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[Invited Lecture]

Recent advances in the kinetic and fluid modeling of Resistive Plate Chambers

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Abstract: This work explores and describes new advances in fluid and kinetic modeling of resistive plate chambers (RPCs). RPCs are gaseous particle detectors often used for triggering and timing purposes in many high-energy physics experiments. At the Large Hadron Collider at CERN, all mega science experiments, ATLAS, CMS, ALICE, and LHCb, use RPCs in slightly different configurations, mainly for triggering muons and particle identification (Abbrescia et al. 2024). RPCs are also used for detecting charged particles in extensive air showers, which are cascades of secondary particles created when a high-energy cosmic ray interacts with the Earth's atmosphere (Abreu et al. 2018). RPC detectors are a vital component of the Iron Calorimeter detector at the India-based Neutrino Observatory (Kumar et al. 2017). They are used to detect muons produced by neutrino interactions with the iron plates in the Iron Calorimeter. RPCs can also be used for air quality monitoring by analyzing ionization caused by pollutants. They also found their way in novel medical imaging technology that combines RPC technology and Positron Emission Tomography (Fonte et al. 2023). In most of these experiments and applications, RPCs are operated with a gas mixture composed of $C_2H_2F_4$, iso-C_4H_{10}, and SF_6. Due to the very high global warming potentials of $C_2H_2F_4$ and SF_6, the search for a suitable replacement for $C_2H_2F_4$ and SF_6 is currently one of the major concerns in RPC technology. This work explores the possibility of using $C_3H_2F_4$ and

C_3HF_5 instead of $C_2H_2F_4$, as well as CF_3I, $C_5F_{10}O$, and C_4F_7N instead of SF_6. Using a swarm method of deriving cross sections, we have developed complete and consistent cross-section sets for electron scattering in these gases. Cross sections are then used as input to solve the Boltzmann equation. The hierarchy of kinetic equations resulting from a spherical harmonic decomposition of the Boltzmann equation in the hydrodynamic regime is solved numerically by expanding the moments of the distribution function in terms of Sonine polynomials about a variety of Maxwellian distributions at different temperatures (Dujko et al. 2010). Electron swarm transport coefficients and distribution functions are calculated under a wide range of conditions found in RPC detectors. Additionally, we calculate critical electric fields for both pure gases and RPC gas mixtures, which ultimately determine the minimal operating voltages of detectors. Special attention is paid to the explicit and implicit effects of electron attachment and ionization on the drift and diffusion of electrons. In the final stage of modelling, we apply the fluid equation-based model to study the inception and propagation of streamers in both standard RPC mixtures and new eco-friendly gas mixtures. Calculations and analysis are performed under LHC-like conditions. We use the first-order fluid model, which involves an advection-diffusion reaction equation for electrons, reaction equations for positive and negative ions, and assumes a local field approximation. Both axisymmetric and 3D settings are used to implement the model in the AMReX environment. AMReX is an open-source C++ library for massively parallel block-structured adaptive mesh refinement applications (Zhang et al. 2019). The system of partial differential equations is solved using its mathematical machinery, where one of the most critical parts is the accurate and efficient solving of the Poisson equation (Simonović et al. 2024). The inception and propagation of positive streamers are simulated by assuming a certain level of background ionization, as accurate models of photoionization for complex RPC gas mixtures are not yet available. Nevertheless, in 1.5-dimensional setup, we employ a simple model of photoionization, in which the photon mean free path and the photoionization quantum efficiency are considered as effective values, averaged over the relevant photoemission bands (Bošnjaković et al. 2016). We calculate the electron density, densities of positive and negative ions, and electric field as a function of the externally applied electric field for both standard and new eco-friendly gas mixtures. Other streamer characteristics, like velocity and radius, are also calculated and discussed. It has been found that the streamer radius depends on the electric field and its uniformity, gas pressure, and streamer polarity.

Keywords: Resistive Plate Chambers, Electron transport, Streamers, Boltzmann equation, Classical fluid model, AMReX

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