Calibration of the ILD TPC*

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Need for calibration: The TPC is used to reconstruct the tracks of the charged particles between the vertex detector and the calorimeters and to measure their momenta. The goal momentum resolution is dictated by the need for Z recoil peak visibility in e+e- -> ZH, with the Z into lepton pairs. For the TPC alone, it corresponds to a resolution of $\Delta p/p^2 = 10^{-4}$ GeV^{-1}. For a 100 GeV/c track in a 3.5 T magnetic field, with a lever arm of 1.2 m, the sagitta is 1.9 mm, and the required $\Delta s/s=\Delta p/p=10^{-2}$ corresponds to a 19 μm absolute uncertainty on this measurement. This gives the scale of the maximum tolerable systematics on the sagitta internal to the TPC. Considering now the full ILD tracking, including the vertex detector and the silicon tracker, the lever arm is 1.8 m, the sagitta for a 100 GeV Gev/c track is 4.2 mm. The requirement for $\Delta p/p^2$ to be less than 2.10^{-5} GeV^{-1} translates in to a required relative accuracy of $2\ 10^{-3}$ on the sagitta, thus an absolute accuracy of almost 10 μm.

From these simple considerations, the conclusion on the systematics on the sagitta measurement is that the systematic errors internal to the TPC have to be well below 20 μm and the overall positioning of the TPC with respect to the other tracking detectors has to be well within 10 μm.

The absolute energy scale of the momenta is given by the magnitude of the magnetic field and can be cross-checked with the effective mass of known particles, such as K^0_S or J/ψ.

The z coordinate measurement – along the magnet axis – relies on the drift velocity measurement. It is subject to distortions (E-field inhomogeneity) and variations with environmental conditions. Time-dependent non-uniform space charge due to primary ionization might have non-negligible effects. To match the attainable accuracy of 300 μm over the maximum drift length of 2.2 m, the drift velocity has to be constantly monitored at the $1.4\ 10^{-4}$ level. There is no physics-driven need for such accuracy however, and an order of magnitude less would be sufficient to allow the reconstruction to be performed correctly.

To use the dE/dx measurement for particle identification (mainly π/K/p separation) a calibration at the (few) percent level is also necessary. The need for an equalization of the amplifiers will depend on the detailed technological choices, but this is by now a standard procedure implemented from the design phase of the electronics. Once this equalization carried out, normal data will be sufficient to perform the calibration of the dE/dx analysis parameters. Depending on the technology and quality of the manufacturing of the amplification device, gas gain might also need to be mapped. As usual in a TPC, environmental conditions and gas composition will be constantly monitored.

To summarize the calibration goals, alignment of the modules with respect to neighbors will be necessary, as well as global alignment, knowledge of the magnetic field, drift velocity and dE/dx calibration.

Alignment strategy

To reach the O(10µm) accuracy, ILD will use all the available possibilities listed below.

At module production and mounting on the endplate, a detailed geometry survey of every pad position and module position will be carried out.

Two alignment systems can be used and will be studied: one with UV laser straight tracks sampling various parts of the TPC, and one where UV photons are used to extract photo-electrons from various points and lines formed with a low-work-function material on the surface of the cathode.

Cosmic data will easily be used in the surface at the end of the TPC assembly phase. However after mounting the TPC underground, the overburden of 100m will limit the rate. If cosmic data have to be used during the data taking with beams in collision, the power pulsing implementation for the readout will have to be studied to this end. For instance major power-consuming tasks, as digitization, can be subjected to the occurrence of a cosmic trigger in the concerned region, limiting the continuous power consumption to preamplifiers and memories.

The same thing may be applied after TPC installation into magnet with B field.

All these data would be used for the initial parameter of alignment/calibration procedure. But the final parameters would be obtained from beam data as in predecessor’s experiences.

The alignment must be done with the magnet turned on, since the magnetic field can cause displacements of the subdetectors. Data with the magnet off can also be used for certain corrections.

LEP experience suggests carrying out serious systematic study of TPC behavior to find key parameters for alignment/calibration. We may encounter unexpected conditions during beam run such as field cage shorts, gate HV problems and so on. Beam data is the only data to obtain these calibration parameters. Since the other trackers (VTX, inter/outer Si tracker) can be aligned separately and provide good track information, it will help TPC and overall calibration. Iteration of alignment would be necessary.

If we use anti-DID, we should map the magnetic field with and without anti-DID field, as there may be periods where it is not available. Moreover, as the anti-DID field is conceived as a tunable machine parameter, it must be possible to interpolate it within some range. As measuring it might be a difficult operation, the use of Maxwell equations to interpolate the field between measurement points should be considered.

Experience from LEP and LHC experiments.

ALEPH and DELPHI detectors comprised a large TPC as a central tracker and took e^+e^- data from 90 to 209 GeV c.m. energy.

First, a general comment. As seen from the list of types of calibrations there are several, each with errors on the calibration parameters.

Z-pole running offers, with its well-known energy (e.g., two back-to-back 45 GeV muons from Z to μμ decays) a perfect alignment constraint, which can be used to reduce the overall uncertainty. The word ``calibration'' below will refer to both alignment and calibration. Procedures similar to those cited here can be used by the ILD TPC.

The Z running data was also used for the other Aleph, Delphi and Opal subdetectors, but mainly the TPC information will be described here.

Aleph Werner Wiedenmann (CERN/Atlas), one of the main developers of the methods cited here, wrote : `Muon pairs from Z decays with its kinematic constraints provided a unique reaction to measure residual distributions in the TPC directly with data.'

Werner's slides :

https://wiedenma.web.cern.ch/wiedenma/TPC/Distortions/Cern_LC.pdf, contain many more details than can be covered in this note.

The initial basic calculations were done using a few thousand Z to μ pairs from the first run periods at Lep1. Later, at Lep2, corrections to the basic parameters were obtained by fitting them to about one thousand Z to μ pairs from the Z-pole running for calibration. There were about 300 parameters used for the corrections. Also, the Aleph TPC had a laser system, which was used for monitoring various parameters, but ended up not being used for alignment.

Delphi

In Delphi (also having a TPC as main tracker) the methods used were very similar to the ones in ALEPH, using the mu-pairs collected from Z running. In addition, a common UV laser system for the Inner Detector Jet chamber and the TPC was developed, but abandoned in the case of the ID, using instead the extrapolations from the nearby Vertex Detector. Note that the Delphi Vertex Detector had 3 layers, so not only the overlap regions of the different phi-sectors, but the whole sector surfaces could be used to constrain the internal alignment of the VD, where in the latter case also isolated 3-hit tracks from hadronic Z decays were used. This illustrates the use of other subdetectors for the alignment of the TPC

For the TPC the 2 x 6 laser rays, one at a fixed position in each of the sectors, parallel and close to the anode (readout) plane, were reflected at the outside radius back to the inner radius, close to the central cathode. In this way, every cathode pad and anode wire detected two hits, from which a very precise determination and monitoring of the drift velocity could be done, to better than 2 x 10^{-4}.

Opal

The Opal Jet Chamber was clearly a much more complicated detector than ILD-TPC. The Jet Chamber operated at 4 bars in a 0.435T solenoid as a main tracking detector. The Jet Chamber had 24 rϕ sectors separated by planes of cathode wires. Each sector had 160 anode wires parallel to beam axis, with length varying from 3.4m at 26 cm inner radius to 4.1m at outer radius of 1.8m.

Calibration and alignment were done with Z events at startup. Cathode crossing tracks were used to monitor drift velocity and time offsets during normal running. Drift velocity and Lorentz angle could be determined with a statistical error of 0.01% and 0.1% with these events. Laser calibration/monitoring events were also injected at a rate of 0.04 Hz interleaved with physics events during normal running. During LEP Phase II, the machine energy eventually reached 209 GeV, and each new running period started with Z running for experiments to check calibration and alignment. OPAL also used Nd:YAG lasers situated outside the detector for monitoring. In the centre of each of the 48 half-sectors, parallel laser beams with a spacing of 10 mm in the rϕ plane were injected through quartz windows. Sectors were selected using moveable mirrors outside the Jet Chamber. The beams originated from both sides. Complete laser scans are performed during LEP shut downs.

Experience at LHC

CMS uses data to align the silicon tracker. The Milipede program is used to globally fit the alignment parameters over millions of tracks, with special care, by reference to other subdetectors, to resolve ‘weak modes’ (indetermination of some parameters due to degeneration of the χ^2).

Though it is not a TPC, the experience from the muon spectrometer of ATLAS provides a valuable learning experience. At high momentum, the resolution is determined by point resolution (80 µm per tube) and alignment. The required maximum systematics error from alignment is about 30 µm over several meters of lever-arm for part of the system. The number of alignment parameters is 40,000.

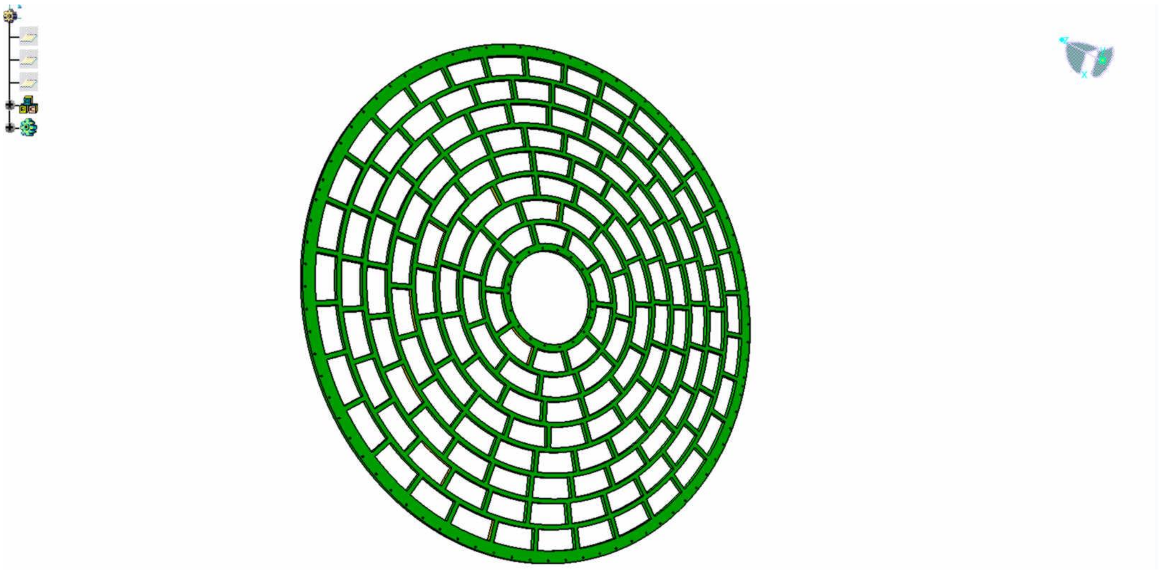
ATLAS has optical sensors on muon chambers to measure the position of each muon chamber with an accuracy of 50 microns over several meters. These are called RASNIK (coded mask with 875 nm IR light) for the barrel and B-cam (by reference to Brandey) for the end-cap. The initial (called absolute) alignment is obtained by the survey, which provides only a mm accuracy on the position of the detector modules. This is improved to 200 µm in the barrel and 100 µm in the endcap thanks to the optical system. Switching on the magnet leads to displacements of the order of several mm, leading to systematics on the track sagitta at the level of 1mm. Once per Run period of 2 to 3 years, data are taken with B=0 (10^8 cosmic rays in barrel and beam data in the endcap, representing of the order of 10^7 muons in total after severe selection cuts). These ‘straight-track’ data are used to obtain the reference geometry, which is followed optically at B=1 every 2 hours, and corrected when necessary. Usually, the system is very stable unless specific action is taken (access for instance).

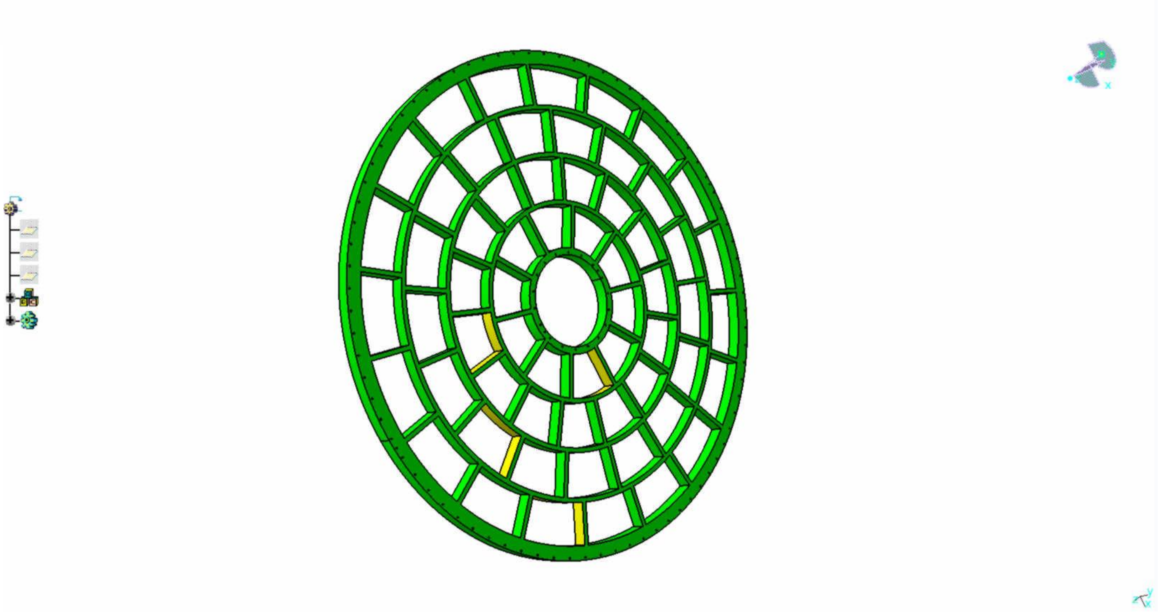
Usage of the tracks to align the TPC modules

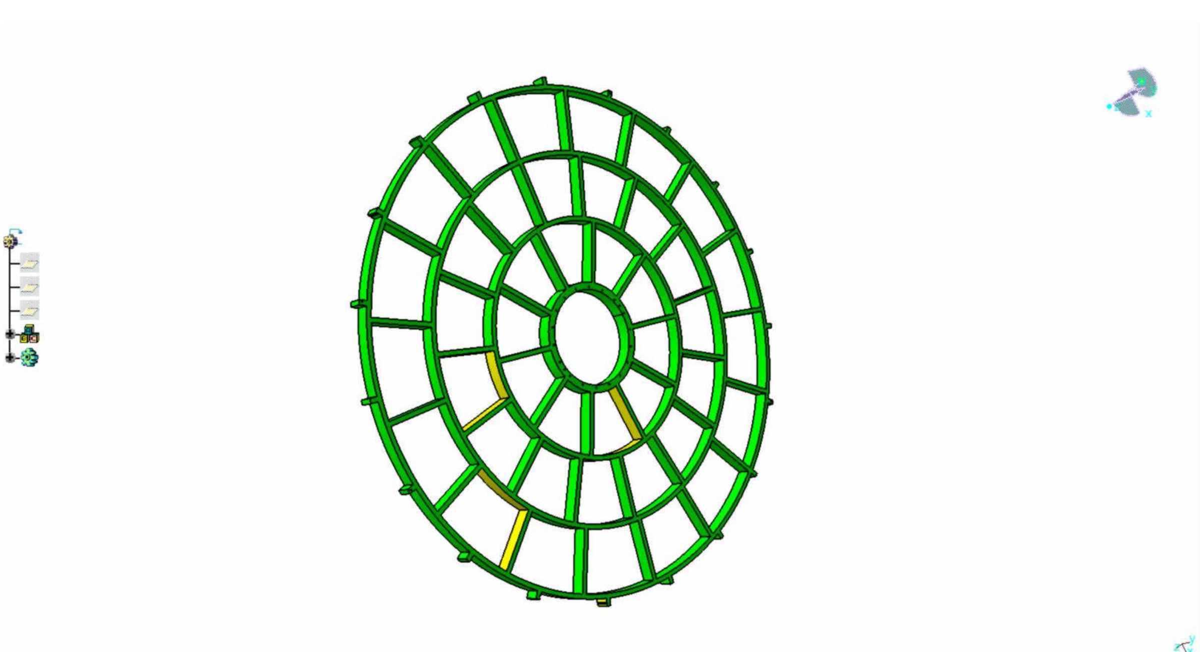
In a 3.5 T field, and for a suitable gas choice (with a high $\omega\tau$), the transverse diffusion is considerably reduced, so that the point resolution per pad row is expected to remain below 100 µm at all drift distances. The internal geometry within each module will be controlled by a survey and care will be taken to keep the conditions stable during operation. The position of a module with respect to an absolute frame is defined by 3 angles and 3 translations. However only one angle (rotation around the perpendicular to the module) and one translation (in the $r\phi$ direction) have an impact on the sagitta and they can be probed by radial tracks coming from the interaction point.

In the following, we will consider 3 possible (preliminary) designs of the endplate, defined by the size and number of the modules. The design with 8 module rows (‘wheels’) uses modules with a size about that of the Large TPC prototype. Such a TPC would have 171 modules on each side (note that a 240-module design also exists). If 4 time larger modules could be built, 4 wheels would suffice and they will be covered by 61 modules. If even larger modules can be built, we would have 42 modules each side (see drawings below).

Assuming 5mm-long pads for the time being, we would thus have respectively 34, 68 and 90 pad rows per module. Each track segment would then give a positioning of 17 micron accuracy (resp. 12, and 10 micron), requiring 300 (resp 150 and 100) ‘good’ tracks crossing a module to determine the relative module to module shift along rϕ at the micron level and the rotation angle with a 6 μradian accuracy (respectively 3 and 2 μradian).







Alignment of the TPC with respect to tracker and calorimeter

Considering that tracks which cross the external wheel also cross the others, to fully align the TPC internally at the micron level we need 10 000 tracks in the worst case, 3000 in the medium case of 4 wheels and 2000 suffice in the 3-wheel case.

With the above number of tracks, the TPC can be aligned globally at the sub-micron level. Such a number of ‘good’ tracks can easily be obtained during the standard running. Even muon pairs from 2γ interactions with transverse momenta above 10 GeV can be used. Note however that there is no momentum constraint for these tracks.

Other kinds of events can be used for the alignment with respect to the external silicon and the calorimeter. For instance the muons from the beam halo (some estimates are 10 per train crossing, meaning 50 Hz) allow a global rotation with respect to the endcap calorimeter to be measured.

Conclusions

To profit from an increase in cross-section over 3 orders of magnitude, running at the Z pole about 5% of the time is a very tempting solution, if it is practicable. The Z-> μμ process at the pole provides clear 2 track events with momentum constraint and common origin, which can be used to check the tracking systematics. Non-trivial adaptation will be necessary if one wants to use the cosmic-rays to help aligning the detector. All handles have to be considered for the alignment: survey, gauges, laser beams, and physics data itself.

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