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Development of a TPC for the future linear collider

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Abstract. A Time Projection Chamber is the primary option for the main tracker of the detector at a future e^+e^- linear collider. The tracking system has to face significantly more complicated event topologies and higher backgrounds compared to previous e^+e^- colliders, which puts stringent requirements on its overall design. The design issues and R&D plans for developing such a high performance TPC are presented. Particular emphasis is put on the R&D for a new type of gas amplification system, based on micro pattern gas detectors.

1 Introduction

Recently general consensus has been achieved within the particle physics community that the next large accelerator project after the startup of the LHC should be a high luminosity electron-positron linear collider (LC) with a centre-of-mass energy up to 1 TeV. The physics goals for an LC and the technical design of the accelerator have large implications on the detector concept. With respect to LEP more complex final states are expected and a wider range of particle energies – from GeV to TeV – must be measured. In addition the detector has to be adapted to the time structure of the accelerator and has to cope with its background.

However, the most important constraints to the overall detector design are given by the expected event signatures. For example the unbiased reconstruction of Higgs strahlung events using only the two charged leptons from the Z decay requires an excellent momentum resolution of the tracking system. Ideally, the recoil mass spectrum of the lepton pair (see Fig. 1) should be limited only by the natural width of the Z boson and not by detector resolution. This requires a momentum resolution of about $5 \cdot 10^{-5}$ GeV^{-1} for the overall tracking system.

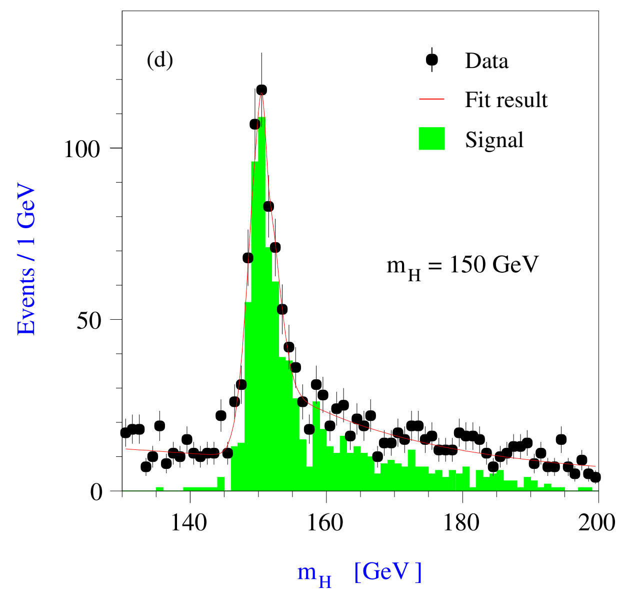

Fig. 1. Recoil mass distribution in simulated $e^+e^- \to HZ \to X\mu^+\mu^-$ events, including background [1]

2 Design of a TPC for the linear collider

A Time Projection Chamber (TPC) is foreseen as the main tracker of the detector for the TESLA e^+e^- linear collider [1]. The TPC alone should provide a momentum resolution of $\delta(1/p_t) < 2 \cdot 10^{-4}$ GeV^{-1} to exploit especially the physics of final states with high energy leptons. Additionally the specific ionisation $\mathrm{d}E/\mathrm{d}x$ should be measured with a precision better than 5% to allow particle identification in hadronic jets.

To reach these goals readout planes with the finest possible granularity are required. They must provide a single point resolution of 100 – 150 μm and their systematic distortions must be controlled to better than 10 μm over the measured track length of 1.6 m. Enough charge amplification has to be provided by the system to keep the signals well above the noise level of modern readout electronics. At the same time the produced ions have to be suppressed intrinsically, to limit positive ion build-up in front of the gas amplification region. Active gating is impossible in between a TESLA bunch spacing of 337 ns and ions can only be removed after the 1 ms long bunch train. The goal is to keep the material budget below 3% of a radiation length in the barrel region and below 30% in the endcaps where the gas amplification system, the front-end electronics and other infrastructure reside. In the TESLA

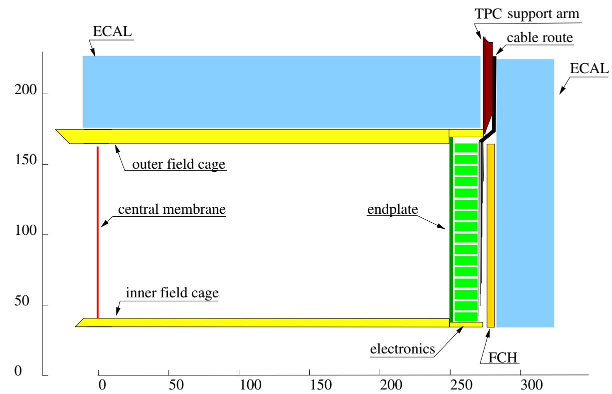

Fig. 2. Proposed layout of the TPC

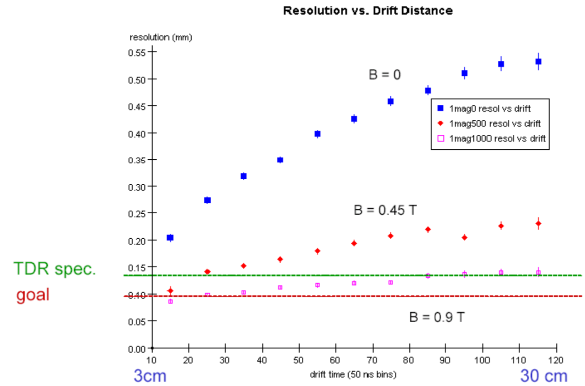

Fig. 3. Position resolution versus drift distance

design the main tracker is a TPC of 5 m length and 3.5 m diameter. The layout of one quadrant is shown in Fig. 2.

A conventional TPC using multi wire planes for charge amplification is limited by the $\mathbf{E} \times \mathbf{B}$ effects in the region close to the wires. In strong magnetic fields these effects can result in a broadening of the electron cloud and a worsening of the resolution. Additionally, as the wires define a preferred direction, the reconstructed hit location depends on the projected angle between track and wires. Gas Electron Multipliers (GEM) [2] or Micromegas [3] as the charge amplifying system could solve some of the drawbacks of wire planes. When using micro pattern devices for the TPC end plate the pads directly detect the amplified electron cloud which results in a fast and narrow charge signal. Also the slow ion tail is cut off since the ion cloud does not reach the induction region. These devices show no preferred direction, thus any $\mathbf{E}\times\mathbf{B}$ effects will be isotropic. And finally the back drift of the produced ions, the ion feedback, can be largely suppressed using highly asymmetric electric fields between drift and amplification region.

3 Study of micro pattern readout

The R&D activities [4] for the linear collider TPC are currently concentrated on the adoption of micro pattern devices for the gas amplification stage. Several questions have to be adressed before GEM or Micromegas can be considered as an option for the linear collider TPC:

– Do the micro pattern devices reach the postion resolution needed, i.e. is the charge cloud after the avalanche process broad enough to allow the determination of the centre-of-gravity of the electron cloud with a limited number of readout pads?
– Can the ion back-drift be suppressed to an acceptable value and which level of ion back-drift can be accepted in the linear collider enviroment?
– Is the collection efficiency of these devices high enough to reach the required resolution in $\mathrm{d}E/\mathrm{d}x$?
– Do they preserve these properties in high magnetic fields?

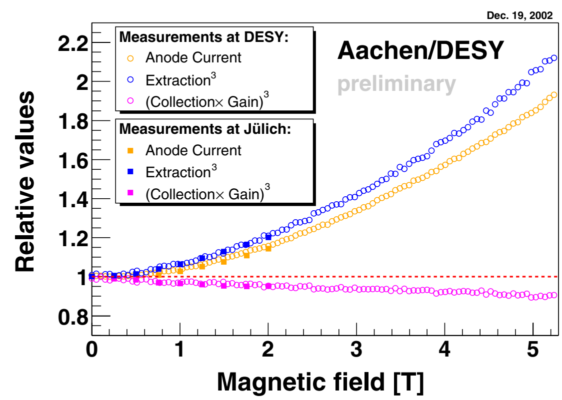

Fig. 4. Measurement of anode current versus magnetic field

Several small prototype TPC's have been operated using micro pattern structures at the readout plane. Figure 3 shows as an example the result of a cosmic run of a test TPC with a triple GEM tower. The measured position resolution is shown with respect to the drift distance of the track. One can see that the TDR goal has already been achieved with a moderate magnetic field of 0.9 T.

The drift of electrons in electric and magnetic fields is described by the Langevin Formula

$$\mathbf{v}_{\mathrm{drift}} \propto \hat{\mathbf{E}} + \omega\tau\,(\hat{\mathbf{E}} \times \hat{\mathbf{B}}) + \omega^2\tau^2\,(\hat{\mathbf{E}} \cdot \hat{\mathbf{B}})\,\hat{\mathbf{B}}\ ,$$

where $\hat{\mathbf{E}}$ and $\hat{\mathbf{B}}$ are unit vectors of the fields and ω is the cyclotron frequency. For high magnetic fields the last term, proportional to ω^2, could dominate and most electrons would stay on drift lines perpendicular to the GEM surface and eventually reach the GEM's copper coating. Those charges would be lost for the signal and consequently decrease the chamber's $\mathrm{d}E/\mathrm{d}x$ capabilities.

In Fig. 4 the measured anode current arising from irradiation with a ^{55}Fe source is shown as function of the magnetic field. It rises by a factor of two between 0 T and 5 T. Simultanously the extraction efficiency of the electrons out of the last GEM in front of the anode plane was measured. Because the chamber was operated with a symmetric setup (all GEM voltages and electric fields at the same value) the increase of the anode current can fully be explained by the improved extraction efficiency to

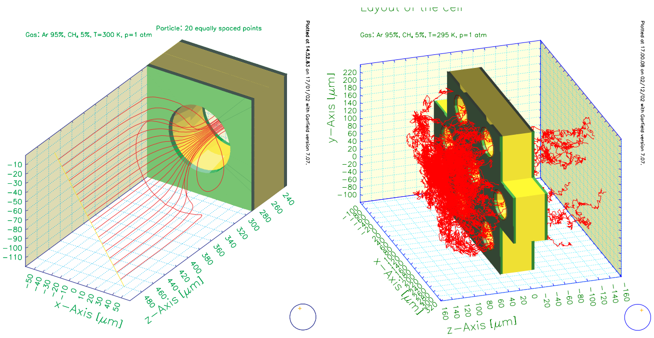

Fig. 5. GARFIELD simulation of electron drift

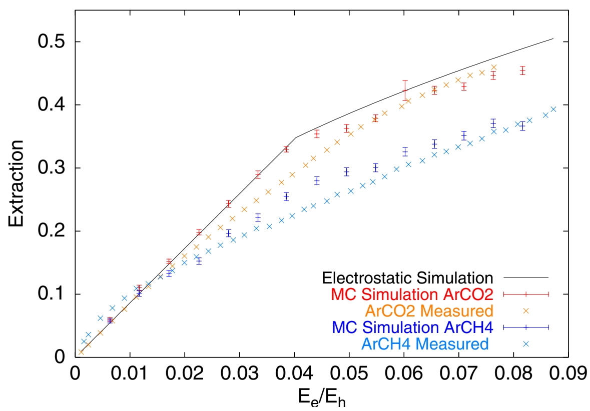

Fig. 6. Measurement and simulation of the extraction efficiency of GEM structures

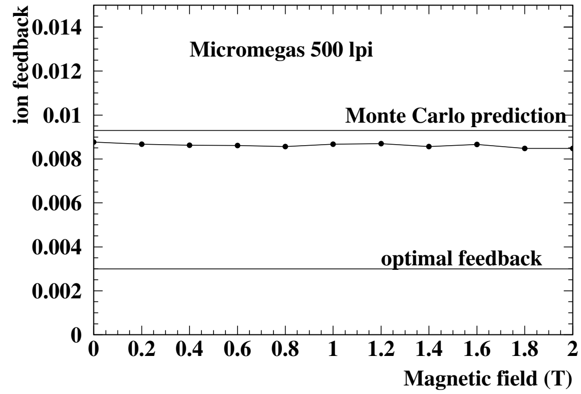

Fig. 7. Measurement of the ion back-drift in micromegas

the power of three. This shows that the product of collection efficiency and gain are not affected by the change of the magnetic field. Losses of primary ionisation charge is hardly visible.

The experimental work is accompanied by numerical simulations of micro pattern devices. For example, the electrical field map of a GEM is simulated using the finite element program MAXWELL [5]. This field map is fed into the gas detector simulation program GARFIELD [6] to calculate the drift lines of individual electrons and ions. The result of such simulations are illustrated in the pictures of Fig. 5, where the influence of the magnetic field and of gas diffusion on the electron drift has been studied. The numerical results of these simulations can then be parametrized and compared to measurements. The goal is to extract an overall model for the charge transfer in GEM structures. Within this model one can then optimize geometry and electric fields of such GEM structure for the needs of a TPC.

One result of the numerical calculations is presented in Fig. 6. It shows that the measured extraction efficiency for electrons in two different gases can be reproduced by the numerical simulation both qualitatively and quantitatively.

One important charge transfer parameter is the so called ion feedback, which describes how much ion charge is transfered into the drift volume per electron charge collected on the anode plane. Figure 7 shows the measured result for a mircomegas structure compared to the theoretical expectation. Ion feedback below the 1 % level has been achieved.

4 Summary and outlook

Many R&D projects have started on the development of a TPC for the future e^+e^- linear collider. In particular the possibility to use micro pattern gas detectors as the gas amplification stage is being studied intensively. Here the main focus lies on the charge transfer properties and the position resolution of these devices. In addition measurements in high magnetic fields are underway to investigate the implications on the drift and amplification region.

The next step following the start-up activities should be the design and construction of a large prototype including its operation in high magnetic field and test beams. Beside being a proof of priciple for the LC TPC it would serve as a test bench for the mechanics and field cage design.

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