Overview of the PANDA Detector design at FAIR

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Abstract. PANDA (antiProton ANnihilation in DArmstadt) is the central experiment to fully exploit the physics research potential of antiproton beams at the international accelerator Facility for Antiproton and Ion Research in Europe (FAIR), currently under construction at GSI. Phase-space cooled high intensity antiproton beams up to 15 GeV/c will be provided by the High Energy Storage Ring (HESR) at FAIR to interact with PANDA internal proton or nuclear targets enabling a broad range of exciting studies in Particle and Nuclear Physics. The PANDA detector features two spectrometers, the Target Spectrometer with a superconducting solenoid magnet of 2 T around the interaction region with hermetic coverage and the Forward Spectrometer with a 2 Tm dipole magnet for coverage of the forward boosted particles. Several modern particle detector systems are employed in PANDA to provide excellent charged particle tracking, particle identification, calorimetry and muon detection, over the full momentum range in both spectrometers throughout the lifetime of the experiment. Focusing on the various PANDA detector systems we present an overview of recent developments, the detector construction progress and conclude with an outline for a phased deployment of PANDA at FAIR.

1. Antiprotons at FAIR

FAIR, the new international Facility for Antiproton and Ion Research in Europe [1], is a multipurpose accelerator facility that will provide beams, of protons up to uranium ions, over a wide range of intensities and energies, to produce high intensities of high quality secondary beams of rare isotopes and antiprotons. FAIR is currently under construction at Darmstadt next to the GSI facility [2], the Helmholtz Centre for Heavy Ion Research, in Germany. Primary and secondary beams of the future FAIR accelerators at the existing GSI facility, see figure 1, enable a broad scientific program which is structured into four research pillars [3] organized by large collaborations (in alphabetical order): APPA, serving communities in Atomic, Plasma Physics and Applications; CBM, the Compressed Baryonic Matter experiment; NUSTAR, the NUclear STructure, Astrophysics and Reactions program; and PANDA (antiProton ANnihilation in DArmstadt) [4], [5], the key experiment for hadron and nuclear physics using antiproton beams at FAIR.
The antiproton production chain at FAIR starts with the pLinac providing protons of 70 MeV which are accelerated further in the SIS18 to 4 GeV and injected into SIS100. Every 10 seconds $2.5 \times 10^{13}$ protons will be accelerated in the SIS100 to 29 GeV and compressed into a bunch of 50 ns. Antiprotons with energies around 3 GeV will be produced through inelastic collisions of these high energy protons with nucleons of a metal target at rest. A pulsed magnetic horn will focus the antiprotons down the pbar separator which will accept only the antiprotons for transfer to the Collector Ring (CR). Fast cooling in the CR allows the efficient collection of antiproton bunches which are injected for accumulation and stochastic cooling and post–acceleration in the antiproton ring, the High Energy Sorage Ring, HESR.

1.1. The PANDA experiment at HESR

The HESR (see figure 2) is designed as a racetrack–shaped storage ring with a circumference of 575 m and magnetic bending power of 50 Tm. It is based on a lattice of normal-conducting magnets designed to deliver antiproton beams in the momentum range from 1.5 to 15 GeV/c.

An important feature of this new facility is the high-bandwidth stochastic cooling [6] capable to provide phase-space cooled antiproton beams with which the PANDA internal targets (proton or nuclear targets) opens outstanding capabilities for high precision...
Two operation modes are foreseen: a) the high luminosity mode with peak luminosities of up to $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ and b) high resolution mode with a relative momentum spread of the order of a few $\times 10^{-5}$. Annihilations of antiprotons–protons have enormous advantages compared to proton–proton collisions, such as small momentum transfer at maximum released energy with well-defined initial states. Furthermore, the stochastic cooling available at HESR over the full momentum range, allows for production experiments with high-precision beam energy scans capable to reveal and study unknown features of underlying resonance structures with the PANDA detector [8], [9]. An overview of PANDA physics prospects at FAIR have been presented in this workshop [10] and the PANDA physics program with first beams has been recently published [11], while here, emphasis is given to an overview of the PANDA detector systems.

2. PANDA Detector

The PANDA detector, see figure 3, covering about 12 m along the beam pipe with about 6 m maximal height, will be located in one of the straight sections at the HESR within a dedicated experiment building. As a fixed target experiment the PANDA detector features two spectrometers, the Target Spectrometer (TS) with installation of an internal target within a superconducting solenoid magnet of 2 T around the interaction region and the Forward Spectrometer (FS) with a 2 Tm dipole magnet for the forward boosted particles. Both spectrometers are equipped with several modern particle detector systems to provide excellent charged particle tracking, particle identification, calorimetry and muon detection, over the full momentum range.
Both spectrometers are placed on support platforms, movable into the HESR beam line, and out into the maintenance area of the experiment hall.

In the TS the detector system is enclose the interaction region in a typical onion-like structure, similar to detector designs in collider experiments, providing nearly $4\pi$ coverage. While in the FS the detector systems are arranged along the beam line to cover the forward boosted particles in polar angles up to $\pm 10^\circ$ horizontally and $\pm 5^\circ$ vertically.

2.1. Targets

A cluster jet or pellet target system will be used to provide either a cluster beam of a target gas or frozen hydrogen pellets at distance of about 2.1 m from the source to the interaction point. The Cluster Jet Target system [12] is very advanced with a prototype operating successfully in the Cooled Synchrotron at Forschungszentrum Jülich, achieving world record densities of $4 \times 10^{15}$ atoms cm$^{-2}$. The technical design of the pellet target system is in progress to provide a constant stream of frozen hydrogen pellets of order about 10$\mu$m. Other target types and materials, such as thin foils or noble gases, are also planned in PANDA enabling a variety of novel antiproton-nucleus studies [13].
2.2. Magnets

Two different PANDA magnets [14], are employed in the spectrometers. In the TS the superconducting (SC) solenoid magnet will provide a magnetic field up to 2 T (with a homogeneity of ±2%) in the beam direction. The solenoid with an inner bore of 1.9 m has a segmented coil allowing the target pipe to cross through. Prototypes of SC cable productions by a joint venture of BINP and Russian manufacturer show good progress. The yoke is octant-shaped with retractable doors at either end. Each octant of the yoke is segmented as well as the laminated doors and will be instrumented with chambers for muon identification. All octants and doors of the yoke are produced at BINP and preparations for the first assembly are in progress. The dipole magnet is based on a normal-conducting design and forms part of the HESR beam line. The detailed design is being finished and its production procurement started. It will provide a integral field of 2 Tm for the FS. Within the dipole magnet part of the forward tracking detector systems will be placed.

3. Particle Tracking

Tracking detectors to measure the direction and momentum of charged particles are provided in both PANDA spectrometers. Depending on particle rates and occupancies and fiducial coverage a variety of detector systems are employed.

3.1. Micro Vertex Detector

Closest to the interaction point a silicon based tracker, the Micro Vertex Detector (MVD) as foreseen in the Technical Design Report [15], is arranged in several concentric barrel layers and discs, within an envelop of $25 - 135\text{mm}$ radialy from the Interaction Point and $20 - 230\text{mm}$ in the forward direction along the beam pipe. At the inner most barrel and disc layers Hybrid-pixel sensors of $100 \times 100\mu\text{m}^2$ are planed, and elsewhere double-sided strip sensors of different shapes, rectangles and trapezoids, are foreseen with pitch of $130\mu\text{m}$ and $70\mu\text{m}$ and with stereo angles $90\mu\text{m}$ and $15\mu\text{m}$, respectively. Sensor readout ASICs developed in PANDA [16]will be used with radiation hard front–end readout links and power drivers developed at CERN [17, 18]. Mechanic designs of staves and disk carriers for the sensors, aiming at low material budget $X/X_0 \leq 1\%$ per layer, including cooling and services routing is advanced and prototype tests in-beam show that vertex resolutions of about $50\mu\text{m}$ and an overal momentum resolution of $\leq 2\%$ are achievable.

3.2. Straw Tube Tracker

Closely surrounding the MVD, the Straw Tube Tracker (STT), will be used for tracking charged particles reaching transverse momenta resolutions lower than about 1% in the magnetic field of the Target Spectrometer. The STT, As described in the TDR [19],
uses layers of drift tubes covering the transverse region within \( r_{\text{min}} = 150\,\text{mm} \) and \( r_{\text{max}} = 420\,\text{mm} \) along the length of 1500\,mm. It is based on a self-supporting drift tube design with 10\,mm diameter of 27\,\mu m thin aluminised Mylar with a gold-plated tungsten wire, operated with Ar/CO\(_2\) at overpressure. In total 4600 tubes will be arranged as planar layers parallel to the beam with several layers skewed at a stereo angle of \( \pm 3^\circ \) resulting in a total material budget as low as 1.3\% transverse to the beam. The STT will use ASICs developed in PANDA [20] which can be interfaced to readout systems developed at GSI [21]. Several beam tests with prototypes have demonstrated resolutions of \( \leq 130\,\mu m \) exceeding the design goals and promising PID capabilities of \( p/\text{MIP} \, 4\sigma \) at low momenta \( \mathcal{O}(0.8\,\text{GeV}/c) \). At the time of writing all the tubes for the STT have been produced and the module production along with the mechanical designs and cooling concepts are in advanced stages, including the production of the ASICs and the associated readout cards. Fully operational Straw Tracker Stations based on the STT tube design have been constructed, in planar arrangements akin to the PANDA Forward Tracker (see section FT), for installation at the GSI based HADES (High Acceptance Di-Electron Spectrometer) experiment [22].

### 3.3. Gas Electron Multiplier

In the downstream region, following the STT, the TS will be equipped with a Gas Electron Multiplier (GEM) tracking the forward flying charged particles within the solenoid. Three circular GEM detector stations with successively increasing diameter from 0.9 m to 1.5 m perpendicular to the beam, are being designed, each measuring four projections. The use of large area GEM foils and the tight space requirements with the readout electronics at the outer circumferences place stringent technology demands. A GEM demonstrator has been build to address the challenges of large GEM foil production and detector construction.

### 3.4. Forward Tracking

In the PANDA Forward Spectrometer, the Forward Tracker (FT) System, as described in the TDR [23], is distributed along the beam line in several stations close to the dipole magnet, at the downstream and upstream sides, and within its aperture. The FT uses the same drift tube design as for the STT, yet the drift tubes are placed next to each other and in two staggered layers to form modules which are arranged in planes perpendicular to the beam. Each station comprises four consecutive planes along the beam line, with the outer two oriented vertical to the beam and the inner two at opposite stereo angles of 5\,\degree. The FT will use the same ASICs as for the STT developed in PANDA [20] for readout at the upper and lower ends of the tubes. Two fully operational Straw Tracking Stations are build and installed in the HADES experiment at GSI, which are due for commissioning with beam in the framework of the PANDA@HADES physics program [24, 25]. Recently the LHCb former Outer Tracker [26] stations have become available and are considered as tracking stations behind the dipole during the initial
beam commissioning and data taking phase in PANDA [27].

3.5. Luminosity Detector

Furthest away from the IP, about 11 m downstream along the beam line, the Luminosity Detector (LMD) [28] will be located using elastic scattering of antiprotons on protons to determine the interaction rate by measuring antiprotons deflected at low angles. Thereby the LMD determines the absolute and relative luminosity of the interactions in PANDA. The detector uses High Voltage Monolithic Active Pixel Sensors (HV-MAPS) which are silicon pixel sensors \((80 \times 80 \mu m^2)\) with digital processing on chip, placed on CVD diamond supports. These are mounted on several retractable half-discs, perpendicular to the beam, within a secondary vacuum around the beam pipe. Studies with sensors in test beams at COSY [29] are in progress as part of the FAIR Phase 0 program, along with advanced mechanical prototypes toward detector construction.

4. Particle Identification

Particle identification of pions, kaons and protons and muons in both spectrometers will utilize information from several Cherenkov-light detectors and Time-of-Flight systems and from the muon detection system over the full momentum range in PANDA.

4.1. Barrel DIRC

In the central part of the TS surrounding the inner trackers MVD and STT, the Barrel DIRC (Detection of Internally Reflected Cherenkov light) [30] detector, will be located at 450mm from the IP with polar angle coverage \(22^\circ - 140^\circ\). Rectangular radiator bars of synthetic fused silica, to cover a length of about 2.5 m, with mirrors at one end and compact solid expansion volumes, prisms, on the readout end, coupled with innovative focusing lenses, provide Cherenkov-light of traversing charged particles. The photosensors coupled to the prisms are lifetime-enhanced MCP-PMTs [31], of high granularity and B-field tolerance, are read out with fast FPGA-based electronics developed at GSI [32]. Extensive test-beam campaigns at CERN of advanced prototypes have demonstrated that the PID goals are fulfilled or exceeded, such as the 3 standard deviation pion/kaon separation up to 3.5 GeV/c. The Barrel DIRC construction is underway, currently with radiator bars production at Nikon Corp., Japan, and extensive QA measurements at GSI and with the validation of MCP-PMTs from different vendors at FAU-Erlangen in progress. In addition, FAIR Phase 0 activities at JLAB are in progress using revived BaBar DIRC detectors to optimize simulation and reconstruction code with experimental data from GlueX DIRC [?].

4.2. Disc DIRC

PID of the forward flying charged particles within the TS is provided by the Endcap Disc DIRC detector [34] covering polar angles \(5^\circ - 22^\circ\). This novel design uses four large area
radiator plates of synthetic fused silica, arranged perpendicular to the beam line, with only 5cm thickness. The optical expansion and focussing elements are coupled at the outer rims, including the MCP-PMTs and their ASIC-based readout. This novel design has been validated with particle beams and shown to reach the PID goal of 3 standard deviation pion/kaon separation up to 4 GeV/c. Optimizations and technological updates are in progress with increasingly advanced first-of-series components.

4.3. Forward RICH

Particle identification in the FS will be provided by a Ring-Imaging Cherenkov detector (RICH). The compact detector uses a focusing aerogel-based design with radiators made of stacks of multiple aerogel tiles with different refractive indices placed perpendicular to the beam pipe. Segmented focussing mirrors reflect the Cherenkov light to photosensors, multianode photomultipliers above and below the beam pipe. Prototypes of high-quality transparent aerogel tiles with finely-tuned refractive index produced at NSU [35] demonstrated in beam tests at BINP a PID performance of $\leq 3$ standard deviation pion/kaon separation for 2-10 GeV/c.

4.4. Barrel TOF

In the TS surrounding the Barrel DIRC, a Time-of-Flight system (ToF) [36] is foreseen sharing the same mechanical structure around the IP region within the solenoid field. Individual scintillator tiles use photosensors SiPM (Silicon Photomultiplier) on their edges are placed within fibre structures to result in a segmented hodoscope along the 2.5m length, while signal transmission of each tile to the ASIC-based readout is provided by embedded long multilayer PCBs. Prototype tests of the Barrel TOF have shown resolutions as low as 60ps, and further advanced tests and system optimizations for components series production are in progress.

4.5. Forward TOF

In the FS a Forward Time-of-Flight wall [37] is foreseen, downstream of the RICH. Based on a planar geometry of long plastic scintillator slabs with photomultiplier tubes at both ends, top and bottom, and FPGA-based readout, resolutions better than 100 ps are achievable as shown in beam tests at PNPI. Component tests, validations and system optimizations at PNPI are in progress prior to starting series production.

4.6. Muon Detectors

Instrumentation for muon detection [38] in PANDA for both the TS and FS is based on Mini Drift Tubes with readout of the wire and the orthogonal cathode strip (two coordinates) using modern, newly developed FPGA systems. About 4200 Mini Drift Tubes interspersed within iron absorbers will be employed for muon detection, pion background discrimination and neutron registration by means of penetration range and
patterns. In the TS the muon detectors are inserted within the laminated yoke octants of 3 cm thick iron absorbers and planar absorbers 6 cm thick in the forward magnet doors and muon filter. While in the FS the Muon Range System with 15 layers of 6 cm thick iron plates is placed perpendicular to the beam further downstream of the FSC. Extensive beam tests with the muon range system prototype at CERN and simulations [39] show that muons, pions and neutrons can be resolved down to momenta of sub-GeV/c.

5. Calorimetry

In the TS the whole EMC [40] is based on second-generation lead tungstate (PWO II) crystals in three distinct detectors providing hermetic coverage almost to the beam pipe. These crystals exhibit high qualities of scintillation yield, optical transmission and radiation hardness with a small radiation length, about $22X_0$ for 20 cm long crystals used in PANDA and a short decay time about 6.5 ns and with further increased light yield since in PANDA they are operated at $-25^\circ C$. In several beam tests advanced prototypes have been validated, achieving an energy resolution of $1.5%/\sqrt{E}$, with E in units of GeV. In the FS a sampling calorimeter, Shashlyk-type [41] is foreseen.

5.1. Barrel EMC

The Barrel EMC, within the solenoid, surrounds the Barrel DIRC and TOF with a total of 11360 crystals placed in 16 similar slices adjacent in azimuth. Within a slice different tapered geometries of crystals facing the IP region, are placed inside high-precision compartments, the alveols, inside the cold volume (at $-25^\circ C$). Two photosensors, large area Avalanche PhotoDiodes (APDs) $7 \times 14 \text{mm}^2$, designed for PANDA, are glued on the rear face of each crystal with pre-amp ASICs, developed at GSI [42]. Dedicated irradiation screening of all crystals, photosensors and pre-amp ASICs are well underway and all mechanical components, such as alveols, have been produced. The first fully assembled slice is subject to extensive system tests while preparations to assemble further slices are in progress as crystal production continues.

5.2. Forward Endcap EMC

The forward region of the TS is covered by the Forward Endcap EMC with 3856 crystals of a single tapered type placed on a circular frame perpendicular to the beam. Due to the high occupancy in the center of the endcap the photosensor chosen there is the VPTT, whereas elsewhere the large area APDs are used. On detector readout is provided with sampling ADC systems located on the rim of the frame. With all crystals available, the production of submodules are well advanced and final system checks are on-going before mounting the units onto the frame; ready for beam.
5.3. Backward Endcap EMC

Hermeticity, upstream of the IP region, is provided with the Backward Endcap EMC with 524 straight crystals with large area APDs. With all crystals produced and all components available submodule series production and detector construction is due to commence. In addition, FAIR Phase 0 activities are scheduled to use the Backward Endcap EMC in high-resolution electron scattering experiments at MAMI [43].

5.4. Forward Shashlyk Calorimeter

In the FS the Forward Shashlyk Calorimeter [41] is foreseen in front of the Muon Range System. It is designed with interleaved plastic scintillator tiles (0.3mm) / lead absorber plates (1.5mm) over a length of 680 mm using WLS fibers coupled to PMTs and readout with sampling ADC systems. Several prototype system beam tests show an energy resolution of $3\% / \sqrt{E}$ and time resolutions of $100 \text{ps} / \sqrt{E[GeV]}$ can be achieved. Component production at IHEP and procurement of PMTs and SADCs are being prepared while optimization studies continue [44].

6. Data acquisition and Controls

6.1. DAQ

The Data AcQuisition (DAQ) in PANDA is based on a triggerless readout scheme with flexible data selections in order to accommodate numerous physics channels. A new type of intelligent readout of the front-end electronics (FEE) is being considered, where kinematical constraints can be imposed online on event data across the PANDA detector systems. Developments are centered around a common hardware design throughout PANDA, operating within the common clock-domain, yet with detector specific FEE connectivity and flexible processing functionalities. Also, recent TDC front-end developments at GSI [45] are being used in several detector systems. A data reduction factor of up to about $10^3$ is expected to be achieved by employing this technique for the whole detector, resulting in a data rate of about $10^4$ events/s to transfer for offline processing and analysis in the local FAIR Computing Centre at GSI.

6.2. Detector Control System

Controls, configuration, and monitoring for each detector system in PANDA will be based within the framework of Experimental Physics and Industrial Control System (EPICS) [46], as described in the dedicated Technical Design Report[47]. This provides a layered approach with detector system specific drivers, connected to a PANDA-wide generic access layer and a supervisory layer with interfaces to control and monitor GUIs for the shift crew on the status of the detector, the DAQ and the HESR beam line.
7. Outlook

FAIR is a large-scale project with a phased schedule being implemented, with the PANDA experiment planning fully embedded. The staged approach to FAIR science and progressive commissioning of accelerators and detectors encompasses: the FAIR phase 0, currently in progress, followed by FAIR phase 1 with start configurations of experiments in place and the accelerators progressively approaching design parameters. Several PANDA detector systems are currently in a procurement and construction phase while other completing advanced prototype studies with validations and optimizations in dedicated beam tests. Already PANDA detector instrumentations are actively involved in the FAIR phase 0 program. FAIR is a unique opportunity for world science, with a fascinating and broad science program, with world class and pioneering experiments. Antiproton beam facilities are firmly embedded in the FAIR planning and the PANDA experiment is fully integrated in the FAIR schedule.

References

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