Triggerless Micro Vertex Detector with low material budget in the PANDA experiment

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Abstract. Besides the typical features characterizing the silicon detectors in the High Energy Physics such as good spatial resolution, energy loss measurement, limited material budget and radiation hardness, the Micro Vertex Detector (MVD) for the PANDA experiment (at the FAIR Facility in Darmstadt connected to the GSI Laboratory) is requested to cope with special issues. The expected study of many physics channels at high antiproton-proton annihilation rates (2·10⁷ ann/s) is asking for a triggerless readout with a continuous data transmission and a good time resolution. The wide particle momentum distribution starting from some hundreds of MeV/c asks both a very limited material budget and a high dynamic range. The MVD is composed of: hybrid pixel (100μm ×100μm) detectors with thin silicon epitaxial sensor and readout developed by 130nm CMOS technology and double sided silicon strip detectors with supporting mechanics based on carbon fibres. Carbon foam layers will improve the heat transfer towards the cooling system based on water and working in vacuum-operated mode. Last developments in the MVD design and results concerning the prototyping phase are reported.

1. Introduction
PANDA [1] is one of the main experiments foreseen at the new FAIR [2] facility at GSI, in Darmstadt.

The apparatus will be installed in the antiproton High Energy Storage Ring (HESR). Antiproton momentum starting from 1.5 GeV/c and ranging up to 15 GeV/c extends the field of physics study performed many years ago at the LEAR (Low Energy Antiproton Ring) facility at CERN. New physics goals will be: precision spectroscopy of the charmonium states, establishment of gluonic excitations, search for modifications of meson properties in the nuclear medium and precision gamma-ray spectroscopy of single and double hypernuclei.

To achieve this physics program the PANDA apparatus has to be characterized by a coverage extended nearly to 4π solid angle, vertex reconstruction and good particle identification performances. A characteristic aspect of the experiment is the triggerless data acquisition system to manage an average number of 2·10⁷ antiproton proton annihilations/s, meaning that hit identification, digitalization and data sparsification must be made locally since a continuous data transmission of all events will be implemented.

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In particular, the core of the apparatus is the Micro Vertex Detector (MVD) which is envisaged for the detection of charged particle hits with a performance that yields an overall spatial resolution accuracy better than the characteristic decay lengths of the involved charmed mesons (123 μm in the case of D⁰) as well as those from kaons and hyperons. Owing to particle momentum spectrum starting from few hundreds of MeV/c, a limited material budget, only a few percent of the total radiation length, and large dynamic range for energy loss measurement, to help particle identification, are requested. Besides the detector has to cope with a fluence of about 5·10¹³ n [1MeVeq]/cm², estimated per year considering a 50% duty cycle of data taking, for antiproton-proton interaction and incident antiprotons with a 15 GeV/c momentum.

To manage these requirements the MVD layout is based on both pixel detectors and double sided silicon strip detectors, supported by lightweight mechanical structures and using carbon foam material to improve thermal dissipation of the electronics part. The layout has been translated using a CAD converter to the PANDARoot simulation framework and its optimization is ongoing.

In particular, the pixel detectors are based on the standard hybrid technology but using a custom solution for the front-end readout chip, developed by 130nm CMOS technology, and thinned epitaxial silicon sensors equipped with pixels of 100μm x 100μm size. At present, a reduced scale prototype for the front-end (ToPix v2), using the Time-over-Threshold (ToT) [3] technique to implement the energy loss measurement, has been completely tested both for electrical functionalities and radiation damage. Meanwhile first hybrid assemblies with thinned epitaxial sensors were tested using radioactive sources, showing good performances [4]. Displacement damage test of some silicon diodes with neutrons from a nuclear reactor has been performed, showing annealing effects on the high resistivity epitaxial silicon material used for these first prototypes.

Concerning the double sided silicon strips first prototypes using a reduced scale sensor have been assembled and a tracking station has been built [5].

2. The Micro Vertex Detector
The MVD (figure 1) is composed of four barrels, the two innermost ones made of pixels, and the two outermost ones made of double sided silicon strips. They are arranged around the interaction point where there is the junction between the beam pipe and the target pipe.

![Figure 1. MVD detector around the beam pipe. The outermost pixel barrel and the two double sided strip barrels are partially drawn to allow the six pixel disks visible. The last two pixel disks are surrounded by double sided strip rings.](image-url)
Six disks based on pixels are positioned in the forward direction, the last two surrounded by a ring of double sided silicon strips each.

This asymmetric layout depends on the emitted particle distribution being strongly peaked in the forward region in the case of antiproton-proton interactions. Meanwhile the foreseen study of antiproton-nucleus interaction is asking for a more symmetric arrangement of the silicon detectors around the antiproton direction. Figure 2 and figure 3 show overall emitted particle distributions with respect to polar angle Theta as a function of hydrogen and argon target respectively, with an incident antiproton momentum of 15 GeV/c.

![Figure 2. Expected particle distribution from antiproton-proton interaction.](image1)

![Figure 3. Expected particle distribution from antiproton-argon interaction.](image2)

The total coverage of the hybrid pixel part requires about 10.5 Mpixel, with a partition of about a half on the barrels and the second half on the forward disks, arranged in hybrid pixel modules.

A hybrid pixel module is a stack consisting of tiled readout chips (each chip is equipped with 12760 readout cells), directly connected by bump bonding to the same epitaxial sensor. On the other side of the sensor the bus for signal and power routing is glued and on the top a controller chip is foreseen to communicate with the readout chips. Hybrid modules with a different number of readout chips (2, 4, 5 and 6) are needed in the detector; they are completed by controller chips that serve small sets composed of two or three ToPix readout ASIC with the possibility of daisy chaining to save on cables. For the outermost pixel barrel staves two 6-chip modules will be in chained configuration to keep a lower number of cables. The maximum event rate per cm² is ~12.3 MHz and the maximum data rate per readout chip is ~800 Mbit/s.

Each stave of the pixel barrel foresees hybrid pixel modules glued to a carbon foam layer supported by an Omega shaped structure, based on carbon fibers, including a cooling pipe made of MP35N Ni-Co alloy (2 mm external diameter, 1.84 mm internal diameter) (figure 4). All pixel disks are made from two parts along the vertical plane. In a preliminary design two slices of carbon foam, each 2 mm thick, glued together embedding cooling pipes make a pixel half disk (figure 5). The hybrid pixel modules will be glued to both sides of the half disk in an alternating configuration to obtain the optimum angular coverage.

The strip part coverage is obtained with rectangular sensors for the barrel part and with trapezoidal sensors for the rings, a 250 µm thickness is planned. The rectangular sensors feature a stereo angle of 90° and a readout pitch of 130 µm and the trapezoidal sensors are distinguished by a stereo angle of 15° and a smaller pitch of 70 µm due to the smaller stereo angle which tends to worsen the spatial resolution. The foreseen strip readout channels are about 0.2 Mchannel.

A mapping of the material budget concerning the MVD layout under study has been obtained reporting the contribution of different parts (sensors, electronics…) and from which a X/X₀ ~ 1% is reached for each MVD layer (figure 6). In particular for the cabling part this analysis takes into account, for the pixel part, aluminum busses and cables, as obtained by a preliminary study of prototypes carried out with the aluminum deposition technique. The enhancement at 40° is due to the mechanical supports of the strip rings and to the pixel disk cables and cooling pipes bending towards the upstream region.
The MVD allows a momentum resolution improvement up to 50% when its information is added to the tracking in PANDA and it is mandatory for obtaining the single track resolution [6]. Benchmark channel studies (pbar-p \( \rightarrow D^+D^- \)) confirm good primary and secondary vertex resolution: \( \sigma_{x,y} \leq 35 \mu m \) and \( \sigma_z \leq 100 \mu m \) [7]. The maximum data flow foreseen from MVD is \( \sim 100 \) Gb/s.

**Figure 4.** Hybrid pixel module, equipped with five readout chips, for a barrel stave.

**Figure 5.** Half disk of the hybrid pixel detector

**Figure 6.** Mapping of the material budget of MVD

3. Hybrid pixel detectors, results from first prototypes
ToPix_v2, developed in the 130 nm CMOS technology, is a reduced scale prototype, self triggering, equipped with two 128 columns and two 32 columns controlled by a simplified end of column circuit.

Each pixel readout cell consists of a charge amplifier with a feedback circuit with a constant current discharge capacitor, then the amplifier output signal feeds a comparator. A 12 bits time stamp generated by a Gray counter is propagated in parallel to all cells. The time stamps corresponding to the leading and trailing edges of the comparator output signal, respectively, are stored in two registers. The first one is the event time, while the time difference gives the ToT information proportional to the particle energy loss. The communication for the chip testing was implemented at 50 MHz and the measured average gain is 152 ns/fC with a \( \sigma = 6 \) ns/fC over a 100 fC range. The noise due to the analog part is around 0.025 fC (160 electrons). The overall noise level is about 0.032 fC (200 electrons) and takes into account also the quantization error. Radiation damage tests were performed from which it was concluded that enclosed structures for the transistors of the analog part of the readout cell and triple redundancy scheme for the registers of the digital part to avoid total ionizing dose and single event upset effects are needed [9].
Concerning the sensor, n-type epitaxial material is under study. Diodes featuring parameters as shown in table 1 and irradiated with neutrons from a reactor for displacement damage test show a reverse annealing in the full depletion bias voltage measurements [9]. New diodes will be tested to study the reverse annealing as a function of the epitaxial resistivity.

Table 1. thickness and resistivity of the epitaxial layers

| Epi layer | Thickness  | Resistivity  |
|-----------|------------|--------------|
| Epi-50    | 49 ± 0.5 μm| 4060 Ω·cm    |
| Epi-75    | 73.5 ± 1 μm| 4570 Ω·cm    |
| Epi-100   | 98 ± 2 μm  | 4900 Ω·cm    |

A first reduced scale prototype of a disk (figure 7) to study electronics cooling has been built. Resistors simulating readout chips and dissipating a relative power of 1 W/cm² (a 2 safety factor has been considered) are glued on the Poco-HTC carbon foam [8] and the cooling fluid is water with 18.5 °C inlet temperature. The maximum detected temperature was 32 °C. A half disk prototype picture is shown in figure 8.

Figure 7. Prototype for studying the disk cooling system. Six resistors simulating readout chips are glued on both side of a 4 mm carbon foam layer embedding cooling pipes.

Figure 8. Half disk prototype consisting of a 4 mm carbon foam layer with three embedded cooling pipes.

4. Double sided silicon strip detectors, results from first prototypes
First prototypes of double sided silicon strip detectors have been assembled and tested. In particular a 2 cm side silicon sensor, characterized by a 300 μm thickness, 90° stereo angle and 50 μm pitch, is readout by APV25-S1 chips. In figure 9 a schematic view of one prototype based on a modular concept is shown. The silicon sensor is glued to two L-shaped circuit boards allowing a double sided readout with a total number of six readout chips via ceramic pitch adapters.

In figure 10 the energy distribution obtained using a ⁹⁰Sr source is shown next to the linear correlation between the charge collection from both sensor sides indicating a proper operation of the sensor under study. Figure 11 shows a 2D image of an SMD device from which a resolution of 49 (±7) μm has been evaluated [5]. Four prototypes have been assembled in a tracking station for tracking algorithms study.

5. Conclusion
The MVD design of the PANDA experiment is in progress with a parallel software development to evaluate physics performances. The prototyping phase has started and results from first prototypes have been obtained both for hybrid pixel detectors with the epitaxial material study and first readout chip prototype tests and for double sided strip detector with the characterization of a 2 cm side sensor. In addition first cooling tests have been done and first lightweight mechanical supports have been built. Still some challenging tasks have to be studied and optimized.
6. Acknowledgement
The authors thank all people of the PANDA MVD group made by the collaboration among the HISKP of Bonn, the Forschungszentrum of Julich, and the INFN of Torino.

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