PANDA Technical Assement Group: Tracking

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Contents

1 Introduction

This document is a working document dealing with the effort made by the PANDA Technical Assessment Group (TAG) tracking. Main scope of this TAG is the definition of requirements for the tracking detectors and the procedure needed to come to a final concept and layout of the PANDA tracking system. Apart from the author members of the TAG are:

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Significant contributions from other members of the PANDA collaboration have been integrated as well.

Since this is a working document it reflects the current status of the work and will be updated regularly after discussions among the TAG team until it reaches its final version. Therefore comments and remarks are included to highlight where more work is needed or inaccuracies and mistakes are given.

2 Requirements for the tracking detectors

Requirements for the tracking of the PANDA detector should be derived from the important physic channels. To ensure an easy access to the required information we defined a small set of channels which are regarded as important concerning the tracking properties of PANDA and will therefore serve as tracking benchmark channels in future, see section chapter 2.1.

The requirements for each tracking component inside PANDA are discussed individually to accommodate the specific technology of each detector part. Scope of this document is not to define such requirements but to specify in detail the performance questions on the basis of the detector technology which have to be addressed by the simulation of the benchmark physics channels. This discussion shall be concentrated in terms of figures of merit which of course have to be defined for each sub-detector in the first place. Now given values are based on experience and educated assumptions about the needs within PANDA and the possibilities of the different detectors types and are summarized in the Appendix 5.

The simulation work needed to derive the final requirements can be divided into a two stage process. In the first stage basic figures of merit for each sub-component are used to optimize the detector design and layout. In a second stage the entire PANDA tracking system is considered to incorporate also more complex processes and requirements in the optimization work.

To reflect this approach one can find in this document for each sub-detector a dedicated chapter concerning their questionnaire to the simulation in order to derive requirements and optimize the detector layout, see chapter 2.2, 2.3 and 2.4. Finally the overall tracking requirements for PANDA are summarized in terms of the most important figures of merit like track-, vertex- and momentum-resolutions taking into account a combined tracking system to which all tracking components contribute, see chapter 2.5.

2.1 Benchmark channels for tracking

It is clear that the requirements for the PANDA tracking system must be driven by the physic goals of PANDA. In the TP a lot of benchmark channels are given and optimization of the tracking detectors with respect to all of them seems not very suitable. To streamline the discussion and the needed simulation work on this topic we decided to choose a smaller subset of channels which can be regarded as 'tracking benchmark channels'. This means definition of tracking requirements and optimization of detectors should be done with respect to these channels in the first place.

The channels reflect the main applications of tracking detectors inside PANDA like high precision track measurement and subsequently high precision momentum measurement for charged particles in an energy region from 100 Mev up to 15 GeV. Furthermore special emphasize is given to the secondary vertex capabilities for c- and s-quark particles. In particular the tracking benchmark channels are:

- $\bar{p}p \rightarrow D^{*+}D^{*-}$ with $D^{*\pm} \rightarrow D^0\pi^\pm$ and $D^0 \rightarrow K^-\pi^+$, $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$ or $D^0 \rightarrow \bar{K}^0\pi^+\pi^-$; all single sided. This channel sets mainly the requirements for secondary vertex finding capabilities of the MVD in the case of close displaced vertices in the range of several hundreds of μm. A good tracking of all involved charged particles is necessary and especially the slow pions from D^*-decays are demanding.

- $\bar{p}p \rightarrow \bar{\Lambda}\Lambda \rightarrow p\pi^-\bar{p}\pi^+$ which has to be distinguished from the K^0 production, i.e. $\bar{p}p \rightarrow K^0_S K^\pm\pi^\mp$ with $K^0_S \rightarrow \pi^+\pi^-$. In this sense the channel is

spatial resolution for track points	σ_s in rφ, σ_s in z
resolution for vertex reconstruction	σ_v in x, y and z
relative resolution for charged particle momenta	Δp/p

Table 1: Basic figures of merit for the MVD.

similar to the previous channel regarding the tracking but the reconstruction of the Λ decay vertices also relies on the outer tracking detectors. In addition the channel $\bar{p}p \to \bar{\Xi}\Xi \to \bar{\Lambda}\pi\Lambda\pi$ shall be considered to introduce a two stage decay cascade with two relative long life particles decaying outside the MVD volume.

- $\bar{p}A \to J/\Psi X$ with $J/\Psi \to \mu^+\mu^-$ or $J/\Psi \to e^+e^-$ serve as a benchmark channel for high p_T charged tracks in a multi-track environment.
- Finally the elastic $\bar{p}p$-scattering $\bar{p}p \to \bar{p}p$ serve as benchmark for tracking and momentum measurement in particular for the forward tracking detectors.

We believe that these channels are the most relevant for the tracking properties of PANDA but of course we encourage a careful verification of the deduced requirements with other channels once the optimization of the tracking system layout has been done.

2.2 Micro Vertex Detector (MVD)

The current layout of the innermost tracking component of PANDA, the micro vertex detector (MVD), incorporates 4 barrel layers and six disk layers. Altogether roughly 400 double sided strip modules and 140 hybrid pixel modules covers an active area of about 1 m^2 with 10^7 readout channels. More details concerning the design and the layout can be found elsewhere [1, 2, 3]. Main task of the MVD is a high resolution tracking for charged particles and the vertex reconstruction of primary and secondary vertices. Especially for the open charm physics an excellent reconstruction of D-meson decay vertices in all three spatial dimensions is mandatory. These task defines the important figures of merit which are collected in table 1.

The requirements of the MVD for these figures of merit will primary derived from the $\bar{p}p \to D^*D^*$ benchmark channel which allows a determination of the crucial secondary vertex detection for the short lived D-mesons together with tracking of low momentum pions coming from the D^*-decays. A first estimation of the expected performance in terms of the figures of merit, diveded into the pixel and strip part of the MVD, based on experience and guesswork is given in table 2, second column and third column respectively.

Apart from the requirements directly connected with the physics performance of the MVD a lot of more requirements exist which can't be expressed easily in terms of figures of merit. They are mostly given by the environmental and operational conditions of the MVD and can be therefore derived from background process simulations or they are given by the needs from of the outer detector components. With this in mind these requirements can be expressed much more solid although changes are still possible depending on the input from background simulations and other detector components constraints. These requirements are:

- Radiation tolerance up to $3 \cdot 10^{14}$ $n_{eq}cm^{-2}$ for the innermost pixel layers and up to 10^{14} $n_{eq}cm^{-2}$ for the strip layers.
- Material budget less than 1.2% of a radiation length per pixel layer and less than 1% per strip layer including all support structures and services.
- Single pixel occupancy up to some kHz for $50 \cdot 400$ μm^2 pixel size and up to some 10 kHz for single strips.
- Total count rates per FE chip of about 10 MHz for the pixel part and 8 MHz for the strip part.
- Time resolution σ_t must at least better than 50 ns to separate the single events; an improved resolution of about 2 ns is desirable for further event deconvolution in later DAQ stages.
- $\frac{dE}{dx}$-resolution in the order of a few percent for low momentum particles, especially kaons, pions and protons well below 1 GeV momentum.

The determination of the MVD requirements and the optimization of the MVD layout requires extensive simulation studies and can be divided into three stages. The first stage contains detailed simulations which define the needs for the readout electronic chain. Peak and average data rates together with rate distributions at all levels of the readout architecture have to be investigated, e.g. rates and distributions at FE, module and several multi-module levels. The time structure of events needs to be considered, latency distributions at different readout levels are needed to investigate the influence of overlapping events and event rate fluctuations. Finally also the energy deposition and it distribution has to be evaluated to define the required dynamic range for the FE-electronics of the MVD. For all these simulations full background processes $\bar{p}p$ and $\bar{p}A$ for different nuclei are needed.

The second stage deals with geometrical optimization of the MVD layout. To this field all kind of possible layout options belongs, in particular:

- Variation of pixel sizes and shape, e.g. $50 \cdot 400\ \mu\text{m}^2$ or $50 \cdot 200\ \mu\text{m}^2$ or $100 \cdot 100\ \mu\text{m}^2$.
- Strip pitches between 50 and $200\ \mu$m and strip crossing angles between 1° and 90°.
- Different pixel and strip module sizes and shapes, e.g. wedge strip modules for disks, rectangular modules for barrels etc.
- Variation of active sensor thickness between 200 and $100\ \mu$m silicon and different sensor sizes to optimize the ratio between dead and active areas.
- Arrangement options of modules on the local supports, e.g. overlap of modules versus straight module placement.
- Local support and services options.

For all the geometrical aspects the $\bar{p}p \rightarrow \bar{D}D$ and $\bar{p}p \rightarrow \bar{D}^*D^*$ resp. are the important benchmark channels. The according figures of merit are the single track, vertex and momentum resolutions. For the later aspects like module arrangement and local support and services options the overall material budget drives the optimization process because the amount and distributions of material of the MVD has severe consequences for the outer detector components and must be minimized.

Of special interests concerning the layout of the MVD is question whether the detector should be optimized for charm meson tagging or strange particles (hyperon) detection. Since the decay lengths of strange particles are of the order of cm the arrangement of barrels and disks in the forward part may contradict the D-meson layout which favors layers as close as possible to the interaction point. To balance this two cases apart from the $\bar{p}p \rightarrow DD$ the $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ benchmark channel must be considered concerning the secondary vertex resolution and the momentum resolution of the particles from hyperon decays.

All these simulation studies to optimize the geometry of the MVD can't be done without a re-consideration of the impact of the proposed layout changes to the points discussed under the first simulation stage. Therefore an iterative process is needed which keeps the readout electronic requirements under control during this optimization. The result of this process should then be the identification of a limited set of key design parameters together with their range which respects the electronic and material constraints. These key parameters will then go to a final optimization stage which considers not only the bare figures of merit but also environmental challenges in form of background processes. The benchmark channel is again the $\bar{p}p \rightarrow \bar{D}D$ and $\bar{p}p \rightarrow \bar{D}^* D^*$ resp. signal process now hidden in the background. Apart from the vertex resolutions also the efficiency and purity for the D- and D*-meson identification has to be optimized.

2.3 Central Tracker

Input needed. Should be coordinated by a sub-detector representative.

2.3.1 Straw Tube Tracker (STT)

This and the following subsections can be used for special remarks to the different options under discussion, if needed!

2.3.2 Time Projection Chamber (TPC)

2.4 Forward Tracker

Input needed. Should be coordinated by a sub-detector representative.

2.4.1 Mini Drift Chambers (MDC)

2.4.2 Straw Tubes (ST)

The new issue about the forward tracking inside the target spectrometer must be menitioned/discussed here as well.

2.5 Overall tracking performance

It is clear that the demanding goals of the PANDA tracking system can only be reached if the information from the different sub-systems are combined appropriately. This task is devoted to the tracking software group which is currently developing code within the PandaRoot framework. Main issues are the pattern recognition, track following and track fitting for all kind of tracks and track pieces.

Currently different approaches are discussed; among them are for instance a track finding and fitting for each sub-component individually followed by an overall track fitting. But also other solutions like a more integrated approach using all hits from all tracking detector at once are investigated. This situation is complicated because the options for main tracking devices, the Central Tracker - TPC or STT - are quite different in terms of providing the hits. For TPC case up to 560 events or 3,000 tracks are superimposed in one ’picture’ whereas the STT provides up to 30 hits per track within 300-400 ns.

However, this work is still ongoing and the results will of course influence the requirements of the tracking detectors. Eventually the full simulation of the tracking benchmark channels will contain the complete track reconstruction of the entire PANDA tracking system and therefore can be used for deducing the final requirements for each tracking component. This is especially true for any kind of efficiency and purity studies taking into account the full background processes. Apart from that it can also be that a direct impact from one tracking component to another can be stated in an earlier stage. Like the necessity of a number of hits in the MVD serving as a track seed for the TPC or the restriction and relaxation of the material budget in some acceptance areas.

3 Design choices

There are several design choices which have to be taken in the next years but it is agreed that the most important ones are connected with global Central Tracker and Forward Tracker design, in particular:

1. Central Tracker: Straw Tube Tracker (STT) or Time Projection chamber (TPC).
   - Skewed STT design.
   - TPC using TUM design.
2. Forward Tracker: MDC or Straw Tubes.
   - High-rate MDC design (i.e. ”PSI design”).
   - MDC using ”Dubna design”.
   - Straw Tube Design

Some of these different design option might be vanish before the time for decision will come. However, for both sub-detectors, CT and FT, at least two completely different approaches are proposed so it is very likely that two options will be developed until a ”TDR” stage.

There are of course many more choices to be taken, e.g. the different mechanical design options for STT, the number of layers needed for the forward spectrometer or the choice of the Pixel FE-chip. Many of them deal with the particular design of the sub-detector and are therefore not as controversial as others. Rather such decisions will evolve naturally during the R&D phase and may not need any formal procedure. However, all chosen options must at least demonstrate that the required criteria coming from physics or from technical aspects are fulfilled.

3.1 Criteria for design choices

The criteria given here are mostly connected to the already mentioned 'important design choices', i.e. the Central Tracker and forward tracker decision. First the criteria to be applied for all decisions are presented, afterwards the more specific criteria for each decision are discussed.

Surely the design choice criteria must driven from the physics performance of the eligible detector option which must be shown by simulation and prototype performance results. Therefore a set of central figures of merits have been defined which allow to characterize the central performance issues of the detector options.

- Point resolution distributions of single tracks versus elevation angle Θ and transversal momentum p_T; additionally the derived vertex resolution distributions for kaon and hyperon decay vertices.
- Momentum resolution of single tracks and hyperon track pieces versus elevation angle Θ and transversal momentum p_T.
- Reconstruction efficiency of single tracks and hyperon track pieces.
- Reconstruction efficiency and purity with pile-up and realistic background conditions for single tracks and hyperon track pieces.
- Material budget distributions in terms of radiation length X_0 and hadronic interaction length λ respectively versus elevation angle Θ and azimuth angle φ.
- Particle Identification capability in terms of dE/dx separation power versus particle momentum p.

Apart from these central criteria there are a set of 'softer' criteria dealing with feasibility, production and maintenance of the detector. Although the impact of the criteria has to be adjusted for each decision individually it is clear that the relative weighting of the following criteria are lower.

- Technical feasibility of the concept:
  - Readout concept and data handling issues.
  - Mechanical issues and interaction with beam- and target-pipe (if appropriate).

  - Capability to cope with expected rates.
  - Time resolution and trigger issues.
  - Influence on other detector components.

- Feasibility of the production:
  - Person power.
  - Available infrastructure.
  - Costs and financing issues.

- Complexity and costs during operation and maintenance.

3.1.1 Criteria for the Central Tracker decision

Here is space for the specific and important points for the two CT options; I just collected a few points from the discussions to start with. But of course the experts are asked to give their opinion here!

The most controversial decision will be the Central Tracker decision because two quite different approaches are followed up. Here are now specific issues within the the criteria for each option are collected which must be addressed before a decision can take place. With this in mind the listed issues can be regarded as a weighting of the general design choice criteria.

1. Straw Tube Tracker
   - Demonstrate that the required single track resolution and transverse momentum resolution is achievable with this self supporting concept keeping the total amount of material (including global support structures) around 1% of a radiation length.
   - Show the tolerance of the single straws against the expected ageing effects.
   - Demonstrate that the single point resolution is sufficient, i.e. below 150 μm in $r\varphi$ for the 1.5 m long self-supported straws.
   - Show dE/dx capability of low momentum tracks.
2. Time Projection Chamber
   - Show that the required single track and momentum resolution is possible even for forward tracks which deposited charge has to drift through the entire TPC including the deteriorated field region in the forward area.

- Demonstrate capability of handling the 1,000 superimposed events per TPC 'picture'.
- Show the feasibility of coping with the expected space charge coming from positively charged ions at Panda like interaction rates.

3.2 Roadmap towards a decision

For the central tracker design decision which won't be taken before end 2008 it is too early to define a procedure right now. Rather it should be waited for results coming from the simulation effort and prototyping. However, one solution could be an external review process which might be executed as follows:

Since not all of the required criteria can be fulfilled on the same time scale or with the same effort a two step procedure is proposed if we have to decide between elaborated design options.

1. For each design choice a report covering the important items of the defined criteria shall be prepared 3-6 months before the decision have to taken. Afterwards it will be refereed by an internal group and a decision may be taken by the CB if appropriate.
2. After a further evaluation period which should not exceed the time scale for the sub-detector TDR a final report covering all criteria for each choice will be prepared and presented to a group of internal and/or external experts (Design Review). The reviewers are asked to formulate a recommendation to the CB for a final decision.

As already pointed out not all design choices or design options need to go through the whole process but the criteria should be valid for all decisions. For each 'design choice decision' the described process can be adjusted accordingly.

4 Milestones to a PANDA TR

The current schedule to prepare a Technical Review of the PANDA detector (TR) until end of 2007 or early 2008 might clash with the time needed to take all necessary design choices. Therefore different options might be presented in the TR although an already taken decision is desirable. However, this TR is an intermediate step towards the individual sub-detector Technical Design Reports (TDR) which will come roughly a year later. It is an important milestone for the PANDA project and a definitive time frame for the open design choices must be given in this TR. Apart from a more detailed technical description of detector components the implementation of the production must be covered too. This includes productions milestones as well as feasibility and financing of the production. Many of the given information can of course go to the different TDRs as well to avoid duplication of the work. But in contrast to the TR the TDRs shall be as close as possible to the detector as it will be built. In order to cope with the current tight FAIR/PANDA schedule the sub-detector TDRs should by finished by mid/end of 2009.

The the moment it seems feasible that both sub-detectors groups, CT and FT, could finish their R&D phase for the different design options by 2009 so the natural time to take the design decisions will be 2009. For the case of the FT the decision between the Straw Tube and MDC approach could be taken by end of 2007 leaving only the final MDC layout decision (if MDC are chosen) for 2008.

However, the scope of this document is not the planing for the 'official' paperwork but the definition and planing of the needed tracking detector work including open R&D questions. Therefore the proposed milestones could be:

1. Final Draft of this document concerning tracking requirements: July 2007
2. Fix time frames for design choices: September 2006.
3. Definition of work-packages for sub-detector R&D: September 2007.
4. Decision between Straw Tubes and MDC for the FT: December 2007
5. Decision upon the CT design: 2009

References

[1] T. Stockmanns, *The micro-vertex-detector of the PANDA experiment at Darmstadt*, Nuclear Instr. Meth. A. **568**, 294-300 (2006).

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5 Appendix

	MVD		CT		FT
Requirement for	Pixel	Strips	STT, skewed	TPC	MDC/ST
spatial resolution σ_s for track points	rφ = 40 μm z = 40 μm	rφ = 40 μm z = 100 μm	rφ = 150 μm z = 1-2 mm	rφ = $100 - 200$ μm z = 0.2-1 mm	x, y = 0.2-0.3 mm z = 1 mm
resolution σ_v for vertex reconstruction	x = 100 μm y = 100 μm z = 100 μm	x = 100 μm y = 100 μm z = 200 μm	- - -	- - -	- - -
time resolution σ_t	20 ns	2 ns	?	?	?
relative resolution Δp/p for particle momenta	1%	1%	1.5%	1.2-1.5% (m.i.p.)	1%
relative resolution ΔE/E for energy deposit	5-10%	5-10%	?	2.5-5.5%	-
material budget X/X_0	1.2% per layer	1% per layer	1% (active volume)(	2-4%	0.01% (active area)

Table 2: Expected performance of the different detector options for the tracking system of PANDA.