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CMOS Technologies in Detector Readout Systems of Modern Particle Physics Experiments

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Abstract

In the times of constantly expanding knowledge of particle physics and the improvement of the large accelerators, increases the luminosity of experiments. Consequently, it requires better detectors and more precise and faster readout systems. Mostly every system contains the Application Speci c Integrated Circuits (ASIC) that allow to preprocess particles' signals from speci c detector.

The main focus in this research is on the readout system for straw tube tracker detectors, done with collaboration between groups of the Jagiellonian University and AGH University. The detectors are used in two experiments, in future $\overline{P}$ANDA (Straw Tube Tracker (STT) and Forward Tracker (FT)) and in upgraded HADES (Straw Tracking Stations (STS)), both at the FAIR facility in Darmstadt. The readout is based on the PASTTREC ASIC developed by the AGH University group. Since more than 5000 chips are used in both experiments, the main goal was to prepare the measurement setup for mass tests and quali cation procedures. Everything was veri ed by measurements with the straw tube module and ^{55}Fe source. As a part of this work, also the optimisation of the Front-End Boards (FEBs) containing PASTTRECs was done and one week internship in HADES during beamtime.

The second part of the research concentrates on the development of ASICs for future experiments. In modern systems, not only the information about the signal's amplitude is needed, but also the measurement of time starts to be required. Therefore, the main focus was on developing a Time-to-Digital Converter (TDC) using 130 nm CMOS technology based on 10-bit SAR ADC (Successive Approximation Register Analog-to-Digital Converter) [1, 2]. The 8-channel prototype TDC was designed that allows time measurements with con gurable resolution from 10 to 100 ps. The aforementioned 10-bit SAR ADC was also part of HGCROC ASIC for HGCAL in CMS experiment designed by OMEGA group from Ecole Polytechnique in collaboration with the CEA-IRFU Institute in Saclay, CNRS from Paris, CERN and AGH UST. The AGH University group was responsible for ADC design, whose measurements and settings optimisation were part of this thesis.

Streszczenie

W czasach stale rozwijajacej sie wiedzy z zakresu zyki czastek elementarnych oraz udoskonalania wielkich akceleratorów, wzrasta swietlność eksperymentów. W zwiazku z tym zwieksza sie zapotrzebowanie na coraz lepsze detektory oraz bardziej precyzyjne i szybkie systemy odczytu. Przewaznie kazdy system zawiera dedykowane uk ady scalone (ang. Application Speci c Integrated Circuits (ASIC)), które umozliwiaja wstepne przetwarzanie sygna ów czastek z skiego detektora.

G ówna czesc tej pracy jest system odczytowy dla adowych detektorów s omkowych, realizowany we wspó pracy z zespo em z Uniwersytetu Jagiellońskiego. Detektory te sa uzywane w dwóch eksperymentach, w przysz ym eksperymencie PANDA (w Straw Tube Tracker (STT) i Forward Tracker (FT)) oraz w zmodernizowanym eksperymencie HADES (Straw Tracking Stations (STS)), oba w orodku FAIR w Darmstadt. Ich odczyt bazuje na uk adzie PASTTREC zaprojektowanym przez grupe z AGH. W zwiazku z wykorzystaniem ponad 5000 chipów w obu eksperymentach, g ównym celem by o przygotowanie uk adu pomiarowego do testów masowych i procedur kwali kacyjnych chipów. Wszystko zwery kowano pomiarami z modu em detektora s omkowego i źród em elaza ^{55}Fe. W ramach tej pracy wykonano równiez optymalizacje p ytki drukowanej (Front-End Board (FEB)) zawierajacej chipy PASTTREC oraz odbyto tygodniowy staz w eksperymencie HADES podczas pomiarów na wiazce.

Druga czesc badan koncentruje sie na rozwoju uk adów ASIC do przysz ych eksperymentów. W wspó czesnych eksperymentach istotna staje sie nie tylko informacja o amplitudzie sygna u, ale równiez pomiar czasu. W zwiazku z tym g ówny nacisk po ozono na opracowanie uk adu do pomiaru czasu (konwerter czasowo-cyfrowy TDC, ang. Time-to-Digital Converter) z wykorzystaniem technologii CMOS 130 nm w oparciu o 10-bitowy przetwornik anologowo-cyfrowy SAR ADC (ang. Successive Approximation Register Analog-to-Digital Converter). Zaprojektowano 8-kana owy prototyp TDC, który umozliwia pomiar czasu z kon gurowalna rozdzielczoscia od 10 do 100 ps. Wspomniany 10-bitowy przetwornik SAR ADC jest równiez czescia uk adu HGCROC dla HGCAL w eksperymencie CMS, CERN zaprojektowanym przez grupe OMEGA z Ecole Polytechnique we wspó pracy z Instytutem CEA-IRFU w Saclay, CNRS z Paryza, CERN i AGH. Grupa z AGH by a odpowiedzialna za uk ad ADC, którego pomiary i optymalizacja ustawia a czesc tej pracy.

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Acronyms

$\overline{\text{P}}$ANDA anti-Proton ANnihilation at DArmstadt. xiii, 1, 2, 4–6, 8–14, 17, 18, 30, 43, 44, 89, 91

ADC Analog-to-Digital Converter. xvii, 1, 2, 14, 61–63, 65–74, 77, 79, 82–85, 90, 91

AGH University Akademia Górniczo-Hutnicza University of Krakow. 2, 8, 11, 19, 61, 62, 82, 90, 91

ASIC Application-Specific Integrated Circuit. xiii–xv, xvii, xix, 1, 2, 8, 11, 12, 14, 15, 17–19, 21, 25, 28–33, 36–39, 41, 42, 61, 63, 75, 77, 79, 80, 82, 89–91

BGA Ball Grid Array. 83

CBM Compressed Baryonic Matter. 5

CERN European Organization for Nuclear Research. 2, 5, 61, 82, 91

CIB Charge Injection Board. xiv, 23, 24

CMOS Complementary Metal–Oxide–Semiconductor. 1, 14, 15, 61, 62, 71, 89

CMS Compact Muon Solenoid. xiii, 1, 2, 5, 6, 61, 89, 91

CP Charge Pump. xvii, 63–68, 70, 73, 77

CVD Chemical Vapour Deposition. 7, 10

DAC Digital-to-Analog Converter. xiv, xvii, xviii, 18, 19, 25–27, 30, 32, 33, 35, 38, 45, 62, 64, 67, 69, 79, 83–86

DAQ Data Acquisition. 2, 54, 60

DIRC Detection of Internally Reflected Cherenkov light. 10

DNL Differential Non-Linearity. xiv, xvii, xviii, 25, 26, 62, 69, 72, 73, 75, 83–87, 90, 91

DSP Digital Signal Processing. 14

ECAL Electromagnetic Calorimeter. 8

EMC Electromagnetic Calorimeter. 5, 6, 10

ENC Equivalent Noise Charge. xiv, 28, 30

ENOB Effective Number of Bits. 62, 69

FAIR Facility for Antiproton and Ion Research. xiii, 2, 5, 6, 8, 9

FEB Front-End Board. xiii–xv, 1, 2, 12, 17–27, 29–31, 33, 35, 40, 43, 57, 89, 91

FPGA Field-Programmable Gate Array. 12, 14, 19, 80, 81, 83

FRPC Forward Resistive Plate Chamber. 8

FS Forward Spectrometer. 9, 10

FT Forward Tracker. xiii, 6, 10–13, 18, 20, 23, 43

GEM Gas Electron Multiplier. 10

GSI Gesellschaft für Schwerionenforschung. 5, 6, 17, 54

HADES High Acceptance DiElectron Spectrometer. xiii, xvi, 1, 2, 5–8, 11, 13, 14, 17, 18, 21, 43, 44, 54, 55, 58, 59, 89–91

HC Hadron Calorimeter. 5, 6

HESR High Energy Storage Ring. 8–10

HGCAL High Granularity Calorimeter. 1, 2, 61, 91

HGCROC High Granularity Calorimeter Read-Out Circuit. xvii, xviii, 1, 2, 61, 77, 82–87, 89, 91

HL High Luminosity. 61

HV High Voltage. xvi, 11, 25, 46, 50–52, 54, 55, 90

HV-MAPS High Voltage Monolithic Active Pixel Sensors. 10

INL Integral Non-Linearity. xvii, xviii, 62, 69, 72, 74–76, 78–80, 83–87, 90, 91

LDO Low Dropout. 18, 20, 21

LED Leading Edge Discriminator. 18

LHC Large Hadron Collider. 4–6, 61

LSB Least Signi cant Bit. 69

LVDS Low-Voltage Differential Signalling. 18, 19

MDC Mini (cell) Drift Chambers. 7, 19

MIM Metal-Insulator-Metal. 69

MIP Minimum-Ionising Particle. 43, 82

MSB Most Signi cant Bit. 63, 69, 77, 90

MVD Micro Vertex Detector. 10

OTA Operational Transconductance Ampli er. xvii, 67, 68, 73

PASTTREC PANDA STT REadoutChip. xiii, xiv, xix, 2, 8, 11, 12, 14, 17–20, 23, 25, 27, 28, 30–33, 36, 38, 55, 58, 89

PFD Phase Frequency Detector. xvii, 63–69, 73

PZC Pole Zero Cancellation. 18

QA Quality Assurance. 58

QCD Quantum Chromodynamics. 4, 6, 8

R&D Research and Development. 63

RHIC Relativistic Heavy Ion Collider. 5, 6

RICH Ring-Imaging Cherenkov. 7, 8, 10

RPC Resistive Plate Chamber. 7

SAR Successive Approximation Register. xvii, xix, 2, 61–63, 66, 68–70, 77, 82, 83, 90, 91

SINAD Signal-to-Noise and Distortion Ratio. 62, 69

STS Straw Tracking Stations. xvi, 6, 8, 11, 13, 17, 18, 20, 21, 23, 43, 54–60, 90

STT Straw Tube Tracker. xiii, 6, 10, 11, 18, 20

TAC Time-to-Analog Converter. xvii, 61–64, 66, 68–71, 73, 79, 90, 91

TC Tail Cancellation. 14, 18

TDC Time-to-Digital Converter. xvii, 1, 2, 12, 14, 19, 38, 61–64, 69–75, 77–82, 89–91

TOA Time-Of-Arrival. 11, 14, 17, 19, 52, 82

TOF Time of Flight. 7, 8, 10

TOT Time-Over-Threshold. xiv, xvi, xix, 11, 17, 19, 25, 26, 29, 44, 45, 47, 50, 51, 53, 58–60, 82, 90

TRB Trigger Readout Board. 12, 14, 19

TS Target Spectrometer. 9, 10

TWEPP Topical Workshop on Electronics for Particle Physics. 17, 89

VCM Voltage Common Mode. xvii, 63, 67, 68, 73

Introduction

The question of how the matter around us is built has always been asked by people since ancient times. Along with the development of technology, knowledge of matter was also expanded, creating the field of particle physics. Through the years, people have discovered smaller and smaller particles that build surrounding matter. To observe the new particles that were expected by theory, high-energy physics experiments with large accelerators had to be constructed. The particle beams are speeded up in the accelerator and then hit with each other or the target at very high energies. The particles created in this collision have to be detected in large detector systems, which allow one to measure particle's momentum and energy. One of the most important parts of detector is the readout electronics system that reads signal from detector and converts it to data that can be then analysed. Modern experiments have a large number of channels, placed very densely, but modern technologies allow reducing the size of circuits and reducing power consumption. Furthermore, the detector and readout electronics have to work under high radiation conditions. These factors cause almost every detector to need its own dedicated Application-Specific Integrated Circuit (ASIC).

The aim of this thesis was the development of detector readout systems for particle physics experiments such as $\overline{\text{P}}$ANDA (Antiproton Annihilation at Darmstadt), High Acceptance DiElectron Spectrometer (HADES) and Compact Muon Solenoid (CMS). The main purpose was to optimise the front-end electronics of the straw tube detectors for experiments HADES and $\overline{\text{P}}$ANDA, to prepare the setup for mass tests of their Front-End Boards (FEBs) and to analyse the data from the first bench of boards. The next objective of the thesis was the development of dedicated ASICs for future experiments. Modern experiments require more often time measurement (for example, for the measurement of arrival time of particle). Therefore, the aim was to design the Time-to-Digital Converter (TDC) circuit with 10 to 100 ps time resolution which could be the part of ASIC for future experiments. The last goal was the Analog-to-Digital Converter (ADC) optimisation for High Granularity Calorimeter Read-Out Circuit (HGCROC) ASIC for High Granularity Calorimeter (HGCAL) detector in CMS experiment.

This work allowed the author to be involved in every part of the process of creating the readout system, starting from designing the electronics circuit in submicron Complementary Metal–Oxide–Semiconductor (CMOS) technology, through prototype tests, preparation of the test setup, final tests with detector and qualification measurements of ASICs, and finally participation in experiment monitoring during beamtime.

This thesis consists of an introduction, three chapters describing the 4-year work, and a summary. The first chapter describes the basics of particle physics and introduces the subject of particle

physics experiments. The overview of typical experiment is presented based on CMS experiment. In the second part of the chapter, two experiments important for this work, HADES and future $\overline{\text{P}}$ANDA , are presented. Both are located at the Facility for Antiproton and Ion Research (FAIR) facility in Darmstadt, Germany. Particular attention is given to the straw tube tracking detectors used in the aforementioned experiments, $\overline{\text{P}}$ANDA and HADES. The chapter ends with a description of the development of ASICs for modern particle physics experiments.

The second chapter focusses on the readout electronics for the $\overline{\text{P}}$ANDA and HADES experiments. This project was carried out in close collaboration between groups from Jagiellonian University and Akademia Górniczo-Hutnicza University of Krakow (AGH University). The Jagiellonian University group is responsible mainly for the straw detector part and the Data Acquisition (DAQ) system, while the AGH University group is in charge of the front-end electronics. At the beginning of the chapter, the readout system is presented, which is based on $\overline{\text{P}}$ANDA STT REadout Chip (PASTTREC) ASIC mounted on a dedicated FEBs. First, the optimisation of FEBs was performed. Since more than 5000 chips had to be produced for both experiments, the mass test setup was required. Hence, the next part of the chapter discusses this setup together with measurement procedures and quali cation requirements. The main part of the chapter are the results from the above mentioned mass tests and then the results obtained with straw tubes and ^{55}Fe source in the Jagiellonian University laboratory. Finally, the monitoring of the HADES beamtime detector is described due to the completed one-week internship at HADES during beamtime.

The third chapter concentrates on development of dedicated ASICs for future experiments. The main part of this work was the design of Time-to-Digital Converter (TDC). Hence the rst part of the third chapter presents the design of TDC, results from simulations and the design of an 8-channel prototype ASIC together with the preparation of the prototype measurement setup. In the second part of this chapter, the ADC measurements of HGCROC ASIC are presented. The HGCROC is a readout ASIC for the HGCAL detector in the CMS experiment, European Organization for Nuclear Research (CERN). The AGH University group contributed to the design of the fast 10-bit Successive Approximation Register (SAR) ADC for the HGCROC readout ASIC.

Chapter 1

Particle physics experiments

1.1 Introduction

People have always wondered how the world around us is built. Philosophers in ancient Greece have already used the term *atom* as something very small from which the matter is built and cannot be divided. Then through the last centuries more discoveries have proven the particle structure of matter: first atom concept of John Dalton (1808), periodic table of Mendeleev (1896), but finally it was proven that atoms are built of smaller parts, like proton, neutron and electron. In 1897, J. J. Thomson, after almost 50 years of research, claimed the presence of negatively charged electrons, and at the turn of the 19th and 20th century the presence of proton in the atomic nucleus was confirmed (Rutherford). In the next years further particles were discovered: positrons, muons, neutrinos, etc. The second part of the 20th century has brought a fast development in technology that also caused a development in particle detection, and hence, widening knowledge in the field of particle physics.

In the 1970s of the 20th century, the term *Standard Model*, similar to what we know now, was introduced to the world of science by Abraham Pais and Sam Treiman. The Standard Model of Particle Physics (Figure 1.1) so far contains 12 particles, fermions, from which matter is made and 13 particles, bosons, that are responsible for transferring interactions between other particles.

The fermions are grouped into 3 generations. Six of them are known as quarks (up u, down d, charm c, strange s, top t and bottom b) and the other six are leptons (electron e, muon μ, tau τ, electron neutrino ν_e, muon neutrino ν_μ and tau neutrino ν_τ). All fermions have spin equal to $\frac{1}{2}$, they differ in mass and charge. Three leptons have negative charge -1, and the other three are electrically neutral and very light corresponding neutrinos: ν_e, ν_μ and ν_τ. Additionally, there are 12 antiparticles, respectively, to the mentioned fermions with opposite charge.

Quarks can be seen so far only in hadrons, together with other quarks or gluons. They have the additional property of colour, red, green, or blue, and antiquarks that have respective anticolor, antired, antigreen, or antiblue, which gives the possibility of strong interactions. To form the hadron, they have to have neutral colour, white: colour-anticolour or three different colours/anticolours. The most common hadrons are mesons (pairs of quarks) and barions (triples of quarks). Mesons have spins 0 or 1, so in this understanding they are also bosons, while barions have spins

Figure 1.1: Standard Model of Particle Physics [3].

$\frac{1}{2}; \frac{3}{2}; : : :$, which makes them complex fermions. It is predicted that only 5 of the quarks take part in creating barions, since the has too fast decay time to last and create any hadron. One of the most common barions are and n. Now all barions that are formed of only and quarks are called nucleons, among other (uud) and n (udd). All hadrons have their antiparticles, created from respective antiquarks. Hadrons can also be formed in tetraquarks (in 2014, the LHCb experiment observed a Z (4430) 4-quark hadron), glueballs or other exotic hybrids, which will be observed, among others, in future Anti ANihilation at DArmstadt (ANDA) experiment.

The matter that we see on Earth is built only of the particles from the I fermion generation of the Standard Model. Particles from the II generation, and (except) come with cosmic radiation with particles such as pions and kaons . The rest of the fermions require very high energy to be produced.

The other part of the Standard Model contains bosons. They have an integer value of spin, and they are responsible for the transfer of interactions between other particles. There are: two, W^+, W , and one Z^0 boson, which mediate weak interactions, eight gluons that mediate strong interaction between quarks or other gluons, photon responsible for electromagnetic interactions and the Higgs boson observed in 2012 that gives masses to particles interacting with the Higgs eld.

At the beginning of the universe in the rst few millionth parts of the second there was a hot and dense mix of quarks and gluons, which then, after cooling, created protons, neutrons, and other particles. Quantum Chromodynamics (QCD) is a theory that describes the strong interactions of quarks, antiquarks, and gluons that bond them into hadrons. Modern experiments such as Large

Hadron Collider (LHC) or Relativistic Heavy Ion Collider (RHIC) simulate hot and low baryonic density conditions, probably observed in the early universe. On the other hand, in compact stars, a cold and very high internal baryonic density is present. This part will be reconstructed in Compressed Baryonic Matter (CBM), Facility for Antiproton and Ion Research (FAIR) experiment, but also High Acceptance DiElectron Spectrometer (HADES) experiment will produce reference data.

New particles, their complex interactions and internal structures can be studied only with high energies, since not all particles are observed on Earth; some of them were present only in the early universe or now in stars. To broaden our knowledge of particles, particle accelerators are needed, where the particles' beams are speeded up and then hit with each other at very high energies (proton beam collisions of two counterrotating beams with energies 0.9-13 TeV in Compact Muon Solenoid (CMS) at LHC at European Organization for Nuclear Research (CERN)) or with target (proton beam collision with metal (gold) foil with energies up to 4.5 Gev (29 GeV after upgrade) in HADES at Gesellschaft für Schwerionenforschung (GSI) or antiproton beams with metal foil with energies about 3 GeV in PANDA at FAIR).

After collision, very precise detection of created particles is needed to understand their structure and features. A typical detection system contains four main parts: a tracking system, calorimeters: Electromagnetic Calorimeter (EMC) and Hadron Calorimeter (HC), and muon chambers. Additionally, to obtain the momentum results from trackers, there is also a large magnet (4 T magnetic field by solenoid magnet in CMS) that bends the particles' paths, the more momentum the particle has, the less curved its path is. The example of the detector system (CMS [14]) is presented in Figure 1.2. Since in the CMS two particle beams collide, the detector has the shape of a barrel (the slice is seen in Figure 1.2) with appropriate endcaps to close all the space around the collision point.

Figure 1.2: CMS detector slice with example particles [4].

Closest to the interaction point, there is a tracking system. To obtain particle's momentum information, a very accurate particle's track in a magnetic eld (only charged particles are bent) is provided. Moreover, the trackers must be lightweight, to disturb particle ight as little as possible; therefore, they are usually made of silicon (CMS) or gaseous straw tubes (Straw Tracking Stations (STS) in HADES or Straw Tube Tracker (STT) and Forward Tracker (FT) in $\bar{P}$ANDA). Calorimeters are systems that measure the energies of particles; hence, the particles are fully absorbed there. EMC measures the energies of and . In the CMS experiment, lead tungstate ($PbWO_4$) crystals are used, which are ideal for stopping high-energy particles because they are heavier than steel. The crystals are transparent and scintillate, producing light proportional to the energies passing through e and . After EMC, there is HC that measures the energies of hadrons. In CMS alternately layers of brass/steel and plastic scintillators are placed. Brass and steel layers are very dense materials that cause stopping of the particles that then produce signals in plastic scintillators that are read by photodiodes. Muons interact very weakly with matter; therefore, the muon chambers are at the end of the whole detector system interleaved with iron planes. In the CMS experiment, it is one of the most important parts, because it is predicted that muons are a relevant part of new particles' decays, hence in the system there are four stations. There are four types of detector used, all based on different types of gaseous detectors. The multilayer system provides the possibility to measure the trajectory of the particles, and as a result the momentum information is obtained.

1.2 HADES experiment

The High Acceptance DiElectron Spectrometer (HADES) [15] is a magnetic spectrometer at the SIS18 accelerator at the GSI Helmholtz Center for Heavy Ion Reasearch in Darmstadt, Germany, which has been operating since 2002. The SIS accelerator delivers proton beams with energies up to 4.5 GeV that are collided with proton or nuclear xed targets reaching energies up to few GeV. This results in induced reactions of proton, secondary pions and heavy ions that can be measured on HADES as charged hadrons (proton, pions, and kaons), leptons (electrons and positrons), or photons.

Experiments such as LHC or RHIC provide information only on regions with high temperatures and very small baryon densities; therefore, HADES will provide a complement to these data at lower energies. The main goal of the HADES is to investigate the electromagnetic structure of baryonic resonances and their production mechanisms for energies of several GeV. To explore it, the nucleus-nucleus and nucleusreactions are used. The HADES measurements will provide reference data that can be important for upcoming heavy-ion experiments, among others from FAIR, studying the QCD phase diagram in the high baryon density region. Particular attention will be given to the proton-proton reaction from which the hyperons (hadrons with at least one s quark but without c, b, t, existing in stable form within the core of some neutron stars) will be produced. In particular, there is almost no information on the production of multi-strange hyperons with larger masses in the beam energy range provided at the HADES. Higher hyperon resonances can also affect the thermodynamics of QCD or the evolution of the early universe [16]. To achieve these goals, the proton beam energy must be increased to 29 GeV, and the HADES spectrometer

must undergo several hardware changes. The feasibility studies from 2021 [5] show that the upgraded HADES can deliver information about the structure of hyperons and the function of strange quarks in their structure.

The schematic cross-sectional view of the upgraded HADES spectrometer is presented in Figure 1.3. So far the HADES has included the system covering angles 18 to 85 around the beam axis in the forward direction. This part of the detection system contains six identical sectors in circular shape together with superconducting coils providing a magnetic field up to 3.6 T placed in the middle of the detection system. The closest to the interaction point is the START-VETO detector to determine the reaction time (part of the Time of Flight (TOF) measurement) and monitor the properties and quality of the beam. The START subdetector is placed 2 cm in front of the target and built of 50 m thickness Chemical Vapour Deposition (CVD) diamond detectors that provide low noise at high rate with radiation hardness better than silicon. The VETO subdetector is 100 m thick polycrystalline diamond detector placed about 70 cm behind the target. Next, there is the Ring-Imaging Cherenkov (RICH) detector, position sensitive for e^+e^- pair identification, and hadrons are not visible by it. It is filled with C_4F_{10} gas which emits Cherenkov light, then it is reflected by carbon fibre mirrors and detected by photocathodes. After RICH, the low mass Mini (cell) Drift Chambers (MDC), multilayer drift chambers are placed. They provide a precise measurement of the spatial position of the hit points and the energy loss. They are built from four tracking planes. Two of them (I, II) are placed before a superconducting toroid, and two after it. Each of the tracking planes contains 6 trapezoidal layers, which gives 24 layers in total. Layers contain cells that are of size 5 mm (I layer) to 10 14 mm (IV layer); in total, there are about 27000 cells [17]. To measure the TOF of particles, the TOF detector for outer time measurement and the Resistive Plate Chamber (RPC) detector for inner time measurement are placed behind the MDC. Each sector of the TOF detector contains 8 cases with 8 scintillating bars whose signal is read by photomultipliers to reconstruct TOF with a resolution of 100-150 ps.

Figure 1.3: Schematic cross-sectional view of the upgraded HADES spectrometer [5].

Recently, in the upgraded version, two changes were implemented in 2019. The first of them was the upgrade of RICH in order to enhance the dilepton identification. Second, the Electromagnetic Calorimeter (ECAL) has been added for the gamma reconstruction that covers 16 to 45 around the beam axis. This provides electron-pion separation and studies of neutral meson production. Finally, in 2021, the Forward Detector was added to HADES, which provides the measurements in the forward direction, and adds information about particle tracks and their velocities. It contains two Straw Tracking Stations (STS) - STS1, STS2 and a Forward Resistive Plate Chamber (FRPC) for measurements of TOF. They are located 3.1 m, 4.6 m and 7.5 m from the target, respectively. They provide full azimuthal coverage from 0.5 to 7 polar angles. The STS is made up of gas straw tube tracking detectors (developed by the Jagiellonian University group) with front-end electronics based on a dedicated PANDA STT REadout Chip (PASTTREC) Application-Specific Integrated Circuit (ASIC), which was developed by the Akademia Górniczo-Hutnicza University of Krakow (AGH University) group. The detector system, together with the readout part, was developed preliminary for the $\bar{P}$ANDA experiment and will be described in Section 1.4. The STS was installed in HADES at the end of 2020, it passed first tests in February 2021 with a proton beam up to 4.2 GeV [18] and the first beam measurements with proton beam energies up to 4.5 GeV were made in the first part of 2022.

1.3 PANDA experiment

anti-Proton ANnihilation at DArmstadt ($\bar{P}$ANDA) is a future experiment in the FAIR facility in Darmstadt, Germany, which is under construction - Figure 1.4. In $\bar{P}$ANDA experiment, a very high intensity antiproton beam with energies of about 3 GeV will be used. The antiproton beam will be produced by the SIS100 synchrotron, hitting the high-energy proton beam with a metal target. Then the antiproton beam will be accumulated in High Energy Storage Ring (HESR) in two modes: high intensity and high resolution [6]. It leads to even $2 \cdot 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ luminosity in high-intensity mode. The high energy range provided in the experiment will allow wide physics studies [19, 20].

One of the main goals of the $\bar{P}$ANDA experiment will be the spectroscopy studies of charmonium and open charm mesons, as well as charmed baryons. Furthermore, there will be the possibility to study gluonic excitations or, generally, more precise experiments within QCD [21]. Anihilation of antiproton-proton instead of collision of proton beams gives a unique opportunity to produce hyperons above 4 GeV energy and will allow their more detailed studies.

Figure 1.4: Overview of FAIR facility [6].

$\overline{\text{P}}$ANDA experiment will be placed on the straight part of the HESR racetrack shape ring. It will have two main detector systems Target Spectrometer (TS) and Forward Spectrometer (FS) [6] - see Figure 1.5. The first one is a typical collision spectrometer barrel shape with endcaps that will provide 4π coverage around the interaction point. The second part will give information about particles in forward direction behind the collision along the beam line. It will cover angles of ± 10 horizontally and ± 5 vertically. Both parts will provide complete data: tracking, particle identification, calorimetry and muon detection in full momentum range.

Figure 1.5: Schematic view of $\overline{\text{P}}$ANDA experiment setup at FAIR [7].

The TS will contain three-step charged particle tracking Micro Vertex Detector (MVD), Straw Tube Tracker (STT), and Gas Electron Multiplier (GEM). The rst and second will cover the space around the interaction point, and GEM will track the charged particles in the forward direction. The MVD detects short-lived charged particles and provides a high vertex resolution of about 50 m. It contains four barrel layers and six discs in the forward direction. The rst two barrels and all disc (except the last one) layers are pixel detectors, and the rest (2 last barrels and last disc layer) are double-sided silicon strip detectors. The STT is a straw tube gasous detector placed around MVD barrel part. It is described in more detail in the next subsection. The GEM contains 3-circular stations with a diameter of 0.9 m (rst) to 1.5 m (last), placed after MVD in the forward direction. The almost 2 T magnetic eld in the beam direction surrounding the TS part will be provided by the superconducting solenoid. To identify particles, the Barrel Detection of Internally Re ected Cherenkov light (DIRC) will be located after STT, 450 mm from the interaction point, with angles22 140 . It will allow to separate charged pions from kaons in momenta in the range from 0.5 to 3.5 Gev/c. The same role in the forward direction will be performed by a 5 cm thick Disc DIRC, located after GEM. Behind Barrel DIRC the time measuring Barrel TOF will be situated. It contains bre structure photosensors that form a 2.5 m long hodoscope and ensure that the time resolution is less than 60 ps. The calorimetry in TS will be performed using a 3-part EMC spectrometer containing: Barrel, Forward Endcap and Backward Endcap to ensure full coverage. All of them consist of lead tungstate ($PbWO_4$) crystals providing good resolution for photons up to 15 Gev.

In FS the tracking will be provided by Forward Tracker (FT) which is based on the same straw tubes as in STT and is described in the next subsection. Part of the tracking system will be placed in the dipole magnet which will also be part of the HESR beam line. The identi cation of particles in the forward direction will be delivered by Forward RICH located behind the FT. It consists of focussing aerogel tiles placed perpendicularly to the beam with segmented mirrors and re ecting Cherenkov light to photosensors located below and above the beam line. The pion-kaon separation will be done in the range of 2-10 Gev/c. Time measurement, with less than 100 ps resolution, will be carried out by Forward TOF constructed of plastic scintillator plates with photomultiplier tubes above and below. The calorimetry in the forward direction will be done with the Forward Shashlyk Calorimeter (behind Forward TOF) containing plastic scintillator tiles placed alternately with 1.5 mm lead absorber plates over the 68 cm length.

Additionally in both parts will be Muon Detectors, that will provide mostly muon detection. Together, they contain 4200 Mini Drift Tubes placed alternately with iron absorbers of 3 cm long in TS (except forward part) and 6 cm long in FS and forward part of TS.

At the end of the FS (behind Muon Chambers), 11 m from the interaction point, the Luminosity Detector will be located, which will deliver information about the relative and absolute luminosity of $\bar{P}$ANDA experiment by measuring antiprotons de ection at low angles. The measurement is performed by High Voltage Monolithic Active Pixel Sensors (HV-MAPS) that are silicon-pixel sensors placed on the CVD diamond support perpendicularly to the beam.

1.4 Straw tube tracking detectors for PANDA and HADES experiments

The Straw Tracking Stations (STS) detectors from the HADES are built on the basis of the central Straw Tube Tracker (STT) and the Forward Tracker (FT) of the future $\overline{\text{P}}$ANDA experiment. The work is done in close collaboration between the groups from Jagiellonian University that developed the straw detector system and AGH University that developed the electronic readout system based on PASTTREC ASIC that is used for all mentioned detectors.

The above detectors provide the determination of drift time by measuring Time-Of-Arrival (TOA) and the identification of low-momentum particles by the Time-Over-Threshold (TOT) method measuring energy loss in straw trackers [15, 22]. For the first time, the TOT method was used by the ATLAS experiment [23] and the HADES in multi-wire drift chambers [24].

The STT and FT are built of the 10 mm diameter straw tube detectors [8, 9]. The grounded cathodes are made of aluminised Mylar foil of 27 μm thickness. The anodes are 20 μm gold plated tungsten wires connected to High Voltage (HV). The internal pressure of the gas is equal to 2 bars, which mechanically stabilises the straws and provides their self-support. Additional detector frames are used only for straw positioning. The straws are filled with the 90% Ar + 10% CO_2 gas mixture that minimises the ageing effects. The straw tubes provide a gas gain of about $5 \cdot 10^4$, about 130 ns maximum drift time, and a spatial resolution for minimum ionising protons of about 0.13 mm. The detection efficiency on a single straw was measured to be about 95% for 2 Gev/c momentum protons [9].

The $\overline{\text{P}}$ANDA STT straw tubes are of 150 cm length and are arranged in 12 double layers around the beam axis in a hexagonal pattern and placed in an aluminium cylindrical frame as shown in Figure 1.6. The internal radius is 15 cm and the external radius is 41.8 cm. Layer 5 is inclined to +3 and layer 6 to -3 [8].

Figure 1.6: 3D visualisation of the STT for $\overline{\text{P}}$ANDA experiment [8].

In the FT, straws are arranged in detector planes built of separate modules that contain 32 straws organised in two layers each. The length of the straws is adjusted to the tracking area of each detection plane (described in the next paragraph). The modules are mounted side-by-side on a support frame and, in this way, form a double-layer detection plane. The possibility of removing a single module without dismounting others simpli es the replacement of modules if necessary. Each module has its own two front-end electronic cards (Front-End Boards (FEBs)) and each of them comprises two PASTTREC ASICs [25]. Furthermore, multichannel Time-to-Digital Converter (TDC) are implemented in Trigger Readout Board (TRB) [26]. So far the experiment used version 3 of TRB, but there is work to replace it with updated version 5 that contains newer Field-Programmable Gate Arrays (FPGAs) and newer construction.

The FT contains six tracking station planes set in pairs. The rst pair is installed in front of the dipole magnet (FT1, FT2), the second inside the magnet spacing (FT3, FT4), and the last behind the magnet (FT5, FT6). The schematic view of FT in the $\bar{P}$ANDA experiment is presented in Figure 1.7 and the double layer mounted on a prototype frame in Figure 1.8. Each station contains four double layers of straw tubes, from which the rst and last are vertically arranged and the middle ones are aligned by an inclination of, respectively, and -5 . The tracking area at the FT stations ranges from 134×64 cm (FT1, FT2) to 392×120 cm (FT5, FT6) - a more detailed description can be found in [27].

Figure 1.7: Schematic view of the FT stations position in $\bar{P}$ANDA experiment with dipole magnet [9].