Study of Streamer Development in Resistive Plate Chamber

Jaydeep Datta, a,b 1 Sridhar Tripathy, a,b Nayana Majumdar a,b and Supratik Mukhopadhyay a,b

a Saha Institute of Nuclear Physics, Sector 1, AF Block, Bidhan Nagar, Salt Lake, Kolkata 700064, India
b Homi Bhabha National Institute, Training School Complex, Anushaktinagar, Mumbai 400094, India

E-mail: jaydeep.datta@saha.ac.in

ABSTRACT: This work has been carried out to simulate the working mode of a Resistive Plate Chamber and corroborate it with experimental measurements in order to develop a numerical tool for studying the performance of the device for any gas mixture. This will allow us to explore the feasibility of operating these chambers in the Iron Calorimeter setup at India-based Neutrino Observatory with any eco-friendly substitute. The simulation has considered a hydrodynamic model of charge transport to emulate the electronic and ionic growths in the device as a function of the applied voltage which determines its working mode as either of the avalanche or streamer. In order to validate, the simulation result has been compared with compatible experimental data available in the literature.

KEYWORDS: Gaseous detectors, Resistive-plate chambers, Detector modelling and simulations II

1 Corresponding author
1 Introduction

The magnetized Iron Calorimeter (ICAL) setup at India-based Neutrino Observatory (INO) [1] is designed to address the issue of neutrino mass hierarchy by studying the matter effect on neutrinos and anti-neutrinos traveling through the earth. It will have a modular structure consisting of 151 horizontal layers of iron plates of 50 kt mass in total, interleaved with more than 29000 Resistive Plate Chambers (RPCs) leading to a setup of dimension $48m \times 16m \times 14.5m$. The layers of RPC will be operated for tracking the muons produced by the charged current interaction of neutrinos with the iron nuclei while passing through the ICAL for determination of their momentum, charge and flight path. The requirement of the experiment demands RPC operation in avalanche regime in order to achieve excellent position resolution and long-term operation. A gas mixture of R134a, iso-butane and SF$_6$ (95.5: 4.2: 0.3) has been chosen for this purpose. These gases have high global warming potential and hence better be replaced with eco-friendly ones, however, without compromising the performance of the RPC and the objectives of the experiment thereof.

This report presents a simulation framework built on the basis of hydrodynamic model of electronic and ionic transports to study the growth of charge in the RPC for incident cosmic muons and determine the working mode (avalanche or streamer) of the detector for each event. The efficiency and the streamer probability of the RPC have been estimated at different applied voltages and compared to published experimental data [2] for testing the efficacy of the simulation framework. The entire framework has been developed on the platform of a commercial Finite Element Method (FEM) package, COMSOL Multiphysics [3]. It has been augmented with few other packages as tool kits to yield relevant information of primary ionization (using HEED [4]) and electron transport parameters in the gas medium (using MAGBOLTZ [5]) that are required to simulate the growth of charge in the RPC. At higher voltages, when the avalanche grows sufficiently large in size, the space charge effect eventually becomes significant. At a certain stage, the avalanche starts evolving under its own space charge field where additional physical process like photo-ionization contributes to the...
growth of charge. It leads to development of large charge content and eventually a plasma filament [6] which is called the streamer. To account for the photo-ionization contribution, the cross-section of the same for different gas components have been taken from relevant sources [7, 8].

Many attempts have been made to simulate and understand the working principle of avalanche and streamer modes of RPC. Most of them are based on either Monte Carlo methods [9–13] or hydrodynamics [14–16]. A review of different simulation methods can be found in this reference [17].

2 Simulation Method

In the present work, a model following the design parameters of the RPC of ICAL setup has been built. The growth of electronic charges in the gaseous medium detector through the multiplication of primary electrons created by incident cosmic muons has been simulated following transport equations of hydrodynamics and shown in figure 1 for a given applied voltage. The details of the simulation procedure have been discussed below.

2.1 Model Geometry

Due to limitation of time and computational resources, a 2D model of the RPC has been used. The electrodes have not been considered explicitly in the simulation. The gas gap has been 2.0 mm thick along Z-direction. The gas, considered for simulation, has been a mixture of R134A and butane (97 : 3) without SF$_6$ component (to compare with the experimental data [2]). The electric field has been applied in Z-direction. Along the X-direction, the length of the RPC has been considered 1.0 mm only. It is justified because the maximum radius of avalanche or streamer never exceeds $\frac{1}{\alpha}$ [6], where $\alpha$ is the first Townsend coefficient. It is of the order of 10 mm$^{-1}$ for the gas mixture in consideration. The growth of avalanche has been calculated in X and Z-directions. The model has assumed geometrical symmetry along the Y-direction up to the length mentioned in the physics modules which is 1.0 mm in this case. The voltage distribution in the RPC in absence of any ionizing event as obtained with the COMSOL has been illustrated in figure 2.

2.2 Event Generation

The cosmic muon has been chosen as the incident particle on the RPC. A total number of 10000 muons has been used in the HEED with their energy ($E_{\mu}$) varying between 1 to 10 GeV and the flux has been calculated following modification of Gaisser parameterization [18] by Tang et.al. [19]. The directionality of the muons has been considered following the zenith angle coverage (around 90°) of the experimental setup as mentioned in [2]. The primary ionization in the gas gap of the RPC caused by the muons has been simulated using HEED. It has provided information on the number of primary electrons and the position of the clusters formed by them which have been used for generating events to emulate RPC signal. The primary electrons have been assumed to form a cluster following a two-variable Gaussian distribution. The spread in the Z-direction has been varied along with the mean Z-position in such a way that the 5 $\sigma$ of the Gaussian should not extend beyond the electrodes. Since the muons are mostly vertical, the spread in X-direction has been very small and therefore, kept constant. The number of electrons has been varied in step of 5, between 10 to
60, following the histogram of primary electrons produced by the HEED (see figure 3) where more than 90% cases have fallen within the said range. The weighted mean of the primary electrons’ position has been calculated using the cluster information from HEED. The mean position of primary electrons in Z-direction has been varied in step of 0.1 mm, starting from 0.1 mm to 1.9 mm. The variation of the number of primary electrons with their mean Z-position has been shown in figure 4.

2.3 Growth of Charge

In the simulation, the growth of charge has been emulated by calculating the charge at time steps optimized by COMSOL. This requires the electric field to be estimated at each time step. It should be noted that in practical situation, the space charge can modify the electric field. To calculate the
electric field at each step, the "Electrostatic" module of COMSOL has been used. The equations involved in calculating the electric field configuration $\vec{E}$ taking into account the space charge $\rho$ are given below,

$$\vec{E} = -\vec{\nabla}V$$  \hspace{1cm} (2.1)

$$-\vec{\nabla}d(\varepsilon_0 \vec{\nabla}V - \vec{P}) = \rho$$  \hspace{1cm} (2.2)

where $V$ is the potential, and $\vec{P}$ is the polarization vector, while $\varepsilon_0$ is the permittivity of the vacuum, and $d$ is the thickness in Y-direction. As a 2D model has been used, the change of electric field has been considered only in the two directions and in the third direction, it has been considered constant. The growth of the electron and ion avalanches have been calculated using the "Transport of Dilute Species" module which assumes that the species (electron or ion) concentration is much smaller than that of the solvent (neutral gas molecules). The module has studied transport of the species through diffusion and convection. The governing equations are the following.

\[
\frac{\partial n_e}{\partial t} + \vec{\nabla}(-D\vec{\nabla}n_e) + \vec{u}_e \vec{\nabla}n_e = S_e + S_{ph} \\
\frac{\partial n_i}{\partial t} + \vec{\nabla}(-D\vec{\nabla}n_i) + \vec{u}_i \vec{\nabla}n_i = S_e + S_{ph} \\
S_e = (\alpha(\vec{E}) - \eta(\vec{E}))|\vec{u}_e|n_e(x, t) \\
S_{ph} = Q_e \mu_{abs} \psi_0
\]  \hspace{1cm} (2.3-6)

where $n_e$ and $n_i$ denote electron and ion density, respectively. The electron transport parameters in the gas medium have been expressed by $\vec{u}_e$, $D$, $\alpha$ and $\eta$ which represent the drift velocity and then diffusion, the first Townsend and attachment coefficients, respectively. These are functions of local electric field and have been calculated using MAGBOLTZ [5]. Due to absence of significant magnetic field, the off-diagonal terms of diffusion tensor have become zero. This has led to a $2 \times 2$ diagonal matrix for diffusion where the diagonal terms are the diffusion coefficients along X and Z-directions. The terms $S_e$ and $S_{ph}$ represent the numbers of electrons produced due to gaseous ionization and photo-ionization, respectively. While $S_e$ depends upon the transport parameters and the electron density, $S_{ph}$ is dependent upon $Q_e$, $\mu_{abs}$, and $\psi_0$ where $Q_e$ is the quantum efficiency of the gas for electron generation from photo-ionization, $\mu_{abs}$, the photon absorption coefficient of the same and $\psi_0$, the photon flux. The absorption of electrons in the anode has been taken care of by assuming drift of the electrons through the anode and similar condition has been set about the ions to take care of their absorption at the cathode. To incorporate the phenomenon of electron and ion diffusing and drifting out of the simulated volume, the two boundaries other than the cathode and the anode have been assumed open for them.

In streamer formation, electrons from photo-ionization plays an important role [6]. The work done by Capeillère et.al. [20] shows that photon propagation in the gas volume can be described by the following equation.

$$\vec{\nabla}(-c \vec{\nabla}\psi_0) + a\psi_0 = f$$  \hspace{1cm} (2.7)

where

$$c = \frac{1}{3} \mu_{abs}, \hspace{1cm} f = \delta S_e, \hspace{1cm} a = \mu_{abs}$$
Here, $\delta$ is the number of excited neutral molecules for each ionized molecule. In the present work, the photon propagation has been accounted for using "Coefficient Form Partial Differential Equation" module, which has been used to solve the equation 2.7. As the electrodes are made of material which does not emits photon, the photon flux at the electrodes will be zero which has been used as Dirichlet condition in the model. Like the charges, the photon propagation out of the simulation volume has been taken into account by considering the two boundaries other than the electrodes open for them.

### 2.4 Stopping Conditions

The range of voltage where the RPC is operated, gives rise to positive streamers [21]. In case of positive streamers, the plasma moves back to the cathode, leading to a rise in the electron density. On the other hand, all the electrons leave the gas gap in case of avalanche mode operation. These two conditions have been utilized to identify the streamer and avalanche and then stop the simulation. They have been implemented in the present work in the following way:

1. In each step, the model has calculated the total number of electrons in the gas gap. When it has become less than 1, the simulation has stopped and the case has been identified as avalanche.

2. When the density of electrons at the cathode has turned out to be non-zero, the simulation has stopped, identifying the mode of operation as streamer.

### 3 Results

For each combination of number and position of primary electrons, the evolution of the charged fluid has been simulated. Criteria discussed in section 2.4 have been used to determine the mode of RPC operation, as either of avalanche and streamer. To determine the efficiency of the RPC, threshold criteria mentioned in [2] have been used where it has been considered that the amplitude of the signal should be greater than $30 \text{ mV}$ which is equivalent to a $0.1 \text{ mV}$ signal acquired across a $25 \text{ }\Omega$ resistor [2]. Using these information, the corresponding current has been calculated and used as threshold criteria in the present simulation. The induced current has been calculated following [9] which depends upon the relative permittivity ($\epsilon_r$) and the thickness (b) of the electrode and the thickness of the gas gap (d) through the following equations.

$$ i(t) = \frac{\tilde{E}_w \bar{u}_e}{V_w} e_0 N(t) $$

(3.1)

$$ \frac{E_w}{V_w} = \frac{\epsilon_r}{2b + d\epsilon_r} $$

(3.2)

where $i(t)$ is the instantaneous current, $e_0$, the electron charge, $\tilde{E}_w$ (weighting field), the electric field in the gas gap when the electrode of interest is raised to potential $V_w$, while all other electrodes are grounded, $\bar{u}_e$, the electron drift velocity and $N(t)$ is the number of electrons present at time t. $E_w$ is the magnitude of $\tilde{E}_w$. The equation 3.2 is derived assuming two electrodes and one gas gap.
which differs from the actual experiment. The event that has given rise to a current profile satisfying the above-mentioned condition has been considered as a valid event. For each case of number of primary electrons, the minimum mean Z-position of the primary electrons to get a valid event has been estimated. Similarly, using the criteria to identify a streamer event, the minimum Z-position to yield a streamer event has been found. Using these information and figure 4, the number of valid events and the streamer events have been calculated. The ratio of those valid events to the total events has been described as the efficiency of the detector and the streamer probability has been defined as the ratio of streamer events to the total events. The comparison of the simulated efficiency and streamer probability to the experimental data by Camarri et.al. [2] has been shown in figure 5 and 6. In figure 5, the efficiency assuming two different values of $\epsilon_r$ of the electrode, using equation 3.1 and 3.2, has been plotted as the $\epsilon_r$ can vary from 4 – 10 for the electrode material depending upon its grade. It can be noted from the figures that the simulation results have followed the experimental trend quite closely, although a quantitative agreement between them could not be achieved. There could be several reasons for the observed disagreement. The simulation itself has several sources of error, such as, fluctuation in HEED information, mean position of the electrons etc. The most significant reason may be the difference of various parameters, such as, ambient temperature, bulk properties of the electrodes etc. as used in simulation from those in real experiment which are not explicitly mentioned. All those possible sources of uncertainties are being studied to understand the discrepancies between data and simulation.

4 Conclusion

A numerical simulation framework based on a hydrodynamic model has been developed and used to emulate the dynamics and identify the working mode of RPC designed for ICAL experiment at INO. For validation, present numerical results have been compared to the published experimental results. Though the simulation result and experimental data have differed quantitatively, they have followed the same trend. To improve the agreement between these two, the authors plan to reduce the error in the simulation by taking smaller steps in mean position of the primaries,
reduce the relative tolerance and increase HEED statistics. Possible reasons of difference between experimental conditions and the numerical parameters will also be investigated. However, since the overall trends are in agreement and the streamer probability estimated from simulation and that found in experiment lie in the same order of magnitude, it is expected that the same framework may be used to study the RPC performance for other gas mixtures.

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