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High Pressure Xenon Gamma-Ray Spectrometers for Field Use

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Report period: July 1999 – September 2003

Introduction

This project explored a new concept for high-pressure xenon ionization chambers by replacing the Frisch grid with coplanar grid electrodes similar to those used in wide band-gap semiconductor gamma-ray spectrometers. This work is the first attempt to apply the coplanar grid anode design in a gas ionization chamber in order to achieve to improved energy resolution. Three prototype detectors, two cylindrical and one parallel plate configurations, were built and tested. While the detectors did not demonstrate energy resolutions as good as other high pressure xenon gamma-ray spectrometers, the results demonstrated that the concept of single polarity charge sensing using coplanar grid electrodes will work in a gas detector.

Phase 1: July 1, 1999 – June 30, 2000

During the first year of the project, extensive Monte-Carlo simulations using EGS4 were performed on gamma-ray interaction with xenon gas having a density around 0.5 g/cm^3. The results showed that for 662 keV gamma rays, Compton scatter will dominate the interactions with about 70% probability in our detectors. The expected energy spectrum of 662 keV gamma-rays was also obtained, which can provide a useful tool for the diagnosis of problems within the actual detectors. Monte-Carlo simulations were also performed to study the size of electron cloud due to gamma-ray interaction with xenon gas. This study showed that the average electron cloud diameter is about 3 mm at 662 keV, which is comparable to the pitches of coplanar grid electrodes in both cylindrical and parallel plate designs. The results indicate that it is crucial to have high enough coplanar grid bias voltage to have full collection of electrons. This is important especially for those electrons generated underneath the non-collecting anode.

In parallel with the simulation work, two identical cylindrical high-pressure xenon gas chambers were designed and built. Each detector was made of stainless steel pressure vessels with a diameter of 4 inches. The anode rod was made of Macor ceramic with a diameter of 1 inch and a length of 10 cm. A design was developed for a simple coplanar detector using two metal wires helically wound about the Macor ceramic rod. A pitch of 4 mm on the anode wires was determined after calculating the inter-strip capacitance via electrostatic simulation with the Coulomb 4.0 package, and after considering the required coplanar bias for complete collection of electrons. A picture of the anode rod sitting inside the pressure vessel is shown in figure 1.

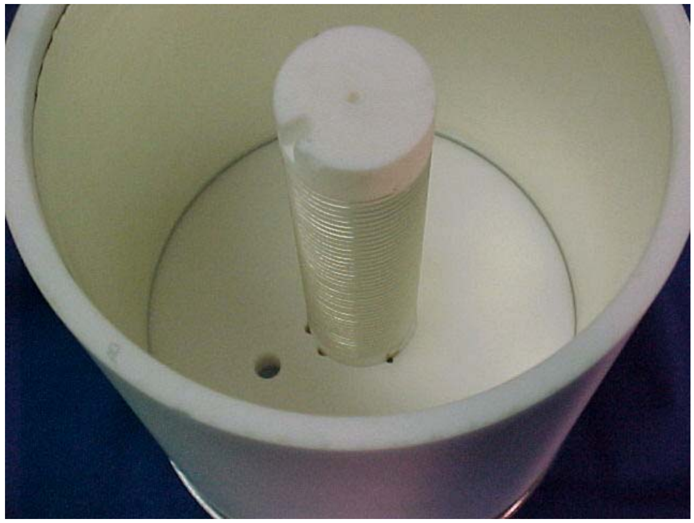

Figure 1. The picture of one cylindrical detector

After the first detector was tested, it was found that electrons could not be fully collected by the collecting anode, even at a much higher coplanar anode bias voltage than that predicted by electrostatic calculations. But in the simulations, the anode electrode was assumed to be on the same surface with the anode rod. In the actual detector, the anode wires are sitting inside a groove cut into the ceramic rod. It was believed that this different geometry (compared to that assumed in the simulations) caused the incomplete charge collection.

Phase 2: July 2000 – June 2001

Based on the analysis of the experimental results from the first detector, anode wires with larger diameter were employed in the second cylindrical detector. The diameter was chosen so that the wires were large enough to protrude about half-way from the groove. The test results showed significant improvement on energy spectrum. A clear photopeak of 662 keV gamma rays was obtained with a cathode bias of –3000 V and a coplanar anode bias of 700 V. However, the energy resolution was only about 11% FWHM at 662 keV, much worse than expected. Diagnostic measurements indicated that electrons could still be collected by the non-collecting anode, even at a bias of 1700 V between the coplanar anodes. The calculations predicted that only 200 to 300 V would be required to achieve full electron collection.

In order to understand the discrepancies between the simulation and experiments, several factors that could cause incomplete charge collection were studied in detail, including possible surface charge accumulation on the anode rod between coplanar anode wires, possible inductance effect due to the helical structure, capacitance coupling of the anodes and the possible effect of the groove on the operating electric field.

In order to verify that the coplanar grid technique would work in high-pressure xenon gas chambers, a “proof of principles” detector was constructed using a parallel plate electrode structure. The electrodes were placed in an existing pressure vessel that was not optimized for this structure. As a result, there was a dead region of xenon in a cylindrical shell about the center, the active region. Thus, more counts in the lower energy portion of the spectrum would be expected from Compton scatter events into this dead region. A side view of this "proof of principle" detector is shown in figure 2.

The coplanar anodes were made using an interdigitized spiral patterns as shown in figure 2. This design is very similar to the design used for cylindrical coplanar grid CdZnTe detector. Considerable attention to the design of the anode pattern was required in order to minimize the difference in weighting potentials between the two anodes. Any difference in the weighting potential will result in a difference in the measured induced charge, thus the degraded energy resolution. The separation between the anode and the cathode electrodes is 3 cm, and the diameter of the anode electrodes is about 5 cm. The anode structure was made by depositing a thin layer of gold onto an alumina ceramic with copper wires brazed to the surface for the collecting, non-collecting and the peripheral anode connections.

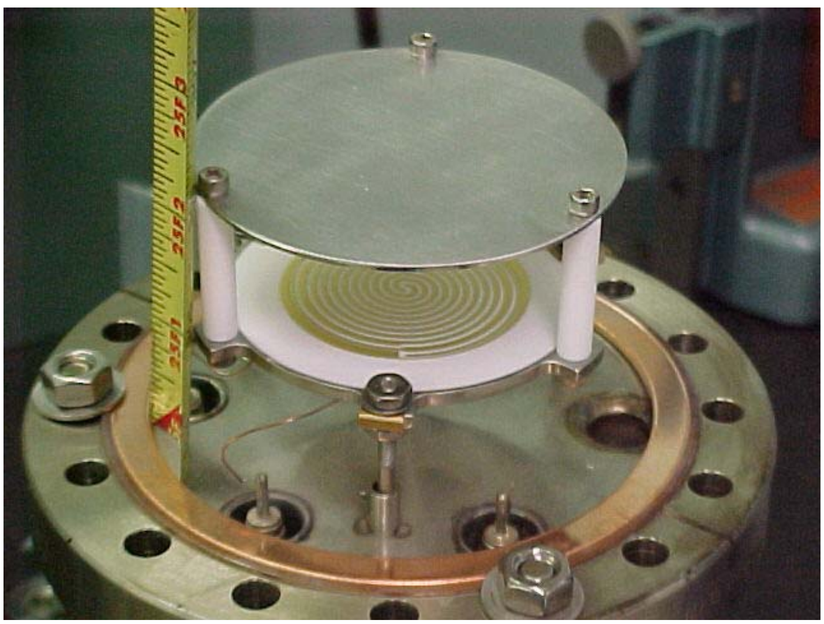

Figure 2. The third high-pressure xenon detector using parallel plate electrodes.

Phase 3: July 2001 – June 2002

The parallel plate high-pressure xenon detector was extensively tested during the last project period. Correct coplanar-grid pulses were observed 100% of the time at coplanar anode bias of 240 V with a cathode bias of –4000 V, which did not differ significantly from the calculated value of 232 V. This was the first time that the coplanar anode technique was shown to work in high-pressure xenon detectors. The spectroscopic results, while not very good, demonstrated that the coplanar readout can improve the energy resolution over a conventional planar readout for this detector. However, many limitations to optimal operation were discovered that resulted in broad photopeaks.

The first and most obvious source of resolution degradation was due to the high electronic noise. It was demonstrated that, at the coplanar anode bias required for coplanar mode operation, the surface noise is too high. One possible source is from surface contamination that could cause large fluctuations in the leakage current.

Another problem was discovered when the detector capacitance was measured. The total capacitance between the coplanar anodes, and between the anode and the boundary anode, and between the anode and the pressure vessel is about 160 pf. This should be reduced in future designs of the coplanar-grid xenon chamber. This high capacitance caused large noise in the readout system.

Lastly, the sharp increase of the surface noise as the coplanar anode bias was increased prevented using a higher coplanar anode bias, which is needed for good collection of electrons on the collecting anode.

Phase 4: July 2002 – September 2003 (no cost extension period)

In previous years, the parallel-plate high-pressure xenon detector suffered from many problems. For example, the inability to repeat experimental data, the inability to discern a "classical" energy spectrum using a gamma-ray radiation source, and confusion over the source of a large tailing effect at low energies in the measured energy spectra. During the last year of the project, much progress has focused on diagnosing deficiencies in the parallel-plate detector and optimizing that detector for best-possible performance; in addition, insight into a detector performance characteristic was made by simulating the detector using the Geant4 computer code developed by CERN.

Firstly, our experimental investigation revealed that the detector suffered from many electrical grounding problems; these grounding issues were significant in that they were the source of preamplifier pulses of (1) high count rate and (2) varying amplitude. The large count rate meant that measurements tended to be skewed by the large number of spurious counts from the detector electronics. The varying pulse amplitudes were severely dependent upon the positioning of all preamplifier equipment. Thus rotating the preamplifier box on the detector or moving a cable caused the amplitude of the electronic noise pulses to change; hence the irreproducible experimental results. Proper grounding of the preamplifier electronics solved this issue.

A second problem that had been identified on the parallel-plate xenon chamber was the inability to create a "classical" energy spectrum, meaning there was no Compton edge. Instead, a peak had always been observed sticking out of a large continuum that grew rapidly toward lower energies. This issue was resolved by rebuilding the preamplifier circuits and the subtraction circuit. The subtraction circuit inverts the output of one preamplifier (the *noncollecting anode* signal) and then adds it to the output of the other preamplifier, which gives the signal from the *collecting anode*. These two anodes are the key to success for this detector, as they form the basis of single-polarity charge sensing; in other words, they do away with the need to collect the output signal induced by positive charges in the detector by normalizing the signal from electrons in such a way that all equivalent energy depositions will create equal output signals.

With these two problems solved, it was possible to collect an energy spectrum with the detector. Figure 1 shows a spectrum taken with a ^{137}Cs gamma-ray source. In the figure we can see a photopeak and a Compton edge located at the expected energies (662 and 478 keV, respectively). This is the best spectrum obtained on a high-pressure xenon chamber featuring coplanar anode strips with an energy resolution of 7.8% FWHM at 662 keV. There are also two other notable features that will be discussed further: the broad peak produced by injecting pulses from an electronic tail-pulse generator and the large-amplitude low-energy tail.

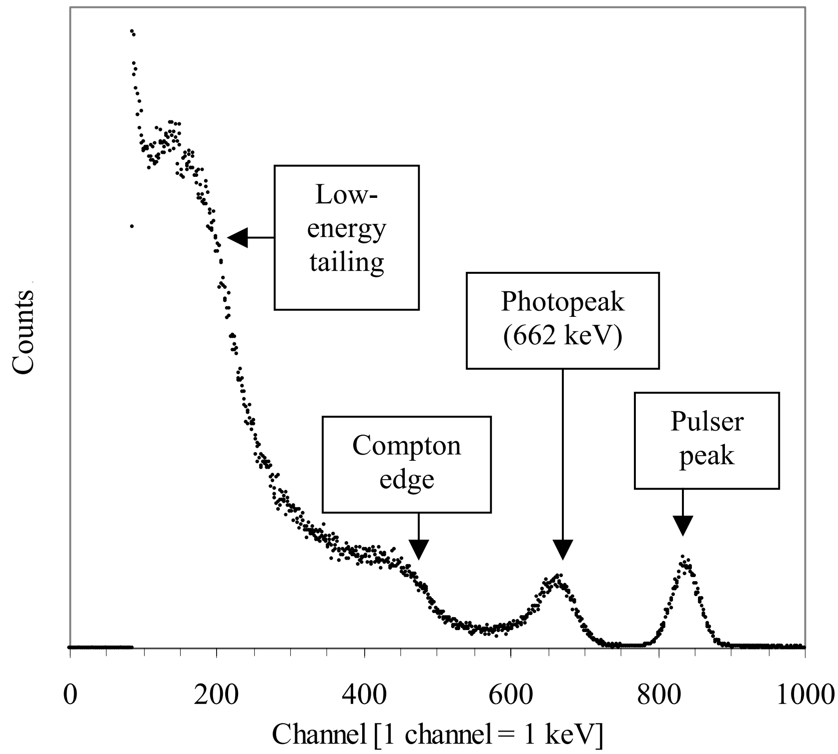

Figure 1. A parallel-plate high-pressure xenon chamber spectrum using a ^{137}Cs source.

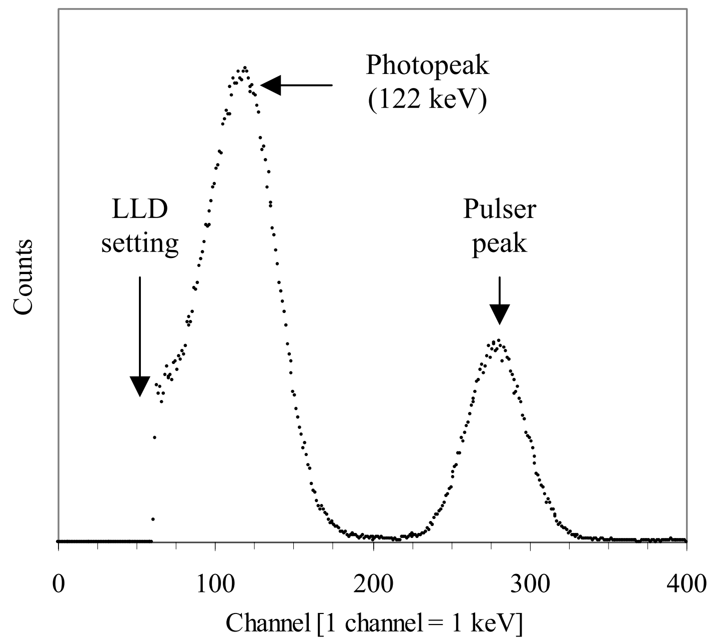

Figure 2. A parallel-plate high-pressure xenon chamber spectrum using a ^{57}Co source.

Figure 2 shows a ^{57}Co spectrum using the same detector. The gamma ray emitted by ^{57}Co is 122 keV; the photopeak is clearly visible in the data set. This radiation source emits the weakest photons that have been discerned as a peak using the parallel-plate xenon detector. Prior to April 2003, this photopeak would have been buried in electronic noise, and could not have been distinguished.

Detector performance can be hampered by incomplete charge collection due to ion recombination in the gas. To determine whether charge losses are an issue at the parallel-plate detector's typical operating conditions, a spectrum was taken with a cathode-anode bias of 3000 V. This was followed by a spectrum at a bias of 4500 V, where all other system variables remained the same. If charge losses were an issue, the change in electron drift velocity would change the ion recombination rate, and the charge induced on the anode strips would change. This would translate into the photopeak centroid channel shifting from one measurement to the next. This experiment was repeated with both the ^{137}Cs and ^{57}Co sources, but no significant change in either photopeak centroid channel was measured. Thus, incomplete charge collection should not be compromising detector performance.

By injecting pulses matching typical ^{137}Cs pulses in rise and fall times from the pulser onto one anode, the collecting-noncollecting strip capacitance was calculated by measuring the resultant voltage on the opposing anode strip. Using this method, the capacitance between anode strips was measured at 18.9 pF. Thus, it seems plausible that the argument of large effective capacitance hindering detector performance may be valid (since the total capacitance on the collecting anode that affects its noise is the sum of collecting-noncollecting, collecting-cathode and collecting-housing).

When examining the ^{137}Cs spectrum taken with the parallel-plate xenon detector, one can see that at energies below about 300 keV, there is a sharp rise in the number of counts per channel. A review of the open literature shows this effect is present in nearly all high-pressure xenon gas detectors. One theory for this "tailing" effect is that since the electron drift velocity is quite low in xenon gas, any photon that deposits energy in two locations will contribute to two low-energy channels in the spectrum instead of one high-energy channel. This could happen if a photon undergoes an initial Compton scattering event, and then the scattered photon is absorbed via the photoelectric effect. The energy depositions could be far enough apart in space that, due to the slow electron drift velocity, the moving charges created in each event would induce signals on the cathode at times separated by more than the amplifier's shaping time. This would, in effect, create two separate low-energy events in the spectrum. In a conventional detector, the electrons would move fast enough to create only one high-energy event in the energy spectrum.

To test this theory, simulations using the Geant4 code were performed. In Geant the parallel-plate detector's geometry and gamma-ray source conditions were modeled as accurately as possible. Using this setup, two energy spectra were collected: one in the conventional mode where all energy deposited by a primary photon is summed and then the spectrum is updated; a second where all separate energy deposition events are added to the spectrum individually. If the theory is correct, this simulation would show two spectra that differed greatly in both the number of counts in the photopeak and in the shape of the Compton continuum at low energies. The simulation results are shown in Figure 3, and do not support the hypothesis of the previous paragraph. The reduction in photopeak counts from the "summing" spectrum to the "separated" spectrum is 30%, and the change in the Compton continuum is not significant. A rough manual calculation using detector dimensions and xenon physical properties yielded a guess that the reduction should be on the order of 16%, which is roughly in agreement with the simulation results.

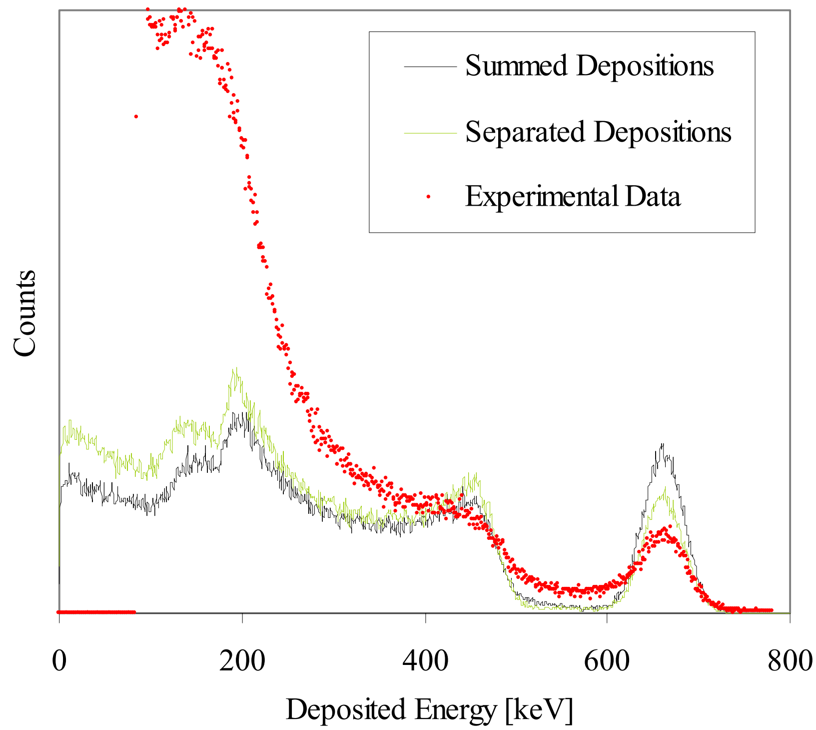

Figure 3. Simulated and experimental ^{137}Cs gamma-ray source energy spectra.

From the simulation results, it seems unlikely that the separation of energy deposition events in time is the reason for the low-energy tailing in high-pressure xenon chambers. Furthermore, experimental results by Bolotnikov and Ramsey[1], measured using a detector very similar to the parallel-plate detector in gas density and geometry, do not exhibit this low-energy tailing effect. The data presented in their publication lends support to our conclusion that the electron transport properties of xenon gas are not the reason for the low-energy tailing, since a fundamental physical property such as the electron mobility would not change from experiment to experiment. It is more likely that the cause of the tailing does not originate in the gas, with one possible reason being electrode design, for example.

Summary

From the experimental results, it is clear that the coplanar grid readout technique will work in high-pressure xenon gamma-ray spectrometers. However, more studies will be necessary to investigate the surface noise between anode electrodes, and how to optimize the design of the coplanar grid anode to achieve low capacitance in a gas chamber having a large detection volume. More studies on the design of the anode will be needed in order to advance this concept further to achieve better energy resolution in the future.

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[1] Bolotnikov, A., and Brian Ramsey (1997). "Improving the Energy Resolution of High-pressure Xe Cylindrical Ionization Chambers." IEEE Transactions on Nuclear Science **44**(3): 1006-1010.

Publications of this project

Ph.D thesis: "Single polarity charge sensing in high pressure xenon using a coplanar anode configuration," Clair J. Sullivan. October 2003. University of Michigan. [Dr. Sullivan is now a staff member at Los Alamos National Laboratory].

"A High Pressure Xenon Gamma-Ray Spectrometer using a coplanar anode configuration," C.J. Sullivan, Z. He, G.F. Knoll, G. Tepper, D.K. Wehe, Nuclear Instruments and Methods in Physics Research A505 (2003) 238-241.