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 Strontium-90 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 $\mathcal{E} = 1.0$ 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 $\mu_+ = 0.08 \pm 0.02$ mm²/Vs 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.

Keywords: Liquid Argon Calorimetry, Space-charge effects, Noble Liquid Ionization Chambers

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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, ap-

31 proximately time-constant and spatially uniform ionization environment is the
32 subject of this report.

33 We employ nine liquid argon ionization chambers, three at a time, in our
34 study. Integrated into six of the nine chambers, two at a time, are beta sources
35 distributed such that they ionize the argon approximately uniformly over a re-
36 gion of the chamber volume. The other three chambers act as controls. Each
37 chamber is connected to an external circuit. Our observables are the currents
38 through these external circuits. The parameters we vary are 1) the beta source
39 activity (only two values), 2) the width of the chamber gap (only three val-
40 ues) and 3) the potential applied across the chamber gaps over an exceptionally
41 wide range of values of both polarities at closely spaced intervals. The relatively
42 simple geometry is amenable to straightforward predictions from analytic ap-
43 proximations and from more detailed and realistic simulations. We determine
44 directly the threshold ionization rate above which space-charge effects degrade
45 the performance of the liquid argon ionization chamber. This is the primary
46 goal of this study. By comparison to predictions we are able to extract the
47 positive argon ion mobility.

48 **2. Phenomenology**

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

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

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

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

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

85 As we raise the ionization rate in a liquid argon ionization chamber the
 86 density of the slowly drifting positive argon ions builds up and distorts the
 87 electric field in the gap between the electrodes. But as long as the electric
 88 field is significant everywhere in the gap, the highly mobile electrons drift out
 89 of the gap at a rate which is high compared to the bulk recombination rate
 90 and, therefore, the RDR does not appreciably affect the current in the external

91 circuit. But with further rate increases we eventually reach a threshold where
 92 the electric field near the anode is so distorted that it is almost completely
 93 screened, i.e. the electric field is infinitesimal. The density of electrons then also
 94 builds up in this same region to equal the density of the positive argon ions so the
 95 net charge density is zero. All ionization created in this region suffers the RDR
 96 so the only ionization contributing to the current in the external circuit is that
 97 created outside of this region of the chamber. As the ionization rate increases
 98 further, this screened region expands toward the cathode. The current in the
 99 external circuit is no longer directly proportional to the ionization rate. We
 100 say that the ionization chamber is in the space-charge limited regime. A full
 101 discussion can be found in reference [8].

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

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

117 But in varying V_0 we not only change D_c we also change D_i because the RIR
 118 depends on V_0 . However, by accurately measuring the HV plateau curve we can
 119 correct for the change in D_i due to the RIR. So our strategy is the following: We
 120 first determine the HV plateau curve using the weaker of our two beta sources.
 121 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 $D_{i1} = D_0P(V_0/a)$ and $D_{i2} = AD_0P(V_0/a)$ 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:

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

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

152 Again, using ref. [8] we write the net current densities (including the RDR)
 153 generated in our ionization chambers by the two source activities:

$$J_1 = \begin{cases} r_1 J_c & \text{for } r_1 < 1 \\ r_1^{3/4} J_c & \text{for } r_1 > 1 \end{cases} \quad (2)$$

$$J_2 = \begin{cases} r_2 J_c & \text{for } r_2 < 1 \\ r_2^{3/4} J_c & \text{for } r_2 > 1 \end{cases} \quad (3)$$

154 For each source activity we can vary r so that the ionization rate in the chamber
 155 is either in ($r > 1.0$) or out of ($r < 1.0$) the space-charge limited regime. We
 156 can vary r by varying D_c . And we vary D_c by varying V_0 .

157 Let us now define the critical potential V_c as the potential across the elec-
 158 trodes at which $D_c = D_i$, i.e. where $r = 1$. For a given gap width there will be
 159 a different value of V_c for each of the two different source activities. These two
 160 values are obtained by solution of the two transcendental equations:

$$\frac{D_0 a^4}{4\epsilon\mu_+} = \frac{V_{c1}^2}{P(V_{c1}/a)}; \quad \frac{AD_0 a^4}{4\epsilon\mu_+} = \frac{V_{c2}^2}{P(V_{c2}/a)} \quad (4)$$

161 Note that $V_{c2} > V_{c1}$ and $r_2 > r_1$ for the two different ionization chambers with
 162 the same V_0 and a . When $V_0 > V_{c2}$, then $r_2 < 1$ (and, of course $r_1 < 1$) so at a
 163 given V_0 , we have

$$J_2/J_1 = r_2/r_1 = D_{i2}/D_{i1} \equiv A \quad (5)$$

164 As we lower V_0 below V_{c2} but still above V_{c1} , i.e. for $V_{c1} < V_0 < V_{c2}$, gap 2 is in
 165 the space-charge limited regime but gap 1 is not and we get

$$\begin{aligned}
J_1 &= aD_0P(V_0/a) \\
J_2 &= AaD_0P(V_0/a) \left(\frac{V_0}{V_{c2}} \right)^{1/2} \left(\frac{P(V_{c2}/a)}{P(V_0/a)} \right)^{1/4}
\end{aligned} \tag{6}$$

$$J_2/J_1 = A \left(\frac{V_0}{V_{c2}} \right)^{1/2} \left(\frac{P(V_{c2}/a)}{P(V_0/a)} \right)^{1/4}$$

166 The last factor is close to unity when the HV Plateau Curve is relatively flat
 167 between V_{c1} and V_{c2} . And, even if not, the small value of the exponent makes
 168 this factor close to unity. So, as a further approximation, we can ignore this
 169 factor. Then we expect the ratio of current densities in the region $V_{c1} < V_0 < V_{c2}$
 170 to be approximately

$$J_2/J_1 = A \left(\frac{V_0}{V_{c2}} \right)^{1/2} \tag{7}$$

171 As we further lower V_0 below V_{c1} both gaps enter the space-charge limited regime
 172 and we get

$$\begin{aligned}
J_1 &= aD_0P(V_0/a) \left(\frac{V_0}{V_{c1}} \right)^{1/2} \left(\frac{P(V_{c1}/a)}{P(V_0/a)} \right)^{1/4} \\
J_2 &= A^{3/4}J_1
\end{aligned} \tag{8}$$

$$J_2/J_1 = A^{3/4}$$

173 So, as the potential V_0 across each of the pair of electrodes is varied from
 174 infinity down to zero, the ratio of current densities from the two beta source
 175 activities should range from a high value of A down to the low value of $A^{3/4}$
 176 with a transition region starting at V_{c2} and ending at V_{c1} . In the ratio of the
 177 strong source current to the weak source current the variation due to the HV
 178 plateau curve largely cancels out. A measurement of V_{c2} and V_{c1} gives the
 179 ionization rate at which each liquid argon gap passes through the transition
 180 from normal operation into the space-charge limited regime. And because V_{c2}
 181 and V_{c1} depend on the argon ion mobility μ_+ we can extract this previously
 182 poorly known parameter from our data.

183 3. Beta Sources

184 The betas which ionize the liquid argon originate from a Strontium-90 ($^{90}_{38}\text{Sr}$)
185 source with half-life of 28.8 years. Strontium-90 emits a beta with a kinetic
186 energy spectrum whose end-point is 0.546 MeV. The decay product is Yttrium-
187 90 ($^{90}_{39}\text{Y}$), also a beta emitter with a kinetic energy spectrum whose end-point
188 is 2.281 MeV and half-life of 2.67 days. The decay product of Yttrium-90
189 is stable Zirconium-90 ($^{90}_{40}\text{Zr}$). The few gammas are produced primarily via
190 Bremsstrahlung. Beta spectra can be found in ref. [9]. It is traditional to quote
191 only the activity of the Strontium but, within weeks of production, the Yttrium
192 has accumulated to an activity almost equal to that of Strontium so the actual
193 activity is nearly twice the quoted value.

194 4. Apparatus

195 Each liquid argon ionization chamber structure consists of two electrodes.
196 One electrode is a solid copper rod of diameter of 4.712 mm for the strong
197 source and 4.702 mm for the weak source. In the following we will refer to the
198 dimensions for the strong source only but we should remember that the rod
199 diameter for the weak source is slightly smaller, making all gaps for the weak
200 source slightly larger than the gaps for the corresponding strong source. Into
201 one end of this rod a co-axial cavity (diameter of 4.212 mm) has been hollowed
202 out to a depth parallel to the axis of about 14 mm. A Strontium-90 beta source
203 was uniformly deposited onto one side of a 60 μm thick by 10 mm long copper
204 foil. The foil was then rolled into a cylinder, with the source material on the
205 outside surface, and inserted into the cavity such that the restoring force of the
206 foil caused it to hug the cavity wall. A solid copper rod of diameter 4.712 mm
207 with a concentric shaft of diameter 3.0 mm and length 19 mm extending from
208 one end, threaded at the end, was screwed into a threaded hole at the far end of
209 the cavity and was then laser welded to the open end of the cavity, thus sealing
210 the cavity with the source inside. From the outside the resulting assembly looks
211 like one 150 mm long solid copper rod.

Figure 1: Liquid argon ionization chamber with Strontium-90 beta source. The perspective drawing on the left shows a cut-away of the two electrodes: a copper rod (yellow) within a thin-walled copper tube (green). The rod is held in place within the tube by an insulating PEEK fiber (red) wound helically around the rod. The gap between the rod and tube fills with liquid argon forming the ionization chamber. A power supply (not shown) provides a potential difference between the rod and tube. The solid copper rod has a concentric cavity machined out to a depth, along the axis of the rod, of 14 mm. Inserted into this cavity is a rolled copper foil (blue) of 10 mm length, coated on the outer surface with the Strontium-90 beta source. The drawing on the right shows a cross-sectional close-up of this structure. Overlaid is the track of one simulated beta, from the Yttrium decay product of a Strontium-90 decay, leaving the source on the surface of the foil with kinetic energy of 1.48 MeV and passing through the liquid argon gap. An energetic delta ray, produced by this beta in the liquid argon, is represented by the red track.

212 Three different types of tube were used for the other electrode. The first type
 213 is a stainless steel tube with inner diameter of 4.990 mm and outer diameter of
 214 6.350 mm. In this case a 102 μm PEEK fiber, helically wound around the rod,
 215 holds the rod concentric within the 150 mm long tube leaving a gap of 138 μm
 216 between the electrodes. The second type is a copper tube with inner diameter
 217 of 5.250 mm and outer diameter of 5.753 mm. Here a 250 μm PEEK fiber,
 218 helically wound around the rod, holds the rod concentric within the 150 mm
 219 long tube leaving a gap of 268 μm between the electrodes. The third type is a
 220 copper tube with inner diameter of 6.51 mm and outer diameter of 7.01 mm.
 221 In this case the helically wound polystyrene fiber has diameter of 835 μm and

222 the gap is 898 μm . When in the cryostat, liquid argon fills the gap between the
223 two electrodes. The second of these ionization chamber structures, without the
224 rod with the shaft, is shown in Fig. 1. In liquid argon the capacitance of the
225 chambers with a gap of 138 (268, 898) μm is about 214 (117, 39.0) pF.

226 Two such rod assemblies were produced in October of 2007 with source
227 activities specified to be 2 mCi (weak source) and 50 mCi (strong source). A
228 third rod assembly with no beta source (0 mCi) was used as a control. Each of
229 the three rod assemblies was inserted into three identical tubes which were one
230 of the three tube types. These three physically identical chambers, differing only
231 in source activity, were inserted into three of four holes drilled near the center
232 of a solid copper cube 150 mm on a side. (The copper cube was designed to
233 minimize personnel radiation exposure.) The holes formed a 2×2 square array
234 with center-to-center nearest-neighbor separation of 12 mm. The strong source
235 chamber was equidistant from the 0 mCi and from the weak source chambers
236 so that the 0 mCi chamber could measure the radiation from the strong source
237 leaking through to the weak source chamber.

238 The copper cube with the ionization chambers was mounted in a liquid argon
239 cryostat which had been cleaned with alcohol. After closing the cryostat the
240 interior was evacuated and then filled with argon gas which had evaporated from
241 a liquid argon dewar and had then passed through a getter [10]. This evacuation
242 and filling process was repeated several times with modest heat applied to bake
243 out moisture. After the final filling, liquid nitrogen was flowed through coils
244 near the top of the cryostat. The argon gas pressure was adjusted to about 0.1
245 bar above the room pressure of about 0.93 ± 0.02 bar and argon condensed on
246 the coils, eventually filling the cryostat to the top of the copper cube. A tube
247 extending to the bottom of the cryostat and penetrating the top of the cryostat
248 was connected to two oxygen analyzers in parallel [11]. When the valves to the
249 oxygen analyzers were opened, liquid argon rose in this tube to a level a little
250 above the level in the cryostat where it evaporated. The gas flow rate was slow
251 enough that the tube temperature remained above the ambient dew point at
252 the penetration. The oxygen contamination was below 0.25 ppm. Argon gas

Figure 2: Schematic current readout circuit. Shown at the signal connection end are two ionization chambers with copper parts in yellow and liquid argon in red. HV is the high voltage power supply and each pA is a picoAmmeter. The tubes are at high voltage, either positive or negative, while the picoAmmeters are connected to the ground of the supply.

from the argon dewar was slowly flowed into the cryostat through the getter
to make up for the loss through the oxygen analyzers. The liquid nitrogen
flow rate was controlled by a nitrogen-gas-powered pressure regulator and valve
located at the output of the cooling coils after a long run through a heated
copper tube. The nitrogen gas at the regulator valve was warm enough that no
condensation and freezing would affect the valve. Excess nitrogen gas was then
routed to the signal feedthroughs to prevent condensation of moisture from the
room air, thereby minimizing leakage currents. A separate circuit monitored
the negligible leakage currents.

The liquid argon temperature was measured with three temperature sen-
sors [12] and the absolute pressure of the argon gas above the liquid surface was
measured with a mechanical gauge [13].

265 The tubes of the three ionization chambers in use at any one time were
 266 wired together to a HV feedthrough. This feedthrough was then connected to
 267 one of four HV power supplies [14, 15]. Each of the rods of the three ionization
 268 chambers was connected to its respective signal feedthrough. Only two of these
 269 feedthroughs were connected to the two picoAmmeters [16] for any one run.
 270 The simplified wiring diagram in Fig. 2 shows these connections. Each circuit
 271 has a protection resistor in series with the picoAmmeter, 4 M Ω for the strong
 272 source chamber and 10 M Ω for the weak source chamber. Because of the small
 273 currents in this study, the potential drops across these resistors required only a
 274 very small correction.

275 **5. Data Taking**

276 Data acquisition was managed automatically by a PC running LabVIEW [17].
 277 Once a run was started the LabVIEW program cycled through a series of read-
 278 ings. In each cycle it read the two picoAmmeters, a monitor of the HV supply
 279 potential, and the cryostat pressure transducer. After each cycle it recorded
 280 these readings to a disk file, along with the time since the beginning of the
 281 run and the value of the potential it sent to the HV supply. Each cycle took
 282 approximately 0.5 seconds. At one time during the run the PC read out two
 283 temperature probes located in the liquid argon at a depth close to the ionization
 284 chambers. These were recorded at the end of the run. The date and time (to
 285 the nearest second) of the start of the run was encoded into the raw data file
 286 name.

287 At the beginning of each run the LabVIEW program read in a command
 288 file which contained the values of potential to which the HV supply should
 289 be set. For each value of potential there were 40 cycles of readings (taking
 290 approximately 20 seconds). The file started with 90 potential values of zero so
 291 there were 3600 cycles of readings with the HV supply set to zero. Then there
 292 was one non-zero potential value (40 cycles) followed by another 30 to 40 values
 293 of zero. We call these non-zero potentials “steps” because when the LabVIEW

294 program progressed to such a value it stepped-up the potential from the nominal
295 zero value to the potential read from the command file. This change in potential
296 usually occurred between two cycles of readings but sometimes there was a cycle
297 with readings somewhere between the readings at zero potential and the readings
298 at the requested potential. At the end of the step, i.e. after 40 cycles of readings,
299 the LabVIEW program set the HV supply potential back to zero. But it took
300 many cycles for the current readings to return to their values before the step.

301 The range of HV potentials in a run was limited by the HV power supply. To
302 cover the full range of potentials in this study we used four HV power supplies,
303 two of which had a manual switch to select one of two ranges. Half of these HV
304 power supplies provided positive potentials and the other half provided negative
305 potentials. We covered the full range of potentials in eight runs, usually taking
306 eight days.

307 For the primary data runs, the two picoAmmeters read out the strong source
308 and the weak source ionization chambers. But we interspersed background
309 eight-run sequences reading out the 0 mCi ionization chamber and what we
310 called the “leakage” channel. This channel had connections from the HV supply
311 and picoAmmeter to the cryostat feedthrough. But nothing was connected to
312 this feedthrough on the inside of the cryostat. The purpose was to measure any
313 residual leakage currents.

314 The cryostat was filled with liquid argon and we started taking data with the
315 268 μm ionization chambers on 11 February 2009. We took data continuously
316 until 18 December 2009 at which time we warmed up the cryostat. We filled
317 the cryostat again and started taking data with the 898 μm ionization chambers
318 on 19 March 2010. We took data continuously until 2 August 2010 and again
319 warmed up the cryostat. We started taking data with the 138 μm ionization
320 chambers on 10 November 2010 and ended on 17 December 2011.

321 We raised the potential on the various ionization chambers until the argon
322 broke down, drawing excessive current which then tripped the power supply.
323 For production running we backed off a bit from the trip point so as to avoid
324 excessive trips. The electric fields we achieved are much larger than is often

Figure 3: Raw current readings from the $268\ \mu\text{m}$ strong source gap for six good steps at three different potentials (from top to bottom, red - 260 V, green - 60 V, dark blue - 60 V, black - 60 V, cyan - 1.0 V, and gray - 1.0 V) superimposed in time. The current readings for the two steps at 1.0 V have been multiplied by 10. The potential was turned on between reading numbers 9 and 10 and turned off between reading numbers 49 and 50.

possible in planar electrode structures with the same gap. We have never observed a breakdown which didn't clear after lowering the potential. That is, we have never developed a short across the gap.

6. Data Reduction

We examined plots of the raw data starting from current readings just before a potential step to just after that potential step to spot anomalies in the data. Fig. 3 shows a plot of two typical ideal steps in red and black. Most steps look

Figure 4: Step currents in the 268 μm ionization chambers at the operating potential of 260 V as a function of the time of the run, after correction for the decay of the beta sources. Red (green) data points are at positive (negative) polarity. The error bars are the systematic uncertainties described in the text. This potential corresponds to the standard electric field of approximately 1 kV/mm used by many liquid argon calorimeters.

like these. The rest of the steps in Fig. 3 are classified as good steps but are a challenge to interpret. For the ideal case in red, note that current reading 10 is slightly higher than the succeeding readings. This is due to the excess current required to charge the chamber electrodes. The charging time constant was of order 30 ms so we see only the tail of this charging current on top of the ionization current. Ranges of good steps were determined for all runs. Most often the range for a run included all of the steps in that run.

The HV supply would automatically reset within seconds of a trip so it was sometimes possible to classify a step as good even if a trip occurred. But usually steps with a trip were classified as bad.

Figure 5: Step currents from the ionization chambers with $268 \mu\text{m}$ gaps versus the potential applied across the electrodes of the ionization chambers. Both polarities are shown. For data taken with the negative HV supply the currents and potentials have been multiplied by -1. For potentials at and below 200 V the data points are plotted twice, once using the potential axis at the bottom of the plot and once using the potential axis at the top of the plot. The two horizontal arrows each connect two of many identical data points, the one on the left plotted against the top axis and the one on the right plotted against the bottom axis. For potentials above 200 V data points are plotted only once using the axis at the top. The step currents from the weak source ionization chamber are multiplied by 21.37 to show how the step currents agree in shape at higher potentials. The step currents from the 0 mCi ionization chamber, multiplied by 21.37, are also shown. A solid curve shows the HV plateau curve of Eq. 11 in the region of potential where the data was fit. This parameterization, extrapolated to lower potentials, is shown as a dashed line. A vertical arrow on the top axis shows the nominal operating point for many liquid argon calorimeters.

After rejecting such bad steps (and occasionally whole bad runs) the raw data was analyzed to extract a summary current which we call either the *step current* or the *gap current* for each potential step from the 40 current readings on the step and from 10 current readings just before the step. At the lower potentials the current readings during the step were not constant. Example steps at 1.0 V are shown in Fig. 3 in cyan and gray, multiplied by a factor 10. We assume a thin, insulating layer builds up on the electrodes perhaps from ionized impurities in the liquid argon. This thin layer has a very large capacitance and breaks down at low potentials somewhat like a reverse-biased zener diode. Our data-taking procedure was adapted to avoid complications from this presumed effect. For

352 the runs covering a range of low potentials we fit the individual current readings
 353 on the step with a quadratic polynomial and extrapolate back to the beginning
 354 of the step where we presume no potential has yet built up across the thin layer.
 355 Therefore at that time the applied potential is across the liquid argon gap and
 356 none is yet across the layer. As the potential across the layer slowly builds up,
 357 the potential across the liquid argon gap drops, causing the current to drop as
 358 well. In this fit we excluded the first four current readings after the beginning
 359 of the step in order to avoid the distortion due to the charging of the chamber
 360 capacitance. (The layer capacitance is many orders of magnitude larger than the
 361 chamber capacitance. So the potential across the liquid argon gap is established
 362 in tens of milliseconds while the potential across the layers takes many seconds
 363 to build up.) We also excluded current readings after reading number 30 (i.e.
 364 20 after the beginning of the step) because we didn't have a fit function which
 365 would reasonably represent all shapes. We assign a systematic uncertainty to the
 366 extrapolated step current due to this procedure of one third of the difference in
 367 the current extrapolated to the beginning of the step and the current averaged
 368 over the last 20 current readings in the step. A more detailed description of
 369 this layer effect and our method for avoiding its consequences can be found
 370 in Ref. [18]. The potential step at 1.0 V in cyan was taken about 7 months
 371 before the one in gray. While they both extrapolate to approximately the same
 372 current at the time of reading 10, the later potential step falls faster with time
 373 suggesting a smaller capacitance, a higher breakdown potential, and therefore a
 374 thicker layer. In special runs we recorded steps at these low potentials as long as
 375 one hour and were unable to determine an asymptotic current. An asymptotic
 376 current would indicate the breakdown potential of the layer.

377 For steps at potentials just below the critical potential V_c we observe a
 378 variety of pathologies. For some runs the raw current readings, such as the
 379 black current readings at 60 V in Fig. 3, are constant as they are for the 260 V
 380 step (red) but for other apparently identical runs the raw current readings rise
 381 over a period of seconds and then level off. Examples are the two 60 V steps
 382 (green and dark blue) in Fig. 3. We have been unable to correlate this behavior

Figure 6: Ratio of the strong source chamber step currents to the weak source chamber step currents as a function of the potential across the ionization chamber for, from left to right, the 138 μm gap, the 268 μm gap, and the 898 μm gap. Data for the two polarities of potential and the three gaps are shown as small, solid circles. In many cases the data points for the negative polarity overlap the data points for the positive polarity, obscuring them. The yellow bands indicate the overall systematic uncertainty in the data. Simulation data points are represented by open markers.

383 with any other observable and we have no explanation for it. We arbitrarily
 384 extract step currents for these steps and assign a systematic uncertainty via the
 385 same procedure as described above.

386 At the higher potentials the current readings on the step after the first few
 387 readings were constant throughout the rest of the step. If arcing occurred at
 388 the highest potentials it typically happened early in the step and then the gap
 389 rapidly recovered allowing constant current readings from there to the end of the
 390 step. To avoid discarding too much of the highest potential data we averaged
 391 the last 20 current readings and used this for the summary step current in place
 392 of the extrapolation to the beginning of the step.

393 The pedestal current before the step is not exactly zero. This is due in
 394 part to the HV power supplies which don't put out exactly zero potential. It is
 395 also due to some residual potential which we presume to be across the putative

layer. The potential applied at the step is on top of this residual potential so we use the pedestal current to estimate this residual potential across the liquid argon gap and correct the step current using the slope of the step current versus potential curve at the applied potential. We assign a systematic uncertainty of half the magnitude of the correction.

There is a small potential drop across the protection resistors (see Fig. 2). Rather than correct the potential we instead correct the step current, again using the slope of the step current versus potential data. We do this so that we can directly compare step currents from the different chambers at the same potential data-point by data-point. No uncertainty is attributed to this correction.

The individual systematic uncertainties, along with an additional 0.1%, are added in quadrature to obtain the overall systematic uncertainty for each step current. The systematic uncertainty is negligible for potentials above V_{c2} , i.e. in the range of normal operation, and is large in the space-charge limited regime.

Summary data for each step in a run was written to an intermediate file. These files were read by a program which corrected the step currents for the small decay in activity parameterized by the half-life of Strontium-90. For a given potential, these corrected step currents were plotted as a function of the time of the run. This allowed us to inspect the stability of the data with time. An example is shown in Fig. 4. The rms fluctuations in the step currents shown in this figure are about 0.1% with no apparent trend. The data suggests that the stability of the liquid argon ionization chamber at high ionization rates is at least as good as our ability to measure it.

The rms deviation from the average of the multiple step currents at the same potential is used as the statistical uncertainty. While this uncertainty is quite small for potentials such as was chosen for the data shown in Fig. 4, for potentials just below V_c the rms deviation is much larger. This is likely related to the pathologies seen in the steps at 60 V shown in Fig. 3. We interpret this as an instability of unknown origin.

Before plotting, the weak source step currents were corrected for the radiation leaking into the ionization chamber from the nearby strong source chamber.

427 This is done by use of the step currents measured in the 0 mCi chamber which
 428 comes only from radiation from the equally nearby strong source chamber. This
 429 was important because the spectrum of betas and gammas penetrating a part
 430 of the copper cube and reaching the gap of the weak source chamber is different
 431 from the spectrum coming directly from the foil. In principle the Plateau Curve
 432 for a different spectrum will have a different shape. This is a very small but not
 433 quite negligible correction to the weak source step currents.

434 Fig. 5 shows the corrected step currents as a function of the potential across
 435 the gaps of the 0.268 μm chambers. The step currents from the weak source
 436 chambers have been multiplied by $A = 21.37$ to easily see that the data points
 437 overlap at the higher potentials. This overlap is expected for RIR processes.
 438 Moving to lower potentials we see the two sets of data points diverge. This
 439 is a manifestation of the onset of space-charge effects, i.e. RDR effects, in the
 440 strong source gap which we will analyze quantitatively. Moving to even lower
 441 potentials we see the weak source currents diverge from the HV plateau curve.
 442 At these low potentials the weak source gap is also in the space-charge limited
 443 regime.

444 The step currents from the 0 mCi (no) source, multiplied by $A = 21.37$, are
 445 shown to give a feeling for the correction (already made) to the weak source
 446 step currents. The leakage currents (not shown) are everywhere smaller than
 447 the 0 mCi currents, roughly proportional to the potential with inverse slope of
 448 approximately 30 T Ω .

449 A plot of the ratios of the strong source step currents to the weak source
 450 step currents as a function of the potential applied to the ionization chambers is
 451 shown for the three chamber gaps in Fig. 6. At the highest potentials the ratios
 452 for the 138 μm gap and the 268 μm gap are constant at $A = 21.37$. This confirms
 453 with some precision that the HV plateau curve is rate independent, i.e. it is an
 454 RIR effect. For the 898 μm gap the ratios appear to be approaching $A = 21.37$.
 455 Moving to lower potentials we approach a critical value V_{c2} (different for each of
 456 the three gap widths) where the ratios begin to fall rapidly. Continuing to lower
 457 potentials, the ratios approach a lower constant as the potential approaches

a second critical value V_{c1} (also different for each of the three gap widths). We interpret the ratio data below V_{c2} as a manifestation of the strong source chamber entering the space charge limited regime. Below V_{c1} both the strong source and the weak source chambers are in the space charge limited regime.

Also shown in Fig. 6 are the analytic approximations in equations 5, 6, and 8 with the positive argon ion mobility μ_+ set to $0.08 \text{ mm}^2/\text{Vs}$. The neighbor lines show the result of increasing and decreasing μ_+ by $0.02 \text{ mm}^2/\text{Vs}$. Open symbols show the results of a detailed simulation which will be described in the next section.

7. Simulations

7.1. Energy deposit

The EGSnrc Monte Carlo simulation code for electron and photon transport [19] was used to predict the energy deposited in the liquid argon gap by the betas. The origin of each beta was chosen via a uniform random distribution somewhere on the outer surface of the foil. The initial direction was also chosen via a uniform random distribution within a solid angle of 4π . The initial kinetic energy of each beta was chosen from a random distribution which represents the beta spectra of the combined Strontium-90 and Yttrium-90 in equilibrium [9]. Each beta was then tracked, along with all produced delta rays, gammas, and the occasional positron, until the kinetic energy fell below the threshold of 30 keV. Steps along each track in the liquid argon were limited to a maximum of $1 \text{ }\mu\text{m}$ in length. All energy deposits were tallied.

In a production simulation we generated $n_\beta = 10\,000\,000$ betas. Of these only $m_\beta = 806\,116$ (810 279, 821 012) deposit any energy in the 138 (268, 898) μm liquid argon gap. The others either head off in the wrong direction or range out before reaching the gap. The total energy deposited in the 138 (268, 898) μm liquid argon gap by all of the betas in the simulation is $E_{\text{Tot}} = 72\,425$ (131 271, 337 442) MeV. For a source activity of $A_\beta = 50 \text{ mCi}$

Figure 7: The plot on the left shows the average energy density deposited in the liquid argon gap as a function of distance across the gap in 1 μm bins for the 10,000,000 generated betas. The Black (Red, Green) histogram is for the ionization chamber with the 138 (268, 898) μm gap. The source is closest to the surface of the rod which, in the plot, is where the abscissa is zero. The plot on the right shows the simulated current density J at the center of the gap for a strong source activity as described in the text at $\mathcal{E}_T = 22$ kV/cm, neglecting the RDR, as a function of x , the coordinate along the chamber symmetry axis. The Strontium-90 beta source extends from $-5 < x < +5$ mm. Because of symmetry about $x = 0$ we show only half of the relevant range. At $x = \pm 5.0$ mm the current density has fallen to half the value in the uniform region. The same color code as on the left is used here.

the simulations predict the rate of betas entering the 138 (268, 898) μm liquid argon gap is about $f_g = 298$ (300, 304) MHz.

We convert the energy deposited in the liquid argon to ionization charge as follows: Measurements of the 976 keV monochromatic kinetic energy conversion electron from ^{207}Bi , ranging out in liquid argon, show the average deposited energy required to create one electron-ion pair as $W(\mathcal{E}_T) = 23.6 \pm 0.3$ eV at an electric field of $\mathcal{E}_T = 22$ kV/cm [20]. Using the density of liquid argon (1.396 g/cm³) and the ionization energy loss of minimum ionizing betas in the liquid (1.349 MeV/(g/cm²)) [21] we find the average number of ionizations is

about 8000 per mm of track length at $\mathcal{E} = \mathcal{E}_T$. Considering that the kinetic energy spectrum of betas in the liquid argon from our Strontium-90 sources is softer than the Bismuth-207 betas but that some fraction of our Sr-90 betas have higher kinetic energy and pass through the liquid argon, ranging out in the copper tube, we guess that the RIR effects are about the same. We therefore use this same conversion factor $W(\mathcal{E}_T)$. We use the High Voltage Plateau Curve to apply this conversion at other values of the electric field. That is, we normalize the High Voltage Plateau Curve to unity at $\mathcal{E} = \mathcal{E}_T$ and interpret the resulting curve as the average number of electron-ion pairs which are created whenever the beta loses 23.6 eV of kinetic energy and which survive RIR processes.

Using $e = 1.602 \times 10^{-19}$ C, $W(\mathcal{E}_T) = 23.6$ eV, and $1 \text{ Ci} = 3.7 \times 10^{10}$ Bq we obtain the current at $\mathcal{E}_T = 22$ kV/cm of

$$I_0 = \frac{eE_{\text{Tot}}}{W(\mathcal{E}_T)} \frac{2A_\beta}{n_\beta} = 181 \text{ (326, 815) nA} \quad (9)$$

for a 50 mCi source. With the 138 (268, 898) μm ionization chamber, the measured current for the strong source, interpolated to 22 kV/cm or 304 (590, 1976) V and then correcting the 898 μm data for RDR effects, is 284 (520, 1325) nA. So at the time of our measurements the activity of the strong source was actually 78 (80, 81) mCi. Both the strong source and the weak source were produced in 2007 and the activity determined by the manufacturer in November 2007 just before delivery. Extrapolating from the time of measurement to the production time we estimate the production activity of the strong source to be 86 mCi. Using the ratio of currents at high electric fields we similarly estimate the production activity of the weak source to be 4.0 mCi. These are substantially higher than we requested.

The analytic calculations described in section 2 assume the energy deposition is uniform over the full volume between parallel plate electrodes. Fig. 7 shows the radial (left) and axial (right) dependence of the energy deposition in the cylindrical geometry of the EGSnrc simulation. The 898 μm ionization chamber differs the most and the 138 μm ionization chamber differs the least from the

523 simplifying assumptions used for the analytic approximation.

524 In the left panel of Fig. 7 the histogram for the chamber with the 898 μm
525 gap does not overlap the histograms for the chambers with the 138 and 268 μm
526 gaps for several reasons, one of which is that some betas, after crossing the gap,
527 multiple scatter through large angles in the copper tube and return to the liquid
528 argon. An example is the simulated track in Fig. 1. The spectrum of energies
529 deposited by those betas which enter the liquid argon is shown in Fig. 8.

530 7.2. Drift currents

531 A custom simulation [22] of charge production, charge transport, charge loss
532 at the electrodes, and charge loss via recombination (RIR and RDR) was written
533 to compare with our data. We considered not only electrons and positive argon
534 ions but also some other positive charge carrier in addition to argon ions and
535 a small contamination of oxygen molecules which easily attach free electrons to
536 become oxygen molecular ions. The simulation suggests we have little sensitivity
537 to additional positive charge carriers so we do not include this mechanism in
538 the following.

539 The simulation program assumed the electric field and the drift velocities are
540 purely radial in a cylindrical coordinate system. The gap between the coaxial
541 cylindrical electrodes was divided into cells of uniform steps in radius and the
542 charges in each cell were tracked as a function of time. At the beginning of a
543 simulation run the cells contained only neutral argon and a small contamination
544 of neutral O_2 . A constant time step was chosen such that the fastest electron
545 drifts less than a quarter of the way across a cell in one time step. In each
546 time step the number of each charge species in a cell changed due to ionization,
547 attachment, recombination, and/or drift (or diffusion) into a neighbor radial cell
548 or, in the case of the radial cell at each end, to an electrode. Then the electric
549 field in each cell was calculated via Gauss' Law with the constraint that the line
550 integral of the electric field equaled the potential across the gap.

551 The magnitude of the ionization rate-density D_i in each radial and axial
552 cell at $\mathcal{E}_T = 2200 \text{ V/mm}$ and ignoring RDR effects was derived from the rate-

density of the EGSnrc energy deposit in that region divided by $W(\mathcal{E}_T) = 23.6$ eV per ionization. We use $D_i = 8.703 (8.281, 6.467) \times 10^{10}$ ionizations/mm³/s averaged across the gap for the strong source and $D_i = 3.937 (3.810, 3.015) \times 10^9$ ionizations/mm³/s for the weak source. This can be compared with $D_i = 6.3 \times 10^{10}$ ionizations/mm³/s at $\eta = 4.7$ in the ATLAS liquid argon forward calorimeter at a depth near EM shower maximum at the design center-of-mass energy of 14 TeV and luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and at $\mathcal{E}_T = 2200 \text{ V/mm}$.

Many of the mechanisms in this simulation are poorly known or not known at all. We employed reasonable descriptions and explored a range of parameters in our attempt to find a set which produced results in agreement with our data.

Of the poorly known parameters, the one of most importance in this study was the positive argon ion mobility. We presumed this single parameter describes the argon ion velocity at all electric fields. This mobility is the critical parameter which determines the threshold ionization rate above which the chamber passes into the space-charge limited regime. Some [23, 24] have suggested that an argon ion may combine with one or more neutral argon atoms to form a singly-charged argon molecular ion. And the possibility of positive charge transport in solid argon [25] suggests that hole transport (charge exchange) may play a role in liquid argon as well. Others [26] suggest that impurity atoms or molecules with an ionization potential lower than argon can capture the charge from the drifting argon ions and the resulting positive ions have a lower mobility than the argon ions. This mechanism suggests that the space-charge threshold will depend on the impurities. So there could be multiple positive charge carriers each with a different mobility. We don't pursue this possibility in this report.

For the free electron drift velocity in liquid argon as a function of electric field we used a parameterization similar to that in reference [27]

$$v_e(\mathcal{E}) = \begin{cases} A(\mathcal{E}/\mathcal{E}_a)^a & \text{for } 0 < \mathcal{E} < \mathcal{E}_a \\ B(\mathcal{E}/\mathcal{E}_b)^b & \text{for } \mathcal{E}_a < \mathcal{E} < \mathcal{E}_b \\ C(\mathcal{E}/\mathcal{E}_b)^c & \text{for } \mathcal{E} > \mathcal{E}_b \end{cases} \quad (10)$$

where $v_e(\mathcal{E})$ is in units of mm/s and the electric field $\mathcal{E}$ is in units of V/mm. The parameters are $\mathcal{E}_a = 20$ V/mm, $\mathcal{E}_b = 2000$ V/mm, $A = \mu_e \mathcal{E}_a$, $B = v_m/(\mathcal{E}_0/\mathcal{E}_b)^b$, $a = 1$, $b = \ln(v_m/A)/\ln(\mathcal{E}_0/\mathcal{E}_a)$, $c = 0.1$, $\mu_e = 5 \times 10^4$ mm²/Vs, $v_m = 4.2 \times 10^6$ mm/s, and $\mathcal{E}_0 = 1000$ V/mm.

Superimposed on the gap current data in Fig. 5 is a parameterization of the shape of the HV Plateau Curve whose free parameters were adjusted to give a good fit in the region where RDR can be neglected. Several phenomenological models were available [28–30]. We used the Birks' Law [31] inspired parameterization of equation 11 where the first term is meant to approximate the ionization from minimum-ionizing betas and the next two terms are meant to approximate successively more densely ionizing betas and delta rays.

$$P(\mathcal{E}) = \frac{\alpha}{1+\mathcal{E}_1/\mathcal{E}} + \frac{(1-\alpha)\beta}{1+\mathcal{E}_2/\mathcal{E}} + \frac{(1-\alpha)(1-\beta)}{1+\mathcal{E}_3/\mathcal{E}} \quad (11)$$

where $\mathcal{E}$ is the electric field, and $\mathcal{E}_1$, $\mathcal{E}_2$, and $\mathcal{E}_3$ are characteristic electric fields. In this paper we used $\alpha = 0.22$, $\beta = 0.80$, $\mathcal{E}_1 = 1.5$ V/mm, $\mathcal{E}_2 = 35$ V/mm, and $\mathcal{E}_3 = 1500$ V/mm. The shape of this parameterization is similar to that used in ref. [18] and [32] at intermediate and high electric fields.

Bulk recombination was parameterized as

$$D_r \equiv -\frac{dn_+}{dt} \equiv -\frac{dn_-}{dt} = R_r n_+ n_- \quad (12)$$

where D_r is the rate of bulk recombination per unit volume, R_r is the rate constant, and n_+ and n_- are the electron and positive argon ion number densities which depend on the rate of high energy particles. The value of R_r depends on electric field $\mathcal{E}$. The measurements of the bulk recombination rate constant in reference [33] covered electric fields up to 80 V/mm. We could not find reasonable agreement between the simulation and our data with such high values. So we used $R_r \approx 0.005$ mm³/s for $\mathcal{E} < 200$ V/mm and $R_r \approx 0.001$ mm³/s for $\mathcal{E} > 200$ V/mm.

The attachment rate of electrons to oxygen molecules is a bulk effect similar to the bulk recombination rate of electrons to positive argon ions in equation 12

and so was parameterized with an electric field dependent rate constant which has been well measured [34–37].

On the other hand the mobility of oxygen molecular ions in liquid argon is very uncertain, particularly near a pressure of 1.0 bar where we operate [24, 38]. And the rate constant for oxygen molecular ion recombination with positive argon ions has not been measured. We use $\mu_X = 0.078 \text{ mm}^2/\text{Vs}$. And we use $k_X = e(\mu_+ + \mu_X)/\epsilon = 1.89 \times 10^{-6} \text{ mm}^3/\text{s}$ as suggested by R.Holroyd [39].

While our custom simulation reported the full charge and current configurations within the gap, the only observable was the external current. Within the simulation the current was calculated three different ways. We recorded the current at the boundary of the first cell next to the anode and the current at the boundary of the last cell next to the cathode. We also calculated the net production of charges within the chamber after the recombination effects. Because the simulation relaxed to a steady-state all three current measurements should be the same and Maxwell’s displacement current within the chamber gaps was zero. These three currents agreed to more than three significant digits.

We ran several checks of our custom simulation. For example, with the HV plateau parameterization set to unity above $\mathcal{E} = 0.1 \text{ V/mm}$, with uniform ionization, with the bulk recombination rate set to the low value of $3 \times 10^{-4} \text{ mm}^3/\text{s}$, and with no oxygen contamination the simulation returned currents in good agreement with the analytic approximation. The ratio of currents from the simulation still agreed well with the analytic approximation in equations 5, 6, and 8 when using the realistic HV plateau curve of equation 11.

The various unknown or poorly known parameters were varied and the simulation currents were then compared with the data in Fig. 5 for the $268 \text{ }\mu\text{m}$ gap and with the corresponding data for the other two gaps. Ratios of the simulated currents were also compared to the data in Fig. 6. The simulation was also adapted to the HiLum project [40] and the simulation parameters were required to agree with this data as well.

The best value of positive argon ion mobility to one significant digit is $\mu_+ = 0.08 \pm 0.02 \text{ mm}^2/\text{Vs}$. The simulation shows rounding near the thresholds in

rough agreement with the data. The simulation ratio approaches $21.37^{3/4}=9.93$ very approximately at low electric fields.

With an oxygen contamination in the simulation consistent with our oxygen analyzer readings the simulated currents showed more degradation than we observe. We obtained simulation results in good agreement with our data when using an oxygen contamination below 0.05 ppm.

As the weak source gap crossed into the space-charge regime the simulation was excessively sensitive to many effects. We were unable to find parameters for which the simulation agreed with the data for all three gaps. It is possible that the data itself is also very sensitive to extraneous effects at these low potentials. But our focus is on the behavior at higher potentials where the simulation and the data appear to be dependent only on the processes we have discussed.

8. Space-Charge Effects

If there were only RIR effects then the current ratios in Fig. 6 would be constant, independent of potential. The change in this ratio with the gap potential indicates the presence of RDR effects.

The current in each strong source chamber drops with decreasing potential below V_{c2} relative to its corresponding weak source chamber due to the additional RDR effects. This is seen most clearly in Fig. 6 where the ratio of strong source currents to weak source currents cancels out the RIR effects, leaving only RDR effects as the cause of variations with potential. The potentials over which each gap current drops is sensitive to the positive argon ion mobility. But what we measure directly is the somewhat gradual threshold for entering the space-charge limited regime. The threshold is not as sharp as suggested by the analytic approximation of Section 2. This threshold is softened by the electron-positive argon ion recombination. If the positive ion velocity is not well described by a mobility and/or if there are multiple species of positive charges then our interpretation in terms of a single positive argon ion mobility may be incorrect. In this case we take our value of positive ion mobility as a convenient

parameter to characterize the space-charge threshold.

At lower potentials each weak source chamber also reaches its threshold (at V_{c1}) and enters the space-charge limited regime. At potentials below this threshold the current ratio tends to flatten out again at roughly the predicted value. This confirms our understanding of the space-charge phenomenon we are observing.

9. Summary

Our measurement of the stability of the ionization current at the 0.1% level over a period of more than 10 months in a high radiation field suggests that liquid argon calorimetry is a radiation tolerant technology for long exposures in high rate environments. This exposure corresponds to an integrated luminosity of about 330 fb^{-1} for an ionization chamber at $\eta = 4.7$ at a depth in a calorimeter near EM shower max at a distance of about 5 m from the interaction point.

Of the many measurements of the HV plateau curve (RIR effect) in the literature, the data presented here is of high precision and covers a wide range of potentials. From this data it is evident that our HV currents continue to slowly rise for electric fields above $\mathcal{E} = 22 \text{ kV/cm}$ [20] rather than “plateauing” as some suggest. This observation challenges the assumption that the measurement of $W=23.6 \text{ eV}$ is at an asymptotic electric field. While our parameterization in equation 11 does approach an asymptotic current, this occurs above our range of electric fields.

It should be noted that HV plateau curves are not universal. That is, these plateau curves are not necessarily the same as those taken with a different beta energy spectrum or with different species of ionizing particles.

The precision of our step currents allows a precise comparison at high potentials where RDR effects are negligible. We see a constant ratio of strong source current to weak source current of $A = 21.37$ with good accuracy. At the lowest potentials the ratio of strong source current to weak source current appears consistent with the predicted constant of $A^{3/4} = 9.94$.

Between these two extremes the strong source currents deviate from equation 11 at a potential of 27.5 (104, 1004) V for the 138 (268, 898) μm gap. The weak source step currents deviate from equation 11 around 5.3 (21, 206) V. The current ratios, compared to our analytic approximation or to our simulation, allow us to extract the positive argon ion mobility of $\mu_+ = 0.08 \pm 0.02 \text{ mm}^2/\text{Vs}$ at a temperature of $88.0 \pm 0.5 \text{ K}$ and pressure of $1.02 \pm 0.02 \text{ bar}$. We note that this parameter serves to indicate the threshold for the on-set of space-charge (RDR) effects even if the mechanism of positive charge transport may be more complicated than our simple assumption.

The threshold for entering the space-charge limited regime is not as sharp as suggested by the analytic approximations. The bulk recombination rate constant rounds these sharp thresholds so that deviations from rate independence begin to appear below the threshold, i.e. above the critical potential. We have found that our data are not consistent with the large bulk recombination rate constants reported in reference [33].

Operating a liquid argon calorimeter at ionization rates above the critical value (equation 1) will lead to space-charge effects which will degrade the performance. The practical method to forestall the on-set of space charge effects, that is, to raise the threshold ionization rate, is to build a liquid argon calorimeter with smaller gaps.

By measuring the d.c. currents we have determined the behavior of liquid argon ionization chambers in calorimeters faced with the approximately constant bombardment of particles from the most common hadron collisions. When occasionally there is a collision of interest the ionization chamber then produces a transient pulse. The behavior of such pulses on top of this d.c. background is a different story not addressed in this report.

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729 [1] Lyndon Evans and Philip Bryant (editors), “LHC Machine”, 2008 JINST
730 3 S08001.

731 [2] ATLAS Collaboration, “The ATLAS Experiment at the CERN Large
732 Hadron Collider”, 2008 JINST 3 S08003.

733 [3] CMS Collaboration, “The CMS Experiment at the CERN LHC”, 2008
734 JINST 3 S08004.

735 [4] ATLAS Collaboration, *et al*, EPJC 70 (2010) 755.

736 [5] Bruno Rossi, “High-Energy Particles”, Prentice-Hall, Inc. Englewood Cliffs,
737 N.J. 1965.

738 [6] By “asymptotic potential” we mean the potential at which the HV Plateau
739 Curve becomes independent of electric field. It is not clear that there is
740 such a potential. If there is it must be low enough that the argon does not
741 break down or that the cathode does not experience field emission.

742 [7] We are neglecting “columnar recombination”. In the liquid argon calorime-
743 ters in ATLAS none of the incident particles are parallel to the drift field.
744 Perhaps more important, most of the ionization comes from shower parti-
745 cles several generations removed from the incident particle. These particles
746 are spread over a wide range of angles so that a negligible number are
747 parallel to the drift field.

748 [8] J. Rutherford, Nucl. Instr. and Meth. A 482 (2002) 156 and references
749 therein.

- 750 [9] E. Fermi, Zeitschrift für Physik 88 (1934) 161; Jack P. Davidson, Jr., Phys.
751 Rev. 82 (1951) 48.
- 752 [10] MonoTorr Phase 1 3000, SAES Pure Gas, Inc., San Luis Obispo, California,
753 USA.
- 754 [11] Trace Oxygen Analyzer Model FA30111A, Delta F Corporation, 4 Consti-
755 tution Way, Woburn, MA 01801-1084. Illinois Instruments Model 912, 2401
756 Hiller Ridge Road, Johnsburg, IL 60050, USA.
- 757 [12] CY7-SD7 Temperature Sensor, OMEGA Engineering, INC., One Omega
758 Drive, Stamford, CT 06907, USA.
- 759 [13] PX176-025A5V Pressure Transducer, OMEGA Engineering, INC., One
760 Omega Drive, Stamford, CT 06907, USA.
- 761 [14] Ortec 710 Quad Bias Supply, Oak Ridge, Tennessee, USA.
- 762 [15] HV Power Supply Model 375P and Model 380X, Bertan Associates, Inc.
763 121 New South Rd., Hicksville, NY 11803 USA.
- 764 [16] Keithley 485 Autoranging picoAmmeter, Cleveland, Ohio, USA.
- 765 [17] LabVIEW is a product of National Instruments, Austin, Texas, USA.
- 766 [18] B. Toggerson, A. Newcomer, J. Rutherford, and R.B. Walker, Nucl. Instr.
767 and Meth. A 608 (2009) 238; doi:10.1016/j.nima. 2009.07.013.
- 768 [19] http://www.nrc-cnrc.gc.ca/eng/solutions/advisory/egsnrc_index.html
769 This is an extension, primarily to lower energies, of the SLAC software
770 simulation package EGS4.
- 771 [20] M. Miyajima, T. Takahashi, S. Konno, T. Hamada, S. Kubota, H. Shiba-
772 mura, and T. Doke, Phys. Rev. A 9 (1974) 1438 and Erratum in Phys. Rev.
773 A 10 (1974) 1452.
- 774 [21] <http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html>. Select
775 “unique material” and specify the parameters for liquid argon.

- 776 [22] See section 10 of reference [8] for an earlier description of the computer
777 code used to simulate charge creation, transport, and loss in liquid argon.
- 778 [23] Bob L. Henson, Phys. Rev. 135 (1964) A1002.
- 779 [24] T.H. Dey and T.J. Lewis, Brit.J.Appl. Phys. (J.Phys. D) 1 (1968) 1019.
- 780 [25] W. Spear, P. Le Comber, in: M.L. Klein and J.A. Venables (ed), "Rare
781 Gas Solids, Vol. II" (1976), p. 1120.
- 782 [26] M.A. Kirsanov and I.M. Obodovski, Probory i Tekhnika Eksperimenta,
783 2010, No. 2, 31 (in Russian); [Engl. Transl. in Instruments and Experimen-
784 tal Techniques 53 (2010) 185.]
- 785 [27] E. Aprile, K.L. Giboni, and C. Rubbia, Nucl. Instr. and Meth. A 241 (1985)
786 62.
- 787 [28] J. Thomas and D.A. Imel, Phys. Rev. A 36 (1987) 614.
- 788 [29] J. Thomas, D.A. Imel, and S. Biller, Phys. Rev. A 38 (1988) 5793.
- 789 [30] M.L. Andrieux, J. Collot, P.de Saintignon, A. Ferrari, J.Y. Hostachy, and
790 Ph. Martin, Nucl. Instr. and Meth. A 427 (1999) 568.
- 791 [31] J. Birks, "Theory and Practice of Scintillation Counting", Pergamon Press,
792 1964.
- 793 [32] Elena Aprile *et al.*, IEEE Trans. Nucl. Sci. 35 (1988) 37.
- 794 [33] K. Shinsaka and Y. Hatano, Nucl. Instr. and Meth. A 327 (1993) 7; K.
795 Shinsaka, M. Codama, T. Srithanratana, M. Yamamoto, and Y. Hatano,
796 J. Chem. Phys. 88 (1988) 7529.
- 797 [34] M. Adams, P. Buchholz, A. Dahloff, D. Freiden, V. Gaertner, M. Grams,
798 M. Haarmann, A. Hergesell, F. Hoelldorfer, G. Ielapi, K. Jakobs, T. Jung,
799 L. Koepke, E. Kuhnert, D. Meder, U. Schaefer, A. Schmidt, Y. Schue, C.
800 Schwarz, W. Walkowiak, D. Weber, D. Wilke, C. Zeitnitz, Nucl. Instr. and
801 Meth. A 545 (2005) 613.

- 802 [35] G. Bakele, U. Sowada, and W. Schmidt, J. Phys. Chem. 80 (1976) 2556.
- 803 [36] S. Biller *et al.*, Nucl. Instr. and Meth. A 276 (1989) 144.
- 804 [37] W. Hofmann, U. Klein, M. Schulz, J. Spengler, and D. Wedener, Nucl.
805 Instr. and Meth. A 135 (1976) 151.
- 806 [38] H.T. Davis, Stuart A. Rice, and Lothar Meyer, J. Chem. Phys. 37 (1962)
807 2470.
- 808 [39] R. Holroyd, Brookhaven National Accelerator Laboratory Chemistry De-
809 partment, emeritus. Private communication.
- 810 [40] A. Glatte *et al.*, Nucl. Instr. and Meth. A 669 (2012) 47.

Figure 8: Histogram of the energy deposited in the liquid argon by each simulated beta. The average energy deposit per beta is about 90 (162, 411) keV. For comparison, a beta with kinetic energy of 1.0 MeV travelling in a straight line across the gap (normal to the electrode surfaces) would lose about 27, (52, 173) keV [21] in the liquid argon.