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**TECHNICAL REPORT**

# Alternative connection scheme for PMTs in large, low energy LXe detectors

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ABSTRACT: In particle-astrophysics large liquid xenon detectors are used for Dark Matter Search, and these detectors seem continuously to grow in target mass. Specially developed PMTs fulfill all the requirements for an efficient light read out, however, as the number of PMTs increases the connection of the signal and HV lines to the outside world becomes more problematic; feedthroughs and connectors are difficult to realize within the limited space of a detector, and coaxial cables can trap many impurities afterwards to be released into the clean liquid. We propose the use of flexible Kapton strip lines combining the signals and anode HV from 32 PMTs in one 2” wide, 0.004” thick band. We compared a 1.5 m long, unshielded strip line with coaxial cable of the same length. Minimal changes to the base are required without any risk of additional impurities or radio activity. The quality of the signal is compatible.

The HV connections can be easily realized without additional capacitors on the base by grounding the second but last dynode. This reduces the voltage on the anode to less than 300 V, compatible with the strip line specifications. All the cathodes are connected to one common negative HV. Such a scheme does not cause cross talk and preserves the possibility to adjust the gain of each PMT separately.

KEYWORDS: Instrument optimisation; Instrumental noise; Dark Matter detectors (WIMPs, axions, etc.); Special cables

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## 1 Introduction

Historically nearly all liquid xenon (LXe) detectors were used as ionization chambers [1], although the qualities of LXe as efficient scintillator were recognized long ago. The light, however, was used only as trigger with PMTs mounted outside the detector volume, coupled by UV quartz windows. The large difference in refractive index made the light collection very inefficient. Note that the equivalent of optical grease to improve the coupling of the PMT to the window does not exist, neither for the vacuum ultraviolet (VUV) wavelength of xenon scintillation (178 nm), nor for cryogenic temperatures (-100°C).

The first experiment to overcome the light collection problem was the MEG experiment [2] using newly developed VUV sensitive metal-channel PMTs specifically designed to be immersed directly into the liquid. In the mean time several such PMT models are available for efficient light detection in liquid xenon with a quantum efficiency above 30 % at 178 nm.

Recently many large LXe detectors are projected or in operation for Dark Matter (DM) search [3]. Such experiments can exceed an active xenon mass of 1 ton required to detect the scarce light from nuclear recoil events occurring with very low cross sections. Arrays of many PMTs cover large portion of the surface. For example, the PandaX-I detector [4] has 180 PMTs, the XENON100 detector [5] has about 250 PMTs and XMASS [6] even 641 PMTs. A large number of PMTs then creates a challenge for the cabling, for connectors, and for the feedthroughs. For example, the XENON100 detector contains about 2.7 km of cables within the clean volume of the detector.

To achieve the required noise immunity and to limit cross talk many coaxial cables are regularly bundled together. The bases of the PMTs are in direct contact with the liquid xenon, and so are the cables, at least partially. The cables must therefore meet the stringent requirements for purity and low radioactivity like all other materials close to the active volume of the detector. With so many connections the cables form large bundles. Trapped air or impurities on the surface are not so easily removed from inside the bundles. Additionally, routing the cables is problematic since a bundle of many even thin coax cables can make up a considerable diameter. Twisted pair cables or even better flexible strip lines would simplify the installation and servicing of the detector.

They are widely used in industrial equipment, but normally with a 110 Ω impedance for balanced transmission. Such cables, however, are not rated for the HV range of PMTs.

For flexible Kapton strip lines multipin connectors are readily available, and the connection density is much larger than for coaxial cables. Finally, Kapton is proven not to affect the purity of liquid xenon. In our tests we used a line offering 34 pairs in a 46 mm wide, 0.1 mm thick Kapton band.

## 2 Experimental test set up

For all the experimental tests a 1” square PMT [7] was used, a model which is also used in some DM searches [4, 5, 8]. The PMT is mounted on a base with a resistive divider, a standard circuit originally suggested by the manufacturer of the PMT. This circuit is shown in figure 1, and figure 2 shows a photo of the assembly as mounted in our test set up on an ISO flange inside a 4” diameter tube. On the other end of the 30 cm long tube another ISO flange carries a LED[1] with a light diffuser out of Teflon (PTFE). The construction is like a vacuum vessel, but can easily be opened to implement changes and guarantees that the PMT and LED are in a light tight volume.

The PMT is located in close proximity of the feedthroughs. A SHV feedthrough is used for the cathode HV connection, and 2 pins of a small instrumentation connector are used to connect the signal via flying wires. Since this connection is very short no attempt was made to match the impedance. On the outside either a 1.5 m long coaxial cable (RG174) can be connected or the Kapton strip line of the same length. In order to avoid the additional costs of a new design, a layout previously prepared for the CERN WA105 experiment is used. The strip lines were manufactured at the CERN PCB Workshop. The length of 1.5 m is the original design length, and a maximum of 2 m length can be manufactured at CERN. No connectors are mounted on the strip lines, and short pieces of wires are soldered directly to make the connections.

The pulse transformers [9] at the other end are taken from a commercial Impedance Converter circuit [10] which converts up to 16 channels of balanced signals to 50 Ω coax of the read out electronics. It proved unnecessary to use a pulse transformer on the PMT base. It is therefore not necessary to verify the radioactive background or the purity of the pulse transformers.

The pulse height of the LED driver was set arbitrarily. To get an understanding of the signal strength during our experiment figure 3 shows a background subtracted single photo electron (SPE) spectrum taken with the strip line. The standard pulse height used afterwards in all the tests corresponding to about 7 PE.

## 3 Signal read out with strip lines

Any changes to the PMT base and the connections have to be compared with a standard circuit, in our case the base of figure 1. With a somewhat arbitrary setting of the HV supply and the LED driver we observe a ‘standard pulse’ corresponding to 7 photoelectrons as shown in figure 4. This pulse shape was acquired with a 1.5 m coaxial cable, the same length as our strip line. The pulse looks as expected, and small impedance mismatches are negligible.

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[1] Driven by a CAEN model C529 LED driver, a CAMAC module modified for manual control.

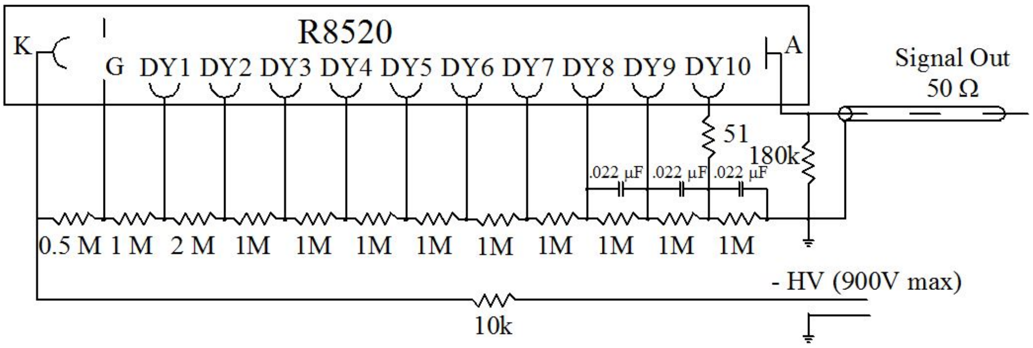

**Figure 1**. Circuit diagram of the PMT base used in the tests. The original circuit is read via a 50 Ω coaxial cable.

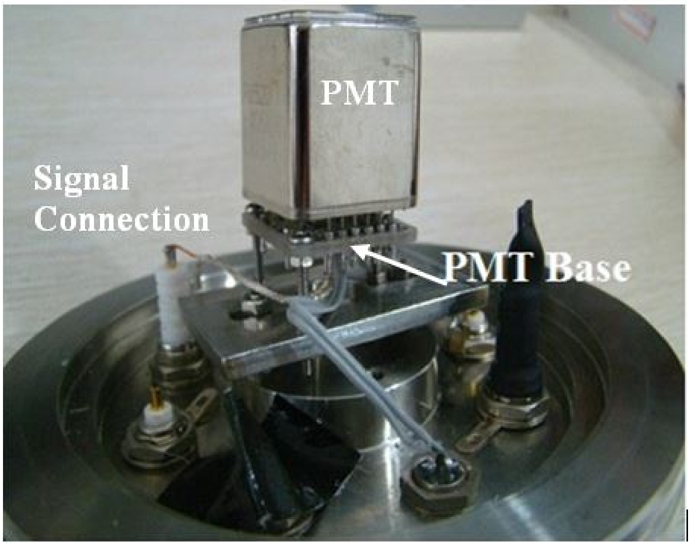

**Figure 2**. Photo of the PMT base connected to a Hamamatsu R8520 PMT.

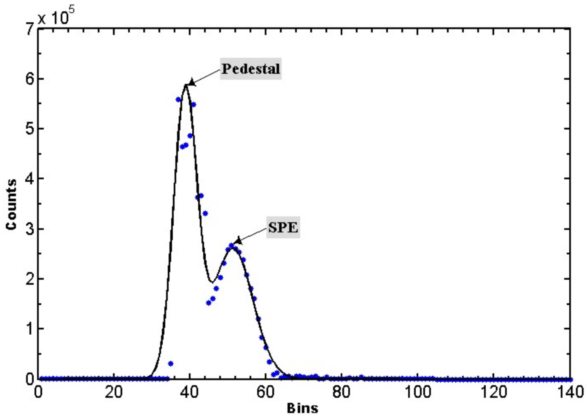

**Figure 3**. Noise subtracted SPE spectrum.

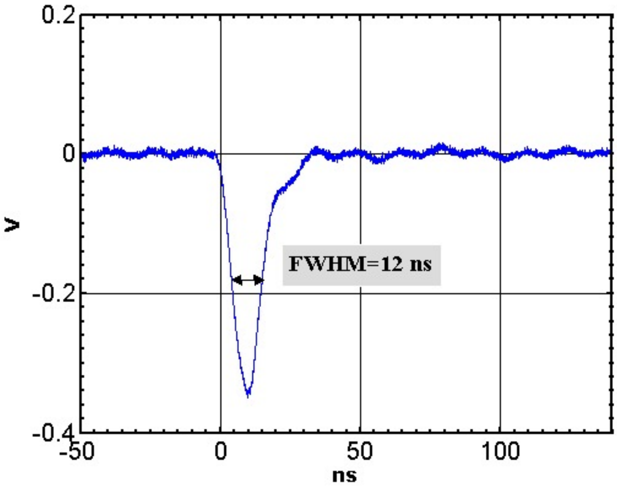

**Figure 4**. Standard pulse read out with a coaxial cable.

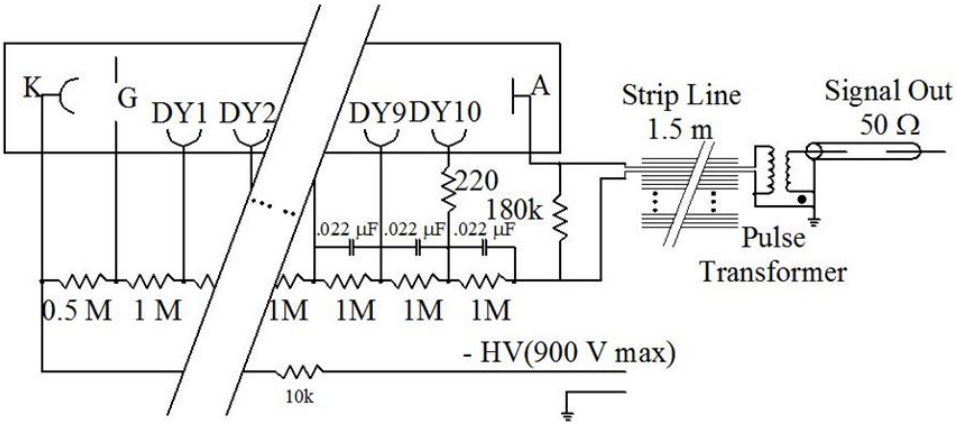

**Figure 5**. Diagram of the base after conversion to strip lines, 1.5 m long.

The anode of a PMT collects the electron current originating in the last dynode. For an optimal pulse shape the resistor to the last dynode has to be adjusted. Experimentally we determined that 220 Ω would give the best results with the least amount of reflections or signal deformation. The final circuit with this resistor is shown in figure 5. We would like to point out that the change of the resistor was the only modification to the base. Figure 6 is a photo of the set up also showing the arbitrary positioning of the strip line.

Figure 7 shows a representative pulse obtained with the strip line. The shape looks slightly longer, i.e. there might be an integration of the pulse, however, it is still a very fast pulse with a width of the same order as the original. The pulse shape looks good and the base line is stable, despite the fact that the strip line is not shielded. Furthermore there are small pieces of wiring between the strip line and the base. These wires were now introduced for convenience in connecting the strip line. In a future set up these connections would be replaced by a printed fan out of the channels, connected to the bases via standard Zero Force Insertion (ZIF) connectors. Although an impedance mismatch, the impact of the short wires is minimal in our case.

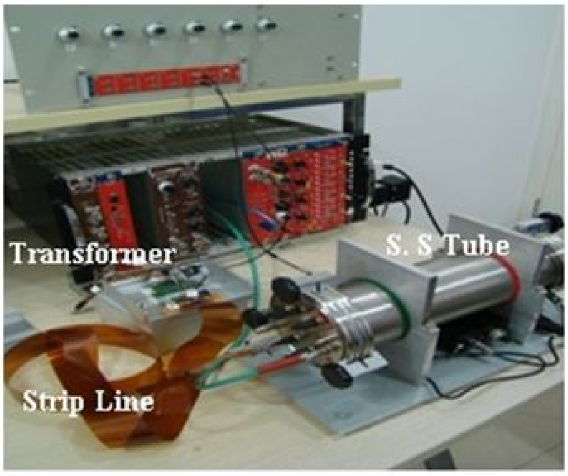

**Figure 6**. Photo of the test set up with strip line read out. The strip line is unshielded.

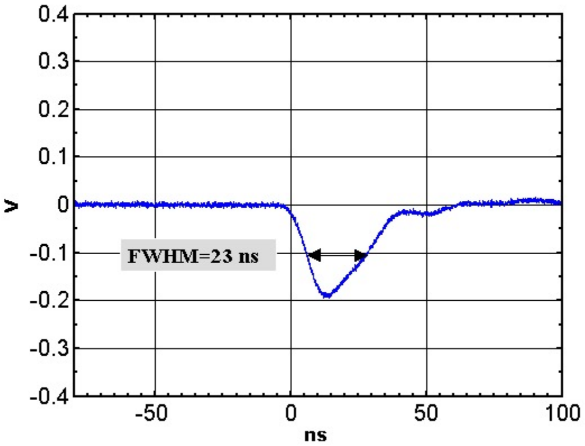

**Figure 7**. Signal observed with a strip line read out. The signal can be compared with figure 4.

The stability of the base line would tell the noise immunity. In figure 3 the pedestal had a sigma of 2.4 ADC channels from a Gaussian fit. The pedestal subtracted SPE line is at 12 ADC channels, i.e. the noise is of order 20 % of a SPE. Better shielding of the end connections would reduce this value, but a single electron is the smallest signal to be observed, and already in the present set up the noise immunity is sufficient.

A major concern with the strip line is cross talk since there is no additional shielding to the signal connection. For the pulse height of figure 7 the signal on the neighboring pair was measured to be about 0.4 %, and even lower on the subsequent strip. If this remaining cross talk should be of significance it can be defeated by separating the signal lines and use only every second strip pair. The two unused strips can be grounded. This signifies, however, practically four strips are used for each PMT, two signal strips and one ground strip on either side. Our strip line has 34 pairs, sufficient for 32 PMT, or 16 PMT in case the ground strips are implemented.

The use of a pulse transformer also helps with noise filtering. The frequencies involved in creating a pulse are very high, and the transformer has the right impedance, but for much lower frequencies such as introduced from power supplies, the few turns of the winding act as a direct short circuit. Also base line variations are thus effectively suppressed.

## 4 HV supply and grounding of base

The signal read out is not the only challenge in the design of large LXe detectors. The HV distribution is another problem. It must be possible to control the gain of each PMT, i.e. each PMT requires an additional HV cable, although there are schemes to supply the HV via the signal lines.

There is a subtle difference between strip lines and coaxial cables. In a strip line nothing distinguishes the 2 strips from each other, whereas in a coaxial cable the outer shield has to be connected to the ground of the assembly. Thus, instead of connecting one strip to ground, it can also be connected to a DC HV, which is still an analog ground. The full anode HV, however, would be too high a potential difference, if not for the strip line itself surely for many commercially available connectors and feedthroughs. The anode has to be on a much lower potential with respect to the assembly ground, i.e. the steel vessel, etc. This can be easily accomplished by grounding the second but last dynode instead of the cathode, Dynode 8 in our 10 stage PMT. Nothing in the physics of PMTs prevents such a solution. In this scheme all cathodes can be on a single HV supply, e.g. -600 V in our set up, and the anode is on +250 V for a total potential difference between anode and cathode of 850 V, as used before. Such a connection scheme is shown in the circuit diagram of figure 8.

The resistor ladder is now split into two parts, a Cathode part and an Anode part. With the much lower current flowing in the cathode part of the PMT also the current in the resistive ladder can be much smaller for the same stability of the potentials. We therefore can increase the resistor values in this part of the ladder by a large factor 5–10. Choosing 10 MΩ instead of 1 MΩ for each resistor in the cathode ladder and leaving the anode ladder with 1 MΩ resistors reduces the dissipated power from 7.2 mW to 0.13 mW per PMT. The gain of each PMT can still be adjusted separately by adjusting the anode HV. In the extreme case, a PMT even can be turned off by removing the anode HV when it disturbs the data acquisition. Figure 9 shows our standard pulse with the new HV scheme. As expected choosing a different point for grounding (in this case Dynode 8) does not affect the pulse shape. Figure 9 shows our standard pulse observed with the new HV connection scheme and also with the strip lines. As expected, the different grounding did not change the pulse shape.

## 5 Conclusion

Large LXe detectors with a xenon mass above 100 kg, such as used for Dark Matter search employ hundreds of PMTs for the detection of the very low light levels of nuclear recoils. Routinely these PMTs are connected via coaxial cables which can trap a lot of impurities. The practical disadvantages of coaxial cables can be avoided by the use of Kapton strip lines. The changes in the base circuitry amounts to adjusting one resistor value. On the outside of the detector a pulse transformer restores the 50 Ω impedance to connect standard electronic read out modules.

The use of strip lines suggests a change in the grounding scheme of the PMTs to use the second-but-last dynode as DC HV ground. This does not change the response of the PMT signals,

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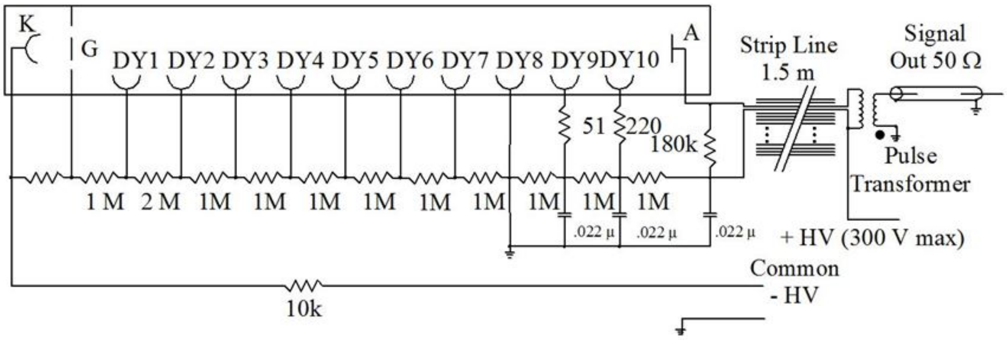

**Figure 8**. Circuit diagram of the base with split supply connection.

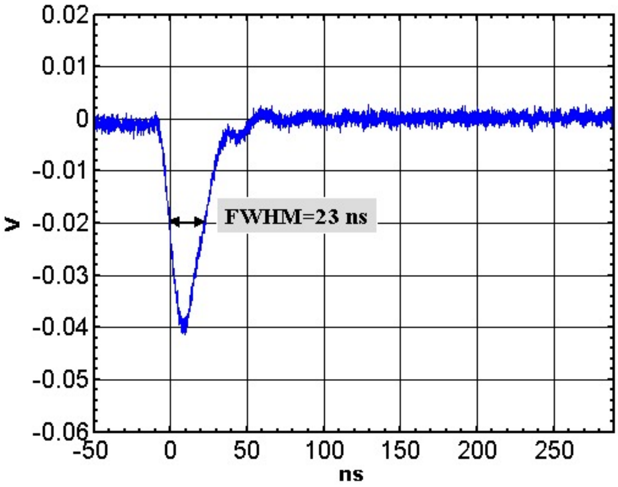

**Figure 9**. Signal observed with split supply connection.

but reduces the anode voltage well below 300 V, i.e. to a value supported by a typical strip line and many commercial multipin connectors and feedthroughs.

The changes to an existing base design and layout are minimal. In particular the radioactivity of the base is unaltered since the single transformer per channel is mounted outside of the detector, right in front of the read out electronics. In our example, 32 PMT can be connected with a strip line 4.6 cm wide and 0.1 mm thick.

## Acknowledgments

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