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Rad Hard Active Media For Calorimeters

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Abstract

Zero-degree calorimeters have limited space and extreme levels of radiation. A simple, low cost, radiation hard design uses tungsten metal as the absorber and a suitable liquid as the Čerenkov radiator. In other applications a PPAC (Parallel Plate Avalanche Counter) operating with a suitable atmospheric-pressure gas is an attractive active material for a calorimeter. It can be made radiation hard and has sufficient gain in the gas that no electronic components are needed near the detector. It works well even with the highest concentration of shower particles. For this pressure range, R134A (used in auto air conditioners) has many desirable features.

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1 Introduction

Some of the CMS detectors will suffer unacceptable radiation damage with the proposed 10 times luminosity upgrade for the LHC (the SLHC). The zero-degree calorimeters (ZDC) have limited space and the most extreme levels of radiation [1]. We consider here a design for a ZDC that is simple and inexpensive but highly resistant to radiation damage. We also present some recent measurements with a simple PPAC (parallel-plate avalanche counter). A PPAC is the "hydrogen atom" for gas detectors with gain. We show that it can be fast with excellent energy resolution, as well as being resistant to radiation damage.

2 Čerenkov Liquid With Tungsten Metal

A ZDC for CMS (and also ATLAS) must fit in a space 9.6 cm wide, 1.0 m long, and 61 cm deep with the beam located 6.7 cm above the bottom of the space. The current design of the ZDCs at the LHC and at RHIC makes use of tungsten metal (ALICE uses tantalum) as the absorber and quartz fibers as the active material. Quartz fibers have served well at RHIC and may be adequate at LHC energies and normal luminosities. A more radiation hard alternative uses a suitable liquid, which can be easily replaced, instead of quartz.

The proposed ZDC design uses blocks of tungsten metal at the bottom of a polished aluminum tank that is open at the top. The tungsten is polished and flashed with aluminum to increase its reflectivity. The blocks have hooks on the top so that they can be easily lifted out of the tank. The photocathodes of the photomultiplier tubes (PMT) are immersed in the liquid to provide the maximum optical coupling. The liquid also serves as a radiation shield for the PMTs.

Because the ZDC is so narrow (it must fit between the two beam pipes) that part of the energy of showers from 2.75 TeV neutrons will leak out the sides of the active region causing the size of the signal to depend on the horizontal position of the incoming neutron. Our latest design uses liquid both between the tungsten blocks and at the sides. Most of the light is from the core of the shower in the space between the blocks, but shower leakage out the side will produce light in the liquid at the side to compensate for lost energy. Figure 1 is a schematic view of this arrangement looking at the tungsten blocks from the top. Careful simulations using GEANT-4 will be made to determine the optimum dimensions of the spaces.

The tungsten-liquid ZDC is easily subdivided horizontally in both the longitudinal and transverse directions. This is done with thin, polished aluminum sheets that go from the bottom of the tank up to the level of the PMTs.

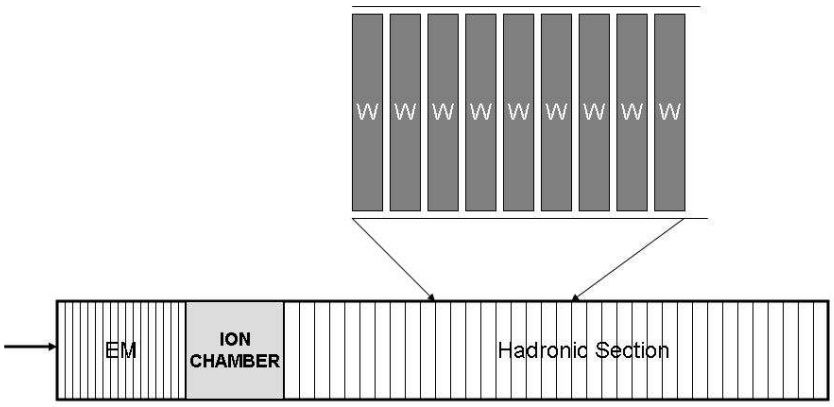


Figure 1: Interior of ZDC seen from above.

In principle, almost any liquid could be used, but there are properties that affect the size of the signal. The liquid

needs to be transparent over wavelengths accepted by PMTs. A larger refractive index will increase the light output, but it is also useful to have the refractive index match that of the PMT entrance window. Our simulations have shown a small increase with reduced density, because shower particles have greater range in the liquid.

For convenience, the liquid should not be corrosive, too volatile, a health or fire hazard, or acquire any such noxious characteristics under radiation. It must also be available in adequate purity at a reasonable price. If the liquid is damaged by excessive radiation it can be easily replaced, provided it does not form polymers that coat the tungsten blocks. Water is a possibility, but it has a low refractive index, n = 1.33, and things grow in it. An interesting possibility is ethylene glycol, n = 1.43, which is antifreeze without additives. Another candidate is mineral oil with n = 1.46 and a density of only 0.78 g/cm^3. MiniBooNE at FNAL has 106 l of it.

A large increase in light could result from adding a wavelength shifting material to the liquid because most of the Čerenkov photons are produced in the UV at wavelengths too short to be seen by PMTs. The number of photons produced is proportional to $1/\lambda^2$. Finding a suitable wavelength shifting material and liquid will require considerable study. The liquid with the wavelength shifting material should have the desirable qualities given above. Because most wavelength shifting materials are large molecules, there will be some difficulty finding a material that is not too sensitive to radiation and does not polymerize.

3 PPAC Studies

In some applications a PPAC (parallel plate avalanche counter), operating with a suitable atmospheric-pressure gas is an attractive active material for a calorimeter. It can be made radiation hard and has sufficient gain in the gas that no electronic components are needed near the detector. It works well even with the highest concentration of shower particles. For this pressure range, the gas R134A (used in auto air conditioners) has many desirable features.

A PPAC is the simplest type of gas detector with gain. It consists of two conducting plates with a gas between them. Much of what we learn about PPACs is useful in understanding the operation of more complicated gas detectors.

Our study of PPACs is basic research with possible applications related to CMS. The primary motivation for starting this project was to find a replacement for some of the scintillators in HE (the endcap calorimeter in CMS) for use with the SLHC. A PPAC can be made of materials that are not affected by radiation and can have excellent time and energy resolution. Our findings will have applications with other, similar detectors, such as resistive plate chambers (RPCs), which are used in the muon system of CMS. We are working with a group at Argonne National Laboratory on the application of RPCs for use in a digital calorimeter for the ILC.

We have studied a dozen different gasses with pressures from 5 torr to one atmosphere. We looked at the fast electron and slow ion signals as a function of voltage and the area and separation of the plates and found that a PPAC can have excellent time and energy resolution [2]. The best gas we have found for use at one atmosphere is R134a.

For the HE upgrade, PPACs would operate at atmospheric pressure. Small gas leaks are then unimportant if the gas is non-toxic and nonflammable. A minimum ionizing particle (MIP) will make about a dozen primary electrons with a spacing of 0.5 mm using the heavy gas, R134a. This may be compared with two electrons from the photocathode for a MIP in the present HE scintillators [3]. The gain, corresponding to the photodetector gain, is the increase in the number of electrons caused by the avalanche. As with photodetectors the gain depends on the applied voltage. The number of primary electrons is easily estimated. The ideal gas law gives 0.2 mg/cm^2 for R134A, mw 102, with a plate separation of 0.5 mm. Assuming a MIP loses 2 MeV in 1 g/cm^2 and that one electron-ion pair requires 30 eV, the number of primary electrons is 13. Because of the factor of 6 improvement, compared to scintillating tiles, HE would still have adequate energy and position resolution with some of the PPACs turned off.

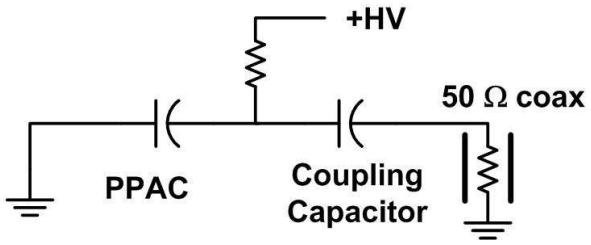
The small, 0.5 mm, plate spacing is used to keep the voltage under 4 kV. For small area detectors the width of the large electron signal is between one and two ns. The slow ion signal is so small that it can be ignored in most situations. To maintain a constant gas gain the high voltage may need small adjustments to compensate for small temperature and barometric pressure changes, which change the number of gas molecules between the plates.

Compared to the scintillating tiles, PPACs provide better energy resolution, a better time structure, and can be made entirely of radiation hard materials. Any small leaks of the slightly above atmospheric pressure gas are harmless because the gas is not toxic or flammable. The signals are put directly into 50 Ω coax cable so that no sensitive electronics are needed near the detector. The 3 kV required for the detector is not a hazard because the currents

are only at the microamp level. The cost of a PPAC system is less than for the original scintillating tile system. It is basically a simple device, two flat plates with a gas between them - a proportional counter having plane parallel symmetry.

The gas in the PPACs should be constantly replenished to keep it pure and free of decomposition products caused by radiation. This can be done by a flow rate that replaces the gas once each hour. Because the plate spacing is only 0.5 mm, the total amount of gas in the PPACs is small.

For large area detectors the width, W, of the electron signal is determined by the detector capacitance and is approximately W = RC, R = 50 Ω and C is the capacitance of the PPAC. The circuit for a PPAC is simple.



The signal divides between the coupling and detector capacitances, but the energy available to a spark is the sum of the two capacitances. For many applications the two capacitances should be set equal. This provides half of the maximum signal size to the coax with a minimum of stored energy.

With the present scintillating tiles, the signal from HE extends over three beam-crossing intervals of 25 ns each. PPACs with area of up to 100 cm^2 provide a signal short enough so that the entire signal fits into a single 25 ns time interval. A 100 cm^2 area provides better position resolution than is needed for HE. To get the same time structure for a larger area, signals from individual 100 cm^2 plates can be brought out of HE on small coax cables and combined by a simple summing amplifier.

PPACs are not affected by the large magnetic fields in HE because the electron motion in the PPAC is parallel to the magnetic field. In any case the effect of a magnetic field is small because the electrons travel less than 0.5 mm in an electric field of 60,000 V/cm.

We have studied the performance of PPACs with many different gasses at pressures from 5 torr to one atmosphere with a variety of plate spacings and configurations. Most recently we have concentrated on PPACs operating at atmospheric pressure. For large systems, other pressures complicate the design, increase the cost, and reduce the reliability. At atmospheric pressure a MIP gives a useful signal with even the smallest plate spacings.

A 1.0 GHz oscilloscope (Tektronix TDS 5104) is used to observe the signals directly from the detector. Because of the noise in the scope we sometimes use a fast 10 X amplifier to improve the signal to noise ratio for small signals near the operating voltage threshold of the PPAC. Much information can be obtained from the study of the signals.

The signal that is seen on the scope is caused by charges moving between the plates, not, as might be expected, by the charge that is being collected. With normal operation a PPAC signal has a fast electron part with a width of a few nanoseconds and a small ion signal that is constant for about the first 2/3 of the time and linearly approaches zero for the last third. During the constant part of the signal the ions are moving between the plates. The signal goes toward zero as the ions are collected at the cathode. Because of the exponential growth of the avalanche, most of the charges are generated close to the anode. The electron signals are short because the electrons have a large velocity, because of their small mass, and travel only a short distance. The last electrons formed in the avalanche fall freely in the electric field without any additional collisions with gas molecules. The ions travel slowly over a much longer distance with many collisions on the way. The presence of ions does not interfere with formation of a new avalanche. The fractional change in the potential between the plates is insignificant and the cross section of a single avalanche is minute.

The ion transit times with R134a gas are long, even longer than one would expect for such a heavy ion (MW: 102). This is caused by the highly polar nature of the R134a molecule. R134a is 1,1,1,2-tetrafluoroethane, which means that three of the fluorine atoms are at one end of the molecule. Since the fluorine strongly attracts electrons, this arrangement results in a large electric dipole moment for the molecule. The dipole moment is about the same as for water, which owes many of its peculiar properties to its large dipole moment. The symmetric R134 (1,1,2,2-tetrafluoro-ethane), with two fluorine atoms on each end and no dipole moment, gives electrical signals that are identical except for the ion part, which is faster than for R134a, but with the same area. The attraction of the polar

R134a molecules interferes with the motion of the ions, which results in a longer ion-collection time. The counter used for these measurements consists of two circular plates, each with an area of 1.0 cm^2, separated by 0.5 mm and operating at 700 torr and 2120 V. The ion signal is constant for a time t_0 and then goes linearly to zero at time t_1. The values of t_0 and t_1 are 1.3 μs and 1.8 μs for R134a, but only 0.8 μs and 1.3 μs for R134. These are not precise times because the signals are very small and the values depend on the location of the primary ion formation (from a 137Cs γ source). During the constant part of the signal the ions are moving between the plates. The signal goes toward zero as the ions are collected at the cathode. For both gasses the large signal from the electrons is fast with a full width at half maximum of only 1.0 ns.

References

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[3] CMS TDR 2, **CERN/LHCC 97-31**, p.224.