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Space-charge effects in liquid argon ionization chambers

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ABSTRACT

We have uniformly irradiated liquid argon ionization chambers with betas from high-activity ^{90}Sr sources. The radiation environment is similar to that in the liquid argon calorimeters which are part of the ATLAS detector installed at CERN's Large Hadron Collider (LHC). We measured the resulting ionization current over a wide range of applied potential for two different source activities and for three different chamber gaps. These studies provide operating experience at exceptionally high ionization rates. In particular they indicate a stability at the 0.1% level for these calorimeters over years of operation at the full LHC luminosity when operated in the normal mode at an electric field $\mathcal{E} = 1.0\,\text{kV/mm}$. We can operate these chambers in the normal mode or in the space-charge limited regime and thereby determine the transition point between the two. This transition point is parameterized by a positive argon ion mobility of $\mu_+ = 0.08 \pm 0.02\,\text{mm}^2/\text{V s}$ at a temperature of 88.0 ± 0.5 K and at a pressure of 1.02 ± 0.02 bar. In the space-charge limited regime the ionization currents are degraded and show signs of instability. At the highest electric fields in our study (6.7 kV/mm) the ionization current is still slowly rising with increasing electric field.

1. Introduction

At the Large Hadron Collider (LHC) [1] at CERN, the two general purpose detectors, ATLAS [2] and CMS [3], are searching for new, fundamental interactions in proton–proton collisions at very high energies. These new processes are expected to be extremely rare. On the other hand, more ordinary proton–proton collisions have large cross-sections which rise slowly with energy. The detectors must therefore be capable of picking out the very rare but interesting processes in the midst of a large number of ordinary processes. At the LHC energy and luminosity, these ordinary and plentiful proton–proton collisions produce a large number of relatively low energy particles which hit the detector at high rates.

The ATLAS detector includes liquid argon sampling calorimeters to measure the energies of the particles produced in the proton–proton collisions. A major component of these calorimeters is a dense metal in which each incident particle produces a shower of particles. That is, the relativistic collision products interact with the nuclei of the dense metal of the calorimeter and produce more particles. Most of these secondary particles are energetic enough to produce more particles in subsequent interactions with other nuclei. This showering process continues until the shower particles have too little energy to produce more particles.

Interspersed in a regular pattern with the calorimeter's dense metal are a large number of liquid argon ionization chambers through which the shower particles also pass. The charged shower particles ionize the liquid argon. This ionization then drifts in an electric field $\mathcal{E}$ toward the chamber electrodes inducing an electrical signal in an external circuit.

At the LHC design energy and luminosity the average rate of ordinary proton–proton collisions is about 1 GHz. In a typical 2 mm ionization chamber gap with a potential of 2000 V across the electrodes, the electrons drift out in about 434 ns [4] while the positive argon ions take of order 25 ms. As a first approximation we consider the ionization rate as constant in time. The study of the performance of a liquid argon ionization chamber in this large, approximately time-constant and spatially uniform ionization environment is the subject of this report.

We employ nine liquid argon ionization chambers, three at a time, in our study. Integrated into six of the nine chambers, two at a time, are beta sources distributed such that they ionize the argon approximately uniformly over a region of the chamber volume. The other three chambers act as controls. Each chamber is connected to an external circuit. Our observables are the currents through these external circuits. The parameters we vary are (1) the beta source activity (only two values), (2) the width of the chamber gap (only three values) and (3) the potential applied across the chamber gaps over an exceptionally wide range of values of both polarities at closely spaced intervals. The relatively simple geometry is amenable to straightforward predictions from analytic approximations and

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from more detailed and realistic simulations. We determine directly the threshold ionization rate above which space-charge effects degrade the performance of the liquid argon ionization chamber. This is the primary goal of this study. By comparison to predictions we are able to extract the positive argon ion mobility.

2. Phenomenology

High energy charged particles passing through liquid argon knock loose outer shell electrons from those argon atoms close to the particle track [5]. In each ionization an electron is separated from an argon atom leaving a positively charged argon ion. In the spectrum of ionization electrons, some (called delta rays) have sufficient kinetic energy to themselves create significant additional ionization. At each primary ionization process the high energy charged particle loses an amount of energy which is typically small compared to its kinetic energy.

Without an electric field, the ionization electron would likely recombine with its argon ion. But in the presence of an electric field the ionization electrons may escape and drift towards the anode while the argon ions drift towards the cathode.

Several forms of recombination deplete the ionization electrons. We will divide these forms into two classes. In the first class the ionization electron may recombine with its argon ion. Or, in a dense cluster of ionization, as from a slowly moving delta ray, electrons may recombine with other ions produced by the same track or with other time-correlated tracks. We will call such processes “rate-independent recombination” (RIR). This form of recombination is independent of the rate of high energy charged particles producing tracks in the chamber and dominates the recombination processes at low rates where the tracks are widely separated in time. The wide separation makes it unlikely that the ionization from one track overlaps with that from a non-time-correlated track. The so-called high voltage plateau curve of current versus electric field, normalized to unity at asymptotic potential [6], can be interpreted as the probability that the ionization charges survive these RIR mechanisms.

For these RIR processes we will assume that the electron and ion recombine so quickly that they do not drift far enough to contribute to a current in the electrical circuit attached to the electrodes [7].

The second class occurs when the rate of high energy charged particles is high enough that the bulk density of drifting electrons and positive charges can become significant. The probability that an ionization electron produced by one high energy charged particle combines with an ion produced by a different high energy charged particle becomes large. In such a “rate-dependent recombination” (RDR) process the probability of recombination depends on the rate of the high energy charged particles. Here the electron and ion may drift an appreciable distance before recombining, thus contributing to the current induced in the external circuit.

As we raise the ionization rate in a liquid argon ionization chamber the density of the slowly drifting positive argon ions builds up and distorts the electric field in the gap between the electrodes. But as long as the electric field is significant everywhere in the gap, the highly mobile electrons drift out of the gap at a rate which is high compared to the bulk recombination rate and, therefore, the RDR does not appreciably affect the current in the external circuit. But with further rate increases we eventually reach a threshold where the electric field near the anode is so distorted that it is almost completely screened, i.e. the electric field is infinitesimal. The density of electrons then also builds up in this same region to equal the density of the positive argon ions so the net charge density is zero. All ionization created in this region suffers the RDR so the only ionization contributing to the current in the external circuit is that created outside of this region of the chamber. As the ionization rate increases further, this screened region expands toward the cathode. The current in the external circuit is no longer directly proportional to the ionization rate. We say that the ionization chamber is in the space-charge limited regime. A full discussion can be found in Ref. [8].

We define D_i as the ionization rate-density at finite $\mathcal{E}$-field. That is, it is the ionization rate at asymptotic $\mathcal{E}$-field minus the ionization lost to RIR processes at the working $\mathcal{E}$-field. In order for us to map out the transition into the space-charge limited regime we would ideally vary the ionization rate by varying the activity of the beta source at fixed potential and measure the current density J. As we raise the source activity we would expect [8] the measured current density to rise in direct proportion until the ionization rate D_i reaches the critical value D_c. Above this critical value the electron and argon ion charge densities build up to levels where the RDR becomes significant and the current density would then rise more slowly than the source activity.

But we have only two source activities, not a continuum, so we have developed a different approach. This approach is based on the observation that the critical ionization rate D_c depends on the potential V_0 applied across the two electrodes of the liquid argon ionization chamber. Instead of varying D_i (by varying the source activity) we, instead, vary D_c (by varying V_0).

But in varying V_0 we not only change D_c we also change D_i because the RIR depends on V_0. However, by accurately measuring the HV plateau curve we can correct for the change in D_i due to the RIR. So our strategy is the following: we first determine the HV plateau curve using the weaker of our two beta sources. We then use this HV plateau curve to separate the two classes of recombination processes which modify the current density from the stronger of the two beta sources. The RDR effect depends on the ionization rate and is significant only when the ionization chamber is driven into the space-charge limited regime.

Here we develop an analytic calculation to frame our further discussion and analysis. In order to derive simplified expressions certain approximations were necessary. We will identify our assumptions and their short-comings and overcome these short-comings with detailed numerical simulations described in Section 7.

The beta source with the weaker activity is numbered 1 and the source with the stronger activity is numbered 2. The strong source has activity A times larger than the activity of the weak source. At asymptotic potential (where the RIR and RDR can be ignored), the ionization rates in the liquid argon ionization gaps, here assumed to be homogeneous throughout, are D_0 and AD_0 respectively where A is of order 20. At finite potentials, the ionization rates are $D_{i1} = D_0 P(V_0/a)$ and $D_{i2} = AD_0 P(V_0/a)$ where a is the gap width between the two electrodes and $P(V_0/a)$ is the HV plateau curve normalized to unity at asymptotic potential. Here we are assuming that the electric field in the ionization chamber is equal to the average value V_0/a. This requires an electrode structure approximating parallel plates and a negligible charge density between them. This latter assumption is a poor one when the charge densities in the ionization chamber are large enough, i.e. when the net charge in the gap becomes a major fraction of the charge on the electrodes. In this case the electric field in the chamber gap is not even approximately at the average value [8].

We will find it convenient to define the dimensionless parameters $r_1 \equiv D_{i1}/D_c$ and $r_2 \equiv D_{i2}/D_c$. When $r > 1$, the ionization chamber is in the space-charge limited regime. The critical ionization rate D_c and the associated critical ionization current density J_c are derived in Ref. [8] and in other references cited therein:

$$D_c = \frac{4V_0^2 \epsilon \mu_+}{a^4}, \quad J_c = aD_c \tag{1}$$

where ϵ is the permittivity for liquid argon ($\epsilon = 1.51\epsilon_0$) and μ_+ is the positive argon ion mobility.