MainzTPC: A Time Projection Chamber for the Study of Liquid Xenon Light & Charge Response

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This proceeding is an overview on the development and construction of a dual-phase liquid xenon time projection chamber in Mainz. It will be used for the measurement of the scintillation and ionization yield of electronic and nuclear recoils of xenon atoms in a scattering experiment across a wide range of energies. In addition, we aim at measuring the pulse shape of the scintillation light with high bandwidth and study its suitability as a discrimination method for background events.

1 Introduction

One of the most promising generic candidates for Dark Matter is the Weakly Interacting Massive Particle (WIMP). A recent review on direct WIMP Dark Matter detection can be found in [1]. Direct detection experiments seek to measure the recoil of WIMPs scattering off target nuclei in the detector. The currently most sensitive class of such experiments consists of dual-phase xenon time projection chambers (TPCs) such as XENON100, shown schematically in Fig. 1. The latest results of XENON100 can be retrieved from [2].

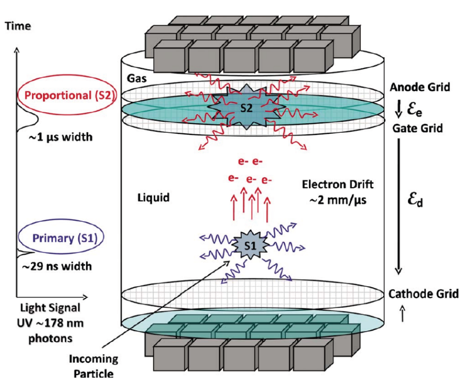

Figure 1: 1: Principle of a dual-phase LXe TPC [6].

The energy deposited in the target material in such an interaction is in the keV range, therefore high sensitivity and a good understanding of the background are crucial for the measurement.

If a particle (e.g. a WIMP) scatters in the liquid xenon (LXe), the deposited scattering energy leads to excited and ionized xenon atoms, resulting in a prompt scintillation signal and free electrons. While the scintillation light is detected as S1 signal by the photomultiplier tubes (PMTs) on top and bottom of the TPC, the electrons are forced to drift upwards in an applied electric field. For this three thin meshes are used to apply the high voltage, a cathode mesh at the bottom, an anode mesh at the top and a gate mesh just a bit below the anode mesh. The phase transition from liquid to gaseous xenon (GXe) is sited in the middle between gate and anode. The electrons encounter a higher electric field between

gate and anode and are extracted to $\approx 100\,\%$ into the gas phase, where they are accelerated additionally. This leads to a proportional scintillation called S2 signal which is primarily seen by the upper PMT array.
Using the time difference between S1 and S2 and the electron drift velocity, the z-coordinate of the interaction point can be determinated. Furthermore, the x-y-position of the interaction can be read out by the illumination pattern of the S2 signal on the top PMT array. This provides a 3D position reconstruction, allowing the definition of a fiducialized volume inside the LXe and discrimination of single vs. multiple site events. This volume is chosen to reject interactions in regions near the edges of the TPC where influences of electronics, electric field inhomogeneities and other background sources are most likely. Further information on the working principle of Dark Matter searches with xenon TPCs can be found in [6].

2 Liquid xenon low-energy response and scintillation pulse shape

Background discrimination is a crucial factor in Dark Matter search experiments. Therefore a well-founded knowledge of the possible background is necessary. One distinguishes between electronic recoils, caused by gamma-rays or electrons, and nuclear recoils, which result from neutron or WIMP scattering. The Mainz TPC is designed to examine two different approaches for discrimination.
After the scattering of a particle in LXe, the xenon atoms form excimers and dimers, respectively, and eventually deexcite, recombine and decay to ordinary xenon atoms. By dimer deexcitation, scintillation light is produced. Different types of recoil lead to different population of singlett states (with decay time $\tau_\mathrm{S} = 2.2\,\mathrm{ns}$) and triplett states ($\tau_\mathrm{T} = 27\,\mathrm{ns}$) of the xenon excimer, hence the shape of the primary scintillation signal S1 depends on the interaction type. Therefore the scintillation light will be measured with fast electronics to investigate pulse shape as discrimination criterion.
Furthermore, the ratio between prompt scintillation light S1 and free electrons, leading to the proportional scintillation signal S2, is dependend on the scattering process; for electronic recoils S2 is much larger than S1 while for nuclear recoils less electrons are produced and therefore S2 is reduced. This is already used for background discrimination in e.g. XENON100. The best approach to measure energy and discriminate between nuclear and electronic recoils consists of a 2D analysis in S1 and S2 simultaneously. This, however, requires precise knowledge of scintillation and charge yield at low energies, where measurements so far are incomplete or imprecise. The Mainz TPC will be used to probe low-energy recoils down to $\approx 2\,\mathrm{keV}$ with high precision.

3 TPC design

The TPC design is optimized for a Compton scatter experiment. This means especially that the active volume is relatively small with only 52 mm in diameter and 50 mm in height to reduce multiple scattering. Due to this small dimensions it is impossible to have an array of PMTs on top and bottom, hence just one cylindric 2 inch-diameter PMT is used on top and bottom each. This has additionally the advantage that there are no gaps between different PMTs resulting in a higher light yield of the TPC. To achieve x-y-position resolution by measuring the S2 signal, which is not possible using just one PMT, we added an array of 8 large area avalanche photodiodes (APDs) surrounding the liquid gas interface looking inwards. The active volume is surrounded by a PTFE cylinder, as PTFE is highly reflective for VUV wavelength. Besides this, the construction design was chosen to have the least amount of passive materials possible.

3.1 Electric field

The electric field is produced by meshes with a wire-width of only 14 μm and a pitch of 268 μm. Four meshes are implemented: A shield mesh above the bottom PMT to avoid influences of the electric field on the readout, the cathode mesh at the lower end of the active volume, at the upper end the gate mesh below the liquid gas interface, and the anode mesh just above. A mesh shielding the top PMT was not implemented, since we will use negative high voltage on the cathode and ground potential on the anode so that there is no field influence on the top PMT.

The uniformity of the electric drift field is crucial to get clean data sets. Nonuniformities would require corrections to the reconstructed interaction position in z and r for some parts of the active volume and might also require to decrease the size of the fiducial volume to avoid edge effects. To make the electric field as uniform as possible, a flexible printed circuit board with parallel conduction lines is used as electric field cage (brown cylinder in Fig. 3). The geometrical properties for the meshes as well as for the field cage were examined in finite element simulations. According to these the meshes and PCB were designed/chosen and we can achieve a very uniform drift field with deviations of the field in the outermost corners of the active volume of less than $\approx 5\,\%$ for very low drift fields (0.1 kV/cm). For stronger drift fields (3 kV/cm) the deviation is below 1%.

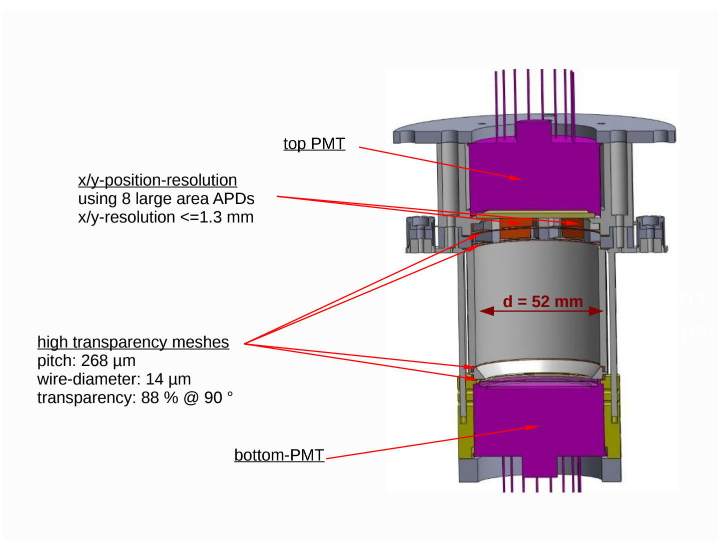

Figure 2: CAD section drawing of the TPC design.

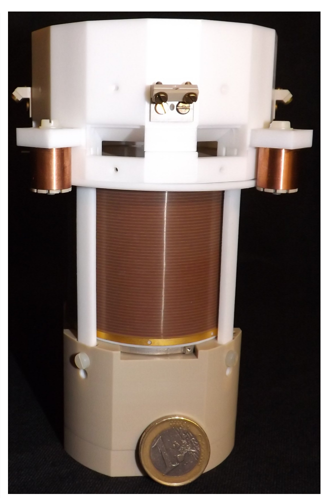

Figure 3: Photograph of the assembled TPC without photosensors.

3.2 Light readout

The PMTs have been chosen for their compact design, their fast response and their high quantum efficiency (> 30%, stated by manufacturer [4]) in the VUV wavelength regime.
As mentioned before the PMTs in our TPC cannot be used for x-y-position resolution and therefore the APDs are introduced. Avalanche photodiodes provide relatively high internal gains ($\sim 10^3$), small housing and only little passive material while providing suitably large active areas (>1 cm^2) [5]. The APD model we use has been measured to achieve QE of > 30 % at 178 nm in [7] and gains up to several 1000.
Both PMTs and APDs have to be characterized since their performance strongly depends on bias voltage and temperature and also because each device has slightly different properties which have to be taken into account for high precision.

3.3 Simulations

The classical Compton scatter experiment uses the scattering angle to determine the energy deposit in the scattering target (in this case the active volume of the xenon TPC) by using the Compton formula. Experimentally this is done using a scintillation detector (e.g. NaI) to measure the scattering angle. However, especially for low energy deposits (small angles) this method leads to large uncertainties due to the fact that the Compton formula only applies for electrons at rest. Bound electrons in an atomic potential have a certain momentum which has to be taken into account and results in a statistical smearing of the deposited energy for fixed angles.
This effect, called the Doppler effect, has been examined in a Geant4 simulation (see Fig.: 4). The plot shows the relative energy resolution for the deposited energy in the active volume, the red curve being the smeared resolution obtained by the angle measurement, in black the Doppler broadened resolution for a perfect angle measurement and in blue the resolution with a germanium detector which measures the scattered energy directly. As can be seen, the energy resolution for the direct energy measurement with the Ge detector is far better than for measuring the scattering angle. Therefore a Ge detector is implemented in the Mainz TPC setup as an improvement compared to some of the previous work by other groups.
Another simulation carried out was the study of the x-y-resolution for the 3D position reconstruction using the above mentioned APDs. In a Geant4 simulation we compared different numbers of APDs and different sizes. The simulations, based on code developed and tested for XENON100 [8], showed for a configuration of eight 13x13 mm^2 APDs a reconstruction error of less than 1.3 mm in the whole TPC (see also Fig.: 5). The z-position resolution was not simulated, as we expect it to be at least as good as in XENON100.

3.4 Electronics

As one of the main goals of our TPC is to measure the S1 pulseshape, we require very fast response of the photosensors and need accordingly very fast digitizers. That is the reason why we decided to use a 5GS/s 10bit FADC to digitize the PMTs signals. This will allow us to precisely measure the fast and slow decay time constant.
To make use of the good energy resolution of the Ge-detector it is necessary to use a digitizer with low noise and large dynamic range. Therefore a 16bit FADC will be used.

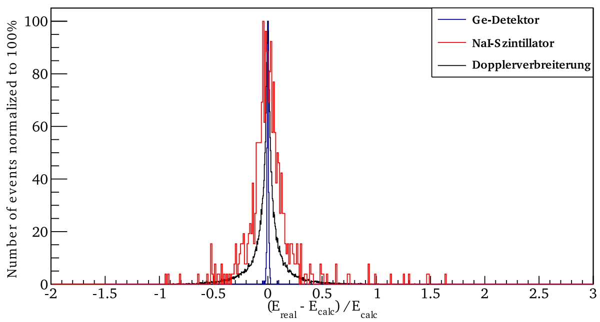

Figure 4: Comparison of simulated energy resolution with germanium (blue) or NaI (red) as secondary detector. [9]

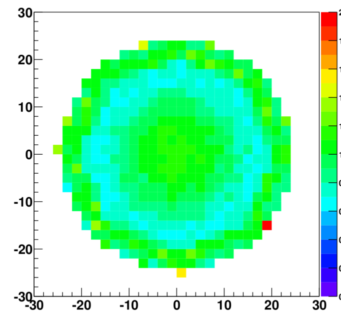

Figure 5: Position reconstruction error.

4 Summary & Outlook

The MainzTPC is designed to measure the liquid xenon light and charge response of low-energy electronic and nuclear recoils, including the pulse shape of the primary scintillation light. These measurements aim to improve our understanding of interaction signatures in direct Dark Matter searches with xenon, as well as to better discriminate backgrounds. The design of the TPC and the measurement setup for the Compton scatter experiment have been optimized with Monte Carlo and finite element simulations. Much of the hardware is already in place, while some components are still being worked on. First tests with the MainzTPC are planned for early 2014, and we hope to report on first measurements at the PATRAS 2014 meeting!

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