Nuclear Instruments and Methods in Physics Research A 719 (2013) 101–108

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Simulation of space-charge effects in an ungated GEM-based TPC☆

F.V. Böhmer*, M. Ball, S. Dørheim, C. Höppner, B. Ketzer, I. Konorov, S. Neubert, S. Paul, J. Rauch, M. Vandenbroucke

Technische Universität München, Physik Department E18, D-85748 Garching, Germany

ARTICLE INFO

Article history:
Received 18 September 2012
Received in revised form
20 March 2013
Accepted 4 April 2013
Available online 21 April 2013

Keywords:
Time Projection Chamber
Gas Electron Multiplier
Particle tracking
Ion backflow
Space charge
Drift distortions
Laser calibration

ABSTRACT

A fundamental limit to the application of Time Projection Chambers (TPCs) in high-rate experiments is the accumulation of slowly drifting ions in the active gas volume, which compromises the homogeneity of the drift field and hence the detector resolution. Conventionally, this problem is overcome by the use of ion-gating structures. This method, however, introduces large dead times and restricts trigger rates to a few hundred per second. The ion gate can be eliminated from the setup by the use of Gas Electron Multiplier (GEM) foils for gas amplification, which intrinsically suppress the backflow of ions. This makes the continuous operation of a TPC at high rates feasible.

In this work, Monte Carlo simulations of the buildup of ion space charge in a GEM-based TPC and the correction of the resulting drift distortions are discussed, based on realistic numbers for the ion backflow in a triple-GEM amplification stack. A TPC in the future $\overline{\text{P}}$ANDA experiment at FAIR serves as an example for the experimental environment. The simulations show that space charge densities up to 65 fC cm^{-3} are reached, leading to electron drift distortions of up to 10 mm. The application of a laser calibration system to correct these distortions is investigated. Based on full simulations of the detector physics and response, we show that it is possible to correct for the drift distortions and to maintain the good momentum resolution of the GEM-TPC.

1. Introduction

A Time Projection Chamber (TPC) [1] can be regarded as an almost ideal device for charged-particle tracking. A large number of 3-dimensional space points measured along a particle track (typ. 50–100) eases the task of pattern recognition in a dense environment and allows particle identification (PID) via the measurement of specific ionization. Large solid-angle coverage combined with very little material in the active part of the detector makes this device very attractive for applications in which high resolution is to be combined with small photon conversion probability and little multiple scattering. TPCs have been successfully used as large volume tracking devices in many particle physics experiments, e.g. PEP-4 [2], TOPAZ [3], DELPHI [4], ALEPH [5], NA49 [6], STAR [7], CERES [8] and ALICE [9].

In a TPC, electrons created by ionizing particles traversing the chamber are drifting over distances of the order of 1 m, before they undergo avalanche multiplication on a plane of proportional wires. The reconstruction of a track from the measured arrival point in space and time of the ionization electrons requires a precise knowledge of the drift of electrons and hence of the electric and magnetic fields in the chamber.

Electrons have drift velocities of the order of several cm μs^{-1} and are thus quickly removed from the drift volume. The drift velocity of ions, however, is three to four orders of magnitude smaller (see Table 1 for the values used for our simulations), leading to a slow buildup of space charge in the chamber. There are two principal sources of ions in a TPC:

- Gas ionization by fast charged particles traversing the drift volume: The created ions slowly drift towards the cathode end-plate of the TPC.
- Avalanche multiplication: During avalanche amplification, a large number of electron–ion pairs is created, given by the total gain G, which is typically of the order of 10^3–10^4. Without further measures, the ions created in the amplification process would move back into the drift volume and lead to significant distortions of the electric field.

The total amount of charge accumulated in the drift volume depends on the rate and momentum distribution of the incident particles, the properties of the gas, and the amount of ions from the avalanche region drifting back into the drift volume. To prevent avalanche ions from reaching the drift volume, TPCs are

☆This work has been supported by the 7th Framework Program of the EU, the German Bundesministerium für Bildung und Forschung and the DFG Cluster of Excellence “Origin and Structure of the Universe”.

* Corresponding author. Tel.: +49 89 289 12592; fax: +49 89 289 12570.
E-mail address: felix.boehmer@tum.de (F.V. Böhmer).

0168-9002/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nima.2013.04.020

Table 1
Parameters of the space charge simulation.

Event rate	2×10^7 s^{-1}
Beam momentum	$p_{\bar{p}} = 2.0$ GeV/c
Gas mixture	Ne/CO_2 (90/10)
Average energy per electron-ion pair	W_I=36.7 eV
Nominal drift field	$\mathbf{E}$=(0,0,400 V cm^{-1})
Magnetic field	$\mathbf{B}$=(0,0,2.0 T)
Nominal ion drift velocity	$u^+ = 1.766$ cm ms^{-1}
Electron mobility	$\mu^- = 6.828 \times 10^3$cm^2(Vs)$^{-1}$
Nominal electron drift velocity	$u^- = 2.731$ cm μ s^{-1}
Long. diffusion	229 μm cm$^{-1/2}$
Trans. diffusion	128 μm cm$^{-1/2}$
TPC dimensions (active volume)	r=(15.75,41.2) cm z=(−39.5,109.5) cm
Ion yield	$\epsilon = 4$

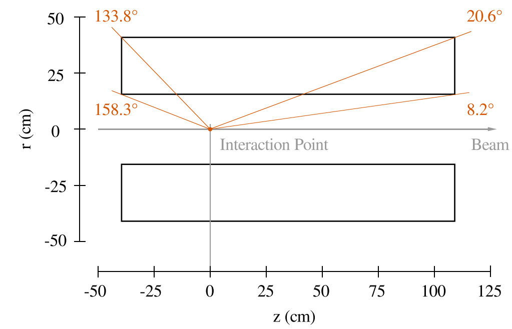

Fig. 1. Geometry and dimensions of the active part of the $\overline{\text{P}}$ANDA TPC (cross-section). In its final form, the field cage of the $\overline{\text{P}}$ANDA TPC was designed to be split into two identical and independent volumes of half-circular cross-section to make room for the target pipe which traverses the TPC vertically.

normally operated in a pulsed mode, where an electrostatic gate to the readout region is opened only when an interaction in the target has occurred, and is closed immediately thereafter [10]. The time needed to remove the ions as well as the switching time of the gate constitute dead times for the experiments, which limit the trigger rates to several hundred per second.

Modern particle physics experiments, in contrast, require high interaction and trigger rates and little or no dead time of the detector systems. In order to benefit from the advantages of a TPC in a high-rate experiment, one has to find other means of space charge suppression. As an alternative to ion gating, the usage of (GEMs) [11] for gas amplification has been proposed, since these devices feature an intrinsic suppression of the ion back-drift [12,13]. Operating a TPC at interaction rates which are large compared to the inverse drift time of electrons – which is of the order of 100 μs for typical drift distances of 1 m – means that several events will be overlapping in one drift frame. The TPC hence acts as an “analog track pipeline” with signals arriving continuously at the readout pads. Instead of an event-based, triggered readout, the appropriate readout mode of such a device is then a continuous electronic sampling of signals combined with an autonomous detection of hits, which are further processed based on their individual time stamps. The association of these hits to tracks and of tracks to distinct physics events (“event deconvolution”) requires real-time tracking capabilities of the data acquisition system. The successful development of a continuously running TPC, though challenging, opens the possibility to benefit from the advantages of such a detector in future high-rate experiments.

Among other options, a GEM-based TPC was proposed as the central tracker of the $\overline{\text{P}}$ANDA (Antiproton Annihilations at Darmstadt) experiment [14] at the future international Facility for Antiproton and Ion Research (FAIR). $\overline{\text{P}}$ANDA will use an intense, cooled antiproton beam with momenta from 1.5 to 15 GeV/c impinging on different targets and will reach luminosities of up to 2×10^{32} cm^{-2} s^{-1}, resulting in a $\bar{p}p$ interaction rate up to 2×10^7 s^{-1}. The dimensions of the $\overline{\text{P}}$ANDA GEM-TPC are shown in Fig. 1. It consists of a cylindrical vessel with 150 cm length and an inner (outer) radius of 15.5 cm (41.5 cm) with GEM amplification at the upstream endcap [15], placed in a 2 T solenoidal magnetic field. Owing to the fixed-target geometry of the experiment, the interaction point is not located in the middle of cylinder axis, but shifted upstream. Detailed simulations of the TPC have shown the potential to provide excellent standalone pattern recognition and momentum resolution of the order of a few percent [16]. At typical event rates at $\overline{\text{P}}$ANDA about 4000 tracks are superimposed in the drift volume at any given time.

Track densities similar to this environment are expected for the ALICE TPC after an upgrade of the LHC, foreseen for the year 2018 [17]. At an expected luminosity for Pb–Pb collisions of 6×10^{27} cm^{-2} s^{-1}, a continuous readout of the TPC is required to make full use of the interaction rate of about 50×10^3 s^{-1}. This cannot be achieved with the present gated MWPC-based amplification system. A replacement by a triple-GEM amplification using large-size foils is currently under evaluation.

The ion leakage from a multi-GEM detector, however, is considerably larger than that from a closed gating grid, which is typically $< 10^{-4}$ [9]. It is therefore important to develop an understanding of the effects of residual space charge in a GEM-based, continuously running TPC. To this end, we have developed a computer simulation of space charge accumulation and drift distortions for such a device. The simulation is based on the following steps:

- transport particles from minimum bias physics events through the detector setup and calculate their energy loss;
- generate electron–ion pairs accordingly and propagate them through the detector including drift, diffusion, and avalanche amplification;
- model the drift of ions to obtain the spatial distribution of space charge;
- calculate the resulting electric field in the drift volume using finite element methods;
- solve the drift equation for electrons in electric and magnetic fields to get a map of drift distortions as a function of the point of generation;
- simulate a laser calibration system to measure the drift distortions.

In the present paper, the example of the $\overline{\text{P}}$ANDA TPC is used as a case study to investigate the distortions expected in a GEM-based TPC due to space charge effects. We focus on calculating the order of magnitude of distortions expected for a GEM-TPC in a high-rate environment and show that corrections are possible. We use an iterative numerical method to calculate the space charge distribution due to ionization and backdrifting ions, assuming an azimuthally symmetric problem. As such, the method is readily applicable to other TPCs with cylindrical geometry. In case the azimuthal symmetry is broken due to unexpected problems at the field cage or the amplification stage, the method can in principle be extended to three dimensions. In order to decrease computing time, also analytical solutions of the electric field due to an arbitrary charge distribution [18] could be plugged into our simulation framework. Section 2 describes the detector setup