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Juraj Habala

Matrikelnummer: 11912384

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der Österreichischen Akademie der Wissenschaften
und am Atominstitut
der Technischen Universität Wien

Betreuung

Betreuer/in: Privatdoz. Dipl.-Ing. Dr.techn. Christoph Schwanda

Mitwirkung: Univ.Lektor Dipl.-Ing. Dr.techn. Thomas Bergauer

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Abstract

In the pursuit of understanding the hidden mechanics of our universe, particle colliders have become one of the most vital components in the exploration of novel physics. In this field, silicon-based detection systems serve as a standard method for accurate tracking and vertex identification. Advances in semiconductor fabrication have made it possible to integrate CMOS electronics directly onto high-resistivity materials and allow high-voltage operation. These developments have led to the creation of radiation tolerant CMOS monolithic active pixel sensors (HV-CMOS). Unlike traditional silicon pixel detectors, HV-CMOS technology combines charge collection mechanisms and signal-processing electronics on a single wafer, thereby improving performance, increasing sensitivity, and reducing material budget. Additionally, the now standardized CMOS manufacturing processes enable cost-effective mass production for large-scale applications. One example of such a sensor is the TJ-Monopix2, currently studied by the Belle II collaboration for the VTX sensor upgrade. In this thesis, the data acquisition system developed for TJ-Monopix2 and similar sensors, including both hardware and software components, was studied, optimized, and further enhanced. In the following the DAQ system was used during a test campaign at the DESY particle accelerator facility. The acquired data were analyzed and interpreted to gain deeper insights into the effects of irradiation, operating temperature, and other factors on sensor performance. These findings contribute to the ongoing development of monolithic active pixel sensors for future high-energy physics applications.

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1 Introduction

In recent years, marked by new struggles and challenges for humanity, the question of why we should pursue fundamental research has perhaps resonated more than ever before in modern history. However, as a wise man once said, “We can’t solve problems by using the same kind of thinking we used when we created them.”. This idea calls for new approaches, better solutions, and creative techniques. The call for innovation should span across all scientific fields, but none embodies the spirit of “new thinking” as profoundly as particle physics.

In the studies of the fundamental forces and particles, the Standard Model (SM) was developed. A theory that describes our reality at the smallest scales with remarkable accuracy. At the largest scales, reality is well described by General Relativity (GR). While many natural and cosmic phenomena can be successfully explained by our these two, there is still much we do not understand. The origin of neutrino masses, the matter–antimatter asymmetry, and the nature of dark matter and dark energy are just a few of the examples that neither the SM nor GR can account for. That’s where new physics comes into play. Every day, scientists come up with new ideas and theories, and each one has to be tested to see if it can bring us further.

Until today, the best tool we have for exploring novel physics is the particle collider. These machines can accelerate and collide particles at incredible energies with remarkable precision. However, a collider on its own would be useless without a proper detector to record and analyze the collisions. In large particle colliders, the overall structure of the detector is usually similar. A schematic of a typical detector layout is shown in Figure 2.

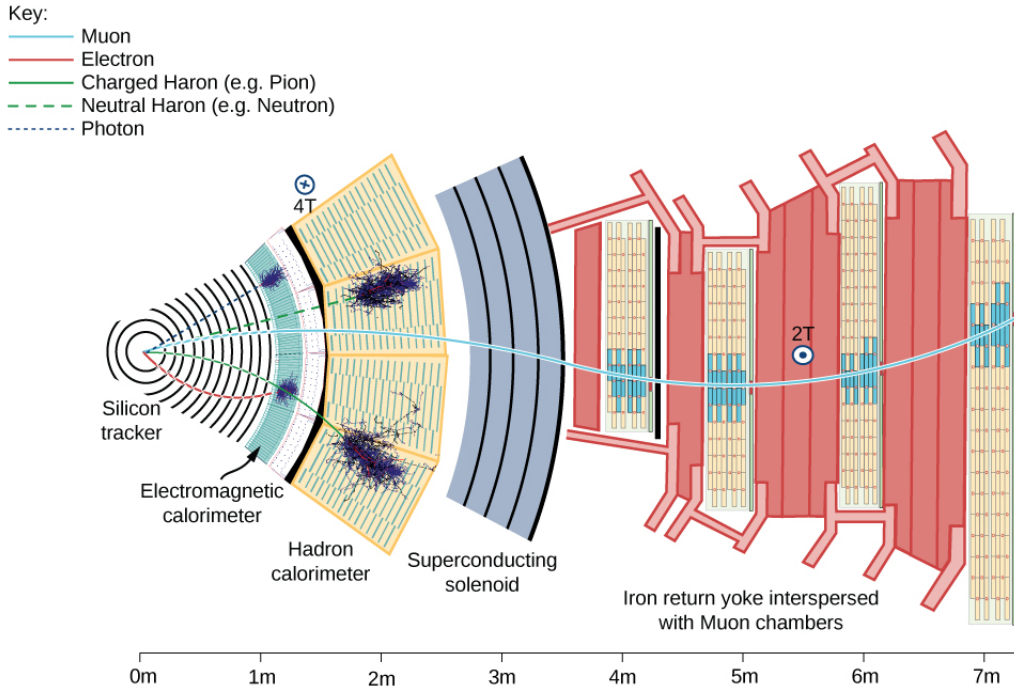


Figure 2: Schematic of a typical High Energy Physics (HEP) detector used in collider experiments. [1]

The various colliders around the world can be divided into two categories based on their exploration approaches. The *energy frontier* colliders, such as the LHC [2], aim for the highest possible collision energies to directly produce heavy particles that cannot be created otherwise. Protons are typically chosen as the colliding particles since, due to their relatively large mass, they can be accelerated to very high energies with manageable radiation losses. Hadron collisions, however, are inherently “messy” as protons are not elementary particles, which leads to substantial background and requires sophisticated data analysis techniques.

The other approach, referred to as the *precision frontier*, focuses on producing extremely clean collisions and precise measurements with high luminosity. In this context luminosity refers to the

number of particle collisions produced per unit area per second, which in turn means that higher luminosity increases the probability of observing rare processes. This is achieved by using well-defined initial states, such as electrons and positrons, which however, also means that the overall collision energies are typically lower. Precision frontier experiments are particularly well-suited for studies of the Higgs boson, electroweak parameters, and rare decays. They can also indirectly probe new physics by searching for tiny deviations from the predictions of the SM. One of the most prominent examples of a precision frontier experiment is the electron-positron collider SuperKEKB [3].

1.1 SuperKEKB and Belle II

SuperKEKB, located in Tsukuba, Japan, was built to test the SM with high precision while simultaneously searching for signs of physics beyond it. The particles produced in these collisions are recorded by the Belle II detector [3]. This collider-detector setup is specially optimized for studying rare B-meson decays with exceptional accuracy. At the heart of Belle II lies the Vertex Detector (VXD), a silicon tracking system composed of two sub-detectors, the Pixel Detector (PXD) and the Silicon Vertex Detector (SVD). In collider physics, a vertex refers to the interaction point of particles. The *primary vertex* corresponds to the location of the initial particle collision, while *secondary vertices* arise from the decays of short-lived particles produced in that collision. The position of these vertices can be reconstructed with high precision from the trajectories of the outgoing particles. This process requires extremely high precision and is only possible if the detector is placed very close to the interaction point. The individual detector layers record “hits” in two dimensions as particles pass through. During data analysis, these hits are linked together to reconstruct the particle’s three-dimensional trajectory. From the curvature of this track in the magnetic field, not only the particle’s vertex but also its momentum can be determined. The physical layout of the VXD is shown in Figure 3.

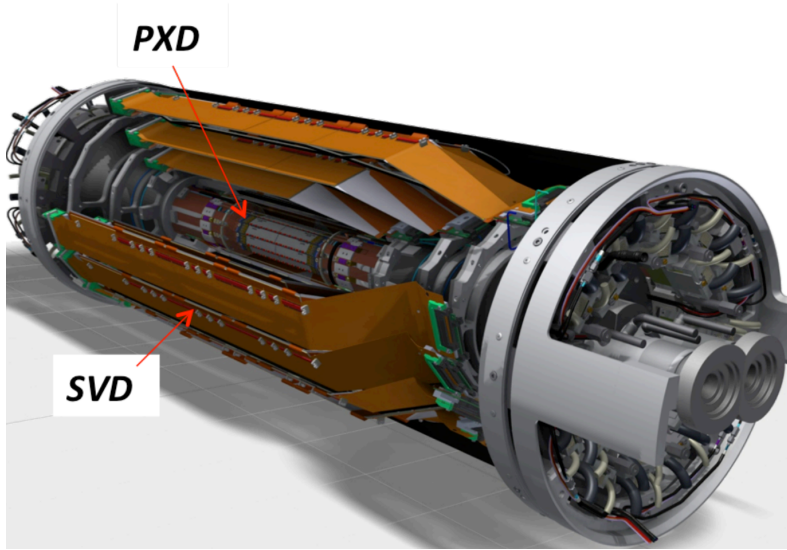


Figure 3: Schematic showing the layout of the Belle II VXD detector. [4]

Currently, two main sensor technologies are used in inner trackers, the silicon strip detectors and the newer pixel detectors. Strip detectors provide one-dimensional position information and rely on scintillation to detect passing particles, while pixel detectors work much like the imaging sensors in modern cameras, providing a two-dimensional picture of the event. Increasingly, experiments are moving away from the older concept of silicon strips and towards pixel detectors. In the case of the VXD, the four outer layers of the SVD consist of double-sided silicon microstrip detectors, while the two innermost layers of the PXD employ Depleted P-channel Field Effect Transistors (DEPFET).

1.2 Belle II VTX Upgrade

To achieve the new target luminosity of $6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$, a redesign of the interaction region is required. Since the VXD is closely integrated with this region, it must also be redesigned, providing an excellent opportunity to upgrade the current detector system [5]. The requirements for the new VXD, also referred to as the VTX, can be summarized as follows [4]

- Match current VXD specifications for resolution, low material budget ($< 3.2 \% X_0$), and acceptance, with enough layers for tracking but not exceeding the material budget.
- Tolerate higher beam background: sustainable hit rates, total ionizing dose (TID), and neutron fluence per updated projections.
- Be resistant to high local ionization effects
- Operate at a 30 kHz trigger rate.
- Aim for 1 μs integration time to control occupancy, bandwidth, and inefficiencies from trigger veto strategies.

To address these requirements, several upgrade proposals have been submitted. Some retain the original separation of the PXD and SVD, while others, such as the CMOS (Complementary Metal-Oxide-Semiconductor) MAPS (Monolithic Active Pixel Sensors) proposal, aim to replace both with a fully pixelated system [6]. MAPS are silicon-based particle detectors that integrate the sensor and readout electronics on a single silicon wafer, hence the term monolithic. They are considered a scalable alternative to current DEPFET pixel sensors, offering reduced material budget and simplified integration. DEPFET technology excels in precision and radiation hardness, making it well suited for vertex detectors, but it requires more complex fabrication and dedicated readout electronics. In contrast, MAPS can be produced using standardized CMOS processes, enabling thinner and lighter detectors with reduced cost and power consumption. The trade-off is that MAPS typically have slower charge collection and may face limitations in radiation tolerance compared to DEPFET. These issues are, however, significantly mitigated in the new generation of monolithic sensors, DMAPS (Depleted Monolithic Active Pixel Sensors), which use high-resistivity silicon to achieve full depletion of the detection region and thus enable faster charge collection through drift in an electric field.

The CMOS MAPS proposal suggest that the VTX should be composed of five to six layers of identical DMAPS. Several silicon detectors developed for similar applications were evaluated for this purpose. Finally the TJ-Monopix chip, originally designed for the HL-LHC upgrade of the ATLAS detector [7], was selected as the stepping stone for further development. This DMAPS chip is fabricated using the TowerJazz 180 nm CMOS imaging sensor process and features fast readout capabilities along with relatively high radiation hardness. This is a critical requirement for sensors positioned near the interaction point. Its successor, TJ-Monopix2, further improves the overall performance by lowering the operational threshold, optimizing the pixel layout, and addressing the limitations of the first generation.

The new chip, developed on the basis of TJ-Monopix2 but optimized for application at Belle II, is appropriately named the Optimized Belle II Pixel Sensor (OBELIX). It is currently under development by the Belle II VTX upgrade collaboration [6]. In order to eliminate the potential issues and enhance the strengths of its predecessor, the TJ-Monopix2, numerous characterization and test-beam campaigns have been conducted with this chip. This is also where the proceeding of this thesis contributes, by setting up the experimental environment, upgrading the data acquisition (DAQ) system, carrying out the experiments, and analyzing the results.

2 Physical Background

In order to meaningfully introduce the objectives and outcomes of the thesis, it is necessary to first explain the underlying principles and concepts. This will establish a fundamental understanding of the framework in which this research is carried out.

2.1 Interaction of particles with matter

In our daily lives, we typically rely on our eyes to observe objects, using scattered or reflected light to identify them. This approach, however, breaks down when the observed structures are smaller than the diffraction limit of light. This issue can be overcome either by using light of a smaller wavelength or by abandoning the optical approach entirely and instead observing the interaction of the object with matter. In particle physics, this strategy becomes essentially the only viable option. The specific case that is particularly relevant to the objectives of this thesis is the interaction of charged particles with matter, as these particles can be accelerated in modern particle accelerators. The concepts behind this type of interaction are explained in the following section.

2.1.1 Interaction of charged particles with matter

A sufficiently fast charged particle loses energy when interacting with matter through three main processes: radiative stopping, electronic stopping, and nuclear stopping. In this work, only the first two mechanisms are discussed in detail, as nuclear stopping is generally negligible for heavy and highly energetic particles [8].

The best known formula for describing the electronic stopping in the range of 0.1 to 1000 units of $\beta\gamma$ is the Bethe-Bloch equation [9],

$$\frac{dE}{dx} \approx -\frac{4\pi\hbar^2 c^2 \alpha^2 n Z}{m_e v^2} \left(\ln \left(\frac{2\beta^2 \gamma^2 c^2 m_e}{I_e} \right) - \beta^2 \right). \quad (1)$$

This equation characterizes the electromagnetic interaction between a single charged particle and atomic electrons. As the charged particle passes through the material, electrons are excited to higher energy levels or completely removed from the atoms, effectively ionizing them. The key variables and constants in the Bethe-Bloch equation are shown in the Table 1. In the original

Variable/Constant	Description
$\hbar$	Reduced Planck's constant
c	Speed of light in a vacuum
α	Fine-structure constant
n	Number density of atoms in the material
Z	Atomic number
m_e	Electron mass
v	Velocity of the incident particle
β	Ratio of the particle's velocity to the speed of light
γ	Lorentz factor
I_e	Effective ionization potential

Table 1: Key variables and constants in the Bethe-Bloch equation.

equation derived by Bethe using quantum mechanical perturbation theory, the target material is characterized by a single variable, the mean excitation energy. This quantity was later approximately calculated by Bloch to be

$$I = (10\text{eV}) \cdot Z \quad (2)$$

where Z is the atomic number. In the full Bethe-Bloch equation an additional dependence on the material is introduced in the form of the atom number density n . It can be expressed as $n = \rho/(Am_u)$ with A the atomic mass number and m_u the unified atomic mass unit. Because protons and neutrons are present in nearly equal amounts in most atomic nuclei, the Z/A ratio stays relatively uniform across different elements. As a result, the ionization energy loss scales primarily with the material's density and is largely unaffected by the material [9]. Since all other

parameters are fixed for a defined material, velocity remains the only variable, thus motivating the representation of this dependence in Figure 4. The interaction can be divided into two main regimes. At low particle velocities, the $1/v^2$ dependence causes a steep decline in energy loss, as seen in the left section of the graph. In contrast, at relativistic speeds where $v \approx c$ can be assumed, the energy loss increases slowly due to the logarithmic term, which can be seen in the right section of the graph. In between these regions, a distinctive minimum in energy loss can be observed. Particles with kinetic energies corresponding to this minimum are referred to as minimum ionizing particles (MIPs). MIPs play an important role in detector design, often serving as a benchmark. In this area, the energy loss is nearly constant across different materials, making the signal produced by a MIP a reliable baseline for defining the minimum detectable signal in silicon detectors.

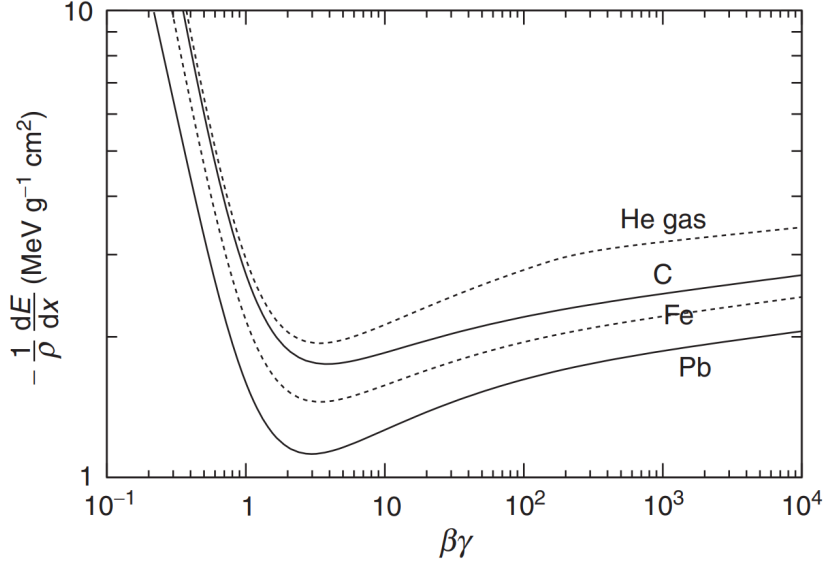


Figure 4: Energy loss of a single charged particle traveling in different materials, as described by the Bethe-Bloch equation. [9]

For moderately relativistic charged projectiles other than electrons, energy loss through ionization remains the dominant interaction with matter. Electrons, however, due to their low mass, start to lose energy predominantly via radiative processes once they exceed a certain critical energy. This critical energy can be approximated by the relation $E_c \sim (800/Z)$ MeV, where Z is the charge of the nucleus. This radiative loss, known as bremsstrahlung, occurs when fast electrons are deflected by the Coulomb fields of atomic nuclei. According to a general principle of electrodynamics, any accelerated charged particle emits radiation. This process is illustrated in Figure 5. The interaction can be mathematically described by the radiation emitted from a point charge accelerated perpendicular to its velocity. The expression in this case is given by [10]

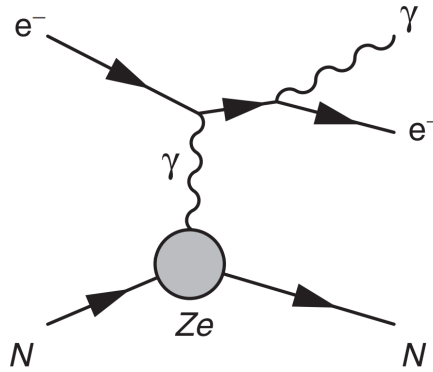


Figure 5: Bremsstrahlung process for a relativistic electron in the Coulomb field of a nucleus N with charge Ze [9]

$$P = \frac{\mu_0 * q^2 a^2 \gamma^4}{6\pi c} \quad (3)$$

Here, P denotes the total emitted power, μ_0 is the vacuum permeability, q is the particle's charge, and a represents its acceleration. Using the relativistic energy relation $E = \gamma mc^2$ and accounting for quantum electrodynamics (QED) effects, the bremsstrahlung power scales with m^{-2} for particles of the same energy. As a result, the radiative energy loss for muons is suppressed by a factor of $(m_e/m_\mu)^2$ [$2.34 \cdot 10^{-5}$] compared to that of electrons. At high energies, synchrotron radiation losses increase drastically, making operation highly inefficient and, beyond a certain point, practically impossible. Therefore, to reach very high energies, either heavier particles or larger accelerator rings are required.

2.1.2 Interaction of photons with matter

As introduced in the previous section, a fast-traveling electron passing through a material leaves behind a trail of high-energy photons. These photons, in turn, can undergo further interactions with the atoms in the material. The three most significant processes are the photoelectric effect, Compton scattering, and electron-positron pair production.

The photoelectric effect, first explained by Albert Einstein [11], describes the complete absorption of a photon by an electron in a lower atomic orbital. For this to occur, the photon must carry enough energy, specifically, an energy $h \cdot \nu$ that exceeds the binding energy required to free the electron from the atom. The surplus energy is transferred to the electron as kinetic energy. For a K-shell electron, the relation becomes

$$E_{kin}(e^-) = h \cdot \nu - (E_{ion} - E_k). \quad (4)$$

This effect is most relevant at photon energies below approximately 1MeV [12]. Above this threshold, Compton scattering becomes the dominant interaction between light and matter. This phenomenon, discovered in 1923 by Arthur H. Compton [13], describes the scattering of an X-ray or gamma photon by a free or loosely bound valence electron. During this process, the photon loses part of its original energy, resulting in an increase in its wavelength. As energy and momentum are conserved, the electron gains the energy lost by the photon. The change in wavelength can be expressed as [13]

$$\lambda_\theta = \lambda_0 + \frac{2h}{m_e c} \sin^2\left(\frac{1}{2}\theta\right) \quad (5)$$

Here, λ_θ and λ_0 represent the wavelengths of the scattered and incident photon, respectively, and $h/(m_e c)$ is known as the Compton wavelength.

The final interaction relevant to this study is electron-positron pair production, which predominantly occurs at photon energies above 10 MeV. This process is illustrated in Figure 6. According to Einstein's theory of relativity, the photon's energy can be entirely converted into the mass of two created particles. However, since the photon is a neutral boson, conservation of quantum numbers imposes strict constraints on the properties of the resulting particles. Additionally, this process can only occur in the vicinity of a nearby nucleus, which is necessary to conserve both energy and momentum at the same time [14].

2.2 Particle Detectors

After introducing the various particle interactions, the next step is to examine how these effects are used to ultimately provide scientists with the required data. This is the domain of particle detectors, which deliberately exploit these interactions in a controlled manner to generate electrical signals that are then converted into digital information.

2.2.1 Semiconductor Detectors

Semiconducting materials, especially silicon, have transformed the world of electronics over the past few decades. Their wide commercial applications drive ongoing research, which in turn opens up new possibilities for their use in other fields like particle physics. Today, silicon detectors are considered the state-of-the-art technology for vertex detectors and appear to be the way forward for future advancements.

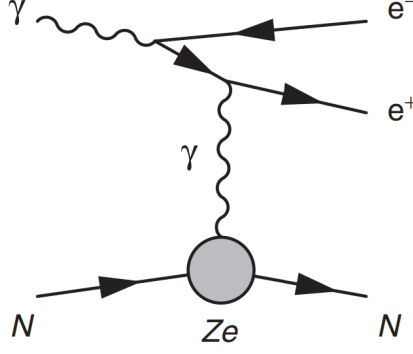


Figure 6: Energy loss of a single charged particle traveling in different materials, as described by the Bethe-Bloch equation. [9]

The ability of certain materials to conduct electrical current is closely related to the band structure introduced by the band theory. Electrons within a solid can only occupy certain almost continuous ranges of energy called energy bands, a concept based on the work of Felix Bloch in 1929 [15], who showed that electron wavefunctions in a crystal lattice have a specific periodic form. Bands are separated by energy gaps, which are regions of quantum mechanically forbidden energies. There is an infinite number of energy bands and gaps in a solid, however only those close to the Fermi energy (E_F) have significance for the conductivity. The Fermi level can be either enclosed by an allowed energy band or a band gap. In the latter case, the two significant bands can be easily identified. The band below the E_F is known as the valence band and the band above is the conduction band. As it can be deduced from the position of the E_F at absolute zero temperature, the electronic states in the valence band are filled, whereas the states in the conduction band are vacant. Hence, electrical conductivity depends on the size of the energy gap, which prevents the free movement of electron from one band to another, as only electrons inside the conduction band and holes in the valence band can act as charge carriers. Materials with a wide band gap and thus very low electrical conductivity ($\sigma \sim 10^{-12} \text{ S cm}^{-1}$ [12]) are called insulators. Semiconductors also possess a band gap, however it is narrow enough, that a efficient thermal excitation process of electrons to the conduction band can take place. This gives rise to a non-zero conductivity ($10^{-6} \text{ S cm}^{-1} < \sigma < 10^3 \text{ S cm}^{-1}$ [12]), which can be further enhanced by carefully introducing impurities inside the solid. In the case when the E_F is enclosed by an allowed band, the distinction between conduction and valence band becomes meaningless, since the partially filled band takes on properties of both. Due to the lack of a band gap, there will always be electrons with energies above the E_F and holes below the E_F , which results in excellent electrical conductivity ($\sigma \sim 10^6 \text{ S cm}^{-1}$ [12]), which also gives these materials their name, conductors. A visual representation of this classification can be seen in Figure 7. Following this broad classification, the focus will now shift solely to semiconducting materials, particularly silicon. Silicon has four valence electrons, which, in its crystalline form, are shared with neighboring atoms to form four covalent bonds, as illustrated in Figure 8 (a). This describes the case of intrinsic silicon, which is highly pure and contains only a negligible amount of impurities. The bandgap energy in this state is approximately 1.12 eV at room temperature. However, empirical studies have shown that the bandgap in most semiconductors is temperature dependent [17]. Temperature not only affects the bandgap size but also increases the thermal excitation of valence electrons into the n_i , is given by [17]

$$n_i = N_C \cdot \exp\left(-\frac{E_C - E_i}{kT}\right). \quad (6)$$

Here, N_C is the effective density of states in the conduction band, E_C the conduction band edge energy, E_i the Fermi level of an intrinsic semiconductor, k is the Boltzmann constant and T is the ambient temperature. This relation is visualized in Figure 9. Reading from the figure, at $T = 100^\circ \text{C}$ the intrinsic carrier concentration for silicon is approximately $n_i \approx 10^{12} \text{ cm}^{-3}$. Using the relation $\sigma = q \cdot n_i \cdot \mu_e$, where σ is the electrical conductivity, q is the elementary charge, and μ_e is the electron mobility, the conductivity of pure silicon can be estimated. Substituting $\mu_e \approx 1400 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ yields an electrical conductivity of $\sigma \approx 2.24 \times 10^{-4} \text{ S cm}^{-1}$. Comparing this to the conductivity of metals introduced earlier ($\sigma \sim 10^6 \text{ S cm}^{-1}$), it becomes clear that intrinsic semiconductors are not suitable for most electronic applications. This limitation, however, can be overcome by deliberately introducing impurities into the crystal lattice in a process known as

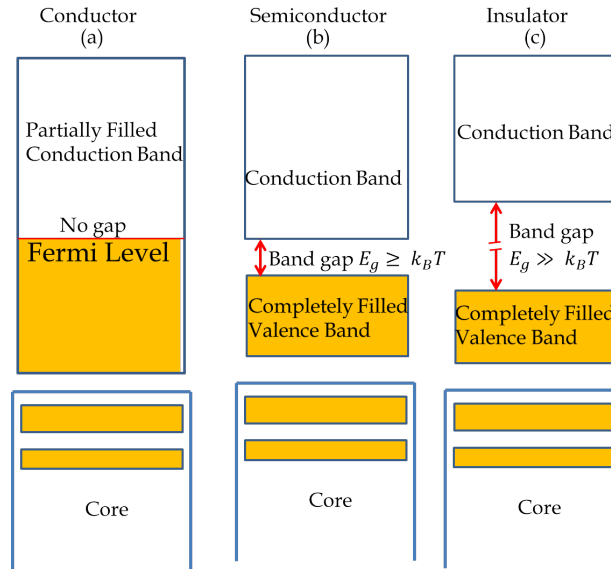


Figure 7: Schematic energy bands of conductor (a), semiconductor (b) and insulator (c) [16]

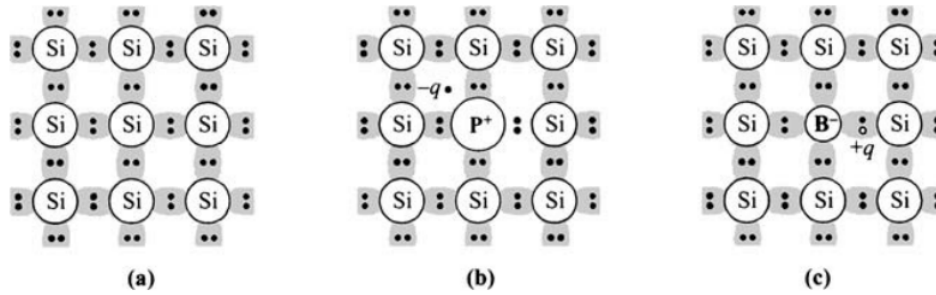


Figure 8: Three basic bonding models of a semiconductor: (a) Intrinsic silicon without impurities, (b) n-type silicon with a donor atom (phosphorus), and (c) p-type silicon with an acceptor atom (boron) [17]

doping.

Figure 8 (b) shows the silicon lattice, where a phosphorus atom with five valence electrons replaces a silicon atom, donating an extra electron to the conduction band. A semiconductor doped in this way is called a n-type while the phosphorus atom is called a donor as it donates a electron. In contrast, Figure 8 (c) shows p-type silicon, where a boron atom with three valence electrons substitutes a silicon atom, creating a hole in the valence band. The boron accepts an electron to complete four covalent bonds and therefore is called an acceptor. Such modifications in the silicon structure introduce new energy levels, known as impurity levels, typically located within the band gap. These levels usually have ionization energies much smaller than the band gap and are comparable to the thermal energy kT , allowing for almost complete ionization even at room temperature [17].

When p-type and n-type doped semiconductors are brought into contact, they form the simplest semiconductor device, a diode also sometimes called a p-n junction. In this junction, the loosely bound donor electrons in the n-type region diffuse into the p-type region and fill the available acceptor holes. As a result, a region of fixed negative charge forms on the p-side and a region of fixed positive charge forms on the n-side, since the ionized donor and acceptor atoms remain stationary. This region, known as the depletion region, is depleted of mobile charge carriers. It continues to widen until the resulting electric field is strong enough to balance the diffusion, establishing equilibrium. The formation of such a junction is shown in Figure 10.

Diodes can operate in two modes. In forward bias, a positive voltage is applied to the p-type region, causing the depletion zone to narrow and eventually disappear once a certain threshold is

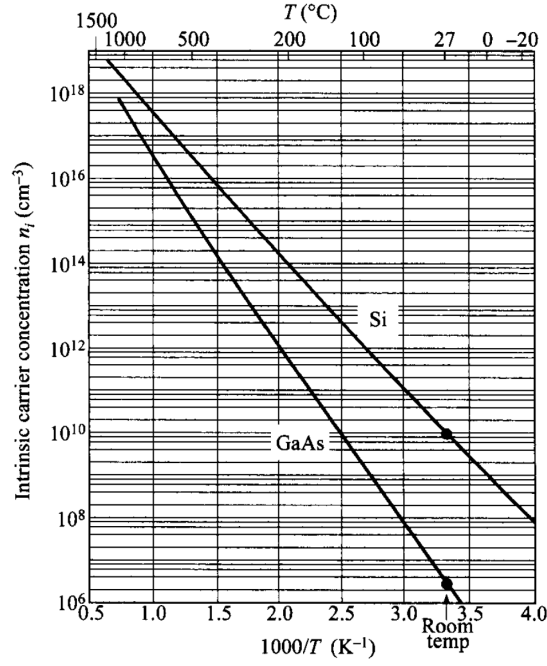


Figure 9: Intrinsic carrier concentration in silicon (Si) and gallium arsenide (GaAs) as a function of temperature [17]

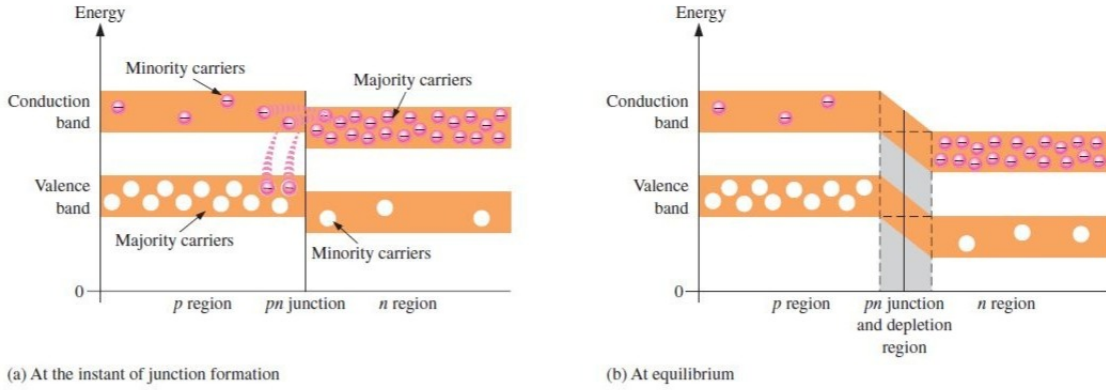


Figure 10: Diagram depicting the creation of a p-n junction [18]

reached. On the other hand in the reverse bias mode, a positive voltage is applied to the n-type region, which causes the depletion zone to widen. If the voltage is high enough, the entire diode becomes depleted of mobile charge carriers which makes the reverse bias mode particularly useful in particle physics. When an ionizing particle or photon passes through the depletion zone, it interacts with the crystal and generates electron-hole pairs. The applied electric field separates these charges and collects them before they can recombine, producing a small electrical current pulse. The size of this current is proportional the number of electron-hole pairs created and therefore to the energy deposited in the detector. For a depletion layer of about 300 μm , around $3 \cdot 10^4$ pairs are typically produced [19]. Charge transport in semiconductors occurs mainly via two mechanisms, drift and diffusion. Diffusion, driven by charge carriers concentration gradients, is relatively slow and not ideal for fast signal collection. Drift transport, on the other hand, is much faster as it is driven by the electric field, which accelerates the electrons and holes [20].

2.2.2 Pixel Detectors

A pixel detector is a broad term that extends beyond its use in particle physics. It generally refers to any device capable of capturing an image by collecting information from an array of small, discrete sensing elements, pixels. The era of pixel detectors began with the development and testing of

linear detectors for the DELPHI experiment at CERN. The newly achieved high interaction rates at Large Electron-Positron Collider (LEP) resulted in a significant rise in ambiguities, making it evident that the only solution was to develop a pixelated detector with a complete electronic chain per pixel [21]. A familiar example implementing such a concept is a digital camera, where each pixel on a sensor chip records and integrates the intensity of incoming photons. The result is a spatial distribution of light that forms the final image [22]. This approach can be adapted to the domain of particle physics, where the role of photons is replaced by elementary particles. In this context, each pixel records the passage of a charged particle, allowing for precise reconstruction of particle trajectories. However, detectors in high-energy physics must operate under much more demanding conditions, such as high radiation levels and even higher interaction rates, particularly in collider experiments. To meet these challenges, there are several design approaches available today. The two introduced in the following section are hybrid pixel detectors and Monolithic Active Pixel Sensors (MAPS), each offering different trade-offs in terms of performance, integration, and radiation tolerance.

Hybrid pixel detectors were the first type of pixel detectors developed for high-energy physics applications by the RD19 collaboration at CERN. The term 'hybrid' refers to their modular design where the sensor and the readout chip are fabricated separately and later connected in a process known as bump-bonding, as shown in the Figure 11. One of the major advantage of this approach is the ability to use different materials and fabrication processes for different purposes. For instance, high-resistivity silicon for the sensor, which is ideal for particle detection, and low-resistivity silicon for the readout chip, which supports faster electronic response. The modular design also makes it flexible, since each part can be reused or combined with a matching counterpart for different uses. However, this technology also has its drawbacks. Bump bonding is a labor intensive and costly process, making large-scale production difficult without trade-offs in speed and cost [20]. Furthermore, the increased material budget, due to the modular structure, increases the possibility of scattering, thus complicating particle tracking.

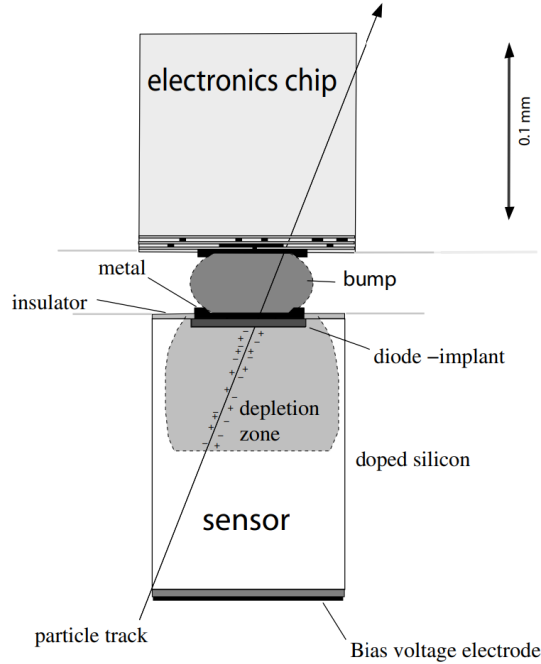


Figure 11: Schematic of a hybrid pixel detector cell. The ionizing particle creates charge in the sensor's depletion zone, which is collected, amplified, and processed by on-pixel electronics [22]

An alternative to hybrid pixel sensors are MAPS, which integrate both the sensor and the readout electronics on the same silicon wafer. Unlike DEPFET (Depleted P-Channel Field Effect Transistor) sensors, which focus on high-resistivity silicon to optimize sensor performance, MAPS rely on a thin layer of low-resistivity silicon [22]. This allows for more complex electronic integration, at the cost of slower charge collection and smaller depletion volumes. The material budget and capacitance are significantly reduced compared the hybrid pixel detectors. Additionally, the manufacturing process becomes simpler, more cost-effective, and more scalable by utilizing the

standardized commercial CMOS (Complementary Metal-Oxide-Semiconductor) process. Like any other technology, MAPS also have their limitations. The use of low-resistivity silicon results in charge collection mainly driven by diffusion, making the process relatively slow and limiting the size of the depletion region. This characteristics makes MAPS unsuitable for high-radiation environments such as those at the LHC, which is why hybrid pixel detectors have so far been preferred for such applications. Additionally, the standard CMOS process typically allows the use of only one type of transistor in the pixel area [23]. These drawbacks, however, have been addressed in the new generation of monolithic sensors known as Depleted Monolithic Active Pixel Sensors (DMAPS).

Advancements in CMOS processes and the ability to utilize the high-resistivity silicon substrates make it possible to fully deplete the detection region. This also enables much faster charge collection, as the transport is now primarily driven by drift in an electric field. Additionally, both types of transistors can now be implemented in the active pixel area [23]. Currently, DMAPS are an active area of research and development and are expected to become the state-of-the-art technology for future tracking applications. Beyond particle physics, these detectors are also gaining popularity in fields such as biology and astrophysics.

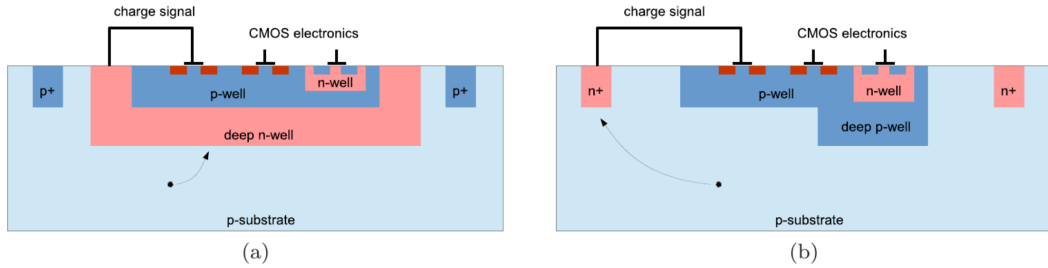


Figure 12: Schematic illustration of the two main DMAPS design approaches: (a) large collection electrode structure, with the digital electronics inside of the collection node and (b) small collection electrode structure, where the charge collection and electronics are separated. [24]

DMAPS sensors can be further optimized by adjusting the size of the charge collection electrode. Two main design strategies for the pixel cell arrangement exist, the large collection electrode design and the small collection electrode design. The large collection electrode implementation, shown in Figure 12a, embeds the transistors within a deep n-well that also serves as the charge collection node, forming a p-n junction with the p-type substrate. This configuration allows the substrate to be biased at high voltage, enabling short drift distances, high radiation tolerance, and the elimination of low-field regions. However, these benefits come at a cost, specifically, a higher sensor capacitance, which increases the overall noise levels. Additionally, the proximity of digital circuitry to the collection well can lead to greater crosstalk and reduced processing speeds. In contrast, the small collection electrode design, depicted in Figure 12b, separates the charge collection node, in this case a small and shallow n-well, from the surrounding digital electronics. This allows for lower sensor capacitance and reduced noise. Furthermore, the separation of the electronics from the collection node allows for faster operation and lower power consumption. However, the lower substrate bias leads to weaker electric fields, longer drift distances and reduced radiation tolerance [24].

As already mentioned in this section, high radiation tolerance is a critical requirement for the next generation of monolithic sensors. To effectively counteract or prevent radiation-induced damage, it is essential to first understand how the sensor material is affected. To compare and quantify damage caused by various particle types and energies, the concept of 1 MeV neutron equivalent fluence has been introduced. It defines the number of 1 MeV neutrons required to cause the same amount of damage as a given mixed radiation field. Radiation-induced effects can be broadly categorized into surface and bulk defects. However, since bulk defects are the dominant concern for silicon detectors, the discussion will focus on them.

Bulk damage arises from high-energy particles that directly collide with atomic nuclei. If the incident energy exceeds the atomic binding energy, atoms can be displaced from their equilibrium positions. This interaction is also known as Non-Ionizing Energy Loss or NIEL, and the resulting damage is referred to as NIEL damage. At lower energies, starting around 175 eV for neutrons and

260 keV for electrons, single-atom displacements, also known as point defects, can occur [25]. Some of these primary single-atom defects are illustrated in Figure 13. At higher energies, approximately

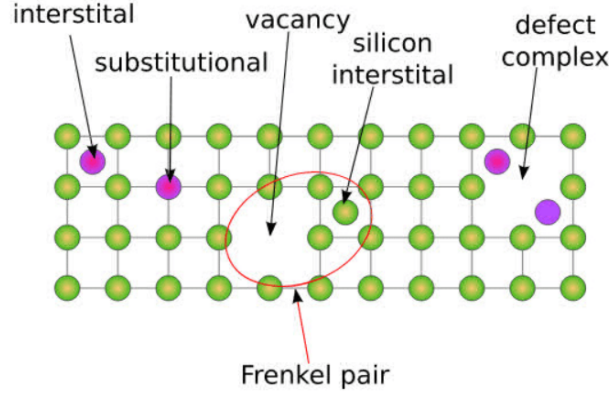


Figure 13: Defects in silicon crystals resulting from interactions with traversing particles.[24]

35 keV for neutrons and 8 MeV for electrons, the recoil nuclei can possess enough energy to displace additional atoms, leading to a localized chain reaction [25]. These highly disordered regions are referred to as defect clusters. The effects of such radiation damage on detector performance can be divided into three main classes [20]:

- *Leakage current:* In a non-irradiated silicon detector, only defect levels near the Fermi level contribute significantly to carrier generation and recombination, and thus to the leakage current. However, irradiation introduces additional defect states, particularly near the middle of the band gap, which serve as additional generation centers. These states, located in the middle of the band gap, significantly enhance the production of electron-hole pairs, leading to an increase in leakage current. Since the number of radiation-induced defects is approximately proportional to the particle fluence, the leakage current in irradiated silicon can be approximated as linearly dependent on the fluence, resulting in the following first-order expression [26]

$$I_{leak,irr} \approx I_{leak} + \alpha_i V_{Vol} \Phi_i \quad (7)$$

where I_{leak} is the leakage current, Φ_i represents the particle fluence, V_{Vol} is the depleted volume of the detector, and α_i is the reverse current damage constant.

- *Changes in doping concentration:* Irradiation-induced damage significantly alters the doping concentration in silicon by effectively removing acceptor and donor atoms. Radiation creates additional vacancies in the crystal lattice, which leads to a net increase in p-type doping. For n-type silicon, this means that the initial n-type doping gradually decreases, resulting in higher resistivity and, consequently, better depletion characteristics. However, this improvement is only temporary. Once the newly introduced p-type concentration exceeds the initial n-type doping, the material effectively "flips" to p-type, leading to increased difficulty to fully deplete the sensor. In the context of this thesis, the active sensor volume is based on p-type silicon. Therefore, radiation damage always leads to worse depletion performance. This limitation means that the detector must operate in a partially depleted state, which significantly affects its overall performance.
- *Charge trapping:* Defects in the bulk material can introduce new energy levels within the band gap, capable of capturing charge carriers generated by ionizing particles. If the trapping time exceeds the integration time of the readout electronics, the trapped charge is effectively lost, leading to a reduction in the total collected signal. When charge trapping becomes significant, it can also introduce timing issues due to the variable release times of trapped charges. To mitigate these effects, one common approach is to increase the bias voltage for stronger electric fields, however, this solution has practical limitations due to power constraints and a potential breakdown.

Radiation hardness, however, is not the only criterion a well-designed pixel detector must meet to achieve optimal performance. The following section provides a brief overview of additional key factors and describes how each contributes to the overall sensor performance:

- *Position Resolution*: Position resolution generally refers to how accurately the measured particle hit or trajectory describes the actual one. In pixel detectors, a first-order approximation of this resolution is given by the pixel pitch which is the physical size of each individual pixel. However, a more accurate description accounts for the possibility that the charge generated by a hit in the sensor can spread across multiple neighboring pixels. When this so called charge sharing is accounted for, the resolution improves beyond the pixel pitch and can be described more by the following expression

$$\sigma = \frac{p}{\sqrt{12}} \quad (8)$$

where p is the pixel pitch while the term $\sqrt{12}$ comes from the standard deviation of a uniform distribution of the measurement error [20]. It is important to note however, that while charge sharing enhances the resolution for single particles, clustering signals from multiple particles can reduce the ability to distinguish closely spaced events.

- *Time Resolution*: Another important performance metric is time resolution, which defines how precisely the time of a particle's arrival can be measured. In pixel detectors, this value is primarily given by the sensor thickness and the charge collection speed. As discussed in the section on radiation hardness, charge collection speed can be adjusted by increasing the bias voltage, which strengthens the drift field thus accelerating the charge carriers. Another important metric used in this context is the dead time or the period during which the detector is unable to register a new event after a previous one. In collider experiments, where particle bunches collide at high frequencies, it is crucial that the detector can assign a precise timestamp to each event before the next collision occurs.
- *Noise*: One of the most important characteristics of a well-designed detector is its ability to minimize the impact of noise on the resulting signal. This capability is often quantified using the Signal-to-Noise Ratio (SNR). In pixel detectors, the sources of noise can generally be categorized into two sections, the intrinsic noise of the sensor and the electronic noise from the readout electronics. The electronic noise is commonly expressed in terms of the Equivalent Noise Charge (ENC), which represents the amount of input charge that would produce a noise level equal to the observed output. This metric thus defines the minimum signal needed to reliably distinguish a hit from background noise. The mathematical expression for the ENC takes the following form [27]

$$ENC^2 = A + B \cdot C^2. \quad (9)$$

Here, A and B are constants characterizing the preamplifier, and C denotes the detector's capacitance. The detector itself is not ideal; due to its finite temperature, there is always a fraction of thermally generated electron-hole pairs, which contribute to the leakage current. This effect can be described by the following equation [27]

$$ENC = \left(\frac{e}{q}\right)^2 \cdot \frac{qIT_p}{4} \quad (10)$$

Combining these two factors, the resulting Signal-to-Noise Ratio (SNR) can be calculated using the following expression

$$SNR = \frac{Signal(e^-)}{ENC(e^-)} \quad (11)$$

- *Power Consumption*: While it may seem trivial at first glance, power consumption is a critical factor in the design of pixel detectors, especially in large-scale high-energy physics experiments, where multiple square meters of sensor area and millions of pixels are involved. Even small differences in power usage, in the order of hundreds of microwatts per pixel, can scale up to significant overall power demands. In addition to the challenge of steadily supplying this power, additional difficulties arise from the fact that most of it is converted into heat, which must be efficiently managed with proper cooling systems.
- *Charge Collection Efficiency*: CCE quantifies how effectively the charges generated by an ionizing particle are collected by the sensor electrode. This efficiency is influenced by the depletion state of the sensor and the applied bias voltage. As previously discussed in detail in the section on radiation hardness, both of these factors can be significantly impacted by radiation damage, making the CCE strongly dependent on fluence. In addition to radiation effects, temperature and charge sharing between neighboring pixels also play important roles in determining the overall CCE.

2.3 Thermoelectric effect

The thermoelectric effect describes the direct conversion of a temperature gradient into an electric voltage and in a closed electrical circuit, into an electric current. It serves as an umbrella term for three related phenomena, the Seebeck effect, the Peltier effect and the Thomson effect. Unlike conventional methods of converting heat into electricity, such as using turbines and generators, the thermoelectric effect enables the design of solid-state converters with no moving parts.

This new and promising field of physics was pioneered by the German scientist Thomas J. Seebeck in the early 19th century during his experiments with voltaic currents and magnetism. In the course of his research, he discovered that a closed circuit made of two different metals, with junctions maintained at different temperatures, would cause a compass needle to deflect [28]. This effect was later investigated in more detail, and the underlying principles became known as the Seebeck effect. The driving mechanism behind this phenomenon is the thermal diffusion of conduction electrons which move from the hotter region, where their thermal velocity is higher, toward the cooler region. The resulting current density can be expressed as [29]:

$$\vec{j}_{ThD}(\vec{r}) = n \cdot \vec{u}(\vec{r}) \quad (12)$$

where n is the concentration of conduction electrons and $\vec{u}(\vec{r})$ represents their thermal diffusion velocity. This process is illustrated in Figure 14. The thermal diffusion velocity depends on the

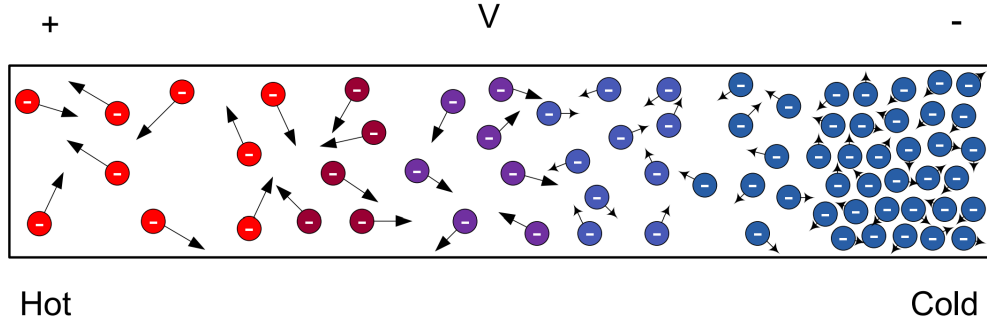


Figure 14: Illustration of the Seebeck Effect. [30]

temperature gradient and can be calculated as follows [29]

$$\vec{u}(\vec{r}) = -\frac{\lambda}{3} \frac{\partial \bar{v}}{\partial T} \cdot \nabla T(\vec{r}) \quad (13)$$

with λ denoting the mean free path, $\bar{v}$ the average velocity of electrons, and $\nabla T(\vec{r})$ the temperature gradient. To compute the total current density, one must consider additional contributions from regular diffusion driven by the concentration gradient and the opposing current induced by the buildup of space charge. The resulting equation takes the following form [29]

$$\vec{j}_{total} = \vec{j}_{Diff} + \vec{j}_{ThD} + \vec{j}_{Drift}. \quad (14)$$

If the circuit is closed, the resulting current density can be measured using an ammeter. In the case of an open circuit, where $\vec{j}_{total} = 0$, the resulting voltage can be measured instead. For easier comparison and handling, a proportionality factor known as the Seebeck coefficient S is introduced. It relates the generated voltage ∇V to the applied temperature gradient ∇T . The complete mathematical expression is given by [29]:

$$\vec{j}_{ThD} = \sigma_{el}(\nabla V - S \cdot \nabla T) \quad (15)$$

with σ_{el} denoting the electrical conductivity and S the Seebeck coefficient. Typical values for the Seebeck coefficient are in the range of 10^{-6} V K^{-1} to 10^{-5} V K^{-1} for metals and approximately 10^{-3} V K^{-1} for semiconductors [29].

The Peltier effect, named after the French physicist Jean C. A. Peltier, is essentially the reverse of the Seebeck effect. It describes the phenomenon where, when an electrical current flows through a junction of two materials with different Seebeck coefficients, one side of the junction cools while the other side heats up. This occurs because the drifting charge carriers absorb heat at one end

and release it at the other [31]. To simplify the relationship between the amount of heat generated (or absorbed) and the electrical current supplied, proportionality constants, known also as Peltier coefficients, are introduced. This relationship is expressed by the following equation [29]:

$$\frac{dW}{dt} = (\Pi_A - \Pi_B) \cdot I \quad (16)$$

where Π_A and Π_B are the Peltier coefficients of the two materials, expressed in joules per coulomb (J/C).

3 TJ-Monopix2

After a thorough introduction to the underlying physical concepts, the focus can now shift to concrete examples where these effects are applied. The most relevant example for the purpose of this thesis is the TJ-Monopix2 sensor.

The TJ-Monopix2 chip represents the next step in the ongoing effort to replace the more complex and costly hybrid pixel sensors. The development of the first chip in this series was motivated by the need for a detector capable of fast readout (~ 25 ns) and radiation hardness up to fluences of 10^{15} n_{eq}/cm², as required for the HL-LHC upgrade of the ATLAS detector [7]. The design of TJ-Monopix2 builds on the ALPIDE chip [32], originally developed for the ALICE inner tracking system upgrade [33]. The chosen technology is the TowerJazz 180 nm CMOS imaging sensor process, which offers the advantage of full CMOS functionality within the pixel while keeping the flexibility in selecting the starting material. The small collection electrode design of a chip developed using this standard TowerJazz 180 nm CMOS process is shown in Figure 16. Here, the n-well

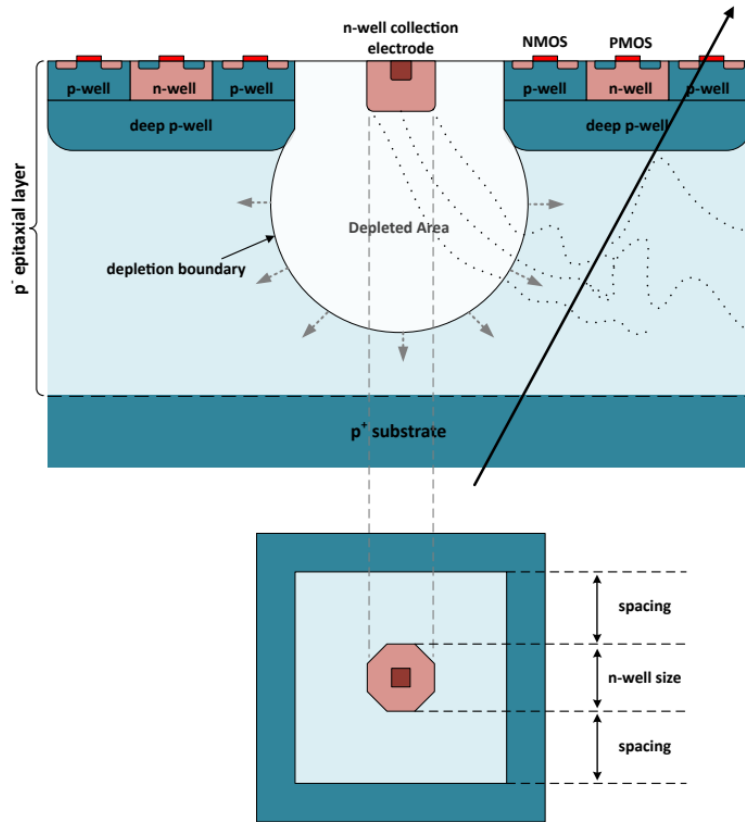


Figure 15: Cross-section of a MAPS pixel design in the TowerJazz 180 nm CMOS process, where the epitaxial layer can not be fully depleted. [20]

electrode and the n-well containing the PMOS transistors are separated, with the latter shielded by a deep p-well. In this approach, the epitaxial layer is only partially depleted, meaning that charges generated in the further regions of the sensitive layer are initially transported by slower diffusion before they are picked up by the drift field in the vicinity of the electrode. This limitation becomes even more pronounced when the chip is subjected to high levels of radiation, as is the case for the ATLAS inner tracking system. To address this issue, a process modification was proposed by CERN in collaboration with Tower Semiconductor [34]. This modification introduces an almost planar junction, separate from the collection electrode, which enables depletion to start at the junction and expand even without applying a reverse bias voltage. The new design is shown in Figure 16. The n-implant dose is a key parameter in the sensor design. It must strike a balance between achieving full depletion at practical voltages, preventing punch-through, minimizing capacitance to optimize the signal-to-noise ratio, and avoiding type inversion under high NIEL irradiation. Following successful initial tests, a large-scale chip implementing the modified process was developed: the TJ-Monopix1 [35]. It employs the standalone column-drain readout architecture pioneered by

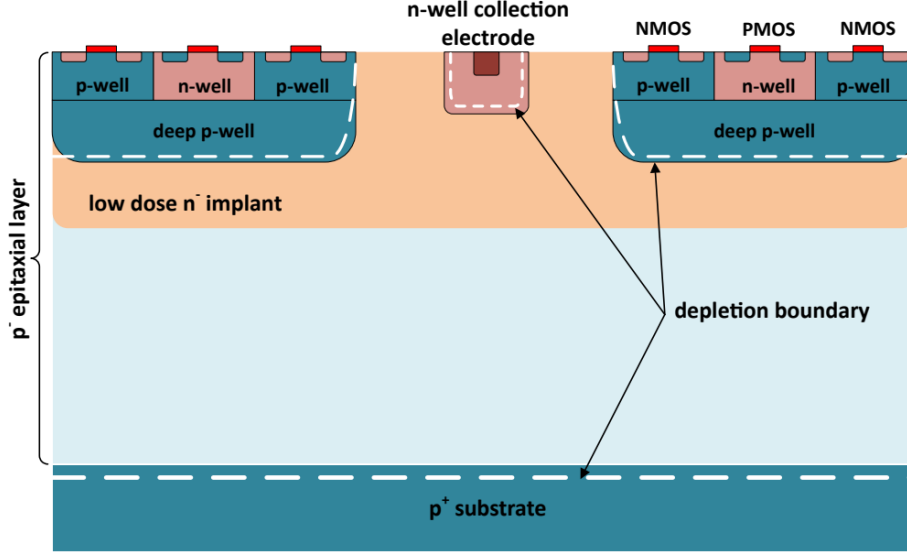


Figure 16: Cross-section of a DMAPS pixel in the modified process enabling full depletion of the epitaxial layer [20]

the FEI3 readout chip [36]. The pixel matrix consists of 224×448 pixels, with an overall size of $1 \times 2 \text{ cm}^2$. Each individual pixel measures $36 \mu\text{m} \times 40 \mu\text{m}$ and is arranged in a double-column layout. The front-end electronics are further divided into four sectors (referred to as “flavors”), each implementing different configurations of the data bus readout circuitry and front-end input reset and coupling schemes [20]. The chip underwent thorough testing and characterization, showing promising results. However, after irradiation to fluences of $10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, a drop in efficiency was observed. This issue, along with various other refinements, was addressed in an additional optimization cycle [37], which ultimately led to the development of the next-generation chip, the TJ-Monopix2.

The TJ-Monopix2 is designed to address the shortcomings of its predecessor while also introducing new features aimed at enhancing overall performance and usability. The two main areas of improvement are the pursuit for a lower operating threshold and an optimized pixel layout. The chip now features a front-end matrix consisting of 512×512 pixels, with the pixel pitch reduced to just $33.04 \times 33.04 \mu\text{m}^2$. Two design strategies have been implemented to enhance radiation hardness. The first approach introduces a hole inside the low-dose n-type implant at the pixel edge, which is then filled with p-type epitaxial silicon. The second approach adds an additional p-type implant underneath the deep p-well [38]. These design variations can be fabricated on different silicon substrates, the relatively high-resistivity epitaxial silicon and highly resistive Czochralski silicon. Like its predecessor, the TJ-Monopix2 offers four different pixel “flavors” though the division between them has been redesigned. The new layout is shown in Figure 17. Both sections with 224×512 pixels are DC-coupled, meaning that the charge collection electrode is directly connected to the front-end electronics. The section labeled *Cascode Front-End (FE)* incorporates an additional cascode transistor, which is expected to increase the gain by a factor of 1.6 [20]. The two smaller sectors are AC-coupled, introducing an intermediate capacitor between the electrode and the front-end electronics. The sector labeled *HV FE Casc.* also includes the additional gain transistor [38]. Further modifications have been implemented, such as increasing the bitwidth of the Bunch Crossing ID (BCID) from 6 bits to 7 bits, adding the option for an in-pixel threshold Digital to Analog Converter (DAC) tuning and introducing the 8b10b data encoding format.

Currently, research on the TJ-Monopix2 chip is primarily driven by the Belle II VTX upgrade collaboration [6]. The OBELIX chip [39], proposed as the successor to TJ-Monopix2, is considered the most promising candidate for the detector upgrade. While various measurements and characterization campaigns have been conducted on the TJ-Monopix2 sensor, many open questions remain. For instance, the relationship between the efficiency of the irradiated chip and its operating temperature is not yet fully understood. Further efforts are also required to improve threshold uniformity and optimize noise performance, while identifying and mitigating the sources of various crosstalk effects [20].

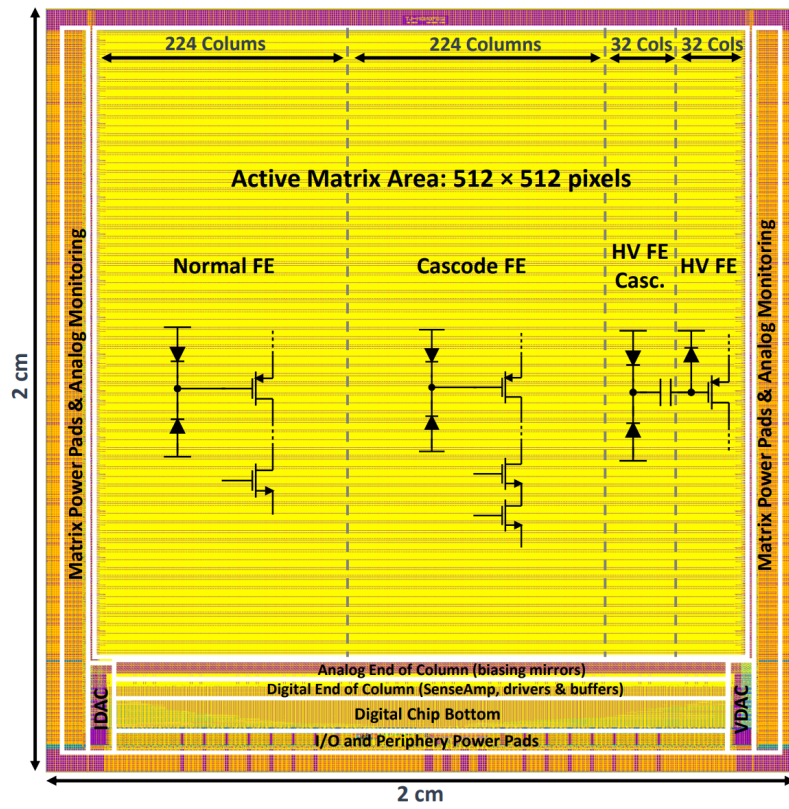


Figure 17: Overview of the TJ-Monopix2 pixel matrix, highlighting the different sector flavors and the chip periphery. [20]

4 Data Acquisition System

Any chip is effectively useless unless the signals it produces can be properly recorded, stored, and processed for further handling. This is the role of the Data Acquisition (DAQ) system. Beyond these obvious tasks, the DAQ system also handles timing measurements, provides error recognition and logging, configures the chip, and acts as the interface between the chip and the user's PC. For use with the TJ-Monopix2 chip, the BDAQ53 readout system was selected. Developed by the RD53 collaboration [40], it was originally designed for RD53-based pixel detectors used in ATLAS and CMS. However, thanks to its highly versatile design, it can also be effectively employed with other sensors. The complete DAQ solution consists of two main components, the hardware and the software.

4.1 Hardware

The centerpiece of the entire hardware setup is the BDAQ53 base board, shown in Figure 18. Beneath the heatsink lies a second commercially available FPGA board, housing a Xilinx Kintex7 FPGA. This FPGA communicates with the Device Under Test (DUT) via the Low-voltage Differential Signaling standard or LVDS. The DisplayPort connectors are used to link the chip board to the base board. As shown in Figure 18, the system supports a multi-chip setup, allowing up to four chips to be connected simultaneously. In addition, the board includes interfaces for connecting to a computer and a Trigger Logic Unit (TLU) via an RJ-45 connection. Power is supplied either through a dedicated VDC interface or via the USB port, which also serves as the uplink when flashing new firmware onto the FPGA.

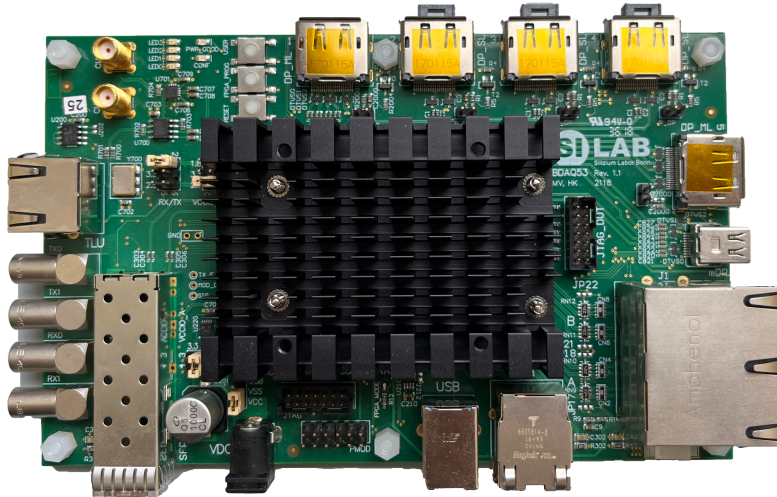


Figure 18: BDAQ53 base board developed by the RD53 collaboration

4.2 Software

The software component can be divided into two main parts, the firmware running on the FPGA, and the Python-based framework running on the PC. The firmware is written in Verilog, a hardware description language commonly used for FPGA development. Like the hardware, the firmware follows a modular design. Essential components such as the main system clock and the Ethernet interface are handled by dedicated input-output modules which makes it possible to also use different FPGAs [40]. Further details about the firmware architecture can be found in Figure 19.

The user ultimately interacts with the Python-based framework, also called Basil, which also stays true to the core philosophy of BDAQ53, modularity. Measurement scripts, such as those for Time over Threshold (ToT) and noise occupancy scans, are designed to be independent of the specific chip type or hardware. These scripts also include the basic EUDAQ states, ensuring

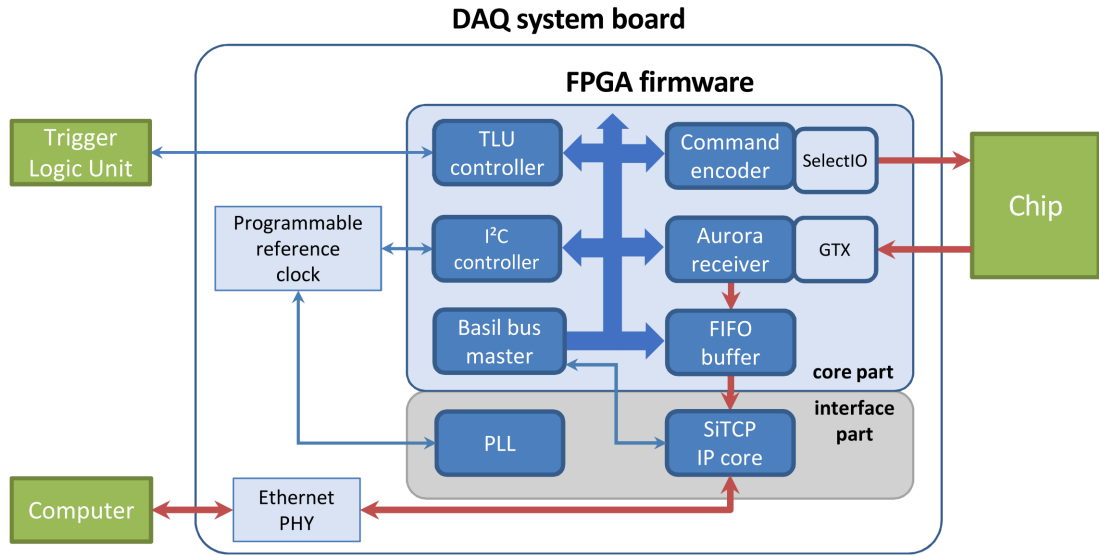


Figure 19: Block diagram of the BDAQ53 data acquisition system, showing the FPGA firmware architecture. [40]

smooth integration into EUDAQ system. After a scan is completed, there is a predefined option to analyze the results, which generates a PDF file containing plots that visualize the recorded data [40].

5 Temperature Control Setup

Among the most important aims of this thesis was the exploration of the effect of temperature changes on the performance of the irradiated chip. Accurate measurements can only be achieved if the temperature control system is well-designed and thoroughly characterized. The requirements for the system were the following:

- Accurate and stable temperature control, with remote operation capabilities, as the experimental area must remain sealed during test beam runs.
- Capability to both heat and cool the chip within a temperature range of 0 °C to 50 °C.
- Minimized adjustment time between temperature runs to maximize measurement efficiency.
- No introduction of additional material into the beam path, to avoid interfering with particle tracks.
- Compact design to fit within the tight spatial constraints between the telescope planes.

To achieve this, a combination of precise hardware and clever software was necessary. The individual solutions in both areas will be presented in the following sections.

5.1 Hardware components

Various techniques could be used to fulfill the first requirement on the temperature control system, however in combination with the other constraints, this presents a significant challenge. The first decision is whether heat should be transported via conduction or convection. Direct forced convection of a liquid around the chip board is not possible due to the electrical circuitry. Gas convection would be achievable to some extent, but likely inefficient because of the tight spatial constraints. These considerations leave conduction, where the heat transfer medium is in direct contact with a surface, as the most viable option. However, this approach also comes with its own challenges. The material used for heat transfer cannot be directly in contact with the chip itself, as this would interfere with the particle paths and compromise the tracking process. The solution is to establish thermal contact with the Printed Circuit Board (PCB) instead, allowing the chip to be cooled or heated indirectly through the PCB. Based on previous experience and testing, it was decided that contact should be made only via a square bump positioned around the chip. Nevertheless, the challenge of how to effectively generate or remove heat remains. While circulating a liquid or gas through a material with good thermal conductivity was considered, the final design settled on using a Peltier element in combination with copper as the conduction material. On one side, the Peltier element is connected to the copper plate, and on the other side, a heat sink with a small computer fan is used to dissipate or supply heat, depending on the desired operation.

Another important aspect is the condensation of water from the surrounding air or gas. The occurrence of this phenomenon depends on several factors and can be expressed mathematically, in its simplest empirical approximation, as follows [41]

$$T_d = \frac{B_1 \left[\ln \left(\frac{RH}{100} \right) + \frac{A_1 T}{B_1 + T} \right]}{A_1 - \ln \left(\frac{RH}{100} \right) - \frac{A_1 T}{B_1 + T}}, \quad (17)$$

where T_d is the *dew point*, which indicates the temperature below which condensation of water occurs spontaneously. This value depends on the relative humidity RH and the ambient temperature T . The coefficients A_1 and B_1 were determined experimentally to be $A_1 = 17.625$ and $B_1 = 243.04$. From this equation, it follows that condensation would occur almost instantly if the copper were cooled in a typical environment with high relative humidity, as the dew point would be high as well. Therefore, it becomes evident that humidity must also be controlled to avoid the buildup of moisture around the chips electronics. To accomplish this, the entire setup was placed inside a custom 3D-printed casing, which can be flushed with dry air or nitrogen. The final design can be seen in Figure 20. The production and final decisions regarding the hardware used were carried out by Christian Irmeler and Stefan Schultschik, to whom I would like to express my sincere thanks.

The power for the Peltier element was provided by a multi-range DC power supply, the Gwinstek PS30-36, which is capable of delivering currents up to 36 A with an accuracy of 30 mA [42]. This was more than sufficient for the intended purposes. However, since the power supply is only



Figure 20: Peltier temperature control system housed in a custom 3D-printed casing with all necessary connections.

capable of delivering positive currents, the setup was expanded by incorporating a switching relay. Using this addition and appropriate circuitry, the current direction could be controlled with the help of a simple Arduino microcontroller.

Adjusting variables like the current and current direction can only be done meaningfully, if the system's response can be monitored as well. Therefore, temperature measurements were performed at multiple points throughout the setup. Probes were placed on the hot and cold sides of the Peltier element, on the copper plate, and during the initial testing phase also on the PCB and directly on the chip. For this purpose, the TC-08 Data Logger by Pico Technology was used. Additional measurements were conducted using the Negative Temperature Coefficient (NTC) thermistor mounted on the chip board, the DHT22 humidity sensor, and a PFM71 digital dry air flow switch. The latter two were also connected to the Arduino microcontroller for power supply and data readout.

5.2 Software framework

With the appropriate hardware in place, the focus can shift now to the software required for the system control. Both the TC-08 Data Logger and the Arduino Uno were connected to a single computer via USB. While the TC-08 comes with a dedicated application for displaying, recording, and visualizing temperature measurements, relying on multiple separate applications during a test beam, one for temperature monitoring, another for temperature control, and a third for reading data from the Arduino, would be impractical. Therefore, a design decision was made to summarize all functionalities into a single Python-based framework.

The TC-08 readout is supported by the PicoSDK, allowing access via a simple Python script, however, the full integration process to retrieve the data is far from trivial. To assist users, the full installation procedure is documented in Appendix A. In contrast, the Arduino can be programmed with a simple script to handle serial communication, sending and receiving data requests that are easily processed within the Python environment. Within the Python framework, data from various sources is processed, combined, and stored in CSV files for both logging and visualization purposes. The current copper plate temperature is fed into a Proportional-Integral-Derivative (PID) controller, which adjusts the control variable to reach the target temperature as quickly and accurately as possible. A simplified data flow diagram and processing logic are illustrated in Figure 21.

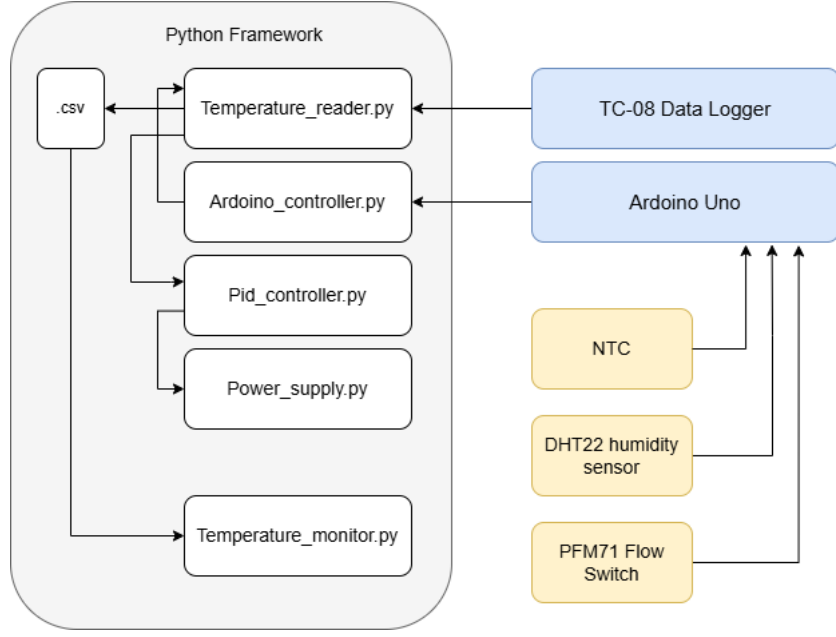


Figure 21: Block diagram describing a simplified data flow diagram and processing logic for the temperature control system

5.2.1 PID Controller

One of the key components of the temperature control setup is the PID controller, which regulates the output current supplied by the power supply based on the target temperature and the current measured temperature. The operating principle of the PID controller is illustrated in Figure 22. The *Setpoint* is periodically compared with the *Output*, and the resulting error e is calculated.

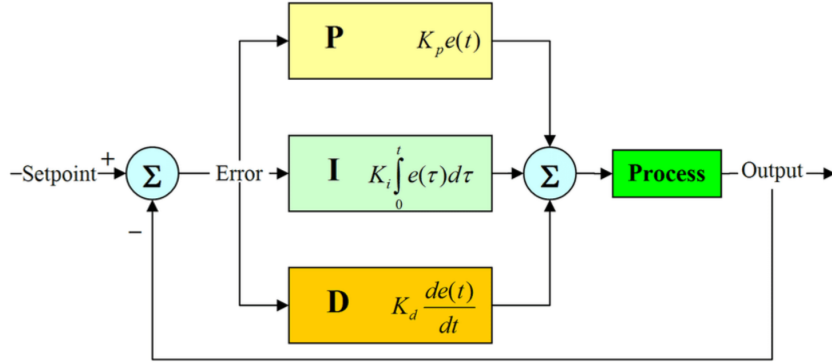


Figure 22: Block diagram of a PID control loop, illustrating the feedback mechanism that minimizes error by adjusting process output. [43]

This error function is then used in three distinct evaluations to calculate the so called process variable u , which is used to adjust the system. The first evaluation is the *Proportional* component, which responds to the error with a directly proportional adjustment. The constant K_p , like all the other constants shown in Figure 22, is process specific and must therefore be determined for each application. The *Integral* component, on the other hand, responds to the cumulative error in order to eliminate persistent steady-state deviations. Finally, the *Derivative* component predicts future errors by evaluating the current rate of change of the error. All of these contributions are then summed together to produce the final process Variable. This process can be mathematically expressed using the following relation:

$$u(t) = K_p \left(e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{de(t)}{dt} \right). \quad (18)$$

This is the so-called standard form of the control function. Comparing this expression to the one in Figure 22, it becomes apparent that the terms are parametrized differently. This is because the

new parameters, the *integration time* constant $T_i = \frac{K_p}{K_i}$ and the *derivative time* constant $T_d = \frac{K_d}{K_p}$, have now a measurable physical significance and can therefore be determined more easily. There are numerous approaches available to determine these parameters, each suited to a specific type of system behavior. Based on the shape of the step response function recorded with the setup shown in Figure 23a, the Cohen–Coon [44] tuning method was selected. This choice is justified by the fact that the system operates in an open-loop configuration which means that before introducing the PID controller, no feedback control is present. Additionally, the response does not exhibit integrators or dominant complex-conjugate poles, which is a key criterion for applying the Cohen–Coon method.

The Cohen–Coon method introduces a new set of parameters that can be directly extracted from the step response function. The first is the delay time L , which, as the name suggests, quantifies how long it takes for the system to begin responding to a change in the input. Secondly, the time constant T characterizes the duration of the system’s response. It can be determined by drawing a tangent line at the inflection point of the response curve and locating its intersection with the steady-state value. Finally, the DC gain K_{DC} reflects the magnitude of the step response. In the case of a unit step input, K_{DC} is equal to 1. This procedure is illustrated in Figure 23b for a single measurement. To ensure statistical reliability, the extraction of these parameters was repeated across multiple measurements. The newly obtained response parameters relate to the previously introduced PID coefficients as defined in Table 2. Here, it can be decided which components of the

Controller	K_p	T_i	T_d
P	$\frac{3T + L}{3LK_{DC}}$	∞	0
PI	$\frac{10.8T + L}{12LK_{DC}}$	$\frac{L(30T + 3L)}{9T + 20L}$	0
PID	$\frac{16T + 3L}{12LK_{DC}}$	$\frac{L(32T + 6L)}{13T + 8L}$	$\frac{4LT}{11T + 2L}$

Table 2: Cohen-Coon tuning formulas for P, PI, and PID controllers.

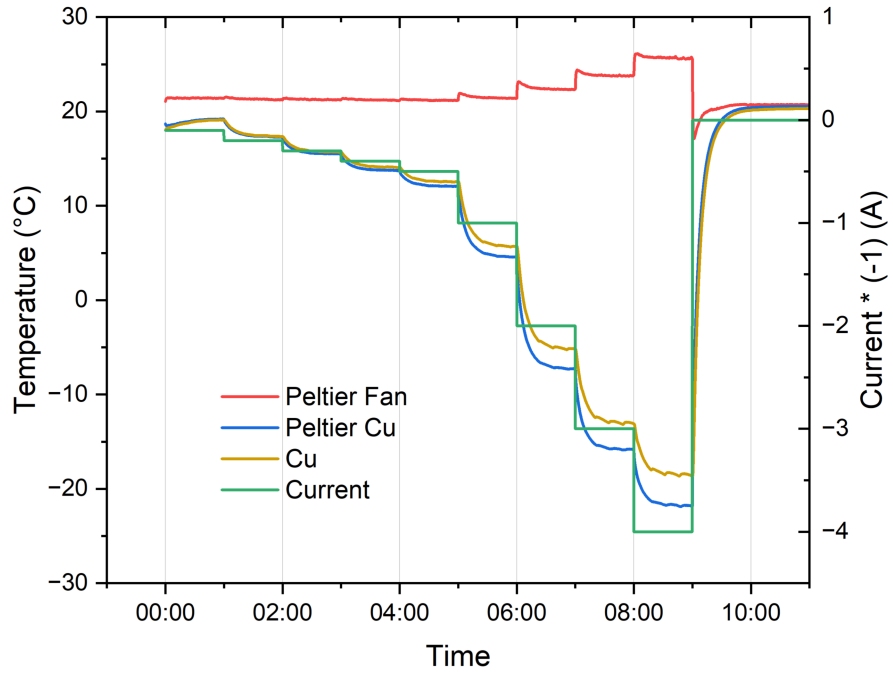
PID controller should be used for a specific application, as not all components are always optimal. For the purpose of this setup, it was decided to use the full PID controller, and the calculated coefficients are:

$$Kp = -0.9, Ki = -0.9/94.77, Kd = -0.9 * 11.1 \quad (19)$$

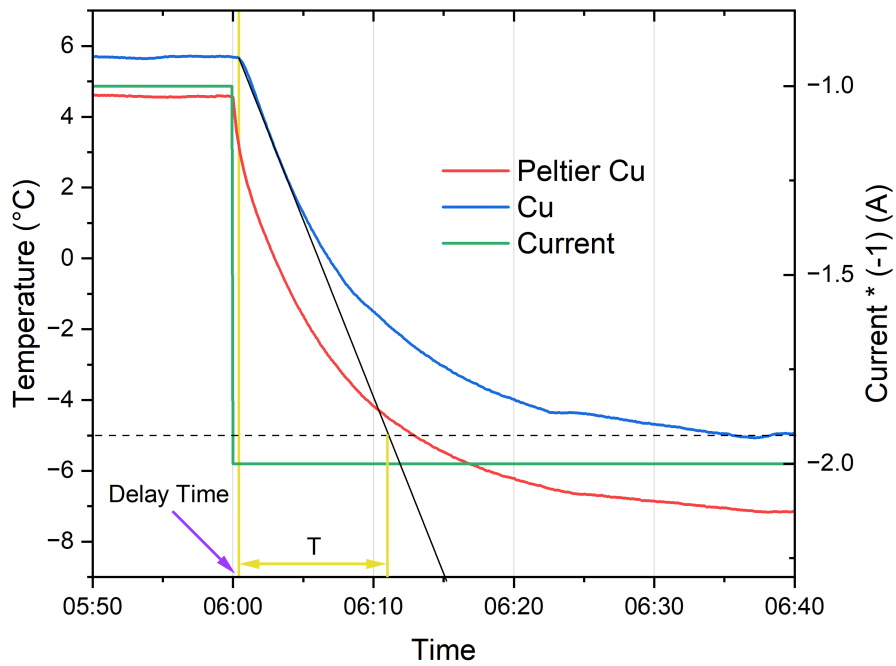
After some testing and adjustments on the physical setup, the following values were found to deliver the best results in terms of minimizing the absolute overshoot and the settling time:

$$Kp = -0.7, Ki = -0.5/94.77, Kd = -0.9 * 11.1 \quad (20)$$

An example demonstrating the behavior of the PID controller with the optimized parameters is shown in Figure 24.



(a) Step response of the temperature control system observed for various currents between 0.1 A and 4 A



(b) Response for a unit step from 1 A to 2 A with further analysis required to determine the PID coefficients using the Cohen-Coon tuning method

Figure 23: Step responses and tuning of the PID controller

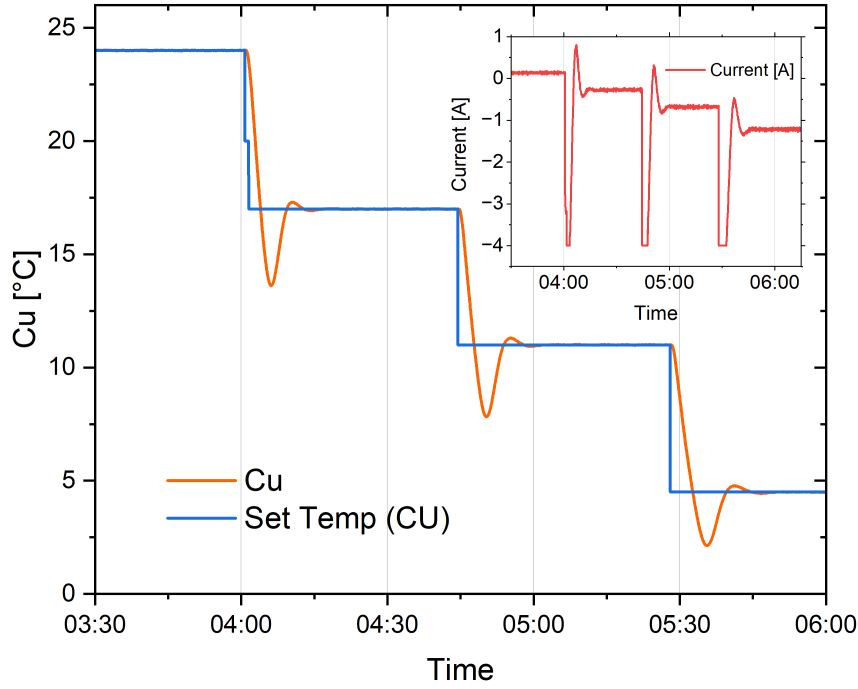


Figure 24: Response of the PID controller to a step change with inset figure displaying the current flow. The observed settling time was approximately 15 minutes.

5.3 User interface

The entire setup would not be complete without a way to both control and display all relevant variables. This task is handled by a user interface (UI), built using Dash [45], a Python framework developed by Plotly for creating interactive web applications, particularly suited for data visualization and analysis. The use of a web-based application is justified by the physical constraints of the setup where the PC controlling the system had to be placed inside the test beam area, while monitoring and control needed to occur remotely from the control room. Additionally, this web-based approach allows multiple devices to connect to the system simultaneously without requiring any specialized software.

The primary function of the UI is to collect various input data and present it in a clear, organized format, while also enabling the user to interact with the background PID controller by setting desired temperature setpoints. The final implementation of the UI is shown in Figure 25. In the top section, the various input channels are displayed over time, while on the right side, the channel selector allows specifying which inputs are currently shown. One of the options is the *Dew point* channel, which is an important quantity to monitor since if any temperature in the systems dips below this point, condensation can form and potentially damage the chip or the setup. In the second row, the value *New Set Temperature* defines the target temperature, whereas the current values of key quantities are displayed on the right. Here, the field displaying the flow of current is supplemented with a sign indicating whether the system is currently cooling or heating, even though the value shown on the power supply is always positive. Finally, in the bottom row, the flow of dry air or nitrogen is represented by a bar, with the target set to 2 liters per minute.

At this point, it should also be noted that several safety features were implemented to protect the setup from damage. In particular, whenever a new target temperature is entered, the dew point is calculated in the background from the most recent measurements. If the new temperature is below the dew point, a pop-up window appears, warning the user that this action could lead to potential damage. Under normal operation, with proper nitrogen or dry air flow, this should never occur since the dew point is significantly lower than the lowest achievable temperature. Furthermore, the system will automatically stop temperature control if any part of the setup exceeds

65 °C, as temperatures above this threshold can cause permanent damage to the Peltier element or other parts of the setup. The temperature difference between the hot and cold sides of the Peltier is also monitored, and if the critical limit of 70 °C is exceeded, the system will automatically perform a safe shutdown.

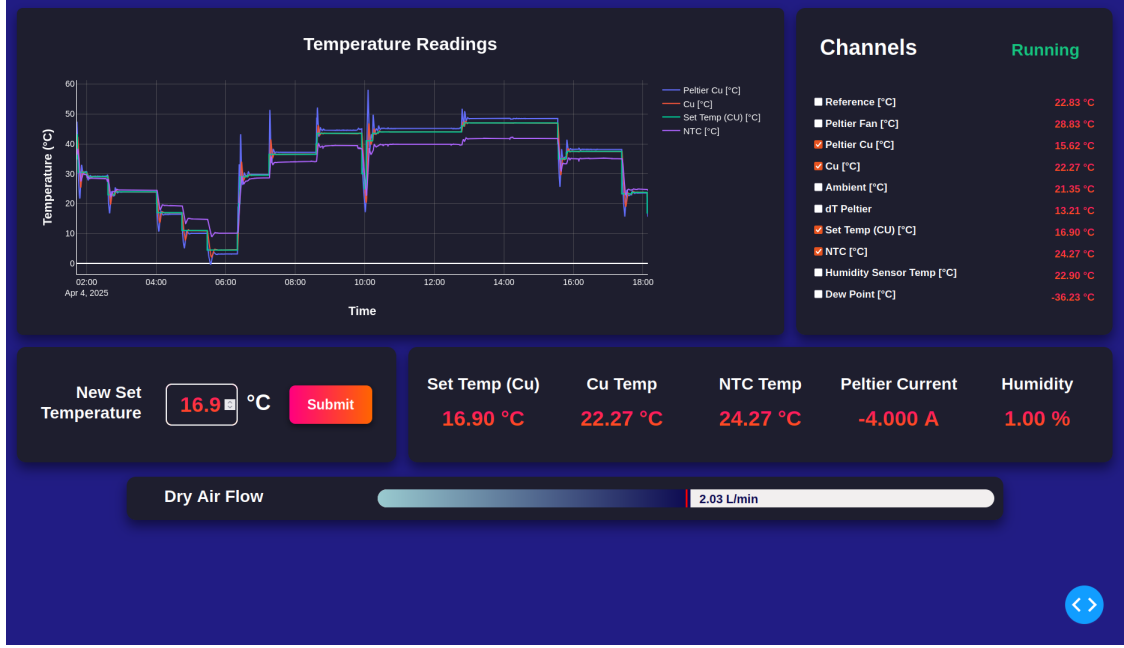


Figure 25: User interface of the temperature control system during operation, with a setpoint of 16.9°C.

5.4 Calibration

Up to this point all adjustment has targeted the copper-plate temperature, but in an actual test-beam run the parameter of interest is the chip temperature. Because a probe cannot be attached directly to the chip during beam tests, a laboratory calibration was performed to relate the copper temperature to the true chip temperature. Two thermocouples were attached to the chip, one at the center and one at the periphery. Furthermore, the on-board NTC sensor, which is the closest measurement point available during the beam test, was included in the calibration process as well. In addition to conventional temperature probes, both the leakage current and the power consumption of the chip were closely monitored, as these two parameters have a strong influence on the actual chip temperature. To simulate and control the chip's power consumption in the laboratory, either the readout frequency or the IBIAS setting can be adjusted. As a first step, the correlation between the copper temperature and the NTC temperature was analysed for several values of the Low Voltage (LV) current, as it serves as a direct indicator of the chip's power consumption. The resulting curves are shown in Figure 26. This plot shows a well-defined linear relationship between the two quantities, which remains consistent across different current settings. This makes the process very convenient, as only a simple linear function is required to estimate the appropriate copper temperature necessary to achieve a desired temperature at the NTC sensor. Specifically, the relationship can be described by

$$NTC_T = 0.79 \cdot Cu_T + 5.83C . \quad (21)$$

This expression allows for straightforward conversion from the copper plate temperature to the expected NTC temperature.

The next step is to establish the relationship between the NTC temperature and the actual chip temperature. This correlation, again evaluated for various LV current settings, is shown in Figure 27a. The linear nature of this process persists in this step as well, however, a noticeable shift between the lines appears for different LV current settings. This variation makes it necessary to account for the LV current as an additional parameter, requiring the definition of a calibration plane rather than a simple line. This relationship is illustrated in Figure 27b, where the fitted

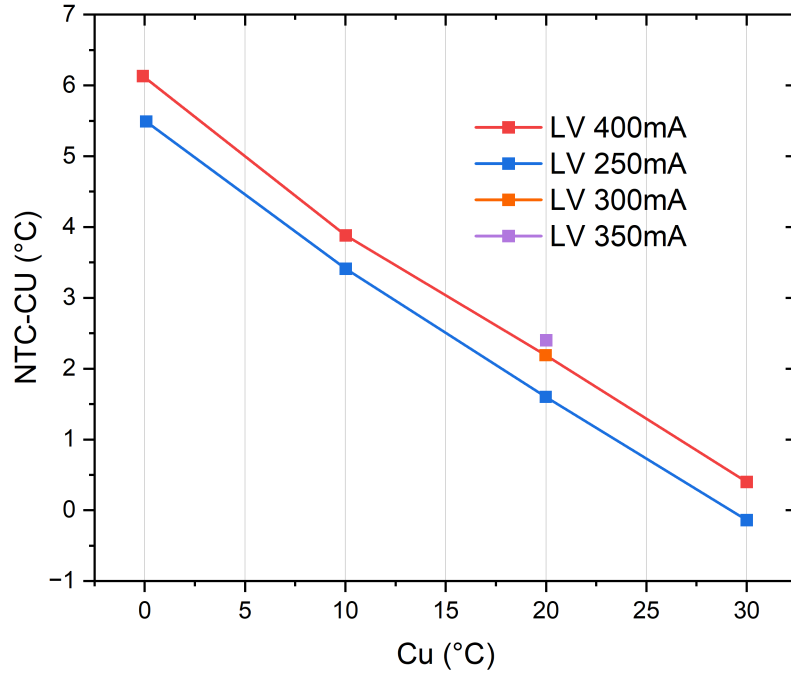
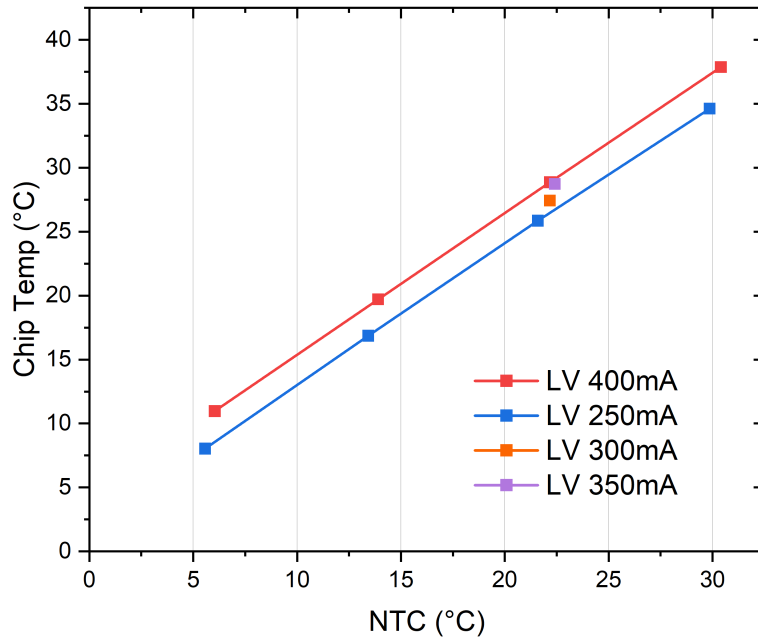


Figure 26: Calibration curves showing the relationship between copper plate temperature Cu and the delta between Cu and NTC temperature at four different LV current settings.

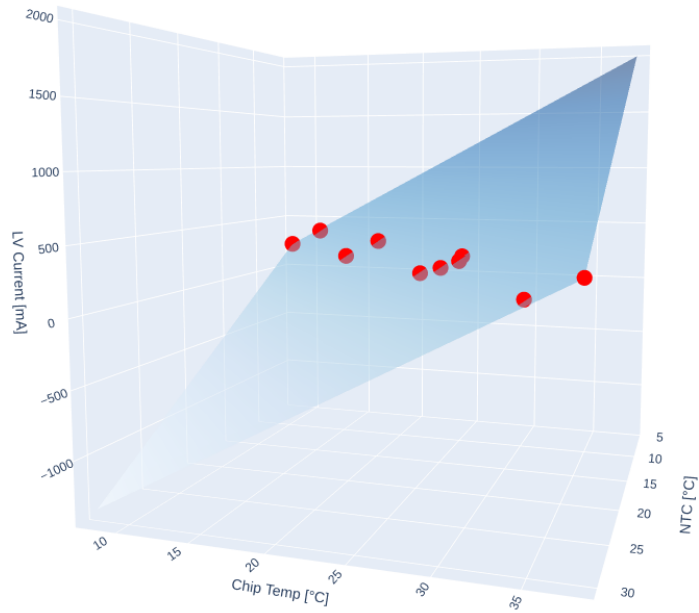
plane is described by the following equation

$$Chip-T = \frac{LV_current - 100.32 + 63.9 \cdot NTC_T}{59.18} . \quad (22)$$

With these functions and their inverses, it becomes possible to seamlessly transform the control variables into the corresponding measurement values and vice versa.



(a) Calibration curves showing the relationship between NTC temperature and chip temperature for four different LV current settings



(b) A 3D plot of all measurement points with a fitted plane

Figure 27: Plots for estimating the chip temperature from directly measurable quantities.

6 Current and Voltage Control System

In addition to monitoring and controlling the temperature, it is equally important to regulate and observe the currents and voltages applied to the chip. Alongside the LV current, which reflects the chip's power consumption, the leakage current, also referred to as HV current, must also be carefully tracked as this variable correlates strongly to the chip temperature. Furthermore, the *PWELL*, *PSUB-PWELL*, and *IFPGA* currents, along with their corresponding voltages, provide valuable diagnostic insights and should therefore be continuously displayed and recorded. Additionally, the voltages should also be precisely adjustable.

6.1 Power supply

In terms of hardware, two power supply units (PSU) were employed, the Keithley 2460 Source Measure Unit (SMU) and the Rohde Schwarz HMP4040 PSU. The SMU was used for biasing and measuring the HV and HV-Cascode frontends, as it is capable of detecting currents down to the microampere range. The PSU, on the other hand, was responsible for powering the DC frontends, supplying the and providing voltage to the *PWELL* and *PSUB/PWELL* terminals. Notably, even when the HV frontend was disabled (i.e., $HV = 0$), the SMU could still measure the leakage current flowing from *PSUB/PWELL*.

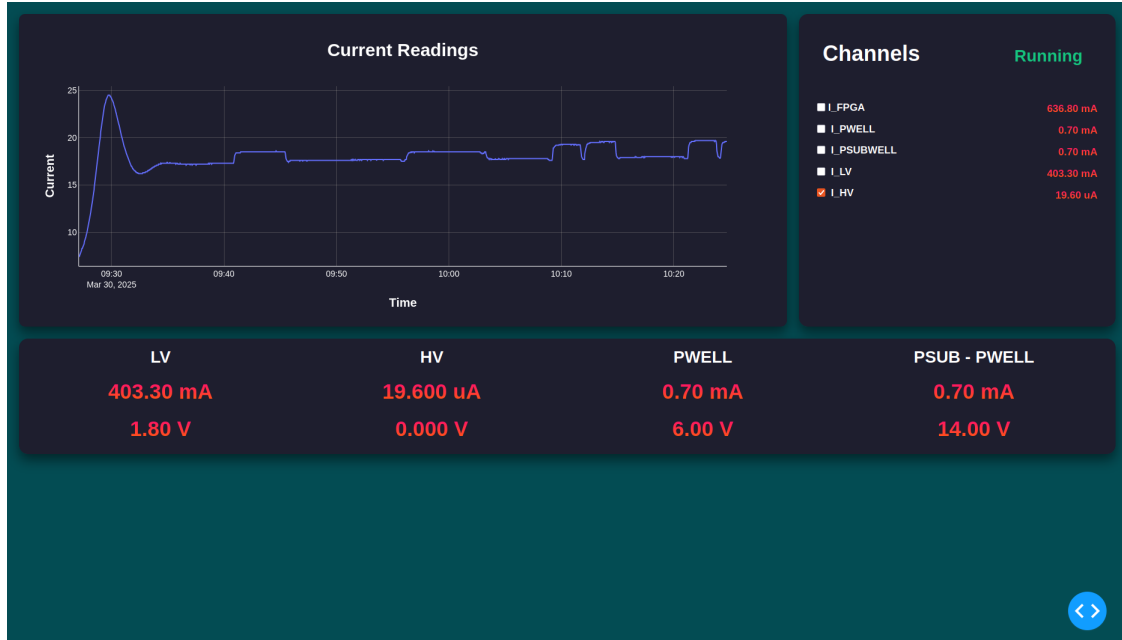


Figure 28: User interface for monitoring current and voltage parameters of the TJ-Monopix2 chip.

6.2 Software

Since both power supplies could be controlled via USB, it was decided to automate the biasing process and develop a similar UI for monitoring the various electrical parameters, as was done for the temperature control. The control was implemented using a Python script, which activated the desired frontends based on specified parameters and periodically recorded all values in a dedicated log file. This CSV file could then be used for real-time monitoring. In addition, safety features were implemented to protect the chip, both from human error and from unexpected events, by safely shutting down all components when necessary. For example, the chip biasing was restricted to specific safe voltage ranges to prevent potential breakdown. As shown in Figure 28, the UI closely resembles the temperature control interface. The top row again displays the current readings over time, while the left panel allows the user to select individual channels. The second row no longer contains an input field, as the biasing voltages are defined by the user when initiating the control script. The bottom overview panel provides live readings of the LV and HV currents and voltages, as well as the *PWELL* and *PSUB-PWELL* values.

7 Test Beam Setup

A test beam in the context of High Energy Physics refers to a designated time slot at a particle accelerator facility, used to test the functionality and performance of a chip or any other kind of sensor before it is deployed in a permanent experiment. Since only a limited number of facilities offer such test beam capabilities and demand for them is high, it is essential to optimize and streamline all tasks during the period to maximize measurement time. Modern test beam setups typically consist of a combination of standardized equipment and custom-designed components tailored to the specific DUT. In the following sections, the individual components of such a setup will be introduced.

7.1 AIDA Trigger Logic Unit

The AIDA2020 Trigger Logic Unit, or TLU, is a device used to synchronize various readout systems and provide essential timing information. It was developed as part of the AIDA-2020 project by David Cussans and Paolo Baesso from the University of Bristol [46]. The TLU is designed to simplify the setup procedure and reduce the number of individual devices and connections typically required when using solely custom-built solutions. The physical device is shown in Figure 29. The HDMI ports on the left-hand side are used to connect the DUTs, while the LEMO connectors receive incoming trigger signals. Upon receiving a trigger, the TLU issues a global trigger signal to all connected DUTs and simultaneously logs the corresponding timing information. To accommodate a variety of experimental setups, the TLU supports multiple handshake modes that define how new events are processed, what information is sent to the DUT, and how timing is managed. For the purposes of this thesis, two modes will be introduced in detail, the asynchronous EUDET mode and the synchronous AIDA mode [46].

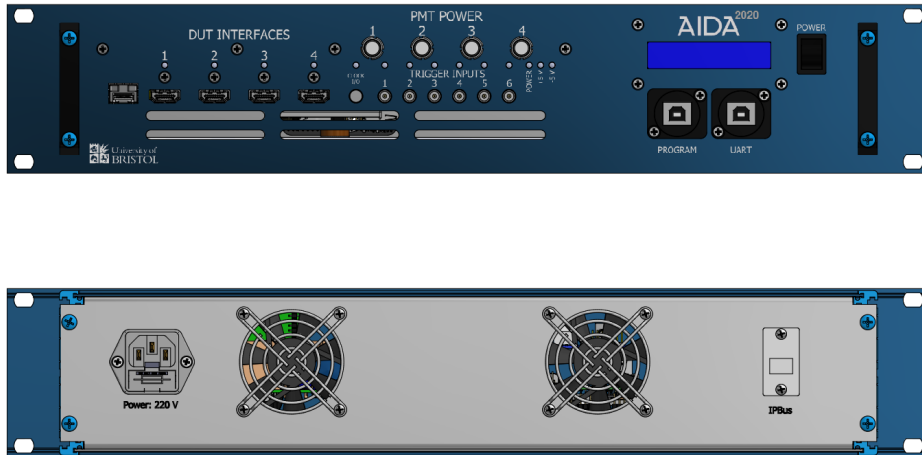


Figure 29: Front and rear views of the AIDA-2020 Trigger Logic Unit (TLU), developed as part of the AIDA-2020 project. [46]

7.1.1 EUDET mode

This mode allows the TLU clock and the DUT clock to operate asynchronously. The basic handshake procedure is illustrated in Figure 30. Upon receiving an input trigger, the TLU generates a new trigger number, a unique identifier that corresponds to a specific event and asserts the *TRIGGER* line to the DUT. The DUT then acknowledges the trigger by asserting the *DUT BUSY* line. At this point, the TLU can deassert the *TRIGGER* line and begin transmitting the trigger number by toggling the *DUT CLOCK* line.

7.1.2 AIDA mode

The AIDA mode is designed to synchronize the clocks of the TLU and the DUT, enabling event identification based on timestamps. The detailed procedure is illustrated in Figure 31. Unlike the EUDET mode, no data is exchanged between the devices, instead a one-clock-cycle-long trigger

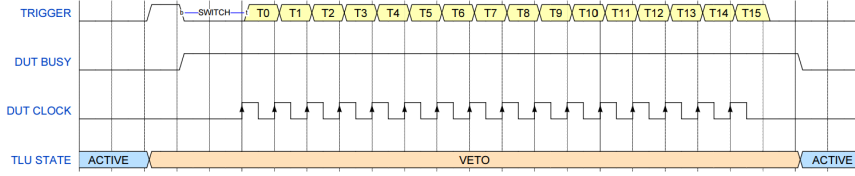


Figure 30: The asynchronous EUDET handshake mode of the AIDA TLU. [46]

signal is asserted. This requires the clocks of both the TLU and the DUT to remain synchronized, which is achieved by resetting the timestamps at the beginning of each run. In this mode, the DUT can assert the *DUT BUSY* line at any time to inform the TLU that new triggers should be temporarily ignored. This behavior can also be modified by configuring the system to ignore *BUSY* signals from specific DUTs, therefore allowing greater flexibility in the overall system configuration.

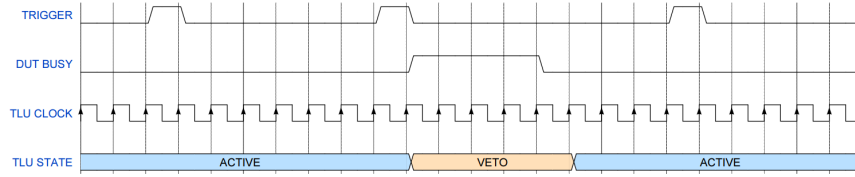


Figure 31: The synchronous AIDA handshake mode of the AIDA TLU [46]

Until now, most test beams conducted with the TJ-Monopix2 employed the older EUDET mode. However, for the purposes of this thesis, a transition was made to the more suitable AIDA mode, which is better aligned with modern applications. AIDA mode offers several advantages, including more flexible trigger handling, reduced *BUSY* downtimes since trigger numbers do not need to be transmitted and improved overall compatibility with a wider range of devices. On the TLU side, this transition required only minor adjustments to the configuration file.

7.2 Telescope

When testing a new detector, its performance is typically evaluated relative to a well-characterized reference. In the context of silicon detectors, this is done by placing the DUT inside a so-called beam telescope. This setup consists of multiple detector planes, usually four to six, arranged in series, with the DUT positioned at the center. An example of such setup is shown in Figure 32. As a particle traverses the telescope, it leaves hits in each of the tracking layers. From these hits, a particle trajectory or *track* is reconstructed. The point where this track intersects the plane of the DUT is considered the expected hit position. However, the actual recorded hit in the DUT typically deviates slightly from this position due to measurement uncertainties. The distance between the expected and actual hit positions is called the *spatial residual*. Similarly, *time residuals* describe the discrepancy between the expected and actual timing of a hit. All of these analyses assume that the particle is detected in both the telescope and the DUT. If a particle is observed in the telescope but not in the DUT, it contributes to a reduction in the measured *efficiency* of the sensor. The overall sensor efficiency is then calculated as the percentage of particles detected by the telescope that also produce a corresponding hit in the DUT.

7.3 Scintillators

In the earlier section about the TLU, it was described how this device receives triggers and forwards them to the connected devices. However, it was not yet explained where these triggers originate. The source of trigger signals can vary depending on the application, but in most test beam setups, this task is handled by scintillators. Scintillators are materials specifically designed to emit light, known as scintillation light, when they are struck by charged particles. To allow for efficient light collection, they must be optically clear. The emitted light can be detected either by a photomultiplier tube (PMT) or by more compact silicon photomultipliers (SiPMs). Both devices convert photons into electrons and with help of further electronics amplify the resulting signal until it becomes measurable by standard readout electronics. Besides scintillators, other types of

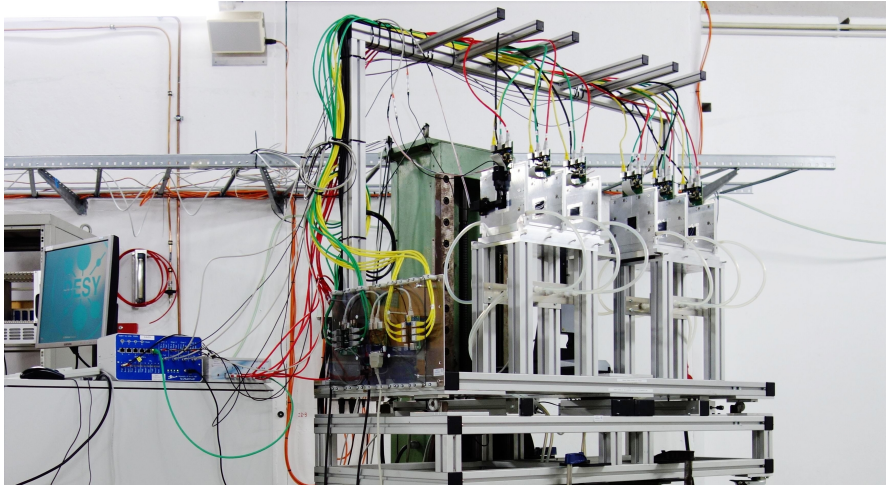


Figure 32: The DURANTA pixel beam telescope, equipped with Mimosa26 sensors, installed at DESY testbeam facility. [47]

well-characterized pixel detectors may also be used to generate trigger signals, especially when precise spatial information is required. To minimize false triggers caused by noise, it is common practice to use a coincidence logic. Signals from two or more scintillators are compared, and only if both detect a particle within a predefined time window, the TLU interprets it as a real event and issues a global trigger to all connected devices.

7.4 EUDAQ Framework

Although the TLU serves to some extent as a coordinating and control entity, its capabilities are quite limited. Tasks such as initiating data runs, managing log entries, or visualizing key information fall outside the scope of the TLU. These functions are handled by EUDAQ, a high-level DAQ software framework designed to coordinate complex test beam setups. EUDAQ is capable of managing custom hardware components, handling data streams, and synchronizing data recording across multiple subsystems. It was originally developed in 2005 by the European EUDET project "Test Beam Infrastructure" to support the development of a high-precision and highly flexible pixel beam telescope, which in turn demanded an equally versatile DAQ system [48]. For the purposes of this thesis, EUDAQ2, the second major version was used. This version incorporates numerous improvements based on years of feedback and experience gained during various test beam campaigns.

The structure of EUDAQ can be categorized as centralized, with distributed processes running on different machines and communicating via the TCP/IP protocol. These individual processes, referred to as *Producers*, are responsible for interfacing with hardware components such as detectors, sensors, power supplies or motor stages as well as for sending and receiving data to and from the central component of the EUDAQ architecture, the *Run Control*. In addition to the command channel used for system control, EUDAQ also implements dedicated data and log channels for transmitting event information and recording system messages, respectively [48]. The run control itself features a user-friendly graphical interface, allowing users to manage the entire setup with ease. The control logic of EUDAQ is built around a state machine, consisting of a series of well-defined system states:

- **Uninitialised** – Initial state after EUDAQ starts and producers connect.
- **Initialised** – All components have completed the initialization process.
- **Configured** – All components have been successfully configured.
- **Running** – Data acquisition is in progress.
- **Stopped** – Data acquisition has been halted.
- **Error** – An error has occurred; the system may require a reset or intervention.

A user can easily transition through the states using simple buttons, each triggering predefined actions within the corresponding producers. These actions also affect other components of the EUDAQ ecosystem, such as the *Data Collectors*, *Monitors*, and *Log Collectors*. The global state of the system only changes once all components confirm that they have successfully completed the defined actions for the new state. This same mechanism applies to errors where if a single producer reports a problem, the run control will receive this information and change the global state to *Error*, thereby pausing data acquisition and recording across all components. The full architecture, including connections and dependencies, is illustrated in Figure 33, where these and many other connections are clearly visible.

The *Initialised* and *Configured* states are of particular importance, as this is when customizable initialization and configuration files are read and the relevant information is distributed to the respective producers. This shifts the fine-tuning of the entire setup from individual program files to a centralized configuration, where all parameters are organized in a structured format. The number of parameters can be easily expanded or reduced by defining the corresponding actions on the producer side. Data taking is organized into so-called *Runs*, which are continuous periods of

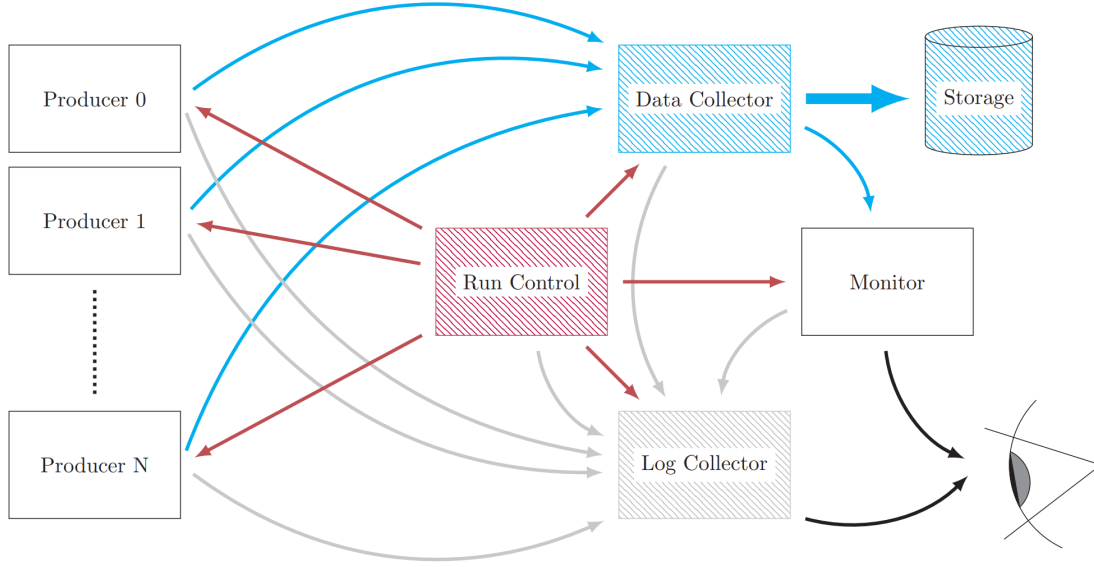


Figure 33: Architecture of the EUDAQ framework, showing how Run Control coordinates multiple Producers, Data Collectors, Monitoring and Logging components during data acquisition. [48]

acquisition with variable durations. Every run is further divided into a series of *Events*, each representing all data collected by every component in response to a single trigger [48]. In addition to the raw data, each event includes metadata such as the run number, trigger number, and relevant status information.

One of the key components that needed to be developed prior to the test beam campaigns was a new producer for the TJ-Monopix2 chip. Although the chip already comes with a fully functional DAQ system, integrating it into the EUDAQ architecture required a dedicated software interface. This producer was based on the *scan_ext_trigger* script, which is designed to respond to external triggers from the TLU, ensuring that data is recorded in synchronization with other components such as the beam telescope and scintillators. The producer accepts the following parameters which need to be specified in the EUDAQ configuration script:

- **start_column** – Starting column index (range: 0 to 512).
- **stop_column** – Ending column index (range: 0 to 512).
- **start_row** – Starting row index (range: 0 to 512).
- **stop_row** – Ending row index (range: 0 to 512).
- **IBIAS** – Bias current setting for the analog front-end.
- **VCLIP** – Voltage threshold for output clipping.

- `ICASN` – Current for the input cascode transistor
- `VRESET` – Reset voltage level for the pixel preamplifier.
- `chip_sn` – Serial number of the chip, used for identification.
- `chip_config_file` – Path to the chip configuration file
- `disable_bcid` – Disables usage of the bunch crossing ID in the data stream.
- `daqboard_ip` – IP address of the DAQ board connected to the chip.
- `output_directory` – Directory where the acquired data will be saved.
- `handshake_mode` – Defines if the EUDET or the AIDA handshake mode is used.
- `scan_timeout` – Timeout (in seconds) for scan operations; 0 disables the timeout.
- `max_triggers` – Maximum number of triggers before stopping the scan; 0 for unlimited.

An important remark about this producer is that once a run has been started and subsequently stopped, it cannot be restarted directly. The configuration process must be re-executed before initiating a new run. This design choice resolves a number of inconsistencies that can otherwise arise, such as mismatched states or incomplete hardware resets.

8 Laboratory Measurements

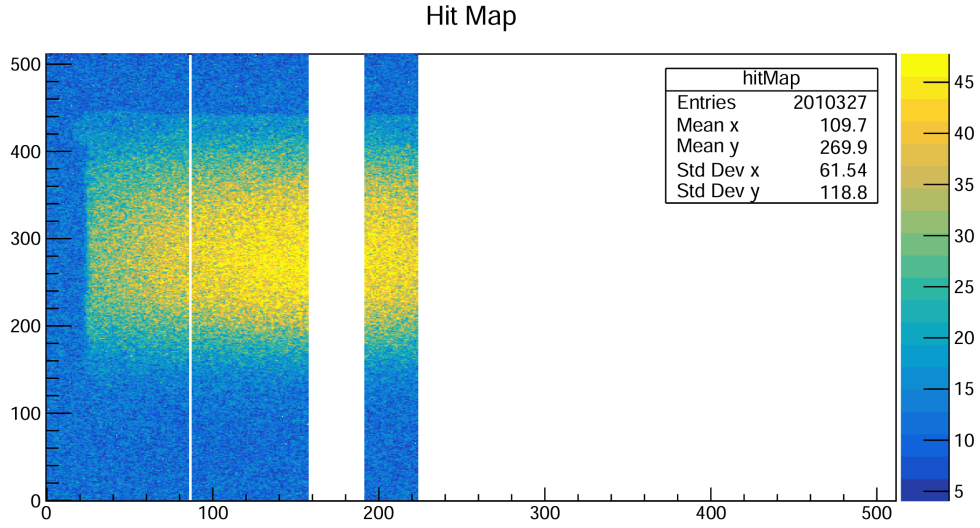
Prior to the beam test campaigns, the entire setup was thoroughly evaluated in a laboratory environment. The main objectives were to verify the compatibility of all devices when operating in AIDA handshake mode, investigate the resulting time correlation structures, and exploring higher readout speeds. The initial test configuration included the AIDA2020 TLU, the TJ-Monopix2 chip, the BDAQ board, a scintillator equipped with photomultipliers, a Sr-90 radioactive source, and two PCs, one running the Run Control and the other operating the TJ-Monopix2 EUDAQ producer. In the second phase of testing, an additional chip was introduced to study the correlation between two TJ-Monopix2 sensors. These were arranged such that radiation from the Sr-90 source passed through the first chip before reaching the scintillator and photomultipliers. Using this setup, a pixel hit rate of approximately 80 kHz was achieved.

8.1 AIDA mode and time correlation

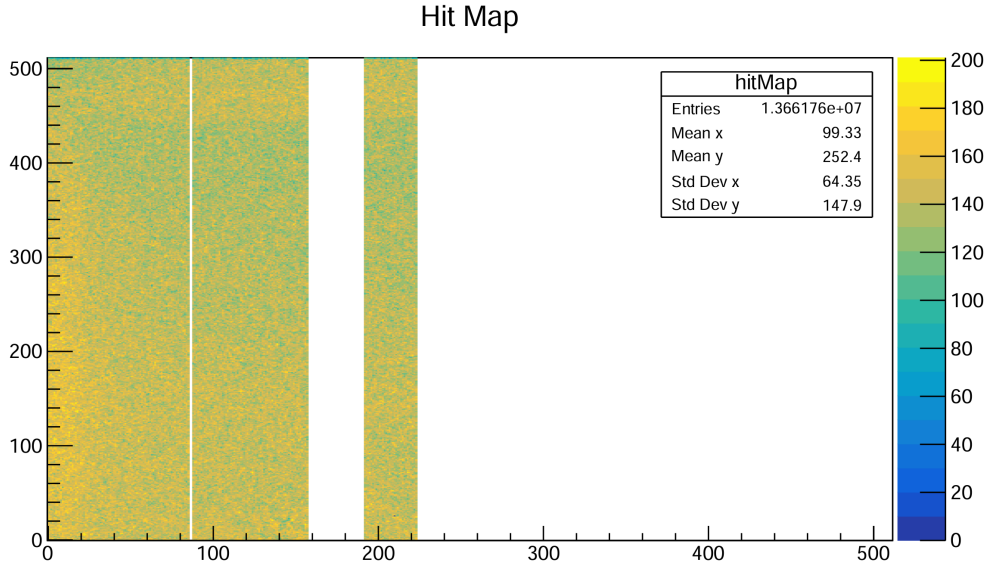
One of the initial goals was to demonstrate the full functionality of the setup using the AIDA mode instead of the EUDET mode. This transition required only minor adjustments to both the TLU configuration and the TJ-Monopix2 DAQ system. After initial tuning and configuration, the first datasets were successfully recorded. The data were then analysed using Corryvreckan [49], a modern test beam analysis framework developed as a successor to tools like EU Telescope [50] and Proteus [51]. Corryvreckan was designed to address the challenges of contemporary research and development in advanced pixel detectors. It features a modular architecture focused on flexibility and speed, while also lowering the learning curve to make it accessible to newcomers. The resulting hitmap for the chip with the serial number W08R19 is shown in Figure 34a. The data was taken using the standard DC frontend, with a few disabled rows due to prior damage and the chip was biased with a voltage of 6 V. In this configuration, event definition was handled via the scintillators and thus triggered by the TLU. The relatively small-sized scintillator (5 mm) is visible at the centre of the plot compared to the large chip area. While the edges appear somewhat diffuse due to particle scattering in the chip, the clearly defined outer boundary is caused by the well absorbing PCB. Figure 34b displays the same dataset as the left panel, but with event definition now based on the TJ-Monopix2 chip itself. In this case, the hit distribution appears significantly more uniform, with only a slight reduction in intensity observed above the scintillator area. This reduction could be attributed to the scintillator’s enhanced absorption capabilities, which may suppress backscattering or internal reflections.

Figure 36a illustrates the time correlation between the scintillator and the pixel detector, using scintillator-based event definition. To enable Corryvreckan’s correlation module to generate this plot for such setup, a workaround was necessary where the scintillator or better the TLU had to be defined as a single-pixel detector. The plot reveals a clear peak around the 3.5 μ s mark, corresponding to the total delay between a hit registered by the scintillator and its processing and readout by the pixel detector. Additionally, a secondary peak appears close to the main one. This feature likely relates to the ToT distribution, shown in Figure 36b. The observed peak splitting is most likely a result of the mean cluster size, which averages around 1.7. This suggests that charge sharing between adjacent pixels is common, with one pixel typically collecting the majority of the charge and the neighbouring one registering only a partial signal. To further support this hypothesis, in the next measurement cycle the *VCLIP* parameter was adjusted. *VCLIP* directly influences the input stage of the charge-sensitive amplifier in each pixel and thus affects the ToT distribution. In these experiments, it was observed that changes in the ToT spectrum were accompanied by corresponding shifts in the time correlation distributions.

In the following phase, the setup was extended by incorporating an additional TJ-Monopix2 sensor (W14R18), thereby creating a the most primitive form of a beam telescope. Upon analysing the time correlation data, a similar distribution was observed when each chip was compared to the TLU as a reference. However, a distinct behavior emerged when one chip was used as a reference for the other. This correlation is shown in Figure 35, highlighting the relative delay in data extraction and readout between the two sensors in response to a single particle hit. This observation led to the idea of manipulating the timing of the *freeze* and *readout* signals, which will be introduced and discussed in detail in the next chapter.



(a) TLU as time reference



(b) TJ-Monopix2 as time reference

Figure 34: Pixel hit map of the DC frontend of the TJ-Monopix2 sensor

8.2 Optimization of readout timing parameters

In the second phase of laboratory testing, efforts were made to reduce the overall readout delay, aiming to enable more efficient data collection during test beam operations. The cumulative readout overhead was measured to be approximately $3.5\text{ }\mu\text{s}$, which is significant given the 25 ns clock cycle duration. Initially, all timing parameters were conservatively defined to ensure system stability. The default timing values are listed below:

- FREEZE_DELAY= 40 ($1\text{ }\mu\text{s}$)
- READ_DELAY = 40 ($1\text{ }\mu\text{s}$)
- LOAD_CONF= 39 + 40 + 40 ($\sim 3\text{ }\mu\text{s}$)
- FREEZE_STOP_CONF= 40 + 40 + 40 ($3\text{ }\mu\text{s}$)
- STOP_CONF= 40 + 40 + 40 ($3\text{ }\mu\text{s}$)

These settings produced the time correlation distribution shown in Figure 37a. By gradually reducing the timing parameters, optimal values were identified that preserved the integrity of the time correlation structure while enabling a more efficient readout process. This optimization led to a reduction in the total readout duration to $1.1\text{ }\mu\text{s}$ which is an improvement of nearly

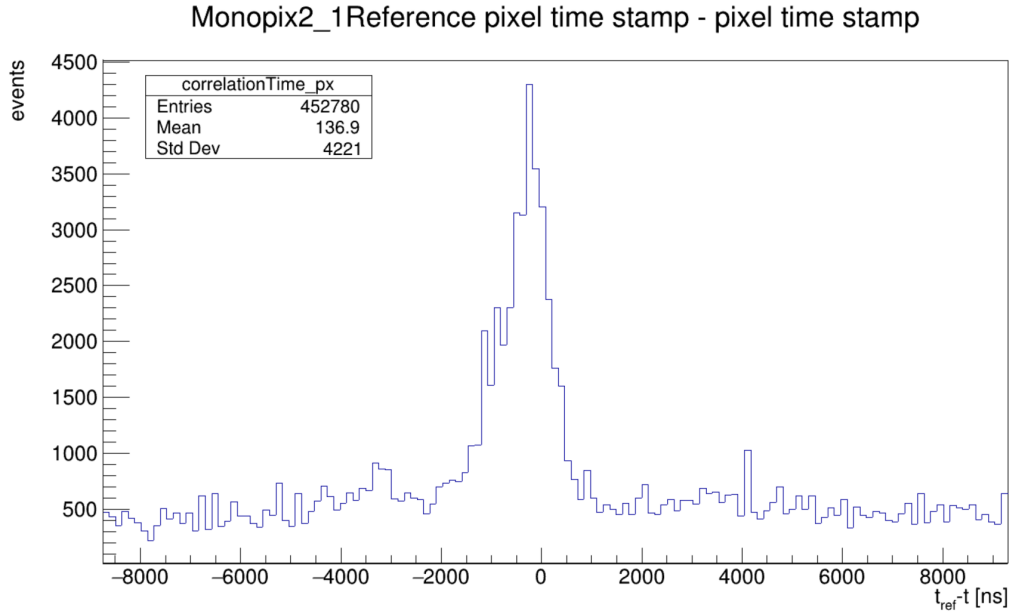
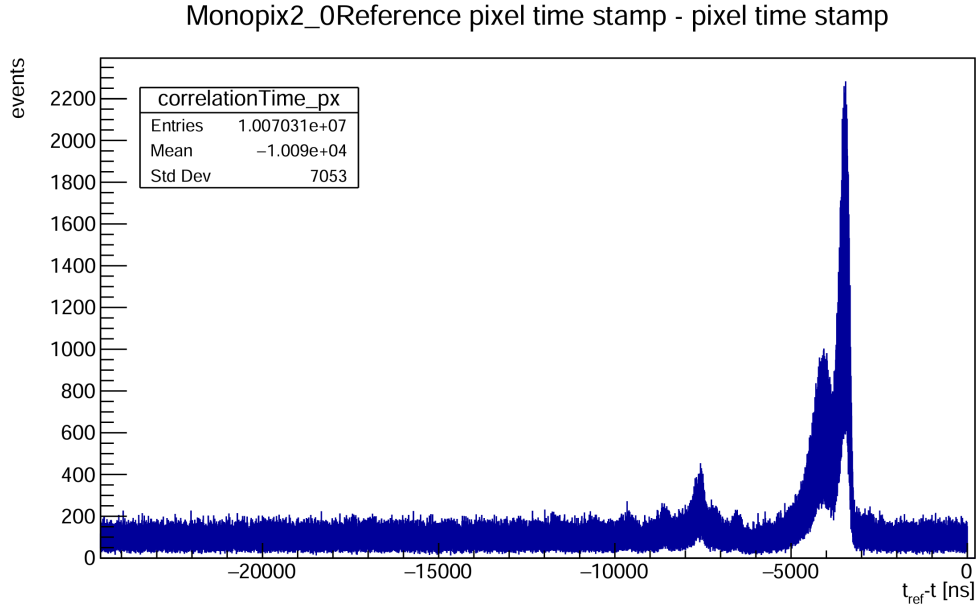


Figure 35: Time correlation between two TJ-Monopix2 sensors measured in a laboratory setup using a radioactive Sr90 source

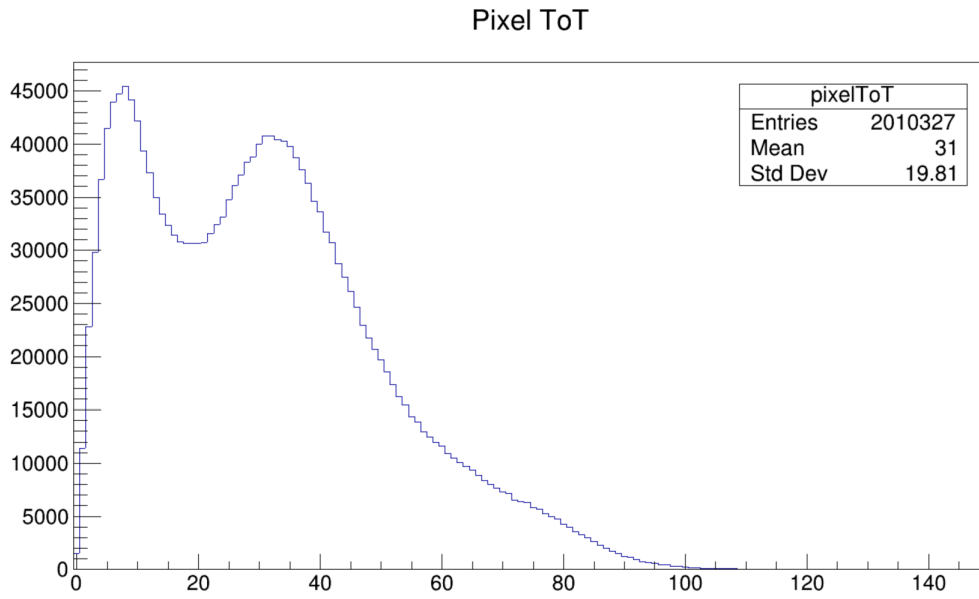
2.5 μ s compared to the default configuration. The results obtained with the accelerated readout are displayed in Figure 37b. This configuration was selected as the new lower limit, as further reductions began to introduce noticeable deviations from the reference structure obtained with the default settings. The final optimized timing parameters are listed below:

- FREEZE_DELAY = 10 (250 ns)
- READ_DELAY = 10 (250 ns)
- LOAD_CONF = 10 + 10 + 10 (750 ns)
- FREEZE_STOP_CONF = 11 + 10 + 10 (750 ns)
- STOP_CONF = 10 + 10 + 10 (750 ns)

This appears to be a simple yet promising modification that could enhance the chip's durability even in high-flux environments, and therefore calls for further investigation. Unfortunately, due to the time constraints imposed by other measurements, it was not possible to test this approach during the final test beam at DESY.

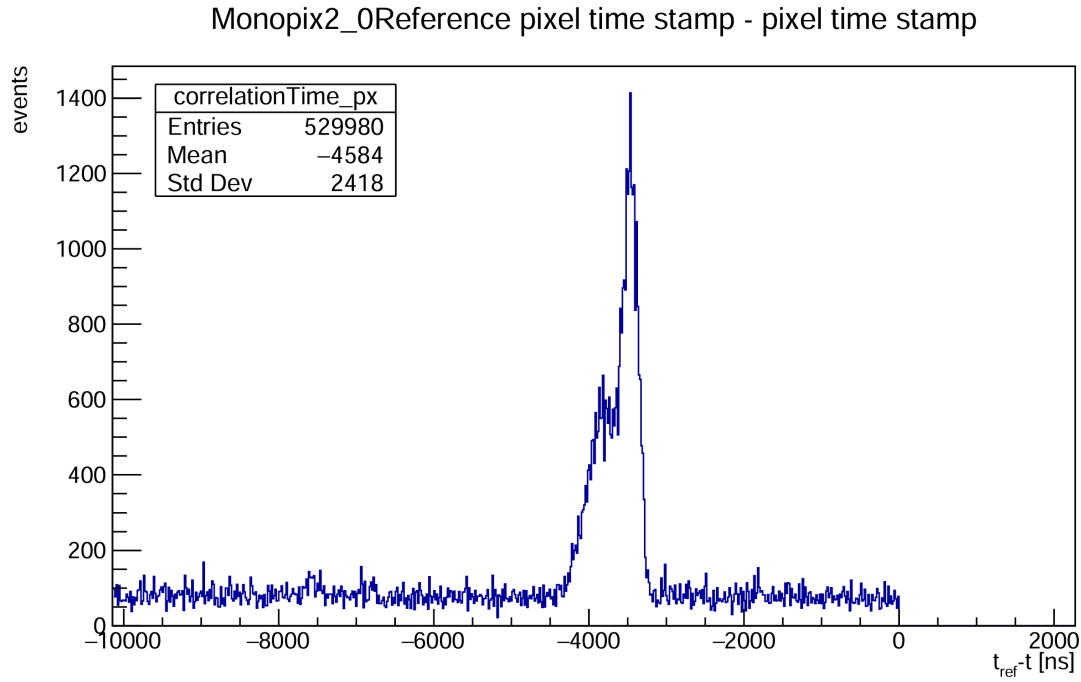


(a) Time correlation between TJ-Monopix2 (W08R19) pixel hits and the scintillator reference signal, with the TLU as reference.

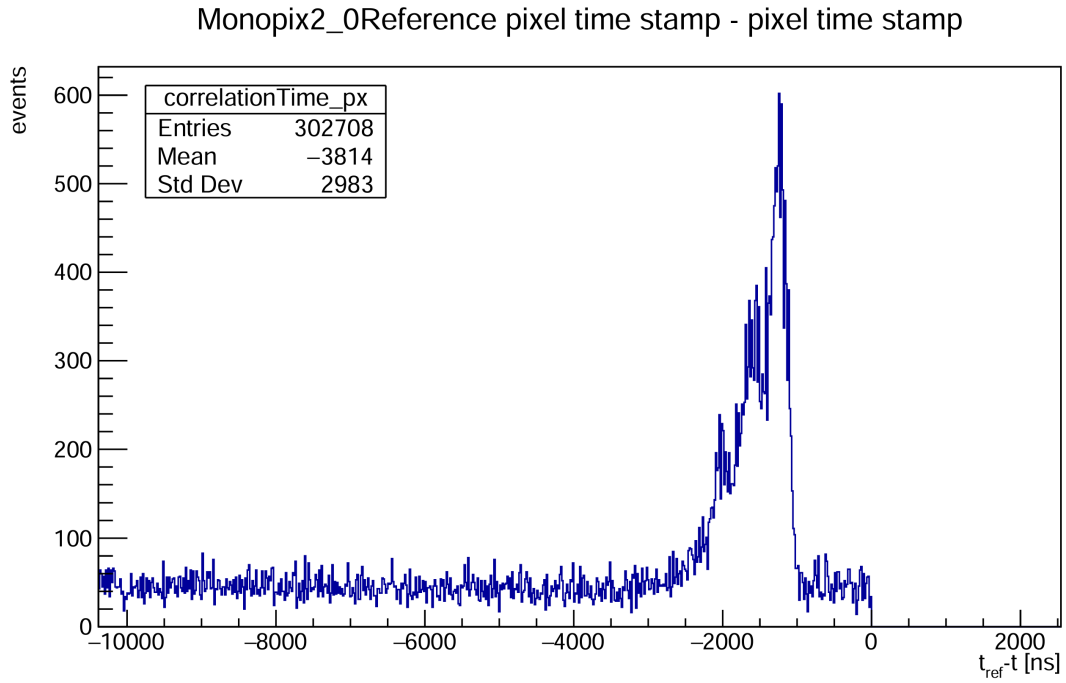


(b) Time-over-Threshold (ToT) distribution of pixel hits

Figure 36: Laboratory test analysis of a high-statistics run of TJ-Monopix2 operated with the TLU in AIDA mode.



(a) With default readout timing configuration



(b) With the shortest feasible readout timing configuration

Figure 37: Time correlation between TJ-Monopix2 (W14R18) pixel hits and the scintillator reference signal.

9 Test beam MedAustron

The second phase of preparations for the upcoming test beam campaign at DESY consisted of testing the setup at MedAustron, a particle therapy accelerator center located in Wiener Neustadt near Vienna [52]. A schematic overview of the entire complex including the synchrotron, its distribution lines, and the associated clinical stations is shown in Figure 38. At the center of this facility stands a particle accelerator capable of accelerating protons to 800 MeV for scientific purposes and carbon ions to 400 MeV u^{-1} for clinical applications. The flux rates used during clinical treatments are too high for detector physics applications, therefore specialized *Low Flux* modes were developed in collaboration with HEPHY. Currently the Low Flux mode is further divided into four separate operational modes: *Low Flux Very Low*, *Low Flux Low*, *Low Flux Medium*, and *Low Flux High*, with even the highest of these being significantly lower than clinical intensities. The repetition rate for these beams is approximately 1Hz.



Figure 38: Schematic model of the MedAustron cancer treatment and experimental facility in Wiener Neustadt, Austria. [53]

9.1 Setup

The setup used in this test beam included two non-irradiated TJ-Monopix2 sensors, two scintillators, and a Silicon Strip Detector (SSD) beam telescope placed directly in the beam trajectory. The SSD beam telescope was developed and tested by Felix Ulrich-Pur as part of his master's thesis, which focused on the development of a proton computer tomography setup [54]. The components were aligned along the beam trajectory as illustrated in Figure 39, with system control and power supplied by the AIDA2020 TLU, two BDAQ boards, and an HMP4040 PSU. The primary objective of this test beam was to validate the setup in a real particle accelerator environment and benchmarking its performance while also evaluating the newly introduced fast readout option. Two non-irradiated chips, with serial numbers W02R01 and W14R18, were selected, each configured with the HV frontend, as both had shown stable performance in previous test beams. Following preliminary runs, the first complete run was carried out under standard conditions: low-flux-low intensity mode with an 800 MeV proton beam, default readout settings, and a bias voltage of 20 V, in line with previous test configurations.

9.2 Analysis

Compared to the laboratory tests, the analysis workflow becomes slightly more complex as the alignment within the telescope must now be closely considered. Information such as position, orientation, material budget, and other necessary details for each plane are stored in a geometry file following Corryvreckan's defined structure. While the basic positions along the beam direction can be measured manually, fine alignment of the remaining axes is performed computationally. This alignment process typically consists of two steps, an initial pre-alignment based on approximate positions and orientations, followed by a more precise and computationally intensive fine-alignment procedure, which ultimately produces the final geometry used for data analysis. For this purpose,

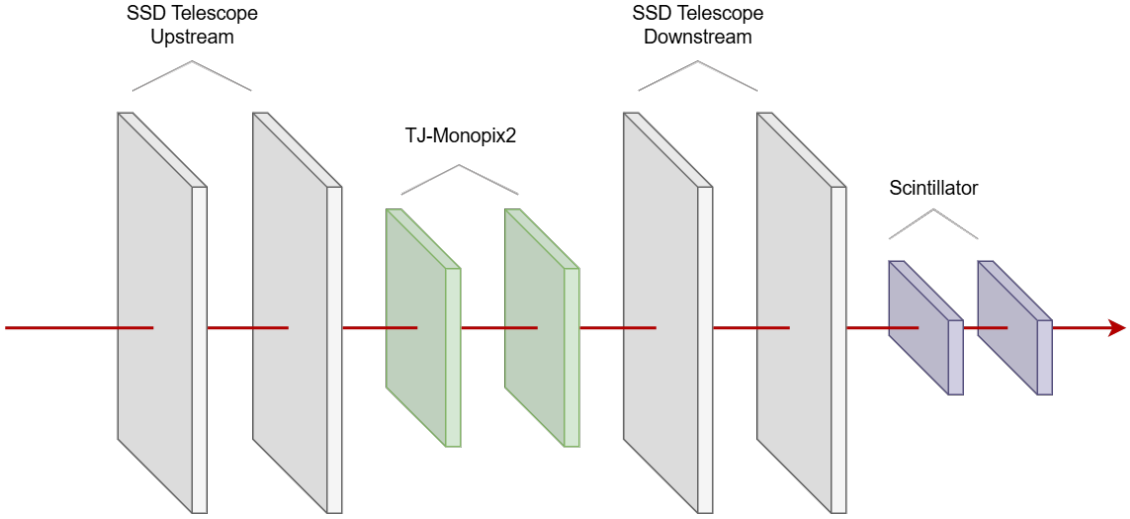


Figure 39: Schematic view of the setup during the MedAustron test beam

the standard *Prealignment* module and the iterative *AlignmentMillepede* module were employed. Additionally, to obtain meaningful results for certain observables, such as efficiency, a masking file is required. This file specifies which columns, rows, or individual pixels should be excluded from the analysis which is for example necessary if only a specific frontend was active during measurements or when noisy pixels, rows, or columns are present. In this particular case, the entire DC frontend was masked, along with a broken double column between the two HV flavors and a few misfiring pixels at the edge of the active area.

To calculate the chip efficiency, a so-called *Tracking* process is required, which can be implemented using the *Tracking4D* module in Corryvreckin. This module operates by linking hit clusters from the first and last planes to form initially straight-line trajectories, which are then readjusted and broken down into smaller liner segments to incorporate hits from the intermediate planes. The procedure is constrained by configurable spatial and timing windows, also referred to as spatial and time cuts. If a track is formed successfully, it is then checked for a corresponding hit in the DUT. When a hit falls within the allowed residual window, it is considered as an successful detection and contributes to the overall detector efficiency. These margins, often referred to as residuals both in X and Y direction, are key indicators of the sensor's overall spatial resolution. The residual distributions for the first standard run were analyzed and are presented in Figures 40c and 40d. The unbiased efficiency, meaning that the DUT was excluded from the track construction procedure, was found to be $97.58 (\pm 0.09)\%$ for the W02R01 chip and $96.67 (\pm 0.11)\%$ for W14R18. In addition to the overall efficiency, a in-pixel efficiency map, shown in Figure 40a and 40b, was generated to illustrate how detection capability varies across the area of an individual pixel. It can be seen that the efficiency around the pixel edges is reduced, as expected. This phenomenon arises due to several factors, including a longer drift path that increases the probability of recombination and trapping, weaker electric fields and charge sharing between neighboring pixels, which can fragment the signal into sub-threshold components.

Furthermore, the detector's spatial resolution can be estimated from those results. An efficient approach, as described by Alexopoulos et al. [55], is to compute both the fully biased and completely unbiased spatial resolutions and then calculate their geometric mean as shown in this formula [55]:

$$\sqrt{\sigma_{biased} \cdot \sigma_{unbiased}} \quad (23)$$

thus providing a realistic estimate of the DUT resolution. This method yields better results by balancing the overestimation caused by the biased calculation while also correcting the underestimation from the fully unbiased evaluation. The biased and unbiased spatial resolutions are calculated by truncating the residuals distribution to the innermost 99% and then computing the Root Mean Squared (RMS) value [56]. The resulting values obtained using this method are presented in Table 3 while a visual comparison of the residuals is shown in Figure 41.

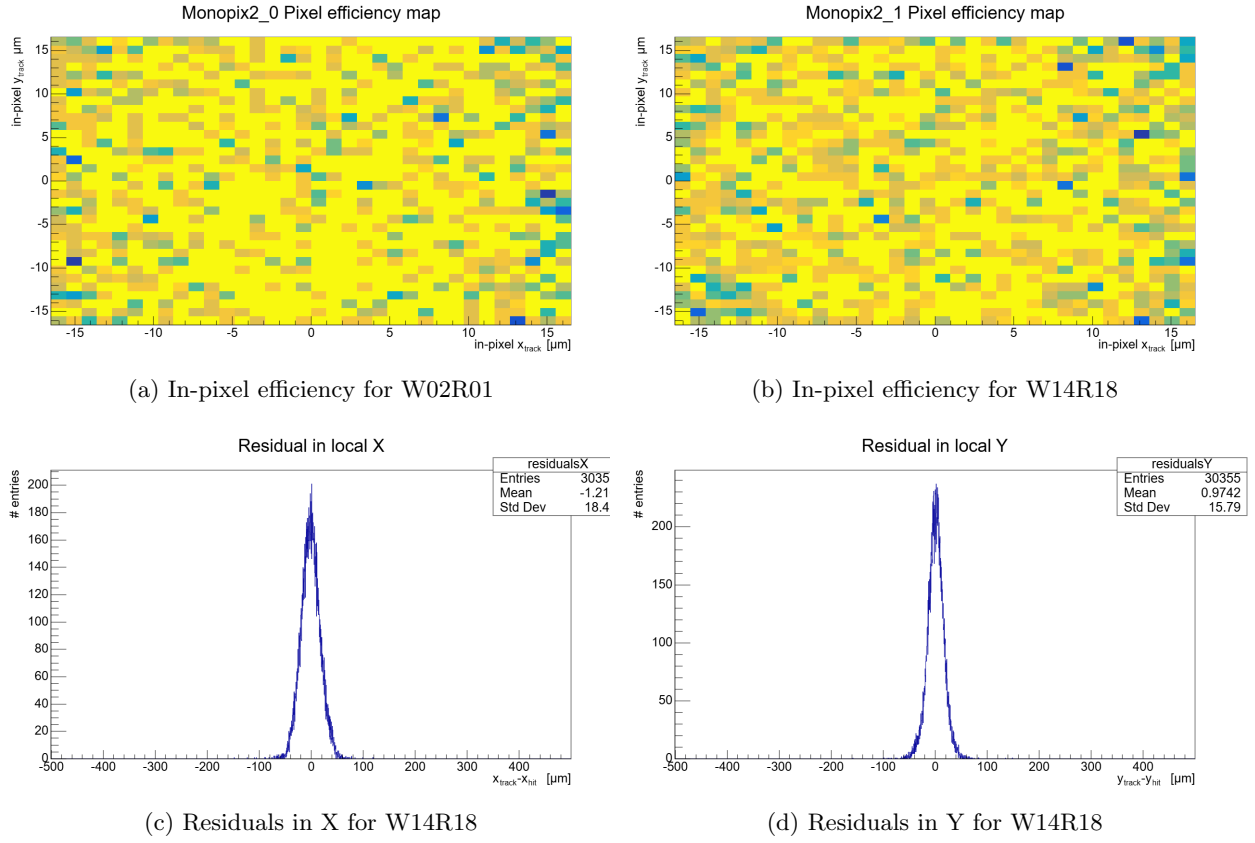


Figure 40: In-pixel Efficiency and Residuals recorded during the initial testing run at the MedAustron test beam

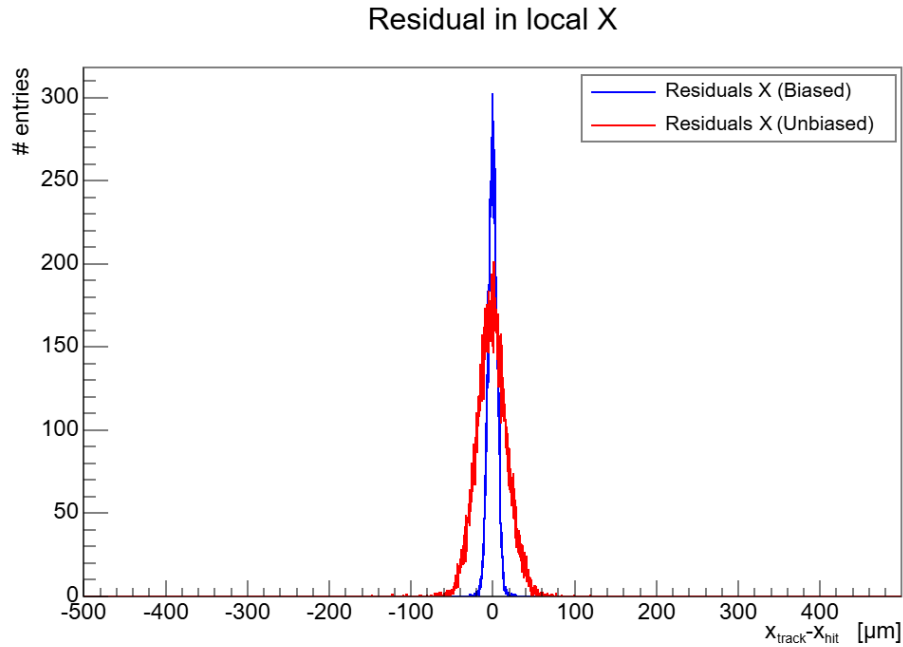


Figure 41: Comparison between the biased and unbiased residuals in X direction for the W02R01 sensor

These calculations can be compared to the approximation introduced in equation 8. Using this formula and the pixel pitch of $33.04 \mu\text{m}$ the estimate for the binary resolution is $9.54 \mu\text{m}$ which is in good agreement with the measured results. Similar results have been found by other researchers, such as in the PhD thesis of C. Bepin who reports a spatial resolution of $9.7 \mu\text{m}$ for the normal frontend and $8.7 \mu\text{m}$ for the cascode frontend on epitaxial silicon [38]. At this point, it should be

W02R01	X-Axis	Y-Axis
Unbiased Residuals	$16.89 \pm 0.086 \mu\text{m}$	$13.46 \pm 0.064 \mu\text{m}$
Biased Residuals	$5.14 \pm 0.011 \mu\text{m}$	$5.77 \pm 0.012 \mu\text{m}$
Geometric Mean	$9.32 \pm 0.051 \mu\text{m}$	$8.81 \pm 0.046 \mu\text{m}$

(a) W02R01

W14R18	X-Axis	Y-Axis
Unbiased Residuals	$18.07 \pm 0.092 \mu\text{m}$	$14.6 \pm 0.073 \mu\text{m}$
Biased Residuals	$5.43 \pm 0.012 \mu\text{m}$	$6.05 \pm 0.013 \mu\text{m}$
Geometric Mean	$9.91 \pm 0.055 \mu\text{m}$	$9.4 \pm 0.051 \mu\text{m}$

(b) W14R18

Table 3: Comparison of RMS values for biased and unbiased residuals and the corresponding spatial resolution estimates for the W02R01 and W14R18 sensors.

noted that based on prior experience, the resolution of TJ-Monopix2 in the x and y directions is expected to be the same. Therefore, the slight offset can be with high probability attributed to a discrepancy in the resolution of the beam telescope.

It should be noted, however, that the theoretical resolution, or the resolution achievable at higher-energy accelerators, cannot be reached in this setup. This limitation arises from the relatively low beam energy of only 800 MeV, which makes the particles significantly more susceptible to scattering processes. When neglecting the more complex effects of spin and screening, these inelastic collisions are generally described by the well-known Rutherford formula [57].

$$\frac{d\sigma}{d\Omega} = z_2^2 z_1^2 r_e^2 \frac{(m_e c / \beta p)^2}{4 \sin^4(\theta/2)}. \quad (24)$$

This equation must be modified, however, when multiple scattering processes are expected, as is the case here. Under these conditions, the particle path follows a seemingly random zigzag trajectory, which can be best described by observing the cumulative effect of numerous small-angle scatterings [57]. This results in an overall deflection of the particle from the initial trajectory. Such statistical effects are far from trivial and are most accurately studied using advanced simulation tools such as the Allpix Squared framework [58]. Performing such calculation is beyond the scope of this thesis and would only introduce a relatively small correction, leaving the current results largely valid.

The timing correlation data structure appears very similar to that observed during laboratory testing, but with lower noise and without additional peaks. This is illustrated in Figure 42a, which also includes the now available spatial correlations in Figure 42b and 42c. These correlations are obtained by comparing the pixel hits from the DUT with those from the reference plane and determining whether a clear association exists. These features are clearly defined and centered at the origin, with a low noise background. The results confirm that the system is operating in synchronization and that no obvious timing issues are visible. Following this run, additional data was recorded with varying readout speeds. The adjustments were applied in two steps. First, an intermediate reduction in timing delay was introduced with the following values:

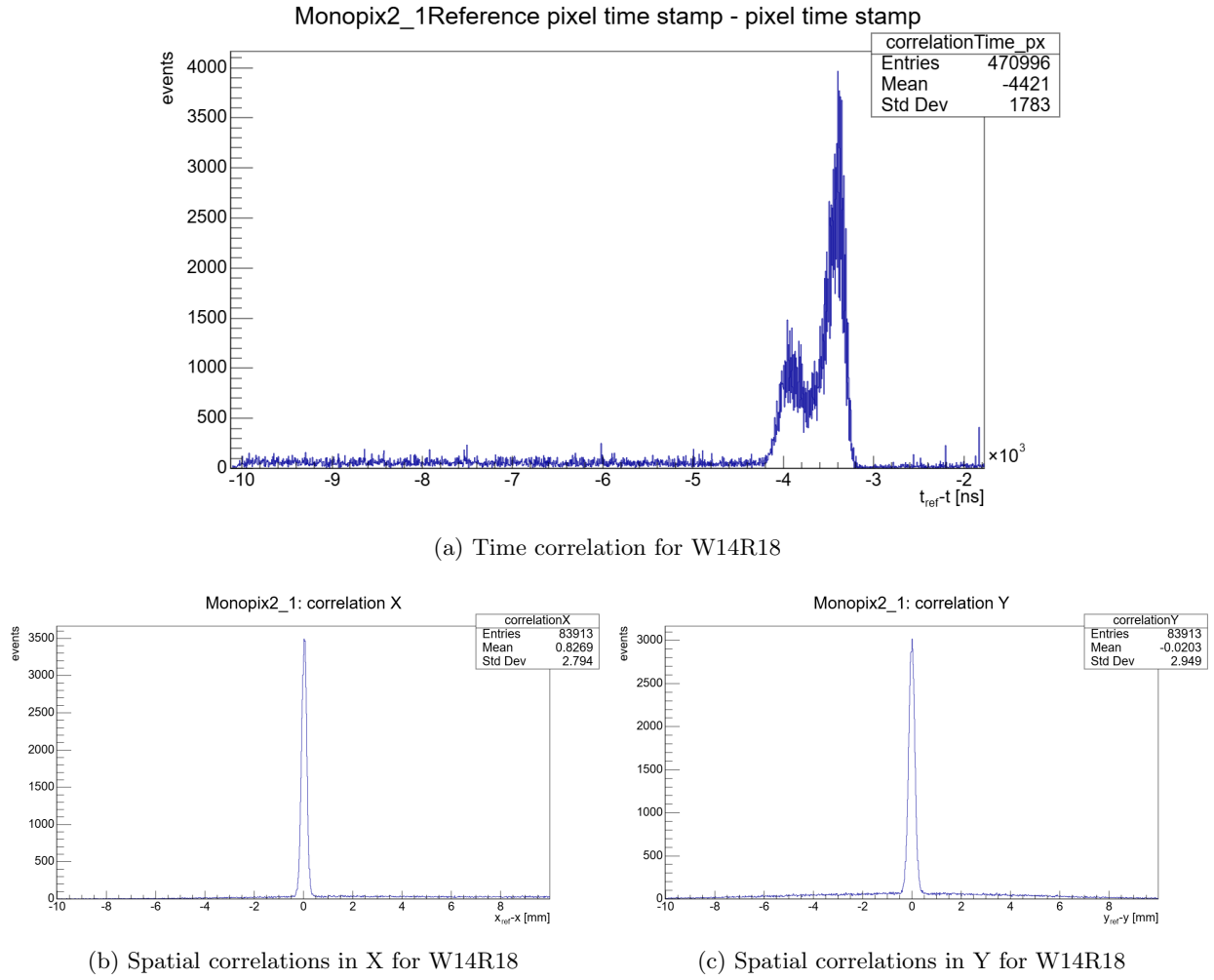


Figure 42: Different Correlations plots obtained for the W14R18 sensor

- FREEZE_DELAY= 20 (500 ns)
- READ_DELAY = 20 (500 ns)
- LOAD_CONF= 20 + 20 + 20 (1.5 μ s)
- FREEZE_STOP_CONF= 21 + 20 + 20 (1.5 μ s)
- STOP_CONF= 20 + 20 + 20 (1.5 μ s)

This adjustment shifted the peak by approximately 1.5 μ s, as shown in Figure 43 (green curve). Apart from this shift, the overall shape of the curve remained essentially unchanged. In the subsequent run, the settings were tuned to the fastest configuration that still ensured reliable operation, as determined during laboratory experiments:

- FREEZE_DELAY= 2 (50 ns)
- READ_DELAY = 2 (50 ns)
- LOAD_CONF= 10 + 2 + 2 (350 ns)
- FREEZE_STOP_CONF= 11 + 2 + 2 (375 ns)
- STOP_CONF= 10 + 2 + 2 (350 ns)

The resulting data, shown in Figure 43 (blue curve), exhibits a slightly reshaped peak shifted by an additional 1.1 μ s. In terms of efficiency, there is virtually no difference as the minor variations can be attributed to statistical uncertainties. The results are summarized in Table 4. The spatial resolution was evaluated using the same method as before, but limited to a single sensor, as the results were found to correlate closely with those of the other chip. The individual components

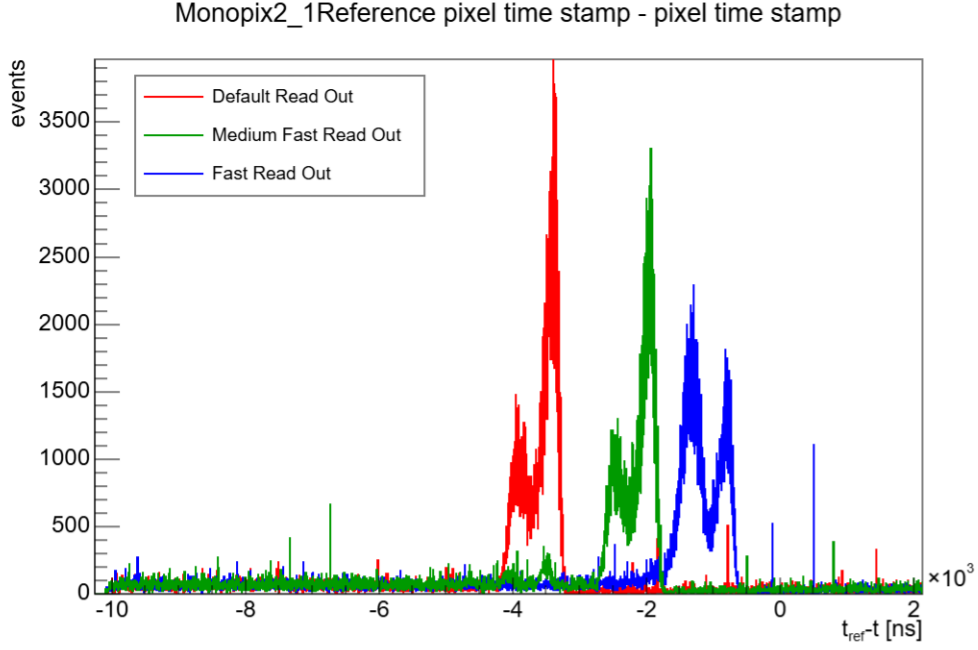


Figure 43: Comparison of the impact of default, medium, and fast readout settings on the timing correlation for sensor W14R18

	W02R01	W14R18
Default Read Out	$97.58 \pm 0.09 \%$	$96.67 \pm 0.11 \%$
Medium Fast Read Out	$97.74 \pm 0.09 \%$	$96.69 \pm 0.11 \%$
Fast Read Out	$97.49 \pm 0.1 \%$	$96.70 \pm 0.11 \%$

Table 4: Total efficiency of both sensors at different readout speeds.

and the corresponding geometric means of the spatial resolution are presented in Table 5.

These results clearly show that, despite the significant increase in readout speed, the key observables remain virtually unchanged. The same holds true for other quantities such as the ToT spectrum, spatial correlations, and in-pixel efficiency, which are not shown here explicitly. These findings support the adoption of a faster default readout, as it has demonstrated performance comparable to the current standard settings. This change becomes particularly beneficial at higher beam intensities, where data that would otherwise be lost due to information overhead can now be reliably recorded.

Default	X-Axis	Y-Axis
Unbiased Residuals	$18.07 \pm 0.092 \mu\text{m}$	$14.6 \pm 0.073 \mu\text{m}$
Biased Residuals	$5.43 \pm 0.012 \mu\text{m}$	$6.05 \pm 0.013 \mu\text{m}$
Geometric Mean	$9.91 \pm 0.055 \mu\text{m}$	$9.4 \pm 0.051 \mu\text{m}$

(a) Default Readout speed

Medium	X-Axis	Y-Axis
Unbiased Residuals	$17.68 \pm 0.088 \mu\text{m}$	$14.59 \pm 0.077 \mu\text{m}$
Biased Residuals	$5.36 \pm 0.018 \mu\text{m}$	$6.05 \pm 0.020 \mu\text{m}$
Geometric Mean	$9.73 \pm 0.058 \mu\text{m}$	$9.4 \pm 0.059 \mu\text{m}$

(b) Medium Fast Readout speed

Fast	X-Axis	Y-Axis
Unbiased Residuals	$17.93 \pm 0.092 \mu\text{m}$	$14.61 \pm 0.077 \mu\text{m}$
Biased Residuals	$5.43 \pm 0.017 \mu\text{m}$	$6.04 \pm 0.02 \mu\text{m}$
Geometric Mean	$9.87 \pm 0.059 \mu\text{m}$	$9.39 \pm 0.058 \mu\text{m}$

(c) Fast Readout speed

Table 5: Comparison of spatial resolution estimates for different readout speeds

10 Test beam DESY

The final test beam campaign was conducted at one of only a handful suitable facilities for this type of experiment, the Deutsches Elektronen-Synchrotron (DESY), located in Hamburg, Germany. DESY provides researchers from all around the world with three dedicated beamlines designed for detector testing [59]. The current accelerator named DESY II, is an electron/positron synchrotron capable of reaching energies of up to 6.1 GeV. Besides providing particles to the three test beam lines, it also functions as a booster for the PETRA III storage ring, which is used for hard X-ray radiation experiments. For test beam users, the particle beams are generated using internal targets, where electrons and positrons undergo scattering processes, transferring their energy to high-energy photons. Just before the beam enters the experimental area, these photons are converted back into charged particles using secondary targets. A strong dipole magnet then allows the selection of the desired particle energy within the 1 GeV to 6 GeV range [59]. In addition, DESY also provides beam telescopes and other standardized infrastructure such as the AIDA2020 TLU and much more.

10.1 Measurements goals

The primary goal of this test beam was to analyze the temperature dependence of the efficiency of irradiated TJ-Monopix2 sensors. This information is particularly interesting, as it provides an approximate benchmark for the cooling requirements in the Belle II VTX Upgrade. The final specifications will be based on similar measurements performed with OBELIX, the successor to TJ-Monopix2. In addition, further data were collected to investigate the requirements on bias voltage for efficient operation, as well as the dependence of threshold settings on temperature. Another objective was to stress test the experimental setup using the synchronous TLU handshake mode, AIDA. Unfortunately, it was not possible to fully evaluate the faster readout mode, as the results needed to remain comparable to previous measurements conducted under default conditions.

10.2 Setup

The setup for this test beam was particularly interesting, as it included a laboratory station for preliminary measurements, helping to save time on the actual beamline. Initially, the laboratory setup featured two temperature control systems, one of which was later relocated to the beamline. The complete arrangement is shown in Figure 44. It can be seen that the systems were operating

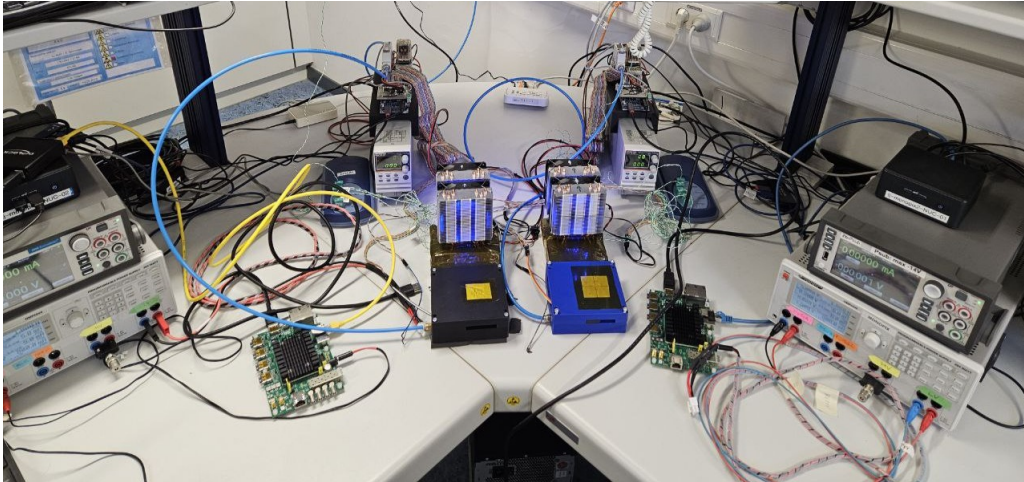


Figure 44: Laboratory setup for characterizing different chips prior to beamline testing.

in parallel, each equipped with separate power supplies, SMUs, BDAQ boards, and various other components. In addition to verifying the functionality of the system on-site and performing a few calibration runs, this setup was primarily used to determine the optimal configuration for each sensor and to carry out all necessary scans that did not require the actual particle beam. During these calibration runs, the PID controller parameters and the conversation functions were slightly adjusted to improve on-site performance.

At the beamline, the setup was similar to the MedAustron test beam configuration, however now with only a single chip placed in the beamline at a time and now including the temperature control system. A schematic overview is shown in Figure 45. Compared to the SSD telescope at

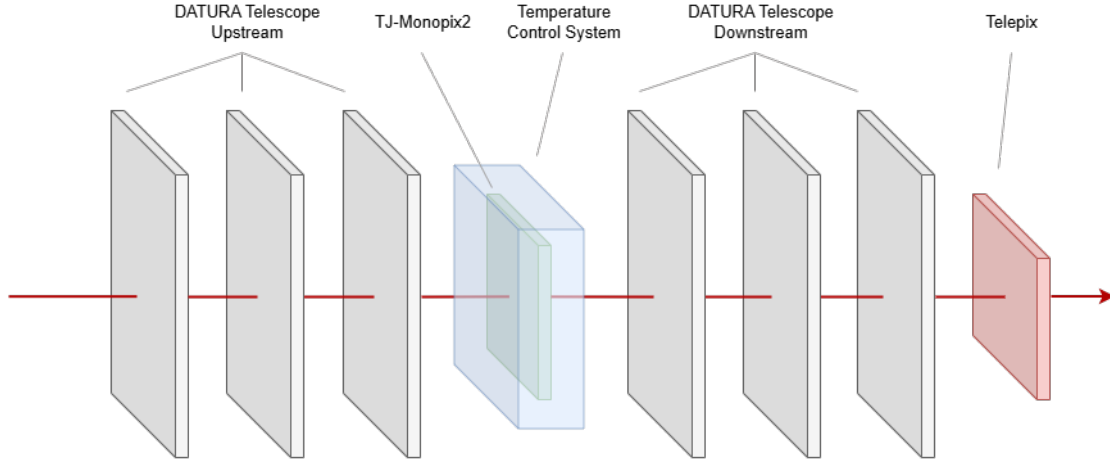


Figure 45: Schematic view of the setup during the DESY test beam.

MedAustron, the DATURA beam telescope used here features six planes, enabling a more accurate tracking process with a mean intrinsic resolution of just $3.24 \pm 0.09 \mu\text{m}$ [60]. These planes are equipped with MIMOSA26 sensors, developed as part of the EUDET project [61]. Another key difference from the MedAustron setup is the triggering mechanism, which is now provided by the Telepix chip. This sensor offers an exceptionally precise timing resolution of 2.4 ns while also delivering great spatial resolution [62]. The blue transparent box indicates the temperature control system, which fully encloses the measured chip.

The physical setup can be seen in Figure 46. In addition to the setup directly at the beamline, this picture also shows the previously mentioned power supplies, SMU, TC-08 Data Logger, and the computer that controls all of these components.

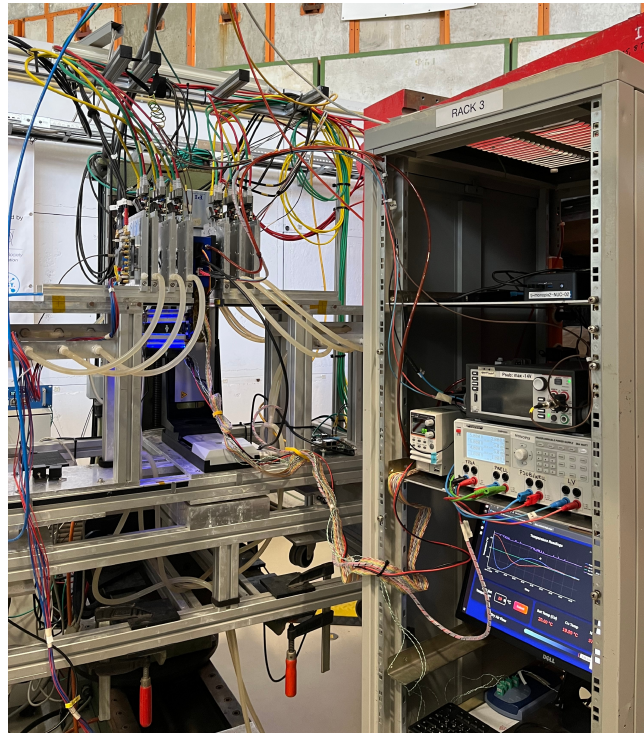


Figure 46: Overview of the physical setup during the DESY test beam.

The chip with its housing, is mounted on a micrometer-precise two-axis stage, allowing fine alignment of the chip with respect to the beam and the beam telescope.

A total of four irradiated chips were tested during this campaign, three of which were proton-irradiated and one electron-irradiated. The respective fluences are summarized in Table 6. Addi-

Chip	Irradiation Type	Fluence (neq/cm ²)
W8R6	p-irradiated	5×10^{14}
W2R17	p-irradiated	2.5×10^{14}
W8R4	p-irradiated	1×10^{14}
W2R5	e-irradiated	5×10^{14}

Table 6: Irradiated sensors to be tested.

tionally, a single non-irradiated chip (W14R12) was used for the initial alignment to confirm that the efficiency and resolution observed in previous test beams could be replicated. This ensures that the similar conditions are present and thus the following results are comparable.

The original plan was to record all data using the synchronous AIDA handshake mode. However, due to technical issues, the first week of measurements had to be carried out using the EUDET mode instead. The cause of this turned out to be the connection board between the AIDA2020 TLU and the BDAQ53 board, which introduced synchronization problems thus causing the bit errors which resulted in the 8b/10b encoding errors.

10.3 Temperature Control System Performance

The temperature control system was a key component for performing the required measurements with irradiated samples. Its main advantage was the significantly faster response and stabilization time compared to a manual approach. To quantify this, the log files can be analysed, as the variation of the setpoint during temperature scans can be viewed as a series of step responses. Selected results are shown in Figure 47. The condition used to determine when the temperature was considered stabilized was defined as the last point with a deviation greater than 0.1 °C from the set temperature. Based on this criteria, the mean stabilization time was calculated separately for both heating and cooling processes, as it was observed that they differ significantly. For heating, the average stabilization time was 8 minutes and 31 seconds, with a standard deviation of 1 minute and 43 seconds. In contrast, the cooling process showed a noticeably longer average stabilization time of 12 minutes and 36 seconds, with a standard deviation of 3 minutes and 16 seconds. After stabilization, the typical deviation from the set temperature was approximately 0.01 °C.

Another interesting correlation to explore is the relationship between stabilization time and the temperature difference between the initial and target temperature. Their relationship is illustrated in Figure 49a for heating and Figure 50a for cooling processes. From these two plots, it is difficult to identify a clear trend. A linear fit was added to help visualize any potential pattern, but it describes the data with only limited accuracy. These discrepancies are largely due to the fact that the recorded temperature changes occurred across different temperature ranges, where the controller performs differently. For instance, a 5 °C heating process from 50 °C to 55 °C takes longer than from 10 °C to 15 °C. To make underlying trends more apparent, normalization was necessary.

The temperature region in which a temperature step occurred was defined by calculating the average of the initial and target temperatures, effectively creating a "center of mass" point for that specific process. This allowed each heating or cooling process to be represented by a single value on a continuous temperature axis ranging from 0 °C to 60 °C. The system's performance across these temperature ranges was quantified using the heating or cooling rate, defined as the size of the temperature step divided by the corresponding stabilization time. Using these two variables, performance plots were generated for heating in Figure 48a and for cooling in Figure 48b. In both cases, a linear fit was applied to approximate the controller's behavior across the operating range. These plots reveal that the system heats more efficiently at lower temperatures, while the heating rate decreases progressively at higher temperatures. On the other hand, during cooling, the system performs better at higher temperatures and slows down as the temperature decreases.

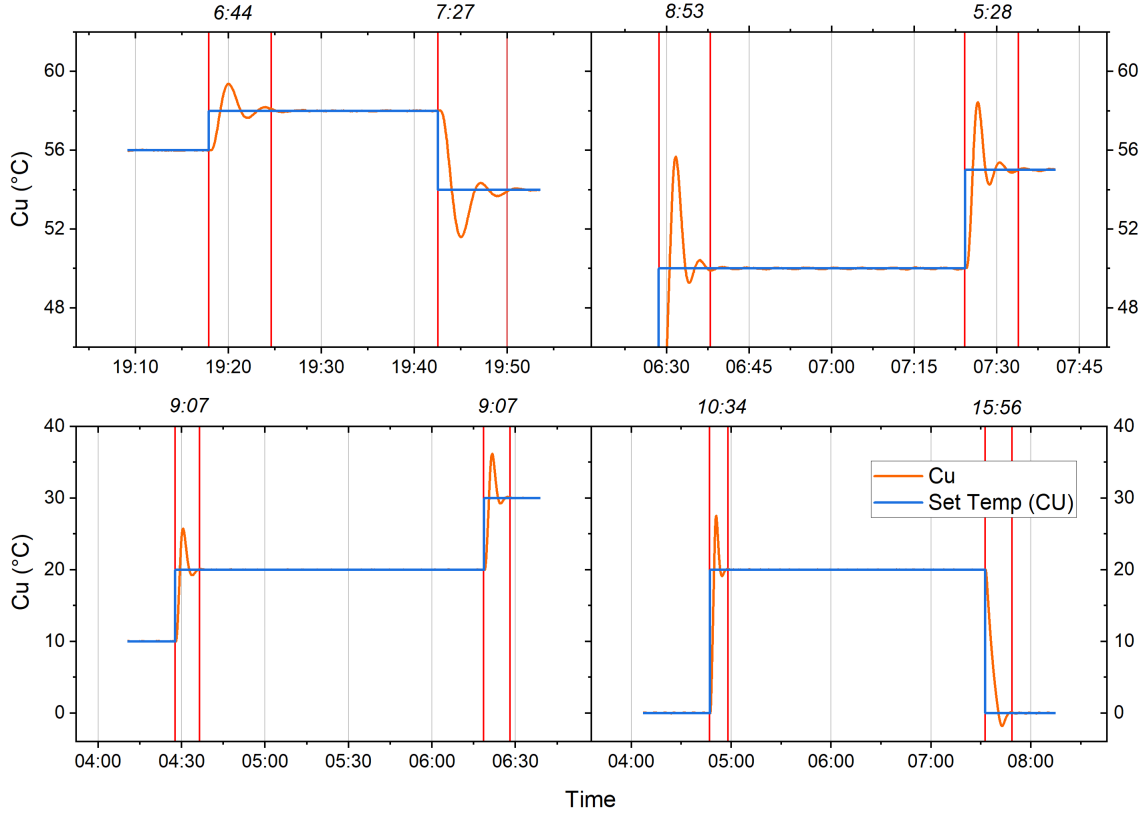


Figure 47: Step response of the temperature control system during the experiment at DESY. Stabilization periods are highlighted, and their durations are noted above.

The fitted functions take the following form

$$y = -0.016 \cdot x + 1.42 \quad (25)$$

and

$$y = 0.012 \cdot x + 0.5. \quad (26)$$

Using these functions, the stabilization times can now be normalized, allowing them to be meaningfully compared across different temperature regions. For the normalization, a reference temperature of 30 °C was chosen, as it lies in the center of the studied range. The normalization was performed using the following formula

$$t_{i,eff} = t_i \times \frac{r(T_i)}{r(T_{ref})} \quad (27)$$

where t_i is the stabilization time, $r(T_{ref})$ is the fit function evaluated at the reference point and $r(T_i)$ is the fit function evaluated for a specific temperature region. Using this normalization, Figure 49b for heating and Figure 50b for cooling were created. The trends are now much more apparent, revealing a clear linear relationship between the effective stabilization time and the temperature difference. This behavior is expected, as the Peltier element was operated exclusively within its well-defined linear regime, far from any saturation points that could introduce non-linear artifacts into the measurement. It should be noted that although the spread of data appears greater for the normalised heating process, the data points now all point in the same direction.

Until now, the focus has been on evaluating the ability of the temperature setup to reach the desired temperature at the copper block. However, this temperature is not equivalent to the actual chip temperature. The NTC probe provides a measurement much closer to the true chip temperature. A corresponding temperature evolution plot is shown in Figure 51. Because the heat transfer must occur through the significantly less thermally conductive PCB, the NTC temperature is more inert. To evaluate the stabilization time, a similar approach was used as for the copper measurements. However, in this case, the saturation temperature was defined as the target temperature, and the last deviation of the NTC temperature greater than 0.3 °C was considered as

the point of stabilization. The stabilization times for heating and cooling processes were found to be very similar. Therefore, the overall stabilization time can be merged into a single representative value of 15 minutes and 43 seconds, with a standard deviation of 4 minutes and 50 seconds.

The final chip temperature cannot be measured directly and must instead be estimated using the known NTC temperature and the LV current. As a result, the calculated chip temperature inherits all the characteristics of the copper and NTC temperature evolution curves. The stabilization time is expected to be even longer than that of the NTC, since heat must now transfer through the narrow contact area between the chip and the chip board. Additionally, this temperature is subject to greater fluctuations, as the chip generates varying amounts of heat during operation.

Overall, the temperature control system performed very well without any major issues. The UI proved to be intuitive and user-friendly, even for operators with no prior experience.

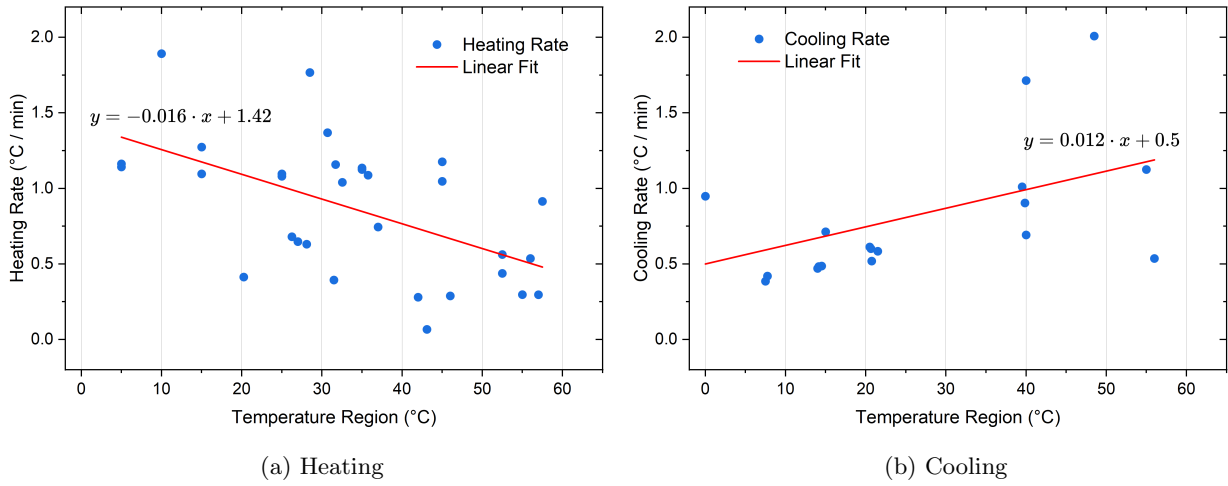


Figure 48: Rate of temperature change plotted against the temperature range in which the change occurred.

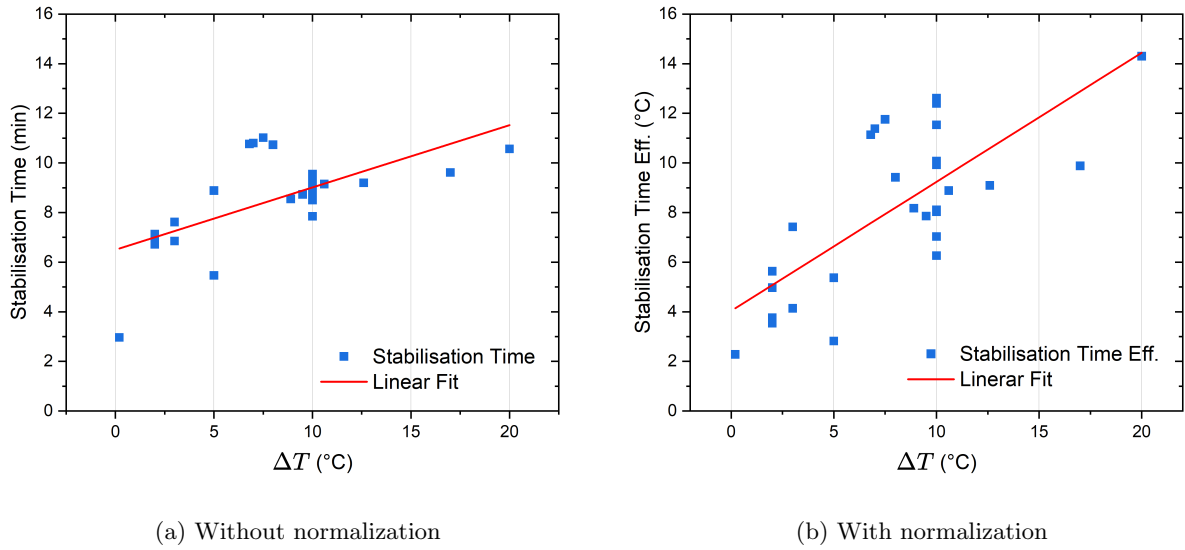


Figure 49: Heating stabilization time plotted against the temperature difference covered.

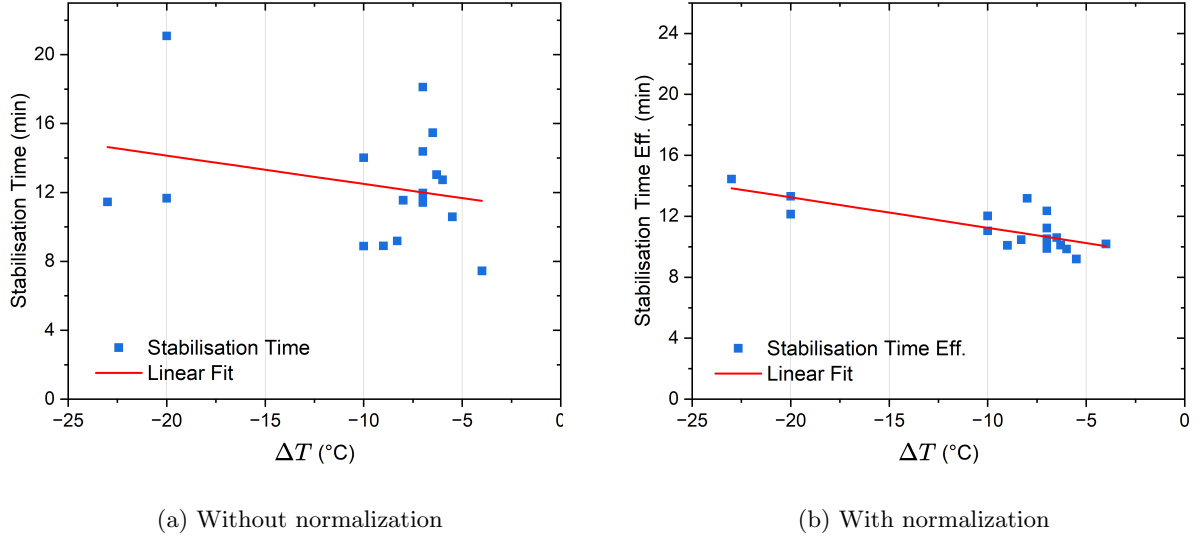


Figure 50: Cooling stabilization time plotted against the temperature difference covered.

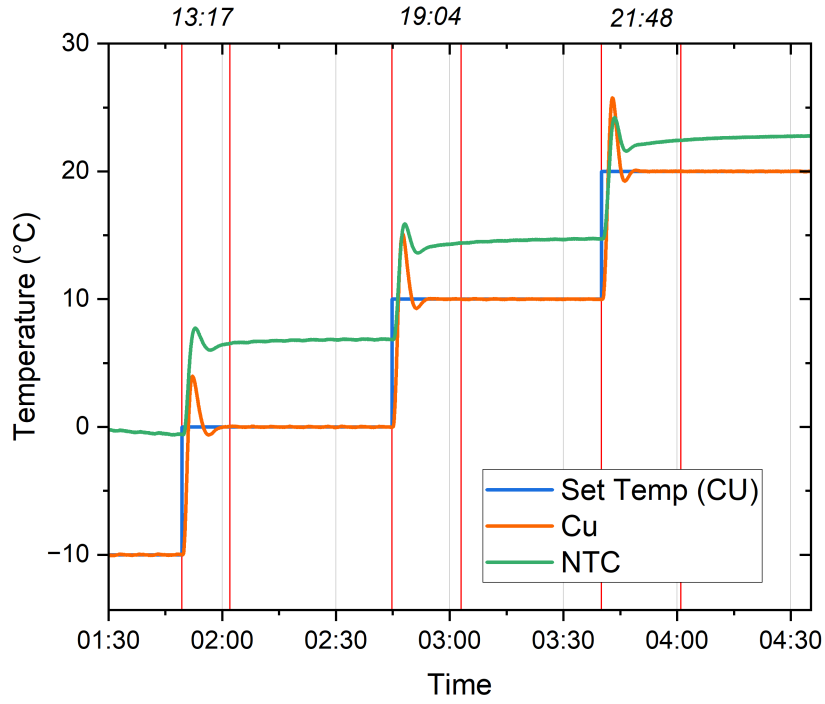


Figure 51: Temperature evolution over time for copper, NTC, and the set temperature, with stabilization periods highlighted and their durations indicated above.

10.4 Results

The first item on the measurement plan was to perform simple measurements on a non-irradiated chip without any active cooling or heating, in order to verify that the results from previous test beams could be reproduced. Once a satisfactory agreement in results was achieved, the DUT was replaced with the first irradiated chip, marking the start of the actual test beam campaign.

First temperature scans were conducted, during which the temperature was varied from 10 °C (as measured on the NTC) up to, when possible, 50 °C. The corresponding chip temperatures were estimated using the conversion tables introduced in Section 5.4. At each temperature point,

data was recorded for approximately 15 minutes. This procedure was repeated for every sensor and for both FE, DC Cascode or DCC and HV Cascode or HVC. The results are presented in Figure 52. These measurements were performed using the so-called *Standard setting*, which can be described as the baseline tuning parameters typically applied for low-threshold operation. For the DCC FE shown in Figure 52a, a slight decrease in efficiency can be observed with increasing chip temperature. Nevertheless, the efficiency remains above the 99% benchmark even at elevated temperatures, with only a single measurement point near 60 °C falling below this threshold. The optimal operational temperature appears to lie between 35 °C and 40 °C, beyond which a visible drop in efficiency is observed across all chips.

The situation is slightly different for the HVC FE, as shown in Figure 52b. The p -irradiated W8R4 and the e -irradiated W2R5 chips exhibit little to no variation in efficiency with increasing chip temperature. In contrast, the more strongly irradiated W8R6 sensor shows a significant negative correlation with temperature above 35 °C. This behavior is likely due to the substantially higher radiation damage, which greatly affects the charge collection. In combination with increased temperature, the leakage current rises exponentially, as shown in Figure 55. This may exceed the noise compensation capabilities of the FE, potentially leading to misinterpretation of real hits or even loss of hits due to signal baseline saturation. Unfortunately, data for W2R17 sensor is missing for this measurement as the HV biasing is not functional, making it difficult to fully confirm and interpret this phenomenon.

When comparing the pixel flavors, the HVC FE appears to offer better durability against rising chip temperatures at lower fluences. On the other hand, for sensors with higher radiation damage, the DCC FE seems to be the better option, as the W8R6 chip retains above 99% efficiency even at temperatures up to 50 °C. In contrast, the efficiency of the HVC pixel drops below the 98% mark. However, these observations should be treated with caution as they are based on the results of a single chip.

At this stage, the in-pixel efficiency maps at various temperatures can also be analyzed. These plots illustrate how effectively different regions within a pixel detect passing particles, on average. This kind of analysis is enabled by precise tracking, which determines positions on the DUT plane with sub-pixel resolution. The results for the W2R5 chip are presented in Figure 53 for the DCC and in Figure 54 for the HVC FE. Although the temperature ranges differ slightly between the two, the comparison still reveals interesting features. In both figures, a decrease in efficiency at the pixel edges is visible at higher temperatures. This is consistent with expectations, as the negative impact of increased temperature on overall efficiency has already been discussed. Furthermore, since edge pixels are located farthest from the charge collection node, they are more susceptible to charge transport losses. Another noteworthy observation is that the data from the HVC FE appear slightly noisier than those from the DCC FE, despite showing higher overall efficiency.

Next parameter strongly influenced by chip temperature is the threshold, as shown in Figure 56. For both FE, a clear exponential increase in threshold with rising temperature is observed. This is expected as the increasing leakage current continuously discharges the collection node. Therefore any charge collected is partially canceled out by the background leakage before it can be fully processed by the amplifier. If the leakage current is high enough to discharge the node during that same time scale as the integrator time window, the signal amplitude is reduced, thus effectively the threshold increases. Since leakage current grows exponentially with temperature, so does the threshold [5].

In addition to the temperature scans, bias voltage sweeps were also performed for all irradiated chips. As expected, the overall efficiency is strongly influenced by the applied bias voltage. For the DDC FE, the bias is set via the PSUB voltage, which was varied between 1 V and 20 V. For the HVC FE, the high-voltage (HV) line was adjusted between 1 V and 40 V. All measurements were again conducted using the standard tuning settings. The results are presented in Figure 57. For the DDC FE, shown in Figure 57a, it is evident that sensors irradiated to different fluences begin to perform effectively above different bias thresholds. As expected, the W8R6 sensor irradiated to the highest fluence shows the poorest performance at low bias voltages. Its efficiency only exceeds the 99% mark at approximately 12 V. For the HVC FE, this threshold is even higher, whereas all DUTs surpass the 99% efficiency mark at around 30 V HV. This behavior at low bias voltages is primarily related to the size of the depletion region. At low bias, the depletion is limited to a small region around the collection electrode. As a result, particles passing through the outer areas

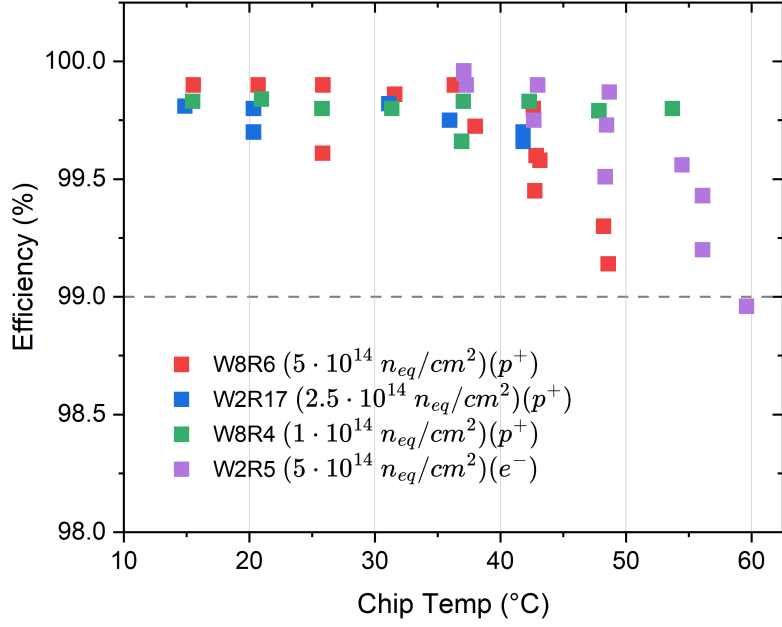
of the pixel may not be detected, leading to reduced efficiency. If observed closely, it can be seen that the relationship between bias voltage and efficiency is non-linear. This is consistent with the dependence of depletion depth on bias voltage for a planar geometry, which is displayed in this equation [63]

$$d(V_{\text{ext}}) = \sqrt{\frac{2\epsilon(V_{\text{bi}} - V_{\text{ext}})}{eN_D}}. \quad (28)$$

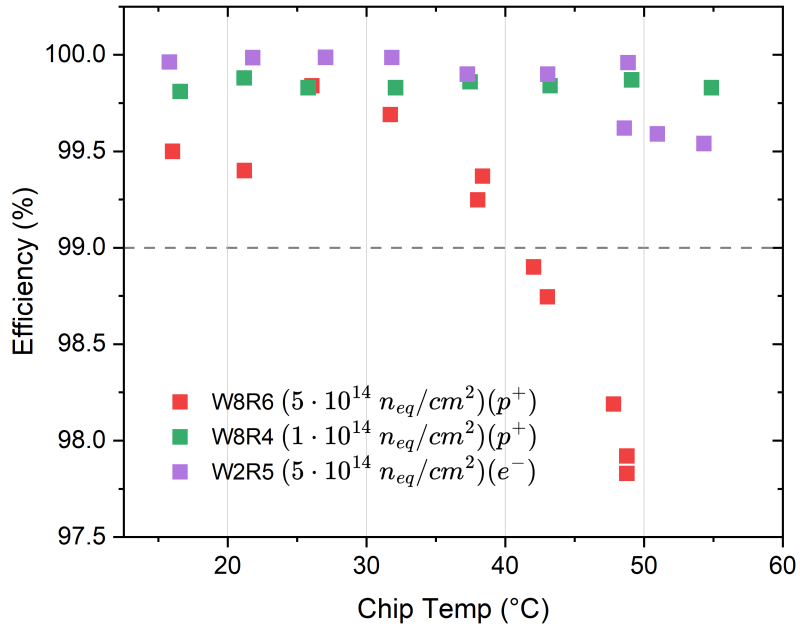
Here d is the depletion depth, N_D the doping concentration of the bulk, ϵ the permittivity of silicon, V_{bi} the built-in potential and V_{ext} the applied reverse-bias voltage. Therefore, if the external bias voltage is doubled, the depletion depth increases only by a factor of $\sqrt{2}$. This, in turn, contributes to the non-linear behavior visible in Figure 57, together with the fact that the efficiency curve samples different regions of the Landau distribution, which itself does not have a constant density.

The residuals in the X and Y directions can also be studied as a function of temperature. This quantity is of particular interest since it directly correlates with the resolution. Therefore, any dependence of the residuals on temperature translates into changes in the overall resolution of the chip. A visual representation of this relation is shown in Figure 58a for the DCC FE and in Figure 58b for the HVC FE. For both pixel flavors, only a weak dependence is observed. However, a closer inspection reveals a small drop around 35 °C. The origin of this effect is not yet understood, but it opens an interesting direction for further investigation.

When comparing the DCC and HVC FE, the differences become immediately apparent. As expected, the HVC FE requires a significantly higher bias voltage to achieve full depletion and consequently, satisfactory efficiency. The DCC FE, on the other hand, performs well even at substantially lower voltages. Therefore, the choice between these two flavors ultimately depends on the specific system requirements and other factors.



(a) Efficiency vs. Chip Temperature for DCC.



(b) Efficiency vs. Chip Temperature for HVC.

Figure 52: Chip efficiency as a function of chip temperature for various irradiated sensors.

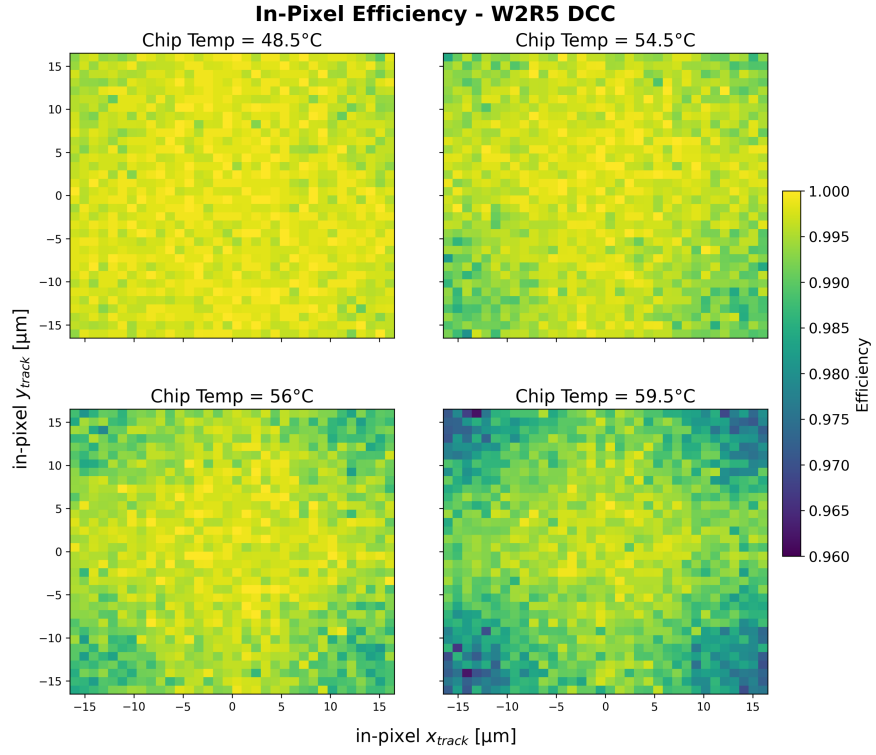


Figure 53: In-pixel efficiency maps for the DCC frontend of the W2R5 chip at different temperatures.

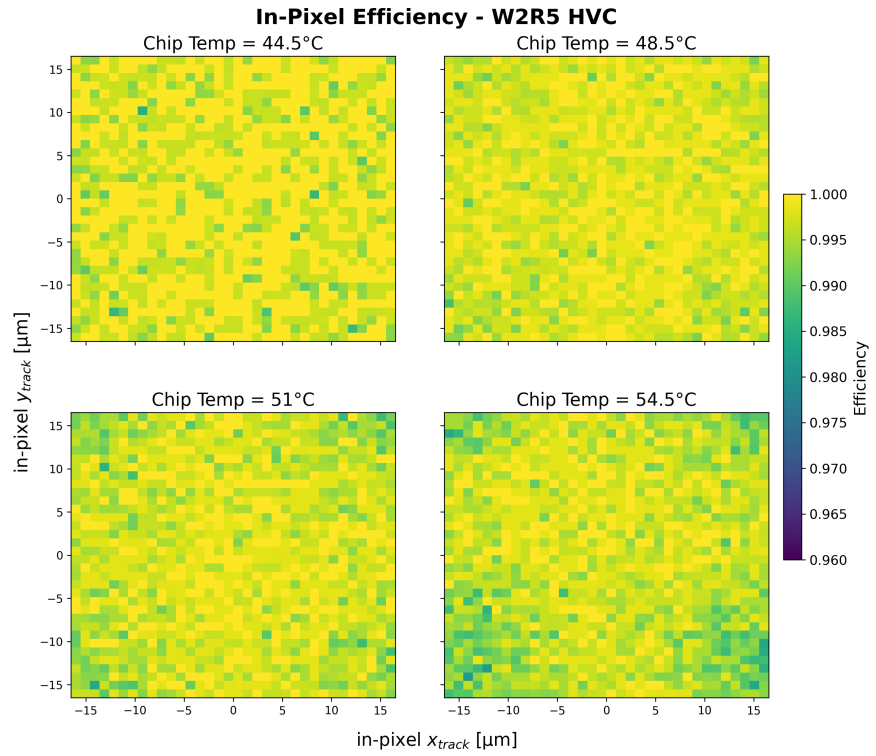


Figure 54: In-pixel efficiency maps for the HVC frontend of the W2R5 chip at different temperatures.

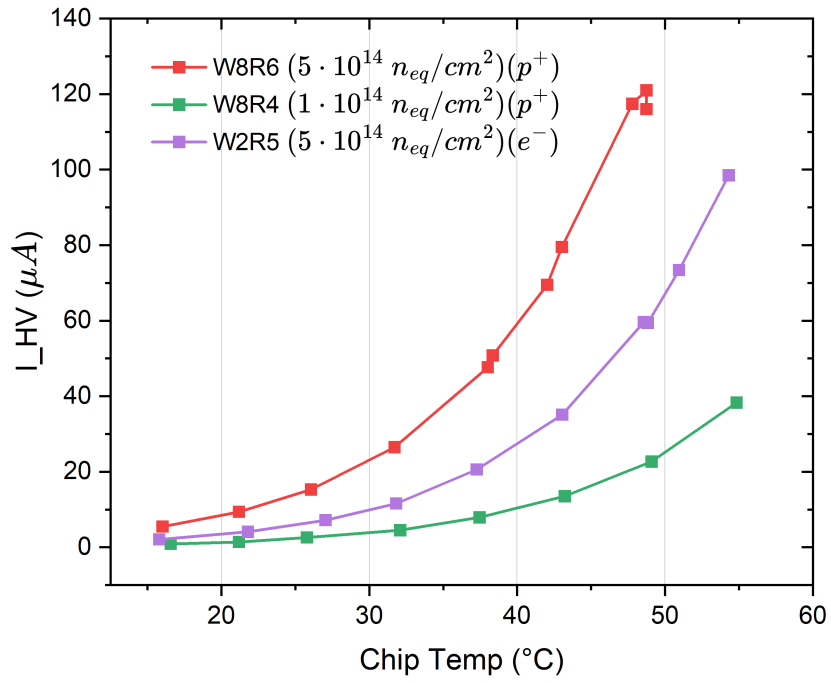
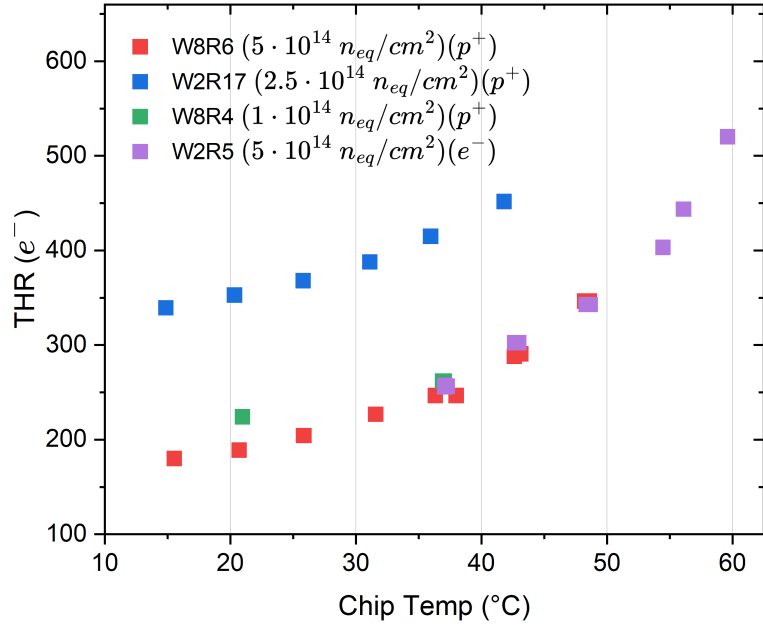
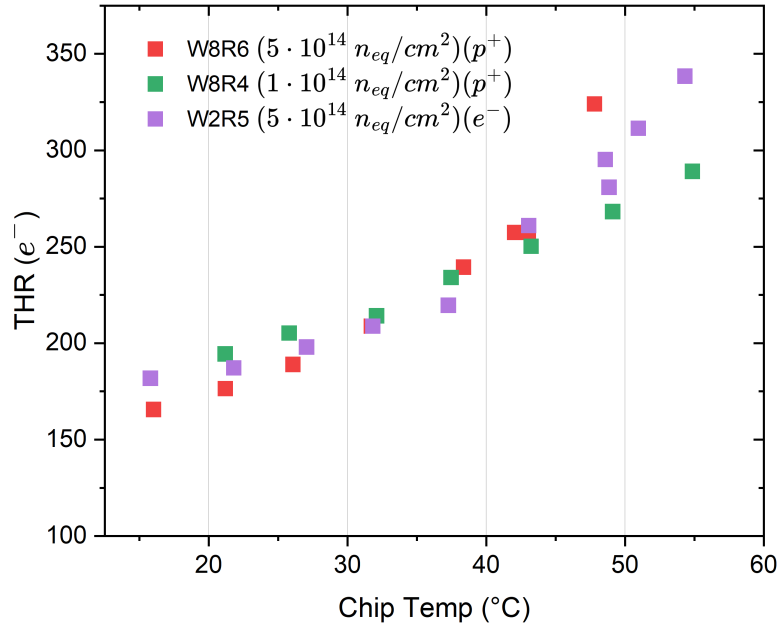


Figure 55: Leakage current as a function of chip temperature for the HVC front-end across different sensor samples.

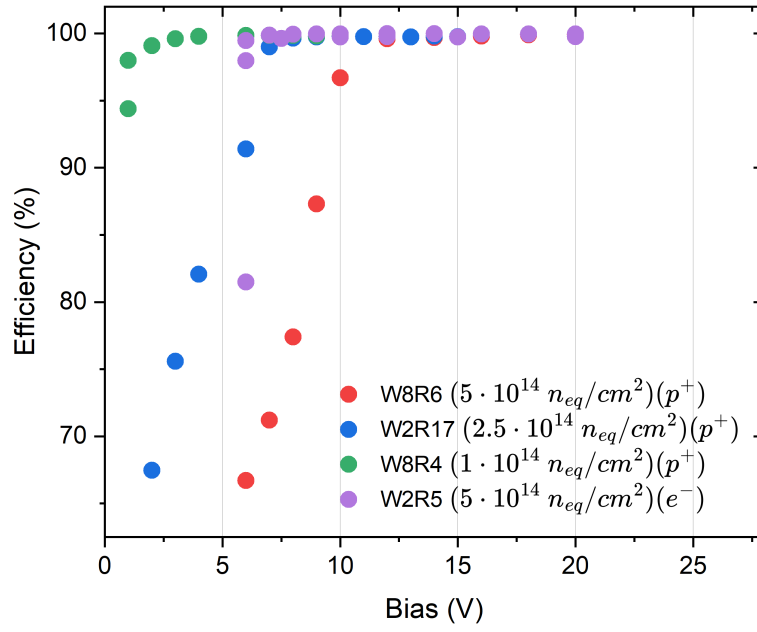


(a) Threshold vs. Chip Temperature for DCC.

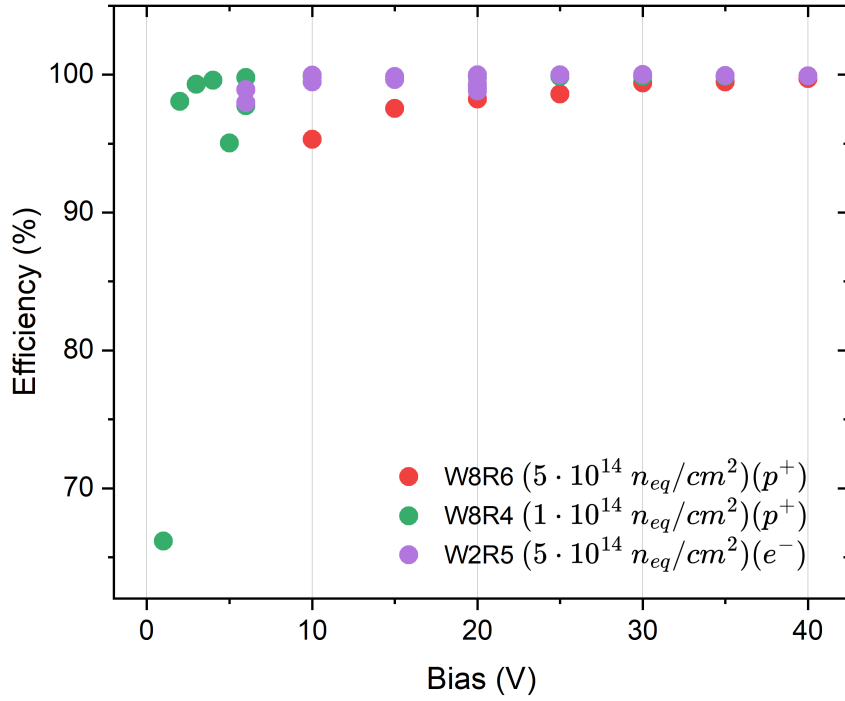


(b) Threshold vs. Chip Temperature for HVC.

Figure 56: Threshold as a function of chip temperature for various irradiated sensors.

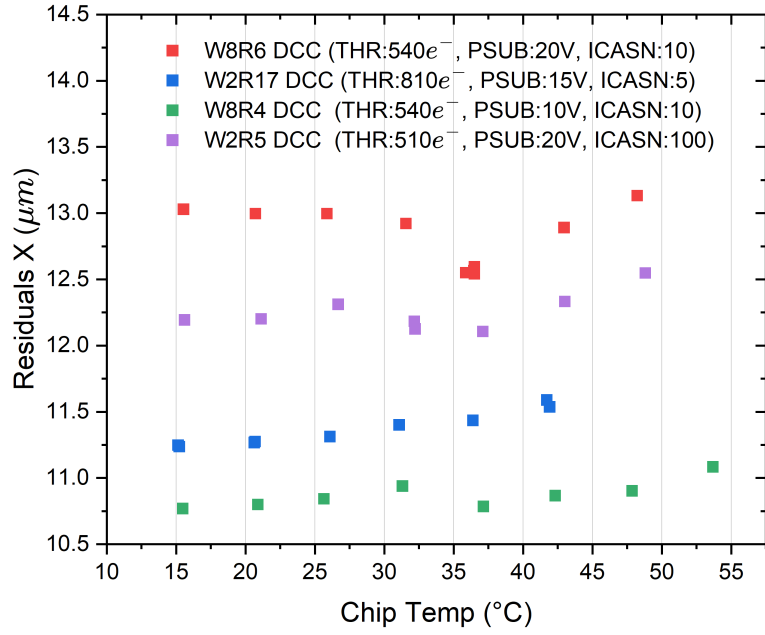


(a) Bias vs. Efficiency for DCC.

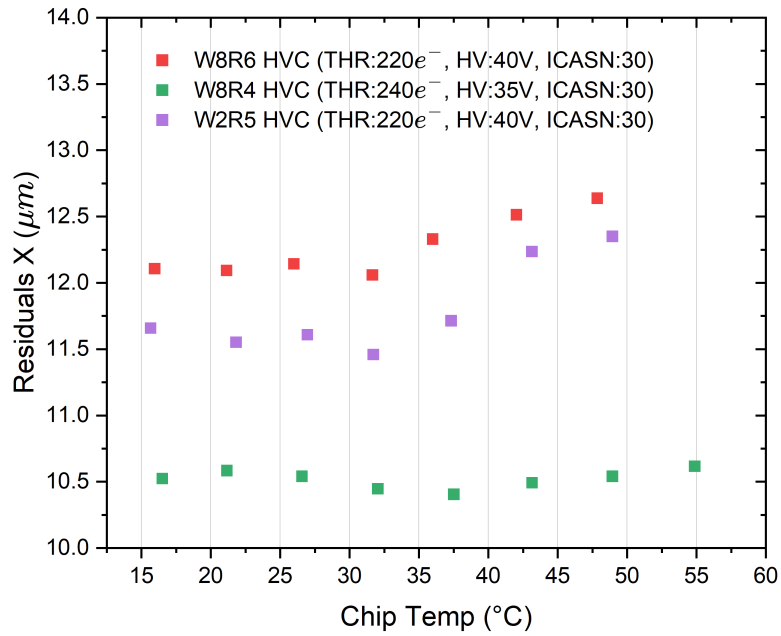


(b) Bias vs. Efficiency for HVC.

Figure 57: Efficiency as a function of bias voltage for various irradiated sensors.



(a) Chip Temperature vs. Residuals in X direction for DCC.



(b) Chip Temperature vs. Residuals in X direction for DCC.

Figure 58: Residuals in X direction as a function of chip temperature for various irradiated sensors.

11 Conclusion and Outlook

In conclusion, the test beam campaigns were carried out successfully, revealing several new properties of the TJ-Monopix2 sensor. Despite significant changes, including a new TJ-Monopix2 producer, an updated TLU handshake mode, an improved temperature control system, and various other modifications, the setup performed well.

More specifically, the AIDA mode of the AIDA2020 TLU proved to be a suitable replacement for the previously used EUDET mode. Although some issues came up during the DESY test beam, these were technical in nature rather than fundamental to the approach. The main takeaway is that, since AIDA mode relies heavily on the quality of the TLU clock, even minor imperfections in signal transmission can cause the entire system to lose synchronization.

The fast readout mode also appears to be a step in the right direction. During the MedAustron test beam, it performed just as well as the default mode while enabling the system to correctly process even higher data loads. To conclusively demonstrate the usefulness of this approach, further test beam campaigns at MedAustron would be desirable to confirm that the results can be replicated and verified. These findings would also be highly valuable for the successor to TJ-Monopix2, OBELIX.

The temperature control setup proved to be a highly effective tool for this type of application. From the physical design to the UI and the cooling and heating performance, it performed well all around. The housing and internal structure were robust enough to endure many cooling and heating cycles, even while being continuously disrupted by DUT exchanges, yet the performance remained consistent. The real-world application of the PID controller confirmed that it was an excellent choice, as it minimized stabilization time while enabling users to set any desired temperature without further adjustments. Although with the TJ-Monopix2 it is not possible to measure the temperature directly, the estimates derived from the NTC probe and the LV current provided a good approximation of the operating temperature. A useful improvement would be the integration of a temperature probe directly inside the sensor, which would also be beneficial for other development groups beyond the Belle II collaboration. The UI also proved to be user-friendly, highly versatile, and easily expandable. The concept of reading and displaying a live log feed from a CSV file could be applied in many other areas with only minor modifications to the display. In the future, this tool, currently implemented as a standalone script, could be developed into a modular application that allows users to adjust the display layout without modifying the code. This would make it possible to use the tool without the need of diving into the python code and making adjustments there.

Finally, the DESY test beam measurements provided new insight into the functionality of the irradiated chip and offered clear guidance for the cooling specifications. Results indicate that chip efficiency is generally stable across temperatures, with only a slight decline at higher values. For DCC, efficiency remains above 99% up to almost 60 °C, while HVC shows slightly stronger sensitivity to radiation damage and temperature. The in-pixel efficiency also decreases moderately with temperature, most noticeably at the pixel edges where charge transport losses are higher. In addition, the effects of bias voltages for the DCC and the HVC FE on efficiency were investigated, yielding new understanding of the depletion depth and characteristics of the different cascode pixel variants. When it comes to final verdict between the examined pixel flavors is not completely clear. Both FE come with some advantages and drawbacks. Moreover, due to incomplete information from the HVC FE, some choices must rely on measurements from a single sensor. Overall, the DCC FE performed better, despite a minor noise issue that is expected to be resolved in the next generation. Nevertheless, additional test beam campaigns could still provide valuable insights for the final phase of the OBELIX development.

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Acronyms

BCID	Bunch Crossing ID.
CCE	Charge Collection Efficiency.
CMOS	Complementary Metal-Oxide-Semiconductor.
DAC	Digital to Analog Converter.
DAQ	Data Acquisition.
DCC	DC Cascode.
DEPFET	Depleted P-Channel Field Effect Transistor.
DESY	Deutsches Elektronen-Synchrotron.
DMAPS	Depleted Monolithic Active Pixel Sensors.
DUT	Device Under Test.
ENC	Equivalent Noise Charge.
FE	Front-End.
GR	General Relativity.
HV	High Voltage.
HVC	HV Cascode.
LEP	Large Electron-Positron Collider.
LV	Low Voltage.
LVDS	Low-voltage Differential Signaling standard.
MAPS	Monolithic Active Pixel Sensors.
MIP	Minimum Ionizing Particle.
NIEL	Non-Ionizing Energy Loss.
NTC	Negative Temperature Coefficient.
OBELIX	Optimized Belle II pixel sensor.
PCB	Printed Circuit Board.
PID	Proportional–Integral–Derivative.
PSU	Power Supply Unit.
PXD	Pixel Detector.
QED	Quantum Electrodynamics.
RMS	Root Mean Square.
SM	Standard Model.
SMU	Source Measure Unit.
SNR	Signal-to-Noise Ratio.

SSD Silicon Strip Detector.

SVD Silicon Vertex Detector.

TLU Trigger Logic Unit.

ToT Time over Threshold.

UI User Interface.

VXD Vertex Detector.

Appendices

A Temperature Control System Installation

This appendix outlines and explains the complete installation process required to use the temperature control system.

A.1 Getting Started

The following devices should be connected to the PC:

1. **Picotech Thermocouple Data Logger TC08**
2. **PSW-Series Programmable Switching D.C. Power Supply** (expected as `ttyACM0`)
3. **Arduino Uno R4 Minima** (expected as `ttyACM1`)

A.2 Installation

A.2.1 PicoScope

Install the necessary SDK from the PicoTech website. Import the public key (only once, no need to repeat):

```
sudo bash -c 'wget -O- https://labs.picotech.com/Release.gpg.key \
| gpg --dearmor > /usr/share/keyrings/picotech-archive-keyring.gpg'
```

Configure your system repository:

```
sudo bash -c 'echo "deb [signed-by=/usr/share/keyrings/picotech-archive-keyring.gpg] \
https://labs.picotech.com/picoscope7/debian/ picoscope main" \
> /etc/apt/sources.list.d/picoscope7.list'
```

Update the package manager cache:

```
sudo apt-get update
```

Install PicoScope:

```
sudo apt-get install picoscope
```

A.2.2 PicoLog

Install PicoLog for testing and channel definition from the PicoTech website.

A.2.3 SWIG

Install SWIG:

```
sudo apt install swig
```

Execute the `pip freeze` command and save the output:

```
pip freeze > requirements.txt
```

Install all requirements:

```
pip install -r requirements.txt
```

A.2.4 USB TC-08

Clone the repository to your machine:

```
git clone git@github.com:bankrasrg/usbtc08.git
```

Add the Pico Technology repository:

```
sudo bash -c 'echo "deb http://labs.picotech.com/debian/ picoscope main" \  
> /etc/apt/sources.list.d/picoscope.list'
```

Import the public key:

```
wget -O - http://labs.picotech.com/debian/dists/picoscope/Release.gpg.key | sudo apt-key add -
```

Update the package manager cache:

```
sudo apt-get update
```

Install the Linux driver for USB TC-08 devices:

```
sudo apt-get install libusbtc08
```

Build the Python module using SWIG:

```
cd usbtc08/source/
```

Edit the following path in the `usbtc08.i` file: From:

```
/opt/picoscope/include/libusbtc08-1.8/usbtc08.h
```

To:

```
/opt/picoscope/include/libusbtc08/usbtc08.h
```

Now run the SWIG command:

```
swig -python usbtc08.i
```

Build the Python package using Distutils:

```
python setup.py build_ext --inplace
```

A.3 Additional Dependencies

The following libraries need to be installed:

```
pip install dash pandas dash-bootstrap-components simple-pid
```