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3D simulation of electron and ion transmission of GEM-based detectors

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ABSTRACT

Time Projection Chamber (TPC) has been chosen as the main tracking system in several high-flux and high repetition rate experiments. These include on-going experiments such as ALICE and future experiments such as PANDA at FAIR and ILC. Different R&D activities were carried out on the adoption of Gas Electron Multiplier (GEM) as the gas amplification stage of the ALICE-TPC upgrade version. The requirement of low ion feedback has been established through these activities. Low ion feedback minimizes distortions due to space charge and maintains the necessary values of detector gain and energy resolution. In the present work, Garfield simulation framework has been used to study the related physical processes occurring within single, triple and quadruple GEM detectors. Ion backflow and electron transmission of quadruple GEMs, made up of foils with different hole pitch under different electromagnetic field configurations (the projected solutions for the ALICE TPC) have been studied. Finally a new triple GEM detector configuration with low ion backflow fraction and good electron transmission properties has been proposed as a simpler GEM-based alternative suitable for TPCs for future collider experiments.

1. Introduction

The physics processes aimed at various on-going and future high energy and particle physics experiments, have pushed the detector requirements to an unprecedented level. Owing to the enormous particle multiplicity per event, these requirements include good momentum resolution, high jet energy resolution, excellent particle identification and ability to cope with the harsh radiation environments. Time Projection Chambers (TPC) [1], due to their low material budget and excellent pattern recognition capabilities, are often used for three-dimensional tracking and identification of charged particles. They constitute the main tracking system in many on-going experiments, such as ALICE [2] and are proposed to be used for several future experiments such as PANDA [3] and ILC [4]. Since the ALICE experiment is an on-going one planning for a significant upgrade within a few years time scale, extensive R & D has been carried out for the upgrade part of its TPC.

ALICE (A Large Ion Collider Experiment) is one of the general-purpose heavy-ion experiments at the Large Hadron Collider (LHC) which is designed to study the physics of strongly interacting matter and the Quark Gluon Plasma (QGP) in nucleus–nucleus collisions. In order to identify all the particles that are coming out of the QGP, ALICE is using a set of 18 detectors that gives information about the mass, the velocity and the electrical sign of the particles. A significant increase of the LHC luminosity for heavy ions is expected in RUN 3 after Long Shutdown 2 (LS2), leading to collision rates of about 50 kHz for Pb–Pb collisions. This implies a substantial enhancement of the sensitivity to a number of rare probes that are key observables for the characterization of strongly interacting matter at high temperature. A continuous ungated mode of operation is the only way to run the TPC in 50 kHz Pb–Pb collisions.

The time necessary to evacuate the ion charge (created in the amplification process) from the detector volume is relatively high for the current Multi Wire Proportional Chamber (MWPC) based readout of the present ALICE-TPC. These ions drift back into the TPC volume, create local perturbations in the electric field and, thus, affect the drift behavior of the electrons from a later track. This ion feedback problem restricts the use of MWPCs in high rate experiments. Although this problem can be solved by using an additional plane of gating grid, it leads to an intrinsic dead time for the TPC, implying a rate limitation of the present TPC.

To fully exploit the scientific potential of the LHC at high-rate Pb–Pb collisions, the ALICE collaboration plans an upgrade of many subdetectors, including the central tracker [5,6]. Different R & D activities

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Table 1
Design parameters of GEM-based detectors.

Polymer substrate	50 μm
Copper coating thickness	5 μm
Hole diameter (copper layer)	70 μm
Hole diameter (Polymer substrate)	50 μm
Hole to hole pitch	140/280 μm
Drift Gap	3 mm
Transfer gap 1	2 mm
Transfer gap 2	2 mm
Transfer gap 3	2 mm
Induction gap	2 mm

have been carried out and converged to the adoption of Gas Electron Multiplier (GEM) [7] as the gas amplification stage of the ALICE-TPC upgrade version [8] while retaining the present tracking and particle identification capabilities of the TPC via measurement of the specific energy loss (dE/dx). The new readout chambers will employ stacks of four GEM foils for gas amplification and anode pad readout. The configuration consists of a combination of standard (S) and large hole pitch (LP) GEM foils, i.e., S–LP–LP–S. Such quadruple GEM stacks have been found to provide sufficient ion blocking capabilities at the required gas gain of 2000 in $Ne/CO_2/N_2$ (90/10/5). However, further optimization of the experimental parameters (geometry, electrostatic configuration, gas composition, material used to build the detector components) can minimize distortion due to space charge by reducing ion feedback in the drift volume [9] and larger signals through improved electron transmission.

In this work, we have tried to develop a thorough understanding of GEM-based detectors from this point of view and made attempts to explore the appropriateness/suitability of these detectors in the context of the TPC in general. Extensive numerical simulations have been carried out to estimate the effects of detector geometry, electric field configurations and magnetic field on electron transmission and ion backflow fraction. To begin with, single GEM configurations have been studied in detail and compared with available experimental data. A good understanding of this device has allowed us to deal with the quadruple GEM configuration with relative ease. The numerical results for the quadruple GEM have been also compared with the available experimental data of ALICE TPC. Finally, we have worked on a new configuration of a triple GEM detector which allows low ion backflow fraction despite providing good electron transmission and may be suitable for the TPCs in future collider experiments. The stability of the detector behavior and the discharge probability are very important for the operation and most importantly they are affected by the geometry and field configurations. In the present simulation, all these issues are not taken into account. Thus, the proposed solutions may need to be evaluated as regard to the overall stability of the detector.

2. Simulation tools

The Garfield [10,11] simulation framework has been used in the present work. The 3D electrostatic field simulation has been carried out using neBEM (nearly exact Boundary Element Method) [12–14] toolkit. Besides neBEM, HEED [15,16] has been used for primary ionization calculation and Magboltz [17,18] for computing drift, diffusion, Townsend and attachment coefficients.

3. Simulation models

The design parameters of GEM-based detectors considered in the numerical work, are listed in Table 1. The model of a basic GEM cell, built using Garfield, is shown in Fig. 1(a). It represents a GEM foil, having two bi-conical shaped holes placed in a staggered manner along with a readout anode and a drift plane on either sides of the foil. The distance between top surface of the GEM and the drift plane is called the drift gap whereas that between the lower surface and the readout plate is named induction gap. The GEM foil separates these two volumes and is responsible for the transfer and amplification of the primary electrons generated in the drift volume. A potential difference V_{Drift} and $V_{\text{Induction}}$ are maintained in the drift volume and the induction volume, respectively. The electric fields, both in the drift (E_{Drift}) and induction ($E_{\text{Induction}}$) volumes, are uniform and the magnitudes have been kept at a value to meet the requirements of the electron drift and diffusion only. The large potential difference (V_{GEM}) between the upper and lower GEM electrodes creates a strong field inside the holes (E_{GEM}) which causes the amplification of the primary electrons.

In comparison to single GEM, in case of multi GEM detector, several GEM foils are placed in between the drift and the read-out plane. The naming scheme used in this work numbers the foils in the order of the passage of electrons coming from the drift region. The first GEM after the drift plane is called GEM 1 and the others are GEM 2, GEM 3 and so on. The gap in between GEM 1 and 2 is called Transfer gap 1 and that between GEM 2 and 3 is called Transfer gap 2 etc. The field in the transfer gap is uniform and the magnitudes have been kept in a range suitable for the requirements of electron drift and diffusion. For example, the simulation models of two different quadruple GEM devices are shown in Fig. 1. Among the four foils, GEM 1 and GEM 4 have the pitch of 140 μm (denoted as S), whereas the middle two foils have a larger pitch of 280 μm (denoted as LP). This arrangement is denoted as S–LP–LP–S. In the first case (QGemI), the central hole of the basic unit from all the four GEM foils are perfectly aligned (Fig. 1(b)). In the other case (QGemII), as shown in Fig. 1(c), the first and the last foils (S) are aligned with each other whereas the second and third foils (LP) are misaligned with them. The basic cell structure then has been repeated along both positive and negative X and Y-axes to represent a real detector. With the help of these models, the field configuration of the detectors have been simulated using appropriate voltage settings. These are followed by the simulation of electron transmission and ion backflow fraction in $Ne/CO_2/N_2$ (90/10/5) gas mixture.

For estimating electron transmission within a GEM detector, electron tracks generated by 5.9 keV photon have been considered in the drift volume. The primary electrons created in the drift region are then made to drift towards the GEM foil using the Microscopic tracking routine [10]. In this procedure, a typical drift path proceeds through millions of collisions and each collision can be classified as elastic or inelastic collision, excitation, ionization, attachment etc.

The electrons during their drift produce avalanche inside the GEM foil. For this calculation Monte Carlo routine has been used. The procedure first drifts an initial electron from the specified starting point. At each step, a number of secondary electrons is produced according to the local Townsend and attachment coefficients and the newly produced electrons are traced like the initial electrons. In parallel, the ion drift lines are also traced. The primary ions in the drift region and the ions created in the avalanche have been considered for the estimation of the backflow fraction.

4. Results

4.1. Electron transmission

Electron transmission can be presented as a function of two mechanisms: electron focusing and transverse diffusion. The field configuration has a strong impact on electron focusing. Due to the high field gradient between the drift volume and the GEM hole, the field lines are compressed, resulting in a characteristic funnel shape. The decrease of E_{GEM} for a particular E_{Drift} or the increase of E_{Drift} at a fixed E_{GEM} affects the funneling, resulting in the termination of the field line on the top surface of the GEM foil. Again, the ratio between the E_{GEM} and $E_{\text{Induction}}$ controls the field lines inside the GEM foil as well as in the induction volume. Since $E_{\text{Induction}}$ is lower than the field inside the GEM hole, the field lines emerging from the hole spread uniformly and finally end at the readout plane. Depending on the field ratio, the