August 31, 2020

Optical readout of MicroPattern Gaseous Detectors: developments and perspectives

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Scintillation light readout of MicroPattern Gaseous Detectors (MPGDs) is a powerful alternative readout approach exploiting state-of-the-art imaging sensors. MPGD structures operated at high gain in suitable gas mixtures, which feature visible light emission, are coupled to low-noise optical imaging sensors to record accurate representations of incident radiation. The high pixel count of commercially available CCD and scientific CMOS cameras allows for a **pixelated readout with good spatial resolution** for intricate event topologies. Advances in the sensitivity of imaging sensors as well as the availability of **ultra-high-speed cameras** open up new avenues for optical readout for future experimental needs as well as instrumentation challenges. Possible benefits of optical readout for the readout of Time Projection Chambers (TPCs) for **3D track reconstruction** as well as for **beam monitoring** are presented in the context of recent developments and novel technologies.

MPGD-based detectors with optical readout are used for applications such as nuclear decay studies [1], proton spectroscopy [2] and nuclear astrophysics studies [3] as well as 2D dose imaging in hadron therapy [4, 5] and radiation imaging including X-ray fluorescence [6] and high-resolution computed tomography (CT) [7]. A number of new experimental endeavours also exploits the advantages of optical readout for **rare event searches** with **optical TPCs** at the core of the CYGNO project for directional dark matter searches [8] as well as the DMTPC detector [9] and the Migdal project employing a hybrid readout approach with **combined optical and electronic readout** [10].

Optically read out TPCs benefit from the advantages of scintillation light readout in combination with MPGDs at their endcaps. Optical elements including **lenses and mirrors** can be used to guide light from the detector structure to the imaging sensor, facilitating the **coverage of large active areas** as well as the **placement of sensitive imaging sensors** away from high radiation dose environments. Detailed 2D track projections are recorded and can be combined with auxiliary timing information from fast photon detectors to obtain 3D particle trajectories. Alternatively, the width and energy deposition profiles of tracks recorded in optical 2D images can be used to extract depth information in large TPCs with good accuracy by using the ratio between signal amplitude and track width as a measure of drift distance and thus interaction depth [11] or by combining a transparent electronic readout anode for timing information with scintillation light readout for fine-grained 2D images [12].
The integrated imaging approach of digital imaging sensors delivers detailed images without the need for extensive event reconstruction. This comes at the expense of limited frames rates with conventional CCD and CMOS devices delivering on the scale of tens to hundreds of frames per second at megapixel resolution. Novel **ultra-high-speed CMOS sensors** overcome this limitation and achieve frames rates of up to **25,000 images per second** at megapixel resolution and up to **1 million frames per second** at reduced resolution. With these inter-frame intervals on the order of a few to tens of microseconds, **resolving drift time differences in TPCs** becomes feasible and 3D track reconstruction without the need for auxiliary timing information from additional readout devices may be possible. While typical drift durations in electron drift TPCs remain challenging for the current generation of ultra-high-speed cameras, **negative-ion TPC readout** with commercially available fast imaging sensors could enable high-granularity 2D pixelated image sequences encoding drift time differences with good depth resolution. Scintillation light emission from **GEM-based detectors** in negative-ion-drift gas mixtures containing **SF_6 or CS_2** has been

demonstrated [13] and drift times on the **millisecond scale** would correspond to tens to hundreds of frames recorded by ultra-high-speed CMOS cameras if sufficient gain and light emission intensity can be achieved. This can potentially enable accurate 3D reconstruction of arbitrary track topologies with high spatial resolution in the XY plane and good Z-depth resolution with a **single readout device** and scalability to large active areas with suitable optics.

In addition to TPC readout, recording scintillation light from MPGDs can also be valuable for realising **low material budget beam monitoring** devices which can record **fine-grained pixelated beam profile** and intensity images. Placing only thin detector components in the beam path minimises attenuation as well as multiple scattering. Cameras used to record emitted scintillation light can be placed outside of the beam path and coupled to the detector with thin foil mirrors. This not only minimises the material budget in the beam but also avoids direct exposure of the imaging sensor to the beam to mitigate radiation-induced damages. Beam monitoring with optically read out MPGD-based detectors is highly versatile and compatible with a **wide range of beam parameters**. In addition to integrated beam measurements taken at low frame rates, such detectors can also rely on ultra-fast CMOS cameras to **stream real-time beam profile or position** measurements. In this case, the high spatial resolution of acquired images can be used to identify detailed structures in beam profiles and provide high resolution beam tracking. If only certain measurements and beam parameters are of interest they may also be directly extracted from images by **real-time image processing** implementations in FPGAs or GPUs to decrease the output bandwidth and retain only information of interest.

Single event detection, particle track reconstruction and beam monitoring are among some applications which can exploit optical readout of MPGD-based detectors to acquire high-resolution images. Recent advances in fast imaging sensors overcome previous frame rate limitations and can enable novel readout approaches for optical TPCs as well as performant beam monitoring instrumentation.

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