 128 analogue channel samples, as shown in figure 3.14 (p. 89). The 12 bits of binary information comprise: a 3-bit digital header; an 8-bit pipeline column address, which identifies the pipeline column from which the data were retrieved and provides a time-stamp; and an error bit, signifying error-free operation of the chip (or otherwise).

The average level of the 128 analogue samples can be adjusted within the dynamic range (approximately defined by the high and low digital levels). The structure observed in the ‘baseline’ levels is due to static dc levels unique to each channel,

\textsuperscript{5}The reader is referred to appendix A for a brief description of the APV25 I\textsuperscript{2}C interface.
known as pedestals. A ‘common mode’ deviation in all channels from these pedestals levels can also be observed, and is usually attributable to an external noise source. Signal and noise are superimposed on these pedestal and common mode levels, which must be subtracted before signal is identified (as performed by the FED).

1.4 Radiation Effects in the CMS Tracker

1.4.1 The Tracker Radiation Environment

The Tracker subdetector will experience one of the most severe radiation environments in the CMS experiment due to its close proximity to the $pp$ interaction point.\(^6\) The Tracker radiation field is largely due to the $pp$ interactions, which generates a particle flux comprising the $pp$ collision products and any subsequent decay products.\(^7\) This component of the flux varies approximately as $r^{-2}$ and is essentially independent of $z$. Low momentum charged particles, mainly comprising pions, are confined to the inner Tracker region by the magnetic field and also contribute to the hadron flux at small radial distances. Additionally, significant neutron albedo is observed in the vicinity of the ECAL; this flux is moderated in the Tracker region to some extent by polyethelene shielding. The integrated charged particle and neutron fluences\(^8\) for $5 \cdot 10^5$ pb\(^-1\) at the innermost barrel layer (22 cm) are $\sim 14 \cdot 10^{13}$ cm\(^{-2}\) and $1.6 \cdot 10^{13}$ cm\(^{-2}\), respectively; the corresponding values at the outermost layer (115 cm) are $0.5 \cdot 10^{13}$ cm\(^{-2}\) and $0.3 \cdot 10^{13}$ cm\(^{-2}\). The absorbed doses\(^9\) at the innermost and outmost layers are 67 kGy (6.7 Mrad) and 1.9 kGy (0.19 Mrad).

This hostile radiation environment has important consequences for the design, operation and performance of the Tracker readout system. As mentioned previously, the high multiplicity of charged particles observed in the Tracker requires high granularity and good time resolution to minimise occupancy and pileup. Furthermore, this environment makes pattern recognition and track-finding difficult. In terms

\(^{6}\)For various descriptions of the CMS radiation environment, see [49, 50, 51, 52].
\(^{7}\)A contribution is also expected from products of interactions between incident particles and the detector system and support/cooling structures.
\(^{8}\)Fluence [cm\(^{-2}\)] is the time-integrated flux.
\(^{9}\)Absorbed or, equivalently, total dose is the energy deposition per unit mass, with units J/kg or Gy. An alternative unit commonly used is defined as $100 \text{ rad} = 1 \text{ Gy} \equiv 1 \text{ J/kg}$. 
1.4 Radiation Effects in the CMS Tracker

of radiation damage to the readout system, there are both instantaneous and cumulative effects; the former comprise ‘single event’ phenomena and the latter are termed as ‘total dose’ effects. Due to the inaccessibility of the tracking system, the instrumenting electronics must be sufficiently radiation-hard and resistant to total dose effects to operate with negligible degradation in performance throughout the 10-year operational lifetime of the experiment.

1.4.2 Radiation Damage to Silicon Sensors

Silicon sensors in the Tracker will suffer both surface and bulk damage. Surface damage is due to the trapping of charge released by ionising particles at the silicon-oxide interface. This results in an increased strip capacitance and therefore an increased noise. Damage to the sensor bulk is a consequence of atomic displacement in the silicon lattice through collisions between incident hadrons and the lattice [53, 54]. This damage affects sensor operation in three ways: firstly, there is an increase in leakage current, resulting in an increased noise; secondly, there is a decrease in the charge collection efficiency, resulting in reduced signal; and thirdly, there is a change in depletion voltage due to doping changes in the bulk [55, 56].

1.4.3 Radiation Effects in Readout Electronics

Damage to the bulk (substrate) of readout electronics is of little concern as all active (and passive) components of an integrated circuit are fabricated in a thin layer at the silicon surface. Total dose effects include the trapping of charge released by ionising particles in transistor gate oxides and at the interface between the gate oxide and the channel of CMOS transistors. The consequences of charge trapping on transistor performance are threefold: firstly, interface traps result in increased noise; secondly, voltage threshold shifts are observed, although the ‘polarity’ of the shift is dependent on the transistor type and whether the charge is trapped in the oxide or at the interface; and thirdly, interface traps result in a decreased mobility. Additionally, increased leakage currents can also result from charge trapping in field oxides used to isolate active areas, such as drain and source implants.

The APV25 chip is fabricated in a commercial 0.25 µm process, which is intrinsically radiation-hard due to its small feature size [57, 58]. The technology
uses 5.5 μm-thick gate oxides, which are sufficiently thin that electron tunnelling is capable of neutralising the trapped charge (that comprises solely positive holes). Additionally, special design rules such as enclosed transistor geometries prevent increased leakage currents as a result of radiation damage. The APV25 chip has been irradiated with X-rays and $^{60}$Co gamma rays to doses well in excess of those expected in the Tracker environment (up to 100 Mrad) without suffering significant degradation in performance [59].

Transient ‘single event’ effects include phenomena such as Single Event Upsets (SEU), Single Event Latchup (SEL) and Single Event Gate Rupture (SEGR). Single event upsets are caused by large and highly localised energy depositions in the vicinity of sensitive nodes of a circuit. If sufficient ionisation charge is collected by the electric field of a reverse-biased p/n junction, the resulting current transient may switch the logic state of a digital circuit component or register as a signal in an analogue circuit. The large energy depositions responsible for SEUs are generated by highly ionising particles, such recoiling nuclei; the mechanism responsible for nuclear recoils is described in the following section.\(^\text{10}\) SEU is a non-destructive phenomenon. The effect has been modelled in order to predict the susceptibility of readout electronics to SEU in the CMS environment [60] and SEU rate measurements have been performed with the APV25 chip by exposing the chip to hadron and heavy ion beams [61, 62, 63]. The studies show that the measured cross sections for SEUs affecting either the digital or analogue parts of the APV25 chip are $O(10^{-12} \text{ cm}^2)$. An extrapolation to the CMS environment predicts an SEU rate of order unity per APV25 chip per minute.

\subsection*{1.4.4 Energy Deposition Mechanisms}

The mean rate of energy loss, $\langle -dE/dx \rangle$, of a particle passing through a medium defines the stopping power of the material.\(^\text{11}\) The predominant mechanism for energy loss of moderately-relativistic charged particles other than electrons\(^\text{12}\) travers-

\(^\text{10}\)Nuclear collisions are responsible for the highly ionising nuclear recoils; the ionisation charge released by a penetrating particle is generally not sufficient to cause this type of error.

\(^\text{11}\)An alternative parameter is frequently used, known as the Linear Energy Transfer (LET), $-1/(\rho \cdot dE/dx) [\text{MeV g cm}^{-2}]$, or energy loss per mass surface density.

\(^\text{12}\)The dominant energy loss mechanism for electrons (and positrons) with energies greater than a few tens of $\text{MeV}$ is Bremsstrahlung radiation.
ing a medium is ionisation. A further important energy loss mechanism is Non-Ionising Energy Loss (NIEL), which involves energy transfers to the atomic nuclei of a medium.

Energy Loss through Ionisation

The Bethe-Bloch function describes the mean rate of energy loss through ionisation, \( \langle -dE/dx \rangle_{\text{ion}} \), to an accuracy better than \( \sim 1 \% \) over the range \( 0.3 \lesssim \beta \gamma \lesssim 43 \).\(^{13}\)

The well-known Bethe-Bloch function is not described here in detail and the reader is referred to [64] for a fuller description of the equation. The Bethe-Bloch function is predominantly a function of the particle velocity, \( \beta \). The function is characterised by a \( 1/\beta^2 \) dependence until a broad minimum at \( \beta \gamma \approx 3 \) is reached. Particles with this \( \beta \gamma \) value are known as Minimum Ionising Particles (MIPs). The minimum is followed by a ‘relativistic rise’ resulting from a logarithmic dependence on \( \beta \).

Non-Ionising Energy Loss (NIEL)

Non-Ionising Energy Losses are due to elastic and inelastic collisions between particles and the atomic nuclei of a medium. This energy transfer results in a nuclear recoil and displacement of the nucleus from its lattice site. Nuclear fragmentation is also observed in the case of inelastic collisions. Sufficiently energetic recoils result in the displacement of further atomic nuclei and all recoiling nuclei (and associated fragments) suffer energy losses through ionisation of the medium. Through this mechanism, collisions between incident particles and atomic nuclei can generate large and localised energy depositions, and this mechanism is responsible for the total dose and single event effects described above.

Elastic scattering of hadrons (and leptons) off atomic nuclei has been extensively modelled, generally using some variant of momentum-space optical models. Examples of models describing high-energy pion-nucleus elastic scattering and the comparison of predicted angular distributions with experimental data can be found in [65, 66]. The angular distribution of the scattered particle is forward-peaked and large-angle scattering is rare; for 100 MeV protons incident on 50 \( \mu \text{m} \) of silicon, more than 90 \% of the protons are scattered into a forward cone subtended by a

\(^{13}\)This \( \beta \gamma \) range is equivalent to a pion momentum range of \( \sim 40 \text{ MeV} \) to \( \sim 6 \text{ GeV} \).
polar angle of $\sim 20^\circ$. Essentially all elastic collisions result in an nuclear recoil with an energy of less than a few MeV, even for the highest incident particle energies.

Inelastic collisions involve fragmentation of the recoiling nucleus and the generation of secondary light hadrons. Projectiles of energies greater than $\mathcal{O}(10 \text{ MeV})$ essentially always collide inelastically with nuclei as this is the magnitude of the nuclear binding energies, \textit{i.e.} nuclear fragmentation is preferred over highly energetic elastic recoils (this is illustrated by the simulation described in section 3.1 and [74]). Consequently, essentially all large energy depositions ($\geq 10 \text{ MeV}$) are due to inelastic collisions.

It is important to be able to predict the magnitude and energy dependence of inelastic hadron-nucleus cross sections, as well as the production rates of the nucleus residual and the various fragments as functions of energy and angle. Accurate predictions of these variables are provided by models based on a two-stage ‘cascade-statistical’ approach, which break the nuclear collision down into two distinct processes: an intra-nuclear ‘cascade’ process, followed by the ‘statistical’ de-excitation of an excited compound nucleus through decay.\footnote{These models are based on work by Metropolis [67] and Bertini [68] on intra-nuclear cascade processes.}

The first ‘cascade’ stage assumes (quasi-free) scattering between the incident hadron and individual nucleons within the target nucleus. These scattered nucleons may collide with further nucleons, which in turn may collide with others, resulting in a ‘cascade’ effect. Sufficient excitation results in the prompt emission of nucleons or light hadrons, such as pions, from the nucleus in the forward direction. The resulting compound nucleus is frequently left in an excited state. The second ‘evaporation’ stage concerns the de-excitation of this excited compound nucleus. De-excitation involves the random ‘statistical’ emission of further nucleons and/or light hadrons with an isotropic distribution in the nucleus rest frame. This process continues until the available excitation energy falls below the nuclear nuclear binding energies. Any remaining energy is observed as kinetic energy and is lost through ionisation.\footnote{This explains why the (kinetic) energy spectra of heavy residual nuclei are suppressed beyond $\mathcal{O}(10 \text{ MeV})$, regardless of the projectile energy, as shown in figure 2 of [74].} Various (independant) examples that use the ‘cascade-statistical’ approach to model...
inelastic hadron-nucleus collisions for a range of projectile energies incident on various materials are found in [69, 70, 71, 72]. In some cases a comparison of observables is made with experimental measurements, which are generally shown to be in good agreement.

Much work has been done by the space, meteorology and communication industries in trying to understanding the underlying physical processes (i.e. nuclear collisions and spallation) that are responsible for single event effects. Only recently have such issues been of relevance to the high energy physics community, with the behaviour of readout electronics in the hostile LHC radiation environment providing motivation for such studies. However, studies of the mechanisms responsible for single event effects are all primarily concerned with energy depositions in small volumes, typically only a few cubic microns, around sensitive circuit nodes of electronics. This implies that only very highly ionising particles, such as (short-range) heavy recoiling nuclei, can contribute significantly to the total energy deposition within a small sensitive volume.

In the CMS Tracker, nuclear collisions will also take place in the silicon sensors. In this case, the ‘sensitive volume’ is essentially the volume of the sensor itself, and all ionising particles produced in nuclear collisions can contribute to the total energy deposition, which can be significant. This has important consequences for the performance of the readout electronics, which will collect all the charge released within the sensor by the nuclear collisions. Furthermore, the large surface area of silicon used in the Tracker coupled with the large hadron multiplicities observed for each event raises the question of how frequently highly ionising events within the silicon sensors, due to nuclear collisions, will occur.

### 1.4.5 Highly Ionising Events in Silicon Sensors

This section provides an estimate of the rate at which inelastic collisions between various hadrons and silicon sensors will occur in the CMS Tracker environment, based on inelastic hadron-silicon cross sections provided by nuclear spallation models and predicted hadron fluxes in the Tracker that are provided by simulation. Additionally, the pertinent results from a study of energy depositions in silicon sensors of various thicknesses due to incident hadrons are presented.
### 1.4 Radiation Effects in the CMS Tracker

<table>
<thead>
<tr>
<th>Hadron</th>
<th>Innermost layer (22 cm)</th>
<th>Outermost layer (115 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pion</td>
<td>2.060±0.030</td>
<td>0.030±0.002</td>
</tr>
<tr>
<td>Proton</td>
<td>0.203±0.007</td>
<td>0.008±0.001</td>
</tr>
<tr>
<td>Neutron</td>
<td>0.330±0.010</td>
<td>0.059±0.001</td>
</tr>
</tbody>
</table>

*Table 1.1: Predicted fluxes \([10^6 \text{ cm}^{-2} \text{ s}^{-1}]\) of the most common hadrons found in the innermost and outermost layers of the Tracker barrel region, at a luminosity of \(10^{34} \text{ cm}^{-2} \text{ s}^{-1}\) [74]. Quoted uncertainties are statistical. Systematic uncertainties are estimated to be 30\% [27].*

#### Calculating the Inelastic Hadron-Silicon Interaction Rate

The probability of a particle traversing a sensor of thickness \(d\) and undergoing at least one inelastic collision\(^{16}\) is given by:

\[
P_{in} = 1 - \exp \left( -\frac{d}{\lambda} \right) \quad ; \quad \frac{1}{\lambda} = \frac{N_A}{A} \rho_{Si} \cdot \sigma_{in}
\]

where \(\lambda\) is interaction length, \(N_A\) is Avogadro’s number, \(A\) is the atomic mass (28.055 for silicon), \(\rho_{Si}\) is the mass density of the medium (2.33 g cm\(^{-3}\) for silicon) and \(\sigma_{in}\) is the inelastic cross section.

The ‘cascade-statistical’ model described in [73] predicts absolute cross sections, including nucleon-nucleus cross sections such \(p\)-Si and \(n\)-Si. A comparison of predicted observables with experimental measurements reveals agreement to within 10\% over a wide projectile energy range. Reasonable agreement between predicted and measured cross sections for pion-nucleus interactions (including \(\pi\)-Si) is also observed.

The (differential) energy spectra of the three most common hadron types in the Tracker (protons, neutrons and pions) are shown in figure 1.10. The most probable energies for pions, protons and neutrons in the Tracker are \(\sim 300\) MeV, \(\sim 100\) MeV and \(\sim 3\) MeV, respectively. Hence, the corresponding hadron-nuclear inelastic cross sections for these particle types and energies, as predicted by the ‘cascade-statistical’ model described in [73], are \(\sim 500\) mb (pions), \(\sim 500\) mb (protons) and \(\sim 800\) mb (neutrons). These correspond to interaction lengths of \(\sim 40\) cm, \(\sim 40\) cm and \(\sim 25\) cm, respectively.

The rate of observing at least one inelastic collision per APV25 chip per second, independent of incidence angle, is given by \(R_{in} = \phi P_{in} A_{sensor}\), where \(\phi\) is the

\(^{16}\)The contribution of elastic collisions is ignored here, as they infrequently generate large energy depositions.
incident hadron flux and $A_{\text{sensor}}$ is the sensor area instrumented by a single APV25 chip. Considering the innermost Tracker barrel layer, where the particle fluxes are highest, the sensor volume instrumented by a single APV25 chip is $119(l) \times 15.36(w) \times 0.32(d)$ $\mu$m. The fluxes of the most common hadron types found in the Tracker are listed in table 1.1; the values listed are the fluxes observed at the innermost and outermost layers for an instantaneous luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$.

Given the interaction lengths listed above, it is possible to estimate the rate of inelastic collisions in a sensor volume instrumented by a single APV25 chip. Hence, the predicted inelastic collision rates at the innermost barrel layer for pions, protons and neutrons at their most probable energies are $7.5 \times 10^{-4}$, $0.7 \times 10^{-4}$ and $1.9 \times 10^{-4}$ per APV25 chip per bunch crossing period (25 ns), respectively. The pion rate is seen to increase to a maximum value of $10.5 \times 10^{-4}$ at a pion energy of 200 MeV. The neutron cross section is seen to increase (slowly) with decreasing kinetic energy, and so larger $n$-Si rates can be expected at lower neutron energies, which are commonplace in the Tracker (see figure 1.10).

As will be shown in chapter 3, sufficiently large energy depositions in the Tracker sensor planes can saturate the APV25 chip and induce deadtime in the readout system. However, the collisions must generate an energy deposition above a certain threshold before deadtime is observed; consequently the rate at which deadtime is observed, is dependent on this threshold.

**Secondaries Generated by Inelastic Collisions**

The ‘cascade-statistical’ model [73] also predicts the production rates of secondary particles generated through nuclear spallation. The model predicts that a heavy residual nucleus, such as magnesium or carbon is generated, along with several hadrons, such as protons, neutrons and pions. Heavier $\alpha$-particles are also frequently produced.

Figure 1.11 plots the mean energy loss of silicon, magnesium, lithium and helium ions in silicon. The heavier ions are highly ionising and consequently short-range; a silicon ion with a recoil energy of 10 MeV is maximum ionising, with a $dE/dx$ of $\sim 3$ MeV $\mu$m$^{-1}$. This compares with the $dE/dx$ of 400 eV $\mu$m$^{-1}$ for a minimum

\footnote{The width dimension is defined by the strip pitch: $128 \times 0.12$ mm = 15.36 mm.}
ionising particle. Lighter ions, such as He (α-particle) are not as highly ionising and so consequently are longer range; the maximum $dE/dx$ for He is 300 keV $\mu$m$^{-1}$. Table 1.2 lists the mean ranges of various ions in silicon. It is clear that a heavy recoiling nucleus (or its residual) will deposit all its energy in the silicon sensor due to its short-range, typically a few $\mu$m. Although light secondaries, such as H and He, are expected to exit a 300 $\mu$m-thick silicon sensor, their highly ionising nature and high multiplicities means that these lighter ions can also contribute significantly to the total energy deposition. Ions that exit a sensor in the Tracker will traverse further sensor planes, within which they will deposit their remaining energy.

**Magnitude of Energy Depositions in Sensors**

Energy deposition measurements for proton-induced nuclear interactions in silicon are presented in [69]. The measurements are performed for 50 MeV to 158 MeV protons incident on silicon sensors with a range of thicknesses up to 200 $\mu$m.
<table>
<thead>
<tr>
<th>Ion</th>
<th>Range (μm) for various ion energies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 MeV</td>
</tr>
<tr>
<td>H</td>
<td>16</td>
</tr>
<tr>
<td>He</td>
<td>3</td>
</tr>
<tr>
<td>C</td>
<td>–</td>
</tr>
<tr>
<td>Si</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 1.2: Mean range of various ions in silicon. Taken from [75].

The study shows that nuclear collisions involving 131 MeV protons (which is comparable to the most-probable proton energy in the Tracker) incident on 200 μm of silicon resulted in energy depositions of up to 90 MeV. This energy deposition is equivalent to 1000 minimum ionising particle traversing 300 μm of silicon. The largest energy depositions observed in a 100 μm-thick sensor was 76 MeV and it is reasonable to expect larger energy depositions in the 320 μm-thick sensors used to instrument the inner region of the Tracker. The study also showed that the probability of a 131 MeV proton resulting in an energy deposition of at least 10 MeV in a 100 μm-thick silicon sensor is $10^{-4}$. An energy deposition of this magnitude is likely to induce deadtime in the APV25 chip (as shown in chapter 3). The probability is seen to scale with sensor thickness.

1.5 Summary

The CMS detector is one of four large LHC experiments being constructed in order to take advantage of the extended physics reach provided by the LHC. The CMS Tracker subdetector will play a major role in all physics searches and is required to provide high performance tracking within a hostile radiation environment.

The Tracker readout system is based on the APV25 analogue readout chip, which must exhibit excellent performance if the Tracker is to meet its performance targets. Chapter 2 describes in detail the screening procedure performed on all APV25 chips prior to integration to ensure only quality chips are used in the final readout system.

The rate at which hadron-silicon inelastic collisions are expected in silicon sensors of the CMS Tracker is $\mathcal{O}(10^{-4})$. Nuclear spallation models show that inelastic collisions will generate multiple highly ionising secondaries and hence large energy depositions can be expected. This is confirmed by experimental measurements,
which show that ~100 MeV protons incident on silicon sensors can generate energy depositions equivalent of up to 1000 minimum ionising particles in 200 μm of silicon. Such energy depositions can be expected in the CMS Tracker, which will saturate the front-end APV25 chip.

Experimental measurements have been performed during beam tests using a near-to-final version of the Tracker readout system. The effect of nuclear collisions in silicon sensors and the resulting large energy depositions on the APV25 readout chip has been quantified in terms of rates, deadtimes and inefficiencies. These studies are complemented by a simulation of pion interactions in silicon and laboratory measurements that characterise the response of the APV25 chip to large signals. The effect has been extrapolated to the CMS Tracker environment. These studies are the subject of chapters 3 through to 6.
Chapter 2

Production Testing of the APV25 Readout Chip

2.1 Motivation

The fraction of quality detector readout channels in the CMS Tracker must be as high as possible in order to minimise readout inefficiencies and maximise the physics performance of the tracking sub-detector. Therefore, it is of paramount importance to screen all APV25 chips prior to their integration into the readout system to ensure the highest quality Front-End Modules. This screening is most efficiently done at the wafer-level (prior to wafer-dicing) using an automated probe station; this maximises throughput and minimises manpower. The wafers are delivered by the manufacturer whole and untested and it is the responsibility of the CMS community to validate the functionality and performance of the individual APV25 sites of each wafer.

Production testing is not designed for qualification of the chip design and performance; this is done through detailed characterisation of individual die using a dedicated low-noise and highly calibrated test-bench [35][76]. Rather, production testing is aimed at identifying chips that exhibit imperfect functionality or performance as a result of either naturally through process variations or fabrication errors (due to out-of-specification processing conditions) or wafer-mishandling (such as electrostatic discharge damage).

The main objectives of a production test station are threefold. Firstly, the station must be capable of automating the screening of all APV25 sites of a wafer and
identifying Known Good Die (KGD), fully functional chips that exhibit excellent analogue performance, with the highest efficiency and confidence. Secondly, the probing procedure must generate a comprehensive data set that fully characterises the performance of each probed site; this information is archived in a database containing information on every APV25 chip tested. Analysis of this information (such as in section 2.6) provides the parameter distributions on which selection criteria for identifying KGD are based. Thirdly, the data collected during the screening procedure are used to assess the effect of processing conditions observed during the fabrication of different wafers and lots on: the uniformity of performance, e.g. in terms of noise and gain; and the parameter settings required for optimum performance. This may influence the selection criteria used to identify KGD.

This chapter describes the production test station set-up and the development of screening test software for the APV25 chip. To date (Nov. 2003), ~300 wafers have been screened by the test station. The results obtained from the screening of these wafers are presented, which highlight the effectiveness of the screening procedure and the excellent performance of the APV25 chip.

2.2 Experimental Setup

The production test station setup, illustrated in figure 2.1, comprises a MicroManipulator semi-automatic probe station, a PC running LabView (a graphical programming language) [80] and a VME crate housing the various modules necessary for the control and data acquisition systems.

Wafers are mounted on the 200-mm stage of the probe station and a custom-designed probe card is used to provide the physical interface via the pads located around the periphery of each chip, as illustrated in figure 2.1 (inset). All sites of a wafer are probed in turn by scanning the wafer under the probe card, with the scanning controlled by LabView-based software running on the PC (described below). The probe station is controlled remotely via a RS232 bus, using a command

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1The contributions of several people from Imperial College London deserve mention here: M. Raymond has been heavily involved in the development of both the present system and an earlier system designed to screen the APV6 chip [77] (the predecessor of the APV25); J. Fulcher and M. Millmore were also involved in the development of the earlier system [78, 79].
syntax based on the Standard Commands for Programmable Instruments (SCPI) format [81]. The VME-based modules comprise: a ‘SEQSI’ sequencer card that provides the 40 MHz clock and triggers necessary for operation of the APV25 chip; a Struck flash ADC card used to capture and digitise the output APV25 data frames; and an I²C card that provides the slow control interface to the chip.

2.3 Wafer Screening Software

This section describes the LabView-based software that has been developed in order to automate and supervise the screening of all APV25 sites of a wafer. The software is based on LabView Virtual Instrument (VI) programs that execute the necessary tasks, such as control of the scanning across all sites of a wafer or the screening of individual sites.

2.3.1 Probe Station Control

A top-level ‘supervisory’ VI program oversees the execution of wafer screening. Following the loading of a wafer on the 200 mm stage, the user is prompted to select the probing mode (which allows various site patterns to be probed) and enter the
The user is then steered through a simple alignment procedure, which accounts for the misalignment of the wafer orientation with respect to the X-Y coordinate system of the prober stage. The user is then required to manually align the probe card with a reference site before the wafer screening procedure begins and the supervisor VI controls the subsequent scan across all sites of a wafer. As each site is probed in turn, the supervisor VI executes the screening test software (described in section 2.3.2), which assesses the functionality and performance of the individual APV25 sites.

The supervisor VI provides a graphical user interface, illustrated in figure 2.2, which displays a map of the wafer and provides real-time information on the status of the wafer screening. PostScript and ascii-based files are also generated, which summarise the results of the wafer screening in the form of a ‘wafer map’. These maps identify sites containing KGD, i.e. those sites that pass all the screening tests. Codes representing the failure modes of those sites that do not pass the screening tests are also listed on the PostScript map. These maps are used to identify sites containing KGD that are to be picked from diced wafers and mounted on Front-End Hybrids. An example of a PostScript wafer map is shown in figure 2.6 (p. 60). The maps also identify a small sample of randomly selected chips to be returned for quality assurance testing (comprising detailed performance characterisation and radiation-hardness studies).
### Functionality-related tests:

<table>
<thead>
<tr>
<th>Test</th>
<th>Function</th>
<th>Type</th>
<th>Terminating?</th>
</tr>
</thead>
<tbody>
<tr>
<td>DvsEvs</td>
<td>Dynamic and enhanced voltage screening.</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>RegisterWrite</td>
<td>Write values to on-chip registers.</td>
<td>DIGI</td>
<td>Yes</td>
</tr>
<tr>
<td>RegWriteRead</td>
<td>Write to and read from on-chip registers.</td>
<td>DIGI</td>
<td>Yes</td>
</tr>
<tr>
<td>StuckBits</td>
<td>Identify stuck bits in on-chip registers.</td>
<td>DIGI</td>
<td>Yes</td>
</tr>
<tr>
<td>DigiHeader</td>
<td>Check digital header of APV data frame.</td>
<td>DIGI</td>
<td>Yes</td>
</tr>
<tr>
<td>RandomTrig</td>
<td>Operation of chip with random triggers.</td>
<td>DIGI</td>
<td>Yes</td>
</tr>
<tr>
<td>ApvAddress</td>
<td>Chip response to I\textsuperscript{2}C addressing.</td>
<td>DIGI</td>
<td>No</td>
</tr>
<tr>
<td>FifoMem</td>
<td>Identify stuck bits in FIFO memory.</td>
<td>DIGI</td>
<td>Yes</td>
</tr>
<tr>
<td>MultiMode</td>
<td>Operation of chip in multi-mode.</td>
<td>DIGI</td>
<td>No</td>
</tr>
<tr>
<td>PipeAddr</td>
<td>Check on pipeline digital logic.</td>
<td>DIGI</td>
<td>No</td>
</tr>
<tr>
<td>Currents</td>
<td>Measure operational supply currents.</td>
<td>POW</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### Performance-related tests:

<table>
<thead>
<tr>
<th>Test</th>
<th>Function</th>
<th>Type</th>
<th>Terminate?</th>
</tr>
</thead>
<tbody>
<tr>
<td>SetBaseline</td>
<td>Set (optimum) baseline position.</td>
<td>CHAN</td>
<td>Yes</td>
</tr>
<tr>
<td>ChanPeds</td>
<td>Measure channel pedestal levels.</td>
<td>CHAN</td>
<td>Yes</td>
</tr>
<tr>
<td>ChanNoise</td>
<td>Measure channel noise.</td>
<td>CHAN</td>
<td>No</td>
</tr>
<tr>
<td>ChanGain</td>
<td>Measure channel gain levels.</td>
<td>CHAN</td>
<td>No</td>
</tr>
<tr>
<td>PulseInt</td>
<td>Check pulse shape uniformity.</td>
<td>CHAN</td>
<td>No</td>
</tr>
<tr>
<td>MuxGain</td>
<td>Measure gain of multiplexer stage.</td>
<td>CHAN</td>
<td>No</td>
</tr>
<tr>
<td>PipeCm</td>
<td>Measure pipeline column ‘common mode’.</td>
<td>PIPE</td>
<td>No</td>
</tr>
<tr>
<td>PipePeds</td>
<td>Measure pipeline cell pedestals.</td>
<td>PIPE</td>
<td>No</td>
</tr>
<tr>
<td>PipeNoise</td>
<td>Measure pipeline noise.</td>
<td>PIPE</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 2.1: Summary of the screening tests performed on each APV25 chip.

### 2.3.2 Overview of APV25 Screening Tests

Each APV25 chip is subjected to a comprehensive series of tests, listed in table 2.1, that exercise all digital and analogue components of the chip; a KGD is required to exhibit full functionality and satisfy stringent criteria in terms of analogue performance. The screening tests are designed to validate the functionality of each chip and assess its analogue performance: the *functionality*-related tests validate the digital components of the chip (identified as ‘DIGI’ in table 2.1) and measure the power consumption of the chip (POW); the *performance*-related tests are concerned with the analogue components of the chip, namely the individual readout channels (CHAN) and the pipeline memory (PIPE).

Additionally, prior to assessing the functionality and performance of each chip, the chip is subjected to voltage screening tests (described below) that are designed to induce failures due to faults in the chip that would not be identified under normal
operating conditions; these tests aim to reduce the infant mortality rate and increase
the reliability of the APV25 chip.

The screening tests are of ‘terminating’ or ‘non-terminating’ type (as indicated
in table 2.1) depending on whether screening continues following a failed test. ‘Ter-
minating’ tests verify those features of an APV25 chip considered essential to its
operation. Generally, functionality-related tests are of ‘terminating’ type, although
there are some performance-related features, such as the setting of pedestal levels
and their uniformity, that are considered essential for effective operation. Following
the failure of a ‘terminating’ test, the screening procedure for that chip is halted and
the prober immediately moves onto the next site; this minimises the testing time
for the whole wafer. Conversely, ‘non-terminating’ tests verify those features of an
APV25 chip that are not considered essential to its operation, which are generally
performance-related.² Screening continues even if a ‘non-terminating’ test is failed,
as these chips may be used in other applications or for research purposes.³ These
reliability, functionality and performance-related tests are described in detail below.
The tests are described in the order they are listed in table 2.1.

2.3.3 Reliability Screening

Premature failure of Integrated Circuits (IC), due to small defects that are not
identifiable under normal operating conditions, can be induced by methods such as
burn-in or voltage screening. These methods help reduce the infant mortality rate
and achieve optimum component reliability. The two predominant failure mecha-
nisms in CMOS technologies are the breakdown of weak gate oxides and opens in
metal tracks due to electromigration.

Burn-in [82] involves subjecting the IC to elevated temperatures (∼100 °C) and
voltages (∼1.5 times the nominal rating) over an extended period of time (typically
several hours) and is considered to be highly effective at reducing infant mortality

²There are some functionality-related tests that are of ‘non-terminating’-type; an example is
the ApvAddress test, as chips that only respond to some addresses may still be useful if they are
otherwise fully functional and exhibit excellent performance.
³It was originally thought that chips exhibiting imperfect analogue performance might be used
in the Tracker in order to maximise the yield and minimise production costs, but high yields are
still achieved using the most comprehensive and stringent test criteria; hence only chips that
pass all the test criteria are selected for use in the Tracker (see section 2.4).
rates due to the failure mechanisms mentioned above. However, burn-in is only practical for screening a small number of components at a time\(^4\) and so this method of reliability screening is consequently time-consuming and expensive. Furthermore, there is some risk of reducing the operational lifetime of quality components and so the screening must be highly optimised to minimise ageing of components.

An alternative method of increasing reliability is to use voltage screening [83], which involves biasing the IC at elevated voltages and, under certain conditions, applying test vectors to exercise circuit components at the elevated voltage. Voltage screening is particularly suited to testing the integrity of transistor gate oxides. Models predict that, under elevated bias conditions, the time required for breakdown of defective oxides is several orders of magnitude smaller than for good oxides, hence screening with suitable bias conditions can be used as an alternative to burn-in to induce early failures in weak gate oxides.

Following discussions with the manufacturer, their recommendation of using voltage screening in preference to burn-in was adopted. Burn-in is proposed for the assembled Front-End Hybrids before integration into the Tracker system. Voltage screening can be performed during wafer probing, just prior to the screening of APV25 chips at the nominal bias ratings, and so introduces no overheads except for a small time penalty. The voltage screen test performed on the APV25 chip is described below.

**“DvsEvs”**

Dynamic Voltage Screening (DVS) involves operating the chip at an elevated supply voltage of 1.5 times the nominal ±1.25 V bias level so that all major components of both the digital and analogue circuitry of the APV25 are stressed. Four of the screening tests described in section 2.3.4 are performed at this elevated voltage. Although the DVS procedure is primarily designed to induce likely failures, the chip is also expected to be fully functional at this elevated voltage. Therefore, the chip is required to satisfy the selection criteria outlined for each of the four screening tests in order to pass the DvsEvs test.

\(^4\)Burn-in at the wafer-level is impractical as it is difficult to simultaneously bias and instrument all sites on a wafer.
Firstly, all eight bits of each on-chip register are toggled (see description of the StuckBits test) in order to stress the digital circuitry associated with the bias and mode registers and the on-chip I²C interface. Secondly, the chip is configured to operate in deconvolution mode by writing to the various on-chip registers (see RegWriteAndRead test). Thirdly, the digital circuitry associated with the pipeline memory is stressed by triggering the chip so that data from each column of the pipeline memory are read from the chip (as in the PipeAddr test). Finally, the chip is randomly triggered (see RandomTrig test).

The DVS test patterns are followed by an Enhanced Voltage Screen (EVS), which provides a further voltage step up to ±2.5 V (twice the nominal bias rating) for 1 s, although the APV25 is not operated under these conditions. All subsequent tests following the voltage screening are performed with the APV25 biased at the nominal voltage rating of ±1.25 V.

### 2.3.4 Functionality-Related Tests

The following tests are designed to assess the functionality of the digital components of the APV25 chip and measure the power consumption of the chip under normal operating conditions. Chips must exhibit full (digital) functionality to be considered for use in the CMS Tracker and so all the following tests are of ‘terminating’ type.

**“RegisterWrite” / “RegWriteAndRead”**

The APV25 chip is configured via I²C ‘write’ and ‘write and read’ transactions with the on-chip registers (see appendix A for a description of the transaction protocol). For a write operation, an acknowledgement from the chip is required after each transaction. For write and read transactions, the on-chip registers are queried after being loaded with appropriate values. There must be no discrepancies between data written to and read from the registers, and an acknowledgement from the chip is again required after each transaction. I²C transactions are performed throughout the screening procedure in order to optimally configure the chip for the various tests. All I²C transactions must be successful.

**“StuckBits”**

A scan for stuck bits in the on-chip registers is performed by writing complementary bit patterns to each of the registers via the I²C interface (as described in the
RegWriteAndRead test above). The complementary patterns ensure that registers containing bits stuck in a high or low state due to a fabrication error are identifiable. Chips must not exhibit any stuck bits.

“DigiHeader”
The chip is triggered once in order to check the validity of the resulting data frame. The 12-bit header of the data frame must contain the correct pipeline address and a high error bit (signifying no error). The chip is deemed to fail this test if either no data frame is generated or an unexpected frame header is observed.

“RandomTrig”
The chip is triggered with 1000 pseudo-random triggers generated by the SEQSI sequencer at a rate of a few hundred Hz. The chip is required to generate a data frame for each trigger and the error bit of each frame header is required to be high, signifying error-free operation of the chip.

“ApvAddress”
Up to 31 chips can share the same I^2C slow control bus with addresses of individual chips determined by the combination of bonded address pads (of which there are five). During probing, contact is made with all five address pads, of which any combination can be switched low (active); hence, all 31 possible (unique) addresses and the global broadcast address (all bits high), can be accessed. Dummy values are written to and read from one of the on-chip registers for each of the 32 addresses. There should be no discrepancies in the data and transaction acknowledgements from the chip for all 32 addresses.

“FifoMem”
The chip is triggered with a predefined trigger sequence so that the 31-deep FIFO pipeline address memory is completely filled. The 8-bit address values of the flagged pipeline locations stored in the memory are read out via the resulting data frame headers. The chip is again triggered so that the FIFO memory is again filled, but using a trigger sequence so that the complementary pipeline address bit patterns are generated. The pipeline addresses are again read out via the data frame headers and compared with those obtained with the original trigger sequence. Stuck bits
in the FIFO memory are identified by addresses that are not complementary. Each 
chip is required to exhibit a fully operational FIFO memory.

“MultiMode”
The chip is configured to operate in multi-mode. The on-chip calibration circuitry 
is used to inject a test signal onto each channel. The chip is triggered twice, with 
triggers separated by 75 ns, so that data from six consecutive pipeline locations are 
output by the chip in six consecutive data frames. With these data, a coarse map 
(every 25 ns) of the resulting CR-RC pulse shape can be reconstructed, which must 
match the detailed reconstruction of the (peak-mode) CR-RC pulse shape performed 
by the ChanGain test to within a predefined threshold.

“PipeAddr”
The chip is triggered such that a scan is performed through the depth of the analogue 
pipeline memory and data are retrieved from each of the 192 columns. For each 
trigger, the 8-bit pipeline column address in the frame header is checked to ensure 
the correct address is output by the chip. This checks the integrity of the pipeline 
digital circuitry. The channel data provided by the output data frames during 
this test are also used to check the quality of the pipeline memory, in terms of 
pedestals, uniformity and noise (see the PipeCm, PipePeds and PipeNoise tests 
described below).

“Currents”
Current screening is effective at identifying the most common defects in CMOS 
devices, such as shorts across insulators and opens in contacts or metals. Such 
fabrication errors frequently lead to abnormal current consumption and this is a 
standard technique widely used in industry to identify processing faults [83][84].

The on-chip registers are first loaded with the recommended values for optimum 
performance of the APV25 chip before the supply currents are measured. The 
currents drawn from the two power rails, $V_{SS}$ and $V_{DD}$, must fall within predefined 
ranges.
2.3.5 Performance-Related Tests

The following tests are related to the performance of the APV25 chip. They assess the quality of the channel and pipeline memory in terms of pedestals levels, uniformity, gain and noise. The various threshold levels used to identify KGD are not discussed here, but in section 2.6 when the analogue performance of the APV25 chip is assessed.

“SetBaseline”
The optimum ‘baseline’ position (defined by the mean pedestal level) is considered to be at the 25 % level of the available dynamic range. The baseline position is adjustable via the VPSP (Voltage bias level for the analogue Pipeline Signal Processor) register and the test involves repeated writes to the VPSP register with incrementing values until the baseline position is raised to the desired level. Failure to do this results in the chip failing this test, which is of ‘terminating’ type.

“ChanPeds”
The pedestal level for an individual readout channel is defined to be the mean level observed in the raw data for that channel. The averaging is performed on data obtained by providing 200 triggers to the chip. Measurement of the pedestal levels are performed in both peak and deconvolution modes. All pedestal levels are required to fall within a predefined range. This test is also of ‘terminating’ type.

“ChanNoise”
The data collected during the ChanPeds test are used to measure the noise associated with each of the APV25 readout channels. The noise is defined to be the $\text{rms}$ spread in the pedestal- and common mode-subtracted data obtained for the 200 triggers. (The pedestals are provided by the ChanPeds test and the common mode is calculated on an event-by-event basis.) The noise measurements are performed with the chip operating in deconvolution mode and the noise levels for all channels are required to be below a predefined threshold.

“ChanGain” / “PulseInt”
The performance of the chip in terms of gain (defined here as the pulse height maximum) and pulse shape uniformity is assessed using the on-chip calibration pulse
generator. The chip is repeatedly triggered, with each trigger following an injection of 5 fC (~31000 electrons) of charge into the front-end of each readout channel. The CR-RC pulse shape provided by the front-end amplifying stages is reconstructed by sweeping the charge-injection time with respect to the (fixed) trigger time so that the entire pulse shape is mapped over a period of 125 ns in steps of 3.125 ns. This pulse shape reconstruction is performed for all 128 readout channels in both peak and deconvolution modes.

The quality of the reconstructed pulse shapes are ensured by integrating the area under the curve obtained for each channel and imposing a threshold on the maximum variation in these integral areas; this check defines the PulseInt test. The maximum pulse height observed for each channel, defined to be the channel gain, is required to be above a minimum threshold. Additionally, channel gain uniformity is ensured by requiring all gains match the chip-averaged gain to within a predefined threshold. Measurements and checks of channel gain are performed in both peak and deconvolution modes and these checks define the ChanGain test.

“MuxGain”
The on-chip calibration circuitry is also used to measure the gain provided by the multiplexer stage. For a given charge injection, the magnitude of the observed signal is measured for each of the five available gain settings (set via the MUXGAIN register). The signal magnitude for the various settings is compared with the (nominal) intermediate setting and the (absolute) fractional changes in the signal magnitude must be greater than predefined thresholds.

“PipeCm” / “PipePeds” / “PipeNoise”
For practical reasons, most of the performance-related tests acquire signals from a single pipeline column only (e.g. the ChanGain test acquires data from a single pipeline location and sweeps the charge-injection time in order to reconstruct the pulse shapes). In order to verify the integrity of the complete pipeline memory, data must be acquired from all pipeline columns. During the PipeAddr test (see above), the chip is triggered so that the entire pipeline memory is scanned and data are retrieved from all 192 column locations. These data are used to assess the quality of the pipeline memory.
The pipeline cell capacitances are required to be uniform throughout the pipeline memory to minimise the dependency of pedestal levels on the pipeline column location and therefore minimise any noise contribution. The 128 (raw) data samples stored in each column location within the pipeline memory are compared with the chip-averaged channel pedestal levels provided by the $\text{ChanPeds}$ test. The mean offset with respect to the channel pedestals for a given column is defined as the pipeline common mode. This pipeline common mode is measured for each of the 192 pipeline columns by the $\text{PipeCm}$ test. The test ensures uniformity throughout the pipeline memory by imposing a threshold on the $\text{rms}$ spread in the measured common mode levels.

The channel pedestals and the measured pipeline common mode levels are then subtracted from the relevant column data, resulting in a $128 \times 192$ array of pipeline cell pedestals. Abnormally high or low cell pedestals indicate faulty pipeline locations; such faults are identified by the $\text{PipePeds}$ test, which imposes a threshold on the maximum pipeline pedestal level. The $\text{rms}$ spread in the pipeline pedestals for a given channel is defined to be the pipeline noise, and provides the noise contribution of the pipeline to the total noise observed for a given channel. The $\text{PipeNoise}$ test measures the pipeline noise for each channel and ensures uniformity in the pipeline by imposing a threshold on the maximum pipeline noise level.

### 2.4 Yields and Related Issues

This section summarises the statistics of KGD accumulated during the wafer screening of one engineering lot (assigned lot number 0) and thirteen production lots (assigned lot numbers 1 to 13). The observed yields and the various failure modes are discussed, along with the studies performed to investigate the variable yields observed for early production lots.

#### 2.4.1 Statistics and Yields

Figure 2.4 (top) plots the number of probed APV25 sites (open bars) and the number of sites identified as KGD (solid bars) per lot, as a function of lot number. KGD are required to exhibit full digital functionality and satisfy all the selection criteria...
2.4 Yields and Related Issues

Figure 2.4: (top) Number of probed sites (open bars) and KGD (solid bars) per lot. (bottom) Mean lot yield and associated \textit{rms} spread (error bars) versus lot number.

Figure 2.5: (top) Total number of failed sites (open bars) and ‘terminating’ fails (solid bars) per lot. (bottom) Frequency of various ‘non-terminating’ failure modes.

described in section 2.6. For the fourteen lots, the total number of probed APV25 sites is 100068 and the total number of sites identified as KGD is 54344. This corresponds to \( \sim 70 \% \) of the total die required to fully instrument the Tracker (excluding contingency).

Figure 2.4 (bottom) plots the lot-averaged yield as a function of lot number; the error bars represent the \textit{rms} spread in the individual wafer yields for a particular lot. The engineering lot (lot 0) exhibited a high yield of \((82 \pm 5) \%\), but this excellent yield was not consistently matched by the subsequent few production lots. Variable yields were observed for the first eight production lots: only lot 3 exhibited a yield comparable to that achieved with the engineering lot (79 \%); in the worst case, lot 6 only yielded 43 KGD (<1 \% yield); the remaining six lots exhibited yields in the range 11\% to 58 \%, and large variations in the individual wafer yields.

Detailed investigations performed by the manufacturer identified the causes of these variable yields (described below) and, following the tuning of the processing conditions, consistently high yields were again observed for all subsequent lots (9 through to 13). These lots achieved (lot-averaged) yields in the range 76 \% to 90 \%, with little variation in the individual wafer yields. Individual wafer yields as high as 95 \% have been observed.
2.4.2 Failure Modes

Figure 2.5 (top) plots the total number of sites failing the screening procedure (open bars) and the number of those failures that are of ‘terminating’ type (solid bars) per lot. The vast majority of failures (79%) are of ‘terminating’ type and the RegisterWrite, RegWriteAndRead and ChanPeds tests are failed with the highest frequency. The two tests involving communication with the on-chip registers are the first ‘terminating’ tests performed during the screening procedure. Hence, these tests are the most likely to be failed if a site exhibits gross failures. Abnormal pedestal levels are frequently observed and so the ‘terminating’ ChanPeds test is also frequently failed.

The frequency of the various ‘non-terminating’ failure modes are summarised in figure 2.5 (bottom). Note that the numbers are not exclusive as a chip can fail multiple ‘non-terminating’ tests (this is not the case for ‘terminating’ failures). For those sites that fail only ‘non-terminating’ tests, the average number of failed tests is 1.8, with the most frequent failure modes involving pulse shaping (gain and uniformity) and pipeline uniformity.

The voltage screening test is also a ‘non-terminating’ test, designed to induce likely failures modes in defective die. Thus, a die failing the DvsEvs test is expected to subsequently fail additional tests; this occurs for ∼97% of die that fail the DvsEvs voltage screening.5

2.4.3 Investigations into Variable Yields

Following the high-yielding engineering lot, the first two production lots (1 and 2) were requested, which subsequently exhibited low (lot-averaged) yields of 29% and 11%. For wafers of lot 1, sites failing the screening procedure were most frequently observed in a concentric ring around a central patch of sites containing KGD, as illustrated by the wafer map in figure 2.6. This pattern of failures is further illustrated by figure 2.7, which shows an image plot indicating the percentage of failures observed per site as a function of site position, for wafers of lot 1. Failures are

5Full functionality at elevated voltages is not guaranteed by the manufacturer and so this could explain the small fraction of chips that do not fail any additional tests; even so, these chips are not used to instrument the Tracker.
most frequently observed in a concentric ring (dark shading) surrounding a central patch of sites containing KGD (light shading), with additional KGD observed at the periphery of wafers. These failure patterns are indicative of processing problems rather than some intrinsic design fault of the APV25 chip, and these observations prompted investigations by the manufacturer into the quality of the wafer processing.

Investigations on sample wafers from lots 1 and 2 revealed defects in the silicide (TiSi$_2$) layer, which provides the contact layer to gates and source or drain implants. Consequently, two replacements lots (4 and 5) were fabricated with careful monitoring of the silicide processing. An additional lot (3) was processed at the time of the silicide investigations (and independently of the first two production lots), and the subsequent screening revealed a high lot-averaged yield, suggesting that the silicide problem was only temporary. However, the replacement lots (4 and 5), with guaranteed silicide coverage, again revealed low lot-averaged yields (16 % and 36 %), which discounted the theory that the silicide problem was responsible for the variable yields. Three further production lots (6, 7 and 8) also exhibited low lot-averaged yields (<1 %, 37 % and 58 %, respectively).

Discussions with the manufacturer revealed that low and variable yields were not observed in other commercial products fabricated at similar times to the APV25 lots. Furthermore, low yields had been observed for chip designs of other high

Figure 2.6: A ‘wafer map’ identifying KGD (unshaded squares) and failed die (shaded squares) for a single wafer of lot 1.

Figure 2.7: An image plot indicating the percentage of passes observed per site as a function of site position, for wafers of lot 1.
energy physics projects, although with lower statistics than for the APV25 chip. A feature of HEP designs is the presence of long metal tracks, not commonplace in commercial (mainly digital) designs. Transistors are susceptible to damage due to the accumulation of charge on metal tracks during processing (known as the ‘antenna’ effect). Test structures were developed by the CERN Microelectronics group and submitted for fabrication with a multi-project wafer run, with the aim of highlighting this damage mechanism. However, no significant differences were observed in the (high) yields for test structures with different track lengths, which discounted the antenna effect as a candidate mechanism for reduced yields.

It was also noted that the APV25 design, along with other HEP-related chips, differs from the typical commercial design in that the distribution of metal defining tracks and capacitor components within the chip layout is relatively non-uniform. The manufacturer suggested that the inhomogeneous filling of metal might lead to problems associated with the thickness of metal and insulating layers. The APV25 chip uses three layers of metal tracks, as shown in the schematic of figure 2.8. The three layers are labelled M1 (closest to the substrate), M2 and MZ, which are connected by vias V1 and V2 and insulated by an inter-level dielectric (ILD). Capacitors are realised using an additional, intermediate metal layer (Q2) separated from the M2 layer by a thin dielectric.\footnote{An example of the non-uniform use of metal in the APV25 design is the increased use of Q2 to provide the weighting capacitors of the APSP stage.}
In order to verify if problems were occurring during metalisation, the manufacturer began a detailed failure analysis on returned sample wafers from lots 4 to 7. The failure analysis techniques include delayering, which involves the gradual removal of layers through a chip, and performing cross sections through defective chips at suspect locations. Possible faults were localised by the use of a temperature-sensitive liquid crystal coating to identify ‘hot-spots’ when the chip is biased. The wafer screening procedure was also modified in order to provide as much information as possible on the failure mechanisms for the APV25 sites of the returned sample wafers, with emphasis on localising observed failure mechanisms to specific areas of the chip.

The failure analysis highlighted two types of fabrication problems. Firstly, evidence of shorts between tracks in the M2 metal layer was found in chips from the sample wafer of lot 6, as illustrated by the cross section shown in figure 2.9. These shorts occurred due to the presence of extraneous Q2 metal in areas where it should have been removed during the patterning of the Q2 layer. This in turn interfered with the patterning of the underlying M2 metal layer. Secondly, opens were observed between the vias (V2) and the M2 metal layer in chips from the sample wafer of lot 4, as illustrated by the cross sections shown in figures 2.10 and 2.11. These opens were a result of the inter-level dielectric (ILD) thickness being close to maximum and the etching used to pattern the vias not being sufficiently deep to ensure contact
with the underlying M2 layer. Similar faults were found in chips from the sample wafers of lots 5 and 7.

Hence, the fault analysis identified the ‘root cause’ of the variable yields as the inter-level dielectric layers being too thick; examples of opens between vias and metal layers were identified on wafers from a number of different lots. An additional problem involving extraneous Q2 metal was also identified that was responsible for the very low yields observed for wafers of lot 6. All subsequent lots were processed with a reduced inter-level dielectric thickness.

2.5 Performance of the Test Station

2.5.1 Screening Reliability

The coverage of possible failure mechanisms provided by the screening procedure must be as exhaustive as possible in order to identify defective chips with the highest possible efficiency. Whilst the screening out of defective chips is of paramount importance, it is also important that good chips are identified as KGD with the highest possible efficiency in order to maximise yields and minimise production costs.

Direct experience accumulated with the production test station suggests that the screening procedure is highly effective at identifying defective chips. This experience comprises the comparison of the screening results from: the manual probing of individual sites following the (automated) probing of a wafer; and the re-probing of wafers. When discrepancies in the screening results have been observed for wafers that have been probed multiple times (using the automated procedure), the appropriate sites have been individually re-probed and in all cases the sites have contained KGD. This suggests that no defective die are escaping the screening procedure, but it does imply that small numbers of chips (<1 %) are lost as a result of being identified as defective when in fact they are good. This loss is thought to be largely due to poor electrical contact between the probe card and the chip, perhaps due to some surface residue left by wafer cleaning agents or extraneous oxide (passivation layer) covering the probe pads. In order to reduce this loss, sites failing ‘terminating’-type tests are immediately re-probed one further time.
Perhaps the best indicator of the number of defective chips that escape the screening procedure is provided by the frequency at which APV25 chips are identified as being defective during the testing of Front-End Hybrids instrumented with KGD (as identified by wafer screening). Very few problems have been directly attributable to ineffective screening and the vast majority of problems arise due to damage caused by wafer dicing (discussed below) or the mishandling of the chips prior to or during integration (such as ESD damage). When real problems have been observed, the screening procedure has been adapted to remove these shortfalls.

Visual inspections are performed following the dicing of all wafers to identify chips that have suffered cutting damage. Direct experience involves the visual inspection of a few diced wafers and the cut quality generally appears to be good, with chips suffering cutting damage at the percent level. The individual KGD of a single diced wafer have been manually re-probed to check the effect of wafer dicing on the yield. Of the 280 KGD tested,\(^7\) five chips failed the screening tests. After a visual inspection, three of these fails were attributed to cutting damage; the cause of the remaining two failures is unknown, but likely to be due to mishandling.

### 2.5.2 Wafer Throughput

The Tracker project is entering the crucial stage of large-scale system integration and the throughput of the APV25 production test station must match the demands required by the Front-End Module production schedule. The foreseen schedule requires 50 wafers a month to be screened, hence two wafers must be screened in every 24 hour period. This imposes a constraint on the time taken to screen a single wafer. The procedure has been tuned so that the screening time for a single APV25 site is only \(\sim 70\) s for KGD (and less for chips failing a ‘terminating’ test). This equates to a wafer test cycle of approximately seven hours, hence a throughput of two wafers per day is achieved with minimal manpower effort (\(\sim 20\) minutes per day).

\(^7\)This study highlights the necessity of the production test station: manual probing of the 280 individual chips took tens of man-hours, compared with a few minutes using the test station.
2.5.3 System Integration

Although there is a well-known correlation between wafer yield and reliability for some technologies [85], assurances from the manufacturer provide some confidence that KGD from low yielding wafers will not exhibit reduced reliability.

Of the first eight production lots, which exhibited variable yields, approximately 11000 KGD from lots 3, 4 and 5, have been used to instrument the Front-End modules. KGD from lots 1, 2 and 6 will not be used to instrument the Tracker. The decision to use KGD from lots 4 and 5 was based on the immediate demand for die by the module assembly line.

Of the high-yielding lots (9 to 13), a further ~13000 KGD have been delivered to the module assembly sites and a further ~18000 KGD are in hand. As there are large stocks of KGD currently available, ~8000 KGD from lots 7 and 8 (which exhibited variable yields) are being held in reserve and will be used only if necessary.

2.6 Assessing the APV25 Performance

By definition, fully functional chips must pass all the digital tests described in section 2.3.4. In addition, each chip must satisfy all the selection criteria described below, which ensure reasonable power consumption, uniform channel gain, low channel noise, and pipeline uniformity. The selection criteria are based on distributions obtained from an analysis of data collected during wafer screening. Only fully functional chips that exhibit excellent performance are considered for use in the Tracker.

The results presented below are those obtained from KGD of the engineering lot and the thirteen production lots. The analysis shows that the APV25 chip exhibits excellent performance, and the effect of the lot yield has negligible effect on the performance of KGD. Only loose selection criteria are required to efficiently identify KGD.

Calibration of the Production Test Station

A precise calibration of gain and noise in the test station environment is both difficult, due to the noisy environment, and unnecessary, as a dedicated test bench set-up is used to characterise chips from production lots on a statistical basis [35][76].
2.6 Assessing the APV25 Performance

![Figure 2.12: (top) Distribution of supply currents for KGD of lot 13. (bottom) Mean supply current consumption for KGD of individual lots, versus lot number.](image)

![Figure 2.13: Contour plot showing the relationship between the currents drawn from the positive (V_{DD}) and negative (V_{SS}) bias rails. Note the logarithmic frequency scale.](image)

However, in order to interpret the results presented below in a meaningful way an approximate calibration can be performed based on the APV25 design features. The output of the APV25 chip is in the form of a differential current and the digital header of the APV25 data frame output takes the values ±4 mA [34]. The range of the digital header of APV25 data frames captured and digitised during screening corresponds to 238 ADCch, and the analogue levels obtained from each of the 128 channels are confined to within this range. The signal gain provided by the APV25 front-end amplifying stages is 1 mA / 25000 electrons (assumed here to be the most probable amount of charge released by minimum ionising pions in 300 μm of silicon), hence the digital header corresponds to approximately 8 MIPs (2 \cdot 10^5 electrons). Hence, 1 MIP corresponds to ~30 ADCch and 1 ADCch corresponds to 840 electrons.

This method of calibration is dependent on the operating conditions of the APV25 chip and intended solely as a guide; a conservative estimate of the associated uncertainty is considered to be 20 %.

2.6.1 Supply Currents

The supply currents drawn from the positive (V_{DD}) and negative (V_{SS}) bias rails by an optimally-configured APV25 chip are measured during the *Currents* test.

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*aADC channels or units.*
Figure 2.14: (top) Channel pedestals for KGD of lot 13; the rms spread corresponds to 0.13 MIPs. (bottom) Mean pedestal and rms spread (error bars) for KGD of individual lots, versus lot number.

Figure 2.15: (top) Channel noise for KGD of lot 13; the mean value corresponds to an ENC of 550e. (bottom) Mean channel noise and rms spread (error bars) for KGD of individual lots, versus lot number.

Figure 2.12 (top) plots the distributions of the measured currents $I_{DD}$ (solid bars) and $I_{SS}$ (open bars) for KGD from lot 13. The mean currents drawn are $I_{DD} = 89.6$ mA and $I_{SS} = 140.2$ mA; this corresponds to an average power consumption of 2.24 mW per channel, which is in good agreement with the value 2.31 mW quoted in [34]. The rms spreads in the current distributions are 1.1 mA and 1.9 mA for $I_{DD}$ and $I_{SS}$, respectively. These small spreads (∼2 % of the mean value) highlight the uniformity in the current consumption observed for KGD of the same lot. Figure 2.12 (bottom) plots the mean $I_{DD}$ (solid markers) and $I_{SS}$ (open markers) current consumption observed for KGD of an individual lot, as a function of lot number. The dispersion in these lot-averaged current consumptions is ∼1 %. Figure 2.13 shows a contour plot that further highlights the uniformity of current consumption (note the logarithmic frequency). The red box indicates the thresholds imposed on current consumption: $70 \leq I_{DD} < 100$ mA and $120 \leq I_{SS} < 170$ mA.

### 2.6.2 Channel Pedestals

Figure 2.14 (top) shows the distribution of pedestal levels for individual channels of KGD from lot 13. The mean pedestal level is observed to be 66.8 ADCch. More importantly, the rms spread of the pedestal distribution is only 3.8 ADCch, equivalent
to \( \sim 0.13 \) MIPs. A small \( \text{rms} \) is necessary as a large spread would imply a reduced dynamic range for signal in those channels with high pedestal levels. Alternatively, the spread in pedestal levels can be characterised in terms of the peak-to-peak spread in pedestals for a single chip.\(^9\) The mean and largest peak-to-peak values observed for KGD of all fourteen lots are 14 ADCch (0.47 MIPs) and 27 ADCch (0.9 MIPs), respectively.

Figure 2.14 (bottom) plots the mean pedestal level observed for KGD of an individual lot, as a function of lot number. The \( \text{rms} \) spread in the pedestal distribution for each lot is represented by the error bars. The plot illustrates the uniformity of the pedestal levels observed between KGD of the same lot and those of different lots. The variation in the mean pedestal level for different lots is \( \ll 1 \% \); this is expected as the \( \text{SetBaseline} \) test defines the mean pedestal level. The variation in the \( \text{rms} \) spread between different lots is also small at \( \sim 2 \% \), implying that KGD consistently exhibit comparable pedestal levels for all the 128 channels. The \( \text{ChanPeds} \) test requires all 128 channel pedestal levels of KGD to fall within the range \( 40-90 \) ADCch.

2.6.3 Channel Noise

The noise associated with each APV25 readout channel is measured during the \( \text{ChanNoise} \) test. Figure 2.15 (top) shows the distribution of noise observed for individual channels of KGD from lot 13. The mean channel noise is observed to be 0.66 ADCch, which corresponds to an Equivalent Noise Charge (ENC) of 550 electrons (with an uncertainty of \( \pm 20 \% \) due to the calibration method). This value is comparable to the noise value of 430 electrons measured using a low-noise and highly calibrated system \([76]\]. The noise values of individual channels are well matched for die of the same lot, with a small \( \text{rms} \) spread of 0.05 ADCch (40 electrons).

Figure 2.15 (bottom) plots the mean values of the noise distributions obtained from KGD of individual lots, as a function of lot number. Again, the magnitude of the \( \text{rms} \) spread of each distribution is illustrated by the error bars. The plot illustrates the uniformity of the channel noise observed for KGD of the same lot and those of different lots. The variation in the mean channel noise and the \( \text{rms} \)

\(^9\)The peak-to-peak pedestal spread is defined by the difference between the maximum and minimum observed pedestal levels.
2.6 Assessing the APV25 Performance

The channel gains for KGD from single lots, versus lot number.

2.6.4 Pulse Shaping and Gain

Figure 2.16 shows the peak (top) and deconvolution (bottom) mode pulse shapes reconstructed for 1000 KGD of lot 13. Each trace represents the average pulse shape obtained from an individual chip. None of the pulse shapes exhibit anomalous values and all are relatively well matched in both magnitude and shape, even though no pulse shape tuning is performed during wafer screening.\(^\text{(10)}\)

Figure 2.17 (top) shows the distribution in gain observed for individual channels of KGD from lot 13, with the chips operated in both peak (solid bars) and deconvolution (open bars) modes. The mean gain observed during deconvolution mode operation is 55.8 ADCch, which corresponds to a signal of 1.9 MIPs; the \textit{rms} spread

\(^{10}\)The peak mode pulse shapes indicate that the on-chip bias registers used to tune the performance of the front-end amplyfying stages are not optimally configured; the pulse shapes exhibit risetimes of \(\sim 55\) ns, which is slightly longer than the ideal 50 ns. This results in a reduced gain when operating the chips in deconvolution mode.
in gain is 3.1 ADCch (0.1 MIPs). Figure 2.17 (bottom) plots the mean gain observed for KGD of individual lots, as a function of lot number; the error bars represent the \textit{rms} spreads of each gain distribution. The lot-to-lot variation in the mean gain and the \textit{rms} spread are 5.7 \% and 21.1 \%, respectively.

The charge injection capacitor used by the on-chip calibration circuitry is implemented by a crossover of two normal metal routing layers.\textsuperscript{11} These capacitors, as well as the resistors that define the gain of the back-end multiplexer stage, exhibit non-negligible tolerances and are sensitive to processing conditions. Hence, significant apparent gain variation between chips can be expected, although this is unrepresentative of the intrinsic gain variation. The observed pulse shape and gain matching are well within requirements and there is ample provision for pulse shape tuning and gain adjustment on-chip and elsewhere in the Tracker readout system.

The performance of the APV25 chip in terms of channel gain is ensured by requiring all individual channel gains to be greater than 20 ADCch and within 15 ADCch of the chip-averaged gain. Loose thresholds are chosen due to the non-negligible tolerances of the aforementioned capacitor and resistor components. The uniformity of the pulse shapes across the 128 channels of an individual chip is checked by the \textit{PulseInt} test. Uniformity is ensured by requiring the integrated area under each curve matches that observed for the chip-averaged pulse shape to within 15 \%.

\subsection*{2.6.5 Pipeline Performance}

Figure 2.18 (top) plots the \textit{rms} spread in the 192 pipeline common mode levels, as measured by the \textit{PipeCm} test, for KGD of lot 13. The lot-averaged spread is small, 1.46 ADCch (0.05 MIPs), and figure 2.18 (bottom) shows that similar spreads have been observed for all lots tested.\textsuperscript{12} The \textit{PipeCm} test requires the \textit{rms} spread in the pipeline column ‘common mode’ levels to be below 2.5 ADCch.

The individual pipeline cell pedestals, as measured by the \textit{PipePeds} test, are also uniformly small for KGD; the mean cell pedestal level, averaged over all lots,

\textsuperscript{11}The more precise Q2-M2 capacitor, as shown schematically in figure 2.8, was not used as its higher intrinsic capacitance per unit area made the small charge injections required impossible to achieve.

\textsuperscript{12}This information is only available from lot 7 onwards.
Figure 2.18: (top) rms of pipeline CM for KGD of lot 13; the mean value corresponds to 0.05 MIPs. (bottom) Mean and rms spread (error bars) for rms of pipeline CM for KGD of individual lots, versus lot number.

Figure 2.19: (top) Pipeline noise for KGD of lot 13; the mean value corresponds to an ENC of 160e. (bottom) Mean pipeline noise and rms spread (error bars) for KGD of individual lots, versus lot number.

is 0.53 ADCch (0.02 MIPs), with a rms spread of 0.16 ADCch. The PipePeds test imposes a threshold of 15 ADCch (0.5 MIPs) on the maximum pedestal level.

Figure 2.19 (top) shows the distribution of pipeline noise observed for each channel of KGD from lot 13. The mean noise level is observed to be 0.19 ADCch, which corresponds to an Equivalent Noise Charge (ENC) of 160 electrons (±20% due to the uncertainty in the calibration method). This value is comparable to the noise value of 110 electrons quoted in [76]. The rms spread in the pipeline noise levels is 0.12 ADCch (100 electrons). Figure 2.12 (bottom) plots the mean values of the pipeline noise distributions obtained from KGD of individual lots, as a function of lot number. The mean pipeline noise is seen to decrease from ~0.3 ADCch for the first seven production lots (and engineering lot) to ~0.2 ADCch for all subsequent production lots, although there is a small increase in the rms spread of the noise distributions. The PipeNoise test requires the pipeline noise of all 128 channels of KGD to be below 2 ADCch.

2.7 Summary

A production test station has been developed to automate the screening of APV25 wafers. Each APV25 site of a wafer is subjected to a comprehensive set of screening
2.7 Summary

tests, which validate the functionality and performance of each chip. Only those sites that satisfy all the selection criteria of the screening procedure will be used to instrument the CMS Tracker. To date, the test station has probed \( \sim 300 \) wafers and screened \( \sim 10^5 \) individual APV25 sites. The station has provided a sufficient throughput of wafers to match the demands of the aggressive module production schedule.

Although the yields of early production lots were variable, serious fabrication errors were identified through a detailed failure analysis performed by the manufacturer. Following the appropriate changes to the processing conditions, consistently high yields have been achieved for several consecutive lots, with yields around the 80–90\% level. Approximately 70\% of the chips needed to fully instrument the Tracker have been accumulated, of which a large fraction have already been integrated into the final Tracker readout system.

The parameter distributions obtained through the analysis of data collected during wafer screening demonstrate the effectiveness of the screening procedure to correctly identify fully functional chips that exhibit excellent analogue performance. In addition, the distributions are indicative of the process uniformity, as all chips are identically configured during the screening tests, and the observed parameter spreads are entirely due to the tolerances associated with the analogue circuit components, many of which are sensitive to the processing conditions. Excellent parameter matching is observed between channels, chips, wafers and lots. This ensures that adequate pulse shaping and gain matching between channels can be achieved immediately upon start-up using a standard set of register settings for all APV25 chips in the Tracker readout system. This feature will aid start-up and debugging; fine-tuning of pedestal levels, pulse shaping and gain can be performed at a later stage.
Chapter 3

Initial Studies of Highly Ionising Events

Nuclear interactions between incident particles and silicon sensors can generate highly ionising collision products that deposit large amounts of energy within the sensor volume. These events, known as Highly Ionising Events (HIEs), involve energy depositions way in excess of those generated by minimum ionising particles. The influence of such events on a prototype version of the CMS Tracker readout system was first noted during a beam test at the CERN X5 beamline in October 2001. The large signals generated by these highly ionising events saturate the APV25 front-end amplifying stages and induce deadtime in all 128 channels of the affected APV25 chip.

It was quickly realised that saturation of the APV25 chip was due to nuclear collisions in the silicon sensors, with event displays clearly showing the production of secondary particles, as illustrated in figure 3.12 (p. 88). Furthermore, the rates at which these effects were observed were consistent with rate calculations based on pion-silicon cross sections and the observed pion flux provided by the X5 beamline, as illustrated in section 1.4.5 (p. 39). This chapter describes an analysis of the data collected during the X5 beam test, which quantified the effect in terms of two measurements: the probability of deadtime being induced in the APV25 as a result of a nuclear interaction, and the magnitude of the induced deadtime.

The magnitude of large energy depositions in the silicon sensors cannot be inferred from the analogue data of the APV25, as large signals are truncated due to
the limited APV25 dynamic range. Furthermore, inter-strip capacitive coupling in the sensors effectively ‘smears’ the signal across an increased number of strips, further masking the true distribution of signal. Therefore, a deeper understanding of the effect requires further studies outside the beam test environment and simulation. The response of the APV25 front-end amplifying stages to large (known) signals was simulated with the HSPICE package [86] and characterised experimentally by simulating highly ionising events in the laboratory. A simulation of nuclear interactions between incident particles and silicon sensors provided information on the magnitude and spatial distribution of the resulting energy depositions and the expected rates. The pertinent results from these studies are also reported in this chapter. Finally, the magnitude of the effect is extrapolated to the CMS Tracker environment and the inefficiencies resulting from the induced deadtime are predicted.

3.1 Simulating Nuclear Interactions in Sensors

Elastic and inelastic interactions between incident particles and a silicon sensor were simulated and the collision products transported within the sensor under zero magnetic field.\(^1\) Two different sensor arrangements were simulated: 320 \(\mu\)m and 500 \(\mu\)m-thick silicon with strip pitches of 80 \(\mu\)m and 120 \(\mu\)m, respectively. These were illuminated with various particles at normal incidence, including 120 GeV pions and muons, and 200 MeV pions.\(^2\) In order to simulate the CMS Tracker radiation environment, the sensors were also isotropically illuminated with protons, pions, kaons and neutrons with their predicted fluxes and energy spectra for the Tracker Inner Barrel (TIB) and the Tracker Outer Barrel (TOB) regions (see table 1.1, p. 40, and figure 1.10, p. 42).

The simulation showed that for elastic interactions in silicon, only large-angle scatterings generate energetic nuclear recoils and significant energy depositions. These rare events are observed to release up to \(~4\) MeV. Essentially all energy depositions of less than 0.1 MeV are elastic in nature. In the case of inelastic collisions,

\(^1\)The simulation was performed by M. Huhtinen, CERN. A detailed description of the simulation and results can be found in [74].

\(^2\)The X5 beamline, described in section 3.4, provided 120 GeV pions and muons. The most probable pion energy in the CMS Tracker is predicted to be \(~200\) MeV; this is also the pion energy of the M1 beamline at PSI, used during a beam test study of highly ionising events in May 2002 (see chapter 4 onwards).
a heavy nuclear recoil is observed, along with the production of nuclear fragments. The nuclear recoils and heavy fragments\(^3\) are observed to have energies up to a few tens of MeV. For nuclear recoils, the energy spectrum is insensitive to the incident particle energy and there is no extension of the spectrum to higher recoil energies. This is because nuclear binding energies are the order of a few MeV and so nuclear fragmentation is preferred over highly energetic nuclear recoils. For light fragments, such as protons and pions, their energy spectra are extended to much higher values for larger incident particle energies.

The maximum rate of energy loss for heavy ions, such as silicon or magnesium, in silicon is a few MeV \(\mu\text{m}^{-1}\) and occurs at an energy of \(\sim 10\) MeV.\(^4\) Thus, the typical range of a heavy nuclear recoil is a few \(\mu\text{m}\), and so the resulting energy deposition is highly localised. In the case of light ions, such as protons or \(\alpha\) particles, the maximum rate of energy loss is an order of magnitude smaller; a few 100 keV \(\mu\text{m}^{-1}\), occurring at an energy of \(\sim 1\) MeV. Therefore, light ions, with energies scaling with the incident particle energy, have much longer ranges of up to several mm. Table 1.2 (p. 43) lists the mean ranges for various ions in silicon.

As highlighted in chapter 1, single event upsets (and similar phenomena) result from large and highly localised energy depositions within a ‘sensitive volume’ of an integrated circuit. This sensitive volume is typically a few cubic microns. In the case of a fully-biased silicon sensor, the sensitive volume is essentially the volume of the sensor itself. Therefore, light nuclear fragments, although not as highly ionising as heavy recoils, can also contribute significantly to the total energy deposition, due to their long ranges and the large sensor volume.

The simulation has shown that essentially all inelastic nuclear interactions between hadrons and silicon generate highly ionising events; elastic collisions rarely generate energy depositions above \(\sim 1\) MeV. Consequently, highly ionising events involving incident muons are also rare, as muons do not interact via the strong force and so inelastic collisions are improbable.

\(^3\)The term ‘heavy’ here implies a mass greater than the nucleon mass, \(i.e.\ Z > 1\).

\(^4\)See figure 1.11, p. 42. For comparison, the rate of energy loss for a minimum ionising particle in silicon is \(\sim 400\) eV \(\mu\text{m}^{-1}\).
3.1 Simulating Nuclear Interactions in Sensors

Figure 3.1: Probability of a hadronic interaction in silicon resulting in an energy deposition $E_{\text{dep}}$ [MeV] per path-length in silicon. Adapted from [74].

Figure 3.2: Probability of a hadronic interaction in silicon resulting in an energy deposition greater than $E_{\text{dep}}$ [MeV] per path-length in silicon. Adapted from [74].

Figure 3.1 shows the differential probability energy deposition spectra provided by the simulation, for various particles incident on a silicon sensor. The plot provides the probability of observing an energy deposition, $E_{\text{dep}}$ [MeV], per path-length in silicon for: 120 GeV and 200 MeV pions at normal incidence in 500 $\mu$m silicon; and hadrons with isotropic distributions and their predicted fluxes and energy spectra in the CMS Tracker Inner Barrel (TIB) and Outer Barrel (TOB) regions. The probability spectra for the TIB and TOB regions are normalised to path-lengths of 320 $\mu$m and 500 $\mu$m, respectively. The magnitude of the energy deposition is seen to scale roughly with sensor thickness. The increase at low values of $E_{\text{dep}}$ is due to the elastic contribution. The shoulder at $\sim$10 MeV is due to the inelastic short-range nuclear recoils, which deposit all their energy in the sensor volume. Events with the highest energy depositions always involve several highly ionising particles. Figure 3.2 shows the cumulative probability energy deposition spectra for the same incident hadrons, and provides the probability of observing an energy deposition $E_{\text{dep}}$ or greater. Energy depositions of up to $\sim$200 MeV are observed; this is equivalent to $\sim$1000 minimum ionising pions in a 500 $\mu$m silicon sensor.

The simulation also provided information on the spatial distribution of the energy depositions resulting from highly ionising events and some general observations can

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5The uncertainties associated with the probabilities predicted by the energy deposition spectra are difficult to assess, due to the uncertainties inherent in physics models provided by the FLUKA code [89], but 500 % is considered to be a conservative estimate [90].
be made here. The bulk of the energy deposition is usually collected on only one or two strips, even for the highest incident particle energies; this is due to the short-range nature of the heavy nuclear recoil. The number of strips which collect a signal of at least 5 MeV is usually fewer than five, for the simulated strip pitches of 80 \( \mu \text{m} \) and 120 \( \mu \text{m} \) (the actual strip pitches of the TIB and TOB sensors are 120 \( \mu \text{m} \) and 183 \( \mu \text{m} \), respectively). Furthermore, the simulation is performed with zero magnetic field, whereas in the Tracker, the 4 Tesla field will act to drive the charged particles out of the sensor planes. Hence, one can assume that the bulk of the energy depositions are collected on only one or two APV25 channels.

### 3.2 The Deadtime Mechanism

The simulation of nuclear interactions in silicon sensors predicts energy depositions of up to \(~200\) MeV, three orders of magnitude larger than signals generated by minimum ionising particles. Signals of this magnitude easily saturate the APV25 front-end amplifier stages, which are designed to handle signals equivalent of up to a few tens of MIPs. Unfortunately, it is not only the few channels on which signal is collected that are affected, but all 128 channels of an APV25 chip. This crosstalk effect is aggravated by the biasing scheme used to power the APV25 front-end amplifier stages.

There is some history behind the development of the biasing scheme for the APV25 front-end amplifier stages. Initially, both the preamplifier and inverter stages were to be biased via a common on-chip V125 (+1.25 V) supply line. A subsequent simulation of this layout revealed that if the impedances associated with the supply lines of the preamplifier and inverter stages differed significantly, the V125 line could provide a possible mechanism for positive feedback around the preamplifier, resulting in instabilities. Thus, to remove this possible feedback loop, the on-chip V125 supply line was split so that the preamplifier and inverter stages were biased via independent V125 power rails, each with a separate input pad. This solution was valid under the assumption that the impedance of the V125 power rails on the front-end hybrid, external to the APV25, were negligible. Laboratory measurements with multiple APV25 chips on a front-end hybrid showed that this was not the case and instabilities were observed.
3.2 The Deadtime Mechanism

Further simulations revealed that stable operation of the front-end hybrid could be achieved by deriving the voltage bias for the source follower and inverter stages from the V250 (+2.50 V) supply rail via an external resistor mounted on the hybrid [91, 92]. The use of two independent power supplies for the preamplifier stage and the source follower and inverter stages removes the feedback loop entirely, ensuring stability. A value of 100 Ω would provide a current of ~100 μA required by the inverter stage. This solution has a small penalty of increased power usage; a resistor value of 100 Ω will dissipate 16 mW on top of the nominal ~300 mW power usage of an APV25 chip [34]. A beneficial feature of this biasing scheme is the effective subtraction of any external common mode signal [93]; the mechanism for this ‘on-chip common mode subtraction’ is described in appendix B.

Figure 3.3 shows a simplified view of the powering scheme used to bias the front-end amplifying stages of the APV25 chip. The inverter stage consists of two identical PMOS transistors, providing a gain of -1. The stage is powered by the V250 supply rail via a 100 Ω resistor, \( R_{\text{inv}} \), which is external to the APV25 chip and located on the front-end hybrid. Under normal operating conditions, this biasing scheme is effective at providing on-chip common mode subtraction, as the potential \( V_R \) at node A (highlighted in the figure) is common to all channels and takes the value of \( V_{\text{cm}} \) (as described in appendix B). However, when the chip is subjected to large...
signals, node A provides a crosstalk path so that all 128 channels are affected. The response of the APV25 front-end stages to very large signals cannot be accurately simulated with the HSPICE package, as the circuit components are operating well outside their design specifications, but a simulation can provide information on the gross behaviour.

The results provided by a HSPICE simulation illustrate the same characteristic behaviours observed with laboratory measurements and beam test data (see below). Figure 3.4 shows the temporal evolution of the source follower output (top) and the inverter stage output (bottom) following the injection of a large positive signal at the preamplifier input. The outputs of both stages are observed to saturate for the channel collecting the large signal (solid lines). Additionally, a negative swing at the inverter output is observed in all other channels for two values of the $R_{\text{inv}}$ resistor (dotted/dashed lines). This is due to the inverter(s) of the channel(s) collecting the large signal being switched hard-on, therefore drawing a large current and pulling the potential $V_R$ low at node A. This results in the inverter stage output of all other channels being suppressed.

These behaviours are manifest in real APV25 data as large positive signals in those channels collecting large signals and a negative shift in all other channels of the chip (i.e. a negatively shifted ‘baseline’). Increasingly large signals result in increasingly shifted baselines, although these baseline shifts are limited to within the $\sim8$-MIP dynamic range imposed by the shaper stage. Importantly, this ‘truncation’ of the baseline shifts means that sufficiently large signals can result in all channels of the affected APV25 chip being insensitive to MIP-like signals. Hence, highly ionising events can induce deadtime and, consequently, inefficiencies in the Tracker readout system.

In order to reduce the effect of large signals on the APV25 front-end stages, possible modifications to the front-end hybrid were investigated through studies with the HSPICE package and laboratory measurements [94]. The proposed modification involved changing the hybrid inverter resistor, $R_{\text{inv}}$, from the nominal value of 100 $\Omega$ to a reduced value of 50 $\Omega$. This modification reduces the capability of large signals to suppress the output of all other channels, by increasing the current available to the inverter stage of each channel. The effect of this modification is illustrated by
the dotted line in figure 3.4 (bottom), which shows a smaller shift than for the 100 Ω case.

The chip can also be operated in non-inverting mode, which involves ‘switching-out’ the inverter stage. Unfortunately, the crosstalk path is still present, as the shaper stage (not shown in figure 3.3) that follows the inverter stage is also powered by the V250 supply line via the external $R_{inv}$ resistor.

3.3 Deadtime Measurements in the Laboratory

Highly ionising events have been simulated in the laboratory by injecting charge directly into a few channels of the APV25 via the input pads on the front-end of the chip.\(^6\) As the magnitude of the injected signal is known, a precise calibration of the APV25 response to a range of large signals can be made. This method cannot expect to accurately reproduce the spatial distribution of charge generated by highly ionising events, but the effect of varying the number of channels on which charge is injected can be investigated.

The simulation of hadronic interactions in silicon, described above, implies that the bulk of the ionisation charge resulting from a highly ionising event is collected on only one or two strips. Therefore, highly ionising events were simulated by injected charge on a single APV25 channel or sharing the injected charge between two adjacent channels. As no sensor was used, adjacent and next-to-adjacent channels were coupled to the injected signal via a capacitor network, to simulate the effects of inter-strip capacitive coupling. The chip was triggered shortly after the injection of the charge and consequently, large (truncated) signals were observed on typically five or six APV25 channels, as observed during the X5 beam test (see below).

In order to build a temporal picture of the APV25 response, charge was repeatedly injected into the front-end of the chip and the chip triggered following each injection. The delay between injection and trigger was progressively increased from 0 ns to 2500 ns in 1 ns steps. This sequence was performed both with and without the injection of a MIP-like signal of 20 fC on an APV25 channel not collecting the

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\(^6\)The laboratory measurements were performed by M. Raymond (Imperial College London). Further details of the study can be found in [87, 88].
3.3 Deadtime Measurements in the Laboratory

HIE signal. The injection of the MIP-like signal, when present, was coincident in time with the trigger.

Trace (a) of figure 3.5 provides an example of the temporal evolution of the output from the channel on which the HIE signal is injected. The channel output is driven to the upper limit of the APV25 dynamic range (~280 ADCch\(^7\)) for a few ns, then to the lower limit (~25 ADCch) for a period of 200 ns, before eventually recovering to the nominal baseline position. The swing to the lower limit of the APV25 dynamic range is observed only when the chip is operated in deconvolution mode; when the chip is operated in peak mode, large (truncated) signals are observed for several hundred ns in the channels collecting the HIE signal (as shown in figure 5.5, p. 123).

Figure 3.5 also shows examples of the temporal evolution of the output obtained from the channel on which the MIP signal is injected. Trace (b) plots the channel output when the MIP signal is injected in coincidence with the trigger; trace (c) provides the temporal evolution of the ‘baseline’ position, by plotting the channel output in the absence of the MIP signal. Trace (d) plots the difference between traces (b) and (c) and so represents the evolution of the observed signal (above the

\(^7\)ADC channels or units.
The evolution of the observed signal was reconstructed for a range of simulated energy depositions, with magnitudes ranging from 5 to 100 MeV and injected on a single channel or shared between two channels. Figure 3.6 shows the evolution of signal for simulated energy depositions injected on a single APV25 channel, with the nominal inverter resistor value, $R_{inv}$, of 100 Ω. The deadtime induced by the simulated highly ionising events is inferred from these traces and is defined to be the period for which zero signal amplitude is observed. Zero deadtime is inferred from the traces obtained with energy depositions of 10 MeV and 13 MeV; larger energy depositions induce deadtimes of up to $\sim$130 ns.

Figure 3.7 plots the observed deadtime as a function of the magnitude of the simulated energy deposition, with the HIE signal injected on one or two channels (with capacitive coupling to adjacent and next-to-adjacent channels) and a nominal inverting resistor value, $R_{inv}$, of 100 Ω. Similarly, figure 3.8 shows the observed deadtime curves for simulated energy depositions injected on one or two APV25 channels with a reduced resistor value of 50 Ω. The injected HIE signal is accurate to $\pm$5 % (this error is largely attributable to the non-negligible tolerance of the
charge injection capacitors) and the deadtime measurement is accurate to ±10 ns (this error accounts for the finite recovery time of the signal).

The magnitude of the observed deadtime for a given simulated energy deposition is sensitive to the number of channels, $N_{\text{chans}}$, on which the HIE signal is injected and the resistor value, $R_{\text{inv}}$. With the nominal resistor value of 100 $\Omega$, the maximum observed deadtimes are $\sim$150 ns and $\sim$350 ns for a HIE signal injected on one or two channels, respectively.\(^8\) By reducing the resistor value to 50 $\Omega$, the maximum observed deadtime is significantly reduced to $\sim$110 ns and $\sim$130 ns for signal injected on one or two channels, respectively. Importantly, the measurements imply that a threshold energy deposition of a few MeV is required before deadtime is observed.

The deadtime curves have been parameterised with equation 3.1. $\Gamma(E_{\text{dep}})$ [ns] is the deadtime induced by a simulated energy deposition, $E_{\text{dep}}$ [MeV]. $E_{\text{thr}}$ [MeV] is the threshold energy deposition required before deadtime is observed, $\tau$ [MeV] characterises the initial exponential dependence, and the following linear rise is characterised by the constants $\alpha$ [ns] and $\beta$ [ns $\cdot$ MeV$^{-1}$]. Fits to the deadtime curves are represented by dashed lines in figures 3.7 and 3.8, and the parameter values obtained for the best fits are summarised in table 3.1.

$$\Gamma(E_{\text{dep}}) = \begin{cases} (\alpha + \beta E_{\text{dep}}) \cdot \left[ 1 - e^{\frac{-(E_{\text{dep}} - E_{\text{thr}})}{\tau}} \right] & \text{if } E_{\text{dep}} > E_{\text{thr}} \\ 0 & \text{if } E_{\text{dep}} \leq E_{\text{thr}} \end{cases} \quad (3.1)$$

The energy deposition required for non-zero deadtime to be observed (as implied by the fits) falls in the range 6–19 MeV and is sensitive to the number of channels, $N_{\text{chans}}$, on which the HIE signal is shared and the inverter resistor value, $R_{\text{inv}}$. A lower threshold is observed when the HIE signal is shared between channels and an

---

\(^8\)As an extreme case, measurements were also performed with the injected charge shared between seven adjacent strips, but without the capacitor network. The largest observed deadtime was $\sim$1500 ns.

<table>
<thead>
<tr>
<th>$N_{\text{chans}}$</th>
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<th>$E_{\text{thr}}$ [MeV]</th>
<th>$\tau$ [MeV]</th>
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Table 3.1: Fit parameters used to parameterise the dependence of the measured deadtime on the simulated energy deposition, for various values of $R_{\text{inv}}$ and $N_{\text{chans}}$. 
increased threshold is observed when the value of the inverter resistor is reduced from 100 Ω to 50 Ω.

The cumulative probability curves for 120 GeV pions incident on 500 μm of silicon and the TOB hadron environment coincide at an energy deposition of ~6 MeV. Therefore, given the comparable magnitude of the thresholds observed with the laboratory measurements, the probability of a nuclear interaction inducing deadtime in the APV25 chip is expected to be comparable for the two environments. Furthermore, the reduction in the value of the inverter resistor is observed to increase the energy deposition threshold; thus, the probability of observing deadtime in the TOB region is expected to decrease by a factor ~2.

The simulation of hadronic interactions in silicon showed that elastic collisions rarely generate energy depositions greater than ~1 MeV, and so it can be assumed that only inelastic collisions between hadrons and silicon can induce deadtime in the APV25 chip.

3.4 Study of Highly Ionising Events with X5 Test Beam Data

3.4.1 The X5 Beam and Readout System

The aim of the October 2001 beam test was to operate a near-final version synchronous readout system under LHC-like operating conditions, as suggested in [95] and requested by [96]. The readout system consisted of six 500 μm-thick Tracker Outer Barrel (TOB) sensors, each consisting of 512 strips at a pitch of 183 μm. Each sensor was instrumented with four APV25 readout chips, which were operated in deconvolution mode. All six modules were equipped with inverter resistors of the nominal 100 Ω value. The APV25 analogue data were delivered electrically to three Front-End Driver (FED-PMC) cards [97]. The analogue data from each triggered event were digitised by the FED-PMCs and written to ZEBRA files [98] in their raw format.

The test beam data were analysed with the TestBeams/X5October2001 software package, developed within the Object-orientated Reconstruction for CMS Analysis (ORCA) environment [99]. As described in chapter 1, the channel data consist of...
3.4 Study of Highly Ionising Events with X5 Test Beam Data

Figure 3.9: The readout system for the October 2001 beam test.

The function of the $X5\text{October2001}$ package is to calculate these separate contributions and then reconstruct hits in the sensors by identifying signal (above a predefined noise threshold) in adjacent channels.

The TOB sensors were exposed to the X5 beamline [100], which is derived from the Proton Synchrotron (PS) and Super Proton Synchrotron (SPS) machines [101]. A 25 ns proton bunched beam is prepared in the PS machine and the contents of $\sim$48 consecutive RF buckets are extracted and injected into the SPS machine. These proton bunch trains, of $\sim$1.2 $\mu$s duration, are then accelerated to 400 GeV/c before being extracted and delivered to the West Area complex at the SPS orbit frequency of $\sim$43 kHz. This structure is repeated throughout a beam spill (alternatively known as a flat-top) of duration $\sim$2.4 s. Consecutive spills are separated by $\sim$13 s.

The X5 secondary beam is derived from the primary bunched proton beam. During the X5 test, the beam comprised negatively charged pions (or muons) and was tuned to a momentum of 120 GeV/c. In summary, the readout system was exposed to a 25 ns bunched pion beam for $\sim$1.2 $\mu$s every $\sim$23 $\mu$s throughout spills of duration $\sim$2.4 s. A similar beam structure was used during the May 2000 beam test, in which every third RF bucket was occupied on average during the bunch trains [102, 103]. The beam structure provided the high instantaneous intensities required
for performance studies of the readout system under high trigger rate conditions, whilst complying with the radiation safety limits imposed in the experimental areas.

Bunch crossings (occupied RF buckets) were identified by observing coincident signals in two photomultiplier tubes instrumenting the same scintillator (placed upstream of the sensors). Triggers were issued to the readout system for particular combinations of occupied and unoccupied RF buckets that allowed various studies on the readout performance. An example is the study on fine-tuning of APV25 parameters to define the optimum deconvolution pulse shape. This was done by requiring an unoccupied-occupied-unoccupied combination of RF buckets (represented by ‘010’). By triggering the readout system on the occupied RF bucket and adjusting the latency so that data for the following RF bucket (\textit{i.e.} the second ‘0’) are read out, it was possible to measure the frequency of ‘fake’ clusters due to an ill-defined deconvolution pulse shape. Further studies were performed with combinations such as ‘0001’ and ‘1001’ (in which two triggers separated by 75 ns are issued to the readout system).

An internal 16-bit counter on the FED-PMC card, incremented with each RF bucket, provided a bunch crossing (BX) number used to time-stamp the triggered events, which was appended to the analogue data from each triggered event. During spills, the counter looped back to zero every \(\approx 1.6\) ms, so the analysis tracks these overflows and provides an accumulating bunch crossing number, \(BX_{tot}\). The bunch crossing information can be used to study the structure of the X5 beam by considering the distribution of triggers in time. The \(BX_{tot}\) data exhibit modularity 924, implying an the SPS orbit period of \(23.1\) \(\mu\)s (\(924 \times 25\) ns).

As described above, the beam was delivered in bunch trains at the SPS orbit frequency. Hence, the temporal distribution of triggers reflects this beam profile and triggers are only observed during certain interval within each SPS orbit period. This is illustrated by figure 3.10, which plots the variable \(BX_{tot}\) modulo 924 (providing the temporal trigger ‘position’ within the SPS orbit period) versus \(BX_{tot}\) (providing the time-stamp).\(^9\) The trigger groups observed are those issued during the same spill, which are confined to the same time interval within the SPS orbit period as

\(^9\)The data are provided by a data run during which pairs of triggers, separated by 75 ns, were issued to the readout system for ‘1001’ combinations of occupied / unoccupied RF buckets.
3.4 Study of Highly Ionising Events with X5 Test Beam Data

Figure 3.10: Temporal distribution of triggers within the SPS orbit period. Triggers of the same spill are restricted to a particular time interval (see ordinate) equal to the duration of the bunch trains.

Figure 3.11: Temporal distribution of triggers within the bunch trains. These distributions are provided by the y-axis projections of the trigger distributions for individual spills shown in figure 3.10.

A result of the finite length and periodic particle bunch trains. The inset plot of figure 3.10 highlights the trigger distribution observed for a typical spill (boxed); triggers are distributed evenly throughout the bunch trains.

Figure 3.10 is complicated further by the fact that the BX counter of the FED-PMC card is reset to zero before each spill and restarted at the time of a spill signal (indicating the advent of a beam flat-top). The time of the first triggered event, which should occur during the first bunch train of the spill, is random with respect to the spill signal, hence there is no correlation between the position of the trigger distributions within the SPS orbit period for different spills. Furthermore, the counter reset is interpreted as a counter loop by the analysis and so successive spills in the plot appear not to be separated in time; in fact the spills are separated by ~13 s of no beam.

The ‘start’ position of the particle bunch trains (of the same spill) within the SPS orbit period can be identified by considering the distribution of triggers to an accuracy of ±2 bunch crossing periods (equivalent to ±50 ns). Figure 3.11 shows the trigger distributions from several spills superimposed, for two different data runs; 20655 with trigger condition ‘1001’, and 20730 with trigger condition ‘0001’. The effect of the trigger requirements on the trigger distributions in the bunch trains is
3.4 Study of Highly Ionising Events with X5 Test Beam Data

Figure 3.12: An example of a highly ionising event. Raw channel data are plotted as a function of strip number for each sensor plane. The event topology, with multiple secondaries observed in the downstream sensor planes is indicative of an inelastic nuclear collision.

pronounced. During run 20730, the condition ‘0001’ is satisfied for the first particle of each bunch train, hence triggers are biased heavily towards the beginning of the bunch trains. During run 20655, the more stringent ‘1001’ condition results in triggers being more evenly distributed throughout the bunch trains, as mentioned above.\textsuperscript{10} This will prove to be very useful when studying deadtime, as described later in this section.

3.4.2 Characterising the APV25 Response to Large Signals

As shown by the HSPICE simulation of the APV25 front-end amplifying stages and the laboratory studies, described in sections 3.2 and 3.3 respectively, highly ionising events are highly identifiable due to the characteristic behaviour exhibited by the APV25 chip in response to HIP signals. When the occurrence of highly ionising event is coincident in time with a triggered event, several adjacent channels are observed to contain large signals, frequently truncated at the upper limit of the

\textsuperscript{10}The unusual shape to the trigger distribution observed for the ‘1001’ trigger condition is likely to be due to sensitivity to the beam particle multiplicity and trigger throttling due to the limitations in the readout system. The distribution could be considered to exhibit a quasi-linear increase during the bunch train period, rather than a ‘bump’ near the end of the period.
3.4 Study of Highly Ionising Events with X5 Test Beam Data

A shift from the nominal baseline position is also observed in all other channels due to the crosstalk mechanism described in section 3.2.

This shift is interpreted as a non-zero (negative) common mode value. An example of a highly ionising event is shown in figure 3.12, in which raw analogue data from the six sensor planes are shown. The analogue data from one of the APV25 chips instrumenting part of the third sensor plane are clearly suppressed relative to their nominal levels (identified by the dotted line) and large signals are observed in several adjacent channels. Signals in the first and second planes\(^{11}\) are a result of the incident (minimum ionising) pion responsible for the nuclear interaction in the third plane. The pion then interacts inelastically with the silicon of the third sensor plane. The resulting highly ionising particles generate a signal that is sufficient to saturate the instrumenting APV25 chip, and high levels of activity, typical of an inelastic collision, are observed in the subsequent three sensor planes.

The distribution of common mode values reconstructed from a sample of triggered events is shown in figure 3.13. Increasingly large energy depositions from

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\(^{11}\)The signal observed in the second plane is inverted with respect to signals in all the other planes due to different APV25 settings used for that plane (the four APV25 chips instrumenting the second detector plane were operated in non-inverting mode).
highly ionising events result in increasingly shifted baselines, producing a tail at negative common mode values. The pronounced peak found at the end of the tail is a consequence of the analogue data being suppressed to the lower limit of the APV25 dynamic range, which limits the common mode to a minimum level, \(C_{\text{min}}\). The minimum common mode level is defined by the position of the lower limit of the APV25 dynamic range relative to the baseline,\(^{12}\) as illustrated by figure 3.14. The analogue levels of an affected APV25 can be suppressed for up to several hundred ns, as shown by the laboratory measurements described in section 3.3, and so negative common mode levels are also observed if the readout system is triggered a short time after the occurrence of a highly ionising event. Evidence for the suppression of signal when the analogue levels are shifted to the lower limit of the APV25 dynamic range is observed in the beam test data. Additionally, the usual pedestal structure observed across the 128 channels of an APV25 chip is also suppressed.

Figure 3.15 shows the distributions of cluster signal (*top*) and cluster width (*bottom*) for the largest cluster reconstructed from the data of an APV25 chip exhibiting a large negative common mode value (*i.e.* at near-saturation).

Two distinct populations can be identified. One population of clusters contain signals of up to several thousand ADCch distributed across several channels, typically five or six. These clusters are identified as resulting from highly ionising events and the typical cluster signal of \(\sim 1300\) ADCch corresponds to \(\sim 20\) minimum ionising particles in \(500\ \mu\text{m}\) of silicon.\(^ {13}\) Such signals are only observed for highly ionising events coincident in time with the triggered event, as the large HIE signal is only observed for \(\sim 25\) ns (as shown by the laboratory measurements).

The other population of clusters is characterised by signals of a few tens of ADCch contained in one or two channels. These signals are not typical of those resulting from highly ionising events and so a highly ionising event is inferred to have occurred just prior to the triggered event, with the APV25 chip still in near-saturation. The signals present are likely to be due to small residual signals in the

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\(^{12}\)During the X5 beam test, the baseline positions of all the APV25 chips were tuned to comparable values, hence a single sharp peak in the common mode distribution is observed at approximately \(-150\) ADCch.

\(^{13}\)Note that expressing the signal in terms of minimum ionising particles is not an indication of the magnitude of the original energy deposition (impossible due to signal truncation), but is simply intended to highlight that such a signal is not due to a penetrating minimum ionising particle.
3.4 Study of Highly Ionising Events with X5 Test Beam Data

Figure 3.15: Cluster signal [ADCch] (top) and cluster width [strips] (bottom) for the largest cluster reconstructed in APV25 data frames exhibiting suppressed baselines. The most probable (HIP) signal of ~1300 ADCch corresponds to 20 MIPs.

Highly ionising events that induce deadtime in the APV25 chip and coincide with the triggering of the readout system can be identified in the data by requiring a common mode level below a threshold value, $CM \leq CM_{thr}$, and a cluster containing signal greater than some threshold value, $S_{clu} \geq S_{thr}$. The threshold values used in this analysis are $CM_{thr} = -140$ ADCch and $S_{thr} = 300$ ADCch.

APV25 chips that are experiencing deadtime induced by a highly ionising event also exhibit characteristic behaviour and so can be identified through features of their analogue data. As described above, no signal is observed in any channel of a ‘dead’ APV25 chip, and the pedestal structure normally observed across the 128 channels is also suppressed. Figure 3.16 shows the distribution of the peak-to-peak spread (i.e. the difference between maximum and minimum values) in the raw analogue data obtained from individual APV25 chips. The peak below 10 ADCch results

Calibration of the readout system indicates that the most probable signal induced by an incident 120 GeV pion, comparable to a minimum ionising particle, is ~70 ADCch.
from APV25 data frames containing fully suppressed baselines with no signal or pedestal structure. The shoulder at $\sim 25$ ADCch is due to the variation in pedestals across a chip, the peak at $\sim 70$ ADCch is due to the presence of signal, and the long tail to large values is due to the large signals resulting from highly ionising events. APV25 chips that are experiencing deadtime when the readout system is triggered are identified in the data by requiring a common mode value of $CM \leq CM_{thr}$ and a peak-to-peak spread in the raw analogue data, $\Delta_{raw} \leq \Delta_{thr}$, where $CM_{thr} = -140$ ADCch and $\Delta_{thr} = 10$ ADCch.

### 3.4.3 Probability of Observing Deadtime

The probability, $P_{dead}$, of an incident particle inducing deadtime in the APV25 chip by generating a highly ionising nuclear collision can be measured by normalising the number of observed highly ionising events, $N_{dead}$, to the total number of path-lengths of beam particles through the silicon sensors. This number is calculated from the product of the following three quantities: the number of triggered events, $N_{trig}$; the mean pion (or muon) multiplicity in a sensor plane, $\langle M_{\pi/\mu} \rangle$; and the number of sensor planes, $N_{plane}$, as shown in equ. 3.2. The TOB sensors used during the X5 beam test were illuminated by pions or muons at normal incidence and with no magnetic field present, so the mean track length of a pion (or muon) in each sensor plane was $\sim 500$ $\mu$m. Therefore, $P_{dead}$, is the probability per 500 $\mu$m path-length in silicon. The APV25 chips instrumenting the second sensor plane were operating in non-inverting mode$^{15}$ and so data collected with this plane were not used in the analysis.

$$P_{dead} = \frac{N_{dead}}{N_{trig} \cdot \langle M_{\pi/\mu} \rangle \cdot N_{plane}} \quad (3.2)$$

Three data runs were used in the measurement of $P_{dead}$; two with pions illuminating the sensor planes and one with muons. Table 3.2 summarises the statistics accumulated during the three runs and lists the value of $P_{dead}$ measured from each data run. The mean value (and associated statistical uncertainty) of the two measurements made with the pion beam is $P_{dead} = (5.4 \pm 0.1) \cdot 10^{-4}$ [per 500 $\mu$m path-length].

$^{15}$The APV25 chips instrumenting the other five planes were operated in inverting mode, the nominal mode of operation.
3.4 Study of Highly Ionising Events with X5 Test Beam Data

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<th>Run ID</th>
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<th>$N_{\text{trig}}$</th>
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<th>$N_{\text{plane}}$</th>
<th>$P_{\text{dead}}$</th>
<th>$\lambda_{\text{dead}}$ [m]</th>
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Table 3.2: Probability, $P_{\text{dead}}$, of an incident 120 GeV pion or muon inducing deadtime in the APV25 through a nuclear collision in 500 $\mu$m of silicon. Statistical errors are quoted; the systematic errors are estimated to be $\sim 15\%$.

equivalent to an interaction length of $\lambda_{\text{dead}} = 93$ cm. For muons incident on silicon, the measured probability, $P_{\text{dead}} = (6.0 \pm 2.3) \cdot 10^{-6}$, is two orders of magnitude lower than the measurements obtained with pions, which reflects the electromagnetic nature of the muon-nucleus collisions. As shown by simulation, elastic collisions rarely generate energy depositions sufficient to induce deadtime in the APV25 chip. The equivalent interaction length is $\sim 80$ m.

The systematic uncertainties associated with $P_{\text{dead}}$ largely result from the determination of the mean pion multiplicity, $\langle M_{\pi/\mu} \rangle$, and the choice of the minimum signal required to identify the highly ionising event. If the threshold signal is reduced (increased) from 300 ADCch to 100 ADCch (500 ADCch), the measured probability, $P_{\text{dead}}$, increases (decreases) by $\sim 10\%$ (3%). The efficiency with which clusters are reconstructed, and hence the mean particle multiplicity observed in each plane, is dependent on the clustering algorithm, but the resulting systematic uncertainty on $\langle M_{\pi/\mu} \rangle$ is expected to be small. The mean multiplicity quoted in table 3.2 is the mean of the multiplicities observed in the six sensor planes, which vary by $\pm 5\%$ with respect to the quoted value. The value of $P_{\text{dead}}$ changes at a rate of $< 1\%$ per 1 ADCch change in the common mode threshold, CM$_{\text{cut}}$. The overall systematic uncertainty is estimated to be $15\%$.

Laboratory measurements have shown that a threshold energy deposition of $\sim 10$ MeV is required for deadtime to be observed. The simulation of hadronic interactions in silicon indicate that only inelastic collisions can generate such large energy depositions. This is confirmed by the muon deadtime probability measurement, which is small due to the elastic nature of the muon-nucleus collisions. Hence, an assumption can be made that only inelastic collisions are responsible for inducing deadtime in the APV25 chip. Therefore, the measured interaction length, $\lambda_{\text{dead}}$, can be compared with that obtained from the inelastic pion/silicon cross section, $\sigma_{\pi Si}^{\text{in}}$. 
3.4 Study of Highly Ionising Events with X5 Test Beam Data

<table>
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<th>‘Beam’</th>
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<th>(R_{\text{inv}}) [(\Omega)]</th>
<th>(E_{\text{thr}}) [MeV]</th>
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<td>1.32</td>
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Table 3.3: Predicted values of \(P_{\text{dead}}(E_{\text{thr}})\) [per path-length in silicon] and the corresponding interaction length, \(\lambda_{\text{dead}}\), for various energy deposition thresholds and radiation environments (X5 and the Tracker Inner and Outer Barrel regions). \(P_{\text{dead}}(E_{\text{thr}})\) is provided by figure 3.2.

at a pion momentum of 120 GeV. The pion-silicon inelastic cross section, \(\sigma_{\pi\text{Si}}^{\text{in}}\), is estimated to be 212 mb, which is equivalent to a nuclear interaction length of 95 cm, in good agreement with the measured value.\(^{16}\)

Furthermore, the cumulative energy deposition probability spectra, shown in figure 3.2, can be used in conjunction with the laboratory-measured energy deposition thresholds (see section 3.3) to predict the probability of a hadronic interaction in silicon generating an energy deposition greater than the threshold required to induce deadtime in the APV25 chip, \(P_{\text{dead}}(E_{\text{thr}})\). The predicted probabilities for various radiation environments are summarised in table 3.3. All probabilities are predicted to be \(O(10^{-4})\) [per path-length in silicon] and the X5 values are in good agreement with the measured probability. Reducing the inverter resistor value from 100 \(\Omega\) to 50 \(\Omega\) is predicted to reduce \(P_{\text{dead}}\) by \(~50\%\) in the TIB and TOB regions.

3.4.4 Deadtime Induced by Highly Ionising Events

The recovery of the APV25 chip after a highly ionising event and a direct measurement of deadtime (as performed in the laboratory) cannot be performed with the data taken during the X5 beam test, due to the moderate trigger rates during data taking; trigger bursts are required for a detailed history of the recovery of the APV25 chip after each highly ionising event. However, the observed trigger rates were sufficiently high to allow the deadtime to be inferred from the observed distribution of ‘dead’ APV25 chips within the particle bunch trains. This deadtime

\(^{16}\)The inelastic pion-silicon cross section, \(\sigma_{\pi\text{Si}}^{\text{in}}\), can be estimated by scaling up the inelastic pion-proton cross section, \(\sigma_{\pi\text{p}}^{\text{in}}\), by \(A^{2/3}\), where \(A\) is the atomic mass number (28 for silicon). Hence, for \(\sigma_{\pi\text{p}}^{\text{in}}(120\text{ GeV}) = 23\text{ mb}\), the estimation for \(\sigma_{\pi\text{Si}}^{\text{in}}(120\text{ GeV})\) is 212 mb.
measurement was only possible due to the special structure of the X5 beam and the trigger conditions used during data taking. The trigger conditions during run 20655 required a ‘1001’ combination of occupied / unoccupied RF buckets, ensuring that triggers were distributed throughout the bunch trains. Consecutive trains separated in time by \( \sim 23 \mu s \).

Figure 3.17 shows the number of highly ionising events and ‘dead’ APV25 chips identified in the data as a function of trigger position. The difference in statistics for the two distributions is due to the increased probability of observing a ‘dead’ APV25 due to the non-zero deadtime. For comparison, figure 3.17 also shows the distribution of triggers observed during the bunch trains.

Normalising the distributions of highly ionising events and ‘dead’ APV25 chips to the trigger distribution provides the probability of observing a highly ionising event or ‘dead’ APV25 in a triggered event as a function of trigger position in the bunch train, as shown in figures 3.18 (a) and (b), respectively. The probability of observing a highly ionising event is constant at \( 3.7 \times 10^{-3} \) during the bunch train and zero before and after. Normalising this probability to the number of 500 \( \mu m \) sensor planes (5) and the mean pion multiplicity (\( \sim 1.6 \)) observing during run 20655 provides a probability measurement of \( \sim 4.7 \times 10^{-4} \) per 500 \( \mu m \) path-length in silicon, which is in good agreement with the pion probability measurements listed in table 3.2.
3.5 Predicting Inefficiencies in the CMS Tracker

Figure 3.18 (b) shows the probability of observing a ‘dead’ APV25 as a function of trigger position. The probability of observing a ‘dead’ APV25 depends on the probability of a highly ionising event occurring in one of the preceding occupied RF buckets of the train. Importantly, the bunch trains are sufficiently spaced so that highly ionising events occurring in one train cannot contribute to any deadtime observed in the following train. Therefore, the probability of observing a ‘dead’ APV25 is zero at the beginning of a train (as there are no preceding occupied RF buckets). This probability increases with trigger position, due to the increasing probability of observing a highly ionising event in a preceding RF bucket, and then saturates. Saturation occurs because only highly ionising events that precede a trigger by a time interval less than the induced deadtime can contribute to the probability of observing a ‘dead’ APV25. The ‘risetime’ of the probability distribution provides an upper limit on the deadtime induced by highly ionising events. The deadtime, as obtained from figure 3.18 (b), is measured to be $350 \pm 50$ ns (equivalent to $14 \pm 2$ bunch crossing intervals), which is in agreement with laboratory measurements.

3.5 Predicting Inefficiencies in the CMS Tracker

The differential energy deposition spectra provided by the simulation of hadronic interactions in silicon can be used in conjunction with the laboratory-measured deadtime curves to predict the inefficiencies resulting from deadtime induced by highly ionising events. For a given energy deposition, $E_{dep}$ [MeV], the predicted inefficiency, $\varepsilon(E_{dep})$ [per path-length in silicon], is given by the equation:

$$\varepsilon(E_{dep}) = \Phi(E_{dep}) \cdot \frac{\Gamma(E_{dep})}{25 \ [ns]} ; \quad \varepsilon_{tot} = \sum_{E_{dep}} \varepsilon(E_{dep})$$

(3.3)

where $\Phi(E_{dep})$ is the probability of a hadronic interaction in silicon resulting in an energy deposition $E_{dep}$, $\Gamma(E_{dep})$ [ns] is the deadtime resulting from an energy deposition $E_{dep}$. The total inefficiency, $\varepsilon_{tot}$, is obtained by summing $\varepsilon(E_{dep})$ over all energy depositions. The probability, $\Phi(E_{dep})$, is provided by figure 3.1, which plots the differential energy deposition probability spectra for hadronic interactions in silicon with incident hadrons of various energy and angular distributions. The
3.5 Predicting Inefficiencies in the CMS Tracker

Figure 3.19: Predicted inefficiency, $\varepsilon(E_{\text{dep}})$ [per path-length in silicon], in the TIB and TOB regions for (simulated) energy depositions collected on one APV25 channel.

Figure 3.20: Predicted inefficiency, $\varepsilon(E_{\text{dep}})$ [per path-length in silicon], in the TIB and TOB regions for (simulated) energy depositions collected on two APV25 channels.

The corresponding deadtime, $\Gamma(E_{\text{dep}})$, is provided by the fits to the laboratory measurements obtained with the simulated energy depositions collected on one or two APV25 channels and inverter resistor values of 50 and 100 $\Omega$, as shown in figures 3.7 and 3.8.

Figures 3.19 and 3.20 plot $\varepsilon(E_{\text{dep}})$, as defined in equation 3.3, as a function of $E_{\text{dep}}$ for the TIB and TOB regions and (simulated) energy depositions collected on one and two APV25 channels, respectively. The inefficiencies, $\varepsilon(E_{\text{dep}})$, are quoted per path-length in silicon; the path-lengths in the TIB and TOB regions correspond to 320 $\mu$m and 500 $\mu$m, respectively. Table 3.4 summarises the predicted total inefficiency, $\varepsilon_{\text{tot}}$ [per path-length in silicon], for the TIB and TOB regions, for simulated energy depositions collected on one and two APV25 channels, and for inverter resistor values of 50 and 100 $\Omega$. The total inefficiency is reduced by an order of magnitude due to a change in resistor value when the energy deposition is assumed to be collected on two APV25 channels; this reduction is much less pronounced when the energy deposition is collected on a single APV25 channel.

The total inefficiency due to hadronic interactions inducing deadtime in the APV25 chip is expected to be highest at the innermost detector layer, where the particle flux is highest. For the following calculation, only the pion flux is considered, which is the most abundant hadron type in the inner Tracker region. The total
3.6 Summary

Essentially all highly ionising events are a result of inelastic collisions between incident hadrons and silicon sensors. The highly ionising products of each collision can generate energy depositions of up to \(~200\) MeV, with the resulting signal typically collected on one or two APV25 channels. These large signals can cause measurable deadtime in all 128 channels of the affected APV25 chip, due to a crosstalk mechanism inherent in the biasing scheme of the front-end amplifying stages.

The effect of highly ionising events on the APV25 has been studied with an analysis of the X5 beam test data and in the laboratory. All results obtained from these studies and a simulation of hadronic interactions in silicon sensors are in good agreement. The inefficiencies resulting from highly ionising events are expected to

<table>
<thead>
<tr>
<th>$N_{\text{chans}}$</th>
<th>$R_{\text{inv}}$ [(\Omega)]</th>
<th>$\varepsilon_{\text{tot}}$ [$\times 10^{-4}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2)</td>
<td>100</td>
<td>44.2</td>
</tr>
<tr>
<td>(2)</td>
<td>50</td>
<td>2.7</td>
</tr>
<tr>
<td>(1)</td>
<td>100</td>
<td>6.4</td>
</tr>
<tr>
<td>(1)</td>
<td>50</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table 3.4: Total inefficiency, $\varepsilon_{\text{tot}}$ [per path-length in silicon], predicted for the TIB and TOB regions, for inverter resistor values of 50 and 100 \(\Omega\) and (simulated) energy depositions collected on one and two APV25 channels.

path-length of pions in silicon per bunch crossing period within a sensor volume instrumented by a single APV25 chip at the innermost detector layer is given by the product of the predicted pion flux, the instrumented sensor volume and the bunch crossing period. The pion flux, as provided by table 1.1 (p. 40), is $2.06 \times 10^6$ cm$^{-2}$ s$^{-1}$; the instrumented sensor volume, defined by the sensor dimensions and strip pitch, is $119(l) \times 15.4(w) \times 0.32(d)$ mm$^3$; the bunch crossing period is 25 ns; therefore, the total (pion) path-length in silicon per bunch crossing period is 302 \(\mu\)m. Hence, the $\varepsilon_{\text{tot}}$ values listed for the TIB region in table 3.4 have to be scaled by a factor 302/320, resulting in predicted inefficiencies of $(2.3\ldots41.6) \times 10^{-4}$ depending on the resistor value and charge distribution. These inefficiencies can be expected to increase due to the contribution of other hadron types, although this contribution is expected to be smaller than the pion-induced inefficiencies.
be at the percent level in the CMS Tracker environment. Laboratory measurements indicate that by reducing the value of a front-end hybrid resistor, the probability of observing deadtime, the duration of the induced deadtime, and hence the resulting inefficiencies in the readout system, can be reduced to a manageable level.

The studies described in this chapter provide much insight into the effect of highly ionising events on the APV25 chip. Unfortunately, the assumptions and systematic errors inherent in the physics simulation and laboratory measurements make an accurate extrapolation of the effect to the CMS Tracker environment difficult to perform. Furthermore, the performance of the readout system, in terms of hit reconstruction efficiency, during the recovery period of the APV25 chip has not been accounted for. Consequently, the predicted total inefficiencies for the TIB and TOB regions of the Tracker are only considered at best to be an estimate; the uncertainties are difficult to evaluate, but are expected to be significant.

The effects of highly ionising events are best studied using a particle beam and a full readout chain. Although this was the case during the X5 beam test, the analysis of beam test data provided a measurement of the rate of observing deadtime for an incident pion momentum of 120 GeV, which is not typical of the pion momentum expected for minimum bias events in the CMS Tracker. Furthermore, the trigger conditions at X5 were not conducive to a detailed study of the recovery of the APV25 after a highly ionising event.

These arguments provided a strong case for a dedicated study using a beam that would provide a radiation environment similar to that expected in the CMS Tracker. Such a study would be based on the measurements described in this chapter and would allow a study of the effectiveness of the proposed solution of reducing the inverter resistor value.
Chapter 4

A Detailed Study of Highly Ionising Events at PSI

4.1 Motivation

The studies described in chapter 3 reveal much about the effect of highly ionising events on the APV25 chip. However, an extrapolation of the effect to the CMS Tracker environment, in terms of predicting the induced inefficiencies, is based on a physics simulation and laboratory measurements and the uncertainties associated with this extrapolation are expected to be large. In order to feel confident about the magnitude of the inefficiencies in CMS, it was felt that a study using a particle beam similar in character to the expected Tracker radiation environment and a near-to-final version of the full Tracker readout chain was necessary. Therefore, a detailed study using the M1 beamline at the Paul Scherrer Institute (Zurich) was proposed [104]. The motivations for the study are listed below.

- The study would allow rate measurements using pion and proton beams with energies comparable to the most probable energies expected in CMS. Furthermore, the use of appropriate trigger conditions and particle vetoes would allow an unbiased and accurate measurement of the rates.

- Customised trigger logic could be used to generate trigger bursts, allowing a detailed study of the recovery of APV25 chips affected by highly ionising events.
The HSPICE simulation and the laboratory measurements described in chapter 3 suggest that a simple modification to a component mounted on the front-end hybrid would reduce the rate of highly ionising events and the magnitude of the induced deadtimes. The effectiveness of this modification could be studied under realistic operating conditions.

Additionally, investigations into the effect of different detector configurations and AVP25 settings on the observed rates and deadtimes could be performed.

This chapter describes the subsequent beam test undertaken in May 2002, in terms of the beam environment, experimental set-up, trigger conditions, the data acquisition and control systems, and the online and offline software packages. The quality of data collected and detector performance achieved during the beam test are also briefly discussed.

4.2 The PSI Beam Test

4.2.1 The M1 Beamline

The CMS Tracker radiation environment will consist largely of low momentum pions confined to the Tracker region by the 4 Tesla magnetic field. The most probable pion momentum is expected to be $\sim 300$ MeV/c [105]. The average pion flux\(^1\) expected at the innermost detector layer of the Tracker (at 22 cm) is estimated to be $\sim 2$ MHz cm\(^{-2}\).

The M1 beamline [106] at PSI is ideally suited to providing a radiation environment similar to that expected in the Tracker. The M1 beamline provides a continuous beam of pions and protons in the momentum range 100–500 MeV at LHC-like intensities. During the beam test, the beam was tuned to a pion momentum of 300 MeV/c, which coincides with the most probable pion momentum in the Tracker and the peak of the $\Delta$-resonance, at which the interaction cross-section for pions and protons (and therefore silicon nuclei) is significantly enhanced. The highest pion flux achievable with the M1 beamline is 0.8 MHz cm\(^{-2}\).

\(^1\)The integrated pion fluence at the innermost Tracker layer is expected to be $10^{14}$ cm\(^{-2}\) for an integrated luminosity of $5 \cdot 10^{-5}$ pb\(^{-1}\) (10 years LHC operation). The estimate of the average flux assumes the LHC will operate at an instantaneous luminosity of $10^{34}$ cm\(^{-2}\) s\(^{-1}\).
4.2 The PSI Beam Test

The tracking system used during the PSI beam test, consisting of twelve sensor planes.

The M1 beamline has a bunch crossing frequency of 50 MHz, compared with 40 MHz clock frequency used by the Tracker readout system. Thus, the M1 beamline clock and the Tracker readout clock were only synchronous every 100 ns, with intermediate bunch crossings out-of-time by up to 10 ns.

4.2.2 Experimental Setup

The tracking system consisted of twelve modules simultaneously exposed to the M1 beamline. The modules were prototypes of the final-version Tracker modules, taken from the module production line and equipped with the most up-to-date components. Each sensor had 512 channels, aligned in the vertical direction and instrumented with four APV25 chips. Various module configurations were used during the study: modules designed for the Tracker Inner Barrel (TIB), Tracker End-Cap (TEC) and Tracker Outer Barrel (TOB) regions were equipped with hybrid inverter resistors of different values. The twelve modules were individually mounted on metallic support plates and housed in two boxes, as shown in figure 4.1.

The first three sensor planes of the tracking system were provided by TIB modules, with sensor dimensions of $119 \times 63 \text{ mm}^2$, a sensor thickness of 320 $\mu$m and a strip pitch of 120 $\mu$m. The first and third modules were equipped with inverter resistors of the nominal 100 $\Omega$ value; the second TIB module was equipped with resistors of the reduced 50 $\Omega$ value.
4.2 The PSI Beam Test

The next three sensor planes were provided by TEC modules. The TEC sensors are trapezoidal and have variable pitch from 163 μm to 204 μm, variable width from 83 to 105 mm, a height of 187 mm and a thickness of 500 μm. All three modules were equipped with inverter resistors of the nominal 100 Ω.

The last six sensor planes were provided by TOB modules, with sensor dimensions of 189 × 97 mm², a sensor thickness of 500 μm and a strip pitch of 183 μm. The six modules (looking in the downstream beam direction) were equipped with inverter resistor values of 50, 50, 75, 100, 50 and 100 Ω.

4.2.3 Triggering the Readout System

Beam particles traversing the tracking system were identified by coincident signals from two photomultiplier tubes viewing the same scintillator, placed upstream of the tracking unit. The counter dimensions were 185(h) × 30(w) × 3(d) mm³. An additional (large area) counter, downstream of the tracking unit, was used to veto events containing protons when collecting statistics with the π⁺ beam. Additionally, the downstream counter was used in anti-coincidence with the upstream counter when operating with certain trigger conditions (see below).

A customised Trigger Sequencer Card (TSC) [107] was used to generate and synchronise a 40 MHz clock for the readout system to the 50 MHz beamline clock. Particle triggers, provided by the upstream counter, were only accepted every 100 ns, when both clocks were in phase. Furthermore, the modified card could generate a burst of triggers for the readout system (described in more detail below) on receipt of a particle trigger, allowing a study of the APV25 recovery following a highly ionising event. Unfortunately, it was not possible to perform a fine tuning of the optimum sampling time of the CR-RC pulse shape using the customised TSC card. Hence, all data were collected using peak mode sampling, as operating the APV25 chip in deconvolution mode requires a timing resolution better than 5 ns. Figure 4.2 (top) plots the temporal evolution of the mean signal associated with hits reconstructed from data collected with trigger bursts. Signal is observed in each of the 30 ‘events’ of a trigger burst, from \( T_{\text{event}} = 0 \) ns to 750 ns, as a result of particles crossing the tracking system throughout the temporal windows provided by the trigger bursts. The time of the particle trigger can be inferred from the time at which the largest
mean signal is observed ($T_{\text{event}} = 75$ ns) and the CR-RC pulse shape is clearly seen (due to the peak-mode sampling every 25 ns).

As the M1 beamline provides a continuous beam, a trigger pre-filter was used during data-taking to remove any measurement bias introduced by highly ionising events occurring in bunch crossings prior to the particle trigger. The upstream counter was used in conjunction with trigger logic to provide a particle veto for the 16 bunch crossings (corresponding to 320 ns) preceding each trigger issued to the readout system. Figure 4.2 (bottom) illustrates the effect of the trigger pre-filter on the trigger distribution observed during data-taking, which plots the separation in time of consecutive triggers, relative to the time of the second trigger, $\Delta T = T_1 - T_2$. Consecutive triggers are always separated by multiples of 100 ns, due to the trigger rules imposed by the TSC card. The minimum observed trigger separation of 400 ns is due to the trigger pre-filter.

Only the central areas of the sensor planes were subject to the trigger pre-filter, due to the finite width of the upstream counter (30 mm). Figure 4.3 (top) plots the beam profile, in terms of the number of reconstructed hits in the data as a function of the hit position, for a low intensity $\pi^-\,$ beam (black line) and a high intensity $\pi^-\,$ beam (red circles). The excess of hits observed with a high intensity beam (relative to the low intensity beam) in the region $60 - 90$ mm is due to pileup.
of signal resulting from particles traversing the sensors prior to the triggered event that are not detected by the upstream counter (and therefore the trigger pre-filter). The presence of out-of-time signal is illustrated by figure 4.3 (bottom), which plots the mean $S/N$ ratio of hits as a function of hit position. The mean $S/N$ ratio is $\sim 35$ within the central region covered by the upstream counter and falls to $\sim 20$ outside this region. This has important consequences for the measurements of the highly ionising event rate.

4.2.4 Control and Data Acquisition

The control and data acquisition systems were based on the prototype Front-End Controller (FEC-PMC) [39] and Front-End Driver (FED-PMC) PCI mezzanine cards [97]. The FEC-PMC and FED-PMC cards were housed in two PCs situated in close proximity to the tracking system; two FEC-PMC and three FED-PMC cards were required for the 12-module tracking system.

The 40 MHz clock and triggers provided by the TSC card were distributed to the Front-End Hybrid components via the two FEC-PMC cards and interface cards mounted on the metallic plates supporting the front-end modules. The FEC-PMC and interface cards also provided the I$^2$C control interface required for configuration of the front-end components. The APV25 analogue channel data were transmitted electrically to one of the FED-PMC cards housed in the nearby PCs. After digitisation, the data were distributed via 100 Mbit ethernet to the counting room. Information regarding event identification and hardware configuration settings were appended to the raw digitised data before being written to a local disk.\(^2\) The control and data acquisition software tools were developed within the XDAQ framework [108, 109] provided by the CMS DAQ group; a dedicated event builder and data storage tools were developed for the PSI beam test [110].

4.2.5 Monitoring and “Quasi-Online” Software Analyses

A Java-based distributed data-monitoring display interface and the underlying on-line analysis software were developed for the PSI beam test [110] to allow real-time

\(^2\)The beam test data can be found on CASTOR at /castor/cern.ch/cms/beamtests/tkpsi.
4.3 Studying Highly Ionising Events at PSI

<table>
<thead>
<tr>
<th>Beam</th>
<th>Momentum [GeV/c]</th>
<th>Intensity [MHz]</th>
<th>Flux [MHz cm(^{-2})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 (\pi^-)</td>
<td>0.3</td>
<td>(low) 0.015</td>
<td>0.01</td>
</tr>
<tr>
<td>M1 (\pi^-)</td>
<td>0.3</td>
<td>(med) 0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>M1 (\pi^-)</td>
<td>0.3</td>
<td>(high) 1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>M1 (\pi^+)</td>
<td>0.3</td>
<td>(low) 0.025</td>
<td>0.017</td>
</tr>
<tr>
<td>X5 (\pi^-)</td>
<td>120.</td>
<td></td>
<td>0.69</td>
</tr>
</tbody>
</table>

Table 4.1: Pion energy, intensities and fluxes provided by the M1 and X5 beamlines. The expected pion flux at the innermost layer of the Tracker is \(\sim 2 \text{ MHz} \cdot \text{cm}^{-2}\).

monitoring of the readout system. This interface provided information such as pedestal levels, channel noise and Landau signal distributions. Additionally, a simple and fast online analysis was written to provide real-time information on highly ionising events [111], including the (highly ionising event) statistics collected during a run and various related distributions.

A more detailed analysis of the data was performed during the beam test using analysis software developed within the ORCA\(^3\) environment [99], described below. The local disks containing recent run data were transported from the ‘event builder’ PC to a dedicated server hosting the ORCA environment, on which a “quasi-online” analysis was performed.

4.3 Studying Highly Ionising Events at PSI

4.3.1 Rate Measurements

Large data samples were collected in single-trigger mode with the trigger pre-filter. The tracking system was illuminated with protons and pions (of both charge polarities) at various intensities, as shown in table 4.1. Furthermore, data were collected with the APV25 chips operating in both inverting mode (the nominal mode of operation, with the inverter stage switched in) and non-inverting mode.

4.3.2 Studying the Recovery of the APV25

Trigger bursts were generated for each particle trigger provided by the upstream counter, with each burst consisting of ten consecutive triggers spaced by 75 ns.

\(^3\)Object-orientated Reconstruction for CMS Analysis
Additionally, the APV25 chips were operated in multi-mode, for which the APV25 outputs peak-sampled data from three consecutive 40 MHz clock cycles for each trigger received. This configuration of triggers and APV25 settings provided data every 25 ns for 750 ns, allowing a sample of data to be collected from which the behaviour of APV25 chips affected by highly ionising events could be studied.

The trigger pre-filter was applied before each trigger burst to remove any bias introduced by highly ionising events occurring prior to the particle trigger. Additionally, a particle veto was applied using the downstream scintillator counter (i.e. anti-coincidence between the upstream and downstream counters) in order to enrich the sample of highly ionising events (as it was presumed that the identity of the incident particle inducing the particle trigger would be lost and secondaries would be few and either short range or scattered away from the beam direction).

The different clock frequencies for the M1 beamline and the readout system ensured that any signal observed was only correctly sampled every 100 ns during the 750 ns time internal. Intermediate samples were out-of-time by up to 10 ns, but no significant effect on the hit reconstruction efficiency is observed, due to the peak-mode operation of the APV25 chips and the excellent signal-to-noise performance of the readout chain observed during the beam test.

### 4.3.3 Trigger Rates and Data Pool

The trigger rates observed during data-taking were limited by the performance of the data acquisition system. The data throughput of the FED-PMC card and the fast ethernet connection were 132 MB s$^{-1}$ and 100 Mbit s$^{-1}$ respectively, but the limiting component in the data acquisition chain was writing data to disk. Tests carried out prior to the PSI beam test showed that the maximum achievable rate was $\sim$2 MB s$^{-1}$. Comparable performances were achieved during the beam test.

For every triggered event, the 48 APV25 chips each generated a data frame consisting of 140 analogue samples. Each sample was digitised and packed into 2 bytes, resulting in 13.4 kB of data per event. Assuming a maximum data rate of 2 MB s$^{-1}$, the average single trigger rate was therefore constrained to below $\sim$150 Hz.

---

$^4$Each frame consists of data from 128 channels and a 12-bit digital header.
Table 4.2: Summary of statistics used in the analysis. $N_{trigs}$ is the number of triggered events (or trigger bursts) in the data sample. $N_{dead}$ is the estimated number of deadtime-inducing highly ionising events in the sample.

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Beam</th>
<th>Data Pool [GB]</th>
<th>$N_{trigs} \times 10^5$</th>
<th>$N_{dead} \times 10^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>$\pi^-$</td>
<td>30.8</td>
<td>19.5</td>
<td>10.6</td>
</tr>
<tr>
<td>Single</td>
<td>$\pi^+$</td>
<td>19.9</td>
<td>12.6</td>
<td>6.9</td>
</tr>
<tr>
<td>Single</td>
<td>$p$</td>
<td>1.8</td>
<td>1.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Burst</td>
<td>$\pi^-$</td>
<td>31.6</td>
<td>0.7</td>
<td>$&gt;0.4$</td>
</tr>
</tbody>
</table>

In the case of trigger bursts, the ‘event size’ per trigger burst was increased by a factor 30 to 403 kB, thus the average rate of particle triggers resulting in a trigger burst was limited to a few Hertz.

Large statistics were collected during the beam test. The analysis described in chapters 5 and 6 is based on the statistics summarised in table 4.2 (and listed in detail in appendix C). In single-trigger mode, $N_{trigs}$ and $N_{dead}$ represent the number of triggered events in each data sample and the estimated number of events in which deadtime is observed, respectively. The estimation of $N_{dead}$ assumes unit pion multiplicity (each triggered event must contain at least one pion and the intensity was low) and the probability of observing deadtime in an APV25 chip to be $5 \cdot 10^{-4}$ per 300 MeV/c pion incident on 500 μm of silicon. In trigger-burst mode, $N_{trigs}$ and $N_{dead}$ represent the number of trigger bursts in the data sample and the number of deadtime-inducing highly ionising events coincident in time with the particle trigger. $N_{dead}$ is likely to be significantly higher than the quoted value due to the sample enrichment as a result of the downstream particle veto. Further highly ionising events are also observed throughout the trigger bursts.

### 4.4 R2 Analysis Software

The R2 analysis software, written specifically for the PSI beam test, was developed within the ORCA Tracker/ApvAnalysisConcrete and TestBeams/TkPSIMay2002 packages [112]. The analysis was used to provide the “quasi-online” analysis during the beam test and, with modifications and improvements, a subsequent detailed data analysis.
Figure 4.4: A schematic of the relationships between the various classes found in the ApvAnalysis library.

The ApvAnalysisConcrete package provides the various calibration algorithms necessary to quantify the contributions to the raw data obtained from the readout system; these include channel pedestals, common mode, noise and signal. The ApvAnalysisConcrete package is based on the ApvAnalysis package, which provides a software framework in the form of virtual C++ classes, from which all concrete implementations of the calibration classes must inherit. Figure 4.4 shows the relationships between the various classes found in the ApvAnalysis library. An instance of the ApvAnalysis class is required for each APV25 found in the tracking system. This class provides the interface to the raw data of the appropriate APV25 chip (via the ApvEventReader class) and to the information provided by the concrete
implementations of the various calibration classes, such as channel noise or zero-suppressed data.

The TkPSIMay2002 package provides the top-level analysis software, hit reconstruction algorithms, and histogramming and ntuple-generation classes.

4.4.1 Calibration Algorithms

The R2PedestalCalculator class is the concrete implementation of the TkPedestalCalculator class. The class accumulates raw event data for each of the 128 channels of a given APV25 chip. The channel pedestals are defined to be the median values of the accumulated raw data for each channel, and are of integer type. The pedestal estimate for a channel is seen to converge quickly, typically within 100 events.

The median estimator has been shown to be effective at removing the signal and noise contributions [113] and is a simple and fast algorithm that does not require iterations.\(^5\)

The R2CommonModeCalculator class is the concrete implementation of the TkCommonModeCalculator class. The class provides an estimate of the common mode level for each triggered event, which is defined to be the median value of the pedestal-subtracted data from the 128 channels of an APV25 chip (and so is of integer type).

Again, the median is used as it is insensitive to the presence of signal or noise. This is highlighted by the distribution of common mode levels shown in figure 4.5 (top), estimated from the pedestal-subtracted data of a single APV25 chip instrumenting a sensor exposed to a pion beam. Even with the presence of signal, the mean of the gaussian fit is close to zero at -0.04 ADCCh.\(^6\) The common mode noise, \(\sigma_{cm}\), is defined as the \(\text{rms}\) of the the observed common mode levels; the small value of 0.84 ADCCh highlights the effectiveness of the on-chip common mode subtraction and implies a highly stable baseline.\(^7\)

The median estimator for the common mode level implicitly assumes that all 128 channels of an APV25 chip are affected in a uniform way. Non-uniform shifts

\(^5\)Alternative definitions consist of variants of a mean estimator for the accumulated data, but the mean is sensitive to signal and noise and therefore requires iterations to remove these contributions.

\(^6\)ADC channels or units.

\(^7\)For comparison, the most probable signal of a minimum ionising pion in 500 \(\mu\)m of silicon was observed to be \(\sim\)50 ADCCh.
4.4 R2 Analysis Software

in APV25 channel data have been observed during system tests involving several modules and, as will be shown later, in chips affected by highly ionising events. Therefore, the class also estimates the common mode level for smaller groups of APV25 channels (again using the median estimator). Nominally, the class provides common mode level estimates for eight groups of 16 channels.

The R2NoiseCalculator class is the concrete implementation of the TkNoiseCalculator class. The class accumulates the pedestal- and common mode-subtracted data from each channel of a given APV25 chip for each triggered event. Figure 4.5 (bottom) shows the distribution of pedestal- and common mode-subtracted data obtained from a single APV25 channel. The data are gaussian distributed around a mean of 0.01 ADCch. The rms spread in the data provides a measure of the channel noise, $\sigma_{\text{chan}}$. The distribution has a rms spread of 1.48 ADCch, which is typical of the channel noise levels observed during the beam test.

The class estimates the channel noise from the difference between the median value and the value found at -1$\sigma$ (15.9 %) of the accumulated data. This noise estimator assumes the data for each channel are gaussian distributed and the hit occupancy is not high. The calculator provides floating-point noise values, which are updated regularly.

\textsuperscript{8}The accumulated data are effectively ‘histogrammed’ and linear interpolation is performed within the ‘bins’ to provide better precision.
The convergence of the noise estimates for 128 APV25 channels is highlighted in figure 4.6, which plots the change in the noise estimate for each channel every ten events. The estimates converge to within 1\% after \sim 500 events.

The \textit{R2ApvMask} class is the concrete implementation of the \textit{TkApvMask} class. The class flags channels that are defined to be noisy or dead. Loose thresholds are used to flag channels that are outside an acceptable range. Additionally, channels that exhibit a noise value greater than $\pm 3\sigma$ from the mean noise value, which calculated from the noise values within the acceptable range, are also flagged as being noisy or dead (depending on the channel noise relative to the mean value).

### 4.4.2 Hit Reconstruction

The \textit{R2Clusterizer} class, found in the \textit{TkPSIMay2002} package, is used to reconstruct hits left by particles traversing the silicon sensors. The class performs clusterisation at the module level and so requires the pedestal- and common mode-subtracted data and channel noise data for all 512 channels of a sensor plane. The clusteriser is based on an algorithm proposed in the Tracker TDR [114].

A hit, or ‘cluster’, is defined as a number of contiguous channels with a signal-to-noise ($S/N$) ratio greater than the threshold, $T_{\text{strip}}$, providing that: (1) the channel with the largest signal, known as the seed strip, has a $S/N$ ratio greater than the threshold, $T_{\text{seed}}$; (2) the cluster has an overall $S/N$ ratio greater than the threshold, $T_{\text{clu}}$.\textsuperscript{9} The nominal values of $T_{\text{strip}}$, $T_{\text{seed}}$ and $T_{\text{clu}}$ are 2, 3 and 5, respectively. Information for each reconstructed hit is recorded, including cluster signal, cluster noise, seed strip signal, position and cluster width.

### 4.4.3 Data Storage with Ntuples

Relevant data provided by the R2 analysis software are written to a data structure (known as an ntuple) for each event using the \textit{R2Ntuple} class, found in the \textit{TkPSIMay2002} package. The data can then be further analysed using the PAW analysis package [115]. The ntuple structure is outlined in appendix D and briefly described below.

\textsuperscript{9}The overall $S/N$ ratio is defined by ratio of the total signal and noise contributions of all the individual channels associated with a cluster.
Information general to an event includes scalars used to identify the event, such as run, spill, trigger counter and bunch crossing numbers. For data collected with trigger bursts, an additional scalar identifies the time of each ‘event’ within a trigger burst. Information specific to individual APV25 chips is also provided; the most important are the common mode levels and a variable that characterises the $rms$ spread in the raw channel data of a given APV25 chip. The decoded pipeline column address for each APV25 chip is also provided, to allow checks on the synchronisation of the readout system. Information describing the reconstructed hits in each sensor plane are also provided and, under certain circumstances (as determined by the top-level analysis software), raw channel data, channel pedestals and channel noise are provided for all 6144 readout channels of the tracking system.

The information written to the ntuplet is dependent on the trigger mode. All the information described above is recorded, except the various channel data, when operating in single-trigger mode. For data taken with trigger bursts, the top-level analysis searches for highly ionising event candidates within each event of a trigger burst. Data are recorded for events identified as containing a highly ionising event candidate, along with all subsequent events of that trigger burst. Channel data are also recorded to allow a detailed study of the behaviour of the APV25 chip during recovery.

4.5 Data Quality and Readout Performance

4.5.1 Event Filter

The tracking unit and data acquisition were highly performant, but problems were occasionally observed. The ‘event filter’ is a simple software algorithm designed to identify events for which problems were observed and remove them from the data samples.

The most frequently observed problem was loss of synchronisation in the front-end electronics, identified by differences in the pipeline addresses of the 48 APV25 chips for a given triggered event. The rate of loss of synchronisation was small, typically $\ll 1\%$. A further problem was related to incorrect sampling of the APV25

\footnote{This variable, known as $\sigma_{raw}$, is defined in chapter 5.}
analogue data by the FED-PMC cards. Data from groups of four modules (instrumented by the same FED-PMC) are seen to exhibit a saw-tooth pattern, as illustrated in figure 4.7. As a consequence, non-zero common mode levels and large numbers of (unphysical) hits with large signals are reconstructed by the analysis software. Such behaviour can therefore simulate a highly ionising event, which is identified in terms of negative common mode levels and large signals. These problematic events are easily identified due to large numbers of clusters being reconstructed in several sensor planes; they are removed by the event filter. Figure 4.8 shows the distributions of cluster multiplicity per plane (top) and common mode levels (bottom), before the event filter is applied to a data sample (black line) and after (red solid). Events with large cluster multiplicities and negative common mode levels are removed; the tail at negative common mode values observed in the filtered data is due to highly ionising events.

### 4.5.2 Signal and Noise Performance

The quality of the readout system can be assessed in terms of its signal and noise performance. The noise levels associated with the 6144 readout channels of the twelve sensor planes are plotted in figure 4.9. The typical channel noise level is $\sim 1.5 \text{ ADCch}$. Several channels instrumented by the first three APV25 chips of the
first TIB plane (looking left to right) and the first two APV25 chips of the third TIB plane exhibit very large noise values and so data from these chips are not used in the analysis.

Figure 4.10 shows the distribution of signal associated with reconstructed clusters in each sensor plane. The most probable signal collected by the TEC and TOB modules, with 500 \( \mu \)m-thick sensors, is 40–50 ADCch. The most probable signal observed in the second TIB plane, with a 320 \( \mu \)m-thick sensor, is \(~30\) ADCch. The distributions for the first and third TIB sensors planes are dominated by noise contributions. The different inverter resistor values used to equip the twelve modules are also listed in the figure.

### 4.6 Complementary Studies

Further studies have been performed since the PSI beam test to complement the studies described in chapters 3 to 6. The studies are briefly described below and
the pertinent results are reported in the appropriate places in the following two chapters.

4.6.1 X5 Beam Test, August 2002

Perhaps the only negative point to arise from the PSI beam test is that no data were collected with the APV25 chips operating in deconvolution mode, the nominal mode of operation. With this in mind, data were collected during a further beam test in August 2002, again using the 25 ns bunched pion beam provided by the X5 beamline. Data were collected with both single triggers and trigger bursts,\footnote{The trigger bursts comprised ten triggers spaced by 75 ns and the APV25 chips were operated in peak or deconvolution mode; hence data were only available every 75 ns for 750 ns.} as at PSI, but the APV25 chips instrumenting the (seven) sensor planes were operated in both peak and deconvolution modes, as well as inverting and non-inverting modes. Unfortunately, problems were again encountered that prevented an accurate ‘timing-in’ to the observed signals. Thus, the track-based method of measuring inefficiencies (described in chapter 5) could not be performed. Even so, some useful information was obtained from the collected data. Details and results of the analysis of the beam test data are described in \cite{116}.

4.6.2 Laser Studies

Highly ionising events were simulated in the laboratory by focussing a high-powered laser onto a small region of a sensor instrumented by APV25 chips \cite{117}. The generated signals were well calibrated, thus allowing a study of the response of the APV25 chip to a range of (known) signals collected by a sensor.

4.7 Summary

The PSI beam test provided a dedicated study of the effect of highly ionising events on the Tracker readout chain. Several milestones were achieved during the test: it was the largest CMS tracking system assembled to date with 6144 detector channels, the majority of which were highly performant; prototypes of the final-version control and data acquisitions software environments were successfully implemented, and
stable operating conditions were achieved for long periods of time; and special trigger logic was designed and used to provide suitable data samples for the study of highly ionising events.

Large samples of quality data were collected for subsequent analysis; the analysis of data collected using trigger bursts is presented in chapter 5, and the analysis of data collected in single trigger mode is presented in chapter 6.
Chapter 5

The APV25 Response to Highly Ionising Events

This chapter reports the analysis of beam test data acquired with trigger bursts, as described in chapter 4. The trigger-burst data allow a detailed study of the behaviour of APV25 chips affected by highly ionising events over an extended period of time.

5.1 Identifying Highly Ionising Events

As shown by the studies reported in chapter 3, highly ionising events are identifiable due to their ability to induce large signals and ‘common mode’ shifts in the data of affected APV25 chips. Hence, each APV25 chip that exhibits a common mode level of $CM \leq -20$ ADCch\textsuperscript{1} during the 750 ns temporal windows provided by the trigger-burst data is flagged as a highly ionising event candidate. The behaviour of these chips is studied throughout the temporal windows provided by the trigger bursts. The various aspects of the APV25 behaviour, such as the temporal evolution of signal, common mode levels and hit reconstruction efficiency, are reported in this chapter.

5.1.1 General Characteristics

The behaviour of the APV25 chip in response to a highly ionising event is illustrated by figure 5.1; the four plots show pedestal-subtracted data obtained from the six

\textsuperscript{1}ADC channels or units.
TOB modules at four different time intervals during a trigger burst.\(^2\)

Evidence for the highly ionising event is first observed at \(T_{\text{event}} = 300\) ns (top-left plot). As a consequence of an incident particle experiencing a nuclear interaction in the fifth sensor plane, large signals are observed in several consecutive channels; the remaining channel data of the affected APV25 chip exhibit (small) negative shifts. At this time, there is no evidence (in terms of signal) for the particle responsible for the nuclear interaction in the upstream sensor planes.

At \(T_{\text{event}} = 350\) ns (top-right), the data from the affected APV25 chip again exhibit large signals in several adjacent channels and the levels of all remaining channels are suppressed to the lower limit of the available dynamic range.\(^3\) This shift in the data, relative to the nominal pedestal positions, is interpreted by the analysis software as a negative common mode level (of \(-125\) ADCch). Furthermore, the signals induced in the upstream sensor planes by the (minimum-ionising) incident particle are observed to reach their peak values. For the purposes of this analysis, particle \textit{tracks} are associated with the event in which their signals are observed to peak. For the case when the incident particle experiences a nuclear interaction, this also defines the time of the highly ionising event; hence, for the example shown in the figure, \(T_{\text{trk}} = T_{\text{hie}} = 350\) ns. In actuality, the time of the particle crossing and highly ionising event is 50 ns earlier.\(^4\) The presence of signal at the (actual) time of the nuclear interaction, at \(T_{\text{event}} = 300\) ns, is due to large signals being sampled into the APV25 pipeline memory throughout the duration of the nominal CR-RC pulse shape period, including during the 50 ns risetime, such is the magnitude of the energy deposition induced by the highly ionising event.

At \(T_{\text{event}} = 525\) ns (bottom-left), the data of the affected chip remain suppressed at the lower limit of the dynamic range. A minimum ionising particle is seen to traverse all six sensor planes. It is clear that the MIP passed through the region of the fifth sensor plane instrumented by the affected APV25, but no signal is observed. At \(T_{\text{event}} = 575\) ns (bottom-right), a further MIP traverses the tracking system, but

\(^2\)Alternatively, raw data could be plotted, but the behaviour of the chip is more clearly shown with pedestal-subtracted data.

\(^3\)Note that the plots show pedestal-subtracted data and so the suppressed channel data of the affected APV25 are not flat, as would be the case if the raw data were plotted.

\(^4\)The delay is accounted for by the multi-mode readout of the APV25 chips and the 50 ns risetime of the CR-RC pulse shape.
Figure 5.1: An example of a highly ionising event and the subsequent inefficient behaviour of the affected APV25 chip. The plots show pedestal-subtracted data obtained from the six TOB modules at four different time intervals.
again no signal is observed in the affected chip, even though the channel levels appear to have recovered somewhat towards their nominal positions. This period of insensitivity, or deadtime, has important consequences for the performance of the Tracker readout system (in terms of hit reconstruction efficiency).

5.1.2 Identifying Deadtime

As illustrated by figure 5.1, highly ionising events generate large signals that act to suppress the output of all channels (not collecting the signal) of the affected APV25 chip; increasingly large energy depositions result in increasingly shifted baselines. Sufficiently large signals are observed to fully suppress the output of the APV25 channels to the lower limit of the APV25 dynamic range and induce deadtime in the chip, as evidenced by the X5 analysis (see section 3.4) and the laboratory studies (see figure 3.5, p. 81). When the baseline is fully suppressed, the spread in the raw channel data due to the pedestal structure observed during normal operation of an APV25 chip is also suppressed. This spread, $\sigma_{\text{raw}}$, is defined by the (truncated) $\text{rms}$ spread of the raw data excluding those channels with the lowest 5% and highest 25% of levels (in order to remove the contribution of signal and noisy or dead strips).

Figure 5.2 highlights the relationship between the $\sigma_{\text{raw}}$ values and common mode levels, CM, reconstructed from channel data of a single APV25 chip. The pedestal

**Figure 5.2:** Truncated $\text{rms}$ spread in raw channel data, $\sigma_{\text{raw}}$, as a function of common mode level, CM. (The box size is representative of the number of bin entries.)

**Figure 5.3:** (top) Truncated $\text{rms}$ spread in raw channel data, $\sigma_{\text{raw}}$. (bottom) Distribution of common mode levels, CM.
structure observed during normal operation ensures that $\sigma_{\text{raw}}$ is typically a few ADCch, as seen at common mode levels of $\sim$0 ADCch. With increasingly negative common mode levels, larger values of $\sigma_{\text{raw}}$ are observed as a result of ‘non-flat baselines’ (see section 5.2). For the most negative common mode levels, when the channel data are suppressed to the lower limit of the APV25 dynamic range, small values of $\sigma_{\text{raw}}$ are observed, typically less than 1 ADCch. Figure 5.3 further highlights this behaviour by showing the distributions of $\sigma_{\text{raw}}$ (top) and common mode levels (bottom) reconstructed from data of a single APV25 chip. The $\sigma_{\text{raw}}$ distribution displays two distinct populations: the strong peak at $\sim$1.6 ADCch is due to the spread in the nominal pedestal levels observed during normal operation; values of $\sigma_{\text{raw}} < 1$ ADCch are observed when the pedestal structure is fully suppressed. The long tail is due to non-flat baselines. The common mode distribution is characterised by a strong narrow peak at 0 ADCch and a tail at negative values. These features are a consequence of the biasing scheme used to power the APV25 amplifying stages; the scheme provides efficient on-chip common mode rejection under normal operating conditions and a crosstalk path when the chip is under the influence of large signals generated by highly ionising events (described in section 3.2). The entries highlighted in red are common mode levels observed when the condition $\sigma_{\text{raw}} < 1$ ADCch is satisfied, proving that the pedestal structure is only suppressed when the channel data are shifted to the lower limit of the APV25 dynamic range. The mean common mode level for these entries is -100.6 ADCch, which provides an estimate of the minimum observable common mode level, CM$_{\text{min}}$, for this particular APV25 chip.$^5$

The $\sigma_{\text{raw}}$ variable allows to differentiate between highly ionising events that are strong candidates for inducing deadtime in the APV25 and those that are not, as well as providing a method to identify APV25 chips exhibiting deadtime on an event-to-event basis.$^6$ APV25 chips identified as exhibiting ‘fully suppressed’ baselines (and therefore likely to be experiencing deadtime) are required to satisfy $\sigma_{\text{raw}} < 1$ ADCch. Chips with only ‘partially suppressed’ baselines (which are thought to be sensitive

$^5$The value of CM$_{\text{min}}$ is defined by the position of the lower limit of the dynamic range relative to the pedestal levels, as shown in figure 3.14 (p. 89).

$^6$Characterising the APV25 sensitivity to signal in terms of the $\sigma_{\text{raw}}$ variable is the analogue of using the peak-to-peak variable, $\Delta_{\text{raw}}$, to identify deadtime in the X5 analysis (see section 3.4).
5.1 Identifying Highly Ionising Events

5.1.3 ‘Timing-in’ and the Evolution of Signal

Particle crossings, and therefore highly ionising events, are not just coincident in time with the particle trigger of each trigger burst, but are observed throughout the 750 ns temporal window provided by each trigger burst. Therefore, some method of ‘timing-in’ to the highly ionising events is required. The occurrence of a highly ionising event implies that the signal induced by a minimum ionising particle should be observed in the sensor upstream to the one in which the nuclear interaction takes place. Figure 5.4 plots the position of MIP signals observed in the upstream sensor plane relative to the position of the cluster identified as containing the signal induced by the highly ionising event (see below for description of method used to identify this signal). Hence, a mean ‘residual’ of -0.68 mm/plane (with a rms spread of 0.90 mm/plane) is observed, which corresponds to a mean beam incidence angle of 0.014 rads from the normal, with a \( \sigma_{\text{raw}} \) spread of 0.018 rads.\(^7\) If a MIP signal is observed within \( \pm 3\sigma \) of this mean, the peaking time of the MIP signal is used to

\(^7\)This is in good agreement with the mean incidence angle of reconstructed tracks, see figure 5.20 (p. 137). The sensor planes were spaced by \( \sim 50 \) mm.
5.1 Identifying Highly Ionising Events

define the time of the highly ionising event, $T_{\text{hie}}$. If no MIP signal is observed, an alternate method of ‘timing-in’ to the highly ionising event is required.

The energy depositions generated by highly ionising events induce large signals in typically five or six adjacent APV25 channels. Hence, the resulting clusters, as reconstructed by the analysis software, characteristically have large seed-strip signals and widths of a few channels. In addition, chips affected by highly ionising events frequently exhibit non-flat baselines, leading to the reconstruction of non-physical hits (see section 5.2). These ‘fake’ clusters can also have large signals and are frequently wide, typically tens of channels, but the signal contained in the seed-strip is generally small. Hence, the cluster with the largest seed-strip signal is identified to be the one containing the signal generated by the highly ionising event, known as the HIE signal.

The evolution of the HIE signal for each HIE candidate can be followed throughout the trigger burst by summing the signal (of either polarity) observed in all channels located within a window of ±5 channels around the position of the HIE signal (i.e. no clusterisation is performed). Figure 5.5 plots the temporal evolution of this sum, $S_{\text{window}}$, for individual highly ionising events (red markers). The temporal evolution of the mean signal sum, $\langle S_{\text{window}} \rangle$, is superimposed on the plot (black squares). The recovery period of those channels collecting the HIE signal is clearly long; signals of $|S_{\text{window}}| > 100$ ADCch are not uncommon even 600 ns after $T_{\text{hie}}$. The negative values of $S_{\text{window}}$ observed at $\Delta T \geq 100$ ns imply that the affected channels are suppressed in relation to all other channels; this is confirmed by visual inspection of the data. At $\Delta T = 0$ ns, $\langle S_{\text{window}} \rangle \approx 600$ ADCch. Note that the largest value of $\langle S_{\text{window}} \rangle$ is observed at $\Delta T = -25$ ns.

The peaking times of the HIE seed-strip signal, the HIE total (cluster) signal and the upstream MIP signal (if observed), are identified for each individual highly ionising event. The peaking times of the seed-strip signal and total signal are observed to precede the peaking time of the upstream MIP signal by mean time intervals of $16.6 \pm 29.4$ ns and $23.3 \pm 28.2$ ns, respectively.

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8 It is convenient to identify the time of each event within a trigger burst, $T_{\text{event}}$, relative to the time of the event with which the highly ionising event is associated, $T_{\text{hie}}$. Therefore,
5.1 Identifying Highly Ionising Events

![Graphs showing distributions of seed and cluster signals](image)

**Figure 5.6:** (top) Seed-strip signal, $S_{\text{seed}}$, and (bottom) total signal, $S_{\text{clu}}$, of clusters identified as the HIE signal.

**Figure 5.7:** (top) Seed-strip signal and (bottom) total cluster signal as a function of common mode level.

Figure 5.6 shows the distributions of the HIE seed-strip signal, $S_{\text{seed}}$, (top) and the HIE total signal, $S_{\text{clu}}$, (bottom) at the peaking time of the seed-strip signal. The $S_{\text{seed}}$ distribution highlights the fact that essentially all significant common mode shifts (i.e. CM \( \leq -20 \text{ ADCch} \)) are accompanied by a cluster exhibiting a seed-strip signal of \( \geq 150 \text{ ADCch} \). The mean seed-strip signal is 248 ADCch, equivalent to 5.5 MIPs (in 500 \( \mu \text{m} \) of silicon). The seed-strip signals are frequently truncated by the limited APV25 dynamic range, hence the $S_{\text{seed}}$ distribution is curtailed at \( \sim 320 \text{ ADCch} \).

A candidate highly ionising event is identified as a genuine highly ionising event if the following criteria are satisfied: data from the affected APV25 chip are required to exhibit both a common mode level of CM \( \leq -20 \text{ ADCch} \) and a seed-strip signal of $S_{\text{seed}} \geq 125 \text{ ADCch}$ at some point during the APV25 recovery period. The seed-strip threshold is required to suppress effects that may fake a highly ionising event, such as an external noise manifest in the data as a non-zero (negative) common mode level. More importantly, the threshold is required to suppress the contribution of ‘out-of-time’ highly ionising events when operating in single-trigger mode.\(^{11}\)

\[ \Delta T = T_{\text{event}} - T_{\text{hie}}. \]

For example, $S_{\text{window}}$ is plotted as a function of $\Delta T$ in figure 5.5.

\(^9\)For comparison, the mean signal induced by minimum ionising pions in the 500 \( \mu \text{m} \)-thick TOB sensors is \( \sim 45 \text{ ADCch} \).

\(^{10}\)These mean separations are provided by distributions of the difference in the peaking times of the various signals.

\(^{11}\)‘Out-of-time’ highly ionising events are observed in single-trigger mode due to the limited...
The mean total cluster signal, $\langle S_{clu} \rangle$, is observed to be $\sim 770$ ADCch, equivalent to $\sim 17$ MIPs in 500 $\mu$m of silicon. The $S_{clu}$ distribution provides no clear indication of a lower threshold on the magnitude of the total signal generated by a highly ionising event. This is essentially because clusters with relatively large signals can be reconstructed due to non-flat baselines and these clusters mask to some extent the true distribution of signals induced by highly ionising events.

The relationship between signal magnitude and common mode level is shown in figure 5.7. Increasingly negative common mode levels are observed for larger values of both $S_{seed}$ and $S_{clu}$. Although the value of $S_{seed}$ is limited by the available dynamic range, shifted baselines effectively increase the available range and so truncation occurs at larger values of $S_{seed}$. The threshold of $S_{seed} \geq 125$ ADCch is valid for all values of common mode below -20 ADCch.

### 5.1.4 Evolution of the APV25 Baseline

The temporal evolution of the APV25 baseline in response to a highly ionising event is illustrated by figure 5.8, which plots the common mode level, CM, as a function of time relative to the highly ionising event, $\Delta T$. The baseline evolution for two different classes of highly ionising event are highlighted: those that fully suppress the APV25 baseline and satisfy $\sigma_{raw} < 1$ ADCch (red circles); and those that only partially suppress the baseline, satisfying $\sigma_{raw} \geq 1$ ADCch (black squares). The minimum observable common mode level, $CM_{min}$, is highlighted by the dotted line.

Baselines that are fully suppressed at the lower limit of the dynamic range frequently remain so for up to $\sim 250$ ns. Furthermore, the baseline recovery frequently overshoots the nominal pedestal levels, resulting in a positive common mode swing. For highly ionising events that induce only partially suppressed baselines, the recovery is much quicker and little baseline overshoot is seen. These behaviours are typical for most of the APV25 chips. A few exceptions show anomalous behaviour and fully suppressed baselines are never observed; chips exhibiting such behaviour coverage provided by the upstream scintillator counter. Note that a relatively loose seed-strip threshold is used, as the peaking time of the HIE seed-strip signal precedes the trigger time (which is coincident with the MIP peaking-time) by $16.6 \pm 29.4$ ns.
are excluded from the analysis.\textsuperscript{12}

The common mode shift induced by the highly ionising event, $CM_{hie}$, is identified to be the lowest common mode level observed during the APV25 recovery. The time at which this $CM_{hie}$ level is observed is delayed with respect to the peaking time of the upstream MIP signal (when present) by $8.3 \pm 28.6$ ns. If no MIP signal is observed in the upstream sensor plane, the time at which $CM_{hie}$ is observed is used to define the time of the highly ionising event, $T_{hie}$.

As highlighted by figure 5.8, the common mode level, $CM$, is limited by the APV25 dynamic range to a value greater than $CM_{min}$. The baseline position can be expressed in terms of the common mode level relative to the minimum observable level, $CM_{min}$, as shown by equation 5.1.

$$CM_{ratio} = \frac{CM}{|CM_{min}|} \quad (5.1)$$

With this definition, $CM_{ratio} = -1$ implies a baseline at the lower limit of the APV25 dynamic range. This ratio allows easy comparison of baseline behaviours between APV25 chips with different pedestal levels.

The $CM_{ratio}$ variable is used to highlight the effect of the inverter resistor value on the baseline evolution following a highly ionising event in figure 5.9. The figure

\textsuperscript{12}These chips also exhibit unusually large inefficiencies following a highly ionising event, even though the baseline is only partially suppressed. These excluded APV25 chips are numbered 29, 34, 35, 43 and 47.
5.1 Identifying Highly Ionising Events

Figure 5.10: Number of highly ionising events as a function of APV number (top) and $T_{\text{event}}$ (bottom). See text for explanation of highlighted entries.

Figure 5.11: Number of highly ionising events identified per event (top) and trigger burst (bottom).

shows the temporal evolution of the mean value of $CM_{\text{ratio}}$ for highly ionising events that partially (top) or fully (bottom) suppress the APV25 baseline. For both classes of highly ionising events, the baseline evolution is shown for modules equipped with 100 $\Omega$ (closed markers) and 50 $\Omega$ (open markers) inverter resistors. There is clearly some reduction in the duration of the recovery period when the modules are equipped with 50 $\Omega$ resistors, especially for highly ionising events that induce fully suppressed baselines. The mean baseline position is observed to remain at or near the lower limit of the dynamic range ($CM_{\text{ratio}} = -1$) for up to ~100 ns with modules equipped with 100 $\Omega$ resistors; this is shortened to ~50 ns for the 50 $\Omega$ case.

An analysis of beam test data collected during the X5 test of August 2002 (as outlined in section 4.6) reveals that comparable periods of baseline suppression (200-300 ns) were observed when the APV25 chips were operated in both peak and deconvolution modes [116].

5.1.5 Highly Ionising Event Statistics

Figures 5.10 and 5.11 summarise the highly ionising event statistics identified in the trigger-burst data; the sample of highly ionising events is defined by the selection criteria $CM_{\text{hie}} \leq -20$ ADCch and $S_{\text{seed}} > 125$ ADCch.

Figure 5.10 (top) plots the number of identified highly ionising events as a function of APV25 chip number; the (repetitive) variation in statistics across groups of
5.2 Baseline Distortions

Four chips is due to the partial coverage of the sensor planes provided by the upstream scintillator. The numbers of highly ionising events for which a MIP signal is identified in the upstream sensor are highlighted (red bars); a MIP signal is identified for \( \sim 60\% \) of the highly ionising events identified in the TOB sensor planes.

Figure 5.10 (bottom) shows the distribution of highly ionising events within the temporal windows provided by the trigger bursts. The majority of highly ionising events are coincident in time with the particle trigger and, as a result of the fixed trigger latency, are observed at 75-100 ns.\(^\text{13}\) Further highly ionising events are observed throughout the trigger bursts due to the finite probability of further beam particles arriving earlier/later than the particle trigger. Entries highlighted by the dashed line are highly ionising events identified as occurring in the first or last event of a trigger burst; these highly ionising events are not used in the analysis as their timing cannot be guaranteed.

Figure 5.11 shows the distributions of the numbers of highly ionising events identified in the same event (top) and trigger burst (bottom).

5.2 Baseline Distortions

Close examination of the trigger-burst data revealed that the channels of a chip under the influence of a highly ionising event are frequently affected in a non-uniform way. The data of the 128 APV25 channels are suppressed by varying degrees, especially when a highly ionising event only partially suppresses the baseline. Furthermore, channels are frequently seen to recover at different rates. These effects result in ‘non-flat’ baselines.

This has consequences for the proposed firmware algorithms of the Front-End Driver card, which perform the zero-suppression of the APV25 channel data before the (reduced) data volume is transmitted from the FED card to the DAQ farm via the S-Link, as described in chapter 1. Presently, the common mode level is estimated from the median value of the 128 channel data of an APV25 chip; this implicitly assumes that the common mode is uniform across all channels of an APV25. The beam

\[ T_{\text{event}} = 75 \text{ ns}. \]  
The ‘secondary’ peak observed at \( \sim 350 \text{ ns} \) is due to data collected before the trigger latency was tuned.
5.2 Baseline Distortions

Figure 5.12: Example recovery of an APV25 chip. Pedestal-subtracted data are plotted as a function of channel number.

Figure 5.13: Example recovery of an APV25 chip. Pedestal- and common mode-subtracted data versus channel number.

test data clearly show that the shifts due to highly ionising events are frequently non-uniform, thus the present method of estimating the common mode level could result in ‘fake’ clusters and/or further inefficiencies.

5.2.1 Baseline Recovery

Figure 5.12 shows the evolution of the pedestal-subtracted channel data obtained from a single APV25 chip affected by a highly ionising event. The channel data are provided every 50 ns from the time of the highly ionising event, \( \Delta T = 0 \) ns, to \( \Delta T = 450 \) ns. The horizontal dashed line shown in each plot represents the median common mode estimate. Figure 5.13 shows the pedestal- and common mode-subtracted channel data from the same chip, over the same time interval. The dashed line shown in each plot represents the threshold used by the FED zero-suppression algorithm to identify signal (twice the channel noise).
5.2 Baseline Distortions

At $\Delta T = 0$ ns, large signals are observed in several adjacent channels and the data of all the other channels are shifted to below the nominal pedestal levels. Importantly, the shifts in the channel data are not uniform across the chip and a sloping baseline is observed. The pedestal-subtracted data in channels 80-127 are significantly above the common mode estimate; therefore, the pedestal- and common mode-subtracted data are above the signal thresholds, as seen in figure 5.13, resulting in the reconstruction of a large, wide non-physical cluster. The small spike observed in channel 54 is due to a minimum ionising particle that is coincident in time with the highly ionising event. However, no cluster is reconstructed as the signal does not exceed the signal threshold for that channel. The large signals induced by the highly ionising event persist for up to $\sim 200$ ns, providing a source of pile-up, before shifting negative relative to all the other channels. This has the effect of biasing the common mode estimate to lower values, which in turn enhances the ‘signal’ content of all the other channels. This leads to the reconstruction of further ‘fake’ clusters, as for channels 0-20 during the time interval $\Delta T = 250$ ns to $\Delta T = 450$ ns.

Figure 5.14 (top) plots the pedestal-subtracted channel data shown at $\Delta T = 0$ ns in figure 5.12, but with the ‘global’ common mode estimate (dotted line) and the ‘grouped’ common mode estimates (dashed line) superimposed. The ‘grouped’ CM$_{16}$ estimator is clearly superior to the ‘global’ CM$_{128}$ estimator. Figure 5.14

14See section 4.4.1 for a description of the two common mode estimators, CM$_{128}$ and CM$_{16}$. 
5.2 Baseline Distortions

(bottom) plots the channel data from the same chip and time interval, after pedestal- and common mode-subtraction using the grouped CM\textsubscript{16} estimator. The dashed line highlights the signal thresholds (again, twice the channel noise). The signal observed in channel 54 due to a minimum ionising particle is now above threshold.

The non-flatness of the baseline, $\sigma_{\text{baseline}}$, can be estimated by the $\text{rms}$ spread in the ‘grouped’ common mode levels CM\textsubscript{16} around the ‘global’ CM\textsubscript{128} value. The temporal evolution of $\sigma_{\text{baseline}}$ is shown in figure 5.15 for chips unaffected (open markers) and affected (closed markers) by highly ionising events. The largest values are observed at or near the time of the highly ionising event, and the baseline non-flatness does not recover to the nominal levels exhibited by unaffected chips within 600 ns after the highly ionising events. This is largely due to the behaviour of the channels collecting the HIE signal, which remain suppressed for several hundred ns. The non-flatness is most pronounced with an inverter resistor value of 50 $\Omega$.

5.2.2 Reconstruction of Fake Clusters

The number of reconstructed ‘fake’ clusters attributable to the effect of highly ionising events on the baseline is assessed by comparing the numbers of clusters reconstructed from data of affected and unaffected APV25 chips. The channel data were zero-suppressed using an algorithm analogous to that proposed for implementation in the FED; pedestal and common mode subtraction were performed, followed by zero-suppression of the data using the thresholds: $T_{\text{strip}} = 2$, $T_{\text{seed}} = 0$ and $T_{\text{clu}} = 5$ (see section 4.4.2 for an explanation of these thresholds). The number of fake clusters, $N_{\text{clusters}}$, and the number of strips associated with these fake clusters (‘fake strips’), $N_{\text{strips}}$, were defined by the difference between the numbers observed in the affected chip and the corresponding (unaffected) chip in the upstream sensor plane.\textsuperscript{15}

Figure 5.16 plots the mean number of fake clusters (top) and fake strips (bottom) as a function of $\Delta T$, for inverter resistor values of 100 $\Omega$ (closed markers) and 50 $\Omega$ (open markers). The ‘global’ (CM\textsubscript{128}) common mode algorithm was used during

\textsuperscript{15}Additionally, the number of fakes were obtained for an unaffected (but not immediately adjacent) chip in the affected sensor plane. The number of fake clusters observed for these unaffected chips were small ($\ll1$) and the results presented here are normalised to these (small) numbers.
the zero-suppression of the channel data. As illustrated above, non-flat baselines are most frequently observed around the time of the highly ionising event, and this is reflected by the increased number of fake clusters and strips around $\Delta T = 0$ ns. Even after 600 ns, the number of fake clusters does not recover to zero. Furthermore, the number of fake clusters and strips is significantly higher for the 50 $\Omega$ case. The effect of using the ‘grouped’ (CM$_{16}$) common mode algorithm on the number of fake cluster and strips is illustrated in figure 5.17; for both resistor values of 100 $\Omega$ and 50 $\Omega$, the number of fake clusters and strips is significantly reduced.

The mean numbers of fake clusters and strips generated by a single highly ionising event for the various combinations of inverter resistor values and common mode algorithms are summarised in table 5.1. The effect is underestimated by this analysis, perhaps by as much as 50 %, as it is clear from the figures that fake clusters will be reconstructed over much longer time intervals than 600 ns, especially when the ‘global’ CM$_{128}$ estimator is used.

An independent study of this effect has been performed [116] on data collected during the PSI beam test and the X5 beam test of August 2002 (as outlined in section 4.6). Comparable numbers were obtained with the PSI data. The X5 data were collected with the APV25 chips operated in deconvolution mode; in this mode of operation, the numbers of fake clusters and strips are a factor 2-3 smaller. This
5.3 Track Reconstruction

The ability to reconstruct tracks allows an investigation into the effect of highly ionising events on the efficiency of hit reconstruction with data obtained from affected APV25 chips (described in section 5.4).

### 5.3.1 The Track-Finding Algorithm

Only the six TOB sensor planes are used during track reconstruction. Track-finding is performed for each individual event of a trigger burst. A simple track-finding algorithm is used, based on a least-squares linear fit to cluster positions, as the particle multiplicities are low and the tracking system is in a zero magnetic field environment. Modules affected by highly ionising events during a particular trigger burst are not considered by the tracking algorithm for the duration of that trigger burst.

A telescope, or ‘region of interest’, is defined by the positions of a pair of clusters found in two seed planes. These seed planes are nominally the first and last (sixth) TOB planes, but if a highly ionising event is observed in first (sixth) plane, then the second (fifth) plane is used instead. All combinations of seed cluster-pairs are considered, providing the resulting telescope passes through all six sensor planes.

The nearest cluster (within a pre-defined window) to the telescope intercept point for each intermediate sensor plane is considered during the track fit.

---

### Table 5.1: Number of fake clusters and strips due to non-flat baselines, for various combinations of inverter resistor values and common mode algorithms.

<table>
<thead>
<tr>
<th>$R_{\text{inv}}$ [$\Omega$]</th>
<th>CM algo.</th>
<th>$\langle N_{\text{clusters}} \rangle$</th>
<th>$\langle N_{\text{strips}} \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>CM$_{128}$</td>
<td>33.9 ± 0.5</td>
<td>190.7 ± 3.2</td>
</tr>
<tr>
<td>50</td>
<td>CM$_{128}$</td>
<td>44.5 ± 0.4</td>
<td>287.0 ± 2.9</td>
</tr>
<tr>
<td>100</td>
<td>CM$_{16}$</td>
<td>18.0 ± 0.3</td>
<td>58.2 ± 0.8</td>
</tr>
<tr>
<td>50</td>
<td>CM$_{16}$</td>
<td>20.5 ± 0.2</td>
<td>57.2 ± 0.6</td>
</tr>
</tbody>
</table>

reduction is attributable to the deconvolution filter, which ‘smoothes’ out the slow time-varying swings observed in the data during recovery.

---

16 The TEC sensors are trapezoidal in design and so would complicate the fitting procedure without improving the tracking performance. The performance of two of the three TIB sensor planes was significantly degraded due to faulty bonding and noisy or dead strips.
A linear fit to the positions of the clusters (including the two ‘seed’ clusters) associated with each telescope is performed; a minimum of four clusters are required by the track fit. The fit quality, defined in terms of the $\chi^2$ probability, determines whether the track candidate is accepted and used in the efficiency studies. If the fit quality is poor (see below for discussion of selection criteria) and the number of clusters associated with the telescope is greater than four, then the cluster exhibiting the largest residual is removed and the fitting procedure is repeated for the remaining clusters. Clusters are uniquely associated with a single track.

The uncertainties used to define the fit arise from the finite cluster size and multiple scattering. The position of single-strip and multiple-strip clusters are assigned errors of $\pm(183 \, \mu m)/2$ and $\pm(183 \, \mu m)/\sqrt{12}$, respectively. The contribution from multiple scattering in $6 \times 500 \, \mu m$ of silicon is significant due to the low pion momentum ($300 \, MeV/c$); it is estimated from the Molière scattering theory [64] to be $\sim 140 \, \mu m$ (see appendix E for discussion), although a value of only $110 \, \mu m$ was added in quadrature to the hit position uncertainties as this provided the best estimate of the total uncertainty based on the $\chi^2$ probability distribution (see below).

Due to the signal pile-up observed when the APV25 chips are operated in multi-mode, ‘identical’ tracks are reconstructed from the same persistent signals for many consecutive events. This pile-up is removed by associating the tracks with a single event, with the ‘time’ of the track defined to be when the mean signal of the track clusters reaches a maximum.

### 5.3.2 Detector Alignment

Before precision tracking can be performed, it is necessary to account for the misalignment of the sensor planes within the tracking system.\(^{17}\) Detector alignment of the six TOB planes is performed in two steps. Firstly, an approximate alignment is performed using clusters. Only events containing a single cluster per sensor plane are used. The ‘seed’ cluster observed in the first plane defines the reference position to which the positions of clusters observed in the subsequent five planes are measured. The mean ‘residual’ observed for each plane provides the necessary

\(^{17}\)Alignment is only performed perpendicular to the strip direction, there is no rotational alignment in the plane of the sensor.
correction. Secondly, a precision alignment is performed using reconstructed tracks. The mean value of the residual distributions for each plane provide the required adjustment; the process is an iterative one and the resulting alignment is better than 1 μm for all six planes, as demonstrated by figure 5.18 (the mean residual is given by the parameter ‘P2’). The tracking resolutions achieved are defined by the rms spread of the distributions (given by parameter ‘P3’); the mean resolution for the six planes is 118 μm.

Figure 5.19 plots the distribution of the signal-to-noise ratio observed for clusters associated with tracks. The Landau fits to the distributions provide estimates for the most-probable signal-to-noise ratios; all six planes exhibit values of $S/N \approx 30$.\textsuperscript{18}

### 5.3.3 Track Statistics

Figure 5.20 and 5.21 summarise the tracks statistics identified in the trigger-burst data. Figure 5.20 (top) shows the distribution of the $\chi^2$ probability, $P(\chi^2)$, which defines the quality of the track fit. The $\chi^2$ probability distribution indicates that the uncertainties associated with the fit are estimated correctly. ‘Good’ tracks are required to satisfy the condition $P(\chi^2) \geq 0.05$, resulting in 23247 tracks reconstructed

---

\textsuperscript{18} These values are in good agreement with the most-probable signal values ($\sim 45$ ADCch) provided by the Landau distributions shown in figure 4.10 (p. 115), assuming a mean channel noise of $\sim 1.5$ ADCch.
from the entire data sample. Of these 23247 tracks, 24 %, 36 % and 40 % are
defined by four, five and six clusters. Figure 5.20 (bottom) shows the
distribution of the slope term used to define the track linear fits. Hence, a mean slope
term of $0.76 \pm 0.91$ mm/plane corresponds to a (mean) beam incidence angle of
$0.015 \pm 0.018$ rads from the normal.

The temporal distribution of tracks within the trigger bursts is shown in
figure 5.21 (top); tracks are most frequently reconstructed in the event providing the
particle trigger ($T_{\text{event}} = 75$ ns), although large statistics are observed throughout
the 750 ns temporal window. The timing of tracks identified as occurring in the first
or last event of a trigger burst (highlighted by the dashed line) cannot be guaranteed
and so are not used in the analysis. Figure 5.21 (bottom) shows the number of tracks
reconstructed per trigger burst; up to nine tracks are reconstructed.

## 5.4 Inefficiencies due to Highly Ionising Events

The effect of highly ionising events on the efficiency of the Tracker readout system
has important consequences for the performance of the Tracker, as inefficiencies
will impact on the ability of the track-finding algorithms to reconstruct tracks. Hit
reconstruction inefficiencies are measured by searching for hits in the affected sensor
planes using reconstructed tracks, as the presence of a track implies that signal
should be observed in the affected plane.
5.4 Inefficiencies due to Highly Ionising Events

Only trigger bursts identified as containing highly ionising events are used in the analysis. For those events within this sample of trigger bursts that contain reconstructed tracks, the channel data of the affected sensor plane(s) are zero-suppressed and cluster reconstruction is performed in order to identify hits present in the data. Track(s) will pass through regions of the sensor(s) instrumented by either: an APV25 chip affected by a highly ionising event; or one of the other unaffected (‘good’) chips of the detector module(s). This defines two samples of tracks, \( N_{\text{trk}}^{\text{hie}} \) and \( N_{\text{trk}}^{\text{good}} \). Tracks pointing towards regions of sensors containing a HIE signal are not used in the analysis.

An efficient APV25 chip is identified by the presence of a reconstructed hit within a window around each track intercept point. The numbers of clusters observed for the two samples of tracks described above are \( N_{\text{hit}}^{\text{hie}} \) and \( N_{\text{hit}}^{\text{good}} \). Hence, the hit reconstruction efficiency is given by the ratio \( N_{\text{hit}}^{\text{hie}}/N_{\text{trk}}^{\text{hie}} \) for both affected and unaffected APV25 chips, \( \varepsilon_{\text{hit}}^{\text{hie}} \) and \( \varepsilon_{\text{hit}}^{\text{good}} \). As both highly ionising events and tracks are identified throughout the temporal windows provided by the trigger bursts, these hit reconstruction efficiencies can be measured as a function of time relative to the highly ionising event, \( \Delta T \).

The temporal evolution of efficiency is studied for two detector configurations (TOB modules equipped with 100 Ω and 50 Ω) and for two different zero-suppression algorithms: the channel data of the affected sensor plane are zero-suppressed using either the ‘global’ (CM\(_{128}\)) common mode estimate or the ‘grouped’ (CM\(_{16}\)) common mode estimates. Clusters (or ‘hits’) are then reconstructed from the zero-suppressed data.

Importantly, efficient behaviour is identified by searching for the seed-strips of clusters within windows around track intercept points. Furthermore, a threshold is imposed on the seed-strip signal-to-noise, \( (S/N)_{\text{seed}} \), rather than on the cluster signal-to-noise ratio, \( (S/N)_{\text{clus}} \). This method of identifying signal is chosen because these efficiency measurements aim to identify inefficiencies solely due to deadtime and non-flat baselines (as highlighted in figure 5.12, p. 130) without being biased by the presence of the ‘fake’ clusters due to non-flat baselines. This method suppresses the bias as follows. Fake clusters can be interpreted as ‘genuine’ signal; hence, a high \( S/N \) threshold for the cluster seed-strip is observed to suppress these wide
5.4 Inefficiencies due to Highly Ionising Events

and flat clusters. Also, MIP signals superimposed on these wide fake clusters may not be identified if the charge-weighted position of the wide fake cluster is located outside the window; defining the cluster position by the seed-strip (and not the charge-weighted) position correctly identifies these MIP signals. The thresholds used to identify signal are: \( T_{\text{strip}} = 3 \), \( T_{\text{seed}} = 10 \) and \( T_{\text{clu}} = 10 \) (see section 4.4.2 for an explanation of these thresholds). Justification for the high \( T_{\text{seed}} \) threshold is provided below.

5.4.1 Effect on Signal Magnitude

The effectiveness of the track-based method to search for signal is highlighted by figure 5.22, which shows the \((S/N)_{\text{max}}\) and \((S/N)_{\text{window}}\) distributions obtained by searching for signal within windows around track intercept points (top and bottom plots, respectively). The \((S/N)_{\text{max}}\) variable is the largest signal-to-noise ratio of a single channel (comparable to the seed-strip \( S/N \) ratio) found within the window around each track intercept point; the \((S/N)_{\text{window}}\) variable is the ratio of the signal and noise totals for all the channels found within the window (i.e. no clusterisation is performed). The distributions were obtained using the sample of tracks, \( N_{\text{trk}}^{\text{good}} \), that pass through sensor planes affected by highly ionising events, but traverse a region of the sensor instrumented by unaffected chips.

A significant signal is observed for essentially all tracks; an efficiency of 98 \% is achieved with the (stringent) condition \((S/N)_{\text{max}} \geq 10\) and a window size of \( \pm 10\sigma \), where \( \sigma \) is the spatial resolution as defined by the track residuals.\(^{19}\) The small (2 \%) inefficiency is due to limitations in the track-finding algorithm and inefficiencies inherent in the readout system, such as noisy or dead channels. The most-probable and mean values of the \((S/N)_{\text{window}}\) distribution (30 ADCch and 35 ADCch, respectively) are in good agreement with those obtained from the signal-to-noise distributions shown in figure 5.19. The comparable values of the most-probable and mean signals implies that the majority of the cluster signal is collected by the ‘seed-strip’ channel.

The effect of highly ionising events on the signal magnitude can also be studied, by using the sample of tracks that traverse regions of sensor planes instrumented

\(^{19}\)This window size is equivalent to approximately 6 strips.
5.4 Inefficiencies due to Highly Ionising Events

by chips that are affected by highly ionising events, $N_{trk}^{hic}$. It is instructive to divide this sample of tracks into two categories; those for which the highly ionising events induce only a partially saturated baseline ($\sigma_{raw} \geq 1$ ADCch) and those that induce a fully saturated baseline ($\sigma_{raw} < 1$ ADCch) during the recovery period of the chip. Figure 5.23 shows the $(S/N)_{window}$ distributions obtained for these two categories.\footnote{These distributions are for APV25 chips using a 100 $\Omega$ inverter resistor.}

For the case of APV25 chips exhibiting partially suppressed baselines (top plot), the most-probable and mean values of $(S/N)_{window}$, as provided by a Landau fit to the distribution, are 29.2 and 34.8, respectively. These values are in good agreement with those provided by fits to the $(S/N)_{window}$ distribution obtained with the $N_{trk}^{good}$ sample of tracks, as highlighted in figure 5.22 (bottom). Hence, the magnitude of MIP signals observed in data of affected APV25 chips for which the baseline is only partially suppressed is not significantly degraded. The distribution obtained for APV25 chips that exhibit fully suppressed baselines at some point during their recovery periods (bottom plot) is significantly shifted to lower values; the most-probable and mean values of $(S/N)_{window}$, as provided by the Landau fit, are 15.1 and 19.3, respectively. Hence, the magnitude of MIP signals is significantly degraded if a highly ionising event induces a fully suppressed baseline at some point during the APV25 recovery.
Table 5.2: Most-probable and mean values of \((S/N)_{\text{window}}\), as provided by Landau fits to the distributions, obtained from APV25 chips equipped with 100 \(\Omega\) or 50 \(\Omega\) inverter resistors and exhibiting partially or fully suppressed baselines.

<table>
<thead>
<tr>
<th>(R_{\text{inv}}) [(\Omega)]</th>
<th>(\sigma_{\text{raw}}) [ADCch]</th>
<th>((S/N)_{\text{window}}) [ADCch]</th>
<th>Most probable</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>(\geq 1)</td>
<td>29.2</td>
<td>34.8</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>(\geq 1)</td>
<td>28.6</td>
<td>38.4</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>(&lt; 1)</td>
<td>15.1</td>
<td>19.3</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>(&lt; 1)</td>
<td>22.8</td>
<td>27.9</td>
<td></td>
</tr>
<tr>
<td>Unaffected APVs</td>
<td></td>
<td>29.3</td>
<td>35.2</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2 summarises the most-probable and mean values characterising the \((S/N)_{\text{window}}\) distributions obtained from APV25 chips equipped with 100 \(\Omega\) or 50 \(\Omega\) inverter resistors and exhibiting partially or fully suppressed baselines. It is clear in the case of fully suppressed baselines that there is some recovery of signal when the APV25 chip is equipped with the 50 \(\Omega\) resistor. These observations are in agreement with those provided by the laboratory measurements (described in section 3.3).

5.4.2 Efficiency Measurements

Figures 5.24 and 5.25 highlight the track and cluster statistics collected with trigger-burst data for single APV25 chips. Figure 5.24 (top) displays the number of tracks that traverse sensor planes affected by highly ionising events, but through regions of sensors instrumented by unaffected APV25 chips (with a resistor value of 100 \(\Omega\)). The track statistics\(^{21}\) (red bars) are plotted as a function of time relative to the time of the highly ionising events \((\Delta T)\). Similarly, the number of hits identified within windows around the track intercept points are also plotted as a function of \(\Delta T\) (open circles, with statistical error). The efficiency \(\varepsilon_{\text{hit}}^i\) is defined by the ratio of the number of hits to the number of tracks, \(N_{\text{hit}}^i/N_{\text{trk}}^i\), observed in the \(i\)th time bin. As highlighted by the figure, \(N_{\text{hit}}^i\approx N_{\text{trk}}^i\) (hence \(\varepsilon_{\text{hit}}^i\approx 1\)) throughout all time intervals for chips unaffected by highly ionising events.

Figure 5.24 (bottom) displays the same information, but for tracks that traverse regions of sensor planes instrumented by APV25 chips affected by highly ionising events. The numbers of reconstructed hits are clearly suppressed with respect to

\(^{21}\)The total number of tracks observed is indicated in the top-right of the plot.
5.4 Inefficiencies due to Highly Ionising Events

Figure 5.24: Number of tracks (red bars) and clusters (open markers) as a function of \( \Delta T \) for a single APV25 with \( R_{\text{inv}} = 100 \, \Omega \) that is either unaffected (top) or affected (bottom) by a highly ionising event.

Figure 5.25: Number of tracks (red bars) and clusters (open markers) as a function of \( \Delta T \) for a single APV25 with \( R_{\text{inv}} = 50 \, \Omega \) that is either unaffected (top) or affected (bottom) by a highly ionising event.

The number of tracks, especially during the first 100 ns time bin following the highly ionising events. However, \( N_{\text{hit}}^i \rightarrow N_{\text{trk}}^i \) with increasing \( \Delta T \), implying a recovery in the efficiency.\(^{22}\)

Table 5.3: Total track and hit statistics collected for APV25 chips equipped with 100 \( \Omega \) and 50 \( \Omega \) inverter resistors and for different common mode algorithms.

<table>
<thead>
<tr>
<th>( R_{\text{inv}} ) [( \Omega )]</th>
<th>CM algo.</th>
<th>Unaffected APVs</th>
<th>Affected APVs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( N_{\text{good}}^\text{trk} )</td>
<td>( N_{\text{good}}^\text{hit} )</td>
</tr>
<tr>
<td>100</td>
<td>CM(_{128})</td>
<td>1031</td>
<td>1013</td>
</tr>
<tr>
<td>50</td>
<td>CM(_{128})</td>
<td>1265</td>
<td>1238</td>
</tr>
<tr>
<td>100</td>
<td>CM(_{16})</td>
<td>1031</td>
<td>1013</td>
</tr>
<tr>
<td>50</td>
<td>CM(_{16})</td>
<td>1265</td>
<td>1237</td>
</tr>
</tbody>
</table>

The track and hit statistics collected by the individual APV25 chips can be grouped according to the value of the inverter resistor; the total collected statistics are summarised in table 5.3 for the two resistor values. Additionally, the analysis is performed using the two different common mode algorithms, CM\(_{128}\) and CM\(_{16}\).

\(^{22}\)There are some exceptions to the rule: chips with identifiers 29, 34, 35, 43 and 47 (as highlighted earlier in the chapter) are excluded from the analysis as they exhibit unusually large inefficiencies and no apparent recovery.
5.4 Inefficiencies due to Highly Ionising Events

The temporal evolution of the efficiency is shown in figure 5.26, for APV25 chips equipped with 100 Ω (top) and 50 Ω (bottom). Each plot shows the temporal evolution of the efficiency for both unaffected chips, \( \varepsilon_{\text{good}}^i \) (open squares) and chips affected by highly ionising events (closed squares), \( \varepsilon_{\text{hie}}^i \); the efficiencies of the latter case are normalised to those of the former \( (\varepsilon_{\text{hit}}^i = \varepsilon_{\text{hie}}^i / \varepsilon_{\text{good}}^i) \) in order to account for the inefficiencies inherent in the track-finding algorithm and the readout system. The efficiency is lowest in the 100 ns time bin immediately following the highly ionising event when deadtime is most likely to be observed. The subsequent trend is a slow recovery in efficiency with time, with improved efficiencies observed for the 50 Ω resistor relative to the 100 Ω case.

The suppression and subsequent recovery of the efficiency following a highly ionising event can be quantified in terms of a ‘time-averaged’ efficiency, \( \langle \varepsilon_{\text{hit}} \rangle \), which is defined by the mean of the individually measured efficiencies, \( \varepsilon_{\text{hit}}^i \), for the seven 100 ns time bins following the highly ionising event (i.e. the interval \( \Delta T = 0 \) ns → 700 ns). An ‘equivalent deadtime’ is also defined that quantifies the observed inefficiencies during the zero-suppression of the raw channel data. Again, the high efficiencies achieved with unaffected APV25 chips highlights the performance of the tracking algorithm. By comparison, the efficiencies measured for chips affected by highly ionising events are suppressed; improvement is observed for \( R_{\text{inv}} = 50 \) Ω relative to 100 Ω and, to a lesser degree, \( \text{CM}_{16} \) relative to \( \text{CM}_{128} \).

Figure 5.26: Efficiency as a function of \( \Delta T \) for APV25 chips equipped with 100 Ω (top) and 50 Ω (bottom) inverter resistors.

Figure 5.27: Efficiency as a function of \( \text{CM}_{\text{thr}} \) threshold, for various combinations of \( R_{\text{inv}} \) values and common mode algorithm.
5.4 Inefficiencies due to Highly Ionising Events

Table 5.4: Measured ‘time-averaged’ efficiencies, $\langle \varepsilon_{hit} \rangle$, and the corresponding ‘equivalent deadtime’, $\Gamma_{hie}$, for two different $CM_{thr}$ thresholds and various resistor and common mode algorithm combinations. Quoted errors reflect the statistical uncertainties only.

<table>
<thead>
<tr>
<th>$R_{inv}$ $[\Omega]$</th>
<th>CM algo.</th>
<th>$CM_{thr} = -20$</th>
<th>$CM_{thr} = -90$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\langle \varepsilon_{hit} \rangle$</td>
<td>$\Gamma_{hie} [\text{ns}]$</td>
<td>$\langle \varepsilon_{hit} \rangle$</td>
</tr>
<tr>
<td>100</td>
<td>0.76 ± 0.03</td>
<td>170 ± 18</td>
<td>0.60 ± 0.04</td>
</tr>
<tr>
<td>50</td>
<td>0.87 ± 0.02</td>
<td>90 ± 12</td>
<td>0.76 ± 0.03</td>
</tr>
<tr>
<td>100</td>
<td>0.76 ± 0.03</td>
<td>169 ± 18</td>
<td>0.60 ± 0.04</td>
</tr>
<tr>
<td>50</td>
<td>0.90 ± 0.02</td>
<td>67 ± 11</td>
<td>0.81 ± 0.03</td>
</tr>
<tr>
<td>$\Gamma_{hie}(50/100)_{128}$</td>
<td>0.53 ± 0.09 ($5.3\sigma$)</td>
<td>0.60 ± 0.10 ($4.0\sigma$)</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{hie}(16/128)_{50}$</td>
<td>0.74 ± 0.15 ($1.7\sigma$)</td>
<td>0.81 ± 0.17 ($1.1\sigma$)</td>
<td></td>
</tr>
</tbody>
</table>

The sample of highly ionising events considered in the analysis is defined using the $CM_{thr}$ threshold, by requiring highly ionising events to induce shifts in the common mode level that satisfy $CM_{hie} \leq CM_{thr}$. Figure 5.27 plots the ‘time-averaged’ efficiency, $\langle \varepsilon_{hit} \rangle$, as a function of the threshold $CM_{thr}$, for the four combinations of inverter resistor value and common mode algorithm. The efficiency is seen to decrease for lower thresholds; this is because the fraction of deadtime-inducing highly ionising events in the sample defined by $CM_{hie}$ increases with decreasing $CM_{thr}$.

The mean efficiency is systematically improved for all values of $CM_{thr}$ with the 50 $\Omega$ resistor value relative to the 100 $\Omega$ case. Furthermore, improved efficiencies are observed with the $CM_{16}$ algorithm relative to the $CM_{128}$ case, although a significant improvement is only observed when the modules are equipped with the 50 $\Omega$ resistor (and this improvement is less significant than that observed due to a change in resistor value). An improvement is only observed for the 50 $\Omega$ case as non-flat baselines are more frequently observed with 50 $\Omega$ and therefore those signals ‘lost’ due to non-flat baselines are again recovered with the $CM_{16}$ algorithm.

Table 5.4 summarises the observed ‘time-averaged’ efficiencies and ‘equivalent deadtimes’ for the various resistor value and common mode algorithm combinations.
and two different $CM_{thr}$ thresholds. The quoted errors reflect the statistical uncertainties only. The systematic contribution is more difficult to assess. The induced inefficiencies are probably underestimated by this analysis as the temporal efficiency curves do not fully recover within the 700 ns period following the highly ionising events (especially in the case of the 100 $\Omega$ resistor). A more significant contribution is likely to be the sensitivity of the measured inefficiencies to the thresholds used to identify signal. This analysis was repeated in full using thresholds analogous to those used by the FED firmware algorithms: $T_{strip} = 2$, $T_{seed} = 0$ and $T_{clus} = 5$. The resulting inefficiencies are up to $\sim 20\%$ lower than those quoted in table 5.4.\textsuperscript{23} Therefore, a conservative estimate of the systematic uncertainty is considered to be 25%.

The ratio $\Gamma_{hie}(50/100)_{128}$ defines the reduction in the inefficiency due to the change in resistor value and, similarly, the ratio $\Gamma_{hie}(16/128)_{50}$ defines the reduction in inefficiency due to a change in the common mode algorithm (for modules equipped with 50 $\Omega$ resistors). These ratios are considered to be less sensitive to the systematic uncertainties discussed above, which are likely to be highly correlated. The uncertainties and significances of these ratios are based purely on the statistical uncertainties associated with the efficiency measurements. For the full highly ionising event sample, defined by $CM_{thr} = -20$ ADCch, the reduction in the inefficiency, or equivalent deadtime, due to the change in resistor value is $47 \pm 9\%$; a further reduction of $26 \pm 15\%$ is observed for a change in the common mode algorithm.

An independent analysis of the PSI data (known as ‘TT6’) also measured the inefficiencies resulting from highly ionising events using a track-based method [116]. The results provided by the TT6 analysis are consistent with the results provided by the R2 analysis (for the appropriate thresholds).

5.5 Identifying Deadtime in the APV25

Although the common mode level is known for each APV25 chip for every triggered event, it is difficult to use this variable to characterise the sensitivity of a chip

\textsuperscript{23}The reduction in the measured inefficiencies is attributable to the inability of the lower thresholds to suppress the bias introduced by non-flat baselines, resulting in ‘fake’ clusters being identified as genuine signal.
5.5 Identifying Deadtime in the APV25

The ability to reconstruct tracks allows this assumption to be tested, by measuring the hit reconstruction efficiency as a function of $\sigma_{\text{raw}}$ (rather than common mode levels, as described in the previous section). Figure 5.28 (top) plots the number of tracks (red bars) passing through regions of sensors instrumented by APV25 chips affected by highly ionising events, and the corresponding number of reconstructed hits (open circles, with statistical errors) as a function of $\sigma_{\text{raw}}$. The distribution is similar in form to that shown in figure 5.3 (p. 121), with a strong peak at $\sim 2$ ADCch, reflecting the presence of the normal pedestal structure, and a number of entries at $\sigma_{\text{raw}} < 1$ ADCch, when the baseline is fully suppressed. It is clear that $N_{\text{hit}} \ll N_{\text{trk}}$ for the region $\sigma_{\text{raw}} < 1$ ADCch and $N_{\text{hit}} \approx N_{\text{trk}}$ for the region $\sigma_{\text{raw}} \geq 1$ ADCch.

The reduction of the hit efficiency is more clearly illustrated by figure 5.28 (bottom), which plots the cumulative efficiency, $\varepsilon_{\text{cum}}(\sigma_{\text{raw}} < \sigma_{\text{thr}})$, as a function of the threshold $\sigma_{\text{thr}}$. For APV25 chips equipped with both 100 $\Omega$ and 50 $\Omega$ resistors, the cumulative efficiency is suppressed to below $\sim 20\%$ until a recovery is observed at $\sigma_{\text{raw}} \approx 1$ ADCch. This behaviour justifies the use of the $\sigma_{\text{raw}}$ variable to differentiate

The distribution is for APV25 chips equipped with the nominal 100 $\Omega$ resistor.
5.5 Identifying Deadtime in the APV25

between APV25 chips that are exhibiting deadtime and those that are not. The cumulative efficiencies tend to the values quoted for the threshold CM$_{thr}$ = -20 ADCch in table 5.4.

### 5.5.1 Inefficiencies due to Deadtime

As described above, the $\sigma_{raw}$ variable can be used to distinguish between highly ionising events that induce deadtime (through fully suppressed baselines) and those that induce only partially suppressed baselines. Thus, the individual contributions of these two classes of highly ionising event to the total inefficiencies quoted in table 5.4 can be determined.

Figure 5.29 plots the temporal evolution of the efficiency for chips equipped with 100 $\Omega$ (top) and 50 $\Omega$ (bottom) resistors, with each plot showing the efficiency evolution for chips affected by highly ionising events that induce either partially suppressed (open markers) or fully suppressed (closed markers) baselines at some point during their recovery period. All efficiencies are normalised to those obtained for unaffected chips (not shown). For APV25 chips exhibiting fully suppressed baselines, the efficiency is heavily suppressed throughout the 700 ns time interval following a highly ionising event, although there is significant improvement for chips equipped with 50 $\Omega$ resistors. For APV25 chips exhibiting only partially suppressed baselines, the efficiency does not fall below $\sim$0.85 at any point during the recovery. Table 5.5 summarises the observed ‘time-averaged’ efficiencies and ‘equivalent deadtimes’ for chips exhibiting partially ($\sigma_{raw} \geq 1$ ADCch) and fully ($\sigma_{raw} < 1$ ADCch) suppressed

<table>
<thead>
<tr>
<th>$R_{inv}$ [\Omega]</th>
<th>CM algorithm</th>
<th>$\sigma_{raw} \geq 1$ ADCch</th>
<th>$\sigma_{raw} &lt; 1$ ADCch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\langle \varepsilon_{hit} \rangle$</td>
<td>$\Gamma_{hie}$ [ns]</td>
</tr>
<tr>
<td>100</td>
<td>CM$_{128}$</td>
<td>0.91 ± 0.03</td>
<td>64 ± 21</td>
</tr>
<tr>
<td>50</td>
<td>CM$_{128}$</td>
<td>0.92 ± 0.02</td>
<td>58 ± 15</td>
</tr>
<tr>
<td>100</td>
<td>CM$_{16}$</td>
<td>0.94 ± 0.02</td>
<td>43 ± 17</td>
</tr>
<tr>
<td>50</td>
<td>CM$_{16}$</td>
<td>0.97 ± 0.01</td>
<td>20 ± 8</td>
</tr>
<tr>
<td>$\Gamma_{hie}(50/100)_{128}$</td>
<td></td>
<td>0.91 ± 0.38 (0.2$\sigma$)</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{hie}(16/128)_{20}$</td>
<td></td>
<td>0.35 ± 0.17 (3.8$\sigma$)</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.5: Measured ‘time-averaged’ efficiencies, $\langle \varepsilon_{hit} \rangle$, and the corresponding ‘equivalent deadtime’, $\Gamma_{hie}$, for highly ionising events that induce partially ($\sigma_{raw} \geq 1$ ADCch) or fully ($\sigma_{raw} < 1$ ADCch) suppressed baselines, and for the various resistor and common mode algorithm combinations. Quoted errors reflect the statistical uncertainties only.
baselines, for the various combinations of resistor value and common mode algorithm.

The ‘time-averaged’ inefficiencies, expressed in terms of the ‘equivalent deadtime’ $\Gamma_{ie}$, are small for highly ionising events that induce only partially suppressed baselines, typically a few tens of ns. However, for highly ionising events that induce fully suppressed baselines, $\Gamma_{ie} \approx 350$ ns for chips equipped with 100 $\Omega$ and $\Gamma_{ie} \approx 250$ ns for 50 $\Omega$. As expected, the improvement in the inefficiencies due to a change in resistor value, $\Gamma_{ie}(50/100)_{128}$, is most significant for fully saturated baselines, whilst the improvement due to a change in common mode algorithm, $\Gamma_{ie}(16/128)_{50}$, is most significant for partially saturated baselines.

An estimate of the mean deadtime period of APV25 chips affected by highly ionising events can be inferred from the numbers quoted in table 5.5. The difference between the ‘equivalent deadtimes’ observed for chips exhibiting fully and partially suppressed baselines during their recoveries, for a given combination of resistor value and common mode algorithm, provides an estimate of the inefficiencies generated solely by deadtime (and not through effects of non-flat baselines). A difference of $\sim 300$ ns is observed for chips equipped with 100 $\Omega$ resistor; this is in good agreement with the deadtime measurements obtained from the efficiency measurements described in chapter 3 and the laser studies [117] outlined in section 4.6.

The period for which the baseline remains fully suppressed ($\sigma_{raw} < 1$ ADCch) can be determined from the trigger-burst data. As the $\sigma_{raw}$ variable is available on an event-by-event basis, this period of baseline suppression can be measured for individual highly ionising events. Table 5.6 lists the mean and maximum values of this period of baseline suppression. The maximum values for the 100 $\Omega$ case are consistent with the deadtime periods inferred from the efficiency measurements described above.

## 5.6 Summary

The analysis of the trigger-burst data has provided much information on the behaviour of an APV25 chip affected by a highly ionising event. The response of the chip to large signals is characterised by a negative shift in all channels that do not
Table 5.6: The mean, $\Gamma_{\text{mean}}$, and maximum, $\Gamma_{\text{max}}$, values for the period for which the baseline remains fully suppressed, as identified by the condition $\sigma_{\text{raw}} < 1$ ADCch, for various resistor and common mode algorithm combinations.

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Deadtime, $\Gamma$ [ns]</th>
<th>$\Gamma_{\text{mean}}$</th>
<th>$\Gamma_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIB 100</td>
<td>99.5 ± 12.0</td>
<td>200 ± 25</td>
<td></td>
</tr>
<tr>
<td>TIB 50</td>
<td>69.6 ± 9.4</td>
<td>250 ± 25</td>
<td></td>
</tr>
<tr>
<td>TIB 100</td>
<td>122.5 ± 12.6</td>
<td>275 ± 25</td>
<td></td>
</tr>
<tr>
<td>TOB 50</td>
<td>100.5 ± 3.6</td>
<td>275 ± 25</td>
<td></td>
</tr>
</tbody>
</table>

| $\Gamma_{\text{mean}}(50/100)_{\text{TIB}}$ | $0.70 ± 0.13$ (2.4$\sigma$) |
| $\Gamma_{\text{mean}}(50/100)_{\text{TOB}}$ | $0.82 ± 0.09$ (2.0$\sigma$) |

collect the large signals. The baseline is frequently suppressed to the lower limit of the dynamic range for periods of up to $\sim$300 ns and the recovery to the nominal levels can take several hundred ns. The channels that do collect the large energy depositions exhibit large, persistent signals for several hundred ns.

Non-uniform shifts observed in the 128 channels of an APV25 at the time of a highly ionising event and different recovery rates of individual channels result in non-flat baselines. This, coupled with the present algorithm used to estimate the common mode level, results in the generation of fake clusters and (small) inefficiencies.

Inefficiencies due to highly ionising events inducing deadtime in the APV25 chip have been measured using a track-based method to search for signal in affected APV25 chips. The induced deadtimes are of the order 300 ns.

The reduction of the inverter resistor value from 100 $\Omega$ to 50 $\Omega$ has significantly reduced the level of inefficiencies generated by highly ionising events, although at a price: the number of fake clusters generated by highly ionising events is increased. This effect can be negated by using a more sophisticated common mode estimator, which also further reduces the inefficiencies.
Chapter 6

Tracker Inefficiencies due to Highly Ionising Events

This chapter presents measurements of the rates at which highly ionising events affect the APV25 chip, under conditions similar to those expected in the CMS Tracker environment. These rate measurements are then used in conjunction with the inefficiency and fake cluster generation measurements described in chapter 5 to estimate the total inefficiency and increase in data rate expected for the CMS Tracker readout system. Finally, the effect of the total inefficiency on the tracking performance of the CMS Tracker subdetector is considered.

6.1 Rate Measurements of Highly Ionising Events

As described in section 3.1, the simulations of nuclear interactions in silicon provide energy deposition probability spectra for hadrons incident on silicon sensors. These spectra can be used to infer the expected effect on the performance of the Tracker and so it is highly desirable to test the validity of these spectra through experimental measurement. This in turn requires that the magnitude of the energy depositions in the sensors are calibrated in terms of the common mode shifts and deadtime observed in the data from the APV25 chip. However, this calibration cannot be performed in the beam test environment as the HIE signals observed in the APV25 data are essentially always truncated by the limited dynamic range. A calibration has been performed under controlled conditions in the laboratory, as described in
6.1 Rate Measurements of Highly Ionising Events

section 3.3 and [117]. However, a simulation of the highly ionising events in the laboratory introduces further complications as the spatial distribution of charge in the sensors cannot be accurately replicated and the induced deadtimes are known to be sensitive to the distribution of the collected signal.

In short, a calibration of the deposition magnitudes cannot be performed using features of the APV25 behaviour, which in turn prevents an accurate extrapolation of the effect to the Tracker environment based on the simulation spectra. However, such an extrapolation is not essential if experimental measurements are performed in an environment similar to that expected in the Tracker region; this is the justification for the PSI beam test. The measurements performed with the 300 MeV/c pion beam allow an extrapolation of the effect to the Tracker environment to be performed with confidence.

An important point worth mentioning here is the need for an accurate determination of the (threshold) energy deposition required to induce deadtime in the APV25 chip. The magnitude of this threshold determines the rate at which deadtime is observed in the APV25 chip and hence the total inefficiency introduced by highly ionising events into the Tracker readout system. Furthermore, relatively large energy depositions can result from heavy electronic ionisation due to slow-moving charged particles. Thus, the magnitude of the energy deposition threshold defines the susceptibility of the APV25 chip to the highly-ionising nature of low momentum particles confined to the Tracker region by the 4 Tesla magnetic field.

6.1.1 Identifying Highly Ionising Events

As described in chapter 5, highly ionising events are identified in the APV25 data by searching for common mode levels of CM$_{hie}$ $\leq$ -20 ADCch$^1$ that are accompanied by a cluster with a seed-strip signal of $S_{seed} \geq 125$ ADCch. These thresholds were defined using trigger-burst data, but should be equally valid for data collected in single-trigger mode. The trigger-burst data show that the time at which the lowest common mode level (CM$_{hie}$) is observed during the APV25 recovery period and the peaking time of the HIE signal ($S_{seed}$) are not coincident in time with the

\footnote{ADC channels or units.}
6.1 Rate Measurements of Highly Ionising Events

Peaking time of the upstream MIP signals (if present) and therefore also the particle trigger when operating in single-trigger mode.\textsuperscript{2} However, this is not expected to impact significantly on the ability of the thresholds to select comparable samples of highly ionising events, due to the ‘persistence’ of the HIE signals and baseline suppression. It is also important that the sample of highly ionising events (for a given set of thresholds) should not be influenced by the different trigger modes used to collect the data samples;\textsuperscript{3} this is particularly important for the calculation of the total inefficiencies generated by highly ionising events (as described in section 6.3), which implicitly assumes identical samples are used to measure the inefficiencies (section 5.4) and rates (section 6.1.6).

Justification for the HIE seed-strip threshold is provided by figure 6.1, which illustrates the presence of ‘out-of-time’ highly ionising events in a sample of triggered events. The figure shows the distributions of the seed-strip signal (\textit{top}) and total signal (\textit{bottom}) of the largest cluster identified in APV25 data that also exhibit a common mode level of CM\textscript{hie} \textless -20 ADCch. Distributions are shown for data obtained from all APV25 chips (open bars) and those chips instrumenting only the

\textsuperscript{2}Note that the method of ‘timing-in’ to highly ionising events with trigger-burst data is not necessary with data collected in single-trigger mode, as the time of the event trigger is tuned to be coincident with the peaking-time of MIP signals.

\textsuperscript{3}For this reason, the author did not agree with the use of the downstream particle veto, used to enrich the highly ionising event sample in trigger-burst mode (described in chapter 4). However, no significant differences are observed between the samples collected for the different trigger modes.

---

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure6_1.png}
\caption{Distributions of seed-strip signal (\textit{top}) and total cluster signal (\textit{bottom}), for all (bars) and selected (markers) APVs.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure6_2.png}
\caption{Number of HIEs (\textit{top}) and clusters (\textit{bottom}) versus APV number. See text for explanation of highlighted (red) data.}
\end{figure}
central regions of the sensor planes (closed markers). The frequency of small signals is enhanced when data from all chips are considered (relative to the distributions obtained for centrally-located chips). This is due to the limited coverage provided by the upstream scintillator, hence the trigger pre-filter is ineffective at suppressing out-of-time particle crossings and highly ionising events in the ‘wings’ of the sensor planes (and therefore highly ionising events are observed with reduced signals). The distributions obtained from centrally-located chips are similar to those obtained with trigger-burst data (see figure 5.6, p. 125). Hence, the use of the threshold $S_{seed} \geq 125$ ADCch is valid for single-trigger mode and the $S_{seed}$ distributions highlight its ability to suppress out-of-time highly ionising events.

The probability of a particle generating a highly ionising event as a result of a hadron-nuclear collision is determined by normalising the number of highly ionising events to the number of particle path-lengths traversing a sensor plane identified within a given data sample. The tracking system used at PSI was illuminated by hadrons at (approximately) normal incidence and with no magnetic field present, so the mean path-length of a hadron in each sensor plane is assumed to be the sensor thickness. Hence, assuming the ‘unit’ path-length to be the sensor thickness, the number of path-lengths, $N_{path}$, is provided by the number of observed clusters. Clusters are reconstructed with the standard TDR-defined algorithm and thresholds, as described in chapter 4.

Figure 6.2 summarises the relevant statistics necessary for a measurement of the HIE probability. Figure 6.2 (top) plots the number of highly ionising events as a function of APV25 chip number, for data collected in single trigger mode with a high intensity beam of (negatively-charged) pions. Again, a repetitive structure is observed, a consequence of the trigger conditions, and fewer statistics are collected with the TIB sensors (chip numbers 1 to 12) due to the reduced sensor thickness. Figure 6.2 (bottom) plots the number of clusters as a function of APV25 chip number (open bars), for the same data sample. The cluster statistics collected with an increased cluster $S/N$ threshold are also shown (red bars).$^4$ Increasing the signal threshold significantly reduces the cluster statistics in the ‘wings’ of the sensor plane,

$^4$The $T_{clu}$ threshold is increased from the nominal value of $= 5$ to 8 (12) for the TIB (TEC/TOB) sensor planes.
due to the suppression of out-of-time signals in regions of the sensors not covered by the upstream scintillator. Five of the chips instrumenting two of the TIB sensor planes exhibit extremely poor noise performance, resulting in the reconstruction of many non-physical clusters.\(^5\) Data from these chips are not considered in the analysis.

### 6.1.2 Cumulative Probability Curves

The distributions of common mode levels induced by highly ionising events for individual APV25 chips, \(N_{\text{hie}}(\text{CM}_{\text{hie}})\), are shown in figure 6.3. The common mode levels of deadtime-inducing highly ionising events, identified by \(\sigma_{\text{raw}} < 1\) ADCCh, are also shown in the distributions (highlighted in red). Data from several chips are not used in the analysis (and their distributions not shown in the figure), as these chips exhibit anomalous behaviour in terms of noise performance or in response to highly ionising events.\(^6\)

The cumulative highly ionising event probability, \(P_{\text{hie}}(\text{CM}_{\text{hie}} \leq \text{CM}_{\text{thr}})\), is defined by the number of highly ionising events inducing a common mode level below the threshold \(\text{CM}_{\text{thr}}\), expressed as \(N_{\text{hie}}(\text{CM}_{\text{hie}} \leq \text{CM}_{\text{thr}})\), normalised to the total number of path-lengths of beam particles through the silicon sensors, \(N_{\text{path}}\):

\[
P_{\text{hie}}(\text{CM}_{\text{hie}} \leq \text{CM}_{\text{thr}}) = \frac{N_{\text{hie}}(\text{CM}_{\text{hie}} \leq \text{CM}_{\text{thr}})}{N_{\text{path}}} = \frac{1}{N_{\text{path}}} \int_{\text{CM}_{\text{min}}}^{\text{CM}_{\text{thr}}} N_{\text{hie}}(\text{CM}_{\text{hie}}) \cdot d(\text{CM}_{\text{hie}}) \quad (6.1)
\]

\(N_{\text{hie}}(\text{CM}_{\text{hie}} \leq \text{CM}_{\text{thr}})\) is obtained from the (differential) common mode distributions shown in figure 6.2. Alternatively, the HIE probability, \(P_{\text{hie}}\), can be expressed in terms of an interaction length, \(\lambda_{\text{hie}}\) [\(\mu\text{m}\)], as defined by \(1/\lambda_{\text{hie}} = P_{\text{hie}}/l_{\text{path}}\), where \(l_{\text{path}}\) [\(\mu\text{m}\)] is the path-length.\(^7\)

---

\(^5\)The noise performance of these chips, numbered 1, 2, 3, 9 and 10, is illustrated in section 4.5.2.

\(^6\)Five chips of the TIB modules, with identifiers 1, 2, 3, 9 and 10, exhibit poor noise performance; chips 17, 18, 19 and 20 of the second TEC plane are poorly configured, with baselines close to the lower limit of the dynamic range; chips 29, 34, 35, 43 and 47 of the TOB modules never exhibit fully suppressed baselines, but still exhibit unusually large inefficiencies.

\(^7\)The path-length, \(l_{\text{path}}\), is equivalent to the sensor thickness for the probability measurements reported in this chapter.
The cumulative probability curves obtained for the individual APV25 chips used in the analysis are shown in figure 6.4. Increasingly large energy depositions result in increasingly shifted common mode levels, hence the slope of the probability curves reflects the reduction in probability of observing increasingly large energy depositions. The cumulative probability is zero for the region $\mathrm{CM}_{\text{thr}} < \mathrm{CM}_{\text{min}}$, which is followed by a sharp increase at $\mathrm{CM}_{\text{thr}} = \mathrm{CM}_{\text{min}}$ due to the pronounced peaks that mark the lower end of the common mode distributions, which is in turn followed by an approximately linear rise with an increasing $\mathrm{CM}_{\text{thr}}$ threshold. The probability curves are observed to saturate at $\mathrm{CM}_{\text{thr}} = -20 \, \text{ADCch}$ due to the definition of a highly ionising event (i.e. requiring a common mode level of below -20 ADCch). Smaller common mode level shifts accompanied by large signals are observed, but these small shifts are not expected to contribute significantly to the total inefficiencies induced by highly ionising events.
Figure 6.5: Cumulative probability curves obtained with a low intensity $\pi^-$ beam.

Figure 6.6: Cumulative probability curves obtained with a medium intensity $\pi^-$ beam.

Figure 6.7: Cumulative probability curves obtained with a high intensity $\pi^-$ beam.

Figure 6.8: Cumulative probability curves obtained with a medium intensity $\pi^+$ beam.

Figure 6.9: Cumulative probability curves obtained with medium intensity $\pi^+$ beam and APV25 chips operated in non-inverting mode.

Figure 6.10: Cumulative probability curves obtained with low and high intensity $\pi^-$ beams for primary highly ionising events.
6.1 Rate Measurements of Highly Ionising Events

<table>
<thead>
<tr>
<th>Sensor type and $R_{inv}$ [Ω]</th>
<th>$P_{hie}(CM_{thr} \leq -20) \times 10^{-3}$</th>
<th>Low intensity</th>
<th>Medium intensity</th>
<th>High intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIB 50</td>
<td></td>
<td>5.5 ± 0.3 ± 0.5 ± 1.5</td>
<td>8.4 ± 0.8 ± 1.1 ± 1.7</td>
<td>6.9 ± 0.4 ± 1.3 ± 0.6</td>
</tr>
<tr>
<td>TIB 100</td>
<td></td>
<td>8.3 ± 0.5 ± 0.7 ± 4.1</td>
<td>7.8 ± 1.1 ± 1.0 ± 1.5</td>
<td>8.9 ± 0.6 ± 1.7 ± 1.2</td>
</tr>
<tr>
<td>TEC 100</td>
<td></td>
<td>14.3 ± 0.3 ± 1.2 ± 4.6</td>
<td>18.5 ± 0.8 ± 2.4 ± 4.7</td>
<td>20.0 ± 0.5 ± 3.7 ± 3.6</td>
</tr>
<tr>
<td>TOB 50</td>
<td></td>
<td>14.8 ± 0.3 ± 1.2 ± 4.2</td>
<td>16.0 ± 0.7 ± 2.0 ± 4.2</td>
<td>17.4 ± 0.4 ± 2.2 ± 2.6</td>
</tr>
<tr>
<td>TOB 75</td>
<td></td>
<td>-</td>
<td>-</td>
<td>19.7 ± 1.2 ± 3.7 ± 3.4</td>
</tr>
<tr>
<td>TOB 100</td>
<td></td>
<td>16.4 ± 0.4 ± 1.4 ± 4.2</td>
<td>19.2 ± 0.9 ± 2.5 ± 5.3</td>
<td>20.4 ± 0.6 ± 3.8 ± 2.9</td>
</tr>
<tr>
<td>$P_{hie}(50/100)_{TIB}$</td>
<td></td>
<td>0.66 ± 0.05 (6.3σ)</td>
<td>1.07 ± 0.18 (0.4σ)</td>
<td>0.77 ± 0.07 (3.1σ)</td>
</tr>
<tr>
<td>$P_{hie}(50/100)_{TOB}$</td>
<td></td>
<td>0.90 ± 0.03 (3.5σ)</td>
<td>0.84 ± 0.05 (3.1σ)</td>
<td>0.85 ± 0.03 (4.9σ)</td>
</tr>
</tbody>
</table>

Table 6.1: Measurements of $P_{hie}(CM_{thr} \leq -20)$ for various module configurations and different intensity $\pi^-$ beams. Also quoted are the statistical and systematic errors and the $rms$ spread.

6.1.3 Probability Measurements with Pions

The statistics accumulated by the individual APV25 chips are grouped according to module configuration in order to provide a weighted-mean probability curve for each group. Figures 6.5 to 6.9 (p. 156) show the cumulative probability curves for various module and beam configurations. There are six different module configurations: TIB modules equipped with 320 μm-thick sensors and 50 Ω or 100 Ω inverter resistors; TEC modules equipped with 500 μm-thick sensors and only 100 Ω resistors; and TOB modules, equipped with 500 μm-thick sensors and 50 Ω, 75 Ω or 100 Ω resistors. The beamline provided 300 MeV/c pions of both charge-polarities and at various intensities. A $\pi^-$ beam was delivered at low, medium and high intensities and the measured probability curves are shown in figures 6.5, 6.6 and 6.7, respectively. A medium intensity $\pi^+$ beam was also used and the APV25 chips were operated in inverting and non-inverting modes; the measured probability curves are shown in figures 6.8 and 6.9, respectively.

Additionally, tables 6.1 and 6.2 list the probability $P_{hie}$ measured from samples of highly ionising events defined by the threshold $CM_{thr} = -20$ ADCch, for the various detector and beam configurations. These measurements can be compared with the upper end points of the curves shown in figures 6.5 to 6.9. The three error values listed for each measurement are in turn the statistical and systematic uncertainties and the $rms$ spread in the probability measurements for a given detector configuration. The error bars associated with the cumulative probability curves shown in the figures on p. 156 represent the quadrature addition of the statistical and systematic uncertainties and the $rms$ spread value.
6.1 Rate Measurements of Highly Ionising Events

Table 6.2: Measurements of $P_{\text{hie}}(\text{CM}_{\text{hie}} \leq -20)$ for various module configurations illuminated with a medium intensity $\pi^+$ beam and APV25 chips operated in inverting and non-inverting modes. Also quoted are the statistical and systematic errors and the $\text{rms}$ spread.

<table>
<thead>
<tr>
<th>Sensor type and $R_{\text{inv}}$ [Ω]</th>
<th>$P_{\text{hie}}(\text{CM}_{\text{hie}} \leq -20)$ [$\times 10^{-4}$]</th>
<th>$\pi^+$, med int, invert.</th>
<th>$\pi^+$, med int, non-inv.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIB 50</td>
<td>7.5 ± 0.3 ± 0.9 ± 1.4</td>
<td>6.7 ± 0.6 ± 1.2 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>TIB 100</td>
<td>10.0 ± 0.5 ± 1.2 ± 4.0</td>
<td>10.7 ± 1.1 ± 1.9 ± 4.9</td>
<td></td>
</tr>
<tr>
<td>TEC 100</td>
<td>20.6 ± 0.4 ± 2.4 ± 7.0</td>
<td>21.7 ± 0.9 ± 3.8 ± 6.4</td>
<td></td>
</tr>
<tr>
<td>TOB 50</td>
<td>21.1 ± 0.3 ± 2.4 ± 6.4</td>
<td>19.8 ± 0.8 ± 3.5 ± 6.2</td>
<td></td>
</tr>
<tr>
<td>TOB 100</td>
<td>24.4 ± 0.5 ± 2.8 ± 7.8</td>
<td>25.7 ± 1.1 ± 4.5 ± 8.6</td>
<td></td>
</tr>
<tr>
<td>$P_{\text{hie}}(50/100)_{\text{TIB}}$</td>
<td>0.75 ± 0.05 (5.4$\sigma$)</td>
<td>0.62 ± 0.08 (4.5$\sigma$)</td>
<td></td>
</tr>
<tr>
<td>$P_{\text{hie}}(50/100)_{\text{TOB}}$</td>
<td>0.86 ± 0.02 (6.5$\sigma$)</td>
<td>0.77 ± 0.04 (5.1$\sigma$)</td>
<td></td>
</tr>
</tbody>
</table>

The ratios listed in the tables define the reduction in the probability due to a change in resistor value or common mode algorithm. These ratios are less sensitive to the (correlated) systematic uncertainties associated with the probability measurements. The errors associated with these ratios reflect only the statistical uncertainties associated with the probability measurements.

The systematic uncertainty reflects the effect of varying the thresholds used to identify highly ionising events and clusters on the magnitude of $N_{\text{hie}}$ and $N_{\text{path}}$. The seed-strip signal threshold, $S_{\text{seed}} \geq 125$ ADCch, is varied by ±20 % and the mean (absolute) fractional change in the magnitude of $N_{\text{hie}}$ defines the systematic uncertainty. The uncertainty associated with $N_{\text{path}}$ is defined to be the mean (absolute) fractional change in the number of reconstructed clusters when the cluster signal threshold $T_{\text{clu}}$ is increased from the nominal value of 5 to the values 8 and 12 for the TIB and TEC/TOB sensor planes, respectively.

The $\text{rms}$ spread is defined to be the spread in the probability measurements obtained from individual APV25 chips of a detector configuration group relative to the ‘weighted-mean’ probability measurement of the group as a whole. This $\text{rms}$ spread is indicative of differences in probability measurements between individual APV25 chips due to: the (in)effectiveness of the threshold criteria to suppress the contribution of out-of-time particles and highly ionising events in the sensor regions not subject to the trigger pre-filter; differences in the sensitivity of individual chips to

*The maximum valid threshold on the HIE seed-strip signal is considered to be 150 ADCch, as illustrated by figure 5.6 (p. 125). This corresponds to an increase of 20 % on the threshold of 125 ADCch chosen to identify HIEs and explains the choice of ±20 % variation in the threshold used to assess the associated systematic uncertainty.
6.1 Rate Measurements of Highly Ionising Events

highly ionising events due to differences in their configuration (notably the position of the baseline within the dynamic range); and the increased illumination of downstream sensors due to collisions between beam particles and the support structure used to house the tracking system.

The HIE probability measurements provide several important results which are summarised below:

- All measurements of $P(\text{CM}_{hie} \leq -20)$ are observed to be $O(10^{-3})$; the total uncertainties associated with these measurements are less than $\sim 25\%$.

- The HIE probability is not expected to scale with beam intensity. The measurements for the three different $\pi^-$ beam intensities differ at most by $\sim 25\%$; this difference is not significant within the measurement uncertainties. This comparison provides an important check on the effectiveness of the selection criteria to correctly identify ‘in-time’ highly ionising events and minimum ionising particles, and also reflects the effect of the different APV25 configurations used during data-taking.

- The probability is seen to scale with sensor thickness; the mean ratio of probabilities measured for TIB and TOB modules is $0.45 \pm 0.06$ (compared with a sensor thickness ratio of 0.64).

- A reduction in the HIE probability is expected for modules equipped with 50 $\Omega$ resistors with respect to those equipped with 100 $\Omega$ resistors. The ratios of the probabilities obtained for TIB and TOB modules separately, $P_{hie}(50/100)_{\text{TIB}}$ and $P_{hie}(50/100)_{\text{TOB}}$, are listed for the various beam configurations in tables 6.1 and 6.2. The mean ratios are $0.71 \pm 0.03$ (9.9$\sigma$) and $0.85 \pm 0.01$ (11.1$\sigma$), respectively.

- The measured probabilities obtained with the medium intensity $\pi^+$ beam are $\sim 40\%$ higher than the corresponding measurements made with the $\pi^-$ beam, which reflects the enhanced $\pi^+$-Si (elastic) cross section relative to the $\pi^-$-Si cross section.$^9$

$^9$Elastic collisions are capable of generating energy depositions of up to a few MeV; such depositions are expected to shift the baseline without causing deadtime.
6.1 Rate Measurements of Highly Ionising Events

No significant difference in the HIE probability is observed for the inverting and non-inverting modes of operation.

6.1.4 Probability Measurements with Protons

The PSI beamline also provided protons with 300 MeV/c momentum \((\beta = 0.31)\), equivalent to a kinetic energy of 46 MeV. These slow moving protons are not minimum-ionising; the Bethe-Bloch equation [64] predicts an energy loss rate of \(dE/dx = \sim 2.4 \text{ keV } \mu\text{m}^{-1}\), equivalent to \~6 minimum ionising pions. The most probable signal induced by these slow moving protons in the TIB and TEC sensor planes are \~180 ADCch and \~270 ADCch, respectively.\(^{10}\) These values are a factor six larger than the corresponding values of \~30 ADCch and \~45 ADCch observed for minimum ionising pions in the corresponding planes. Figure 6.11 (top) shows the seed-strip signal distribution of all clusters reconstructed in the third TEC sensor plane. A strong peak is observed at \~180 ADCch due to the (relatively) highly ionising protons; a peak approximately two orders of magnitude smaller in strength is observed at \~45 ADCch and is due to the small contamination (\~2 \%) of \(\pi^+\) in the proton beam.

\(^{10}\)The majority of the slow moving protons do not reach the second box of TOB sensor planes as the protons must traverse several mm of silicon and aluminium before reaching the first TOB plane. Hence, only the TIB and TEC planes are considered in the analysis.
### 6.1 Rate Measurements of Highly Ionising Events

<table>
<thead>
<tr>
<th>Sensor type and $R_{inv}$ [Ω]</th>
<th>$P_{hie} (\text{CM}_{hie} \leq -40) \times 10^{-4}$ protons, high intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIB 50</td>
<td>4.5 ± 0.8 ± 2.6 ± 1.6</td>
</tr>
<tr>
<td>TIB 100</td>
<td>10.1 ± 1.7 ± 5.7 ± 4.2</td>
</tr>
<tr>
<td>TEC 100</td>
<td>29.5 ± 1.5 ± 16.7 ± 11.2</td>
</tr>
<tr>
<td>$P_{hie}(50/100)_{\text{TIB}}$</td>
<td>0.45 ± 0.11 (5.0σ)</td>
</tr>
</tbody>
</table>

Table 6.3: Measurements of $P_{hie}(\text{CM}_{hie} \leq -40)$ for various module configurations and a high intensity proton beam. Also quoted are the statistical and systematic errors and the rms spread.

The signals generated by the passage of slow protons through the TIB and TEC sensor planes are sufficiently large to induce common mode shifts. Figure 6.11 (bottom) shows the common mode distribution obtained from an APV25 chip of a TEC module illuminated with the 300 MeV/c proton beam. The strong, broad peak centred at -15 ADCch is due to the relatively large (and wide, typically three or four strips) signals generated by the slow protons. Furthermore, the seed-strip signal generated by 300 MeV/c protons is larger than the 125 ADCch threshold required to identify highly ionising events. Hence, slow protons can generate highly ionising events (as defined by this analysis) through electronic ionisation in the silicon sensor planes, as well as through nuclear collisions. This is important as low energy (and therefore relatively highly-ionising) hadrons will be confined to the Tracker region by the 4 Tesla magnetic field.

Physics simulations of minimum bias events in the CMS Tracker predict that only protons will release energies of more than 10 MeV through ionisation, with a probability which is approximately 10 times larger than the probability with which a nuclear interaction results in an equivalent energy release; lower energy releases are observed with increasing probability. However, it can be assumed that the energy depositions generated by these ‘ionisation HIEs’ will not be as localised as those generated by nuclear collisions, hence the likelihood of one or more APV25 channels being driven into saturation is reduced. Furthermore, the reduction of the inverter resistor value to 50 Ω is expected to raise the energy deposition threshold to $\sim$15 MeV. Charged particles other than protons can release up to 2 MeV; it is estimated that 1.5 % of APV25 chips per bunch crossing will be affected by energy releases of this magnitude. However, it is highly probable that only protons will be able to induce deadtime in the APV25 chip through ionisation.
Figure 6.12 shows the cumulative probability curves obtained for three module configurations: TIB modules equipped with 100 Ω and 50 Ω resistors, and TEC modules equipped with 100 Ω resistors. The contribution of ‘ionisation HIEs’ to the cumulative probability is only observed for the TEC modules (the common mode levels induced in the TIB modules by the 300 MeV/c protons are $>-20$ ADCch). Table 6.3 summarises the probability measurements of $P_{hie}(CM_{hie} \leq -40)$; note the value of $CM_{th}$ is chosen so the probabilities reflect only the contribution of nuclear interactions to $P_{hie}$.

The response of the APV25 chip to 300 MeV/c protons can be used to estimate the energy deposition threshold and provide a cross-check of the laboratory measurements. A 300 MeV/c proton is expected to release 0.9 MeV in 500 μm of silicon, which is observed to induce a (most probable) common mode shift of 15 ADCch. Assuming the baseline shift varies linearly with the magnitude of the collected signal and given that a shift of $\sim 120$ ADCch is required to fully suppress the baseline, an energy deposition of $\sim 7.2$ MeV is required to induce deadtime in the APV25 chip. This estimate is comparable to the thresholds measured in the laboratory.

### 6.1.5 Deadtime Probability Measurements

APV25 chips experiencing deadtime are identified by the $\sigma_{raw}$ variable, as described in chapter 5, thus measurements of the deadtime probability, $P_{hie}(\sigma_{raw} < 1)$, are possible. Table 6.4 summarises the deadtime probability measurements obtained for the six groups of different module configurations and various beam configurations. The quoted probabilities can be compared with the lower end points of the cumulative probability curves shown in figures 6.5 to 6.8 (p. 156). The mean deadtime probability measurements for $\pi^-$ traversing 500 μm sensors, instrumented by APV25 chips equipped with 100 Ω and 50 Ω resistor values, are $(7.4 \pm 0.1) \cdot 10^{-4}$ and $(4.1 \pm 0.1) \cdot 10^{-4}$ per 500 μm of silicon. These probabilities correspond to interaction lengths of 68 cm and 122 cm, respectively, which are in excellent agreement with the predictions made in chapter 3 based on the X5 measurements and the physics simulation results. The mean reduction in the deadtime probability due to the change in resistor value is $61 \pm 3$ % and $47 \pm 1$ % for $\pi^-$ traversing TIB and TOB sensor planes, respectively. Again, these reductions are in agreements with those predicted in chapter 3.
6.1 Rate Measurements of Highly Ionising Events

<table>
<thead>
<tr>
<th>Sensor type and $R_{inu}$ [Ω]</th>
<th>$P_{hie}(\sigma_{raw} &lt; 1)$ [×10^{-4}]</th>
<th>$\pi^-$, low int</th>
<th>$\pi^-$, med int</th>
<th>$\pi^-$, high int</th>
<th>$\pi^+$, med int</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIB 50</td>
<td>1.7 ± 0.2</td>
<td>1.4 ± 0.3</td>
<td>1.0 ± 0.2</td>
<td>1.5 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>TIB 100</td>
<td>4.2 ± 0.4</td>
<td>1.6 ± 0.5</td>
<td>2.5 ± 0.3</td>
<td>4.1 ± 0.6</td>
<td></td>
</tr>
<tr>
<td>TEC 100</td>
<td>8.4 ± 0.3</td>
<td>6.1 ± 0.5</td>
<td>5.8 ± 0.3</td>
<td>7.3 ± 1.6</td>
<td></td>
</tr>
<tr>
<td>TOB 50</td>
<td>4.9 ± 0.2</td>
<td>3.0 ± 0.3</td>
<td>3.8 ± 0.2</td>
<td>5.2 ± 2.6</td>
<td></td>
</tr>
<tr>
<td>TOB 75</td>
<td>6.4 ± 0.8</td>
<td>8.9 ± 1.7</td>
<td>7.2 ± 0.7</td>
<td>10.9 ± 2.3</td>
<td></td>
</tr>
<tr>
<td>TOB 100</td>
<td>7.6 ± 0.3</td>
<td>7.5 ± 0.6</td>
<td>8.3 ± 0.3</td>
<td>10.3 ± 1.8</td>
<td></td>
</tr>
<tr>
<td>$P_{hie}(50/100)_{TIB}$</td>
<td>0.41 ± 0.05</td>
<td>0.89 ± 0.33</td>
<td>0.41 ± 0.08</td>
<td>0.36 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>$P_{hie}(50/100)_{TOB}$</td>
<td>0.64 ± 0.03</td>
<td>0.40 ± 0.05</td>
<td>0.52 ± 0.03</td>
<td>0.50 ± 0.02</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.4: Deadtime probability measurements, $P_{hie}(\sigma_{raw} < 1)$, for various module and beam configurations. Also quoted are the total uncertainties.

6.1.6 Predicting HIE Rates in the CMS Tracker

The rate $R_{hie}^i$ at which APV25 chips will be affected by highly ionising events in the CMS Tracker due to particles of type $i$ undergoing nuclear collisions is given by:

$$R_{hie}^i = \frac{1}{\lambda_{hie}^i} \cdot w^i \cdot \bar{l}_{path}^i$$  \hspace{1cm} (6.2)

where $\lambda_{hie}^i$ is the HIE interaction length (defined in section 6.1.2) and $\bar{l}_{path}^i$ is defined to be the average path-length of the $i$th particle type through part of a sensor instrumented by a single APV25 chip per bunch crossing, given by $V \cdot \Phi \cdot T_{bx}$, where $V$ is the sensor volume instrumented by a single APV25 chip, $\Phi$ is the mean flux observed for the $i$th particle type and $T_{bx}$ is the bunch crossing period. The rate is independent of the particle incidence angle. The weight $w^i$ accounts for the probability of the $i$th particle type to generate a highly ionising event through electronic ionisation, relative to the probability of that particle generating a highly ionising event through a nuclear interaction. Based on the arguments presented in section 6.1.4, protons are assigned a weight of 10 and all other hadrons a weight of 1.

The vast majority of highly ionising events expected in the CMS Tracker will be due to interactions between silicon sensors and the particle flux of minimum bias (MB) events. These MB events consist of low momentum hadrons confined by the magnetic field to the inner region of the Tracker. A FLUKA simulation of the Tracker radiation environment [51] provides an estimate of the total hadron flux\(^{11}\)

\(^{11}\)Only pions, protons, kaons and neutrons with energies $>20$ MeV are considered in this ‘total hadron flux’.
6.2 Secondary Highly Ionising Events

Table 6.5: Average particle fluxes, \( \Phi \), and total average (weighted) path-lengths per bunch crossing per APV25 chip, \( w^i \cdot \bar{T}_{\text{path}}^{i} \), for various particles traversing the first TIB and TOB sensor planes. Sensor volumes instrumented by a single APV25 chip are 119(l) \( \times 15.4(w) \times 0.32(d) \) mm\(^3\) and 189(l) \( \times 23.4(w) \times 0.5(d) \) mm\(^3\) for the TIB and TOB sensors, respectively.

<table>
<thead>
<tr>
<th>Particle</th>
<th>( w^i )</th>
<th>Radius of 22 cm (( \sim )TIB1)</th>
<th>Radius of 58 cm (( \sim )TOB1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^\pm )</td>
<td>1</td>
<td>2.06 ( \pm ) 0.03</td>
<td>301 ( \pm ) 0.01</td>
</tr>
<tr>
<td>( p )</td>
<td>10</td>
<td>0.20 ( \pm ) 0.01</td>
<td>297 ( \pm ) 0.01</td>
</tr>
<tr>
<td>( K^\pm )</td>
<td>1</td>
<td>0.18 ( \pm ) 0.01</td>
<td>27 ( \pm ) 0.01</td>
</tr>
<tr>
<td>( n )</td>
<td>1</td>
<td>0.33 ( \pm ) 0.01</td>
<td>48 ( \pm ) 0.01</td>
</tr>
<tr>
<td>Total</td>
<td>1</td>
<td>2.77 ( \pm ) 0.03</td>
<td>673 ( \pm ) 0.01</td>
</tr>
</tbody>
</table>

and the various individual contributions for different regions of the Tracker. The predicted fluxes for the innermost TIB and TOB layers and the estimated total average total path-lengths of the various particles comprising the total hadron flux are summarised in table 6.5.

The rate at which deadtime will be observed in APV25 chips with a resistor value of 50 \( \Omega \), due to pions at the innermost TIB layer (where the pion flux is highest), is estimated as follows. Assuming a HIE interaction length of \( \lambda_{hie}^\pi = 235 \) cm (based on an averaged HIE probability for all \( \pi^- \) beam intensities) and given that the average pion path-length is 301 \( \mu \)m (as quoted in table 6.5), the predicted rate for observing deadtime is \( R_{hie}^\pi (\sigma_{\text{raw}} < 1) = (1.3 \pm 0.1) \cdot 10^{-4} \) per bunch crossing. Similarly, the rate at which highly ionising events will induce a common mode level of \( \text{CM}_{hie} \leqslant -20 \) ADCch is predicted to be \( R_{hie}^\pi (\text{CM}_{hie} \leqslant -20) = (6.5 \pm 0.8) \cdot 10^{-4} \) per bunch crossing.

The total rate, \( R_{hie}^{\text{tot}} \), is estimated by summing the individual rates over all particle types. Assuming the HIE interaction length is comparable for all particle types, the total rate is expected to be (approximately) double the rate observed for pions, as the total (weighted) path-length for all particle types is approximately double that predicted for pions.

6.2 Secondary Highly Ionising Events

The light products of inelastic nuclear collisions, such as protons and \( \alpha \) particles, have ranges of several mm in silicon and so can be expected to exit the silicon sensor
6.2 Secondary Highly Ionising Events

and traverse further sensor planes. For an incident pion momentum of 300 MeV/c, the most probable (kinetic) energies of these light collision products (as predicted by simulation) are in region of 10-100 MeV. Protons of these energies are not minimum ionising and the proton-silicon cross section is also significantly enhanced at these low energies. Thus, the products of highly ionising events can be expected to generate further secondary highly ionising events, either through electronic ionisation or nuclear interactions, and the probability of these secondary highly ionising events is expected to be enhanced with respect to the various (primary) HIE probabilities quoted earlier in this chapter.

6.2.1 Identifying Primary and Secondary HIEs

In order to measure the probability of observing secondary HIEs, it must be possible to distinguish between primary and secondary HIEs. This is difficult, because successful track reconstruction of particles that undergo nuclear interactions is either rare in the case of primary HIEs, or not possible in the case of secondary HIEs. Therefore, primary and secondary HIEs are distinguished by the presence of a MIP signal within a pre-defined window in the upstream sensor plane: if present, the (primary) HIE is assumed to result from a nuclear interaction of a beam particle in a sensor plane; if no signal is present, then the (secondary) HIE is assumed to result from a nuclear interaction between a (scattered) primary HIE collision product and a sensor plane.

6.2.2 Probability Measurements for Primary HIEs

The probability measurements of $P_{\text{hie},1}(\text{CM}_{\text{hie},1} \leq -20)$ and $P_{\text{hie},1}(\sigma_{\text{raw},1} < 1)$ for primary HIEs, are derived from a sample of highly ionising events for which signal is observed within a pre-defined window in the upstream sensor plane.\(^\text{12}\) The measurements are listed in tables 6.6 and 6.7. Only the TOB sensor planes are considered. The corresponding probability curves obtained with low and high intensity $\pi^-$ beams are illustrated in figure 6.10 (p. 156).

\(^\text{12}\)The window size is determined by the residuals observed between the positions of HIE signals and the upstream MIP signals, as shown in figure 5.4 (p. 123).
6.2 Secondary Highly Ionising Events

Table 6.6: Measurements of $P_{hie,1}(\text{CM}_{hie,1} \leq -20)$ for primary highly ionising events (identified by the presence of a MIP signal in the upstream sensor plane). Also quoted are the total uncertainties.

<table>
<thead>
<tr>
<th>Sensor type and $R_{inv}$ [$\Omega$]</th>
<th>$P_{hie,1}(\text{CM}_{hie,1} \leq -20)$ [$\times 10^{-4}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\pi^-$, low int</td>
</tr>
<tr>
<td>TOB 50</td>
<td>$4.1 \pm 4.2$</td>
</tr>
<tr>
<td>TOB 100</td>
<td>$6.5 \pm 4.2$</td>
</tr>
<tr>
<td>$P_{hie,(50/100)}$ [TOB]</td>
<td>$0.63 \pm 0.03$</td>
</tr>
</tbody>
</table>

Table 6.7: Deadtime probability measurements, $P_{hie,1}(\sigma_{raw,1} < 1)$, for primary HIEs (identified by the presence of a MIP signal in the upstream sensor plane). Also quoted are the total uncertainties.

<table>
<thead>
<tr>
<th>Sensor type and $R_{inv}$ [$\Omega$]</th>
<th>$P_{hie,1}(\sigma_{raw,1} &lt; 1)$ [$\times 10^{-4}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\pi^-$, low int</td>
</tr>
<tr>
<td>TOB 50</td>
<td>$1.4 \pm 4.2$</td>
</tr>
<tr>
<td>TOB 100</td>
<td>$4.0 \pm 4.2$</td>
</tr>
<tr>
<td>$P_{hie,(50/100)}$ [TOB]</td>
<td>$0.35 \pm 0.03$</td>
</tr>
</tbody>
</table>

The magnitudes of $P_{hie,1}(\text{CM}_{hie,1} \leq -20)$ and $P_{hie,1}(\sigma_{raw,1} < 1)$ are approximately a factor two lower than the corresponding ‘all-inclusive’ probability measurements presented in section 6.1.3. This is due in part to the presence of secondary HIEs, which result from the scattered products of primary HIEs particles (as opposed to beam particles). However, there is a contribution from out-of-time highly ionising events, for which the upstream MIP signal is no longer observed. Additionally, nuclear interactions between the beam particles and the support and housing structures for the tracking modules can illuminate the sensor planes with slow-moving, and therefore highly ionising, hadrons. These contributions ‘pollute’ the sample of secondary HIEs, hence the secondary HIE sample is likely to be over-estimated.

6.2.3 Probability Measurements for Secondary HIEs

The generation of secondary HIEs is studied using trigger-burst data, as these data provide information over a large time interval, thus more confidence can be attached to correctly identifying secondary HIEs.\(^{13}\) The methodology is as follows. All HIEs identified during each trigger burst are categorised as either primary or secondary HIEs, as described above. All secondary HIEs found within a pre-defined temporal

\(^{13}\)As a cross-check, this analysis is also been performed on data collected with single triggers, for both low and high intensity $\pi^-$ beams. The results are in good agreement.
window around a primary HIE are uniquely associated with that primary.\textsuperscript{14} Secondaries are required to exhibit a seed-strip signal above a (reduced) threshold of 30 ADCch. Only the TOB sensor planes are considered and all APV25 chips are used in the analysis to maximise the statistics.

Figure 6.13 plots the relationship between common mode shifts induced by primaries and those induced by secondaries; the shifts are expressed in terms of the CM\textsubscript{ratio} variable. The CM\textsubscript{ratio} values observed for fully suppressed baselines are highlighted in red. Secondary HIEs are also observed to exhibit fully suppressed baselines.

Of the 2311 primary HIEs identified in the data sample, 16.0\% have an associated secondary HIE in at least one additional plane.\textsuperscript{15} Figure 6.14 (top) shows the (total) cumulative probability curve for a primary HIE inducing a secondary HIEs in at least one additional plane (closed markers). The contributions of the various module categories are also shown (open markers). The curve can be interpreted as “the probability of observing secondary HIEs in at least one plane, one of which exhibits a common mode level of below CM\textsubscript{thr}, given that a primary HIE is observed in a different plane”, expressed as $P(\text{CM}_{\text{hie},2} \leq \text{CM}_{\text{thr}} \mid \text{CM}_{\text{hie},1} \leq -20)$.

\textsuperscript{14}The timing of secondaries relative to primaries is $10.0 \pm 34.5 \text{ ns}$. The temporal window extends from 25 \text{ ns} prior to 50 \text{ ns} after the primary HIE.

\textsuperscript{15}80\% (15\%) of this sample of primaries have secondaries in one (two) plane(s).
Table 6.8: Summary of probabilities for: one primary HIE, two independent primary HIEs, one secondary HIE given a primary HIE, and primary and secondary HIEs, for two different thresholds. See text for further explanation. Total uncertainties are quoted unless otherwise stated.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Probability [per path-length]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{hie,1}(CM_{hie,1} \leq -20)$</td>
<td>$(5.8 \pm 1.5) \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$P_{hie,1}(CM_{hie,1} \leq -20)$ “squared”</td>
<td>$(3.4 \pm 1.2) \cdot 10^{-7}$</td>
</tr>
<tr>
<td>$P(CM_{hie,2} \leq -20 \mid CM_{hie,1} \leq -20)$</td>
<td>$(1.6 \pm 0.1) \cdot 10^{-1}$ (stat. only)</td>
</tr>
<tr>
<td>$P(CM_{hie,2} \leq -20 \cap CM_{hie,1} \leq -20)$</td>
<td>$(9.0 \pm 2.3) \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$P_{hie,1}(\sigma_{raw,1} &lt; 1)$</td>
<td>$(2.6 \pm 1.5) \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$P_{hie,1}(\sigma_{raw,1} &lt; 1)$ “squared”</td>
<td>$(6.8 \pm 5.5) \cdot 10^{-8}$</td>
</tr>
<tr>
<td>$P(\sigma_{raw,2} &lt; 1 \mid \sigma_{raw,1} &lt; 1)$</td>
<td>$(1.3 \pm 0.4) \cdot 10^{-2}$ (stat. only)</td>
</tr>
<tr>
<td>$P(\sigma_{raw,2} &lt; 1 \cap \sigma_{raw,1} &lt; 1)$</td>
<td>$(3.4 \pm 2.2) \cdot 10^{-6}$</td>
</tr>
</tbody>
</table>

6.3 Inefficiencies due to Highly Ionising Events

The total inefficiency, $\eta_{hie}(CM_{hie} \leq CM_{thr})$, expected in the Tracker readout system is provided by the product of the measured inefficiency (expressed in terms of the ‘equivalent deadtime’, $\Gamma_{hie}$) and the predicted rate ($R_{hie}$) for highly ionising events that induce a common mode level below the threshold $CM_{thr}$:

$$\eta_{hie} = R_{hie} \cdot \frac{\Gamma_{hie}}{25 \, [ns]} \quad (6.3)$$

16 This probability is the average value of those measured for the two detector configurations (100 $\Omega$ and 50 $\Omega$) and the low and high intensity pion beams.
6.3 Inefficiencies due to Highly Ionising Events

Table 6.9 summarises the predicted total inefficiencies in the CMS Tracker as a result of $\pi^-$ interactions in silicon at the innermost TIB and TOB layers, for the various combinations of resistor value, common mode algorithm and rates measured with two different beam intensities. The TIB inefficiencies are calculated under the explicit assumption that the same inefficiencies would be observed for the TIB modules as those measured for the TOB modules (i.e. that the different strip pitches have little influence on the magnitude of the observed inefficiencies) and the TIB cumulative probability distributions are simply scaled by a constant factor with respect to those observed for the TOB modules.

All predicted values are at the sub-percent level, with the highest inefficiencies expected at the innermost TIB layer. The reduction in resistor value to 50 $\Omega$ significantly reduces the total inefficiencies by $65\pm7\%$ and $52\pm8\%$ for the TIB and TOB layers, respectively. The change in common mode algorithm from the ‘global’ common mode estimator to the ‘grouped’ estimator further reduces the inefficiencies by $26\pm15\%$ for both the TIB and TOB layers. All the inefficiencies quoted in table 6.9 can be expected to (approximately) double if all particle types are considered.

6.3.1 Inefficiencies due to Deadtime

The total inefficiencies due to highly ionising events that fully suppress the APV25 baseline, identified by the condition $\sigma_{raw} < 1$ ADCch, and those that only partially
### 6.4 Effect of Fake Clusters on the Data Rate

As described in section 5.2, APV25 chips affected by highly ionising events frequently exhibit non-flat baselines during the recovery period of the chip. The proposed zero-suppression algorithms to be implemented in the Front-End Driver card implicitly assume (at present) that the APV25 baseline is flat, hence the presence of non-flat suppress the baseline, identified by the condition $\sigma_{raw} \geq 1$ ADCch, can also be calculated. Table 6.10 summarises the predicted total inefficiencies in the CMS Tracker as a result of $\pi^-$ interactions in silicon, for the innermost TIB and TOB layers and the various combinations of resistor value and common mode algorithm: the inefficiency contributions of highly ionising events that fully suppress, $\eta_{hie}(\sigma_{raw} < 1)$, and partially suppress, $\eta_{hie}(\sigma_{raw} \geq 1)$, the baseline are listed separately. It is clear that the bulk of the inefficiencies are due to highly ionising events that fully suppress the APV25 baseline. The sum of these two contributions (listed in the last column) are in close agreement with the ($\pi^-$, low int.) values listed in table 6.9. As expected, the reductions in the inefficiencies due to the change in the resistor value (common mode algorithm) are most significant for highly ionising events that induce fully suppressed (partially suppressed) baselines.

#### Table 6.10: Total inefficiency due to highly ionising events that induce partially, $\eta_{hie}(\sigma_{raw} < 1)$, or fully, $\eta_{hie}(\sigma_{raw} \geq 1)$, suppressed baselines, for a low intensity $\pi^-$ beam incident on various module configurations. The total inefficiencies are also quoted (last column). Also quoted are the total uncertainties.

<table>
<thead>
<tr>
<th>Sensor plane, CM algo. and $R_{raw}$ [$\Omega$]</th>
<th>$\eta_{hie}(\sigma_{raw} &lt; 1)$ [%]</th>
<th>$\eta_{hie}(\sigma_{raw} \geq 1)$ [%]</th>
<th>Total [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIB1 CM$_{128}$ 100</td>
<td>0.55 ± 0.06</td>
<td>0.10 ± 0.03</td>
<td>0.65 ± 0.08</td>
</tr>
<tr>
<td>TIB1 CM$_{128}$ 50</td>
<td>0.16 ± 0.03</td>
<td>0.08 ± 0.02</td>
<td>0.24 ± 0.03</td>
</tr>
<tr>
<td>TIB1 CM$_{16}$ 100</td>
<td>0.57 ± 0.06</td>
<td>0.07 ± 0.03</td>
<td>0.63 ± 0.08</td>
</tr>
<tr>
<td>TIB1 CM$_{16}$ 50</td>
<td>0.14 ± 0.02</td>
<td>0.03 ± 0.01</td>
<td>0.16 ± 0.02</td>
</tr>
<tr>
<td>TIB1 $\eta_{hie}(50/100)_{128}$</td>
<td>0.46 ± 0.07 (7.3$\sigma$)</td>
<td>0.71 ± 0.30 (1.0$\sigma$)</td>
<td>0.50 ± 0.08 (6.5$\sigma$)</td>
</tr>
<tr>
<td>TIB1 $\eta_{hie}(16/128)_{50}$</td>
<td>0.83 ± 0.16 (1.0$\sigma$)</td>
<td>0.35 ± 0.17 (3.8$\sigma$)</td>
<td>0.72 ± 0.13 (2.2$\sigma$)</td>
</tr>
<tr>
<td>TOB1 CM$_{128}$ 100</td>
<td>0.40 ± 0.08</td>
<td>0.07 ± 0.04</td>
<td>0.50 ± 0.09</td>
</tr>
<tr>
<td>TOB1 CM$_{128}$ 50</td>
<td>0.18 ± 0.09</td>
<td>0.06 ± 0.04</td>
<td>0.21 ± 0.09</td>
</tr>
<tr>
<td>TOB1 CM$_{16}$ 100</td>
<td>0.41 ± 0.09</td>
<td>0.05 ± 0.03</td>
<td>0.49 ± 0.09</td>
</tr>
<tr>
<td>TOB1 CM$_{16}$ 50</td>
<td>0.15 ± 0.08</td>
<td>0.02 ± 0.02</td>
<td>0.16 ± 0.08</td>
</tr>
<tr>
<td>TOB1 $\eta_{hie}(50/100)_{128}$</td>
<td>0.40 ± 0.22 (2.8$\sigma$)</td>
<td>0.60 ± 0.57 (0.7$\sigma$)</td>
<td>0.42 ± 0.20 (2.9$\sigma$)</td>
</tr>
<tr>
<td>TOB1 $\eta_{hie}(16/128)_{50}$</td>
<td>0.86 ± 0.61 (0.2$\sigma$)</td>
<td>0.36 ± 0.46 (1.4$\sigma$)</td>
<td>0.78 ± 0.51 (0.4$\sigma$)</td>
</tr>
</tbody>
</table>
baselines results in the reconstruction of ‘fake’ clusters and an increase in the data transmission rate from the FED card to the DAQ computing farm. The increase in the data rate per FED card, $R_{fake}$ [MB/s], is estimated by equation 6.4:

$$R_{fake} = R_{hie} \cdot f_{T1} \cdot N_{apv} \cdot \frac{(2N_{clusters} + N_{strips})}{(1024)^2}$$ (6.4)

where $R_{hie}$ is the rate at which APV25 chips are affected by highly ionising events, $f_{T1}$ is the T1 trigger rate ($10^5$ Hz) and $N_{apv}$ is the number of APV25 chips instrumented by each FED (196). The FED outputs two bytes of information per cluster (location and width of cluster) and one byte for each strip associated with a cluster [118]. The increase in the FED data rate is summarised in Table 6.11. The estimates are based on the predicted pion HIE rates, $R_{hie}(CM_{hie} \lesssim -20)$, which are scaled by a factor 673/301 to reflect the contribution of all particle types.\footnote{This assumes the interaction lengths of all the particle types are comparable to the pion value. The rates used to estimate the increase in data rate are $(17.5 \pm 3.0) \cdot 10^{-4}$ and $(14.1 \pm 2.1) \cdot 10^{-4}$ for APV25 chips with resistor values of 100 $\Omega$ and 50 $\Omega$, respectively.}

The data rates obtained with the ‘global’ common mode algorithm comprise a significant fraction of the nominal data rate per FED card of 103 MB/s [119]; a significant improvement is observed for the ‘grouped’ common mode estimator, with the extra data rate reduced to a manageable level. Studies performed on data collected during the August 2002 X5 beam test [116] show that the increase in the data rate is at least a factor $\sim$2 smaller for APV25 chips operated in deconvolution mode with respect to those operated in peak mode.

### 6.5 Effect on the Tracker Performance

The effect of highly ionising events on the physics performance of the CMS Tracker has been simulated with CMSIM/ORCA [116]. Physics events were simulated by
superimposing ‘signal events’ over minimum bias (MB) events. The inefficiencies observed in any given event comprise the total inefficiencies generated by the hadron flux of a MB event and those generated by the superimposed ‘signal event’.

A track usually results from a fit to 11 points and is only lost if two consecutive hits are missing [108]. Hence, the tracking inefficiency due to independent highly ionising events\(^{18}\) is estimated to be \(10 \times (\eta_{\text{hie}})^2\). Assuming all particle types are considered and a resistor value of 50 \(\Omega\) is used, the total hit inefficiency due to the hadron flux of MB events at the innermost TIB layer is estimated to be \(\eta_{\text{hie}} = 0.42 \pm 0.07\%\). Therefore, based on this ‘worst-case’ inefficiency, the resulting tracking inefficiency is predicted to be \(~0.02\%\).

The simulation predicts a slightly higher hit inefficiency of \(0.9 \pm 0.2\%\) at the innermost TIB layer for a signal event containing a high-\(p_T\) single muon track, based on the rate and inefficiency measurements presented in [116]. This hit inefficiency increases to \(1.6 \pm 0.2\%\) for signal events containing a high-\(p_T\) \(b\)-jet, due to the increased local hit occupancy within the jet cone.\(^{19}\) Thus, the simulation predicts a tracking inefficiency of \(0.08\%\) for muon tracks and \(0.2\%\) for \(b\)-jets.

Encouragingly, the tracking \(b\)-tagging efficiencies are relatively robust to inefficiencies in the readout system. A very conservative estimate of the upper limit for the hit inefficiencies induced by highly ionising events is considered to be \(5\%\); this results in a (manageable) reduction in the \(b\)-tagging efficiency by \(5\%\).

### 6.6 Summary

Analysis of the single-trigger data has provided cumulative probability measurements for highly ionising events, with various module configurations and different beam environments. The probability of a highly ionising event inducing a common mode level of \(\text{CM}_{\text{hie}} \leq -20\ \text{ADCch}\) is \(\sim10^{-3}\) and the measurements are accurate to \(\pm25\%\). The probability of observing deadtime is approximately a factor two lower.

Significant reductions in the HIE probabilities are observed if the reduced inverter resistor value of 50 \(\Omega\) is used. However, the 50 \(\Omega\) resistor value results in the

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\(^{18}\)No simulations have yet been performed which account for the enhanced rate of secondary HIEs that are induced by primary HIEs.

\(^{19}\)For comparison, the intrinsic readout inefficiencies (e.g. due to Landau fluctuations) are predicted to be \(0.4 \pm 0.1\%\).
reconstruction of an increased number of non-physical hits (due to non-flat baselines) relative to the 100 Ω resistor value. This effect can be negated by using a more sophisticated ‘grouped’ common mode estimator during data zero-suppression, which reduces the data rate increase due to these ‘fake’ hits to a manageable level.

The rates at which APV25 chips are affected in the CMS Tracker have been estimated using experimental probability measurements and hadron flux predictions provided by simulation. These rates are combined with the measurements of the inefficiencies induced by highly ionising events, as described in chapter 5, to predict the total inefficiency introduced into the Tracker readout system. Both a reduction in the resistor value and a change to a ‘grouped’ common mode algorithm results in a significant reduction in the total inefficiency. The predicted total inefficiency is at the sub-percent level in all areas of the Tracker for APV25 chips equipped with 50 Ω inverter resistors. The effect on tracking performance and $b$-tagging efficiency is negligible, even when assuming a very conservative estimate for the total inefficiency.
Conclusions

The motivation for the Large Hadron Collider is the large range of new physics expected at the TeV energy scale. The Compact Muon Solenoid detector is one of four large LHC experiments being constructed in order to take advantage of the extended physics reach provided by the LHC. The CMS Tracker subdetector will play a major role in all physics searches and is required to provide high performance tracking within a hostile radiation environment. The Tracker project has pioneered the use of a commercial 0.25 µm CMOS technology within its control and readout systems, with the readout system based on the APV25 analogue readout chip.

This thesis presents work relating to the production testing of the APV25 chip and a study of the effect of highly ionising events in silicon sensors on the performance of the APV25 chip.

APV25 Production Testing

The CMS Tracker readout system must be of the highest quality if the demanding physics requirements of the subdetector are to be met. Sources of inefficiencies within the readout system must be minimised and therefore the efficient screening of APV25 die before integration into the final system is of paramount importance.

This screening is most efficiently performed using an automated wafer screening procedure and so a production test station has been developed to perform this task. Each and every APV25 chip is comprehensively screening by a series of tests, which validate the functionality and performance of each chip. Only those sites that satisfy all the selection criteria of the screening procedure will be used to instrument the CMS Tracker.
The production test station has proven to be highly effective at screening APV25 die and has matched the demand for screening die required by the aggressive module production schedule. The test station has screened over 300 wafers and approximately 70 % of the chips needed to fully instrument the Tracker have been accumulated, of which a large fraction have already been integrated into the final readout system. An analysis of the data collected during screening illustrates the excellent performance of the APV25 chips selected for use in the Tracker.

**Initial Studies of Highly Ionising Events**

Inelastic nuclear collisions between incident hadrons and nuclei of silicon sensors are capable of generating energy depositions equivalent to several hundred minimum ionising particles. These highly ionising events can saturate the instrumenting APV25 chip, resulting in deadtime and introducing inefficiencies into the readout system.

The effect of highly ionising events on the APV25 chip were first observed during the X5 Beam Test of October 2001. An analysis of the beam test data revealed that the resulting large energy depositions can cause measurable deadtime in all 128 channels of the affected APV25 chip. This crosstalk effect is aggravated by the biasing scheme used to power the front-end amplifying stages of the chip. The analysis revealed that deadtimes of up to 350 ns were observed and deadtime was observed with a probability of $\mathcal{O}(10^{-4})$ per particle crossing.

The measurements provided by the analysis were confirmed by complementary studies involving a physics simulation of nuclear collisions in silicon and a simulation of highly ionising events in the laboratory. The simulation showed that essentially all highly ionising events are a result of inelastic collisions between incident hadrons and silicon sensors, capable of generating energy depositions of up to $\sim 200$ MeV (equivalent to $\sim 1000$ minimum ionising particles). The laboratory measurements revealed that the energy deposition must be above a threshold of $\sim 10$ MeV before deadtime is observed. The measurements also revealed that a reduction in value of a resistor component mounted on the Front-End Hybrid could significantly reduce the effect. The results obtained from these studies were used to perform an extrapolation of the effect to the CMS environment, which predicted total readout inefficiencies of $\mathcal{O}(10^{-3})$. 
Conclusions

**Detailed Studies of Highly Ionising Events**

A dedicated beam test was undertaken at PSI in May 2002 in order to perform detailed measurements to quantify the effect of highly ionising events on a complete readout system using many final-version components in an environment comparable to that predicted for the CMS Tracker. Special trigger conditions were used to provide data sets conducive to clean unbiased measurements of the rates and induced deadtimes.

An analysis of data collected using trigger bursts provided a detailed understanding of the recovery of the APV25 chip following a highly ionising event. Inefficiencies in hit reconstruction due to the effects of highly ionising events on the APV25 chip have been measured using a track-based method, which allows to search for and identify signal in the output data of affected chips. The signals generated by minimum ionising particles are shown to be suppressed during the deadtime period. The recovery of the chip is characterised in terms of the temporal evolution of the measured inefficiencies. The total inefficiency observed during the recovery following a highly ionising event, expressed in terms of an ‘equivalent deadtime’, can be as large as \(\sim 350\) ns. The reduction in value of the hybrid resistor significantly reduces the observed inefficiencies by up to 47%.

Additionally, the 128 channels of an affected chip are observed to recover at different rates, resulting in non-flat baselines. This has consequences for the Front-End Driver card, which employs zero-suppression algorithms that (at present) implicitly assume uniform levels across the 128 channels of a chip. The use of these zero-suppression algorithms consequently introduces further (small) inefficiencies into the readout system and also results in the generation of non-physical signals and, consequently, an increased data rate. The use of a more sophisticated algorithm is shown to negate these effects.

A further analysis has provided a range of precise measurements of the probability of the APV25 chip being affected by a highly ionising event, for various module configurations and beam environments. Significant reductions in these probabilities are observed if the reduced hybrid resistor value is used. Further (small) reductions are predicted if relatively simple changes to the FED zero-suppression algorithms are made.
These measurements allow an extrapolation to the CMS Tracker environment with confidence. The predicted rates of highly ionising events inducing deadtime in the APV25 at the innermost Tracker layer is predicted to be $\mathcal{O}(10^{-4})$ with the reduced hybrid resistor value. The predicted rates are used in conjunction with the inefficiency measurements to estimate the total inefficiency introduced into the Tracker readout system through the effects of highly ionising events on the APV25 chip. The total inefficiency is predicted to be at the sub-percent level in all areas of the Tracker for APV25 chips equipped with the reduced resistor value. The effect of highly ionising events on tracking performance and $b$-tagging efficiencies has been shown to be negligible, even for very conservative estimates for the total inefficiency.
The APV25 chip [34] is configured via a two wire serial interface designed to conform to the Philips I²C standard [48]. This interface provides access to the on-chip registers used to store the parameter settings that define the chip operating modes and the on-chip bias voltages and currents.

**Chip Addressing**

The APV25-S1 may only act as a slave device and a maximum of 31 chips can share the same controller and maintain unique addresses. The chip is addressed using the standard 7-bit mode, where the two MSB are ‘01’ and the remaining five bits are the address bits. On-chip logic compares the address broadcasted via the I²C bus to the chip address (as determined by which of five address pads are bonded) to determine whether the chip is being addressed. The address ‘11111’ is reserved for global addressing, to which all chips respond.

**Communication Protocol**

The APV25 chip has a command register that must be programmed before data may be transferred. The command determines the register to be accessed and the direction of data transfer. The LSB (the ‘read bit’) of the command determines whether a read (bit high) or a write (bit low) transaction will take place.

Data are written to the chip in a transaction comprising three 8-bit data packets: **chip address** (read bit low); **command** (read bit low); **value**.

Reading data from the chip requires two separate transactions. The first transaction involves writing to the command register with two 8-bit data packets: **chip**
Table A.1: Summary of APV25 on-chip registers.

<table>
<thead>
<tr>
<th>Register</th>
<th>Brief description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPRE</td>
<td>Preamplifier current bias.</td>
</tr>
<tr>
<td>IPCASC</td>
<td>Preamplifier cascode current bias.</td>
</tr>
<tr>
<td>IPSF</td>
<td>Preamplifier source follower current bias.</td>
</tr>
<tr>
<td>ISHA</td>
<td>Shaper current bias.</td>
</tr>
<tr>
<td>ISSF</td>
<td>Shaper source follower current bias.</td>
</tr>
<tr>
<td>IPSP</td>
<td>APSP current bias.</td>
</tr>
<tr>
<td>IMUXIN</td>
<td>Multiplexer current bias.</td>
</tr>
<tr>
<td>ISPARE</td>
<td>Not used.</td>
</tr>
<tr>
<td>ICAL</td>
<td>Calibrate edge generator current bias.</td>
</tr>
<tr>
<td>VFP</td>
<td>Preamplifier feedback voltage bias.</td>
</tr>
<tr>
<td>VFS</td>
<td>Shaper feedback voltage bias.</td>
</tr>
<tr>
<td>VPSP</td>
<td>APSP voltage level adjust.</td>
</tr>
<tr>
<td>CDRV</td>
<td>Calibrate output mask.</td>
</tr>
<tr>
<td>CSEL</td>
<td>Calibrate delay select (fine delay for pulse shape reconstruction).</td>
</tr>
<tr>
<td>MODE</td>
<td>Operating modes (see text for explanation).</td>
</tr>
<tr>
<td>LATENCY</td>
<td>Delay between pipeline write and read pointers (set to trigger latency).</td>
</tr>
<tr>
<td>MUXGAIN</td>
<td>Gain of multiplexer stage.</td>
</tr>
<tr>
<td>ERROR</td>
<td>Provides error flags for FIFO memory and latency check.</td>
</tr>
</tbody>
</table>

**address** (read bit high); **command** (read bit high). The second transaction involves reading from the command register, which again comprises two 8-bit data packets: **chip address** (read bit high); **value**.

**Summary of On-Chip Registers**

Table A.1 summarises the on-chip registers accessible via the I²C interface. The **MODE** register allows configuration of several operating modes, including: operation in peak, deconvolution and multi modes; use of calibration circuitry; selection of (signal) inverting and non-inverting modes; and readout frequency (20 or 40 MHz).
Appendix B

On-Chip Common Mode Subtraction

A beneficial feature of the biasing scheme used for the APV25 inverter stage is the effective subtraction of any ‘common mode’ generated by an external noise source. This is illustrated below by considering a small-signal model of the inverter stage (as shown in [93]). Each APV25 inverter consists of two identical PMOS transistors and provides a gain of -1. The inverters are powered by the V250 supply rail via a resistor, \( R \), external to the APV25 chip and located on the front-end hybrid. Node \( A \) is common to all 128 inverters. Here, we consider the case where a signal \( v_{IN} \) is collected by a single channel and a common mode \( v_{CM} \) is observed for all channels; figure B.1 illustrates the signals seen at the inputs of the APV25 inverters.

![On-chip common mode subtraction at the APV25 inverter stage.](image1)

![Small-signal model of the APV25 inverter stage.](image2)
The small-signal parameter $g_m$ is the transistor channel conductance and is defined in terms of small perturbations to the ‘quiescent’ dc values of the potential across the gate and source of a transistor ($v_{GS}$) and the current at the transistor drain ($i_D$) as follows: $g_m = i_D/v_{GS}$. Figure B.2 shows currents flowing through the individual transistors of the inverter. Summing the currents flowing through node $A$, we get:

$$\frac{v_R}{R} = g_m(v_{IN} + v_{CM} - v_R) + 127 \cdot g_m(v_{CM} - v_R) \quad (B.1)$$

$$\Rightarrow v_R = g_m v_{IN} R + 128 \cdot g_m v_{CM} R - 128 \cdot g_m v_R R$$

$$\Rightarrow v_R = \frac{(v_{IN} + 128 \cdot v_{CM})g_m R}{1 + 128 \cdot g_m R} \approx \frac{(v_{IN} + 128 \cdot v_{CM})g_m R}{128 \cdot g_m R}$$

$$\Rightarrow v_R = \frac{v_{IN}}{128} + v_{CM} \quad (B.2)$$

Hence, considering the currents down the left-hand branch of figure B.2 (through the transistors marked 1 and 2):

$$g_m(-v_{OUT}) = g_m(v_{IN} + v_{CM} - v_R)$$

$$\Rightarrow -v_{OUT} = v_{IN} + v_{CM} - \left(\frac{v_{IN}}{128} + v_{CM}\right)$$

$$\Rightarrow v_{OUT} = -\frac{127}{128}v_{IN}$$

Hence, although the signal $v_{IN}$ is superimposed on a common mode level $v_{CM}$ at the inverter input, only the (negated) signal component is output by the inverter. Similarly, considering the currents down the right-hand branch of figure B.2 (through the transistors marked 3 and 4), which represents the 127 channels not seeing the signal $v_{IN}$:

$$v_{OUT} = +\frac{1}{128}v_{IN}$$

This implies that the common mode $v_{CM}$ present at the inverter inputs is not seen at the outputs, although there is a small (positive) shift in the output levels that is
related to the magnitude of the signal $v_{IN}$. In fact, this small shift means that the difference in the inverter output level of the channel collecting signal $v_{IN}$ relative to the inverter outputs of those channels not seeing signal is:

$$
\Delta v_{OUT} = \left( -\frac{127}{128} v_{IN} \right) - \left( +\frac{1}{128} v_{IN} \right) = -v_{IN}
$$

This effect has been shown experimentally in [93]. Hence, on-chip common mode subtraction is very desirable as it results in a very stable baseline.
Appendix C

Run Statistics for the PSI Test

The beam test data collected during the PSI beam test (May 2002) can be found on CASTOR at: /castor/cern.ch/cms/beamtests/tkpsi.

### Table C.1: Statistics collected with single triggers and π⁻ beam at PSI.

<table>
<thead>
<tr>
<th>Run ID</th>
<th>Files</th>
<th>Data Pool [GB]</th>
<th>Events [10³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40090</td>
<td>50</td>
<td>10.06</td>
<td>636</td>
</tr>
<tr>
<td>40149</td>
<td>44</td>
<td>8.77</td>
<td>554</td>
</tr>
<tr>
<td>40194</td>
<td>17</td>
<td>3.44</td>
<td>217</td>
</tr>
<tr>
<td>40196</td>
<td>21</td>
<td>4.17</td>
<td>264</td>
</tr>
<tr>
<td>40197</td>
<td>7</td>
<td>1.27</td>
<td>80</td>
</tr>
<tr>
<td>40199</td>
<td>9</td>
<td>1.69</td>
<td>107</td>
</tr>
<tr>
<td>40200</td>
<td>7</td>
<td>1.39</td>
<td>88</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>155</strong></td>
<td><strong>30.79</strong></td>
<td><strong>1946</strong></td>
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</table>

### Table C.2: Statistics collected with single triggers and π⁺ beam at PSI.

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<th>Data Pool [GB]</th>
<th>Events [10³]</th>
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<td>10</td>
<td>1.86</td>
<td>118</td>
</tr>
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<td>40331</td>
<td>11</td>
<td>2.14</td>
<td>135</td>
</tr>
<tr>
<td>40335</td>
<td>13</td>
<td>2.52</td>
<td>159</td>
</tr>
<tr>
<td>40336</td>
<td>11</td>
<td>2.21</td>
<td>140</td>
</tr>
<tr>
<td>40337</td>
<td>10</td>
<td>2.01</td>
<td>127</td>
</tr>
<tr>
<td>40338</td>
<td>10</td>
<td>2.00</td>
<td>126</td>
</tr>
<tr>
<td>40339</td>
<td>10</td>
<td>2.01</td>
<td>127</td>
</tr>
<tr>
<td>40340</td>
<td>11</td>
<td>2.20</td>
<td>139</td>
</tr>
<tr>
<td>40347</td>
<td>14</td>
<td>2.91</td>
<td>184</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>100</strong></td>
<td><strong>19.86</strong></td>
<td><strong>1255</strong></td>
</tr>
</tbody>
</table>
### Run Statistics for the PSI Test

<table>
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<th>Data Pool [GB]</th>
<th>Events [10^3]</th>
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</thead>
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**Table C.3:** Statistics collected with single triggers and proton beam at PSI.

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**Table C.4:** Statistics collected with trigger bursts and π⁻ beam at PSI.
Appendix D

Ntuple Format

Table D.1: Ntuple structure containing event data from PSI beam test.
Detailed definitions of variables are given in the text.
Appendix E

Multiple Scattering

Charged particles traversing a medium suffer many small-angle scatterings due to their Coulomb interaction with the atomic nuclei of the medium. This multiple scattering is described by the theory of Molière (see [64] and references therein for a more detailed description). The Molière scattering distribution is roughly Gaussian for small angle deflections, but at larger angles behaves like Rutherford scattering and exhibits longer tails than a Gaussian distribution. The width of a Gaussian approximation to the Molière distribution is defined by:

\[ \theta_{\text{rms}} = \frac{13.6 \text{[MeV]}}{\beta c p} z \sqrt{x/X_0} \left[ 1 + 0.038 \ln \left( \frac{x}{X_0} \right) \right] \]  

(E.1)

where \( \beta c, p \) and \( z \) are the velocity, momentum and charge number (in units of e) of the incident particle, and \( x/X_0 \) is the total length of the scattering medium in units of radiation lengths [cm].

Tracking was performed using 300 MeV/c pions incident on six 500 \( \mu \text{m} \)-thick silicon sensor planes. Hence, \( \beta = 0.907 \) and \( x/X_0 = 0.032 \) (for a silicon radiation length).

Figure E.1: Quantities used to described multiple Coulomb scattering of a charged particle traversing a medium. Taken from [64].
length of $X_0 = 9.36 \text{ cm}$). The six planes are considered as a single scatterer, resulting in an $rms$ scattering angle of $\theta_{rms} = 7.78 \cdot 10^{-3} \text{ rads}$.

The relevant variable for estimating the positional uncertainty due to multiple scattering is $s_{plane}$, as illustrated in figure E.1. However, the entry and exits points of the particle in the tracking unit do not define the track entry and exit points, as the track is defined by a fit to the hits observed in all six sensor planes. Hence, the uncertainty in the hit position is estimated to be:

$$\sigma \approx \frac{1}{2} \cdot s_{plane} \equiv \frac{1}{2} \cdot \frac{1}{4\sqrt{3}} \cdot d \cdot \theta_{rms} \tag{E.2}$$

where $d$ is the depth of the tracking unit (25 cm). Hence, the contribution of multiple scattering to the positional uncertainty of hits used in track-finding is estimated to be $\sigma = \pm 140 \mu\text{m}$.
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