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Testing for Effects of Ion Loading in Liquid Ionization Calorimeters

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INTRODUCTION

In an ionization sampling electromagnetic calorimeter,[1] e.g. Pb–liquid argon, the electrons liberated in the sampling gap due to ionization from the shower cascade drift to the electrodes relatively quickly while the positive ions drift much more slowly. For example in a liquid argon sampling gap of 2 mm in an electric field of 1000 V/mm the electrons are removed in about 400 ns but it takes 2 ms or longer for all the positive ions from a single shower to drift to an electrode. When the flux of showers is large enough the positive ions begin to accumulate in the gap producing a space-charge effect.[2] Above a critical value of flux the signal, due to the drifting electrons, begins to degrade. Ionization sampling calorimeters intended for use in high rate environments such as the SSC or LHC must be designed such that operation is below this critical value.

In this paper we calculate the critical value of flux one will need in an electron test beam in order to verify the calculations of the degradation of the signal due to build-up of positive ions in the gap.

SIGNALS ON A BACKGROUND

As shown in reference 2 the critical ionization rate in the sampling medium is given by

$$D_c = \frac{4V_o^2 \epsilon \mu_+}{ea^4}$$

where D is the rate of ion pair creation per unit volume and D_c is the critical value of D at which a number of observables change dramatically, V_o is the potential across the gap,

ϵ is the permittivity in the sampling medium, μ_+ is the mobility of positive ions, a is the distance across the gap, and e is the magnitude of the electron charge. For a Pb–liquid argon sampling calorimeter typical values are $V_o = 2$ kV, $\epsilon = 1.5\epsilon_o$, $a = 2$ mm, and, as a conservative guess, $\mu_+ = 0.06$ mm^2/V·s. (The parameter μ_+ is difficult to measure. Measured values of μ_+ range from 0.02 to 1.0 mm^2/V·s.) This gives

$$D_c = 5 \times 10^9 \text{ ions/mm}^3 \cdot \text{s}.$$

Suppose, as an approximation to the SSC or LHC, there exists an almost time constant background flux of low energy gammas on the calorimeter such that at electromagnetic shower maximum the ionization density in the sampling medium is D. When a high energy gamma from an event of interest strikes the calorimeter the ionization in the gap will suddenly increase and a signal will be measured above the d.c. current from the background. Let us define S to be the signal relative to the signal when the ionization rate due to the background is zero. It is found[2] that S degrades when the relative ionization rate r ($\equiv D/D_c$) rises above unity. The degree of degradation depends on the unknown recombination rate in the sampling medium so two extreme values are reproduced here in Fig. 1.

ELECTRON TEST BEAM

A test beam of monochromatic electrons is, at first sight, a different situation. There are no large signals on top of a constant background. So a word about the "time constant" background is in order. The characteristic time of the space charge effect is dominated by the the drift time of the positive ions. This is clear when $r < 1$ because there is an insignificant accumulation of electrons in the gap. But for $r > 1$ there is a region of the gap where the electric field is quite small and electrons build up to a density almost equal to the positive ion density. In this region of the gap the electrons also have a very small drift velocity so the characteristic time is still dominated by the positive ion drift time. As a consequence the source of ionization need not be precisely time constant for the approximations of reference 2 to hold. Within a Moliere radius R_M, showers need only occur at a rate significantly faster than the positive ion clearing rate conservatively estimated to be 30 Hz.

We will use several simplifications in order to estimate the ionization rate in the sampling medium at shower maximum. We will approximate the longitudinal electromagnetic shower profile as a triangle shape rising linearly to shower maximum and then falling linearly to zero at 20 radiation lengths. If X_o is a radiation length in the absorber material in units of g/cm^2 and x is depth in the calorimeter in units of g/cm^2 then we can define $t \equiv x/X_o$ as the depth in the calorimeter in units of radiation lengths. If dE/dt is the shower energy deposited per radiation length, then at shower maximum this simple picture immediately gives

$$\frac{dE}{dt} = 0.1E_o \quad \text{or} \quad \frac{dE}{dx} = 0.1E_o/X_o$$

where E_o is the incident electron energy. This crude estimate is accurate to approximately 10% for E_o in the range 10 to 300 GeV. This energy at shower maximum is spread transversely over an area whose characteristic radius is of order a Moliere radius R_M.

We will assume that the beam profile at the front face of the electromagnetic calorimeter is uniform over an area large compared to a Moliere radius R_M in the calorimeter and drops to zero outside this area. For a Pb–liquid argon sampling calorimeter the Moliere radius R_M should be larger than 12.3 mm (depending on sampling fraction), much larger than a typical gap width of a=2 mm.

To further simplify the calculations we will assume that our calorimeter has a single sampling gap located at electromagnetic shower maximum; the rest of the calorimeter will be entirely made of absorber as shown in figure 2. Since the sampling gap is very thin compared to the rest of the depth of the calorimeter, we can neglect the gap in the estimation of the shower development. This only simplifies our formulae so the essential ingredients show more clearly. It is straightforward and only a bit more cumbersome to reproduce the following for a more realistic calorimeter.

In the following we will use subscripts A and S to indicate properties of the Absorber material (typically Pb) and the Sensitive material (typically liquid argon). The subscript i will indicate either A or S. The ionization energy loss by a minimum ionizing particle is dE_i/dx in units of MeV/g/cm^2. The depth in the calorimeter is measured from the front face and is designated by x in units of g/cm^2 and by z in units of cm. The density of the sensitive material, the liquid argon, is given by ρ_S in units of g/cm^3. We will use the phenomenological parameter $K(e/\mu)$ to represent the ratio of the response of the calorimeter to showering electrons relative to the response to minimum ionizing particles such as high energy muons (corrected for the relativistic rise and density effects). Most of the $K(e/\mu)$ factor comes from the differences in path length of shower particles due to multiple scattering in the absorber and in the sampling media. For a Pb–liquid argon calorimeter we will use $K(e/\mu)$=0.78. The energy loss by an electron shower in the gap at electromagnetic shower maximum per unit depth of the gap is

$$\frac{dE_S}{dz} = 0.1 E_o K(e/\mu) \frac{\frac{dE_S}{dx}\rho_S}{\frac{dE_A}{dx} X_o}$$

If a flux F of electrons of energy E_o strikes the calorimeter (units of F are cm^{-2}·s^{-1}) then the rate of production of ions in a sampling gap at electromagnetic shower maximum is

$$D = \frac{1}{W} F \frac{dE_S}{dz}$$

where W is the energy deposit necessary to create one ion pair. In liquid argon $W \approx 25$ eV. We will define the critical flux as that flux which gives rise to the critical ionization rate D_c in the gap at electromagnetic shower maximum.

$$F_c = W D_c / \frac{dE_S}{dz}$$

For $E_o = 200$ GeV we find

$$F_c = 2.7 \times 10^4 \text{ cm}^{-2}\text{s}^{-1}$$

If the area of uniform flux is $2R_M$ in radius (i.e. 2.46 cm in radius) then the beam rate necessary to just reach the critical ionization rate is 5.2×10^5 Hz.

If the absorber material is Copper rather than Pb and $K(e/\mu) = 0.98$ then $F_c = 5.7 \times 10^4$ cm^{-2} s^{-1}. So a Copper calorimeter is better suited to very high rate environments. It can perform below the critical ionization rate for intensities 2 times higher than a Pb calorimeter.

Suppose we have the Pb calorimeter of Fig. 2 in a test beam whose flux is just above the critical flux F_c. Call $R_\perp$ the distance from the beam centerline in the transverse direction and assume the incident flux $F(R_\perp)$ is constant for $R_\perp < 2R_M$ and zero for $R_\perp > 2R_M$. Then the ionization rate D will be uniform in the gap near $R_\perp = 0$ but will fall to zero over a characteristic distance of R_M when $R_\perp \sim 2R_M$. Signals due to electrons striking near the center of the beam spot will suffer a degradation as shown in Fig. 1 for $r > 1$. However electrons striking the front face of the calorimeter near the edge of the beam spot will shower at the detector gap in a region where the ionization rate is lower due to shower spreading of order the Moliere radius R_M. Such electrons will give signals which are not degraded. So a pulse height spectrum of signals from the read-out gap will be broadened to the low side as the beam flux increases above the critical value. The signals with lower pulse height are from showers near the center of the beam which are degraded because of the ion loading in the gap.

If the calorimeter has many gaps which are ganged in the readout, then the signal degradation will be less apparent just above the critical flux since only those gaps near electromagnetic shower maximum are degraded and those away from electromagnetic shower maximum are not degraded. The degradation, averaged over depth, is less apparent just above the critical flux. But for fluxes a factor 2 above the critical value the degradation should be easily visible.

The value of the critical flux estimated above depends linearly on the poorly known value of μ_+. We have chosen a fairly pessimistic (low) value here in order to be conservative. An accurate measurement of the critical flux would serve as an improved estimate of μ_+.

PION TEST BEAM

Not many accelerators have high energy electron beams of the required flux. At hadron accelerators the test beams are often dominated by charged pions with a very small admixture of electrons. An even cruder estimate of the ionization rate due to a pion beam starts with an estimate of the hadronic longitudinal shower profile as a triangle starting at zero at the front face of the calorimeter, rising linearly to hadronic shower maximum and then falling linearly to zero again at 10 λ_I where λ_I is a nuclear interaction length in the absorber material measured in units of g/cm^2. So an estimate of the energy

deposited at hadronic shower maximum per unit depth of absorber material is

$$\frac{dE}{dx} = 0.2E_o/\lambda_I$$

where E_o is the incident pion energy. This energy is spread transversely over an area whose characteristic radius is of order λ_I. For Copper and for Pb absorbers dE/dx for pion showers at hadronic shower maximum is a factor 5.2 and 15.2 smaller respectively than for electromagnetic showers at electromagnetic shower maximum. The beam spot size must be of order $2\lambda_I$ in radius or greater to obtain a region of reasonably uniform ionization density in the sampling gap, more than a factor 10 larger in radius than for electron showers. So the critical pion beam flux is roughly a factor 10 above the electron beam flux and the corresponding beam rate over a rather large beam spot is a factor 1000 larger, i.e. of order 5×10^8 Hz.

HADRON COLLIDER

The flux of particles on a normal surface element of the calorimeter of a collider detector is give by

$$F = \mathcal{L}\,\sigma \frac{1}{2\pi}\frac{dN}{d\eta}\frac{1}{R^2 \sin^2\theta}$$

where $\mathcal{L}$ is the collider luminosity which we will take as 10^{33} cm^{-2} s^{-1}, σ is the cross section for minimum bias events which we take as 10^{-25}cm^2 for the SSC at $\sqrt{s} = 40$ TeV, $dN/d\eta$ is the density of particles per unit of pseudorapidity which we take for γ's from π^o decay to be 7.5, independent of η, at $\sqrt{s} = 40$ TeV, R is the distance from the interaction point to the surface element at which the flux is calculated, and θ is the angle the ray from the interaction point to the surface element makes with the beam line. One could use $R_\perp = R\sin\theta$ as the perpendicular distance from the beam line to the surface element. Using these numbers we get[3]

$$F = \frac{1.2 \times 10^8 \text{ s}^{-1}}{R_\perp^2}.$$

For E_o we use the average γ energy which is $E_o = \bar{p}_T/\sin\theta$ where $\bar{p}_T$ is 0.3 GeV/c independent of η. The critical flux is reached when

$$R_\perp^2 \sin\theta = \mathcal{R}^2$$

where

$$\mathcal{R}^2 = \frac{1}{WD_c}\mathcal{L}\,\sigma\frac{1}{2\pi}\frac{dN}{d\eta}0.1\bar{p}_T K(e/\mu)\frac{\frac{dE_S}{dx}\rho_S}{\frac{dE_A}{dx}X_o}.$$

For the Pb–liquid argon calorimeter of Fig. 2, $\mathcal{R} = 2.6$ cm.

REFERENCES

[1] W.J.Willis and V.Radeka, Nucl. Instr. and Meth. **120** (1974) 221.

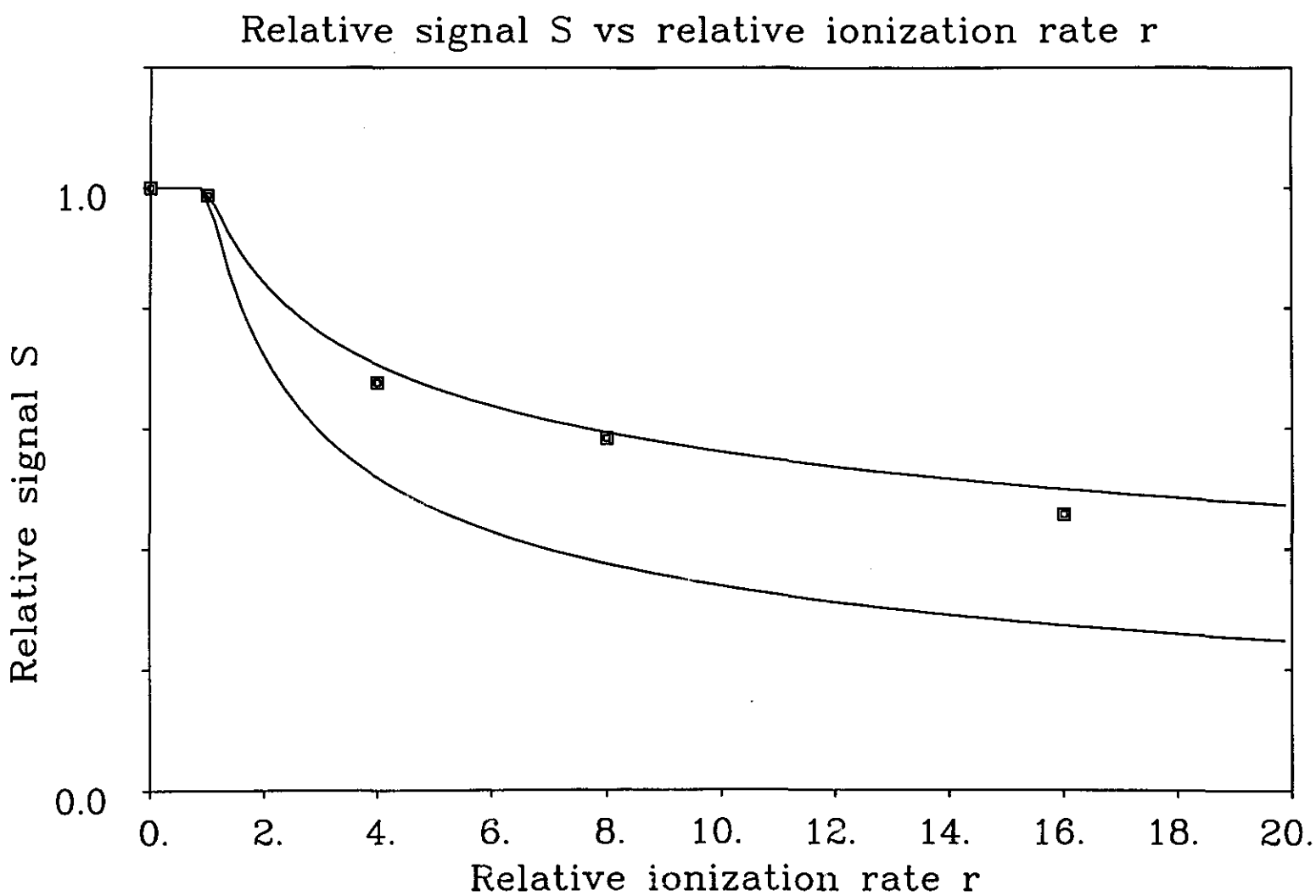
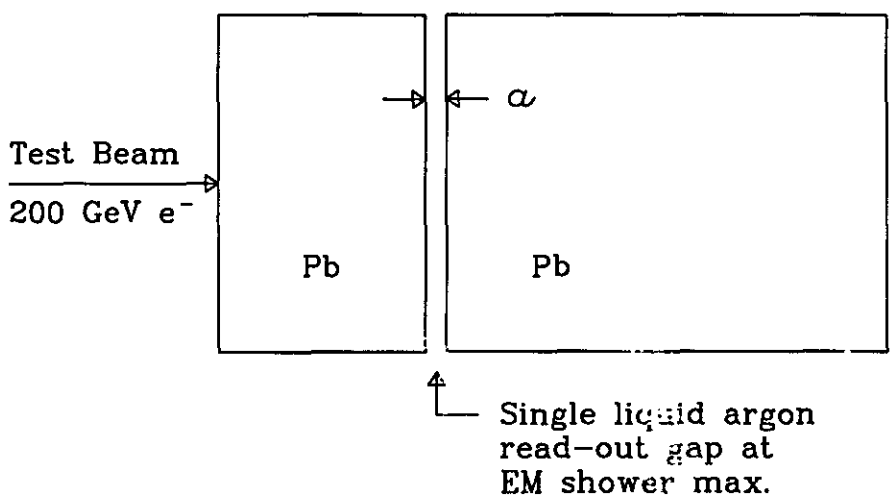
[2] J.Rutherfoord, GEM TN-91-27 (1991).

[3] D.Groom *et al.*, Phys. Rev. **D45** (1992) III.29.

FIGURE CAPTIONS

1) The signal on top of a background relative to the signal with no background versus the relative ionization rate r. Below the critical ionization rate, i.e. $r < 1$, the relative signal is approximately unaffected by the background. For $r > 1$ the signal drops dramatically. The degree of drop depends on the unknown recombination rate in the ionization medium. Two extremes are shown. The upper curve assumes a very small recombination rate and the lower curve assumes a very large recombination rate. The data points are from a simulation which assumed a small recombination rate. The actual curve must lie between these two extremes.

2) A simplified calorimeter with but one gap located at electromagnetic shower maximum.


Relative signal S vs relative ionization rate r
1.0
0.0
Relative signal S
0.
2.
4.
6.
8.
10.
12.
14.
16.
18.
20.
Relative ionization rate r

Simplified Calorimeter for Ion Loading Tests