PANDA at the GSI future facility

Kai-Thomas Brinkmann

"Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden

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Abstract

PANDA is the multi-purpose detector that is under construction to cover most of the measurements using antiprotons from the high-energy storage ring, HESR, which will become possible at the GSI future facility. The detector setup has to meet the requirements of a broad physics programme, which ranges from high-resolution resonance spectroscopy in the charmonium region to the production of open charm in annihilations of antiprotons on heavy nuclei. The interaction rate of up to $10^7$ annihilations per second requires sophisticated trigger concepts, which are in part based on vertex detection. To this end, PANDA will be equipped with a compact state-of-the-art micro-vertex detector. Its data shall be used for D meson identification at data acquisition time. Layout of the vertex detector and its interaction with the other detector parts are discussed and an introduction into the physics programme is given. © 2001 Elsevier Science. All rights reserved

GSI future facility; antiproton physics; PANDA experiment; hydrogen and heavy ion fixed targets; micro-vertex detector

1. Introduction

The PANDA detector will be the site of the internal experiment at the high-energy storage ring, HESR at the GSI future facility, where antiprotons with momenta up to 14.5 GeV/c will be available for experiments on hydrogen and nuclear targets. The main focus of these fixed-target experiments will be on physics involving charm degrees of freedom. Because of the short decay lengths of charmed mesons, their decay into a large number of different channels, and the small cross sections encountered in at least part of the reaction channels of interest, an effective means to enhance the charmed over background events is a prerequisite for the physics programme. Part of this enhancement of useful events in the early trigger chain will be achieved using a compact micro-vertex detector (MVD) made from state-of-the-art silicon sensors. Using a very compact design for the vertex detector and aiming at the

* Corresponding author. Tel.: +49-351-463-34239; fax: +49-351-463-37292; e-mail: KT.Brinkmann@physik.tu-dresden.de.
detection of particles of rather low momentum, the PANDA vertex detector has to be carefully optimised, also with respect to the other detector components.

2. Experiments at the new facility

2.1. General remarks

Physics at the GSI future facility is centred around an assembly of accelerators, which serve a wide variety of requirements for very different experiments. They form an extension of the present Unilac/SIS18/ESR complex, which accelerated ions up to Uranium to relativistic energies in excess of $1\,\text{A}\cdot\text{GeV}$. Here, the upgrade is aiming at an increase in intensity of at least one order of magnitude and an adoption of the system also for very intense proton beams. These beams of very high brilliance and beam power will be used in the plasma physics programme.

The SIS18 then serves as an injector to the SIS100 booster which shall accelerate up to $2\cdot10^{13}$ protons per second to 30 GeV, or $10^{10}$ U ions to 25 A-GeV. These beams can be stored in and slowly extracted from the SIS 200 while the SIS 100 serves other experiments.

The extracted heavy ions are used in experiments on the behaviour of hot and dense nuclear matter. These studies are the focus of the compressed baryonic matter experiment, CBM [1], which proposed a detector that is optimised for the detection of open charm and strangeness as well as lepton pairs. The CBM trigger foresees a clean separation of charm decays and is thus similar to the PANDA ideas in these respects. CBM favours MAPS [2] sensors for the tracking detectors closest to the target and strips for the less critical layers at larger distance.

Apart from the high-quality primary beams, the ability to produce and store secondary beams with high efficiency is a key feature of the facility. To this end, several collector and storage setups exist for radioactive secondary beams, which may be produced by fragmentation, analysed according to mass and charge, and stored in the low-energy storage ring, NESR.

Protons can be used to produce antiprotons, which are collected and cooled to be reinjected into the SIS 100, and then stored at momenta between 0.8 and 14.5 GeV/c in the high-energy storage ring, HESR, where PANDA is located. In normal operation, the HESR will hold $10^{11}$ circulating antiprotons. At a length of about 400 m, the HESR will be equipped with an 8 MeV electron cooler as well as stochastic cooling to counterbalance the beam heating due to the hydrogen target of PANDA. Stable operation will be accomplished with luminosities of $2\cdot10^{32}\,\text{cm}^{-2}\text{s}^{-1}$ at relative momentum spreads of better than $10^{-4}$. For experiments that need optimum momentum resolution, a second mode is foreseen where lower target densities allow relative momentum spreads of better than $10^{-5}$ at luminosities of $10^{31}\,\text{cm}^{-2}\text{s}^{-1}$.

2.2. PANDA physics potential

The proposed PANDA detector serves the needs of a variety of experiments with antiprotons. It has been designed to allow the investigation of the properties of hadrons and their interactions in the relevant energy range up to about 5.4 GeV in the centre-of-momentum system. In particular, the programme is driven by:

- Spectroscopy of charmonium states around the $D\bar{D}$ threshold, where precision measurements of the masses, widths, and decay patterns are still sparse. In particular, there is a lack of information on all states of higher angular momentum that cannot be directly formed in electron-positron collisions.

- Search for gluonic excitations such as glueballs and charmed hybrids, which are theoretically predicted with widths that should make them readily observable among the two-quark states in the charmonium mass region.

- Hypernuclei, which form the “3rd dimension of the chart of nuclei”, will be investigated using a specially designed target that features a wire target in which hyperon-antihyperon pairs will be created, and a sandwiched secondary target in which one of the hyperons is detected in a stack of highly granular detectors in order to tag the interaction of its partner with and its capture in a nu-
The decay of the formed hypernucleus will then be observed with $\gamma$-spectroscopic means. The secondary target is formed with pixel detectors interleaved with sheets of target material. Possible candidates for the detectors are CCD type detectors [3].

- In-medium properties and possible modifications compared to the vacuum for charm quarks will be studied. A possible link to chiral restoration in the nuclear medium has been deduced from the study of pion [4] as well as kaon properties in nuclei [5]. Nothing is known for the charm sector.

- Increasing luminosity will allow further issues to be addressed, such as the search for CP violation in the charmed D mesons and in hyperon-antihyperon pairs. Information on generalized parton distributions complementary to lepton scattering experiments can be extracted from antiproton interactions.

A couple of new, possibly exotic, states have recently been observed in the meson sector (e.g. $D_s$ [6]). There are also surprising candidates observed in proton-antiproton [7] as well as in baryon-excitation reactions [8]. Any of these may come into focus within the next years, so that PANDA may come just in time to contribute important information.

### 3. Detector setup

#### 3.1. Layout of the PANDA detector

The proposed PANDA detector at the High-Energy Storage Ring of the GSI Future Facility is shown in figure 1. Its magnet layout will combine a forward dipole spectrometer with a solenoid field region around the target. Despite the strong forward boost of a fixed-target experiment, coverage in both forward and backward direction is crucial for certain types of reactions where low-energy pions and kaons may be emitted in $4\pi$.

Angles below 10° in forward direction will be covered by a dipole spectrometer with a large 1 m gap, which will be equipped with drift chamber tracking, particle ID layers as well as electromagnetic and hadronic calorimetry.

The central superconducting solenoid surrounding the target has a maximum field of 2 T. Photons will be measured in an electromagnetic calorimeter of high granularity. Due to the operation inside of the instrumented flux return yoke, APD readout is foreseen for the 7150 PbWO$_4$ crystals. This material has been selected for its fast readout capability. A Cherenkov detector of DIRC type [9] in the barrel structure, augmented by a forward RICH, will allow efficient particle identification down to momenta of about 750 MeV/c, where the pion-kaon separation via Cherenkov radiation ceases to be efficient. At lower momenta, time-of-flight measurements will help to identify particle species.

The outer part of the tracking section will consist of 15 double layers of straw detectors. The lightweight design of the 9000 tubes and their self-supporting structure is chosen to minimize straggling and photon conversion. Inside of the straw detector just around the beamline, a micro-vertex detector will be used to give an accurate account of the particle tracks very close to the interaction region.

![Fig. 1: Layout of the proposed PANDA detector at the high-energy storage ring of the GSI future facility (top view; see text for details).](image)

#### 3.2. PANDA targets

The very broad physics programme targeted by the PANDA experiment will require a number of different target setups, which have to be accommodated within the layout of a single detector. Experiments on the proton can be performed using quite different target concepts. Cluster-jet and pellet targets are under discussion. Both concepts will need to bring in the target material from outside of the iron
yoke through a pipe, which breaks the detector rotational symmetry and takes up space, which cannot be equipped with active detector material.

Hydrogen cluster-jet targets reach average densities of the order of $10^{15}$ atoms/cm$^2$, allowing luminosities of $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$ with beams of $2 \times 10^{11}$ protons stored in the HESR. The interaction region of cluster-jet beams will be of the order of cm in length, the diameter will be given by the beam emittance. Under these conditions, the primary vertex of each event will not be known and will have to be inferred from the tracking. With stochastic cooling of the beam, the momentum spread should be kept below $10^{-4}$.

In an alternative concept, frozen hydrogen pellets of a few tens of µm diameter can be formed in a narrow stream traversing the HESR beam, thus reaching $10^{31}$ cm$^{-2}$s$^{-1}$ with beams of $5 \times 10^{10}$ protons stored in the HESR. This mode of operation can be used for high-resolution studies that reach momentum accuracies of $10^{-5}$ in the primary beam when electron cooling can be used, probably up to 8 GeV antiproton energy. The effective target density reached with pellets is about $10^{16}$ atoms/cm$^2$. In principle, the trajectory of each pellet can be monitored to a few µm, so that the primary interaction point for each event is accurately known.

For experiments on heavy ions, heavy gases may be used. Alternatively, wires or foil targets can be mounted inside of PANDA. Then, the primary interaction point in beam direction is known very well.

In any of these cases, $10^7$ interactions per second have to be coped with and scanned with high efficiency for events of any wanted pattern, which in particular concerned displaced decays of charmed mesons. This is not easily done, considering that characteristic decay lengths are of the order of $\tau = 124 \mu$m for the neutral D’s and $315 \mu$m for the charged D’s. The D mesons all show large branching ratios into K mesons, so that detection of displaced strange decays may also help in enhancing D production over background. Quite often, charm tagging refers to offline determination of displaced vertices in the analysis. One of the experimental goals of PANDA is a considerable enhancement of charm events in the online stage of the experiment. This will be done by lepton tagging and, whenever possible, by reconstruction of vertices.

### 3.3. The PANDA MVD

The inner tracking device for the PANDA setup shall allow the determination of secondary vertices with a resolution considerably better than 100 µm. In the conceptual-design phase, standard state-of-art techniques as used in ATLAS [11], CMS [12], and ALICE [13] were considered for the construction of a barrel and forward wheel. Figure 2 shows the schematics of the layout. The very compact detector has about 7.2 million pixels in the barrel part and 2 million forward pixels. The 200 µm thick sensors (corresponding to 0.25% $X_0$) are arranged in five layers in the forward part of the barrel. In the backwards hemisphere, only three layers are foreseen because of the considerably smaller track density.

The bump-bonded readout chips are assumed to be 300 µm thick (0.37% $X_0$). With this initial setup, Monte Carlo studies of the detector performance have been used to improve the detector design.

![Fig. 2: Schematics of the layout of the PANDA MVD. All lengths are given in mm unless other units are indicated.](image)

The layout shown in the figure yields a primary vertex resolution of $\sigma_z = 82 \mu$m in longitudinal direction and a radial resolution of $51 \mu$m for a reaction with four primary pions in the exit channel. While this is within the performance limits, further optimisation may result in even better resolution. In addition, the early simulation rounds did not take efficiency losses due to holes, e.g. for the beam pipes, into account, and cabling, detector mounts and cooling for the readout electronics were not considered. Hence, at present a set of simulations is under way in order to study the balance between all these effects.
3.4. Simulations of the detector performance

3.4.1. General remarks

A series of simulations is under way to study the detector performance. All simulations use the GEANT 4 framework and various event generators designed for the purpose. Optimisation focuses on the mutual interaction of the various detector components as well as a detailed understanding of the operation of each of the components as stand-alone devices. For example, the momentum resolution for charged particles in the target spectrometer is influenced both by the straw tracker and the inner vertex detector that dominates in the primary vertex determination. Figure 3 shows a result of such a simulation for the charged kaons from the $\bar{p}p \rightarrow \phi \rightarrow K^+K^-K^+K^-$ reaction.

The transversal momentum resolution improves with increasing polar angle. In general, it is better than 2.5% over the full momentum range. At smaller polar angles, the resolution is given by the forward spectrometer, which yields an even better momentum measurement.

3.4.2. Micro-vertex detector optimisation

Special attention is given to the optimisation of the vertex detector layout. The setup that is favoured at present is based on available detector technology similar to the pixel detectors used by other experiments [11, 12, 13]. It features however a much more compact design. The $4\pi$ layout is compromised by the need for a target pipe, which causes a gap on top and a second gap in the bottom for the target exhaust. A BeAl alloy beam pipe with a thickness of 500 µm shall separate the accelerator ring vacuum from the detector. If possible, a diameter of only 20 mm (cf. fig. 2) will be used. Some of the target options may however require bigger cross sections to allow for sufficient pumping and extended target beam diameters. Therefore, a 40 mm option is considered as an alternative. It will reduce the angular coverage of the detector significantly, unless the vertex detector is accordingly scaled to larger size.

With the low energies of some of the particles encountered in the experiments envisaged, small angle scattering will be significantly reducing the spatial resolution of the track reconstruction. This has been investigated using a barrel constructed from 90 staves carrying 150 µm thick sensors read out with bump-bonded 100 µm chips on a 200 µm bus and cooled by water pipes which contribute 0.4% of $X_0$. The total effective thickness seen by a particle penetrating the silicon detector barrel thus is between 1% and 3.6% $X_0$ depending on hit position on the five-layer structure. Multiple scattering has been investigated for muons of 1 GeV. Table 1 summarizes the results of this simulation. It can be inferred from the table that small-angle scattering dominates in the resolution that can be achieved with a five-layer structure even for rather energetic muons.

Figure 4 shows that the spatial resolution is well within the design goals of about 100 µm in either direction unless very small or large polar angles are considered where the particles penetrate thicker...
layers of detector material (due to the $1/\cos \theta$ increase of the traversed thickness).

Table 1: Small-angle scattering in the MVD layers; see text for details.

<table>
<thead>
<tr>
<th>Layer (or disk) number</th>
<th>Detector Resolution [µm]</th>
<th>Multiple scattering for different polar angles [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>φ</td>
<td>Z(R)</td>
</tr>
<tr>
<td>1</td>
<td>12 (40)</td>
<td>70 (25)</td>
</tr>
<tr>
<td>2</td>
<td>12 (40)</td>
<td>70 (25)</td>
</tr>
<tr>
<td>3</td>
<td>12 (40)</td>
<td>70 (25)</td>
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<tr>
<td>4</td>
<td>70 (40)</td>
<td>12 (25)</td>
</tr>
<tr>
<td>5</td>
<td>70 (40)</td>
<td>12 (25)</td>
</tr>
</tbody>
</table>

Further optimisation concerns the orientation of the rectangular sensor pixels with respect to the beam. The detector resolution depends on the orientation in each of the layers, with alternating long and short dimensions in beam direction yielding the optimum detector resolution.

3.5. Further considerations in detector design

With a detector system that will be mounted as close as possible to the circulation antiproton beam and an estimated interaction rate of $10^7$ per second even on heavy targets, an appreciable flux of neutrons and low-energy charged hadrons will put a considerable radiation load on the vertex detector. For antiprotons on Fe targets, average multiplicities include ten neutrons, ten protons and ten additional hadrons. At a radius of 10 mm, the neutron flux may reach $10^6$ neutrons per cm$^2$ and second. Then, we expect a maximum integrated flux of $3 \times 10^{13}$ neutrons per year for experiments on heavy targets and less for reactions on hydrogen.

3.6. Data acquisition and trigger

For the data acquisition and selection of events of interest, an electronic design is planned where all detector elements will be synchronized via distribution of a clock with 50 ps time-constant. The signals from the detector will all be digitised in flash ADCs. FPGAs and commercial CPUs will be used to reduce the amount of data on the fly and select events which fulfill the required patterns, e.g. for delayed decay of D mesons. Commercially available computer memory will buffer the data during the computing cycles needed for the trigger decision. This self-triggered data-push architecture will allow parallel selection of very different event types.

4. Summary and conclusions

PANDA at the planned GSI future facility will have a rich physics programme. A very broad range of physics topics shall be covered with a single multipurpose detector. Therefore, this setup has to meet requirements of very different experiments. For most of these experimental challenges, a compact microvertex detector is essential, as can be inferred from the many key experiments that rest upon the detection of charmed mesons, usually accomplished through the identification of a secondary vertex. At PANDA, on-line enrichment of events involving D mesons is a key feature. To reach this end, extensive studies of the detector layout employing state-of-the-art detector technology are under way.

References