Monte Carlo Study of TPC Performance

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We present the status of our Monte Carlo study of TPC performance in the framework of the huge detector concept. We also report on our study of readout pad shape optimization.

1. INTRODUCTION

We propose a Time Projection Chamber (TPC) with a Micro Pattern Gas Detector (MPGD) readout system as the main tracker at the International Linear Collider (ILC). The main tracker is required to have a high enough momentum resolution over a wide angular range so that the recoil mass resolution for $e^+e^- \to ZH$ followed by $Z \to l^+l^-$ is limited not by the tracker but by the beam energy spread. This implies a momentum resolution better than $\sigma_{\mathrm{P}_\ell^\pm}/\mathrm{P}_\ell^\pm \leq 0.4\%$ at $\mathrm{P}_\ell^\pm = 50\mathrm{GeV/c}$. The main tracker should also be able to precisely measure individual tracks in highly collimated jets, which requires a good two-hit separation capability. These physics requirements should be translated into parameters such as spatial resolution, two-hit resolution, angular acceptance, etc., so as to set performance goals for the hardware R&D. This translation involves proper accounts of multiple scattering, energy loss, degradation of spatial resolution due to diffusion in the TPC drift volume, effects of various beam-induced background, etc. Since analytic estimate of these effects is difficult, we need to rely on Monte Carlo detector simulation. Once the performance goals are set for the TPC, we need to optimize various parameters to specify the chamber and its readout system. The optimization of the readout pad shape is in this respect one of the most crucial steps to meet the performance goals. In this talk, we present the status of our Monte Carlo study of TPC performance in the framework of the huge detector concept. We also report on our study of readout pad shape optimization.

2. MONTE CARLO STUDY OF MOMENTUM RESOLUTION

2.1. Simulation Framework

Our Monte Carlo study of TPC performance is based on a detector simulator, JUPITER [1] and SATELLITES[3]. JUPITER is a full detector simulator based on GEANT4 [4], which tracks particles from the interaction point through various detector components, taking into account their various interactions with detector materials. While propagating the particles, JUPITER creates exact hits (Monte Carlo truth). These exact hits are passed to SATELLITES and, after appropriate smearing reflecting detector resolutions, made into measured hits. Those hits from a single particle are collected to form a track by a track maker module of SATELLITES. The track maker inherits from that of the event reconstruction package URANUS[3]. URANUS is equipped with a Kalman-filter-based track fitter, which allows hybrid track fitting with different trackers such as the TPC, an Intermediate Tracker (IT), and a Vertex Detector (VTX), taking into account energy loss and multiple scattering.

The detector model used in JUPITER for this study is GLD/3T, which has the following parameters for the TPC: (1) length = 255×2 cm, radius($\mathrm{R_{out}} - \mathrm{R_{in}}$) = 154cm; (2) B = 3T; (3) the number of sampling = 200; (4) TPC gas – P5 gas(Ar(95%)+$\mathrm{CH_4}$(5%)), diffusion parameters: $\sigma_0 = 55\mu\mathrm{m}, \mathrm{C_d} = 55\mu\mathrm{m}/\sqrt{\mathrm{cm}}$ on XY-axis, $\sigma_\mathrm{Z} = 600\mu\mathrm{m}$. Here, the diffusion is defined by $\sigma_{\mathrm{XY}}^2 = \sigma_0^2 + \frac{\mathrm{C_d^2}}{\mathrm{N_e}\times\alpha} \times \mathrm{Z_{drift}}$ ($\mathrm{N_e} \times \alpha = 28$). In addition, GLD has (a) an IT consisting of four silicon layers with $\sigma = 10\mu\mathrm{m}$, (b) a VTX of four silicon pixel layers with $\sigma = 4\mu\mathrm{m}$.

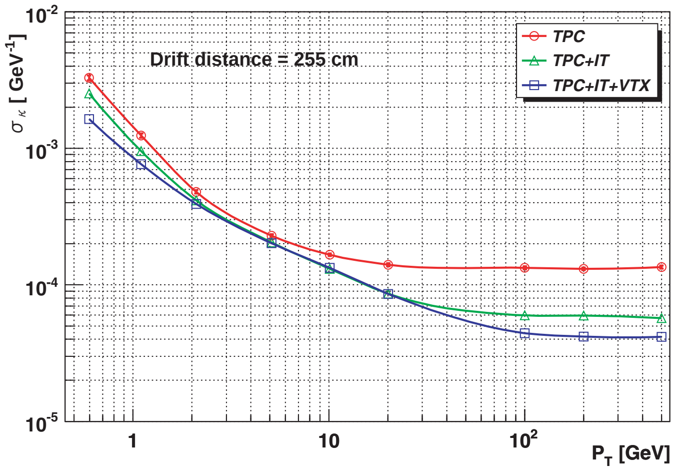


Figure 1: Momentum resolution for single muon tracks with $|\cos\theta| < 0.7$ as a function of transverse momentum; $\kappa = 1/\mathrm{P_T}$.

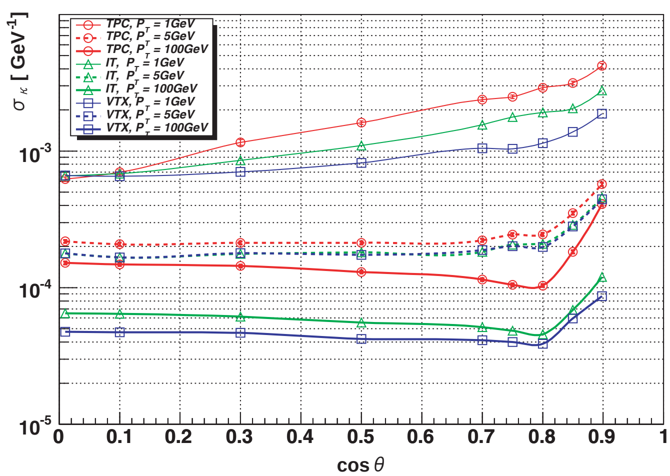


Figure 2: $\cos\theta$ dependence of the momentum resolution for single muon tracks with different momenta, when different combinations of TPC, IT, and VTX are used.

2.2. Momentum Resolution

Using the simulation framework described above, we evaluated the momentum resolution for single muon tracks with various $\cos\theta$ and momentum. Figure 1 shows the momentum resolution as a function of transverse momentum for single muon tracks with $|\cos\theta| < 0.7$. In this figure, IT and VTX means using the hit information from the IT and the VTX, respectively. Combining hit information from all the trackers, we can satisfy the required momentum resolution. Nevertheless, since the TPC alone cannot meet the resolution requirement, further optimization is desired for the TPC design parameters. Notice also a slight improvement of momentum resolution in the low momentum region which is due to the improvement in z coordinate measurements.

Figure 2 shows the $\cos\theta$ dependence of the momentum resolution for single muon tracks. The momentum resolution for high momentum tracks improves as $|\cos\theta|$ increases up to $|\cos\theta| = 0.8$, since the drift length becomes shorter and hence the diffusion becomes smaller for the TPC r-ϕ coordinate measurements. This implies the importance of the use of a low transverse diffusion gas. Above $|\cos\theta| = 0.8$, the number of sampling points starts to decrease, and hence the resolution becomes worse. The effect of inclusion of IT and VTX information is more prominent in the high momentum region, as expected. It is noteworthy, however, that the combination with the IT and the VTX also improves the momentum resolution in the low momentum region in particular for large $|\cos\theta|$ region. This is because, for low momentum tracks, z coordinate measurements gives extra momentum information if and only if $\cos\theta \neq 0$.

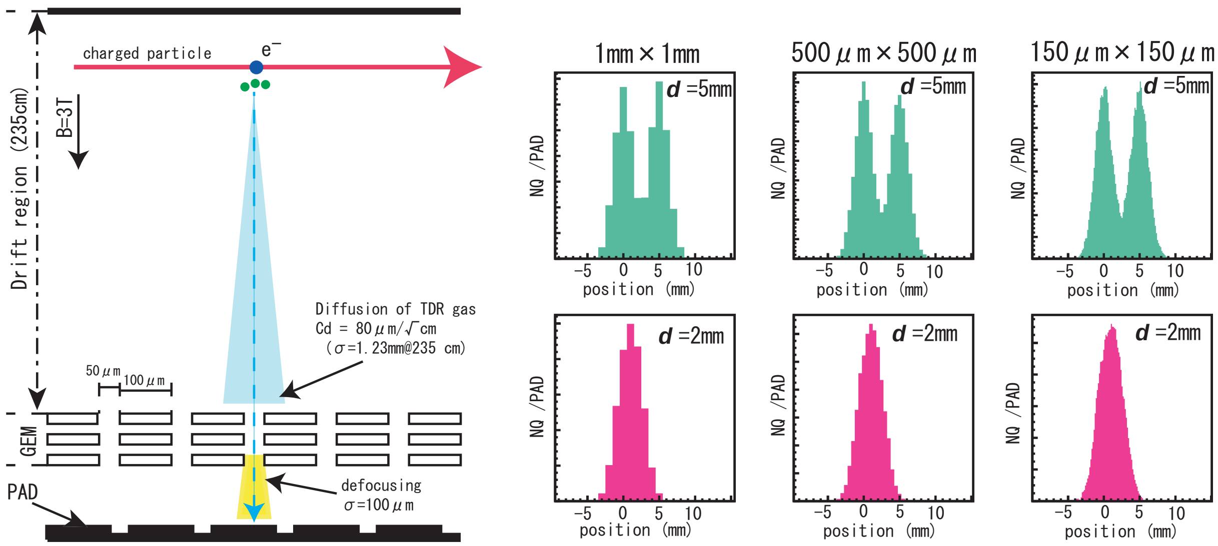
3. PAD SHAPE STUDY

The momentum resolution study described above requires further improvement of the spatial resolution: lower transverse diffusion (choice of gas) and smaller σ_0 (optimization of the readout endplane detector). The readout pad shape for the endplane detector may limit the spatial resolution and the two-track separation and hence has to be optimized, taking into account the diffusion during drift. For example, in the limit where electronic noise is negligible, a smaller pad size is more advantageous for a good spatial resolution and two-track separation, unless the diffusion dominates the pad size. The smaller pad size, however, means the larger number of readout channels and hence a higher cost. The determination of the optimal pad size and shape is, therefore, one of the major R&D items that require dedicated simulation studies. As the endplane readout detector we consider two possibilities: Micromegas (Micro mesh gas detector) [5] and GEM (Gas Electron Multiplier) [6]. Both operate in a gaseous atmosphere and are based on the avalanche amplification of primary electrons. The readout pads collect the amplified charge directly. Since the size of the charge cluster on the pad plane is determined by a small defocussing effect, MPGD can in principle observe individual clusters formed in the gas, if the pad size is small enough and sensitive for a small amount of charge. As for the large TPC as we proposed, it needs a large number of readout pads to get a good spatial resolution and a drift gas with a small diffusion for the long drift distance. We thus have to determine the pad shape for the drift gas we propose to use by the simulation.

As a first step, we have started a very simple pad simulation to estimate the pad response in a GEM TPC. This simulation in based on the analytic distribution formula. The assumptions for the pad response simulation are listed in below,

- The number of primary ionization electrons is distributed according to the Poisson distribution with average of 30/cm
- The number of electrons contained in an ionization cluster fluctuates according to the Landau distribution [7]
- The diffusion of ionization cluster along the drift direction is given by a Gauss distribution. The TPC gas is assumed to be the TDR gas having a diffusion constant of $C_d = 80\mu m/\sqrt{c}m$ at 3T.
- The defocussing effect of the charge cluster between a GEM foil and readout pad follows a Gauss distribution with $\sigma = 100\mu m$.
- The GEM has one layer with 10^3 gain. The hole size on GEM is $\phi 50\mu m$ with a $100\mu m$ pitch.

Figure 3(a) illustrates this simulation. Using this simple simulation, we estimated the pad response for the tracks. In this estimation, we tried square pads with three different pad sizes, $1mm \times 1mm$, $500\mu m \times 500\mu m$, and $150\mu m \times 150\mu m$.
In the following simulation, we assume two parallel charged tracks passing through the TPC at the the drift distance of 235 cm. The two-track distance is assumed to 5mm or 2mm. Figure 3(b) shows the response of one pad row when 1000 pairs of tracks are generated at the same position. The spread of each charge cluster on the pad row is dominated by the diffusion in the TDR gas because the charge spread due to diffusion after 235 cm drift is calculated to be 1.23 mm. The charge clusters from the two-tracks with 2 mm distance overlap each other at the surface of the pad plane. Since the diffusion dominates the charge spread use of small pad size will not help very much in two-hit separation. We definitely needs a smaller diffusion gas mixture for the long drift distance.



(a) Scheme of PAD simulation

(b) PAD response for two-track (1000 events)

Figure 3: (a) Illustration of PAD simulation. (b)The results of PAD response for two-track.

4. SUMMARY

We have started Monte Carlo studies of the performance of a MPGD-TPC for ILC in order to translate physics requirements to performance goals for hardware R&D. For this purpose, we have developed a GEANT4-based full detector simulator (JUPITER/SATELLITES/URANUS), and studied momentum resolution under various conditions. With the GLD/3T model of the trackers, we found a momentum resolution that meets the physics requirements, when all of the TPC, the IT, and the VTX are combined. The TPC alone, however, only marginally satisfies the physics requirements. A better gas mixture with smaller transverse diffusion is desired as well as further improvement of spatial resolution for the zero drift distance. In the course of this Monte Carlo study, we found that the combined fitting of hit information from the TPC, the IT, and the VTX improves the momentum resolution not only in the high momentum region but also in the low momentum region. The simulation presented in this talk, however, assumes perfect track finding and no background hits. We are planning to carry out more realistic simulation including these effects in order to refine the TPC design.

We have also started Monte Carlo simulation of pad response so as to optimize pad geometry. A simple simulation shows that the charge spread is dominated by the diffusion for the TDR gas and the separation of two tracks with 2 mm spacing will be difficult. This again suggests need for a smaller diffusion gas mixture. In any case, since the current simulation is over-simplified in may respects, we are planning to develop a more realistic simulator for the pad optimization.

References

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