A light readout system for gas TPCs

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ABSTRACT: A novel light detection scheme has been tested for use in medium-pressure gas TPCs, in view of rare events searches in low energy particle physics. It has the advantage of minimal interference with the ionization collection system, used for track imaging. It provides an absolute time reference, which allows an absolute determination of the Z coordinate of events, along the direction of the drift field. This makes possible a fiducial cut along the Z-axis, allowing to reduce the background from the ends of the drift volume.

KEYWORDS: Time projection Chambers (TPC); Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs etc); Scintillators and scintillating fibres and light guides

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1 Introduction

Time projection chambers (TPCs) have shown to be powerful tools in low energy particle physics. Gas TPCs at moderate pressure allow to visualize precisely the particle tracks produced in interactions and decays, recording the spatial development of the ionization signal. This makes a stringent selection of events possible, with a corresponding background suppression. This was demonstrated in the search for neutrinoless double beta decay in $^{136}$Xe in the Gotthard underground laboratory [1]. This feature will be exploited as well in the NEXT experiment [2], searching for the same decay. The study of $\nu_e e^-$ scattering at the Bugey reactor [3] also took advantage of that.

The X and Y spatial information, in the plane perpendicular to the drift field, is provided by a position sensitive readout plane at one end, acting as anode, opposite to the HV cathode. The Z coordinate, parallel to the drift field, is reconstructed from the drift time of the ionization charge to the anode. One problem, in non accelerator experiments such as those listed above, is the lack of absolute time reference for the events, so that no absolute Z coordinate reconstruction along the drift direction is possible. This is problematic, as most background sources are located in the materials surrounding the fiducial volume. The cathode is in general quite contaminated, if traces of radon, in particular $^{222}$Rn, are present in the gas of the TPC. Positive ions produced in the decay of $^{222}$Rn and its daughters, starting with $^{218}$Po, can drift to the cathode where they stick. Without absolute Z coordinate, it is impossible to establish a fiducial cut eliminating events from the cathode. To a large extent, the same is true of the anode, a potential background source for similar reasons.

Moreover an absolute Z determination may be useful in a large size TPC to estimate possible charge losses along the drift path, and calculate a correction, in order to improve the energy resolution.
Depending on the gas filling the TPC, however, it is possible to observe the primary prompt scintillation light accompanying the production of ionization charge. This can provide a time reference, leading to an absolute Z coordinate of events. Achieving that is not completely obvious, as gas amplification is necessary to observe tracks from minimum ionizing particles, which requires the addition of a quench gas in many interesting cases. The quench gas may absorb the scintillation light. A careful choice is thus necessary.

A second problem is the position of the light sensors, whether classical photomultipliers, Avalanche Photodiodes (APD) or Silicon Photomultipliers (SiPM). One classical solution is to place them behind the cathode, or anode, made of wire grids with reasonable light transmission. This geometry was adopted in many TPCs using liquid argon or xenon. But this imposes constraints on the anode and cathode construction, which can be problematic. For instance readout planes with micropatterns such as Micromegas [4], which offer great flexibility, cannot be used. Also the solid angle is restricted. Placing the light sensors directly on the side is difficult because of the high electric field gradient.

In this paper we report on tests of a scheme allowing to detect the light on the side of the TPC, with little interference with the ionization collection system. It uses light guides on the sides, coated with a wave length shifter absorbing the primary scintillation light, and converting it to longer wavelengths [5]. A large fraction of the light emitted in the solid angle for total reflection reaches the ends. One end is instrumented with SiPM light sensors, in a region with no or little electric field. A diffuse white reflector at the other end, with a gap, reflects back part of the light, which is retrieved.

We concentrated our tests on two gases suited for use in TPCs. The first is xenon with 1-2 % CF$_4$. This choice was motivated by a possible future study of neutrinoless double beta decay in $^{136}$Xe. The addition of CF$_4$ was shown to give good ionization amplification with Micromegas readout planes [6], to suppress charge diffusion, and to increase the ionization drift velocity. CF$_4$ is expected to be transparent to the primary VUV scintillation light of xenon centered around 175 nm [7]. The second gas which was investigated was pure CF$_4$, which is known to scintillate in a wide range of wavelengths, with a broad peak in the UV, and one in the visible. CF$_4$ has a relatively low Z, with corresponding low multiple scattering leading to straighter tracks, which can be an advantage [3, 8]. For comparison we also studied pure argon, which scintillates in the VUV, with a maximal emission around 128 nm, lower than xenon. The measurements were made at a pressure of 300 kPa, at which particle tracks, even at sub-MeV energy, develop sufficiently to be reconstructed.

2 Experimental set-up

The tests were performed in a small TPC with a fiducial volume of 10 cm diameter, and 20 cm long, housed in a steel vessel. The vessel can be pressurized up to 500 kPa. The fiducial volume is delimited by a field cage made from a Micromegas ionization readout plane acting as anode at one end and a cathode made from a mesh on a frame at the other one. Flat field shaping rings between the cathode and the Micromegas plane guarantee the field uniformity. Rectangular holes are machined in the cathode frame, through which the light guides are inserted. They are located inside the field shaping rings. In total 22 light guides can be deployed, although the tests discussed...
Figure 1. Left: the TPC, with (1) the location of the Micromegas plane (not shown), the field shaping rings (2), the cathode (3), the light guides (4), the grounding disc (5), the SiPMs (6) and their preamplifiers and power supplies (7). Right: the 12 light channels, in green, which were instrumented during the measurements of cosmic muons.

in this paper were done with 12 guides only for practical reasons. The cage is in the vertical position, with the readout plane at the bottom, and the cathode at the top, as shown in figure 1. The gas is constantly circulated through an Oxysorb® filter and a cold trap in the form of a coil made from copper tubing immersed in a cooling agent maintained at -70 °C.

The ionization amplification and readout plane of the TPC is of the bulk-Micromegas type [9]. The gap between the mesh and the resistive layer is 128 µm. The readout plane contains pixels, which are connected to form orthogonal X and Y readout strips read out separately. The pitch is 3.1 mm and the active diameter 10 cm, giving $31 \times 31$ strips. These provide the X and Y information. The Micromegas plane is connected by custom-made flat cables to transimpedance preamplifiers located outside the vessel.

2.1 Light guides

The dimensions of the light guides are $10 \times 3 \times 260$ mm. Two materials were considered for the light guides, polystyrene and UV transmitting acrylic. Both exhibit an acceptable transmission for the UV light, down to 200 nm for the former [10], 300 nm for the latter [11]. A wavelength shifter from UV to visible Tetraphenyl-Butadiene (TPB), which was shown to have a good efficiency, was chosen [12, 13]. The emission spectrum peaks at 450 nm.

At the emission peak of xenon, and argon, the transmission of either acrylic and polystyrene is limited. For this reason the TPB was deposited in thin layers on the surface. The technique
Figure 2. Left: dark counts in a SiPM, the 1, 2, 3 and 4 photoelectron pulses are easily visible; right: the end of a light guide, coated with TPB, with two SiPM’s glued on.

described in ref. [14] was adopted. A mixture of TPB and polystyrene pellets in the proportion of 1:3 were dissolved in toluene (50 ml of toluene per gram of polystyrene). The light guides, acrylic and polystyrene, were dipped for a few seconds, and then allowed to dry. The polystyrene guides were found to be somewhat hazy near the surface in spots. In further tests, when exposed to vacuum, TPB crystallization was observed. For that reason polystyrene was abandoned, and all subsequent work was done with the acrylic-based light guides. These are very clear, have a nice finish, and stand vacuum. The surface TPB doped film is estimated to be less than 10 µm thick, which corresponds to a TPB density of less than $2.6 \times 10^{-4}$ g/cm$^2$.

2.2 Light sensors

We used SiPM light sensors made by Hamamatsu, with a sensitive area of 3×3 mm. The models S10931-050 P (3600 50 µm×50 µm pixels, fill factor 61 %) and S10931-100 P (900 100 µm×100 µm pixels, fill factor 78 %) were used. Early tests were also carried out with model S10362-33-050 C, similar to the S10931-050 P, but with a ceramic casing. The 900 pixel version was finally preferred, because of the better fill factor, which leads to a maximal photon detection efficiency of 73 % at 440 nm. It drops to 48 % for the 3600 pixel SiPM’s. In any case the sensitivity well matches the emission spectrum of TPB. These SiPM’s can easily resolve 1, 2, 3 and 4 photoelectron pulses, as shown in figure 2. This makes calibration fairly easy.

The SiPM’s are glued to the end of a light guide with optical cement. Only one ceramic casing SiPM can be mounted on a light guide. With the other types there is room for two (figure 2). The other end of the light guide rests against the support of the Micromegas readout plane, made from Teflon, and acting as diffuse reflector. The SiPM’s are placed well behind the cathode of the TPC (figure 1). To minimize the electric field around them, a disc with a 5 cm diameter central hole, at ground potential, was placed in front of them.

The pair of SiPM’s of each light guide is fed by the same power supply subunit. The two outputs are connected in parallel to a single high speed transimpedance preamplifier. The power supply regulation and the preamplifiers for all the SiPM pairs are mounted on a circuit board placed be-
hind the SiPM’s. The voltage applied to each SiPM pair can be adjusted from outside, in the range
72±10 V, to match the gains, nominally at $2.4 \times 10^6$. To reduce the dark current, the preamplifiers
can be cooled. The case around them is connected, via copper bands, to a tube in which a cooling
agent consisting of a mixture of glycol and water circulates. The temperature is monitored with
PT100 probes. The temperature of the cooling agent is adjusted so that the SiPM’s are maintained
at 15 °C.

3 Tests and characterization of the light detectors

The light detectors, each composed of a light guide and its light sensors, were tested in various
configurations. First measurements were performed with a radioactive $\alpha$ source and with through-
going cosmic muons to characterize the light detectors. During these, no voltages were applied to
the TPC cathode or to the Micromegas amplification system; there was thus no drift field. Finally
a drift field was applied, and the Micromegas readout plane was used to simultaneously measure
the ionization of the events.

3.1 Tests with an $\alpha$ source

The first tests were performed with two guides, one instrumented with one S10362-33-050 C SiPM,
the other one with two S10931-050 P SiPM’s, and inserted in adjacent positions as described above.
An $^{241}$Am 5.6 MeV $\alpha$ source with an activity of 37 kBq was placed inside the TPC vessel, on
the symmetry axis of the field cage. It could be moved vertically using a remotely controlled
mechanism. In the upper position, at 300 kPa of xenon, the $\alpha$ tracks were contained in a volume
not seen by the light guides. In the lower position, the source was between the grounding disc and
the cathode. The light guides were outside of the range of the $\alpha$’s to avoid direct hits.

The singles rate in the SiPM’s is fairly high due to dark counts. At an arbitrary pulse height
threshold, the coincidence rate between the two light detectors was measured to be 0.2 s$^{-1}$ with
the source in the upper position. It rose to 72 s$^{-1}$ with the source in the lower position. This
demonstrates that the light guides convert a good fraction of the VUV scintillation light of the
xenon to visible light, which is then detected by the light sensors. No difference was observed
between measurements performed with pure xenon, and a mix of 98 % xenon and 2 % CF$_4$. This
clarifies that CF$_4$ does not absorb the VUV light from xenon.

Tests were also conducted with pure argon and pure CF$_4$ at 300 kPa. With these gases however,
part of the $\alpha$ tracks end in the volume seen by the light guides, even with the source in the upper
position. This reflected in a higher coincidence rate (about 20 s$^{-1}$ in CF$_4$). Nevertheless, with the
source in the lower position, a significant coincidence rate increase was observed (50 s$^{-1}$ in CF$_4$).
This demonstrates that our light detectors can be used in these gases as well.

3.2 Tests with cosmic muons

To be more quantitative and to measure at lower energies, we studied the response of our TPC to
cosmic muons. For practical reasons, 12 light detectors only were used for these tests, leaving 10
stations empty, as depicted in figure 1. The guides were instrumented with two 10931-100 P SiPM
each. To minimize the light losses, a Teflon reflector was added between the field shaping rings and
the light guides. A 1 cm gap was left between its lower edge and the Micromegas readout plane
to allow for gas circulation. Four groups of 3 adjacent light detectors were fanned-in together, and
In a first step nearly vertical muons were selected, with two external scintillators above and below the TPC. The coincidence signal of the external scintillators was used as trigger and time reference. The light produced in the fiducial volume of the TPC (20 cm long) and in the gap between the cathode and the grounding disc (5 cm) has a good probability of reaching one of the light guides. The longest possible path of muons in the active volume for light is thus 25 cm. On average this reduces however to about 20 cm, corresponding to an energy deposit of 460 keV for minimum ionizing muons in 300 kPa of xenon.

Coincidences between the external scintillators and the light detectors were clearly seen. To get a first idea of the response, the averaged signal of the sum of all 4 groups, or 12 light detectors,
was produced on an oscilloscope using the external scintillators as trigger. The result is displayed in figure 3. Xenon with 2 % CF$_4$ is seen to give a very fast signal, with a rise time of order 20 ns. With argon a fast component is seen, accompanied by a slower one, with a decay of the order of 1 µs. The CF$_4$ signal is somewhat slower than that of xenon. The total light collected, taking into account the slow argon component, is comparable in all three gases.

To be more quantitative the signals of the 4 groups were sent to a 12-channel charge sensitive ADC. The ADC was calibrated using the 2 and 3 photoelectron peaks, visible in figure 4. For the study of cosmic muons, the ADC was gated by the external scintillators. Events in which all 4 groups had at least one photoelectron were kept. The sum spectrum of all 4 groups for 300 kPa of xenon with 2 % CF$_4$ is shown in figure 4. A clear muon peak is seen. Relaxing the cut on the number of groups with at least 1 photoelectron adds events at low energy, but does not change the position of the peak. The maximum, corresponding to minimum ionizing muons, is around 15 photoelectrons. Considering that these muons deposit roughly 460 keV, we conclude that we observe some 32 photoelectrons per MeV. Knowing that in xenon gas, it takes 72±6 eV to create one primary photon \cite{15},$^1$ our system is seen to have an overall efficiency of roughly 0.5 %. Taking into account the 73 % photon detection efficiency of the SiPM’s, and the 66 % coverage of the light guide end by the SiPM’s, this gives a 1.0 % efficiency for primary photon collection, wavelength conversion and secondary photon collection. With a threshold at the 3 photoelectron level, assuming Poisson statistics, a 5 photoelectrons pulse has a nearly 90 % probability of being detected. We thus conclude that we have a good detection efficiency above 150 keV.

Similarly, the average number of photoelectrons detected for a nearly vertical cosmic muon in CF$_4$ at 300 kPa was measured, and found to be of the order of 20.

### 3.3 Operation in the TPC

Finally, keeping the same configuration, the TPC was turned on. Here all measurements were done with xenon and 2 % CF$_4$ at 300 kPa. First the cathode was raised to -15 kV with the Micromegas grid left at ground which gives a drift field of 750 V·cm$^{-1}$, or 2.50 V·cm$^{-1}$·kPa$^{-1}$. The measurement of the averaged signal of the 12 light detectors using the external scintillators as cosmic muon trigger, presented in section 3.2 for no drift field, was repeated. It was found that the light signal is not affected by the electric field at this moderate pressure. A decrease in light induced by the electric field, suppressing electron-ion recombination, has been observed at higher pressure (see ref. \cite{16}).

Next the cathode voltage was set at -15.9 kV, and the Micromegas grid raised to -925 V, yielding the same drift field of 2.50 V·cm$^{-1}$·kPa$^{-1}$. In that configuration, the light detectors measure, in addition to the primary scintillation light, the copious secondary light produced in the avalanche in the Micromegas gap during the charge amplification process. The two types of light pulses are separated in time, except for events passing through the anode.

First we again investigated nearly vertically through going muons, tagged by the external scintillators as in the preceding section. The light pulses are nearly rectangular, with a length corresponding to the total drift time across the drift volume. The average pulse is shown in figure 5.

$^1$This value of $W_s = 72\pm6$ eV taken from \cite{15} at Xe pressures between 100 and 300 kPa differs significantly from $W_s = 111\pm16$ eV \cite{19} (100 kPa) and $W_s = 23.7^{+7}_{-6}$ eV \cite{18} (4000 kPa). It is worth noting that these measurements were performed using different radiation sources and at different Xe pressures.
Figure 5. Averaged light pulse, dominated by the secondary avalanche light, due to nearly vertical muons in the TPC filled with xenon with 2% CF$_4$ at 300 kPa. The differentiation of the preamplifier was not corrected for. The vertical dotted red lines indicate the start and the end of the pulse. The 33.4 $\mu$s time difference corresponds to the total drift time across the 20 cm long drift volume.

The time difference between the leading edge and the trailing edge is 33.4 $\mu$s, corresponding to the total drift time from cathode to anode, separated by 20 cm. This leads to a drift velocity of 0.60 cm $\cdot$ $\mu$s$^{-1}$, in good agreement with Garfield calculations [17].

Finally, to demonstrate that the primary light pulse can be used to determine a time zero reference, the two external scintillators were moved, in order to select muons with a zenith angle around 45°. A number of these leave the fiducial volume of the TPC sideways, before reaching the Micromegas readout plane.

Two examples are given in figure 6. The small primary light signal, in coincidence with the signal from the external scintillators, is clearly visible. So is the secondary light, the time evolution of which follows that of the ionization signals from the Micromegas readout plane in both the X-t(Z) and Y-t(Z) projections of the events. In the top event a $\delta$ electron is visible, in the light channel as well as in the ionization channels.

With our coordinate system (Z=0 is on the anode), a muon enters from the right (in reality top) and travels to the left (bottom). The time delay between the prompt scintillation and the leading edge of the secondary light signal allows to determine the Z coordinate at which the muon left the fiducial volume through the side. The precision is given by the rise time of the secondary light signal, of order 200 ns, much slower than the primary light signal.

For the top event, the delay is 4.50±0.20 $\mu$s, corresponding to Z=2.70±0.12 cm. Similarly, using the trailing edge of the secondary light pulse, one sees that the muon entered the fiducial volume at Z=9.35±0.12 cm.

The segment of track has a total length of 9.5 cm, corresponding to an energy deposit of 220 keV, assuming the muon to be minimum ionizing, and neglecting the $\delta$ electron.

The bottom event shows a muon entering the fiducial volume at Z=8.57±0.12 cm and leaving it at Z=3.00±0.12 cm. The length of the track segment is 7.5 cm, corresponding to an energy deposit of order 175 keV.

In both cases, the primary light signal is of the order of a few photoelectrons, in agreement with the energy deposited.
Figure 6. Two cosmic muons with a zenith angle around 45°, selected by the external scintillators, which give the time reference; shown are the time evolution of the light signal (bottom) and the X and Y ionization signals from the Micromegas; the primary scintillation light signal in coincidence with the external scintillators (dotted vertical red line) at time zero is small but clearly visible, as well as the secondary light pulse which follows; the latter is in good correspondence with the X-t(Z) and Y-t(Z) projections of the events reconstructed from the ionization signal. In the top event a $\delta$ electron is visible in both the light and ionization channels.

4 Conclusion

We have demonstrated the feasibility of a light readout system suited for gas TPCs. It uses light guides mounted on the side of the TPC. They have a thin coating doped with TPB, to shift the VUV
primary scintillation light, produced by many popular gas fills such as argon, xenon and CF₄, to visible light, which is in turn measured with SiPM’s. Good detection efficiency is achieved with our set up down to 150 keV, at which 5 photoelectrons are seen. It should be possible to enhance the signal and lower further the detection threshold by improving the coverage. For practical reasons we only mounted 12 light guides, while 22 could be installed. It might be interesting to look for ways to make the TPB coating somewhat thicker, to improve the conversion efficiency from VUV to visible. Success is not guaranteed however, because of the short absorption length of VUV light in polystyrene.

We have also shown that the secondary light produced in the amplification avalanche in the ionization readout anode, in our case a Micromegas, is easily detected. The time difference between the prompt primary pulse and the leading edge of the secondary pulse provides a precise absolute determination of the event position in Z, along the drift field. This solves a long-lasting problem in the operation of gas TPCs in rare events searches at low energy. Here also it may be interesting to investigate if the measured secondary light can be used to improve the measurement of energy.

Our tests were conducted at 300 kPa, a pressure at which low sub-MeV tracks develop sufficiently to do tracking. Working at a higher pressure should be easy with the light readout system. The measurement of the ionization would be more problematic. We operated the Micromegas at the maximal gain, before discharges occur. The maximal achievable gain decreases with pressure. It must be said however that our preamplifiers on the ionization channels do not have the lowest possible noise. Improvements are possible on that side.

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