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Master's Thesis

Messung der totalen ionisierenden Dosis des Belle II Pixeldetektors

Total ionizing dose measurement of the Belle II pixel detector

prepared by

Yannik Buch

from Soltau

at the II. Physikalisches Institut

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First referee: Prof. Dr. Ariane Frey

Second referee: PD Dr. Jörn Große-Knetter

Abstract

Der Belle II Detektor am SuperKEKB Teilchenbeschleuniger am KEK in Tsukuba, Japan, macht Präzisionsmessungen, die das Standardmodell testen und nach neuen Phänomenen in der Teilchenphysik suchen. Das innerste Detektorsystem von Belle II ist ein 6-lagiger Vertexdetektor. Der PiXeDetektor (PXD) macht die ersten 2 Lagen aus, welche einen Abstand von 14 mm und 22 mm vom Interaktionspunkt haben. Der sehr dünne und hochauflösende PXD basiert auf der DEPLETED Field Effect Transistors (DEPFET) Technologie. Seit der Inbetriebnahme des PXD vor 3 Jahren, im Jahre 2019, ist der PXD einer grossen Strahlenbelastung ausgesetzt, ausgehend von der hohen Hintergrundstrahlung durch, die in den SuperKEKB Ringen gespeicherten, Teilchen.

In dieser Arbeit wird die ionisierende Dosisrate gemessen, die jedes der PXD Module erhalten hat. Dies ist die erste Messung der ionisierenden Dosisrate der PXD Module für den gesamten Operationszeitraum seit der Inbetriebnahme bis zum Long Shutdown 1. Die Messung nutzt die gemessene online Okkupanz, die als diagnostische Variable vom Belle II Steuerungs und Überwachungssystem EPICS als 1 Hz Zeitreihe gespeichert wird. Die gemessene online Okkupanz wird mit einer heuristischen Funktion modelliert, die die Zusammensetzung der Strahlung aus den einzelnen Quellen beschreibt. Die Komponenten, die berücksichtigt wurden sind die Beam-gas, Touschek und Injektions-Komponenten vom Positronenring und vom Elektronenring und die Luminositätskomponente. Die Modellierung der Okkupanzen erlaubt eine Messung der deponierten ionisierenden Dosis, auch während Zeiten in denen der PXD keine Daten aufnimmt, indem das Model extrapoliert wird. The resultierenden Zeitreihen der ionisierenden Dosisraten werden im Folgenden präsentiert.

Stichwörter: Physik, Masterarbeit, Belle II, Pixeldetektor, TID, Dosismessung

Abstract

The Belle II detector system at the SuperKEKB particle collider at KEK in Tsukuba, Japan, provides precision physics measurements, testing the Standard Model and searching for new physics. The innermost detector system of Belle II is a 6-layer vertex detector. The pixel detector (PXD) comprises the first two layers, that are at a distance of 14 mm and 22 mm from the interaction point, respectively. The very thin, high resolution PXD is based on DEPLETED Field Effect Transistors (DEPFET). Since the beginning of the operation of the PXD 3 years ago, in 2019, the PXD is exposed to large amounts of radiation from the beam background.

In this work, the ionizing dose rate received by each PXD module is measured. This is the first measurement of the ionizing dose rate of the PXD modules for their entire time of operation until the start of the long shutdown 1. The measurement uses the measured online module occupancies, that are saved as diagnostic variables by the Belle II slow control system EPICS as 1 Hz time series. The measured online occupancies are modeled using a heuristic background function, that describes the beam background composition. The considered beam background components are beam-gas, Touschek and injection backgrounds for the low energy positron ring and the high energy electron ring as

well as luminosity backgrounds. Modeling the module occupancies allows for measuring the deposited ionizing dose even when the PXD is not recording data by extrapolating the model. The measurement approach and the resulting ionizing dose rate time series are presented.

Keywords: Physics, Master thesis, Belle II, pixel detector, TID, dose measurement

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1. Introduction

Symmetry is one of the most remarkable properties that pierces through macroscopic phenomena down to the very foundation of our description of matter and radiation. Matter as well as radiation is made up of fundamental particles that are described by the Standard Model (SM) [10–12]. The properties and interactions between SM constituents as well as the symmetries therein are the subject of particle physics research. This research happens at the smallest time and length scales, requiring energies at or beyond the GeV scale.

Fundamental symmetries are, amongst others, translations in time and space of a physical system. According to Noether’s theorem each symmetry corresponds to a conserved quantity. The previous examples of translations in time and space result in the conservation of energy and momentum, respectively. Symmetries can also be discrete in the case of charge (C), parity (P) and time (T). The C-symmetry states that a physical system is indistinguishable from a system in which the sign of the charge of all particles is flipped, i.e. all particles are interchanged with their corresponding antiparticles. The existence of antimatter, more explicitly positrons, the antiparticle of the electron, was proven by Anderson by direct observation in cloud chambers, granting him a Nobel Prize in 1936 [13]. Similar statements can be made for P-symmetry, which corresponds to spatial inversion, and T-symmetry, which corresponds to time reversal. The operations of interchanging particles and antiparticles, spatial inversion and time reversal can also be combined.

During the second half of the 20th century many discrete symmetries and combinations thereof, that were believed to be exact symmetries in nature, were shown to be violated. An important example is P-violation, which was shown in an experiment conducted by Wu using decays of cobalt-60 atoms at ultra-low temperatures [14]. Shortly after, Cronin and Fitch showed that the combination of C- and P-symmetry was also violated [15]. Both discoveries were awarded a Nobel Prize. The violation of CP-symmetry sparked a discussion about the origin of the matter in the universe, since it is able to provide an explanation to the observed abundance of matter over antimatter in the universe. However, the currently observed CP-violation is too small to explain this observation entirely. In pursuit of finding an answer, more data of more precise measurements of

1. Introduction

particles and their symmetries is necessary.

One of the main tasks of the Belle II experiment is to measure the CP-violation, in particular in the B meson system. B mesons are bound states of 2 quarks, of which one is a bottom quark. Belle II is continuing and compounding the work of its predecessor, the Belle detector. The capabilities of Belle II in terms of precision and ability to cope with higher particle rates have been improved significantly. For this experiment, the SuperKEKB collider produces pairs of neutral B mesons via the decays of the bottomonium state $\Upsilon(4S)$, which are created in collisions of 4 GeV positrons and 7 GeV electrons. Belle II is planned to collect a 50 ab^{-1} data set.

To effectively measure the time-dependent CP-violation, a good vertex resolution of $\sim 50 \mu\text{m}$ is required [2]. The two innermost detectors, the silicon pixel detector (PXD) and the silicon vertex detector (SVD), are vertex detectors. At a distance of 14 mm from the interaction point (IP), the innermost pixel detector layer is exposed to copious amounts of radiation. A measurement of the total ionizing dose deposited in the PXD is thus subject of this work. The data set available for this measurement covers the time span from June 2019 to June 2022, before the long shutdown 1 began, but the measurement can be continued and applied to future operation. The measurement used 1 Hz measured online variables from the SuperKEKB archiver. At the heart of this analysis is the heuristic scaling law model that is fitted to the recorded occupancy of the PXD. The PXD occupancy is a unitless measure for the fraction of firing pixels in relation to the total number of pixels. From this model, an ionizing dose time series is extracted. The measured ionizing dose rate can be set in context to observed effects of radiation damages that impact the longevity and performance of the PXD.

This thesis is structured as follows. The SM is briefly described in Chapter 2 followed by an introduction to SuperKEKB, beam-induced backgrounds and Belle II in Chapter 3. The PXD sub-detector, the DEPFET pixel technology and radiation damage in silicon detectors are introduced in Chapter 4. Details of the measurement approach and implementation and the handling of the data is presented in Chapter 5. Results, putting the measured ionizing dose into context, and comparisons to other approaches of measuring the total ionizing dose, that were explored in this work, are shown in Chapter 6.

2. The Standard Model

The SM is to date the most precise theory of particles and their interactions at the smallest time and length scales. Although the SM has been appended multiple times since its emergence in the 1970s, it has prevailed and several predictions on the structure and behavior were confirmed over the years, granting fundamental insights.

The SM is currently comprised of fermions, particles with half-integer spin described by the Fermi-Dirac statistic [16], and bosons, particles with integer spin described by the Bose-Einstein statistic [17]. In the SM, particles are treated like point-like objects without spatial extension and therefore have no inner structure. All SM constituents have been observed to either carry a finite mass or to be massless, and their movement through space and time is described by special relativity [18]. Next to mass, particles also carry other quantities in discrete, i.e. quantized, amounts, for instance electric charge. The particles of the SM are displayed in Figure 2.1.

The SM includes the forces that facilitate the interactions between the particles, namely the weak nuclear force, the strong nuclear force and the electromagnetic force. Interactions are governed by the corresponding relativistic quantum field theories and mediated via their respective gauge boson. Gravity, which is currently known as a fourth force, is not yet described by the SM, meaning that there has not yet been a quantum field theory for gravity that could be confirmed experimentally. The influence of gravity on elementary particles in the context of high energy physics experiments is sufficiently small to be neglected, due to the shortness of the relevant time scales.

The fermions are divided into quarks and leptons and arranged in three generations. Each generation has an up-type quark with an electrical charge of $\frac{2}{3}e$ and a down-type quark with an electrical charge of $-\frac{1}{3}e$, as well as a charged lepton with an electrical charge of $-1e$ and an electrically neutral lepton, called neutrino. The only properties changing between corresponding particles of different generations are their masses and, in the case of leptons, the lepton quantum number. It is empirically found that the mass strictly increases for particles in higher generations. For every charged fermion there is an associated antiparticle with the same mass and opposite quantum numbers, e.g. charge. The bosons each correspond to one of the three forces, which they are mediating. The

2. The Standard Model

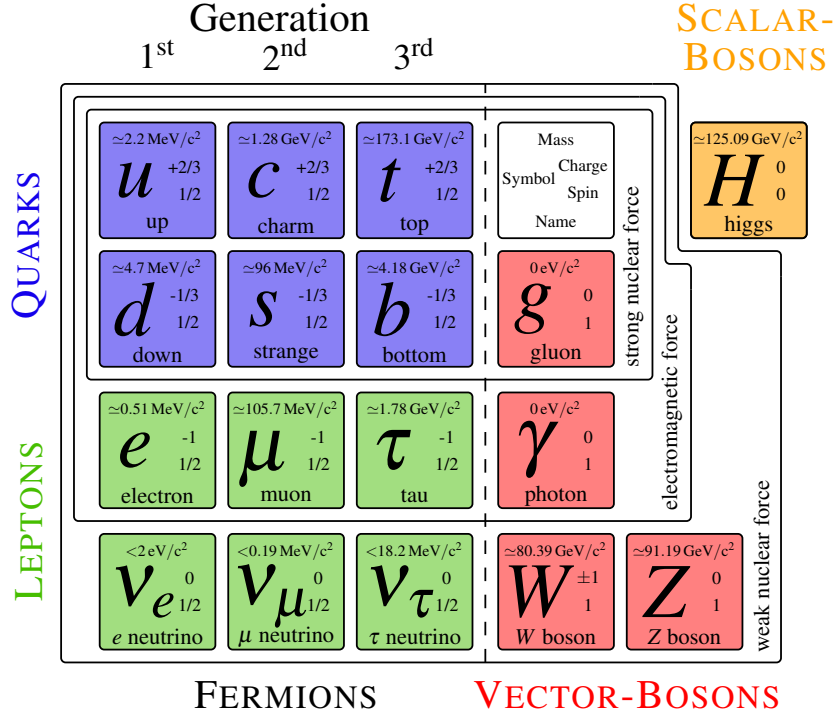


Figure 2.1.: Artistic depiction of the particles in the Standard Model. Measurements are taken from Reference [1].

gluon mediates the strong nuclear force, the photon mediates the electromagnetic force and the W and Z bosons mediate the neutral and charged currents of the weak nuclear force.

Quantum Electrodynamics (QED) is a relativistic quantum field theory that was developed in the 1940s by Tomonaga, Schwinger and Feynman [19–21]. QED describes the interaction between electrically charged fermions and massless photons. At its core, there are three basic processes: the propagation in spacetime of photons and electrically charged fermions and the absorption or emission of photons by electrically charged fermions. Points in momentum space where particles interact and exchange momentum, i.e. absorb, emit or scatter, are called interaction vertices. In order to visualize such interactions graphically and mathematically, the Feynman formalism was introduced. Two examples of Feynman diagrams are displayed in Figure 2.2. A Feynman diagram yields the amplitude of the respective process. The sum of all relevant amplitudes, together with a normalization over particle energies and fluxes, yields a cross-section that can be measured experimentally.

Quantum Chromodynamics (QCD) describes the strong nuclear force that is mediated by massless gluons. In QCD there are three charges, also called colors or color charge.

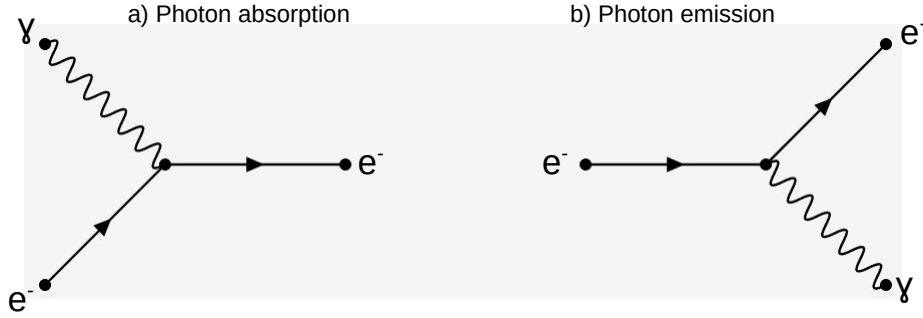


Figure 2.2.: Examples of Feynman diagrams for the absorption (a) and emission (b) of photons by electrons. The time axis points from left to right.

Since quarks and gluons are the only particles carrying a color charge, they alone are subjected to the strong force. While quarks carry one of the color charges, antiquarks carry an anticolor charge, and gluons carry one of eight possible color combinations. Systems with color charged particles prefer neutral states. A neutral color charge state can be achieved by combining all three colors, forming states that are called baryons, or a color and its corresponding anticolor, forming states called mesons. Together, mesons and baryons are called hadrons. The relative strength of QCD processes is $\mathcal{O}(100)$ times larger than for QED processes, depending on distance and energy scales. This results in states that are not color charge neutral to only exist on timescales of 10^{-24} s [22]. This phenomenon is called color confinement.

Quantum Flavordynamics (QFD) describes the weak nuclear force with its two massive bosons, the $W^\pm$ and Z boson. The weak isospin quantum number T_3 governs the weak interaction the same way electric charge does for electromagnetism. The weak force is maximally parity violating when mediated by the $W^\pm$ boson, resulting in left-handed chiral fermions and right-handed chiral antifermions with $T_3 = \pm\frac{1}{2}$ being grouped in doublets, while any other particles exist only in singlets with $T_3 = 0$. In one generation, the doublets are formed with an up-type and a mixture of down-type quarks or a neutrino and a charged lepton. The mixture of down-type quarks in the doublets is given by the CKM matrix. The $W^\pm$ bosons mediate between particles in a doublet and therewith facilitates the flavor changing charged current. The SM also allows for flavor changing neutral currents, though they are massively suppressed by the GIM-mechanism [23]. The Z boson mediates the neutral current of the weak nuclear force.

The transition between different quark flavors via the weak charged current was first described by Cabibbo [24]. This description introduced the representation of weak eigen-

2. The Standard Model

states (d', s') through the superposition of the mass eigenstates (d, s) via

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos \theta_C & \sin \theta_C \\ -\sin \theta_C & \cos \theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}, \quad (2.1)$$

where $\theta_C = 13.02^\circ$ is the Cabibbo angle. After the first publication, the Cabibbo formalism only described two quark generations. This formalism was extended by Kobayashi and Maskawa in 1973 to describe the mixing of three quark generations [25]. This allowed for the introduction of a complex phase into the CKM matrix, which was identified as a source of CP Violation (CPV). The CKM matrix V , that translates between the weak eigenstates and mass eigenstates, is represented by

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad (2.2)$$

or in the Wolfenstein parametrization

$$V(A, \lambda, \rho, \eta) = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4), \quad (2.3)$$

which uses the parameters A, λ, ρ and η . The parameter η is related to the complex phase [1]. The unitarity of the CKM matrix can be represented by a triangle in the complex plane. Without the complex phase of the CKM matrix, the area would be zero. The unitarity triangle can now be overconstrained, using independent measurements of SM parameters, most notably the CKM matrix entries, to test the CPV in the SM. The unitarity triangle is displayed in Figure 2.3. A fit of the unitarity triangle based on currently available data is displayed in Figure 2.4. Measuring the unitarity triangle was a key part of the Belle physics program. The subsequent confirmation of the CKM mechanism awarded a Nobel Prize for Kobayashi and Maskawa.

The CPV then appears as three different types. Direct CPV occurs when the branching fraction of the decay of an initial state to a final state differs from the branching fraction of the decay of a CP transformed initial state into a CP transformed final state. Indirect CPV, or CPV in mixing, can be observed in neutral mesons which can transition to their CP transformed counterpart via a box loop. The transition is described via a Hamiltonian. If the off-diagonal elements of the Hamiltonian differ from the off-diagonal elements of the complex conjugate of the Hamiltonian, the mixing induces CPV. CPV also occurs

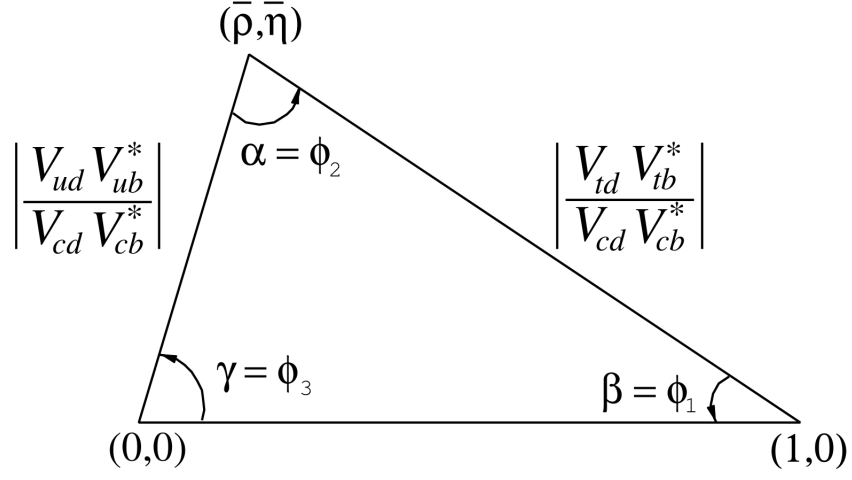


Figure 2.3.: A representation of the unitarity triangle in the complex plane. The figure is taken from [1].

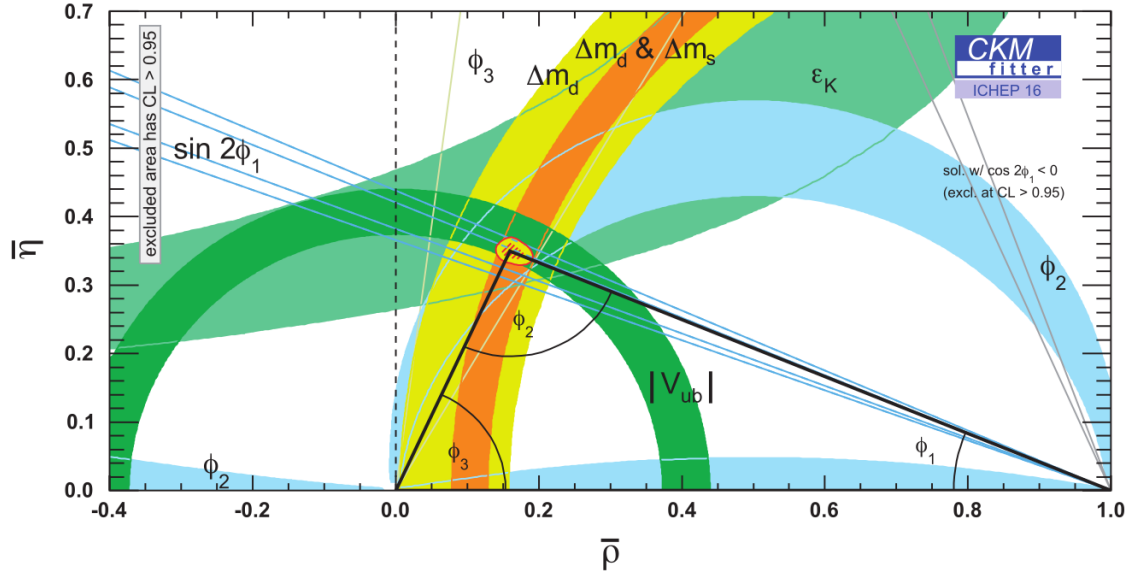


Figure 2.4.: The current unitarity triangle fit determined with CKMFITTER. The figure is taken from Reference [2].

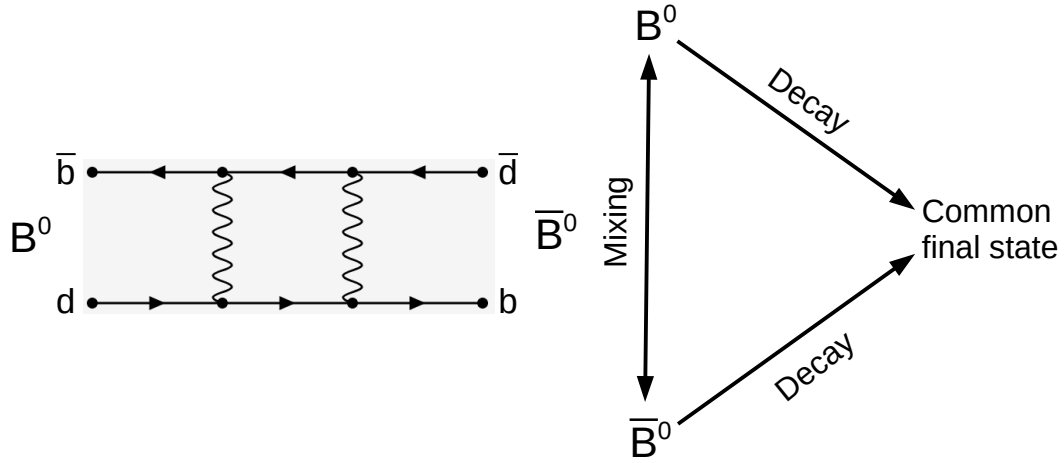


Figure 2.5.: Visualization of the CP violation in the interference of indirect and direct CP violation. The Feynman diagram box loop describes the mixing of the neutral B mesons.

in the interference of the aforementioned modes of CPV when a neutral meson and the corresponding antimeson can decay into the same CP eigenstate. This is visualized in Figure 2.5. The CPV in the interference is the biggest contribution of CPV in the B meson system and is therefore of special importance for Belle II.

3. SuperKEKB and Belle II

3.1. The SuperKEKB collider

The SuperKEKB ring collider in Tsukuba, Japan, at the KEK research facility has two separate storage rings for two asymmetric beams [4, 5]. A schematic view of SuperKEKB is displayed in Figure 3.6. SuperKEKB is an electron-positron collider. It is the successor of the KEKB collider which was an asymmetric electron-positron collider too. The particles inside the storage rings are grouped in particle bunches of $\mathcal{O}(10^{10})$ particles instead of forming a continuous beam. This is due to the accelerator scheme of synchrotrons [26]. The positron bunches in the low energy ring (LER) have an energy of 4 GeV and the electron bunches in the high energy ring (HER) have an energy of 7 GeV. The center-of-mass energy $E_{CM} = 10.48$ GeV sits at the $\Upsilon(4S)$ resonance, which almost exclusively decays into B Mesons [1]. The collider is therefore commonly referred to as B-factory. Since Belle II is the only experiment attached to SuperKEKB, there is only one IP where the positron and electron bunches collide. The approximately 2500 bunches in each ring quickly deteriorate on a timescale of $\mathcal{O}(600\text{ s})$ due to particles lost in collisions and beam-background effects. To keep the currents in the rings and the efficiency up, particles are continuously injected at rate of 50 Hz. The instantaneous luminosity $\mathcal{L}$, or simply luminosity, measures the rate of particle collisions in a collider and is defined as

$$\mathcal{L} = \frac{1}{\sigma} \frac{dN}{dt}. \quad (3.1)$$

The cross-section of the collision process is σ and dN/dt is the collision rate. Integrating the luminosity over time yields the integrated luminosity $\mathcal{L}_{\text{int}}$:

$$\mathcal{L}_{\text{int}} = \int \mathcal{L} dt. \quad (3.2)$$

The integrated luminosity measures the total amount of particle collisions during the given time span and is therefore used to define the size of the collected data set. Values for the luminosity and integrated luminosity for KEKB and SuperKEKB, along other key variables, are displayed in Table 3.1.

3. SuperKEKB and Belle II

Parameter	KEKB	SuperKEKB	Unit
Beam energy	8.0(e^-), 3.5(e^+)	7.0(e^-), 4.0(e^+)	GeV
Beam current	1.2(e^-), 1.5(e^+)	2.6*(e^-), 3.6*(e^+)	A
Number of bunches	1584	2500	-
Horizontal beam size	170	10.1*(e^+), 10.7*(e^-)	μm
Vertical beam size	940	48*(e^+), 62*(e^-)	nm
Instantaneous luminosity	0.21	6.5*	$10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
Integrated luminosity	1.04	50*	ab^{-1}

Table 3.1.: Comparison of performance parameters of KEBK and SuperKEKB [4]. (*) marked values are nominal or design values that have not been reached yet.

The particles injected are continuously created by an electron gun. The electron gun is a laser driven photo cathode radiofrequency gun [4]. The electron beam is extracted by a pulsed electric potential and in the following bunched and accelerated. Then, the electrons are accelerated by a linear accelerator to their target energy or shot onto a target to produce positrons with a conversion factor of 0.1 [4]. The target is a 14 mm thick tungsten plate. The positron bunches go through a damping ring to reduce their emittance before injection into SuperKEKB. A schematic depiction of the linear accelerator is displayed in Figure 3.2. The normalized beam emittance of the LER is 10x higher than for the HER at the end of the linear accelerator [27].

Beam currents of up to 2.6 A (3.6 A) in the HER (LER) are supported by the SuperKEKB design but have not been reached so far. One specific improvement over KEBK, with the aim to increase the instantaneous luminosity, was the introduction of the nano beam scheme [28]. Here, the bunches are vertically squeezed in one dimension by quadrupole magnets directly in front of the IP. The design vertical bunch size is 10.1 nm (10.7 nm) for the positron (electron) bunches [4]. The bunch cannot be squeezed at once over its full length, but only at a small section, just wide enough to fit the crossing bunch's width. A schematic illustration of the nano beam scheme is displayed in Figure 3.3.

While the HER was largely reused from KEBK, the LER was completely rebuilt. SuperKEKB has an array of dipole, quadrupole and sextupole magnets along the beam pipes, totaling to about 1000 magnets. Beam collimators are placed along the circumference of both rings. Their function is explained in Section 3.2. Particle bunches collide every 2 ns, producing the $\Upsilon(4S)$ at a rate of 100 Hz, compared to the rate of 0.5 Hz of KEBK.

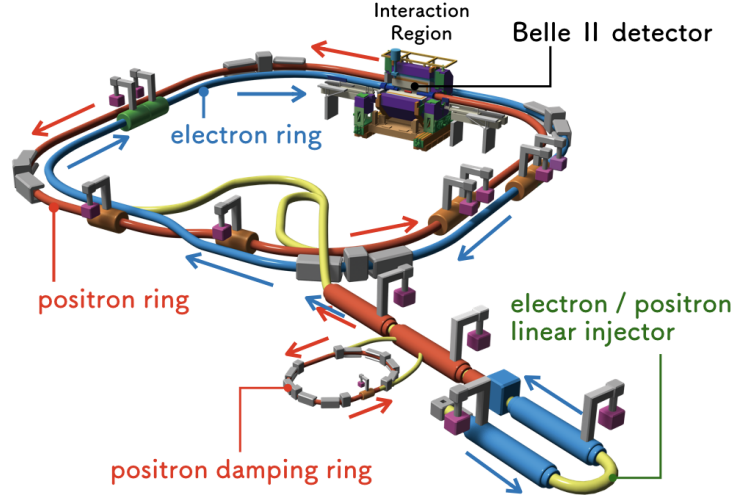


Figure 3.1.: Schematic depiction of the SuperKEKB collider, as well as the linear accelerator and the positron damping ring. The figure is taken from Reference [3].

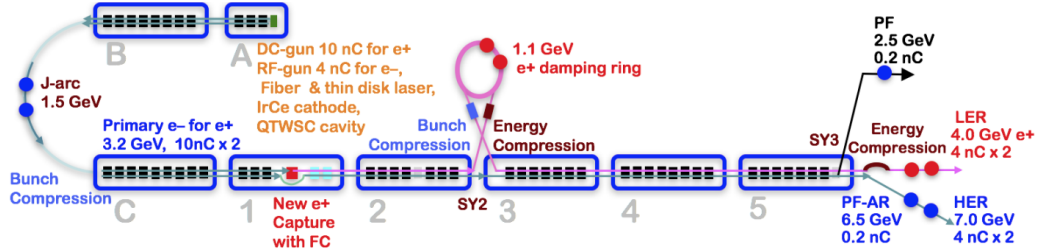


Figure 3.2.: Schematic depiction of the linear accelerator and the damping ring illustrating the different stages and the respective energy and charge of the electron and positron bunches. The figure is taken from Reference [4].

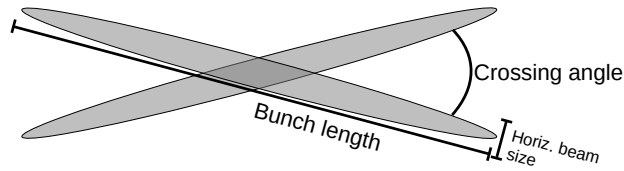


Figure 3.3.: Schematic illustration of the nano beam scheme in the horizontal plane. The crossing angle is 83mrad, the bunch length is ≈ 6 mm and the horizontal bunch size is $\approx 10 \mu\text{m}$ [5].

3.2. Beam-induced backgrounds

Understanding, quantifying and reducing beam backgrounds from the SuperKEKB beams is integral to ensure a safe and efficient operation of Belle II. Extensive background studies have been carried out for the Phase 1 commissioning [29], Phase 2 commissioning [30] and the ongoing Phase 3 operation [31]. While the pursuit of increasing luminosity is a major goal of the experiment to gather the planned 50 ab^{-1} integrated luminosity in a reasonable time, it needs to be balanced with the capabilities of Belle II. The complication is that an increase of the luminosity results in an increase of beam backgrounds. The resulting high particle rates can degrade the detector performance as the hardware is not capable of resolving so many particles and signals overlap, resulting in a loss of information. Other limiting factors are the front-end electronics, that need to cope with higher data rates and the reconstruction software, which are discussed in Section 3.4. Further, high background conditions will, over time, cause long-term damages in detector systems (see Section 4.4 for radiation damage in silicon detectors).

Beam backgrounds can be the product of electrons/positrons deviating from their design orbit due to scattering with molecules or other particles [5]. The electrons/positrons may crash into the beam pipe and create electromagnetic showers. When close to the IP, the generated shower particles might enter Belle II, resulting in higher hit rates in Belle II sub-detectors. An important component to decrease beam backgrounds are collimators. Collimators are metal jaws that can be driven close to the beam orbit, stopping particles that have left the design orbit. While collimators can stop stray particles, they are not designed to stop the entire beam. Collimators can suffer severe macroscopic damage caused to the bulk material by the particle beam. In addition, shielding is installed, e.g. the IP chamber mask, which amounts to $1\text{-}2X_0$ of material, where X_0 is the radiation length. Should the beam conditions approach dangerous levels for the Belle II detector or parts of the storage rings, the beam can be dumped. Diamond-based radiation monitors, also called diamonds, are placed around the IP. If the integrated dose over a time of $10 \mu\text{s}$ (1 ms) surpasses 8 mrad (80 mrad), the sensor triggers a very fast (fast) beam abort [32]. The dose is a quantity that measures the deposited energy in matter per unit mass by radiation. A beam abort takes about $20 - 30 \mu\text{s}$ which is equivalent to 2-3 revolutions around SuperKEKB. In the following, the beam-gas, Touschek, luminosity and injection background sources are introduced.

Beam-gas scattering occurs when electrons and positrons scatter with residual gas molecules in the beam pipes. The scattering rate depends on the beam current, the effective pressure inside the beam pipe and the strength of the final focusing magnets. Typical pressures inside the beam pipe are 10 nPa (20 nPa) for HER (LER) without beam.

The effect can be reduced by vertical collimators along the beam pipe. A schematic visualization is displayed in Figure 3.4. The amount of beam-gas background can be reduced by vertical collimators.

Touschek scattering describes intra-bunch Coulomb scattering. Both involved particles deviate from the design orbit. The scattering rate depends on the beam current and the inverse of the bunch size and number of bunches. The effect can be reduced by horizontal collimators along the beam pipe. A schematic visualization is displayed in Figure 3.4.

All particle processes that scale with the luminosity are summarized as luminosity background. Most processes can result in low momentum electrons that curl in the solenoid field and, depending on their energy, leave multiple hits in the vertex detectors. This is the case for radiative Bhabha scattering ($e^+e^- \rightarrow e^+e^-\gamma$) and two photon processes ($e^+e^- \rightarrow e^+e^-e^+e^-$). In case of the radiative Bhabha scattering there can also be secondary effects. The high energy photon can collide with accelerator magnets downstream and interact with nuclei. As a result, neutrons may scatter back and hit the Belle II detector. At the luminosity target of Belle II, the luminosity backgrounds will be the dominant source of backgrounds.

Freshly injected bunches oscillate around their target bunch they aim to top up. During these betatron oscillations, the background rates are elevated to the point that they could saturate the readout systems. The background is observed to be increased for ≈ 4 ms. With injections happening every 20 ms, a complete masking of the injection background would result in 20 % dead time. To avoid this, a masking scheme is introduced that only masks the time windows when the noisy bunch passes Belle II. The introduced dead time adds up to 5 %, which still amounts to a considerable loss of integrated luminosity.

3.3. Particle detection in high energy physics

Particle detectors are build to detect and identify as many particles as possible. The particles produced in particle collisions fall into three categories:

- stable particles, e.g. photons, electrons, protons and neutrinos,
- long-lived unstable particles with lifetimes $> \mathcal{O}(10^{-10} \text{ s})$, e.g. muons, neutrons, kaons and pions or,
- short-lived unstable particles.

Even at velocities v in the relativistic regime, $v \approx c$, short-lived particles produced at the IP will decay before reaching the detector. The decay products of short-lived particles

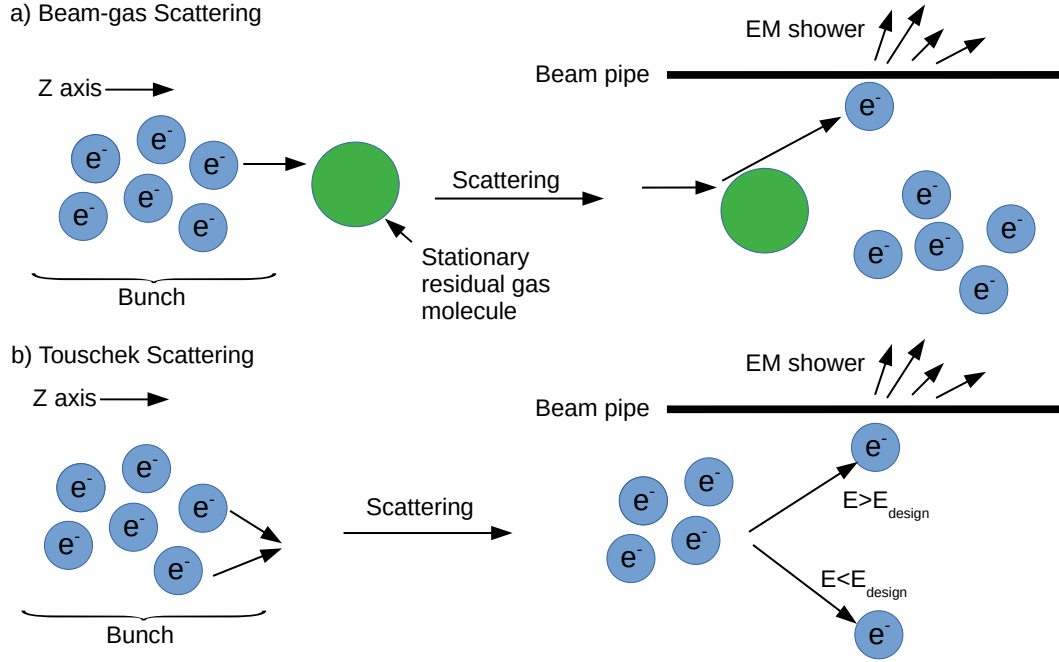


Figure 3.4.: Illustration of the storage beam background processes for beam-gas (a) and Touschek (b).

may (partly) fall into the other categories, allowing for an indirect detection. Long-lived unstable particles may travel several centimeters up to a few meters. These particles reach into the detector volume and can be directly measured. In the case of the muon this does, not rarely, lead to the muon leaving the detector volume entirely without decaying. Whether a particle can pass through the detector, however, also depends on the way a particle interacts with the detector material. A relativistic particle that traverses a medium typically interacts, i.e. scatters, with the bound electrons of atoms. While the atom is ionized, the traversing particle loses energy. The energy loss dE/dx is dependent on the medium and is described by the Bethe-Bloch formula [33, 34]:

$$\frac{1}{\rho} \frac{dE}{dx} \approx -\frac{4\pi\hbar^2 c^2 \alpha^2}{m_e v^2 m_u} \frac{Z}{A} \left(\ln \left[\frac{2\beta^2 \gamma^2 m_e c^2}{I_e} \right] - \beta^2 \right), \quad \alpha = \frac{e^2}{4\pi\epsilon_0 \hbar c}. \quad (3.3)$$

The parameters of the Bethe-Bloch formula are displayed in Table 3.2. The trail of ionization by charged particles can be exploited by tracking detectors. There are two broad categories of tracking detectors. Those that are based on a gaseous medium and those that are based on silicon. In gas-filled tracking detectors a strong electric field is applied to the region in which ionization should be measured [35]. The electrons that are liberated by the ionization are accelerated by the electric field, causing secondary ionization. This amplifies the signal that is left by the primary ionizing particle. The current that emerges

as a result of the drifting ions produced by the ionization is measured on sense wires that are in or at the edges of the detector volume. Silicon-based detectors work similarly, but instead of electron-ion pairs created in a gaseous medium, electron-hole pairs are created in the silicon [36]. The amount of electron-hole pairs produced by the primary ionization is sufficient, and therefore no secondary ionization is needed. Nonetheless, a small bias voltage is needed for the charges to drift towards the charge collection electrode in a reasonable time. The result of multiple measurements is a series of points in space that resemble the flight path, also called track, of the charged particle through the tracking detectors. With the crucial addition of a magnetic field, a momentum measurement of the charged particle is possible. The momentum of a charged particle can be obtained using the formula

$$p \cos \lambda = 0.3BR, \quad (3.4)$$

where p is the momentum in GeV, λ is the pitch, B the magnetic flux density in T (tesla) and R is the radius of the curvature. The curvature is a result of the Lorentz force due to the magnetic field. Usually, a solenoid is creating a near uniform magnetic field with a magnetic flux density of $\mathcal{O}(1 \text{ T})$ for a sufficient curvature.

For electrons in the GeV range the dominant process of energy loss is not ionization anymore but bremsstrahlung. Electrons that undergo bremsstrahlung emit a photon in presence of an electric field of an atomic nucleus. For a photon, which might be a photon produced by bremsstrahlung, four processes are possible, depending on the energy regime. At low photon energies $< 1 \text{ MeV}$ the photoelectric effect dominates the overall cross-section. The incident photon interacts with a bound electron in the shell of an atom. The entire momentum is transferred to the electron, and as a result, the photon is absorbed. In a similar energy regime but with a smaller cross-section, Thomson scattering occurs. It is elastic scattering between an incidence photon and an electron. The key difference to the photoelectric effect is that the photon is not fully absorbed in Thomson scattering. At photon energies of $\mathcal{O}(1 \text{ MeV})$ the dominant process is Compton scattering. It is similar to Thomson scattering but describes inelastic scattering processes. Beyond a photon energy of 10 MeV electron positron pair creation becomes the dominant process. In the presence of a nucleus the photon splits in an attempt to conserve momentum. The resulting high energy electron and positron undergo bremsstrahlung due to the deflection in matter. The photons emitted may continue this cycle, given enough energy. The result of this chain reaction, or avalanche, is called an electromagnetic shower. The cross-sections of interactions between photons and matter is displayed in Figure 3.5. The size of an electromagnetic shower is dependent on the energy of the incidence particle and the

3. SuperKEKB and Belle II

radiation length of the material in which the shower develops. The radiation length X_0 is the average distance needed for an electron's energy to be reduced by a factor of $1/e$. The mean free path for a photon to produce an electron-positron pair is approximately $9/7$ of the radiation length [37]. The development of showers is exploited in shower detectors, for example calorimeters. Scintillation material is deliberately placed in the detector in which an electromagnetic shower develops. Once an electron or photon does not contribute to the shower development due to insufficient energy, it reacts with an atom, leaving it in an excited state. To deexcite, the atom emits a photon, also called scintillation light, that can be measured by photomultipliers. The amount of scintillation light produced by an electromagnetic shower is proportional to the energy of the incidence electron or photon. For a reliable energy measurement, it is important to contain the shower to the scintillation medium. This can be done by increasing the depth of the medium or choosing a material with a small radiation length.

The generation of electromagnetic showers can also happen outside the detector when particles interact with the beam pipe. Although it should be avoided that particles collide with the beam pipe, some processes that result therein can only be reduced and not completely averted. Examples for such processes are Touschek and beam-gas effects that are presented in more detail in Section 3.2.

Hadronic calorimeters utilize the same basic principles as electromagnetic calorimeters but differ in their constructions due to the different nature of hadronic showers. Hadronic showers are significantly larger than electromagnetic showers. The forms and sizes of hadronic showers are not uniform, since many different particles can be part of a hadronic shower. Created particles may interact differently with the medium or decay, creating other particles, e.g. a pair of photons that result from a π^0 decay. These photons create electromagnetic showers within the original hadronic shower. Therefore, to contain hadronic showers, hadronic calorimeters are usually bigger than electromagnetic calorimeters.

Another integral part of a high energy physics detector is the trigger. It is motivated by the fact that the rate of particles going through the detector is very high and each particle results in many signals from the various sub-detectors. While there is a maximum on the particle rate that can be handled, e.g. by a tracking detector, there is a more critical limit on the amount of data that can be written to disk per unit time to be permanently stored. The data rate from the detector thus needs to be massively reduced. To achieve that, a combination of hardware triggers and software triggers is used. The task of the trigger system is to select interesting events that match the individual research interests of the experiment. Data that is not selected by the trigger will be discarded.

Variable	Description
ρ	Density of the medium
$\hbar$	Reduced Planck's constant divided
c	Light speed
e	Elementary charge
ϵ_0	Electric constant
Z	Atomic number
A	Relative atomic mass
m_e	Mass of the electron
m_u	Unified atomic mass unit
v	Particle velocity
β	v/c

Table 3.2.: Variables, and their description, of the Bethe-Bloch formula.

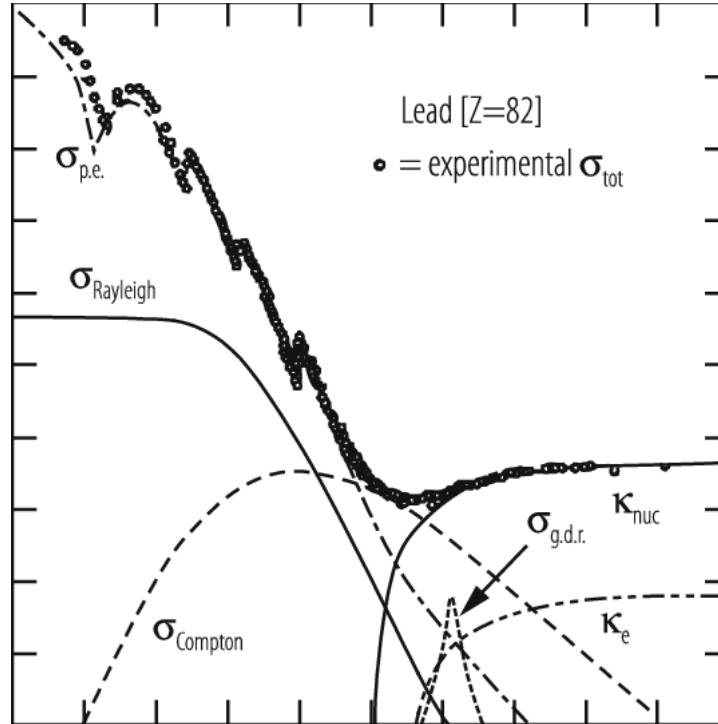


Figure 3.5.: The cross-sections of possible interactions between photons and matter in dependence of the photon energy. Figure taken from Reference [6].

3.4. The Belle II experiment

The Belle II detector is an asymmetric detector with a near 4π coverage [5]. The coordinate system of Belle II has its origin at the nominal IP. The z-axis points towards the electron beam, while the y-axis is directed upwards and the x-axis points outwards with respect to the center of SuperKEKB. The polar angle θ is in the yz-plane and is zero on the positive z-semi-axis, and the azimuthal angle ϕ is in the xy-plane and zero on the positive x-semi-axis. A schematic view of Belle II and its coordinate system are displayed in Figure 3.6.

The Belle II and SuperKEKB commissioning was divided into three phases. The Phase 1 commissioning concentrated on the commissioning of SuperKEKB without particle collisions. For the Phase 2 commissioning most of Belle II was installed except the vertex detectors, which were only partly installed. Instead, the CLAWS detector was installed, using the vacant space close to the beam pipe to measure background levels [30, 38]. The installation of the complete vertex detector systems in 2019 marked the start of the Phase 3 operation of Belle II.

Belle II allows for the reconstruction of events resulting from the collisions at the IP. An event is a snapshot that holds the measurements of the sub-detectors for a defined time window. The captured ‘image’ includes charged tracks and their momentum measurement, clusters and their energy measurement and various other information about particle identification and timing measurements. The latter requires the boost of the created particles due to the asymmetric beam energies and the relatively long lifetime of B mesons to achieve a sufficient displacement between the IP and secondary vertices of the B meson decays. With a lifetime of B mesons of 1.5×10^{-12} s [1] and a velocity of approximately $0.3c$, the distances of secondary vertices from the IP are approximately $135 \mu\text{m}$. The $\Upsilon(4S)$ meson’s lifetime of 10^{-20} s [1] is sufficiently small, so that its decay products can be assumed to originate from the IP. A vertex displacement of two B meson decays is displayed in Figure 3.7. Belle II has a solenoid that generates a 1.5 T magnetic field that engulfs most sub-detectors. The Belle II sub-detectors are discussed and presented in the following sections based on Reference [5].

3.4.1. PXD

To cope with the high occupancies expected below radii of 40 mm, pixel detectors are a necessity. Further requirements are a small material budget and high time and position resolution as well as radiation hardness. A small material budget has three consequences. Firstly, the thickness of the modules needs to be sufficiently small. Secondly, the pixel

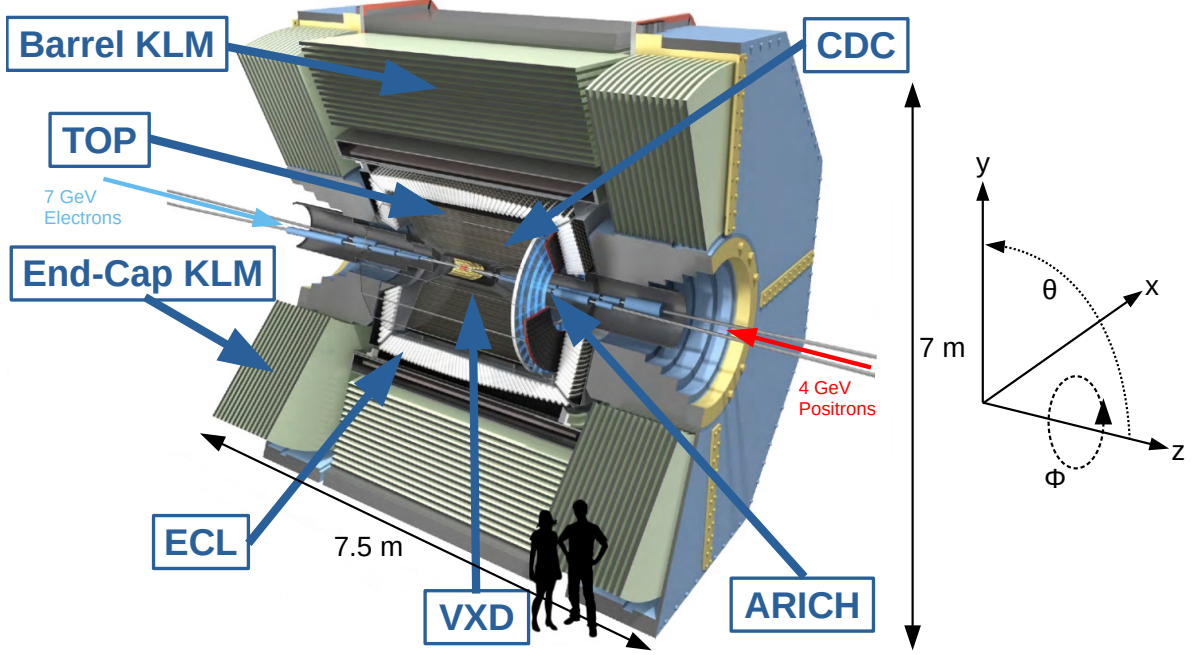


Figure 3.6.: Schematic side-view of the Belle II detector with the indicated beam lines. The coordinate system and the dimensions of Belle II are showcased. The azimuthal angle around the z-axis $\phi = 0$ is defined for $(x, y, z) = (1, 0, 0)$ and the zenith angle of the z-axis $\theta = 0$ is defined for $(x, y, z) = (0, 0, 1)$. Based on Reference [7].

modules cannot require grand support structures. Thirdly, the power dissipation needs to be small enough to allow for passive cooling in the detector acceptance, as active cooling structures would introduce too much material. The option chosen are depleted field effect transistors (DEPFET) [39, 40] with pixel sizes of $50 \times 50 \mu\text{m}^2$ close to the IP and up to $85 \times 50 \mu\text{m}^2$ on the far side of the modules. The resulting single track vertex resolution of $15\text{-}30 \mu\text{m}$ can be maintained over the full angular acceptance with the given pixel sizes. The module thickness in the sensitive region is $75 \mu\text{m}$ and the integration time of the rolling shutter readout is $\sim 20 \mu\text{s}$. Irradiation studies of DEPFET modules have shown sufficient radiation hardness for the planned 200 kGy total ionizing dose (TID).

The PXD is set up as two concentric cylindrical shells at radii of 14 mm and 22 mm . This puts the inner layer at a radial distance of 4 mm from the beam pipe with a radius of 10 mm at the IP. The radial distance between the outer layer and the innermost layer of pixel strips of the silicon vertex detector (SVD) are 16 mm . The inner layer consists of 8 ladders with each ladder being two modules glued together back to back. Each inner module has a sensitive area of $15 \times 90 \text{ mm}$. The outer layer consists of 12 ladders with the sensitive area of each module being $15 \times 123 \text{ mm}$.

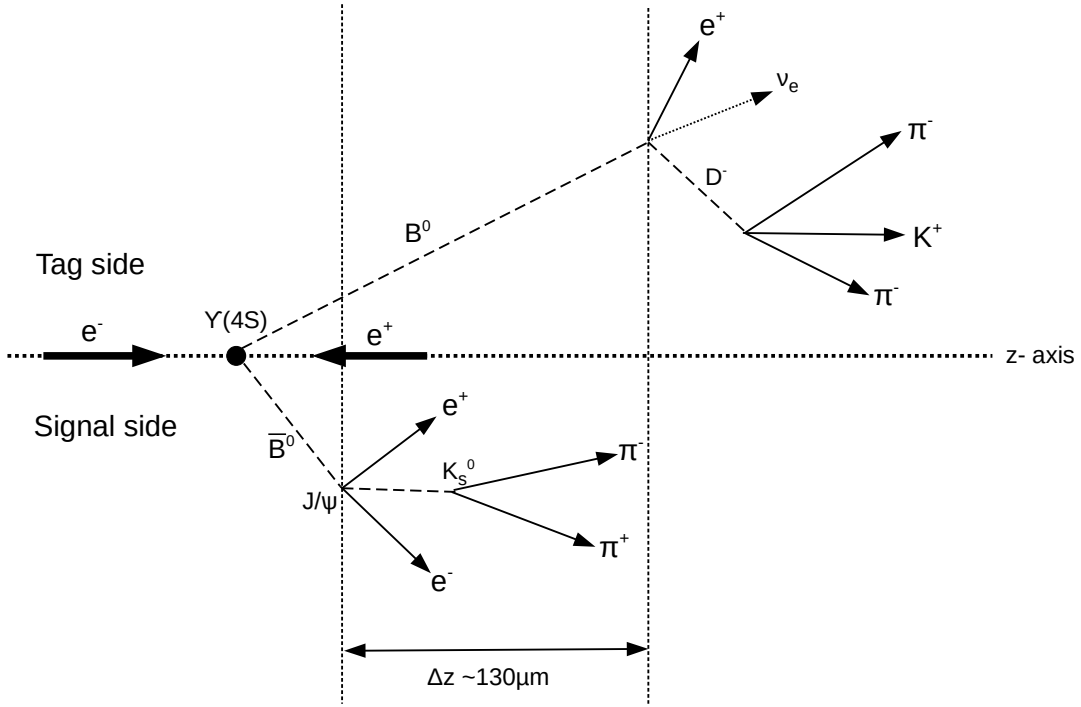


Figure 3.7.: Drawing of two B meson decays with displaced vertices and their distance Δz . The event has a tag side and a signal side. The flavor of the tag side B meson is determined by measuring the charge of the electron, allowing to implicitly infer the flavor of the signal side B meson.

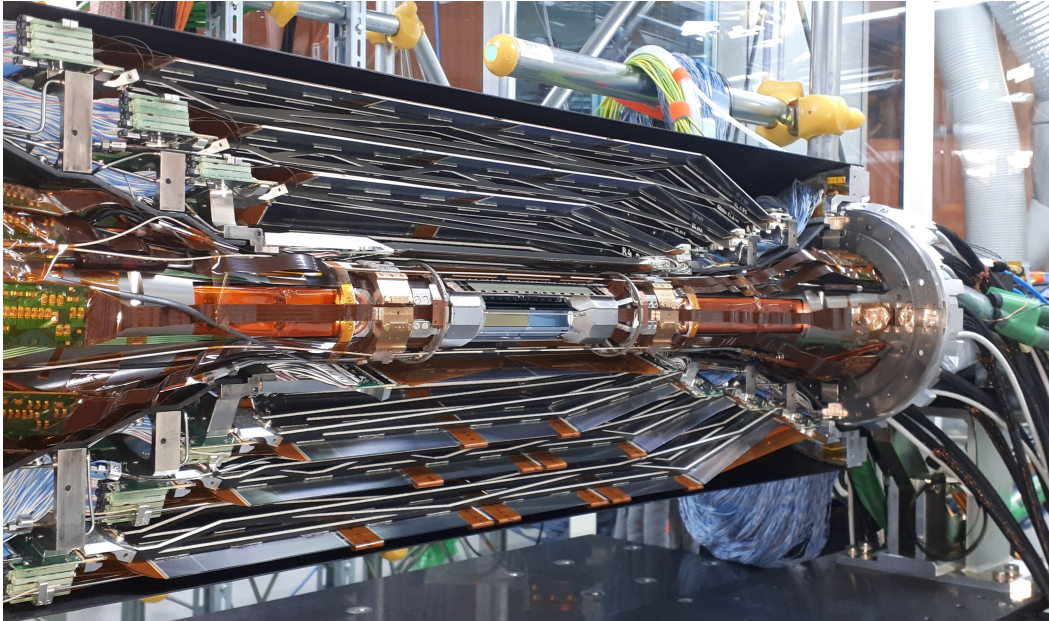


Figure 3.8.: Photograph of a Belle II vertex detector half shell. The inner layer and a partial outer layer of the PXD are visible as well as the 4 SVD layers.

3.4.2. SVD

The SVD is a double-sided silicon strip detector that, together with the PXD, is used to measure B decay vertices. Particles that decay outside the PXD volume, e.g. K_s^0 , can also be reconstructed by the standalone effort of the SVD. The acceptance covers $17^\circ < \theta < 150^\circ$ for all four layers. The layers are numbered and count upwards from the innermost layer to the outermost layer, starting with the number three, as layer one and two are the PXD layers. The radii of the layers reach from 38 mm to 140 mm. The area that is covered by the SVD grows considerably with each layer. To reduce the needed sensor area, the layers three to five are slanted in the forward direction, making the layers effectively shorter but still allowing for the full angular coverage. A picture of the SVD showcasing this geometry is displayed in Figure 3.8. The otherwise rectangular shaped sensor modules of the SVD take a trapezoidal shape in the slanted region. Each layer has an averaged $0.57\%X/X_0$ material budget. The highest contribution to the material budget comes from the 0.3 mm thick silicon sensors. Another purpose of the SVD is to find tracks in a standalone tracking or give additional information to tracks provided by the CDC by merging, or extending, tracks inwards.

3.4.3. CDC

The central drift chamber (CDC) envelops the vertex detector with an inner radius of 160 mm and an outer radius of 1130 mm. The volume is filled with a mixture of 50 % helium and 50 % ethane. Immersed in this gas mixture, 14336 sense wires are arranged in 56 layers. These 56 layers are grouped in 9 superlayers that define the orientation of the wires within each of the superlayers. The three possible orientations are parallel to the z-axis, or tilted forwards/backwards with respect to the z-axis. Parallel wires are called axial wires, while tilted wires are called stereo wires. The different orientations of wires are important to avoid position and direction ambiguities of particles after their measurement. The CDC provides precision momentum measurements of charged particles and reconstructs their flight path, i.e. track. A typical charged particle leaves $\mathcal{O}(40)$ hits in the volume of the CDC. The spatial resolution of the CDC is $100\mu\text{m}$ and the timing resolution is 1 ns. Crucially, the CDC provides the trigger signal for the Belle II detector with a latency $< 5\mu\text{s}$. Knowing the incidence angle of a particle with respect to the CDC, an energy loss measurement with a resolution of 10 % in the gas volume is possible, providing a PID measurement.

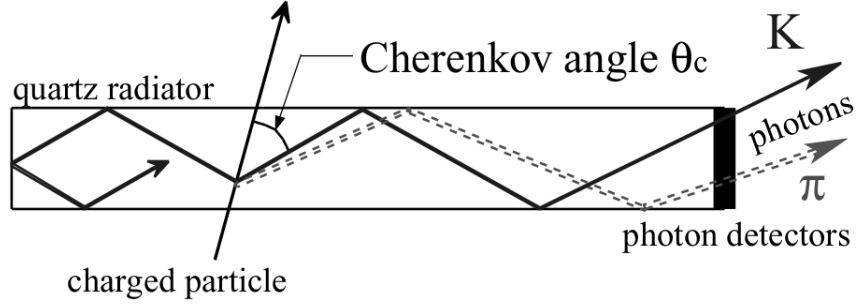


Figure 3.9.: A side cross-section of a TOP detector quartz block. A charged particle traverses a quartz block, resulting in emission of Cherenkov light. The behavior of the Cherenkov light in the quartz block depends on the Cherenkov angle and therefore on the traversing particle, as indicated for a kaon and a pion. Figure taken from Reference [5].

3.4.4. TOP

The time-of-propagation (TOP) counter contributes to the PID measurements made by Belle II in the barrel region. Its main purpose is to differentiate charged tracks between kaons and pions. The TOP counter consists of 16 massive synthetic fused silica quartz bars. One end has a focusing mirror while the other end has an expansion prism. Charged particles traversing the quartz bars produce a Cherenkov cone of photons with a specific incidence angle θ_c . The emission of Cherenkov light is displayed in Figure 3.9. The photons are internally reflected until they reach the expansion prism with the attached micro channel plate photomultipliers (MCP-PMTs). The position in x and y of a photon on the MCP-PMTs, together with the photon timing information, corresponds to a position on the quartz bar. Due to the focusing, the Cherenkov photons are directed differently along the y-axis according to their wavelength. The Cherenkov angle is connected to the refractive index n and $\beta = v/c$, where v is the particle's velocity, via

$$\cos \theta = \frac{1}{n\beta}, \quad (3.5)$$

allowing for a PID measurement by using

$$p = m\beta\gamma c. \quad (3.6)$$

The mass m of the measured particle with momentum p is unique and identifies the particle.

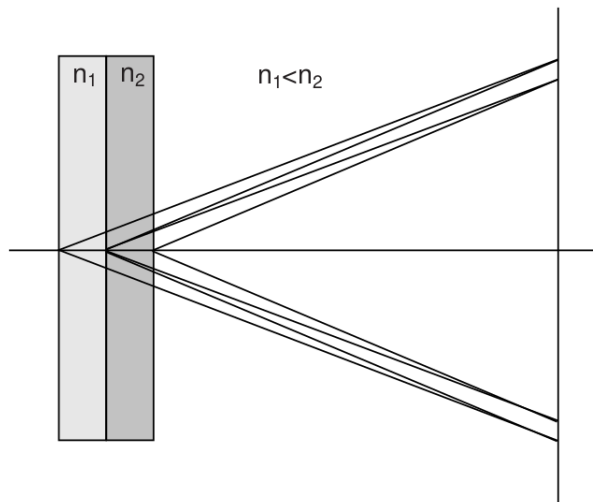


Figure 3.10.: The focusing of Cherenkov cones of different Cherenkov angles using materials different refractive indices n_1 and n_2 , to compensate for the width of the 2 cm aerogel radiator. Figure taken from Reference [5].

3.4.5. ARICH

The aerogel ring-imaging Cherenkov detector (ARICH) provides PID measurements in the end-cap regions. The setup of the ARICH detector includes the aerogel radiator that causes traversing particles to produce a Cherenkov cone. The aerogel radiator consists of two layers with different refractive indices. Behind that is an expansion volume that allows for the Cherenkov ring to expand. The refractive indices of the aerogel layers are chosen such that the two cones with different Cherenkov angles exactly overlap at the end of the expansion volume. This focusing is schematically displayed in Figure 3.10. This is necessary in order to compensate for the 2 cm width of the aerogel radiator. Otherwise, the Cherenkov photons produced at different depths in the radiator will blur the image that is later detected. The 2 cm width is necessary to produce enough Cherenkov photons (of the order of $\mathcal{O}(10)$) to make a reliable measurement. After traversing the expansion volume, a bank of photon detectors is set up to measure the Cherenkov photons. The photon detectors consist of a vacuum tube that encloses an avalanche photo-diode. The PID measurement is realized by using the Cherenkov angle, similar to the TOP counter.

3.4.6. ECL

The electromagnetic calorimeter (ECL) provides crucial measurements of non-charged particles, that are predominantly neutral pions (π^0) and photons. The ECL covers the barrel region as well as the end-cap regions by using over 8500 CsI(Tl) crystals with a depth of 30 cm which equals $16.1X_0$. When a particle traverses the scintillation crystal,

3. SuperKEKB and Belle II

it is absorbed, thus bringing molecules in the crystal to an excited state. The subsequent deexcitation by emitting photons creates a light pulse. The decay constant of a scintillation crystal describes the time after which the intensity of the light pulse has decreased to $1/e$ of its maximum. This particular crystal used in the ECL has a decay constant of $1.3\,\mu\text{s}$. The scintillation light is detected by photodiodes that are glued to the back of the crystals. The ECL measurements also contribute to the luminosity measurements, K_L^0 detection and electron identification and the injection background veto timing is tuned, using the ECL signal. The injection veto and the injection background are described in Section 3.2.

3.4.7. KLM

The K_L and muon detector (KLM) is the outermost detector and envelops the other sub-detectors in the barrel and end-cap region. Importantly, the KLM is also located outside the solenoid and is not submerged in the magnetic field. The purpose of the KLM is to provide measurements of particles that were not stopped in the ECL before they leave the detector volume. The PID of K_L and muons is realized as standalone measurement by the KLM and as a combined measurement of the ECL and KLM. The PID uses charged tracks extrapolated from the CDC, the amount and position of clusters in the KLM and/or ECL with respect to these charged tracks. If no charged tracks are associated with a KLM cluster, it is assumed to be caused by K_L mesons. Otherwise, charged pions, muons, photons and hadrons (that are not identified further) can be identified by this scheme. The KLM is made of layers that alternate between active detectors and iron plates. For most detector layers in the barrel region, resistive plate chambers (RPCs) were used, except for the inner layers. These layers as well as the end-cap regions are equipped with scintillator bars to cope with the high backgrounds. At projected background levels for SuperKEKB, the efficiency of the RPCs would drop to 50 % due to their long dead time. Another complication in the end-cap region are back-scattered neutrons that the KLM is exposed to.

3.4.8. Trigger and data acquisition

The Belle II trigger system uses a level-1 hardware trigger and a high level trigger (HLT) that is software-based. The trigger system has a high efficiency to select hadronic events from $\Upsilon(4S) \rightarrow B\bar{B}$ and from continuum [5]. The maximum trigger rate that is set by the Belle II data acquisition system (DAQ) is 30 kHz, which is 50 % larger than the expected 20 kHz trigger rate at $8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ luminosity. The trigger chain starts the level-1

trigger that has a maximum latency of 5 μ s, after which a trigger needs to be made. This latency is a hard limit as the signals from the sub-detectors cannot be buffered any longer by the readout hardware. The PXD is an exception to this rule, as it does not take part in the trigger decision and data needs to be buffered until the final trigger decision is made. The data is temporarily saved on the Online Selection Nodes (ONSEN) system [41]. The other sub-detectors provide signals that are available fast enough to respect the trigger latency.

The CDC provides track information in the form of track count, 2D and 3D tracks. This information is sensitive to events with a high multiplicity, i.e. events with many tracks, which are mostly hadronic events. The ECL provides cluster counts as well as timings and sums over the energy deposited. The ECL information is sensitive to events with charged and neutral particles with high and low energy clusters. Additionally, Bhabha and two photon events can be identified due to the characteristic signature they leave in the ECL. Various other hit information is provided by KLM, TOP and ARICH. The information is bundled and forwarded to the global reconstruction logic that performs a low-level reconstruction of the event. The output of this reconstruction is used by the global decision logic to make the level-1 trigger decision. If the result is positive, the trigger signal is sent back to trigger the readout of the buffered data of the detector front-ends, marking the first step of the Belle II DAQ. Data that is outside a triggered time windows will be overwritten and permanently lost.

The data is collected by the common pipeline platform for electronics readout (COPPER) via the Belle2Link [5, 42]. The Belle2Link is the data transmission system via optical fibers that connects the front-end electronics and the backend systems. The detector data is sent to the event builder that collects and merges the data into one block. The block of data is input to the HLT that performs a full event reconstruction. Upon the full event, a trigger decision is made, leading to the event to be saved or discarded. If the event is selected, the corresponding data from the PXD is pulled and added to the event. This concludes the trigger chain and data collection of events by the Belle II DAQ. The event is then processed again by the same full event reconstruction used by the HLT but to a higher precision and including the PXD data.

3.4.9. Vertexing at Belle II

Vertexing is integral to the physics analysis of CP violation and/of B decays [2]. To be able to differentiate decay vertices of B mesons and measure their distance along the z-axis, the beams have asymmetric energies so that the decay products are boosted in the direction of the electron beam. The decay vertex distance is displayed in Figure 3.7.

3. *SuperKEKB and Belle II*

From the decay vertex distance, the difference of the B meson lifetimes can be inferred. In particular, this is relevant for time-dependent CP violation measurements that are part of the Belle II physics program [2]. Still, the requirements on the vertex resolution are very high with distances of $\sim 80\,\mu\text{m}$ needing to be resolved. The first step in the vertex reconstruction is the track finding, also called tracking. Tracking describes reconstructing the three-dimensional trajectory of a particle through the detector's (sensitive) volume. To construct tracks at Belle II, hits in the CDC are combined to CDC tracks. This is done by iteratively extending the proposed helical flight path of a particle. Using the CDC tracks, tracks from SVD clusters are extracted, next to an SVD standalone track building. CDC and SVD tracks are then combined in an inwards direction, picking up PXD hits at the end. The tracks are then extrapolated towards the IP, as the B mesons decay before reaching the first detector layer. The extrapolation yields the vertex, i.e. the position, at which the B meson decayed and the extrapolated tracks intersect. In collider experiments particles are prepared with precise momenta. Due to Heisenberg's uncertainty principle, only a macroscopic localization is possible [43]. Position and vertex measurements are on length scales of the order of microns which is sufficiently large. Comparing the vertices of two B meson that belong to the same event yields the distance between the B decays along the z-axis. The average spatial separation of the B meson decay vertices is $130\,\mu\text{m}$.

4. Semiconductors and PXD

4.1. Semiconductors

Silicon semiconductors are an integral part of the detector concept of many high energy physics experiments. Semiconductors have an electrical conductivity smaller than conductors but higher than insulators. The conductivity is temperature dependent and increases for higher temperatures. Doping also influences the conductivity by introducing small impurities into the silicon. The impurities are either atoms with three valence electrons, e.g. boron, for p-doped silicon or atoms with five valence electrons, e.g. phosphorus, for n-doped silicon. The concentration of free positive charges, also called holes, is increased for p-doped silicon, while n-doped silicon has an increased concentration of negative charges, i.e. electrons. The change in concentration of free charges is a local effect and therefore multiple n- and p-doped regions can be created in one silicon crystal. Adjacent n- and p-doped regions form a pn-junction. The free negative charges of the n-doped region diffuse into the p-doped region. Most of the free charges of both regions recombine, thus creating a depletion region in the middle. Subsequently, the depletion region is charged positively towards the n-doped region and negatively towards the p-doped region. This causes an electric field that stops further diffusion as the exerted force points in the opposite direction of the charges' direction of motion during the diffusion. By applying an additional potential, called bias voltage, the size of the depletion can be increased.

A charged particle that traverses the depletion region loses energy due to ionization, creating electron-hole pairs. The amount of pairs created is proportional to the energy lost. The average energy needed to create an electron-hole pair in silicon is 3.6 eV [36]. The charges move under the influence of statistical thermal motion and due to electric fields. This causes a current I on the charge collecting electrode described by the Shockley-Ramo theorem [44]

$$I = E_w v q, \quad E_w = \frac{E}{U}, \quad (4.1)$$

where v is the velocity and q the charge of the charge carriers. The electric field E

normalized by its potential U gives the electric weighting field that is solely dependent on its geometry. The current is the measured signal that indicates the passing of a particle through this depletion region.

4.2. From MOSFET to DEPFET

A metal-oxide-semiconductor field-effect transistor (MOSFET) has three voltages and three contacts. The contacts are usually referred to as source, drain and gate contacts. Assuming an n-channel MOSFET, the main silicon substrate, or bulk, is p-doped, meaning impurities of p-type dopants have been introduced to the silicon crystal, changing its electrical properties. In the p-doped bulk, two n-doped wells are implanted to which the drain and source contacts are connected forming an npn-junction through which no current can flow. Detached from the bulk by a layer of SiO_2 , the gate contact lies between the source and drain. The voltages are the gate voltage at the gate contact, the voltage between source and drain and the threshold voltage. If the gate voltage surpasses the threshold voltage, an n-channel, or inversion channel, forms, allowing current to flow from source to drain. The current flowing increases linearly with the voltage between source and drain until the saturation voltage is reached. As the source-drain voltage V_{DS} approaches the saturation, the npn-junction is pinched off and no additional current I_D can flow. This mechanism is displayed in Figure 4.1 and a qualitative function of the dependence of I_D from V_{DS} for different gate voltages is displayed in Figure 4.2. A formal description can be found in Reference [45]. The saturation voltage depends on the gate voltage and the material/doping used. The transistor can be operated in the linear regime or in the saturation regime, depending on its use.

A DEPFET pixel [39] adds an internal gate and a second FET to clear charges collected in the internal gate. Assuming the aforementioned setup of a MOSFET, the internal gate is a p-doped well below the gate contact in the bulk. A voltage is applied on the bulk to fully deplete it. If charged particles traverse the bulk, electron-hole pairs are created. Depending on the doping of the internal gate, either the electrons or holes drift towards it. The charges are effectively trapped in the internal gate. Charges collected in the internal gate have a similar effect on the p-channel as the gate voltage but inverted. The internal gate under the gate in the bulk is displayed in Figure 4.3. When applying a voltage between source and drain so that a current flows from drain to source, one can infer the amount of charges in the internal gate from the current. To do that, the FET needs to be operated in the linear regime. After the measurement of the charge inside the internal gate, it is cleared using the second FET, where the internal gate acts as source,

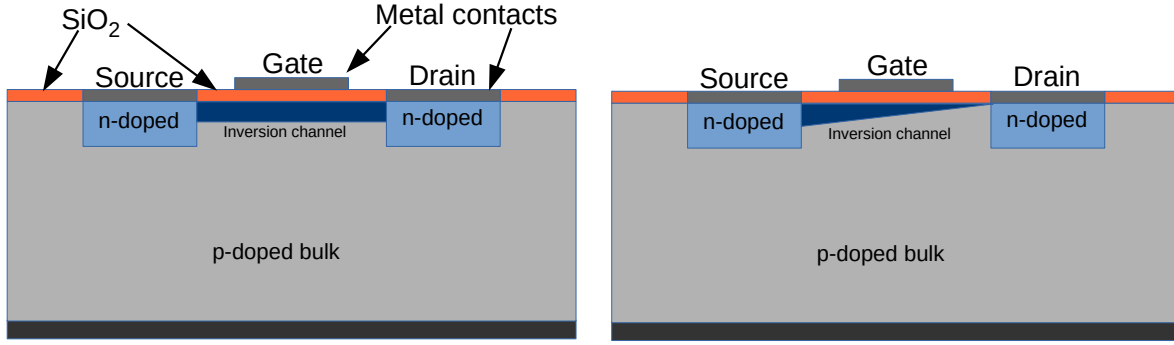


Figure 4.1.: Schematic of a MOSFET transistor with a p-doped bulk and n-doped wells below the source and drain metal contacts. Left: The inversion channel between the source and drain during operation in the linear regime. Right: The inversion channel between the source and drain during operation in the saturation region, when it gets deformed and pinched off.

and a clear voltage is applied to the gate of the second FET, allowing the charges to flow to the drain, or clear contact. This leaves the DEPFET pixel in its initial state. The pixel does not need to be powered, i.e. is not dissipating power, to collect charges. Power is only dissipated during the readout, where rows are turned on and the drain current is sampled.

Every sampling of the drain current results in a measurement that is greater than zero. Meaning that there is a current flowing even though there is no charge in the internal gate. This current needs to be measured beforehand to correctly identify hits in pixels. It is subtracted from following measurements as an offset and is called the *pedestal* of the pixel. The pedestal differs between pixels and modules, due to differences in production, and also changes with time.

4.3. PXD

The PXD consists of four types of modules that are used in dependence of their position. The positions are inner-forward (IF), inner-backward (IB), outer-forward (OF) and outer-backward (OB). Each module type has two matrix regions with different pixel sizes, but the amount of pixels per matrix is 768×250 for all module types. A schematic of a PXD module are displayed in Figure 4.4 The module and pixel sizes for all types is displayed in Table 4.1. The drain over which the current of the DEPFET pixels is sampled is a shared drain line for all pixels of one column. Row-wise the pixels are divided in groups of four rows that are turned simultaneously. With a total of 768 rows, 192 groups of rows need to be read out. Each step takes ≈ 100 ns, adding up to 20μ s for the entire rolling

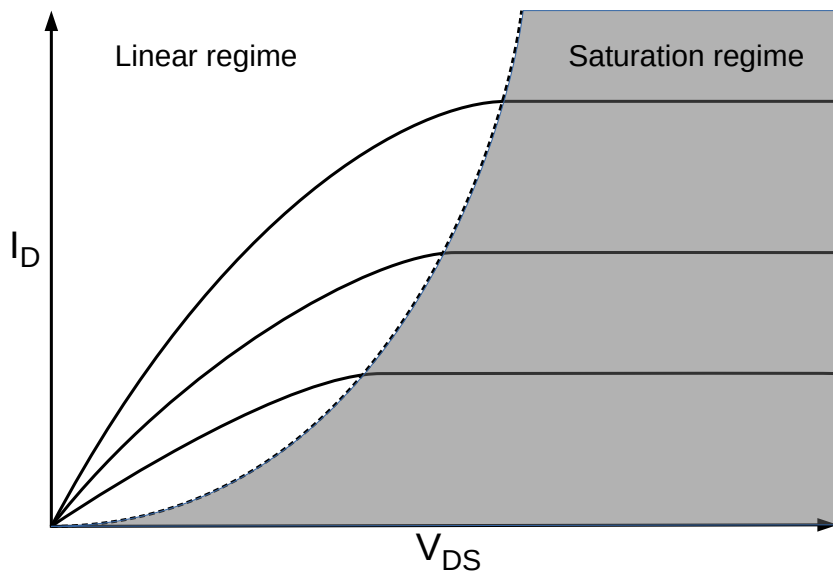


Figure 4.2.: Dependence of the current I_D on the voltage between source and drain V_{DS} for different gate voltages.

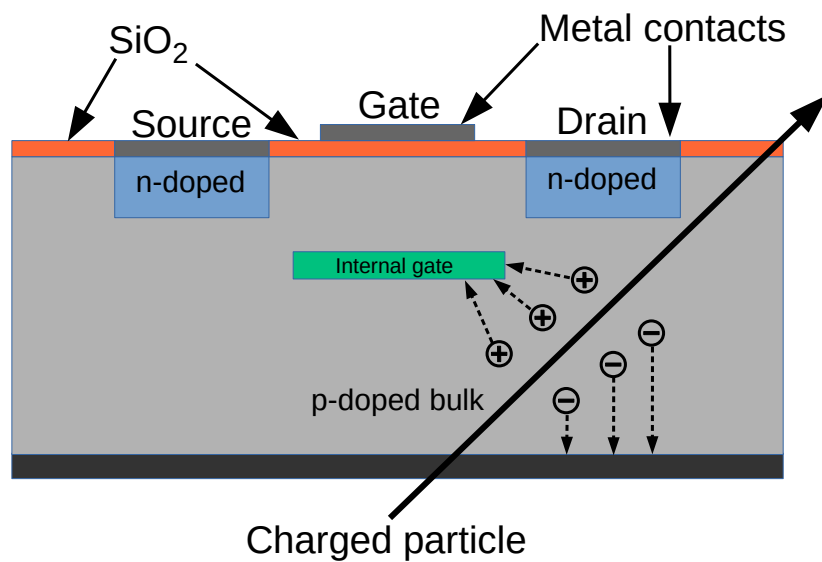


Figure 4.3.: Schematic of a DEPFET transistor indicating the internal gate that collects charges produced by the ionization of the bulk material by a traversing charged particle.

Type	Length [mm]	Width [mm]	Inner pixel size [μm]	Outer pixel size [μm]
IF	44.8	12.5	55×50	60×50
IB	44.8	12.5	55×50	60×50
OF	61.4	12.5	70×50	85×50
OB	61.4	12.5	70×50	85×50

Table 4.1.: Module size and pixel sizes for all module types.

shutter style readout. The integration time readout mode is relatively long and many hits are recorded during each readout. If a pixel is hit twice during one readout cycle, they cannot be differentiated. With the current occupancy during Phase 3 being $< 0.5\%$ for most modules, the effect should be minimal.

The pixel modules are populated with three types of ASICs that facilitate the pixel readout. The six SWITCHERs placed on the long side of the module turn on the groups of pixels rows during the readout [46]. The drain lines end in 4 drain current digitizers (DCD) [46]. Here the analog currents are converted into digital signals. The digitized currents are handled by the digital handling processors (DHP) to reduce the data rate by performing a zero suppression [47]. The DCD and DHP ASICs are placed outside the detector acceptance allowing for active cooling of these components, while the matrix and SWITCHERs in the acceptance region remain passively cooled. The thickness of the module is $75\mu\text{m}$ in the matrix region and $500\mu\text{m}$ for parts of the module with ASICs.

The numbering scheme of the PXD modules is realized with four digits. The first digit indicates an inner (outer) ladder represented by the number 1 (2). The second and third digit indicate the radial position of the ladder. The last digit indicates whether the module is in the forward or backward position in the ladder. A schematic view of the PXD indicating the numbering scheme is displayed in Figure 4.5.

4.4. Radiation Damage in silicon sensors

When particles interact with a silicon sensor, i.e. particles scattering with silicon atoms, reversible and irreversible changes, e.g. to the silicon crystal lattice, can be introduced. The damages can be divided into two categories, the bulk damage and the surface damage, which are discussed in the following sections. This section is based on References [48, 49].

4.4.1. Bulk damage

The bulk is the main silicon body of a semiconductor and is indicated in Figures 4.1 and 4.3. Bulk damage is predominantly produced by hadrons, i.e. protons and neutrons.

4. Semiconductors and PXD

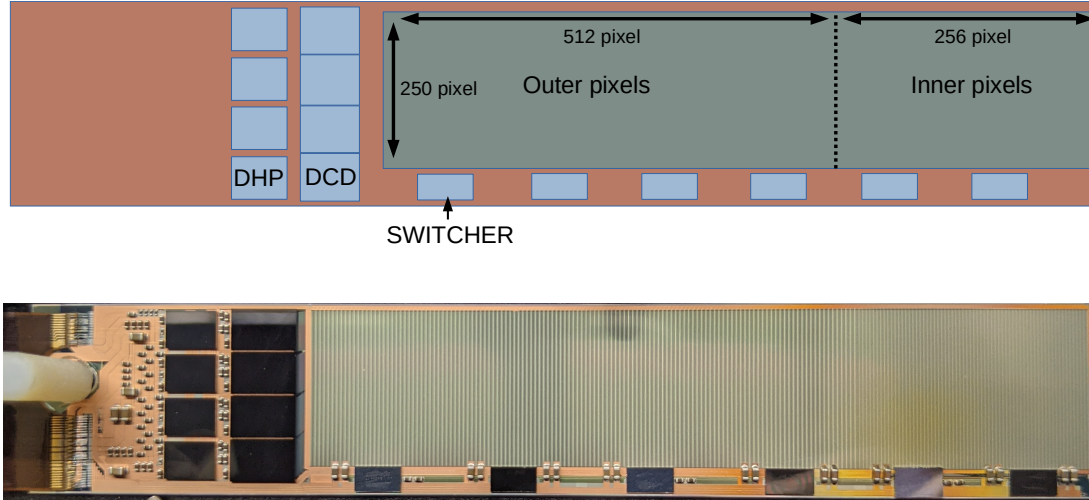


Figure 4.4.: Top: Schematic of a PXD module that indicates the ASICs and the inner and outer pixel areas on the matrix. Bottom: Photograph of a PXD module.

A model that describes these effects is the non ionizing energy loss (NIEL) hypothesis [50]. When a hadron with sufficient energy traverses the silicon, it can kick a silicon atom out of the lattice, leaving a vacant slot and an interstitial atom in the lattice, called Frenkel pair. The energy threshold to create a Frenkel pair in a silicon lattice is 25 eV [49]. The interstitial silicon atom will carry most of the remaining energy of the initial hadron. Depending on the energy of the interstitial silicon, further damage can ensue, which is called cluster damage. If only one atom is affected, the damage is point-like. The NIEL hypothesis assumes that the damage to the lattice is linearly dependent with the energy loss due to the displacement. The damage can be represented as a function $D(E)$ for different types of particles that describes the average recoil energy cross-section (displacement damage cross-section) left in the lattice per unit fluence of the respective particle. To obtain a unified scale to express bulk damage caused by radiation, the equivalent 1 MeV neutron fluence is used. If the type and energy spectrum of the radiation is known a hardness factor can be calculated, that scales the fluence of that radiation to the neutron equivalent dose.

These changes in the lattice affect the electrical properties of the silicon by shifting energy levels or creating energy levels in the band gap, also called forbidden gap. Depending on their position relative to the valence or conduction band, electrons or holes are affected.

Leakage current: In the bulk of silicon sensors there is a constant current that is caused by the thermal generation of electron-hole pairs. The threshold for generating

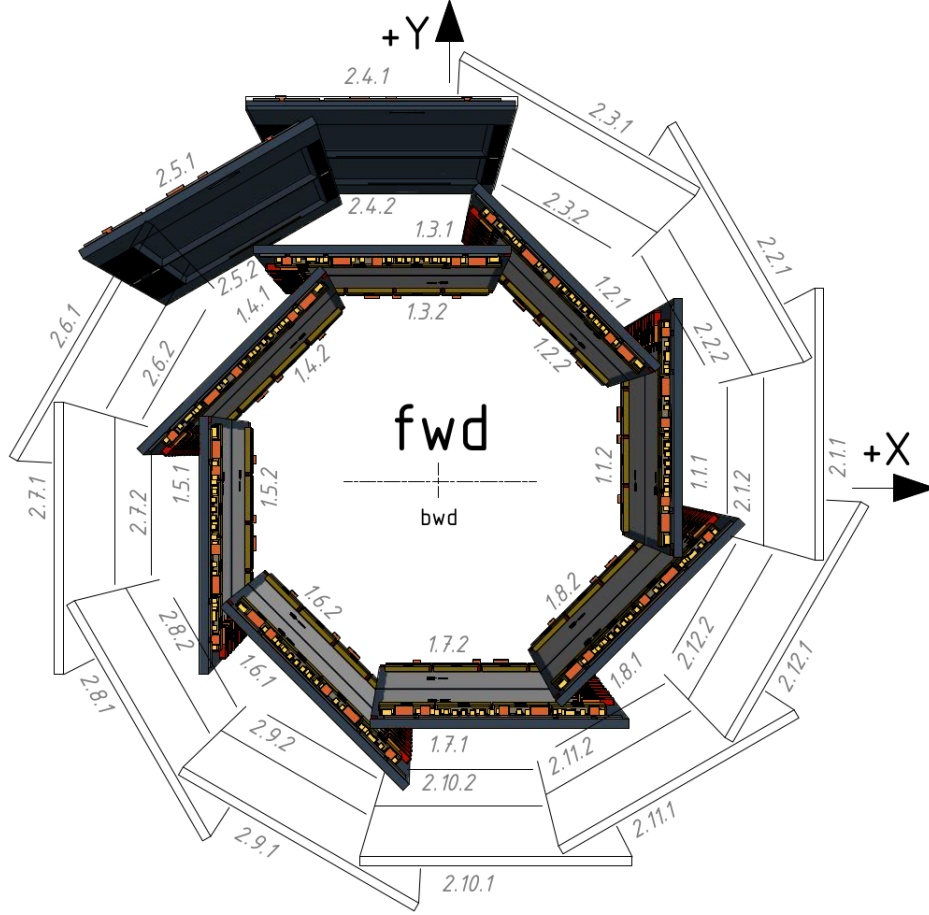


Figure 4.5.: A schematic view of the PXD indicating its position in the coordinate system and indicating the module numbering scheme.

electron-hole pairs is ~ 3.6 eV. Defects with energies in the middle of the band gap need less energy to be ionized, thus the energy needed to generate an electron-hole pair is reduced and the leakage current increases. The increase of leakage current is proportional to the equivalent neutron fluence the sensor has received.

Depletion Voltage: When displaced by irradiation, donor atoms may not be able to further act as donors, and di-vacancy defects (a pair of holes) may be introduced, increasing the density of acceptors. The space charges created in the band gap and the change of concentration of charge carriers change the effective doping concentration and the depletion voltage. In an n-doped substrate, the depletion voltage drops with irradiation until a type inversion occurs. After the type inversion to a p-type substrate, the depletion current rises.

Charge collection deficiency: Electrons and holes may be trapped by defects in the band gap, while drifting towards the charge collection node. The charges may be trapped for times longer than the readout time, effectively reducing the charge sensitive during

the readout.

Most defects, such as interstitial atoms, space charges or impurities, may travel through the lattice. Given enough time, some defects, such as vacancies and interstitial atoms, may recombine in a process called annealing. This effectively reverts defects back to its original, undamaged state. The annealing rate depends on the temperature. Typical lengths of annealing time frames during operation of silicon sensors in particle physics experiments are not enough to fully anneal all damages that occurred.

4.4.2. Surface damage

Surface damage describes damage to the SiO_2 surface and the bulk-surface interface, mostly due to gamma irradiation. Photons with energies below 1 MeV undergo Compton scattering or the photoelectric effect. The secondary electrons produced ionize the material, creating electron-hole pairs. Some electrons and holes may be trapped in the SiO_2 or in the Si- SiO_2 interface, creating oxide charges. Due to their low mobility, holes are more likely to remain in the material, forming a positive oxide charge barrier between the surface and the bulk. Below the oxide charge barrier, electrons accumulate, preventing a full depletion of the pixel volume. Due to the charges, the electrical field is deformed, causing localized high electric fields, reducing the voltage breakdown threshold. Surface damage effects that are caused by photon irradiation scales with the TID deposited in the material, i.e. the energy deposited by ionization per unit mass. Oxide charges may recombine over time and anneal.

Radiation damages can degrade the detector performance up to the point of rendering the pixel inoperable. This can happen due to massive damage to the lattice, creating traps that do not allow for collecting enough charge to cross the signal threshold. Currents and voltages that are vital for the operation of the pixel can be pushed out of their operational ranges. Of particular danger are massive radiation spikes that usually cause beam aborts.

5. Total ionizing dose measurement

To verify if the PXD functions according to previous lab tests under the radiation produced by SuperKEKB a measurement of the TID is necessary. The lab measurements after irradiation include, amongst other measurements, TID measurements, efficiencies, noise and changes of operating voltages [51]. The measurement should feature a reliable and possibly lightweight approach that can be applied on the entirety of Phase 3 and on future operation. Since the measurement covers a lot of data, more than 3 years in fact, the importance of a computationally lightweight is emphasized, without sacrificing measurement accuracy. Currently, there is no other measurement of the PXD TID for the entire Phase 3 operation of the PXD installed in Belle II. The measurement uses 1 Hz process variable (PV) time series from the Belle II archiver. The Belle II archiver is part of the slow control system of Belle II, i.e. the system that monitors and operates the hardware of Belle II. The slow control system and the saved monitoring PVs are explained in more detail in Section 5.1. Using time series would allow to compute the ionizing dose rate as a time series. A time series in the context of this measurement means estimating the dose rate at any moment and integrating this time series yields the TID. The advantage of a time series is that it contains more information as it allows, for example, the identification of moments during which more ionizing dose is deposited compared to other moments in time. Since the PXD measures hits of ionizing particles, the occupancy is related to the ionizing dose. This relation is described in Section 5.2. The online occupancy is modeled using heuristic scaling laws of background contributions which is described in Section 5.2. Two studies need to be conducted before the heuristic scaling laws can be applied on the data. These studies are described in 5.3. The heuristic scaling law for the beam-gas component depends on the beam pipe pressure that is measured in Section 5.3.1. To simplify the fit the Touschek and luminosity components are determined during a background study day and then kept constant during the dose measurement. This measurement is described in 5.3.2. The noise floor of the module occupancy needs to be determined, which is described in 5.4 and the reestimation of sensitivities to obtain the occupancy models that yield the occupancy for the dose measurement is described in 5.5. The results and comparisons are then presented in Chapter 6. An alternative

5. Total ionizing dose measurement

measurement approach is discussed in A.1.

The data taking for Belle II is organized in so-called physics runs. During a physics run all detector subsystems are running nominally and the Belle II DAQ is collecting physics data, as described in Section 3.4. SuperKEKB stores and collides the HER and LER bunches and delivers the target luminosity for the physics measurements. The physics runs are categorized by an experiment number and a run number. The experiment number is used to mark data taking periods that usually last for weeks or months and is changed on occasion. The run number counts the physics runs taken during each experiment period. Once the experiment number is increased by one, the run number is set to 1. Both the experiment number and the run number are strictly increasing by 1 and start at 1.

5.1. Slow control

The slow control is managed by the experimental physics and industrial control system (EPICS) [52, 53]. EPICS uses a structure with multiple servers that communicate with the hardware on the one side and the client on the other side. Information between the server and the client is exchanged in the form of PVs, which are machine observables. These PVs are provided by Input/Output Controllers (IOCs) that interface with the hardware frontend components and the EPICS network. The SuperKEKB archiver is based on the EPICS archiver appliance and is part of this network [54]. It collects $\mathcal{O}(1000)$ PVs as 1 Hz time series that describe the machine state of Belle II and SuperKEKB. Examples for PVs are set and read back values of SuperKEKB magnets that steer the beam or measured values like the PXD occupancy per module. In addition to the general SuperKEKB archiver, there are specialized archivers for different subsystem. The PXD, for example, has an additional archiver, collecting PXD specific information. All stored variables are timestamped to synchronize data afterwards. The flow of data for the PXD starts with the pixel readout on the matrix. The pixel hit information is gathered and processed by the ASICs on each module. This is in more detail described in Section 4.3. The modules are connected via JTAG to the data handling engine (DHE) that is implemented on field-programmable gate arrays (FPGAs). The PXD module is read out in segments and reading out all segments once is one readout cycle. The DHE receives the zero-suppressed hit information gathered during the $20\mu\text{s}$ rolling shutter readout. The DHEs are controlled by the DHH IOC, which communicate with the EPICS network. The number of hit pixels per readout cycle divided by the total amount of pixels defines the occupancy. An illustration of this is displayed in Figure 5.1. To determine the online

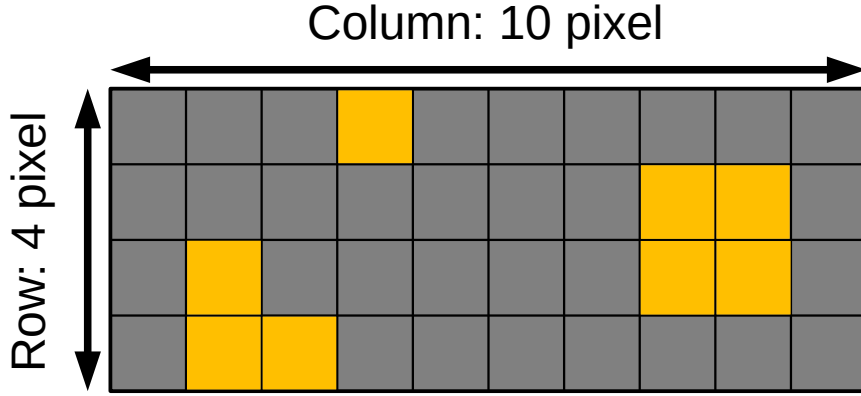


Figure 5.1.: Illustration of the module occupancy. The yellow marked pixels have fired during a readout cycle. Out of 40 pixels, 8 pixels fired, which is equivalent to an occupancy of 20 %.

occupancy the data send to the Onsen system is opened and evaluated, the hits are summed and the online occupancy is calculated. The occupancy is averaged over one second and saved by the EPICS archiver appliance.

The archiver uses data compression on the PXD online occupancies, to reduce the storage space needed. The archiver will only store a data point, when its value differs from the previous data point by a minimum amount. This value is set for each recorded parameter. With time, this minimum difference is coarsened and data that does not fit the updated requirement will be deleted. This can manifest itself in step-like structures and can be seen in the time series of the PXD module occupancies. For example, during beam decays the occupancy is expected to resemble a smooth slope, as the beam current also falls smoothly. Instead, the occupancy rather resembles a staircase. This effect can be observed throughout this chapter and is unrelated to the PXD itself.

A list of all used variables from the EPICS archiver is displayed in Table A.2.

5.2. Measurement approach

The measurement of the TID is based on two equations. The first gives the composition of the occupancy of the PXD using engineered heuristic scaling laws [30, 31]. The second allows for the conversion from an occupancy to an ionizing dose.

The heuristic scaling laws separate the contributions to the background by source per ring and multiply a sensitivity to the dependencies. An H (L) indicates an HER (LER)

5. Total ionizing dose measurement

variable. In the case of this measurement the background contributions included are:

$$\mathcal{O}_{\text{beam-gas}}^{\text{H/L}} = B^{\text{H/L}} \times I^{\text{H/L}} P_{\text{eff}}^{\text{H/L}}, \quad (5.1)$$

$$\mathcal{O}_{\text{Touschek}}^{\text{H/L}} = T^{\text{H/L}} \times \frac{I^{2,\text{H/L}}}{n_b^{\text{H/L}} \sigma_x^{\text{H/L}} \sigma_y^{\text{H/L}} \sigma_z^{\text{H/L}}}, \quad (5.2)$$

$$\mathcal{O}_{\text{inj}}^{\text{H/L}} = F^{\text{H/L}} \times B_{\text{gate}}^{\text{H/L}}, \quad (5.3)$$

$$\mathcal{O}_{\text{lumi}} = L \times \mathcal{L}. \quad (5.4)$$

The variables $B^{\text{H/L}}$, $T^{\text{H/L}}$, $F^{\text{H/L}}$ and L are the sensitivities. The sensitivities must be fitted to the data. They are expected to change over time when SuperKEKB machine parameters are changed. During normal operation of SuperKEKB small tuning changes result in a relevant change of sensitivities. For example, the opening and closing of collimators affect the background conditions immediately. The accumulation of many small changes can also let the sensitivities drift noticeably over time frames of multiple days. The other variables are beam and machine settings. $I^{\text{H/L}}$ is the beam current, $P_{\text{eff}}^{\text{H/L}}$ is the effective pressure in the beam pipes seen by the particles, $n_b^{\text{H/L}}$ is the number of bunches in a ring at a given time, $\sigma_x^{\text{H/L}}/\sigma_y^{\text{H/L}}/\sigma_z^{\text{H/L}}$ are the bunch sizes in x, y and along the beam axis and $\mathcal{L}$ is the instantaneous luminosity. The bunch size along the beam axis, or bunch length, is obtained using

$$\sigma_z = z_0 + z_1 \times \frac{I}{n_b}. \quad (5.5)$$

The variables z_0 and z_1 were obtained by dedicated studies, I is the beam current and n_b the number of bunches in the ring [55]. The variable $B_{\text{gate}}^{\text{H/L}}$ describes the beam gate status and takes the discrete values 0 and 1 when the injection gate is closed or open. When the injection gate is opened charges are injected into the ring and vice versa for a closed injection gate. Using this variable in the injection background contribution effectively enforces the assumption that there cannot be injection backgrounds without injections as the sensitivity $F^{\text{H/L}}$ is multiplied with either 0 or 1. All mentioned variables and observables are available as 1 Hz time series on the archiver except the effective pressure, which is measured in Section 5.3.1.

The ionizing dose rate $\dot{D}$ is linearly dependent on the occupancy O and is given here in SI units Gys^{-1} . The occupancy is defined as the amount of firing pixels per total number of pixels in a readout cycle. The length of a readout cycle is determined by the integration time, which can be calculated using the trigger length $N_{\text{trg_len}}$ and the DHH clock $f_{\text{dhh_clock}}$. Multiplying the occupancy with the inverse of the integration time yields

the number of firing pixels per time unit. To get from the amount of firing pixels to a deposited energy an energy calibration is needed. The energy calibration enters the equation as $\langle \frac{E}{A} \rangle$. It is the average deposited energy per firing pixel. E is the deposited energy per hit cluster and A is the number of pixels in that cluster. This is then averaged over clusters from all possible charged incidence particles and of all energies and positions on the matrix. A cluster is a group of neighboring pixels that fire at the same time due to the same incidence particle. A firing pixel describes a pixel that has recorded a hit. It is derived in an offline analysis where the charge of cluster and the cluster size is known. This is done by calibrating the charge measurement of the DEPFET pixels, summing the total ionization charge of a cluster and dividing by the energy required to produce an electron-hole pair in silicon, which is 3.6 eV. Depending on the machine operation and background composition the variation of the energy calibration factors is observed to be $\mathcal{O}(1\%)$. The energy calibration is dependent on the ϕ angle, i.e. the module position, and has to be measured per module. The calibration used was determined with run 5934 of experiment 12, which is in June 2020, and the values are given in Table 5.1. The product of the energy calibration and the number of pixels firing per time unit yields and energy per time unit. To obtain the TID the energy needs to be normalized to the sensitive mass. The sensitive mass m_{pixel} is obtained by multiplying the sensor volume with the density of silicon. The calculated ionizing dose rate considers the ionizing dose deposited anywhere in the matrix volume, which is consistent with the energy calibration and the normalization with the mass of the matrix. The sensor volumes are dependent on the module type and are summarized in Table 4.1. Writing this as one comprehensive formula yields:

$$\dot{D}_i = \frac{f_{\text{dhh_clock}}}{N_{\text{trg_len}}} \cdot \frac{\overbrace{(O_i - O_{\text{noise},i})}^{\text{fit model prediction}}}{100} \cdot k \cdot \langle \frac{E}{A} \rangle_i \cdot \frac{1}{V_{\text{pixel}} \rho_{\text{Si}}}. \quad (5.6)$$

The dose rate is defined on a per-module basis denoted by i . The energy calibration is in units of GeV, which are converted to SI-units via the conversion factor k . The modules are assumed to be noisy with a constant noise floor that is determined outside the heuristic fit in Section 5.4. The DHH clock is constant and can only take the value $f_{\text{dhh_clock}} = 76.23 \text{ MHz}$ as it is derived from the global Belle II trigger and timing clock. The trigger length is unitless can be configured with higher values leading to higher integration times. The value is approximately 1750 for all modules, but the exact values are archived and used for this formula.

The heuristic background function is used to model the online occupancy that is ob-

5. Total ionizing dose measurement

Module	$\langle \frac{E}{A} \rangle$ [keV]
1.1.1	14.722351
1.1.2	13.247851
1.2.1	13.772629
1.2.2	12.945784
1.3.1	11.831390
1.3.2	-
1.4.1	11.676075
1.4.2	12.417085
1.5.1	11.125662
1.5.2	11.671819
1.6.1	12.627211
1.6.2	12.729321
1.7.1	14.567215
1.7.2	12.800679
1.8.1	14.501510
1.8.2	12.280354
2.4.1	15.083593
2.4.2	14.821886
2.5.1	15.332458
2.5.2	14.963101

Table 5.1.: The energy calibration of all modules to calibrate the average energy deposited per firing pixel. The values are derived by taking the average of the energy deposited per cluster divided by the cluster size. The run used is experiment 12 run 5934. Module 1.3.2 is not operational.

tained from the archiver. The occupancy that is converted into a dose rate is the occupancy modeled by the heuristic background function. The online occupancy does not directly contribute to the calculated dose.

5.3. Measurements of prerequisites

5.3.1. Beam pipe pressure

The vacuum system of SuperKEKB is in more detail described in Reference [4]. The effective beam pipe pressure in the center is needed to properly calculate the beam-gas component. Around the storage rings cold cathode gauges (CCGs) are placed at a distance of 10 m, monitoring the pressure of all twelve sections of each ring. The CCGs measure the pressure constantly and provide 1 Hz time series for each section. The pressure changes depending on the beam conditions and a detailed discussion of this topic can be found in References [56, 57]. The central assumption in terms of pressure changes is that the

pressure has two components. One is dynamic and depends linearly on the beam current and the other component is constant and can be observed when no beam is in the rings [31].

The linear function that describes this proportionality is as follows:

$$P_{\text{beam}} = P_{1,\text{beam}}I + P_{0,\text{beam}} \quad (5.7)$$

$$P_{1,\text{beam}} = \left(\frac{dP_{\text{beam}}}{dI} \right). \quad (5.8)$$

The CCGs, however, only measure the pressure at the circumference of the beam pipe. The dynamic pressure $P_{1,\text{beam}}$ at the center of the beam pipe, that is observed by the particle beam, is expected to be three times higher than at the outer part of the beam pipe $P_{1,\text{CCG}}$ [31], yielding

$$P_{1,\text{beam}} = 3P_{1,\text{CCG}}. \quad (5.9)$$

The constant pressure $P_{0,\text{beam}}$ is expected to be valid throughout the beam pipe, allowing for $P_{0,\text{beam}} = P_{0,\text{CCG}}$ to be valid. Both variables $P_{0,\text{CCG}}$ and $P_{1,\text{CCG}}$ can be obtained by performing a linear fit, preferably during a beam decay, as the current decreases smoothly. This allows for a modelling of the beam pipe pressure using only the beam current.

A different approach for obtaining P_{beam} can be found by substituting the dynamic pressure in Equation 5.7. Starting from

$$P_{\text{CCG}} = \left(\frac{dP_{\text{CCG}}}{dI} \right) I + P_{0,\text{CCG}} \quad (5.10)$$

$$\left(\frac{dP_{\text{CCG}}}{dI} \right) I = P_{\text{CCG}} - P_{0,\text{CCG}} \quad (5.11)$$

yields the substitution, obtaining

$$P_{\text{beam}} = 3(P_{\text{CCG}} - P_{0,\text{CCG}})I + P_{0,\text{CCG}} \quad (5.12)$$

after insertion. The expression is only dependent on the base pressure $P_{0,\text{CCG}}$ and the measured CCG pressure P_{CCG} as is. The advantage of this approach is the independence from the dynamic pressure fit parameter which might be sensitive to changes of beam conditions, which are being directly taken into account by using P_{CCG} , without the need of redoing a fit or modelling the dependence of the pressure on the beam conditions. The base pressure is expected and observed to be approximately stable throughout Phase 3 operation. Therefore, this approach was chosen to obtain the effective beam pipe pressure.

5. Total ionizing dose measurement

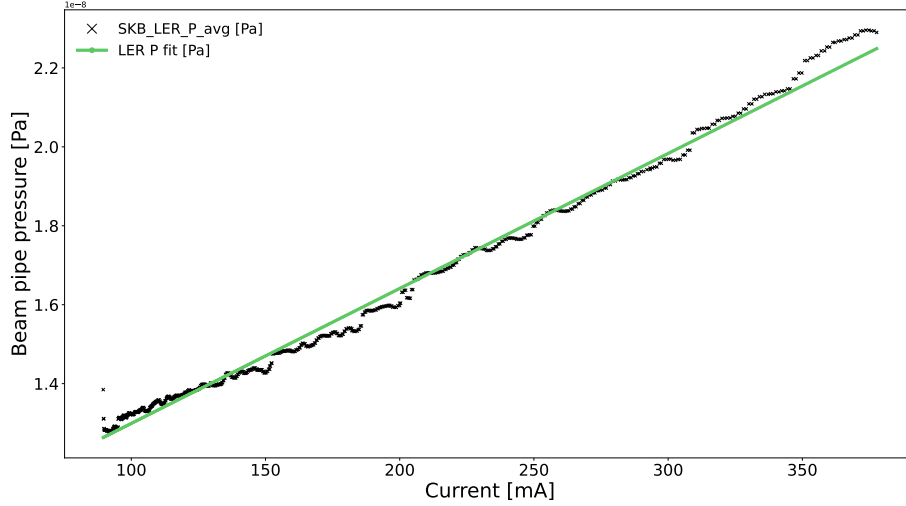


Figure 5.2.: Linear fit of the beam pipe pressure in dependence of the beam current for the LER ring in June 2022.

The base pressure is obtained the same way as in the first approach, by performing the same linear fit, but discarding the $P_{1,CCG}$ fit parameter. The fit algorithm uses the *least squares* method from the Python 3 [58] SCIPY library [59]. This method is used for all fits in this work. Quality constraints are applied to the beam decays used for fitting. The decay needs to happen in the corresponding ring in which the base pressure is determined and the decay needs to be at least 180s long and span a range of at least 50 mA. An example fit is displayed in Figure 5.2. During every month of beam operation every beam decay that satisfies the mentioned quality criteria has been evaluated for all CCGs. The measured base pressure is then averaged at each section to obtain the averaged base pressure at that section in a certain month. Not all sections yield a proper measurement due to noisy and unreliable measurements as some sections measure pressures 10 times higher than neighboring sections. Another problem is the minimum pressure of 10 nPa that can be measured by the CCGs. With the base pressure in some HER sections being close to or below that minimum pressure the respective CCGs report a constant pressure of 10 nPa. Excluding these sections leaves the sections 1, 2, 3, 4, 7, 11 for the LER and 2, 4, 9 for the HER. The pressure over the respective sections is averaged. The results are summarized in Figure 5.3

5.3.2. Sensitivities during background study campaigns

During Phase 3 operations of Belle II, multiple background study campaigns were conducted. The goal of these study campaigns is to determine the beam-induced background composition. This measurement can be used to improve the background simulations for

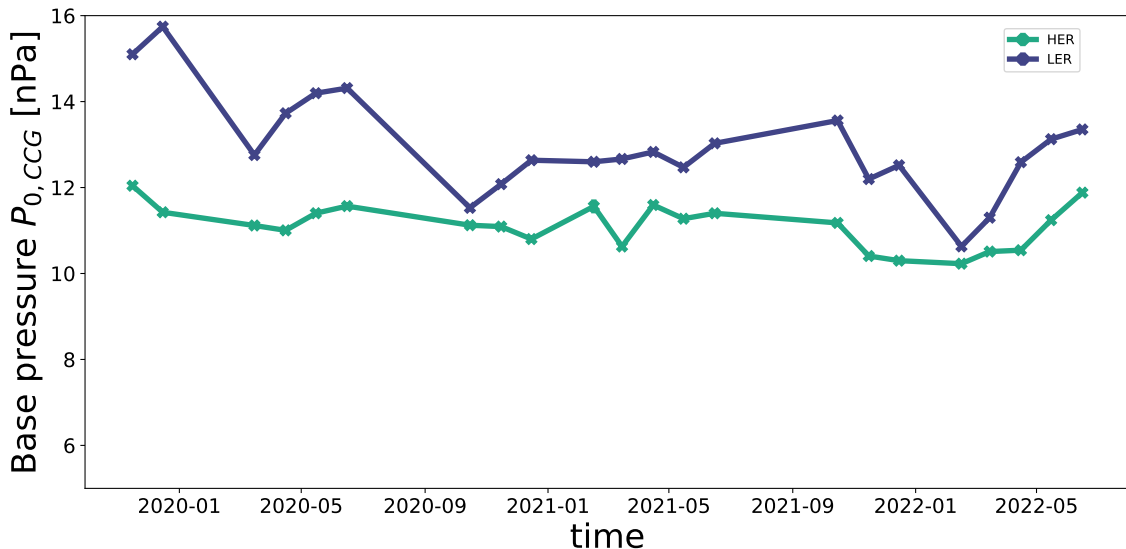


Figure 5.3.: The measured base pressure $P_{0,CCG}$ since the start of Phase 3 operation for both rings.

Belle II [60]. In the context of the dose measurement it is used to measure sensitivities for the heuristic background function, to simplify the fitting procedure described in Section 5.5. Measuring the background composition is not trivial as the background components need to be disentangled. During a single beam decay the storage background components beam-gas and Touschek need to be differentiated. This is done by making multiple background measurements of SuperKEKB configurations, where only certain parameters are varied. These parameters are those that explicitly appear in the heuristic scaling laws of Section 5.2, e.g. the number of bunches. Other parameters that impact the background conditions, like settings of the magnets steering the beam and collimators are the same for every background study campaign. The PXD occupancy is modeled using the heuristic scaling laws and the TID measurement therefore faces the same problem, that contributions need to be disentangled before they can be scaled properly. These configurations and measurement methodology used to disentangle the background contributions during study campaigns are presented in the following. The example used is the background study conducted on the 16.06.2021. Since all background study campaigns yielded consistent results [31], the choice was arbitrary.

The background studies are dividing into four parts. The first measurement is a pedestal, or noise floor, measurement, where all Belle II sub-detectors run nominally, acquiring data without beam in any of the two rings.

The second measurement focuses on the LER beam background contributions. In this single-beam measurement only the LER is filled with $n_b = 393$ up to $I_{LER} = 250$ mA. Once

5. Total ionizing dose measurement

reaching the target current, top-up injections are continued for 5 min, following that the injections are stopped and the beam decays for 15 min. The beam is then aborted and the same procedure is repeated for $n_b = 1174$ and $I_{\text{LER}} = 840$ mA. The beam decay from $I_{\text{LER}} = 840$ mA is split into two parts. The beam decays to $I_{\text{LER}} = 400$ mA with additional 5 min of top-up injections and from there the beam decays for 15 min until it is dumped. By varying the current and the number of bunches multiple times the contributions from Touschek and beam-gas can be disentangled. Using the beam decays the pressure at the center of the beam pipe can be extracted. The injection background is also identified as it immediately vanishes when switching from top-up injections to beam decays, i.e. stopping injections.

The third measurement repeats the single-beam measurement for HER with the same values and timings except the beam current. In the second step, at $n_b = 1174$, the current tops out at $I_{\text{HER}} = 680$ mA, compared to $I_{\text{LER}} = 840$ mA for the LER, before decaying to $I_{\text{HER}} = 400$ mA.

The fourth measurement is the luminosity measurement. Both rings are filled with $n_b = 1174$ and currents of 840 mA (680 mA) for LER (HER). At the target currents the luminosity is varied three times for 15 min each. The luminosity can be varied downwards by purposely mistuning the machine so that the crossing bunches at the IP do not overlap fully. The luminosities are $L_1 = 2.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, $L_2 = 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and $L_3 = 1.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. Then the beams decay for 15 min and the luminosity is set to its initial value. Then another 15 min of top-up injections and decay follow concluding the background study. With the storage and injection backgrounds of the LER and HER known from the previous measurements, the luminosity background can be extracted. An overview of the measurements taken is displayed in Figure 5.4.

The general strategy to obtain a fit of all sensitivities includes the following steps:

1. Using the assumption that during single-beam decays only Touschek and beam-gas contribute to the background, both are fitted first. To differentiate both contributions the different dependencies on the current ($\mathcal{O}_{\text{beam-gas}}^{\text{H/L}} \propto I$ and $\mathcal{O}_{\text{Touschek}}^{\text{H/L}} \propto I^2$) and the number of bunches ($\mathcal{O}_{\text{Touschek}}^{\text{H/L}} \propto 1/n_b$), in the respective ring, is used.
2. During the single-beam top-up injections beam-gas, Touschek and injection backgrounds contribute. The obtained sensitivities for beam-gas and Touschek are kept constant during this second fit, yielding the sensitivity of the injection background.
3. Due to the step-like occupancy data during beam decays, the fit results for beam-gas and Touschek are inconsistent. Therefore, the two-step fitting procedure is combined

into one step, meaning that the separation of the background contributions is not enforced a priori.

4. During beam collisions with top-up injections all background components contribute, but all components but the luminosity sensitivity were obtained during the first two steps. So all previously obtained Sensitivities are kept constant in the last fit, yielding the luminosity sensitivity.

The step-like occupancy in the beam decay fits is a result of the archiver compression. This is explained in Section 5.4. To showcase the performance of the fit during decays and top-up injections, the following results are split into the 2 data sets, although the fit was done on the combined data set. The measured PXD occupancy during the LER and HER single beam studies are displayed in Figure 5.5 and 5.6.

The fit of the luminosity component, which is essentially the complete function as it contains the sensitivities of all background components, is displayed in Figure 5.7. The large spread of data points during top-up injections seen especially in Figure 5.7 is due to injection backgrounds that cause large upwards fluctuations from 0.1 % occupancy up to 0.25 %. These fluctuations are, in part, not well accounted for by the fit. The model assumes a constant contribution of the injection background, while the data has a structure that depends on the opening and closing of the charge injection gate.

The obtained sensitivities for each module are displayed in Table A.3. The uncertainties of the occupancy to obtain proper uncertainties from the covariance matrix are displayed in Table 6.3. The sensitivities have been used to measure the ionizing dose rate directly, which is discussed in 6.2.

As mentioned, the problem of disentangling the background composition is a major problem for the TID measurement. Although it is not necessary to know the actual, physical background composition at all times but the total occupancy resulting from the combined components is vital, i.e. the model needs to scale well. The sensitivities need to be determined as often as possible to ensure a correct scaling. Since the conditions needed to disentangle the background contributions do not appear during regular operation, the model needs to be simplified. This is done by using the luminosity and Touschek sensitivities for both rings determined from this background study campaign. These sensitivities are therefore assumed to be constant. The complication of disentangling the beam-gas and Touschek components is visualized in Figure 5.8. The χ^2 heatmaps showcase the ambiguity of the storage background components for a large area in the parameter space. Many pairs of Touschek and beam-gas sensitivities have a very similar performance for describing the occupancy. When imagining the situation of fitting the heuristic background function in this example it is very likely that the result is highly dependent on the

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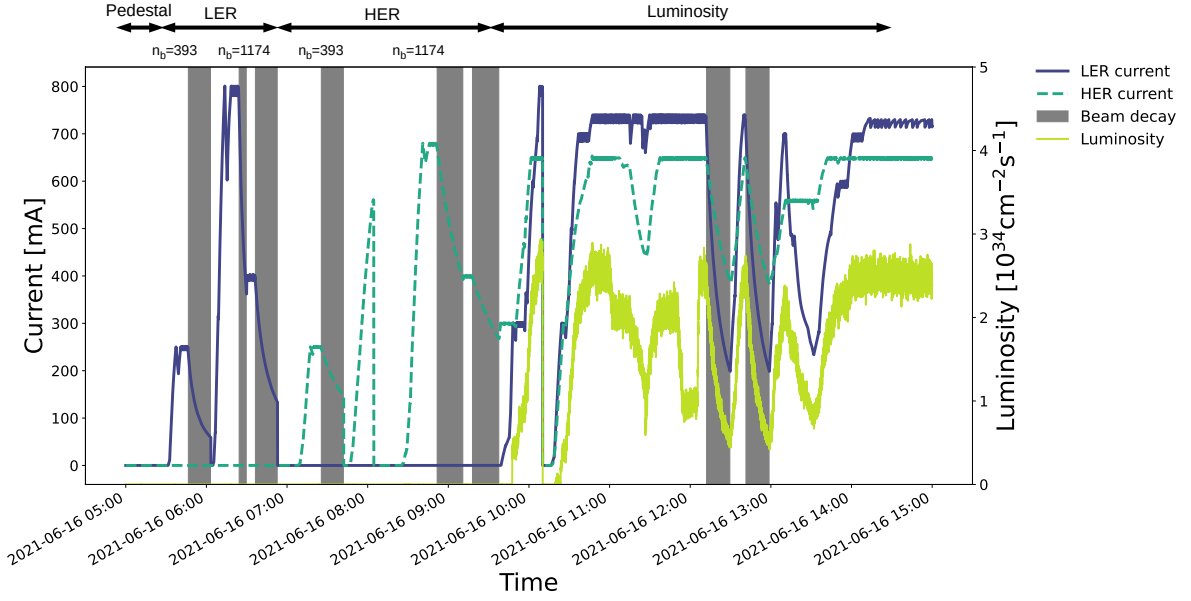


Figure 5.4.: Overview of the measurement segments during the background study campaign on the 16.06.2021. The HER currents, the LER currents and the Luminosity are plotted and the number of bunches n_b for the single-beam studies are indicated.

starting values of the fit. Also, it is likely that the global minimum is never found and that the global minimum is not a sensible result, in the sense that the sensitivities do not represent the physical background composition.

5.4. Estimating the occupancy noise floor

Cleaning the occupancy time series is not an easy task, especially for data from over three years of data taking. To avoid many problems only data that was archived during physics runs will be used to fit the background sensitivities and the extracted fit parameters are applied to all data, inside and outside physics runs. Physics runs, for the most part, guarantee a well-defined machine state and beam conditions. Considering data outside of physics runs is important as the rings can have considerable currents stored without Belle II taking physics data, i.e. without being in a physics run, although downtime of Belle II is minimized, especially while beams are already available. The start and stop timestamps of all physics runs can be obtained from the Belle II run database (RunDB). It contains information about every run that is started for Belle II. The information includes amongst others: Start time, stop time, run and experiment number, events recorded and sub-system status (on or off).

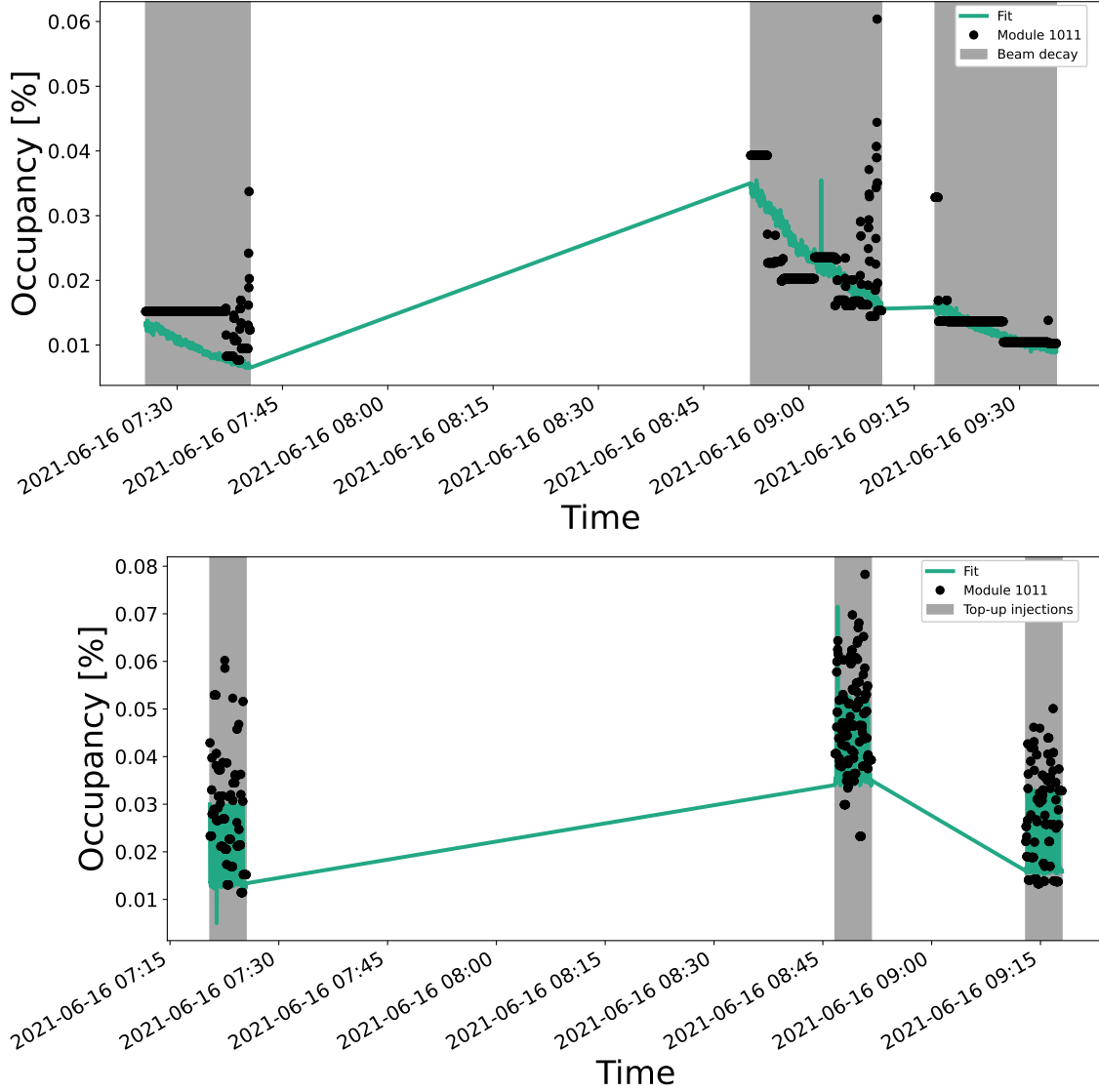


Figure 5.5.: The shaded are marks the data points entering the fit. This example uses the occupancy of module 1.1.1. Top: Fit of the HER Touschek and beam-gas background sensitivities during beam decays. Bottom: Fit of the HER injection background Sensitivity during top-up injections.

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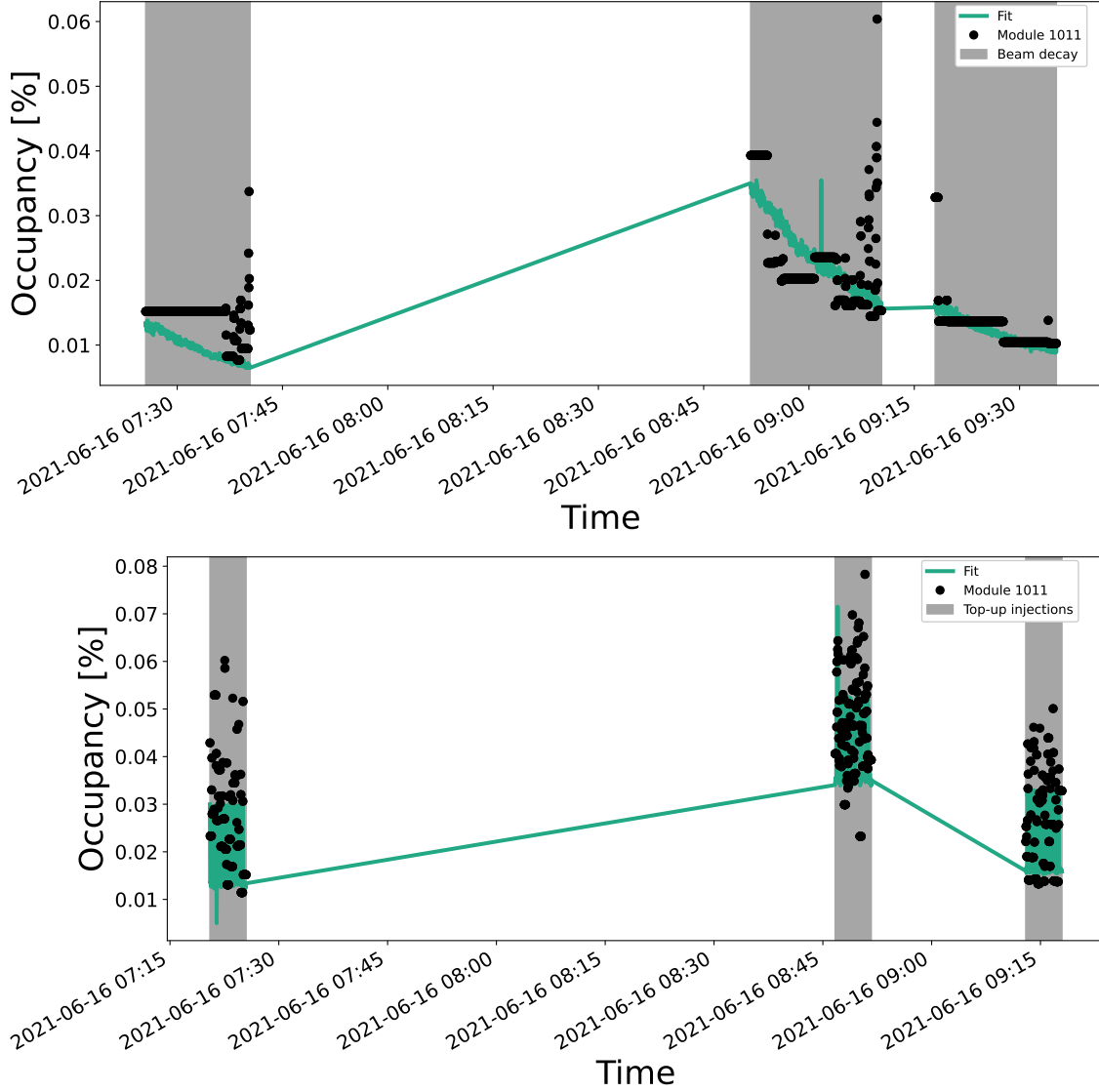


Figure 5.6.: The shaded are marks the data points entering the fit. This example uses the occupancy of module 1.1.1. Top: Fit of the LER Touschek and beam-gas background components during beam decays. Bottom: Fit of the LER injection background Sensitivity during top-up injections.

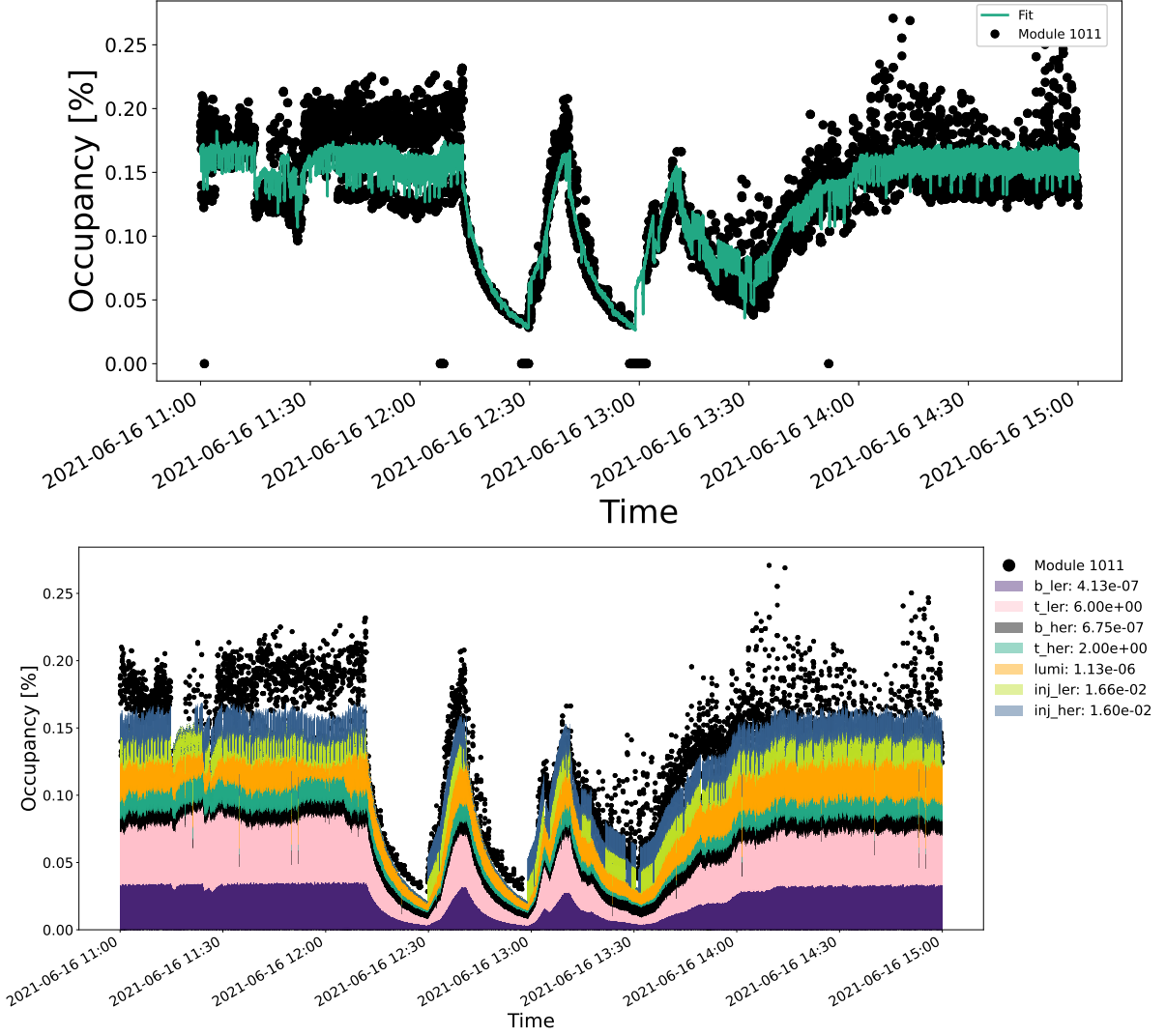


Figure 5.7.: This example uses the occupancy of module 1.1.1. Top: Fit of the luminosity sensitivity and therefore the complete fit that includes all background components. Bottom: Stacked bars indicate the background composition for each point of the function shown in the figure above. The values in the legend are the fitted values of the sensitivity of the respective background component.

5. Total ionizing dose measurement

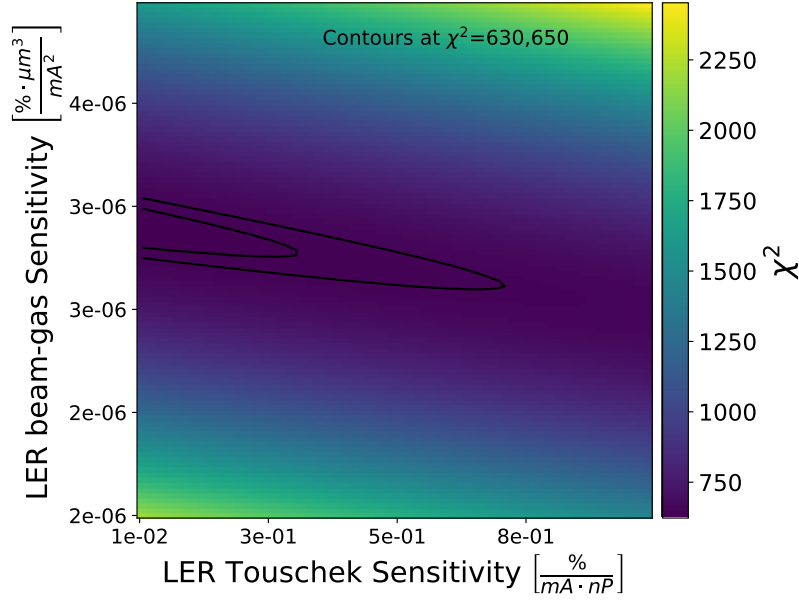


Figure 5.8.: This example uses the occupancy of module 1.1.1 during the first LER decay of the background study campaign discussed in this section. The heuristic background function was given pairs of Touschek and beam-gas sensitivities to describe the module occupancy. The χ^2 value of each resulting function was calculated. The standard deviation of the occupancy was assumed to be 0.00396 %. The value is determined as described in 5.4 and taken from Table 6.3. The heatmap shows of a section of the 2D parameter space of the Touschek and beam-gas sensitivities. The contour lines indicate and ellipse Each point in the heatmaps corresponds to one pair and the color corresponds to a χ^2 value according to the color bar.

Physics runs occur during run, or data taking, periods, which are usually 2 to 3 months long. The run periods are defined in Table 5.2.

The central processing step is the determination of the baseline noise, or noise floor, of each PXD module to correct the online occupancy from the archiver. The noise floor can change with every run, as settings can always be changed between runs. To follow these changes the noise floor needs to be measured as often as possible.

Once again, the heuristic background function is assumed to describe the PXD occupancy. Since the noise floor should be measured, the objective is to determine the noise term by fitting the heuristic background function. The heuristic fit is reduced and only uses three components: LER beam-gas, HER beam-gas and the noise term. The model needs to be simplified due to the complications involved in fitting all components as explained in Section 5.3.2. The injection background contributions can be omitted immediately as only decays are fitted. The Touschek ($\approx I^{2,H/L}$) and luminosity ($\approx I^H \times I^L$) backgrounds were dropped as their contributions are small compared to beam-gas contri-

butions ($\approx I^{\text{H/L}}$) in this scenario as the currents are preferably as small as possible. The PXD occupancy, and the heuristic background function for that matter, are expected to approach the noise floor when the beam currents shrink and reach the noise floor when the currents in both rings fall to 0 mA. This situation, during normal data taking operation, is approximated by beam decays. On a timescale of (10 min) the beams naturally decay once injections are turned off. Most decays are only partial decays, as the injections are usually resumed after a few minutes and the currents never reach 0 mA, therefore only approximating the described scenario of the occupancy reaching the noise floor when the currents vanish. To ensure proper fitting on the data, the length of physics runs is required to be greater than 600 s. The decay needs to be entirely within the time window of the physics run with a minimum length of 300 s.

An additional complication is the archiver compression. To save disc space, the archiver replaces a value at $t = 1$ s by the previous value $t = 0$ s if the delta between the two numerical values is smaller than a threshold. This threshold is increased for older data, resulting in more deleted data. Effectively, this reduces curve-like shapes into discrete steps. Due to this archiver compression, time windows of at least 30 s with constant occupancy values are masked as these plateaus overly bias the fit to bigger or smaller values. An example fit is displayed in Figure 5.9.

To obtain proper errors on the noise component, an error on the occupancy needs to be supplied to the fit algorithm. The error is formulated on the assumption that the expected, or ideal, behavior of the occupancy is described by the fit function. The difference between occupancy and fitted function is taken for each data point, i.e. the residuals are calculated. The outliers below the 10 % quantile and above the 90 % quantile are removed as outliers and the standard deviation of the remaining residuals is calculated. The standard deviation is then supplied to a second pass of the fitting algorithm so that the covariance matrix is well-defined.

5.5. Reestimating sensitivities on physics runs

The main problem is that sensitivities cannot be assumed to be constant. To follow these changes as closely as possible, the sensitivities are reestimated on physics runs, as there are too few background study campaigns. To fit the heuristic background function on normal physics runs a compromise is needed as the ambiguities between the background components cannot be disentangled. The compromise is that the Touschek and luminosity sensitivities are kept constant, while the other sensitivities are reestimated.

The first step of the processing is the resampling of all time series from 1 Hz to 1 min.

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Run period	Start dates	End dates
2019a	08.03.2019	03.07.2019
2019c	16.09.2019	13.12.2019
2020ab	17.02.2020	05.07.2020
2020c	12.10.2020	19.12.2020
2021ab	09.02.2021	08.07.2021
2021c	19.10.2021	23.12.2021
2022ab	21.02.2022	22.06.2022

Table 5.2.: Run periods of physics data taking during Phase 3 operation of the Belle II detector. Usually there are three run periods per year that are called a, b and c. The run periods a and b are taken consecutively. There are regular shutdowns between period b and c, the summer shutdown and between period a and c, the winter shutdown. The shutdowns are mainly used for maintenance.

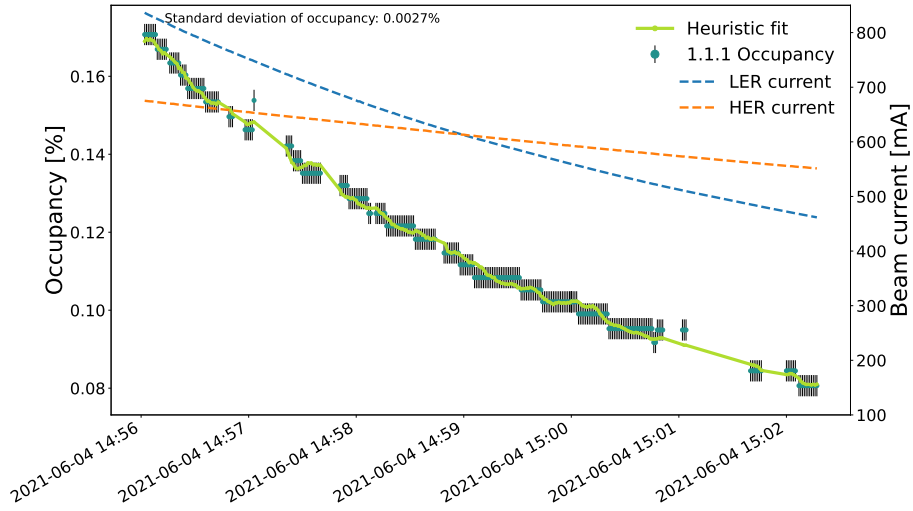


Figure 5.9.: Heuristic fit of a module's occupancy during a beam decay to measure the noise floor with the error on the occupancy that was obtained from the first iteration of the fit.

This saves computing resources and a 1 Hz resolution on the ionizing dose is not of practical value. Possible noise contributions to the occupancy with a pattern that appears with a period smaller than one minute would get indistinguishable from contributions which are not noise by the resampling. The effects from this on the dose measurement was found to be negligible.

Other preprocessing steps, like smoothing, are not necessary since the online occupancy is not entering the dose calculation, but the occupancy modeled by the heuristic background function, that will deliver a smooth and continuous time series of an occupancy to calculate the dose time series.

The next central step is to obtain the time series of the modeled occupancy that spans the entire measurement time frame to convert it into a dose rate. To do this the heuristic function is fitted onto the measured online occupancy utilizing the preliminary steps from the previous sections. The Touschek and luminosity sensitivities are held constant to the values obtained from the background study campaign in Section 5.3.2. The start values of the beam-gas and injection background sensitivities for the fit are set to the values obtained from that same study campaign to better cope with the ambiguities between sensitivities which were also discussed in that same section. The ambiguity of the injection backgrounds during physics runs and top-up injections into both rings was addressed here by only using one component and setting the other to zero. This effectively projects the entire injection background onto one component, which is accounted for by a higher sensitivity of that one injection background component. The arbitrary choice of setting the HER injection background to zero was made. The goal being to obtain sensitivities that reflect the physical background composition as close as possible. The noise component is also held constant, but is assumed to only be valid during the run it was determined in, due to the possibility of changing noise floors.

For practical purposes the measurement is split up into small batches, meaning that only the dose rate for one module during one month is processed at a time. During that month all eligible beam decays during physics runs are used to obtain noise floor values according to Section 5.4. Typically, $\mathcal{O}(10)$ decays are found during one full month of data taking. Once the noise floor during one physics run is determined an iterative fitting scheme is used. Previous and following physics runs are appended in an alternating scheme, which displayed in Figure 5.10. The objective is to reestimate the sensitivities using more data to find sensitivity values that generalize better. The fitting scheme starts by fitting the heuristic function to the measured occupancy of the physics run with a determined noise floor. The residuals between the measured occupancy and the fitted heuristic function are calculated and the interquartile range (IQR) (the distance of the

5. Total ionizing dose measurement

25th percentile and the 75th percentile) of the residuals of the entire fit is determined. If the IQR (in units of the occupancy) is below a threshold the fit interval is increased by appending an adjacent physics run. This is done for a maximum of 10 physics runs in either direction or if the IQR is larger than the threshold. Based on empirical findings, the threshold is either 0.015 % or 0.02 %, depending on the module. As previously mentioned, the noise floor can change drastically from run to run, but is used for multiple runs when fitting over multiple runs. This is because in case of a drastic change in the noise floor the fit will have a bad performance and will not satisfy the IQR threshold. The development of the IQR of the fit is displayed in Figure 5.11 and an example of an obtained occupancy model is displayed in Figure 5.12.

After this is done for all runs where the noise floor has been determined, one is left with sets of sensitivities, or occupancy models, and the start and stop times of the respective fit intervals. The following scheme is used to now obtain a modeled occupancy time series over the entire month from these models:

- The occupancy models are used in the time frames of the respective fit.
- The time spans in between the fit time frames are forward filled. An occupancy model is therefore used until the fitting time frame of the next model begins.
- If the beginning of a month is not inside a fit time frame, the first model fitted in that is applied on that data.
- If an entire month does not yield an occupancy model, the time-wise closest model of a previous or following month to that month is used.

An example of this scheme is graphically showcased in Figure 5.13.

The modeled occupancy is then used as an input to Equation 5.6 obtaining the ionizing dose rate and integrating yields the module TID.

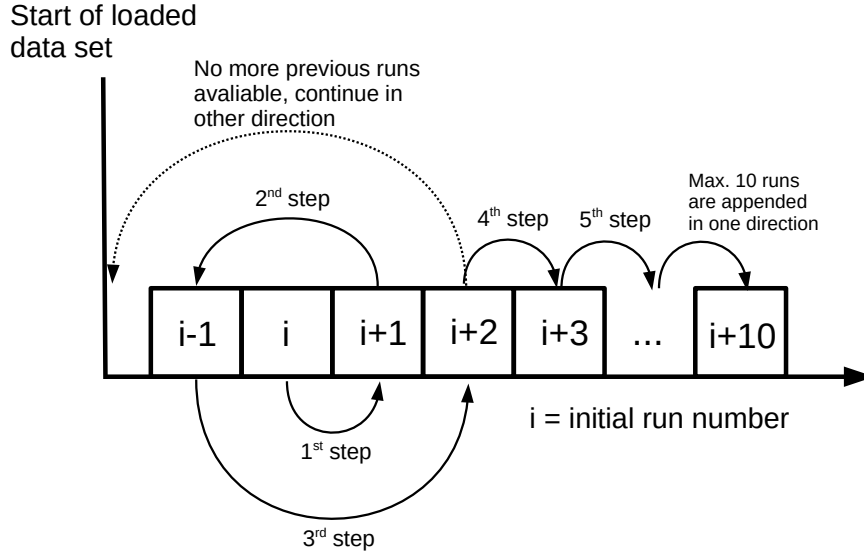


Figure 5.10.: Alternating scheme of appending data of previous and following physics runs to increase the amount of data available for the fit.

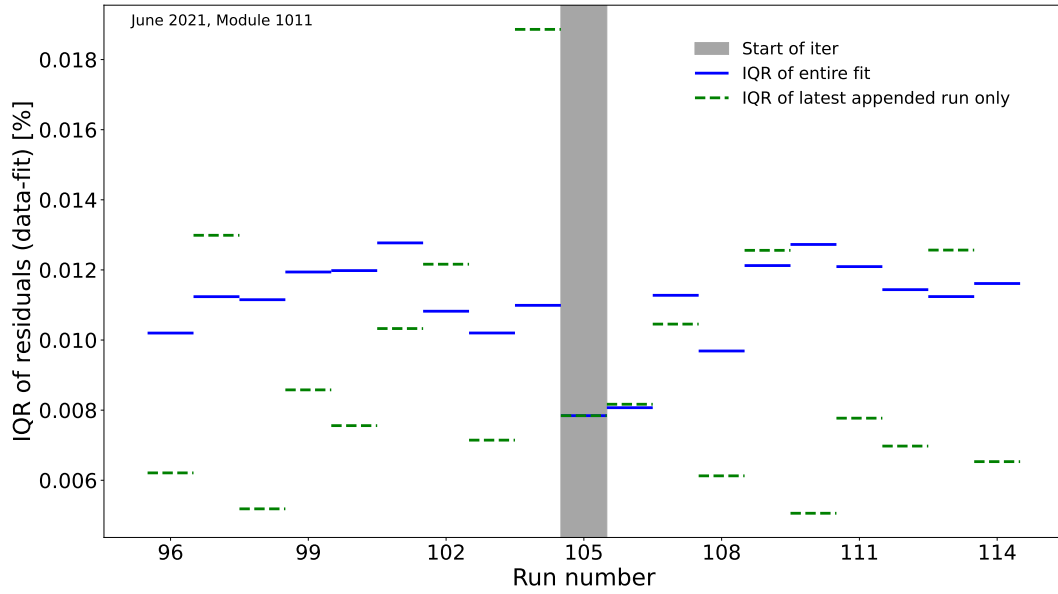


Figure 5.11.: The IQRs of the residuals (measured occupancy - fit) for each step of the iterative fitting scheme. The solid line indicates the IQR of the residuals of the entire fit. The dashed line indicates the IQR of the residuals solely for the latest run that was appended. The residuals of the entire fit are used for the IQR threshold. While the IQRs of the entire fit only experience small changes after a few iterations with small improvements, the IQRs of the latest appended run showcase a random spread. The initial rise the IQRs of the entire fit is expected since a more diverse data set needs to be described by the model but further data beyond the initial rise improves the performance again.

5. Total ionizing dose measurement

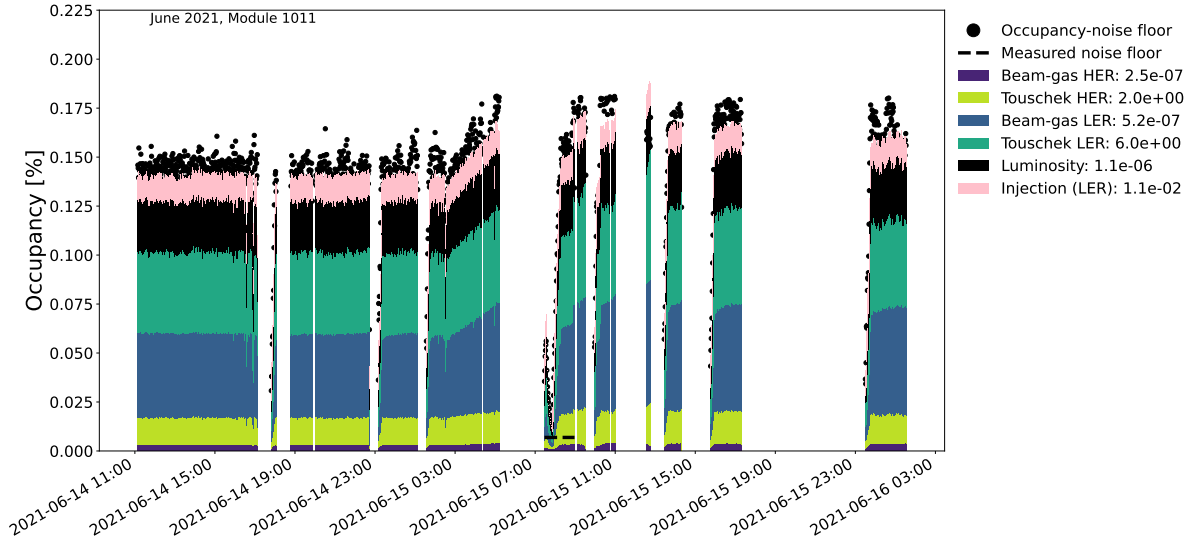


Figure 5.12.: Heuristic fit of a module's occupancy over 2 days using the iterative fit method. The measured occupancy and the composition of the fitted background is indicated. The value of each sensitivity is given in the legend.

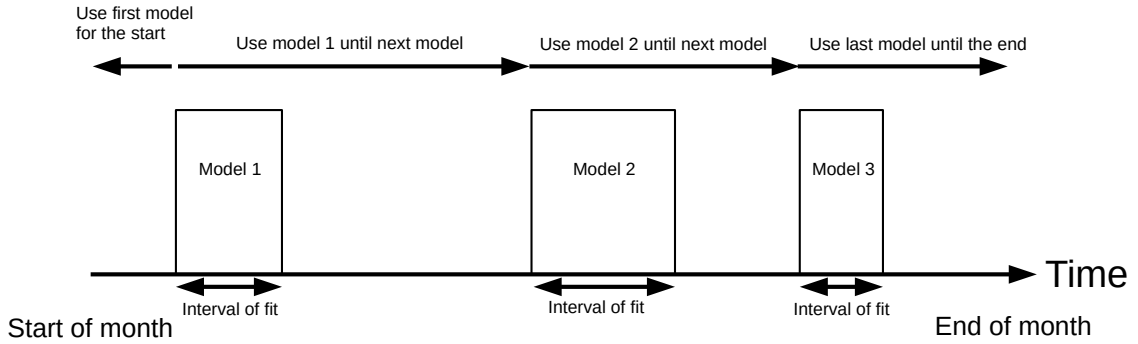


Figure 5.13.: Visualization of the extrapolation scheme of different models obtained during the processing of one month. This method guarantees that exactly one model is valid at any one point in time.

6. Results

The dose rate time series of each module is obtained and integration over time yields the TID. The integrated ionizing dose rate time series are displayed in Figure 6.2 for the IF modules, in Figure 6.3 for the IB modules and in Figure 6.4 for the outer modules. The evolution of the TIDs show the strong increase of the dose rate in recent operation of 2021 and 2022 compared to the operation in 2019 and 2020. The plateaus of the integrated dose rate develop during times outside of run periods. This is expected since the luminosity is steadily increased, resulting in higher beam backgrounds. This increase is displayed in Figure 6.1 as an increase in the total integrated weekly luminosity. The TID from June 2019, the start of Phase 3, until June 2022, start of long shutdown 1, are displayed in Table 6.1. The measured TID of module 2.5.1 is smaller than expected, compared to its neighboring modules, but its uncertainty is also very large. The relative uncertainties reach from 5 % for module 1.8.1 to 78 % for module 2.5.1. The uncertainties are discussed in Section 6.1. The beam background seen by a PXD module is dependent of its position, especially relevant is the ϕ angle. Modules that are located at $\phi \approx 0^\circ$, or in +x direction, are expected to receive more dose, mostly from Touschek backgrounds as simulations have shown [61]. The positions can be compared with Figure 4.5. The TID for the IF and IB modules is displayed in Figure 6.5. The angular spectrum that results is clearly visible, showing a dependency of the deposited dose to the angle ϕ .

6.1. Error estimation

In the following, the TID is explicitly referring to the integrated dose rate over the entire time frame this measurement considers.

For the TID measurement three main sources of systematic errors are considered. These are the archiver compression, study campaign sensitivities and the energy calibration.

The first source of errors is due to the archiver compression. To account for this error the following steps were done. During the noise floor estimation in 5.4 the residuals between the fit and the occupancy data were computed. The error of the occupancy is then assumed to be the standard deviation of the residuals. The obtained error is then

6. Results

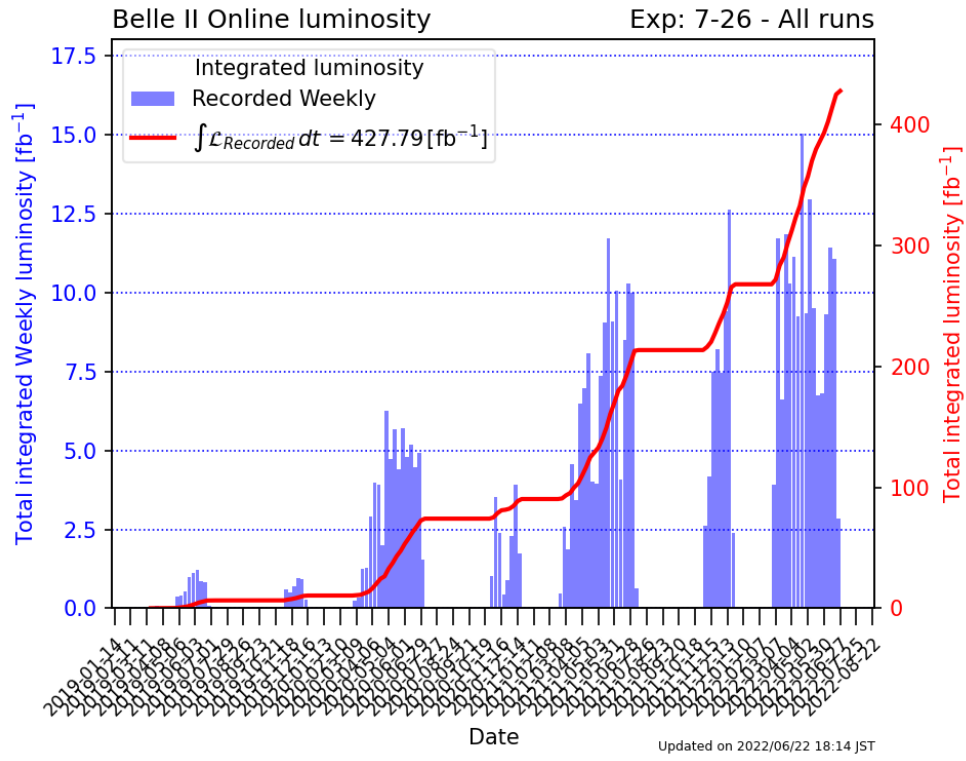


Figure 6.1.: The total recorded integrated luminosity before long shutdown 1. Figure Taken from Reference [8].

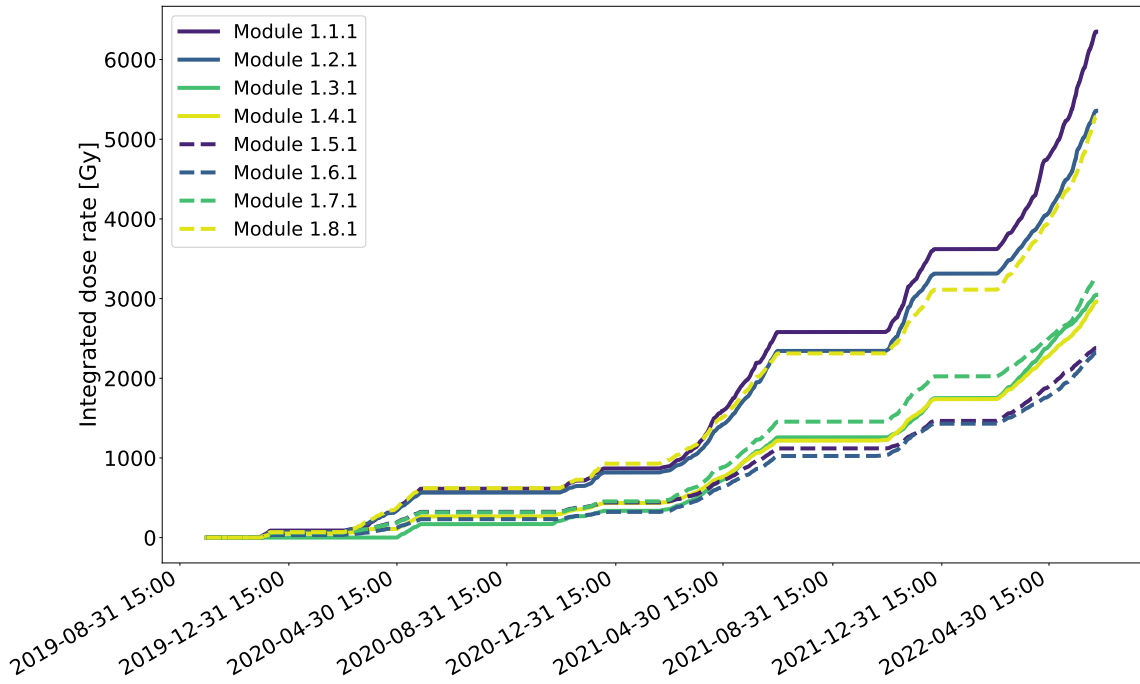


Figure 6.2.: Measured integrated dose rate for the IF modules.

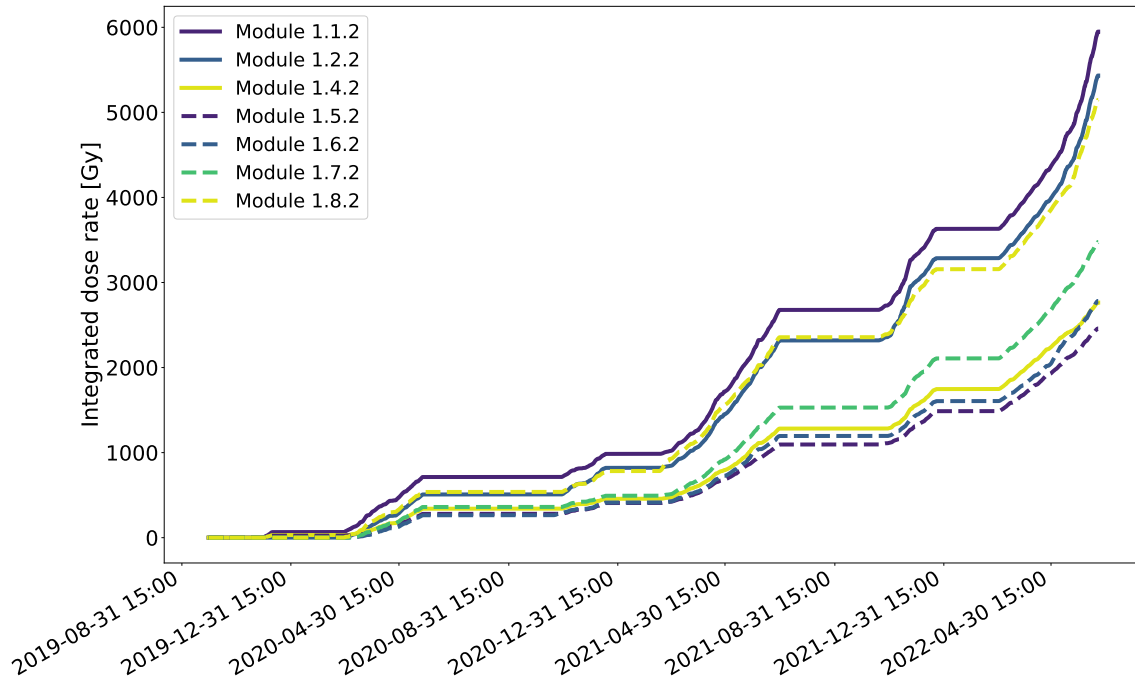


Figure 6.3.: Measured integrated dose rate for the IB modules.

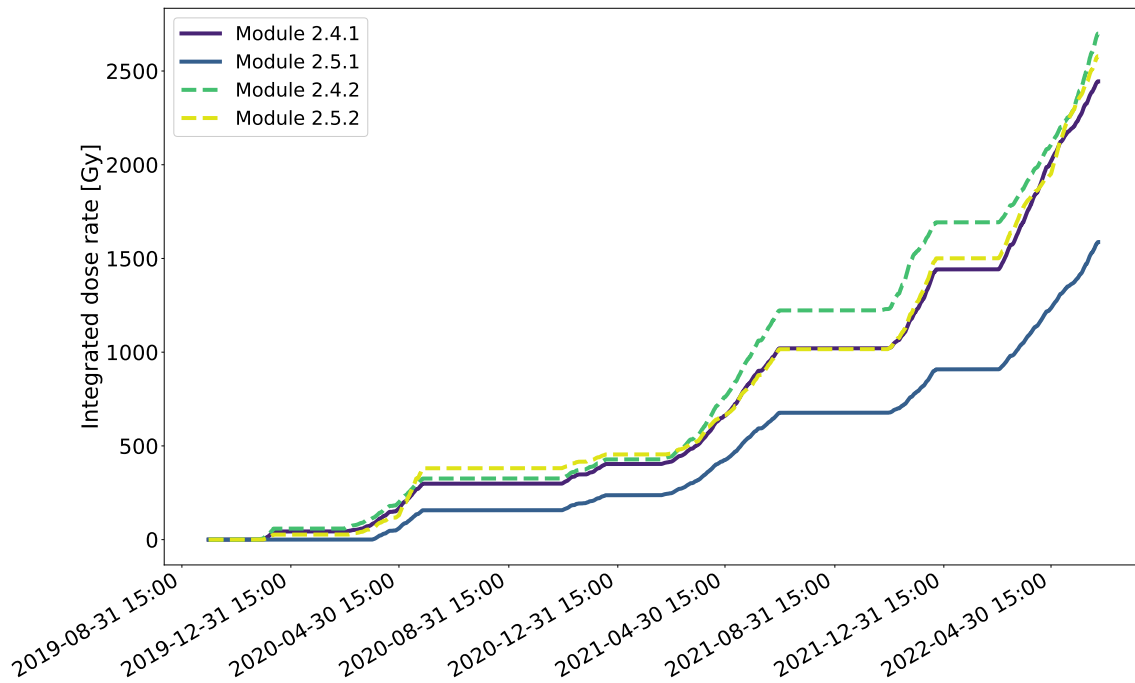


Figure 6.4.: Measured integrated dose rate for the outer modules.

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Forward modules	TID [Gy]	Backward modules	TID [Gy]
1.1.1	5600 ± 1900	1.1.2	5000 ± 500
1.2.1	4837 ± 1400	1.2.2	4600 ± 500
1.3.1	2750 ± 130	1.3.2	-
1.4.1	2600 ± 900	1.4.2	2490 ± 280
1.5.1	2200 ± 300	1.5.2	2200 ± 240
1.6.1	2100 ± 400	1.6.2	2500 ± 800
1.7.1	2900 ± 500	1.7.2	3100 ± 290
1.8.1	4580 ± 260	1.8.2	4500 ± 1300
2.4.1	2200 ± 1400	2.4.2	2400 ± 400
2.5.1	1400 ± 1100	2.5.2	2400 ± 800

Table 6.1.: Table of the TID values for all modules. The module 1.3.2 is not operational. The TID is integrated from June 2019 until June 2022.

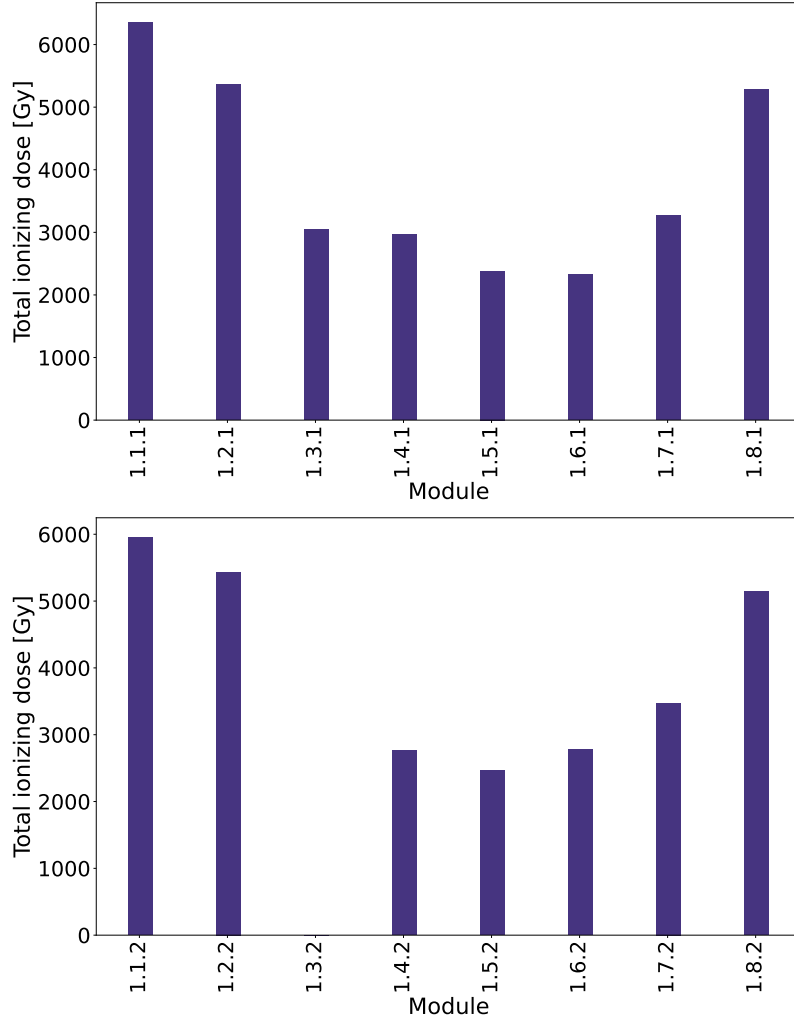


Figure 6.5.: Comparison of the TIDs for the inner-forward modules (top) and the inner-backward modules (bottom), showcasing the ϕ -dependence of the TID.

given to the fit that reestimates the sensitivities on physics runs in Section 5.5. The averaged standard deviations for June 2021 are displayed in Table 6.3.

The second source of errors is related to the uncertainties of the sensitivities obtained during the background study campaign and during the reestimation of sensitivities. The least squares fit provides a covariance matrix from which the uncertainties of the reestimated sensitivities can be extracted. The errors of the modeled occupancies of one model is not independent, in that an upwards fluctuations of a model will affect every data point the same way. This extends to the errors of the dose rates and therefore the error on the TID. The TID calculation in Section 6.2 is used as an example as it describes the trivial case of having a single model. The TID calculation must be considered as one function which is a sum over the Equation 5.6 with the heuristic function substituted for the occupancy and a factor 60 to account for the resampling from seconds to minutes. The sum considers all data points that are described by this model, which are all available data points in this example. Using Gaussian error propagation, the uncertainties of the sensitivities are used to determine the uncertainty of the TID.

In case of the reestimation strategy, the TID is a sum over the dose rates from many models. The uncertainty $\sigma_{\text{model},i}$ of the integrated dose rate of each model i is determined, similar to before. The treatment of the uncertainties of the sensitivities that are held constant during the reestimation is discussed in the next paragraph. The uncertainty of each data point described by one model is therefore treated as dependent. The models, however, are independent of each other. The TID is a sum of all integrated dose rates obtained from all models. The uncertainty of the TID σ_{TID} is therefore assumed to be

$$\sigma_{\text{TID}} = \sqrt{\sum_i^n \sigma_{\text{model},i}^2}, \quad (6.1)$$

where n is the total number of models.

The uncertainty of the reestimated model arise from two sources, the study campaign fit and the reestimation fit itself. The uncertainties of the sensitivities that are held constant during the reestimation are known, but an argument can be made to not consider these uncertainties. Considering the uncertainty would assume that an upwards fluctuation of such a sensitivity would lead to a similar upwards fluctuation of the modeled occupancy. To test this the occupancy of module 1.1.1 in the month of June 2021 was fitted using the same setup used during the reestimation. The sensitivities of Touschek LER, Touschek HER and luminosity were kept constant and the other sensitivities were fitted onto the data. The fit and the histogram of the residuals are displayed in Figure 6.6. The luminosity and Touschek sensitivities are then varied to observe the impact on the

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fit. In this example, the luminosity sensitivity was doubled and the Touschek sensitivities were halved. The fit with the varied sensitivities and the histogram of the residuals are displayed in Figure 6.7. The variation of the sensitivities has no effect on the mean and standard deviation of the residuals. The variation was absorbed by the reestimation fit. In a second test the luminosity was multiplied with 10 while the Touschek sensitivities were divided by 10. The fit with the varied sensitivities and the histogram of the residuals are displayed in Figure 6.8. The effects are clearly visible with a bad fit performance. The reason being that the combined luminosity and Touschek backgrounds are much larger than the total occupancy that is to be modeled, which cannot be absorbed by the reestimation fit. These tests were done for multiple scenarios, some additional figures are in the Appendix A.7. This behavior has been sporadically observed in very rare cases with less than an averaged 0.5 models per month per module exhibiting this problem. The occupancy models for which this is the case will be sorted out by the IQR threshold of the iterative fitting scheme and their impact on the measurement is minimized. Following this argument, the uncertainties of constant sensitivities should not be used.

An argument can also be made for considering these errors. When the fit absorbs the fluctuations of the sensitivities, similar to the situation mentioned above, it can be argued that the generalization of the reestimated model is impacted. For example, if the Touschek and luminosity components already account for most the measured occupancy, the reestimated sensitivities would be close to zero. Assuming that this fit has an acceptable performance for a given time frame, the model would be extrapolated to fill the time frames in between the models (see Figure 5.13). The performance of the model on this data may be dependent of its ability to generalize. It is difficult to constrain the performance of models in the extrapolated time frames, since every point in time needs a model in order for the measurement to be complete, even if the performance of all available models may be bad. Although no such extreme cases were observed, considering the uncertainties of the study campaign sensitivities may be necessary to account for this. A more conservative error estimation is therefore obtained by considering these uncertainties. The conservative errors are used in 6.1. Both discussed variants have been implemented and are compared in Table A.1.

The third source of errors is the uncertainty of the energy calibration used to convert the modeled occupancy into a dose rate. The statistical uncertainty is estimated to be negligible as the energy calibration was done for thousands of runs with variations $\mathcal{O}(1\%)$. The systematic uncertainties are not known and are conservatively estimated to be 20%. The uncertainties on the TID arising from systematic uncertainties of the energy calibration are expected to be dependent for all modules.

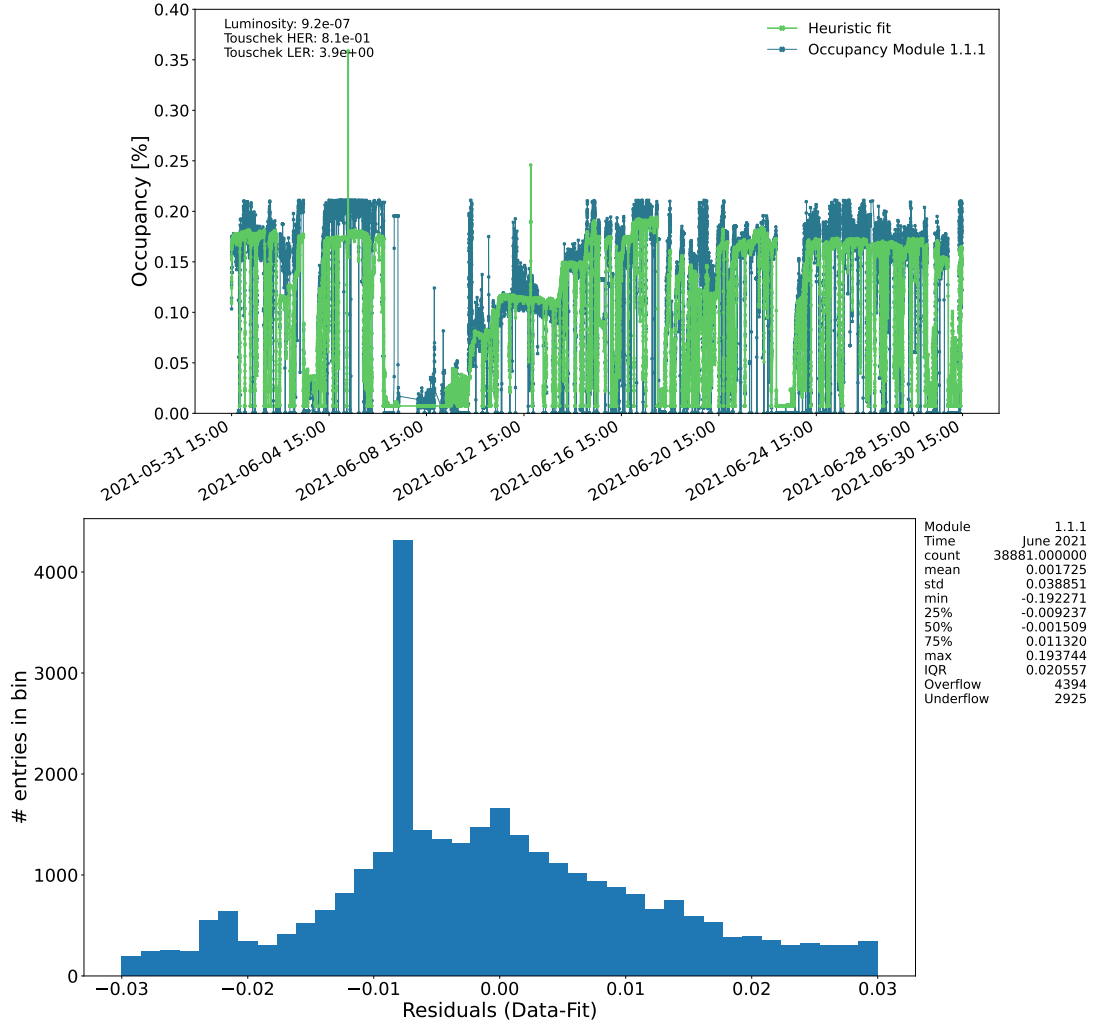


Figure 6.6.: Top: Fit of the occupancy with the heuristic background function. The Touschek LER, Touschek HER and luminosity sensitivities are kept constant during the fit, while the other sensitivities are subject of the fit. The values for the constant sensitivities are the values obtained during the background study campaign. Bottom: Histogram of the residuals with a statistic box.

6. Results

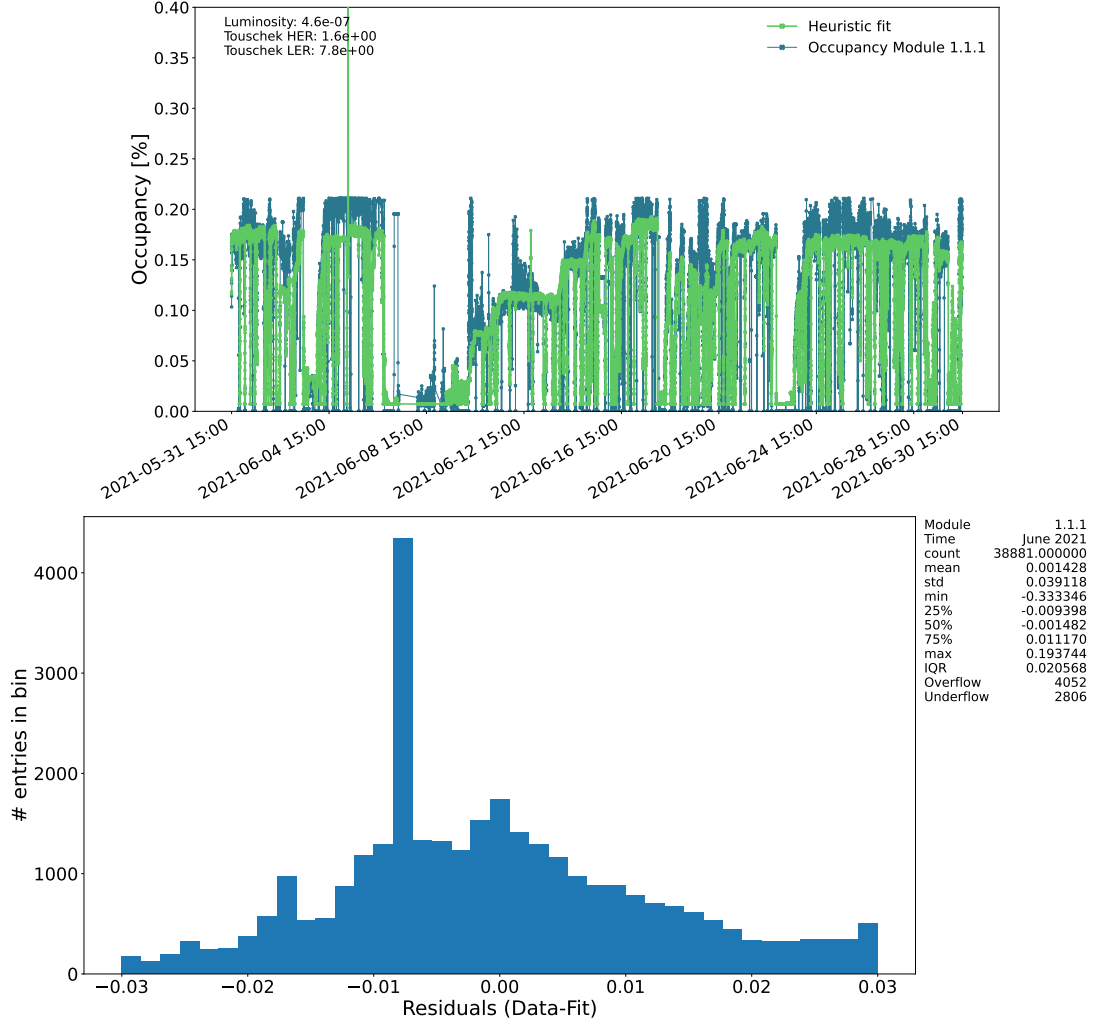


Figure 6.7.: Top: Fit of the occupancy with the heuristic background function. The Touschek LER, Touschek HER and luminosity sensitivities are kept constant during the fit, while the other sensitivities are subject of the fit. The luminosity sensitivity has been doubled while the Touschek background components have been halved. Bottom: Histogram of the residuals with a statistic box.

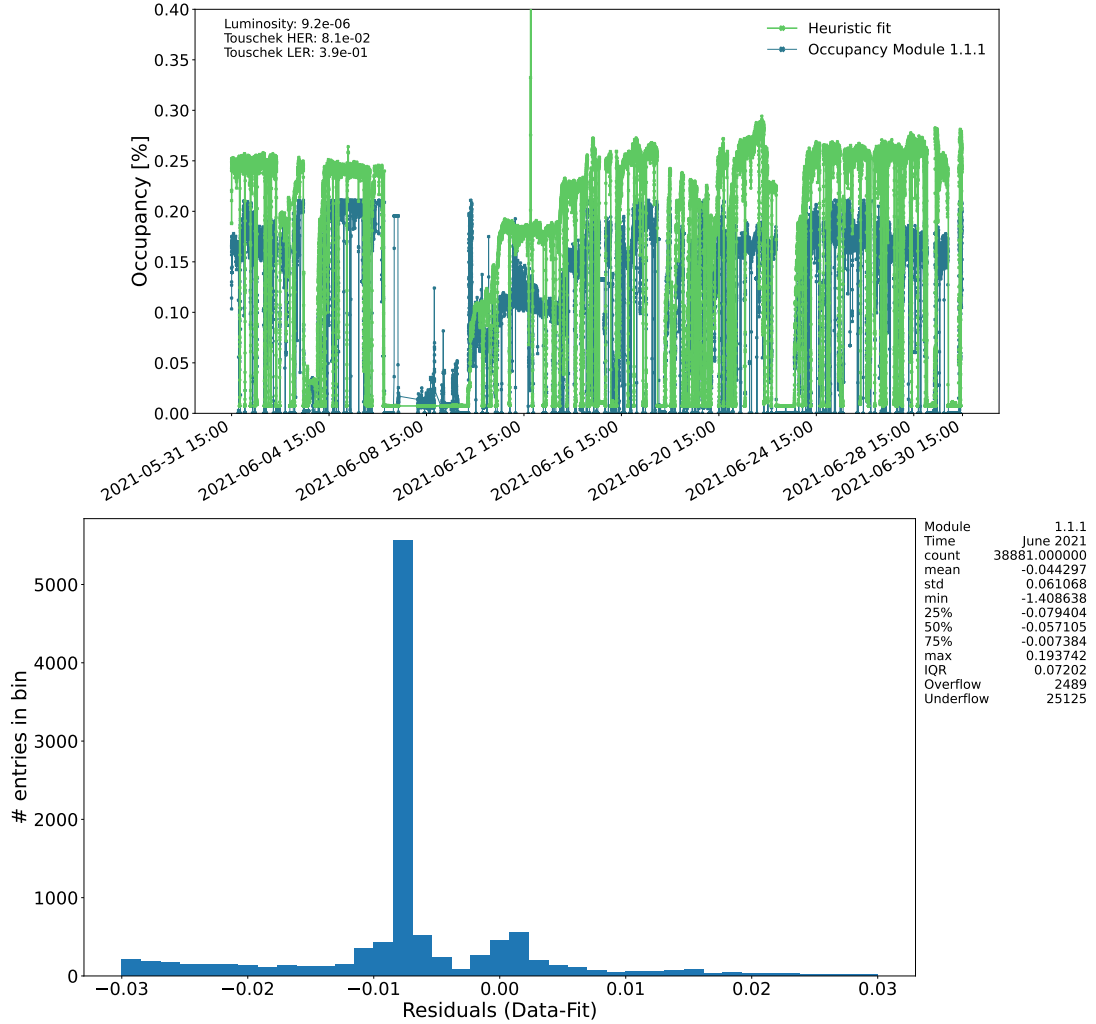


Figure 6.8.: Top: Fit of the occupancy with the heuristic background function. The Touschek LER, Touschek HER and luminosity sensitivities are kept constant during the fit, while the other sensitivities are subject of the fit. The luminosity sensitivity has been multiplied with 10 while the Touschek background components have been divided by 10. Bottom: Histogram of the residuals with a statistic box.

6.2. Comparison to beam backgrounds during background campaign

The background study campaigns have been conducted over the span of the Phase 3 operation to gauge the development of the background conditions. To be consistent and reproducible a fixed set of machine settings is used. These settings originate from conditions and settings used in the early days of Phase 3 operation, where the luminosity and beam backgrounds were much smaller. The settings used in the more recent Phase 3 operation are tuned to achieve higher luminosities, which results in higher beam backgrounds. To gauge how representative the background sensitivities are for the current operation, the background sensitivities obtained in Section 5.3.2 are applied on recent data during normal data taking conditions. The comparison of the heuristic background function and the measured online occupancy of module 1.1.1 for 3 days in May 2022 is displayed in Figure 6.9. While the heuristic background function is typically below the measured online occupancy, the performance of the study sensitivities is not bad. This comparison suggests that the background conditions during the study campaign are slightly smaller.

If it is feasible to use the sensitivities obtained during the background study campaign instead of reestimating sensitivities on physics runs it would simplify the dose measurement tremendously. As discussed, a priori it cannot be assumed that the background sensitivities can universally be used as they are dependent on machine settings, like collimator positions.

More figures summarizing the results of using these sensitivities without reestimation are displayed in Section A.6. The integrated dose rate is also summarized in Table 6.2. Module 1.3.1 exhibits large noise during operation and is the only module reaching occupancies of 1 % during normal operation. Strong oscillations of the occupancies resulted in a poor fit performance. The uncertainties of the modules 1.3.1, 1.4.1 and 1.4.2 are very large, showcasing that the performance of the fit is crucial when relying on a single fit, or model, for the entire time frame. The standard deviation of the module occupancies supplied to the least squares fit method are obtained using the method discussed in 5.4. The determined standard deviations during the month of June 2021 were averaged per module and are displayed in Table 6.3.

6.3. Comparison with SVD

The SVD dose rate was measured in Reference [9]. The TID was determined for each of the four SVD layers but using a different measurement approach. For layer 3 there has

Forward modules	TID [Gy]	Backward modules	TID [Gy]
1.1.1	$10\,000 \pm 9000$	1.1.2	8500 ± 100
1.2.1	7700 ± 100	1.2.2	7600 ± 100
1.3.1	$20\,000 \pm 50\,000$	1.3.2	-
1.4.1	$5000 \pm 14\,000$	1.4.2	$5000 \pm 14\,000$
1.5.1	3500 ± 100	1.5.2	3600 ± 100
1.6.1	4200 ± 100	1.6.2	3960 ± 120
1.7.1	5730 ± 80	1.7.2	5100 ± 100
1.8.1	7270 ± 110	1.8.2	6600 ± 100
2.4.1	3200 ± 250	2.4.2	4000 ± 8000
2.5.1	2700 ± 140	2.5.2	2930 ± 140

Table 6.2.: The total integrated dose rate per module obtained using constant study campaign sensitivities without reestimation. The data covers the time frame from June 2019 to June 2022. The module 1.3.2 is not functional and it does not record any data. The TID for the module 1.3.1 is deviating significantly compared to the other modules in this measurement and also compared to the measurement using the reestimation of sensitivities.

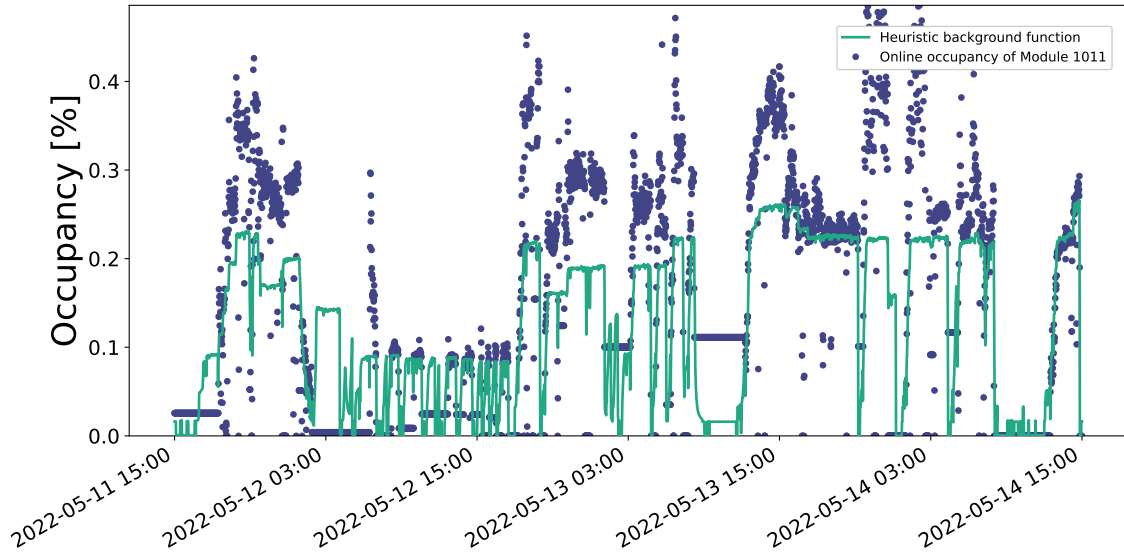


Figure 6.9.: Comparison of the heuristic background function and the measured online occupancy of module 1.1.1 from 12.05.2022 to 14.05.2022. The heuristic background function uses the sensitivities obtained for module 1.1.1 during the study campaign conducted on the 16.06.2021.

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Module	$\bar{\sigma}_{\text{occ}}$ [%]	Module	$\bar{\sigma}_{\text{occ}}$
1.1.1	0.00396	1.6.1	0.00235
1.1.2	0.00199	1.6.2	0.00258
1.2.1	0.00204	1.7.1	0.00154
1.2.2	0.00206	1.7.2	0.00214
1.3.1	0.00365	1.8.1	0.00223
1.3.2	-	1.8.2	0.00172
1.4.1	0.00489	2.4.1	0.00470
1.4.2	0.00384	2.4.2	0.00159
1.5.1	0.00216	2.5.1	0.00270
1.5.2	0.00097	2.5.2	0.00253

Table 6.3.: Averaged standard deviations $\bar{\sigma}_{\text{occ}}$ of the measured online module occupancy of the standard deviations determined in June 2021, according to Section 5.4.

been a dose measurement only using the mid-plane ladders, that, due to their position, receive more dose than other ladders in that layer. Mostly due to the larger distance from the IP, the TID is expected to be much smaller for the SVD layers. This is especially true for the outer layers of SVD. A smaller effect, next to the larger distance from the IP, is the additional material from the PXD and SVD layers, but the material budget is sufficiently small for the distance to be the dominant effect. The dose rate for all SVD layers is displayed in Figure 6.10. The SI unit Gy needs to be multiplied with a factor 0.1 to obtain the unit krad. The integrated dose rates for the PXD modules and the SVD layers are compared in Table 6.4. The measurement of the SVD layers reaches from March 2019 to June 2021. While the PXD dose rate time series was constrained to the same end date, there are no measurements before June 2019 available. The SVD measurement therefore includes the months of March, April and May 2019 that are not included in the PXD measurement, as data needed for this measurement approach is not available in these months. Since the luminosity in these months was small (see Figure 6.1), the dose deposited during this time is expected to be small.

6.4. Pedestal noise

One practical application of the ionizing dose rate time series is to view the development of dose dependent damage and degradation effects. An example of such an effect is the pedestal noise of the module. The pedestal is an off-set to correct for the zero-charge current, that is measured when reading out a DEPFET pixel, as discussed in Section 4.2.

The pedestals are updated regularly either automatically or on request [62]. The

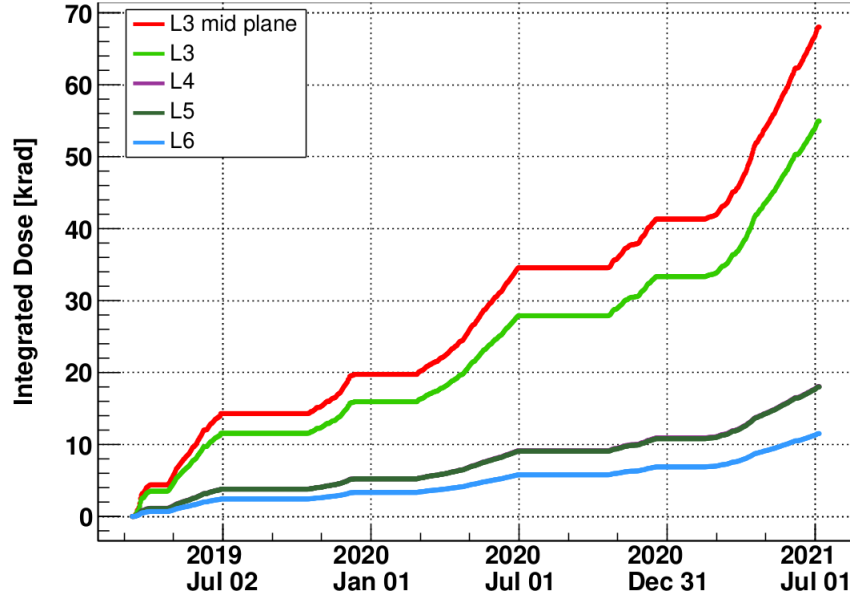


Figure 6.10.: Latest estimate of the SVD TID. Figure taken from Reference [9].

IF modules	TID [Gy]	IB modules	TID [Gy]
1.1.1	2173	1.1.2	2357
1.2.1	1973	1.2.2	1992
1.3.1	1237	1.3.2	-
1.4.1	1114	1.4.2	1103
1.5.1	906	1.5.2	920
1.6.1	892	1.6.2	1085
1.7.1	1214	1.7.2	1290
1.8.1	1914	1.8.2	1932
OF modules	TID [Gy]	OB modules	TID [Gy]
2.4.1	853	2.4.2	1013
2.5.1	562	2.5.2	839
SVD Layer	TID [Gy]	SVD Layer mid-plane	TID [Gy]
3	550	3	680
4	170	-	-
5	170	-	-
6	120	-	-

Table 6.4.: Comparison of the PXD and SVD integrated dose rate. The dose rate of the PXD is given per module, while the SVD dose is given per plane. The mid-plane in case of layer 3 of the SVD describes only the ladders 1 and 2 of layer 3 [9]. The module 1.3.2 is not operational and does not record any data. The PXD modules of layer 2 are receiving more dose than the layer 3 of the SVD, except for module 2.5.1. In comparison with the SVD ionizing dose rate, the ionizing dose rate of 2.5.1 is smaller than expected. The dose measurement of the SVD layers includes three additional months from March to June 2019 that are not available for the PXD dose measurement.

6. Results

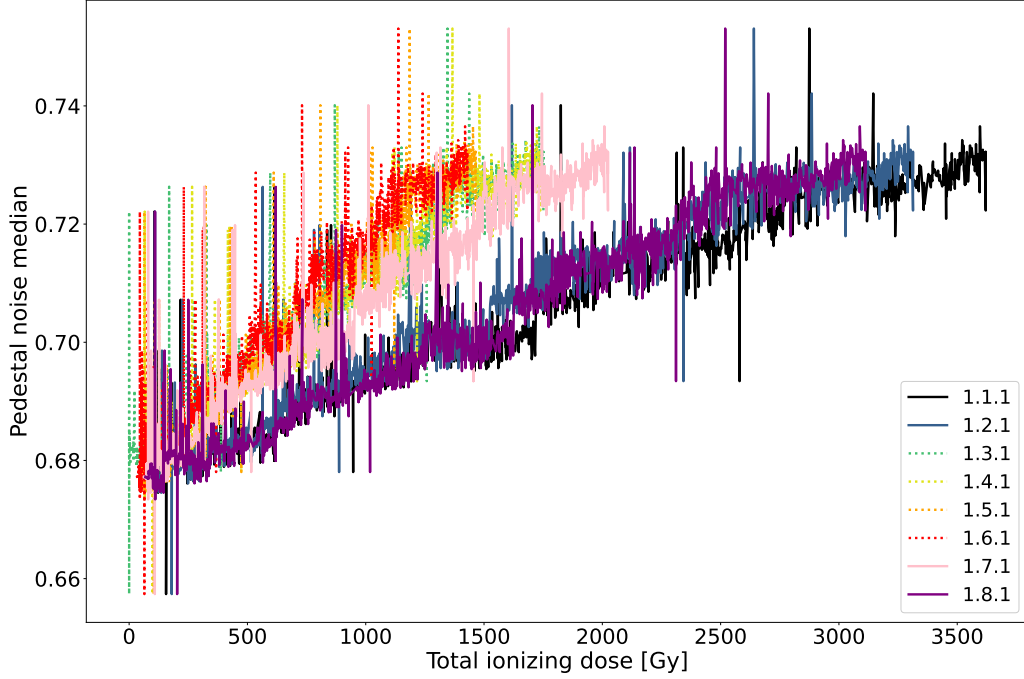


Figure 6.11.: Noise median of the inner-forward modules against the ionizing dose rate.

pedestal of a module is represented by an array that holds the off-set values for the entire matrix. When the pedestal of an individual pixel is determined, the zero-charge current is measured multiple times. The measured values can vary. Following this variation, the standard deviation can be computed. To obtain a measure that describes an entire module, the median of the standard deviations from all pixels of one module is determined.

The median of the pedestals for each module, averaged over one day are plotted against the dose in Figure 6.11 for the inner-forward modules, in 6.12 for the inner-backward modules and in Figure 6.13 for the outer modules. The increase of the pedestal off-set and therefore the zero-charge current from the DEPFET pixels shows a clear correlation to the ionizing dose rate.

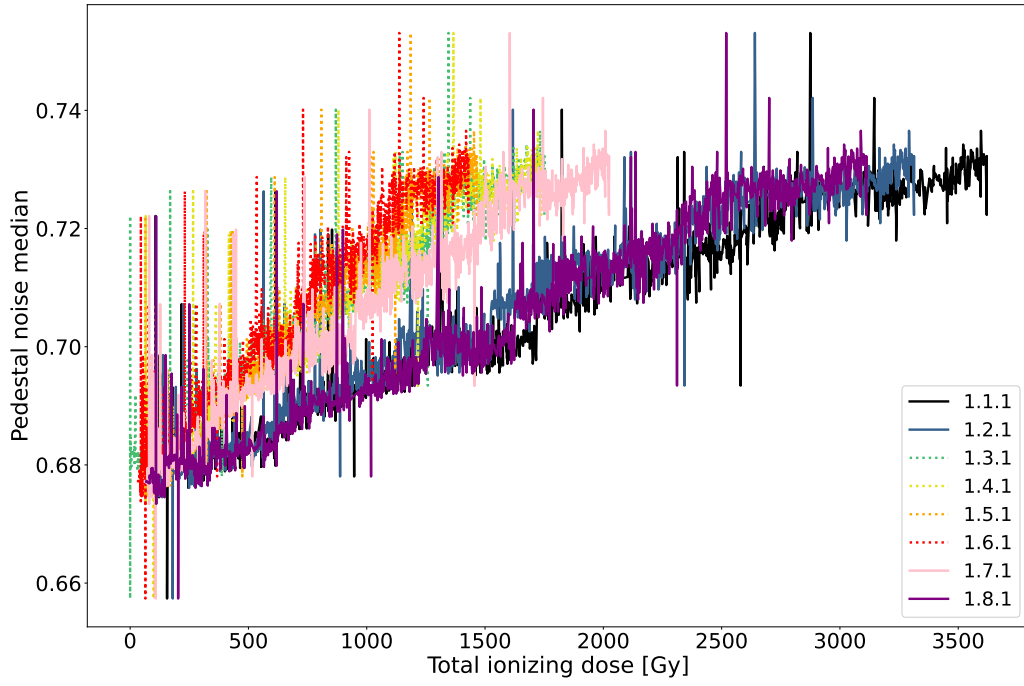


Figure 6.12.: Noise median of the inner-forward modules against the ionizing dose rate.

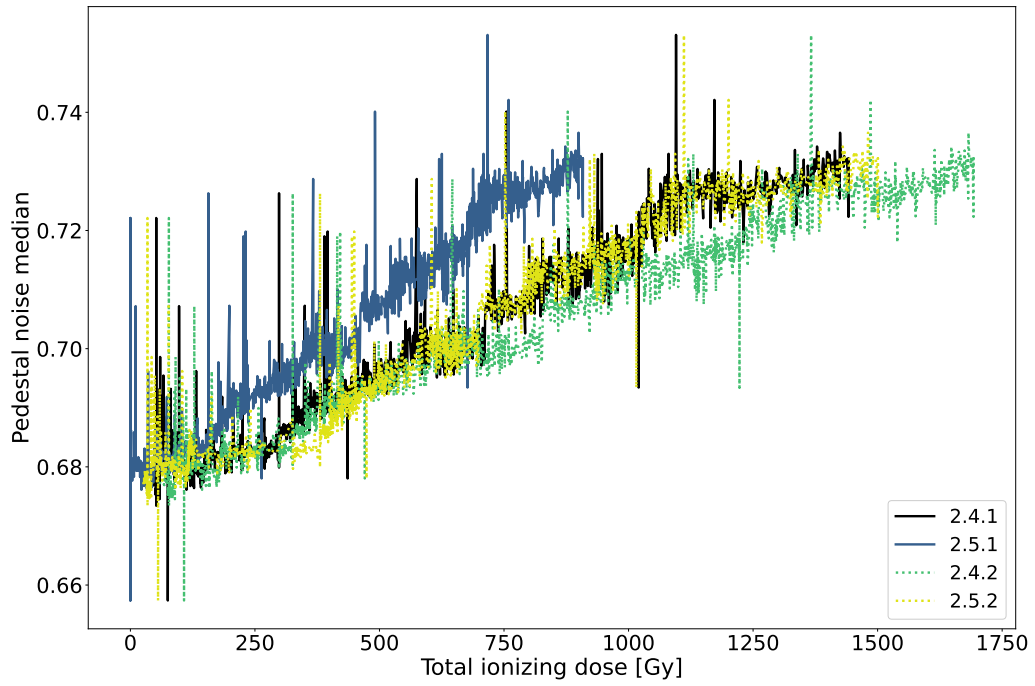


Figure 6.13.: Noise median of the inner-forward modules against the ionizing dose rate.

7. Summary and Conclusion

The PXD is a two-layer semiconductor pixel detector and the innermost detector of Belle II with a distance of 14 mm from the IP for the inner layer. The technology used for the PXD modules are DEPFET pixels. Semiconductor detectors can suffer radiation damage. Some radiation damage effects are dependent on the energy deposited in the pixels by charged particles, i.e. ionizing radiation. To quantify the effects the total ionizing dose, that was received by the PXD, needs to be measured. The measurement is based on the measured online occupancy which is saved by the EPICS slow control archiver appliance as a diagnostic observable. The online occupancy is modeled using a heuristic background function. The heuristic background function is put together from multiple background components, that are the LER and HER storage backgrounds, Touschek and beam-gas, the luminosity background, the injection backgrounds from top-up injections into the LER and HER ring and a constant term for the noise. Occupancy models are obtained by reestimating sensitivities on current data. The modeled occupancy that is obtained from the heuristic background function is converted into a dose rate. The dose rate is obtained per module and as a time series for the time of the Phase 3 (June 2019 to June 2022) operation of Belle II. The measurement can be continued for the future operation of the PXD.

The results are largely self-consistent, within the margin of error, when comparing the TID of neighboring modules in one layer and when comparing the TID of modules of different layers. This is especially evident when looking at the change of the TID depending on the position in ϕ of the module. The uncertainties obtained, that arise from uncertainties of the occupancies and the fits, are mostly between 5 % and 20 % for all modules. An additional source of uncertainties, arising from the energy calibration, is estimated to be 20 %. The dose rate development over time is consistent with the assumption of a steady increase of the TID and an increase of the dose rates as luminosity and beam currents increase.

A simple approach to the dose measurement has been implemented by measuring the dose using only a single model that has been fitted on the data of the background study campaign. The TIDs and uncertainties are, however, not as consistent as the results

7. Summary and Conclusion

obtained using the reestimation method. This method is very sensitive to the fit performance, when relying on a single fit on data of a few hours to model the occupancy for a time span of about three years.

A comparison with a dose measurement of the SVD showed a consistent result, in that the PXD occupancy is much higher due to its much smaller distance to the IP. The evolution of the dose rate of the SVD over time shows a similar structure as the for the PXD. The dose rate has increased in recent years of operation compared to earlier years of operation.

Using the obtained dose rate dose-dependent effects can be illustrated. One example of this was given using the increase of the noise of the pedestal that suppresses hit assignment to zero-charge currents. It is shown that the pedestal noise increased by approximately 8 – 10 % for all modules. The pedestal noise increases steadily with the deposited dose and the development of the pedestal noise could be extrapolated to gauge the pedestal noise during future operations.

A. Appendix

A.1. Alternative Method to measure the dose rate

Another approach to obtaining the ionizing dose is by utilizing measurements from the diamond system [32]. It is a radiation monitoring system consisting of multiple diamond based detectors that measure ionizing radiation. In the following, the individual diamond based sensors are simply called diamonds. They tie into the Belle II EPICS slow control system as part of the environmental monitoring. As previously mentioned in Section 3.2 some diamonds are insensitive, but provide fast signals, that are used to request beam aborts, once radiation levels surpass the safety limits. There are, however, other diamonds that are very sensitive and due to their monitoring function they are always read out even when Belle II is turned off. The diamonds that are on the beam pipe or within the combined PXD and SVD volume are of interest here, as they will monitor radiation similar to the radiation that the PXD is exposed to. These radiation measurements are saved on the SKB archiver as 1 Hz time series, the same way the online occupancy is saved. The diamonds directly measure an ionizing dose and are sensitive to charged particles and indirectly to photons, as they may cause charged particles to traverse the bulk via scattering or pair production, see Section 3.3. Diamonds usually cannot measure neutrons as their volume is too small, even if very high Z materials would be used.

The method relies on rescaling the measured dose of a diamond T with a scalar C , like

$$O = C \cdot T, \tag{A.1}$$

to obtain an estimated online occupancy O . An appropriate scalar can be obtained by dividing a module's measured online occupancy by a diamond's measured dose. This ratio describes the relation between the online occupancy of a module and a deposited dose. The occupancy time series is then translated into a dose using the Equation 5.6 as before. Simply defining $C = O/T$, would not yield any meaningful result. This is where one of the two caveats of this method comes to light. The scalar should only be calculated at appropriate times, for example during physics runs, following similar arguments as

A. Appendix

in Section 5.4. Also, both the online occupancy and diamond dose directly contribute to the dose, making extensive cleaning of the time series necessary for calculating the ratio. Especially the archiver compression needs to be accounted for in both time series by masking data points that are constant for too long. The ratio can also produce huge outliers, when the measured diamond dose rate is very small, producing a large ratio. After masking the outliers, the mean of all obtained ratios during an arbitrary time frame is calculated, yielding C as

$$C = \frac{1}{n} \sum_i^n C_i = \frac{1}{n} \sum_i^n \frac{O_i}{T_i}. \quad (\text{A.2})$$

Here, the n ratios obtained during physics runs, after masking, in a 24 h interval were averaged. This averaged scalar is then applied on the diamond dose time series of that same 24 h interval. Cleaning the diamond dose time series is difficult as masking would essentially mask time frames in which dose is deposited, resulting in an underestimation of the final TID estimate of the PXD modules.

The second caveat is that the assumption that a simple scalar can translate between a dose deposited in a PXD module and a diamond requires the assumption that the background composition of the diamond and the PXD module is the same, which is not the case [30]. The background composition of different detectors cannot be directly compared as the appropriate units may differ. While the observable measured for the PXD modules is an occupancy, the observable for the diamonds is a rate. The background composition of occupancies, rates or other appropriate units is compared by comparing the fraction each background component contributes to the measured total. Depending on the position (ϕ -angle, z-position and radius from the IP) the background composition can be very different.

This, in part, motivates using the heuristic background function approach which addresses both caveats by not directly converting an archiver time series into a dose and by addressing the background composition seen by the PXD modules, albeit without determining the accurate physical composition.

In some cases the dose measurement of one module during one month is systematically higher or lower than expected. The expectation is based on the ϕ -angle spectrum. The ratio of the dose over an arbitrary time frame between the modules is expected to be approximately constant. If an unexpected amount (either higher or lower) of dose is measured the measurement will be replaced by exploiting the angular spectrum.

This involves the following steps. A reference measurement is taken and the dose measurements per month are compared to that spectrum by scaling the reference doses

to match the measured doses. If a module's measured dose shows a large discrepancy to the scaled reference dose it is replaced by this reference dose. Since only singular measurements (or none in most cases) during one month need to be replaced by this, the spectrum is very robust, as it is relying on the 18 other measurements.

The TIDs of the reference measurement are scaled by a simple factor to match the existing TID measurements of the incomplete measurement. Explicitly, this is done by minimizing the difference between the TIDs of both measurements per module. The factor that minimizes the sum of all differences is applied on the reference measurement, yielding dose rates for every module. The missing TIDs can subsequently be substituted.

A major problem with this method is the reference measurement used. Such a reference measurement must first be conducted and uncertainties and biases of this reference will certainly affect the results. A reference could be found in any dose measurement, e.g. the measurement presented in Chapter 5. Depending on how often values are substituted with a scaled reference, the measurement is biased by biases found in the reference measurement.

Due to these problems, this measurement method has not been used.

A.2. Comparison of error estimation approaches

This section contains the comparisons of uncertainties obtained using two approaches as discussed in Section 6.1.

A. Appendix

	Module	σ_{TID} [Gy]	$\sigma_{\text{TID}}^{\text{Alt}}$ [Gy]
h	1.1.1	1884	1867
	1.2.1	1385	1383
	1.3.1	128	50
	1.4.1	861	784
	1.5.1	333	327
	1.6.1	366	355
	1.7.1	527	526
	1.8.1	258	249
	1.1.2	436	432
	1.2.2	472	469
	1.4.2	276	196
	1.5.2	236	236
	1.6.2	821	813
	1.7.2	290	277
	1.8.2	1288	1288
	2.4.1	1385	1284
	2.4.2	367	364
	2.5.1	1050	1032
	2.5.2	755	740

Table A.1.: The uncertainties of the TID σ_{TID} for each module using the conservative approach and including the uncertainties arising from the study campaign fits. The uncertainties of the TID $\sigma_{\text{TID}}^{\text{Alt}}$ are determined without using the uncertainties arising from the study campaign fits.

A.3. Process variables used from the EPICS archiver appliance

This section contains a list of all variables used from the EPICS archiver appliance.

A.4. Alternative approach to measure the beam pipe pressure

PV name	Description	Unit
PXD_O_HXXXX_AVG_OCC_cur*	PXD module occupancy	%
PXD_HXXXX_trg_len_VALUE_set*	PXD module trigger length	—
SKB_LER_current	LER beam current	mA
SKB_HER_current	HER beam current	mA
CG_BTE_BPM_CHARGE_AVE	Average inj. charge into HER	nC
CG_BTP_BPM_CHARGE_AVE	Average inj. charge into LER	nC
CGHINJ_BEAM_GATE_STATUS	Injection gate status	-
CGLINJ_BEAM_GATE_STATUS	Injection gate status	-
SKB_HER_XRAY_SIGMAX	Horizontal HER bunch size	μm
SKB_HER_XRAY_SIGMAY	Vertical HER bunch size	μm
SKB_HER_NOB	Number of bunches in HER	-
h SKB_LER_XRAY_SIGMAX	Horizontal LER bunch size	μm
SKB_LER_XRAY_SIGMAY	Vertical LER bunch size	μm
SKB_LER_NOB	Number of bunches in LER	-
ECL_LUM_MON_ACC	Luminosity measured by ECL	$\frac{10^{30}}{\text{cm}^2\text{s}^1}$
SKB_HER_D02_P_avg	Beam pipe pressure HER sec. D02	nPa
SKB_HER_D04_P_avg	Beam pipe pressure HER sec. D04	nPa
SKB_HER_D09_P_avg	Beam pipe pressure HER sec. D09	nPa
SKB_LER_D01_P_avg	Beam pipe pressure LER sec. D01	nPa
SKB_LER_D02_P_avg	Beam pipe pressure LER sec. D02	nPa
SKB_LER_D03_P_avg	Beam pipe pressure LER sec. D03	nPa
SKB_LER_D04_P_avg	Beam pipe pressure LER sec. D04	nPa
SKB_LER_D07_P_avg	Beam pipe pressure LER sec. D07	nPa
SKB_LER_D11_P_avg	Beam pipe pressure LER sec. D11	nPa
MDI_HV_PERMISSION	HV permission for Belle II	-

Table A.2.: List of all PVs from the EPICS archiver appliance that are used in any part of the measurement. For PVs marked with * replace “XXXX” with the corresponding module number.

A.4. Alternative approach to measure the beam pipe pressure

A competing approach to the method discussed in Section 5.3.1 to measure the beam pipe pressure is presented here. The second possibility to obtain the base pressure is by using transient effects that occur when the beam current suddenly changes. While the current can change momentarily, within a few microseconds, the pressure needs a few seconds to follow the changes. This usually happens during beam dumps at the end of a beam decay. The transient behavior is described by an exponential decay, that asymptotically approaches the pressure at the new current. In the case of a beam dump this new current would be zero and the exponential function approaches the base pressure. The transient

A. Appendix

behavior is well resolved by the 1 Hz time series, especially for beam dumps of beams with a lot of current as the transient behavior is stretched out. The amount of beam decays that end in a beam dump are a lot rarer than beam decays without a beam dump, as beam operation usually resumes without the need of a beam dump. The low statistics resulted in choosing the linear current fit over the exponential fit of transient effects to measure the base pressure.

A.5. Study campaign sensitivities

The sensitivities of the heuristic model of the occupancy that were obtained using data from the background study campaign on 16.06.2021 were obtained in Section 5.3.2. The sensitivities and noise values for each module are displayed in Table A.3.

Module	HER			LER		
	Beam-gas	Touschek	Injection	Beam-gas	Touschek	Injection
1.1.1	1.12×10^{-6}	8.11×10^{-1}	1.15×10^{-2}	8.35×10^{-7}	3.90	5.19×10^{-3}
1.1.2	8.83×10^{-7}	1.79	9.98×10^{-3}	9.01×10^{-7}	3.73	7.60×10^{-3}
1.2.1	7.04×10^{-7}	1.76	7.86×10^{-3}	7.32×10^{-7}	3.66	5.59×10^{-3}
1.2.2	8.08×10^{-7}	1.60	8.44×10^{-3}	8.69×10^{-7}	3.39	7.15×10^{-3}
1.3.1	1.00×10^{-7}	3.75×10^{-11}	3.65×10^{-15}	1.00×10^{-7}	8.74×10^{-12}	1.15×10^{-17}
1.4.1	8.38×10^{-7}	2.28×10^{-11}	5.99×10^{-3}	5.11×10^{-7}	1.52×10^{-12}	2.60×10^{-5}
1.4.2	1.13×10^{-6}	7.70×10^{-10}	3.14×10^{-10}	4.11×10^{-7}	8.25×10^{-1}	7.76×10^{-4}
1.5.1	1.00×10^{-7}	1.14	7.17×10^{-3}	2.15×10^{-7}	1.73	1.77×10^{-3}
1.5.2	1.43×10^{-7}	9.14×10^{-1}	6.65×10^{-3}	2.33×10^{-7}	1.72	2.93×10^{-3}
1.6.1	1.00×10^{-7}	1.35	5.42×10^{-3}	3.21×10^{-7}	8.38×10^{-1}	4.43×10^{-3}
1.6.2	3.99×10^{-7}	7.86×10^{-1}	5.43×10^{-3}	2.74×10^{-7}	1.68	2.79×10^{-3}
1.7.1	5.89×10^{-7}	9.15×10^{-1}	6.99×10^{-3}	3.95×10^{-7}	1.88	3.98×10^{-3}
1.7.2	6.32×10^{-7}	1.23	3.39×10^{-3}	4.31×10^{-7}	2.41	3.88×10^{-3}
1.8.1	8.31×10^{-7}	1.11	9.25×10^{-3}	5.22×10^{-7}	3.71	4.41×10^{-3}
1.8.2	8.27×10^{-7}	1.46	8.39×10^{-3}	7.16×10^{-7}	3.15	6.33×10^{-3}
2.4.1	1.00×10^{-7}	5.29×10^{-1}	5.55×10^{-3}	2.34×10^{-7}	1.04	2.16×10^{-3}
2.4.2	1.35×10^{-7}	3.27×10^{-1}	3.59×10^{-3}	2.89×10^{-7}	1.60	3.08×10^{-7}
2.5.1	1.00×10^{-7}	3.84×10^{-1}	4.31×10^{-3}	1.17×10^{-7}	1.23	1.89×10^{-3}
2.5.2	1.00×10^{-7}	1.94×10^{-1}	4.95×10^{-3}	1.30×10^{-7}	1.78	1.94×10^{-3}

Table A.3.: The sensitivities for each background component and the noise component obtained from the heuristic background fits on the background study campaign on the 16.06.2021.

A.6. Results: Comparison to beam backgrounds during background campaign

In this section additional plots are displayed, showing the results of the dose rate obtained from using the occupancy model obtained on the data of the background study campaign.

A.6. Results: Comparison to beam backgrounds during background campaign

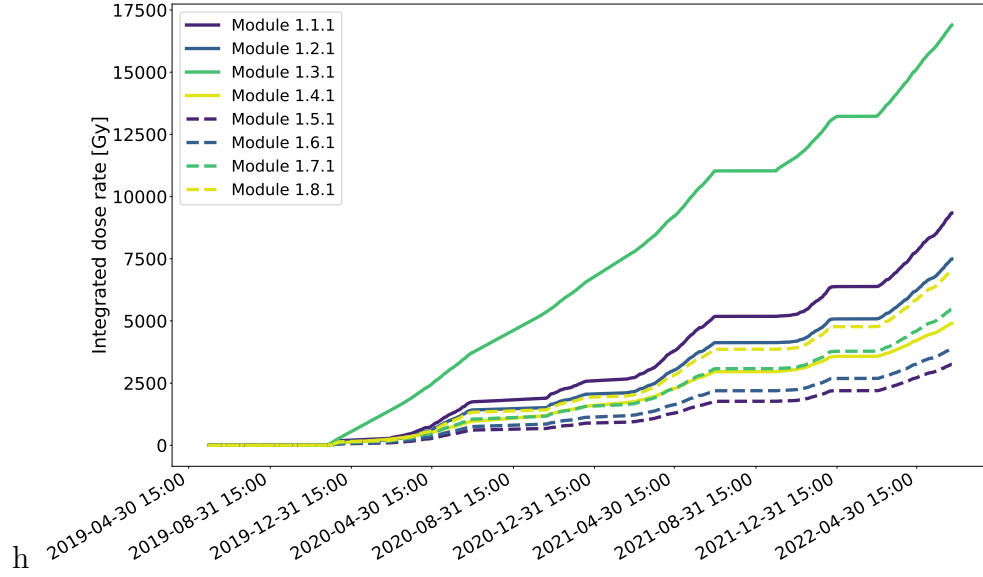


Figure A.1.: Measured integrated dose rate for the IF modules using the sensitivities obtained during the background study campaign without any reestimation.

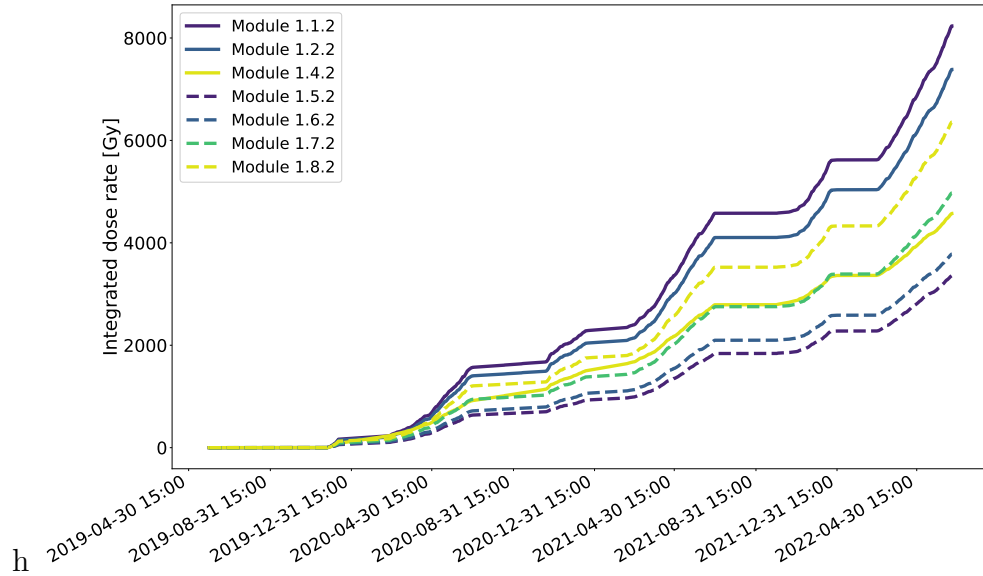


Figure A.2.: Measured integrated dose rate for the IB modules using the sensitivities obtained during the background study campaign without any reestimation.

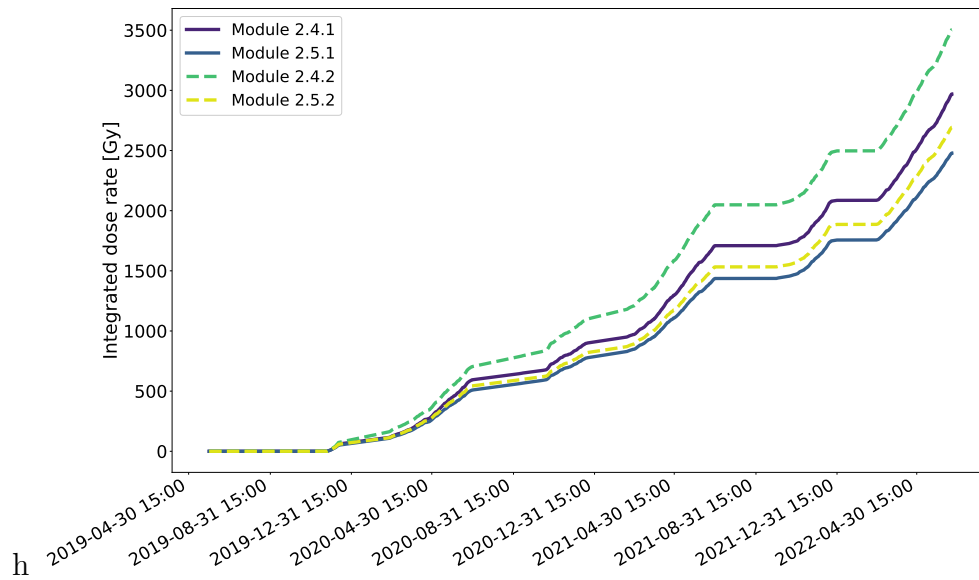


Figure A.3.: Measured integrated dose rate for the outer modules using the sensitivities obtained during the background study campaign without any reestimation.

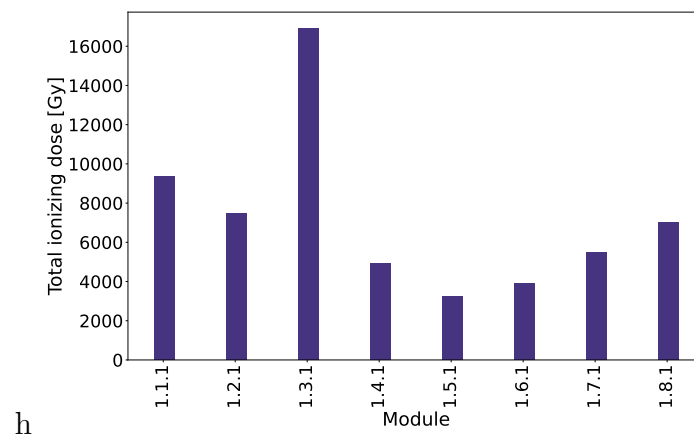


Figure A.4.: Comparison of the TIDs for the IF modules that was measured using the sensitivities obtained during the background study campaign without any reestimation.

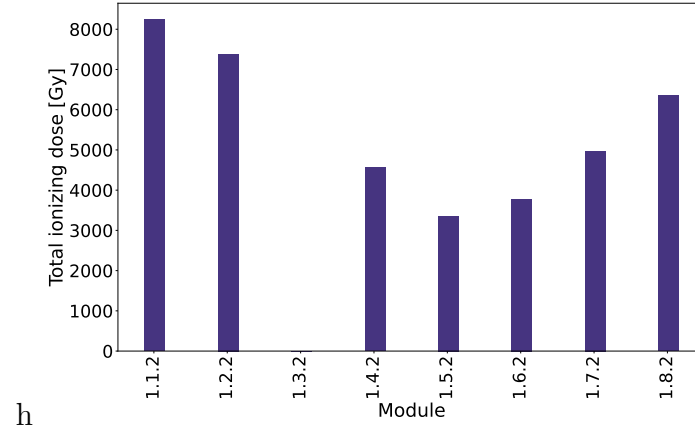


Figure A.5.: Comparison of the TIDs for the IB modules that was measured using the sensitivities obtained during the background study campaign without any reestimation.

A.7. Results: Errors from study campaign sensitivities

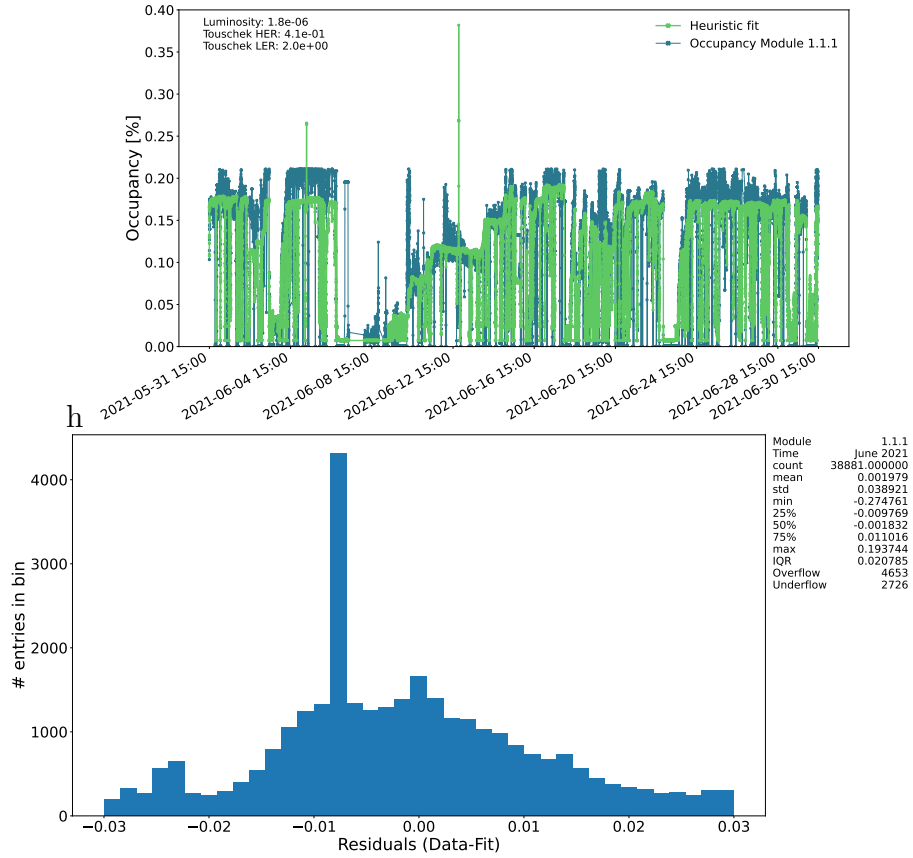


Figure A.6.: Top: Fit of the occupancy with the heuristic background function. The Touschek LER, Touschek HER and luminosity sensitivities are kept constant during the fit, while the other sensitivities are subject of the fit. The luminosity sensitivity has been halved while the Touschek background components have been doubled. Bottom: Histogram of the residuals with a statistic box.

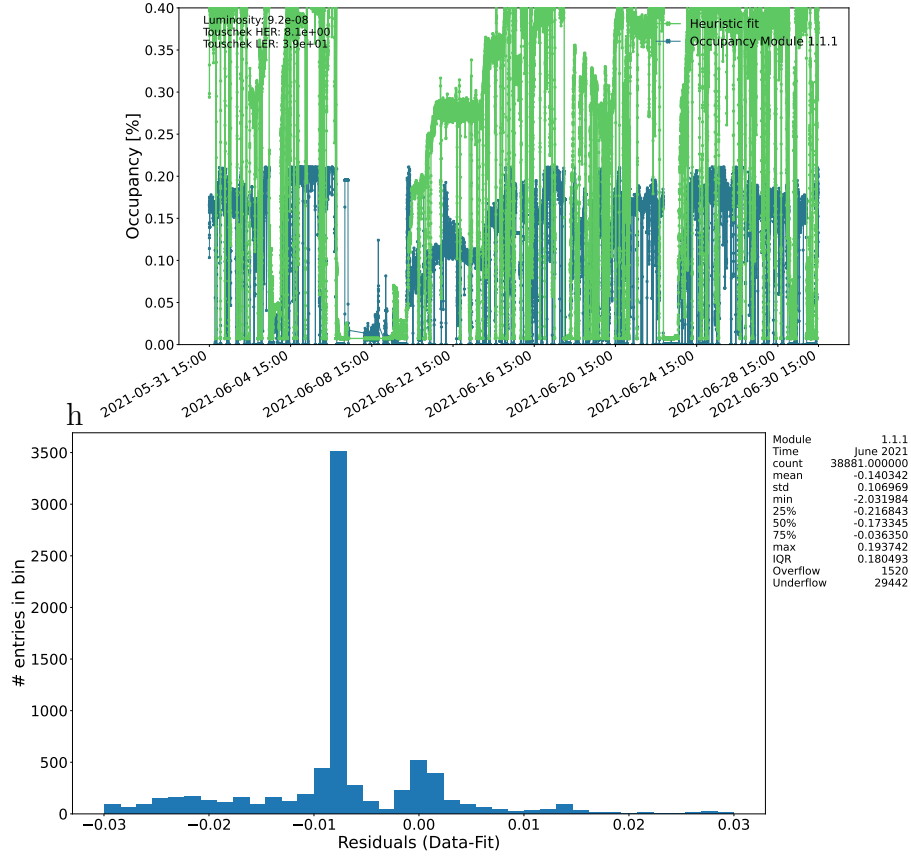


Figure A.7.: Top: Fit of the occupancy with the heuristic background function. The Touschek LER, Touschek HER and luminosity sensitivities are kept constant during the fit, while the other sensitivities are subject of the fit. The luminosity sensitivity has been multiplied with 0.1 while the Touschek background components have been multiplied with 10. Bottom: Histogram of the residuals with a statistic box.

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So here I am, at a sunny Monday afternoon, ready to finally submit my Master's Thesis. Although, it might not seem like a big deal, but this thesis also marks the end of being the student I have been for the past 5 years, since leaving home. Soon, I will be properly employed, earn money doing physics and maybe I am even starting to think that I am good enough to become a good physicist.

For me, it is hard to comprehend how I ended up here after all this time (this might also be correlated with my sleep deprivation from writing this thesis), but I certainly know that my friends have been the bigger part of it. The honorable mentions go to: Motivational Marike, awesome (we can change it to attractive if you want) André and luscious Leon. You guys have made this into the great adventure it has become for me. Thank you <3

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Erklärung

nach §17(9) der Prüfungsordnung für den Bachelor-Studiengang Physik und den Master-Studiengang Physik an der Universität Göttingen: Hiermit erkläre ich, dass ich diese Abschlussarbeit selbständig verfasst habe, keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe und alle Stellen, die wörtlich oder sinngemäß aus veröffentlichten Schriften entnommen wurden, als solche kenntlich gemacht habe.

Darüberhinaus erkläre ich, dass diese Abschlussarbeit nicht, auch nicht auszugsweise, im Rahmen einer nichtbestanden Prüfung an dieser oder einer anderen Hochschule eingereicht wurde.

Göttingen, den 17. Oktober 2022

(Yannik Buch)