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The planispherical chamber: A parallax-free gaseous X-ray detector for imaging applications

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ABSTRACT

Crystallography or X-ray fluorescence experiments which require good signal to noise ratios and high position resolution can take advantage of the outstanding signal amplification capabilities of MicroPattern Gaseous Detectors (MPGDs) such as Gaseous Electron Multipliers (GEMs) coupled with the position resolution achieved by optical readout realized with CCD or CMOS cameras. Increasing the detection probability of incident radiation with thicker drift volumes in these detectors leads to a spatial resolution-limiting parallax error when employing parallel electric field lines in the drift region.

We describe a new GEM-based detector concept, consisting of a cathode, GEM electrodes and field shaping rings suitably segmented and powered to create a radial electric field, thus minimizing the parallax error. A CCD camera is used to record scintillation light originating from charge multiplication in the high field of the GEM holes in an Ar/CF$_4$ (80/20%) gas mixture. Assembled as pinhole camera, the device permits to obtain high detection efficiencies for soft X-rays, exempt from the parallax error intrinsic in the use of standard gaseous detectors with thick conversion layers. The use of several GEMs in cascade allows for high charge multiplication factors. Switching from straight to radially focused drift field lines, a significant reduction of the parallax error as well as an increased signal-to-noise ratio were achieved, effectively paving the way for applications such as X-ray crystallography realized with optically read out GEMs.

1. Introduction

Structural analysis methods such as crystallographic studies by X-ray diffraction or X-ray fluorescence imaging require radiation detectors, which can combine excellent position resolution with strong signals. MicroPattern Gaseous Detectors (MPGDs) such as Gaseous Electron Multipliers (GEMs) [1] have been proven to allow for strong signal amplification as well as a good inherent position resolution [2] and are employed in a number of fields ranging from high energy physics [3,4] and imaging applications [5,6] to medical radiography [7,8].

Recent developments in imaging sensors have made optical readout of MPGDs an attractive concept for achieving high position resolution coupled with reduced sensitivity to electronic noise and a simple way of obtaining visual representations of ionizing radiation without the need for complex front-end electronics and extensive reconstruction algorithms. Several studies and developments demonstrate the potential of the combination of optical readout with MPGDs [9–11].

In the application of gaseous detectors for X-ray crystallography or X-ray fluorescence, a limiting factor is the value of the absorption length, which increases with photon energy. The ensuing lower efficiency can be compensated by the use of thick conversion layers; for non-parallel photon fields, however, this introduces a substantial parallax error resulting in loss of resolution. This error is caused by the uncertainty in the depth of the initial ionization in the gas by the incident radiation in the case of parallel electric field lines as shown schematically in Fig. 1(a).

In an Ar-filled detector at 1 bar, at an incidence angle of ten degrees to the normal, the parallax error is 5 mm for a 3 cm drift gap, while providing a modest 20% efficiency for 10 keV X-rays. This has to be compared to the sub-mm intrinsic resolution of modern MPGDs [12]. Operating at high pressures or with heavier gases such as Kr or Xe reduces these errors but results in technical complications and higher costs.

The parallax error can be reduced by the use of special cathode geometries but remains substantial [13]. A way to overcome the

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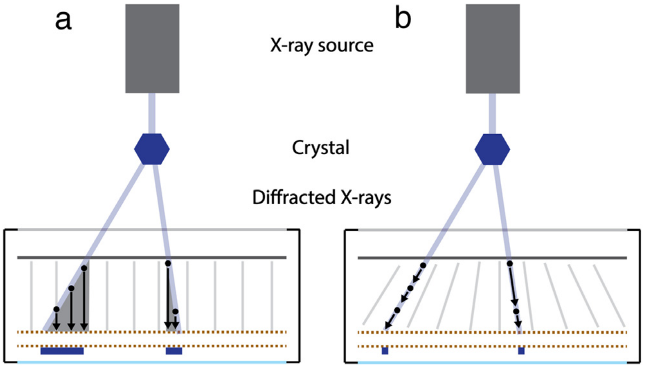

Fig. 1. Parallax error causes broadening of signal in GEM-based detector with thick drift volume in X-ray crystal diffraction measurement. (a) Parallel drift field lines result in signal broadening. (b) Radially focused drift field lines mitigate the parallax error and preserve position resolution.

problem is to record the time of the conversion from the gas scintillation emitted in the primary interaction and deduce the penetration depth from a measurement of the drift time of the ionization electrons. Owing to the small photon yield of the process, this has been successfully achieved only in Xe-filled devices such as the scintillating drift chamber, consisting of a gaseous counter coupled to a photomultiplier detecting both the primary fluorescence and the secondary emission during charge multiplication in high fields [14]. A similar approach constitutes the basis for detection of small energy losses in liquid-Xe time projection chambers designed for rare events physics [15]. The development of GEM detectors with a thin-layer CsI photocathode deposited on the electrodes, sensitive to UV photons above 5.8 eV, has permitted to demonstrate the possibility of recording the time of conversion and detecting the primary scintillation as well as the main ionization charge within the same structure [16]. Requiring a Xe filling, however, the approach remains limited in applications.

Alternatively, the parallax error can be mitigated by constructing a detector with radially focused electric field lines in the conversion volume between a semi-spherical cathode and a mesh. In this case, the ionization charge can subsequently be transferred to a planar amplification structure using a multiwire proportional chamber [17]. Such a device named a spherical drift chamber was successfully used for many years in the analysis of macromolecules by studying X-ray diffraction patterns [18].

A recent development makes use of thermally deformed spherical GEM electrodes to achieve radially focused drift field lines and minimize parallax-induced broadening [19]. In addition to manufacturing difficulties, the spherical GEM foils require specially designed readout electronics and are not ideally suited for optical readout.

While all these previous developments have employed electronic readout and were limited by manufacturing or technical difficulties, we present an experimental demonstration of the simplicity and versatility of combining a planispherical GEM detector achieving radially focused drift field lines with segmented electrodes as shown in Fig. 1(b) with optical readout to realize a fast and stable detector with minimized parallax-induced broadening, which is well-suited for X-ray diffraction and fluorescence imaging applications. Furthermore, the presented design also allows for adjustable focal lengths for increased flexibility and universality.

2. Experimental methods

Two segmented GEM foils, a segmented cathode together with a segmented field shaper and a borosilicate viewport below the second GEM were assembled around a circular POM frame forming the gas volume of the detector, as shown in Fig. 2(a). The segmented GEMs feature five separated ring-shaped electrodes, a circular active region with a diameter of 10 cm and holes with a diameter of 70 μm at 140 μm pitch and were manufactured with a double mask etching technique. The connections to the individual electrodes were routed asymmetrically to the outside of the active detector volume to allow for a minimal dead area due to solid Cu tracks when operating in a dual-GEM setup. Fig. 2(b) shows a schematic representation of the employed GEM layout; Fig. 2(c) is a picture of the assembled detector.

The ring-shaped segments of the cathode and of the first GEM as well as the field shaper were connected at graded potentials with values determined so that the field lines in the 25 mm thick drift region radially focus on a point 10 cm away from the cathode. Designing each ring with a different width with thinner rings on the outside, a voltage divider with equal resistors between sectors could be used to power the GEMs. Resistor chains with selected resistor combinations and multiple power supply channels were used to bias all sectors with the potentials determined by simulation to result in optimized radial drift field lines, while retaining the flexibility to modify amplification and transfer fields easily. While the segments of cathode, field shaper and first GEM were all at different potentials, the second GEM was used in planar mode, i.e. all segments at the same potential, since only a small and correctable distortion is induced by the moderate nonuniformity of the transfer field between the two GEMs. Use of two GEM foils in cascade permits to obtain large photon yields at moderate operating voltages, thus increasing the safety and stability of operation [1].

A six megapixel CCD camera with a cooled image sensor featuring $4.54 \times 4.54\ \mu m^2$ pixels was placed in a light shielding tube below the borosilicate viewport facing the bottom of the second GEM and used to record the secondary scintillation light emitted during avalanche amplification in the holes of the second GEM. The detector was operated in open gas flow mode with an Ar/CF_4 (80/20% by volume) gas mixture at 1 bar since CF_4 has a secondary scintillation spectrum [20], which closely matches the quantum efficiency of the employed CCD camera.

To verify gain uniformity across the active area and compare it to the case of a standard drift field configuration, flood exposures with parallel incident radiation irradiating the whole GEM area were taken

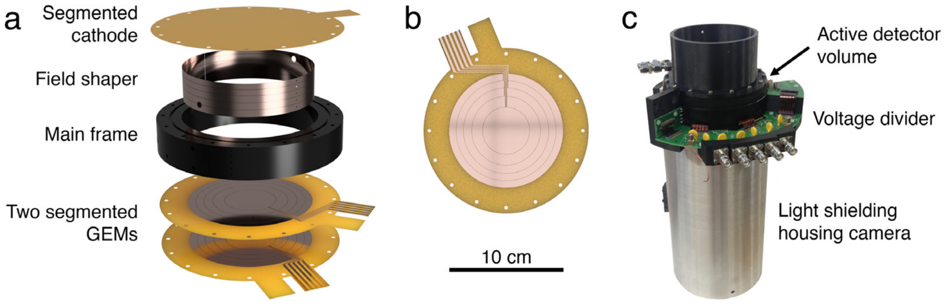

Fig. 2. (a) Exploded view of active detector volume with main frame, segmented cathode, two segmented GEMs and field shaper. (b) Layout of segmented GEM with five ring-shaped electrodes and circular active region with a diameter of 10 cm. (c) Fully assembled detector with light shielding tube housing the CCD camera below the active detector volume as well as the voltage divider and distribution PCBs.